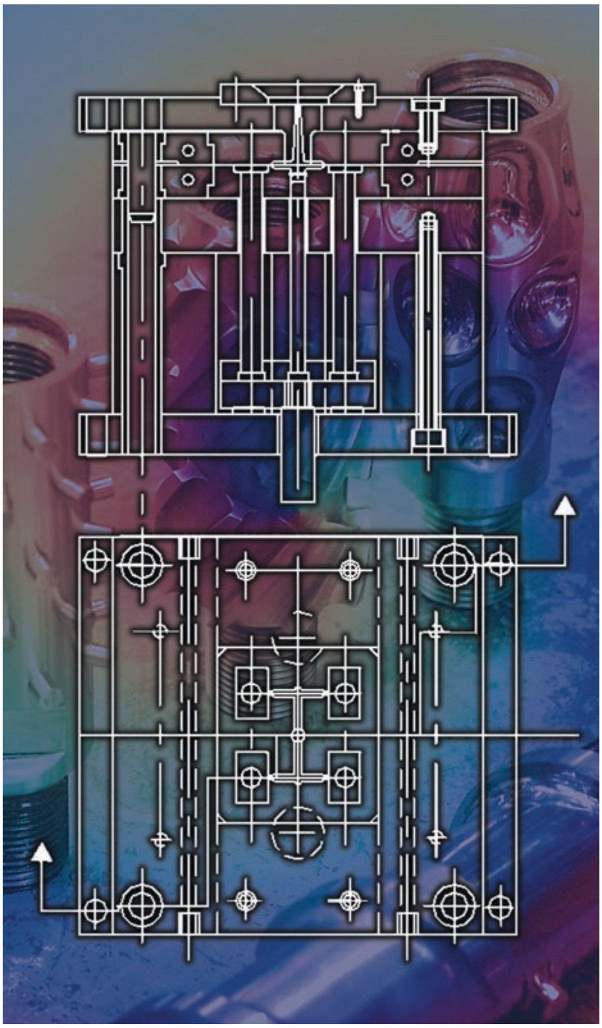
The Mould Design Guide



Peter Jones

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The Mould Design Guide

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Preface

Peter Jones is a practising Consulting Engineer with over thirty five years experience within the plastics industry. He has wide experience of mould tool design, toolmaking, production management and has worked for a number of well-known companies including ICI, United Gas Industries and Smiths.

During his time as an employee he has held positions of Chief Mould Designer, Technical Manager, Production Director and Managing Director–all within the injection moulding industry.

In his capacity as a Consulting Engineer, he has advised several well known national and international companies in the engineering, medical, pharmaceutical, electronic, consumer industries, the oil industry and many others.

Peter has advised on mould design and construction, processing, production and management. In project management roles he has been responsible for setting up complete injection moulding plants for both internal use and as stand-alone units. Several of these have been turnkey projects where all the plant, machines, mould tools and ancillaries and personnel have been provided.

Additionally he has lectured on courses on mould design and injection moulding profitability and related topics to many well-known companies both in the UK and overseas.

The intention of this book is to provide design engineers, toolmakers, moulding technicians and production engineers with an in depth guide to the design and manufacture of mould tools that work successfully in production.

At the end of the day, this is the standard by which the whole design/toolmaking project will be judged. If this can be married with the entire project being profitable–the ideal has been achieved.

The latter point is one that should not be overlooked and kept at the forefront of the design engineer's mind. A wonderful mould tool that produces exemplary quality parts is no good to man or beast unless it results in the injection moulding operation making an acceptable profit from it.

It is recognised that not all design engineers will be able to influence the profitability factor but thinking outside the 'design box' will pay dividends in the future. After all, engineers in this field often progress to become Managing Directors and CEOs.

Peter Jones 28.08.07

1 Introduction

The modern-day injection mould tool is often a complex arrangement of mechanical, electrical, pneumatic and hydraulic components expected to fulfil a range of demanding tasks. Whatever the complexity, the mould design must essentially specify a tool that will operate satisfactorily in production. To achieve this it must meet the following prime objectives:

- It must operate at the required production rate or better and last at least for the predicted design life.
- It must be well designed and produce mouldings to the required specification.
- The design must specify a tool that will operate consistently and be reliable in production. It should not be prone to frequent breakdowns and should not require frequent maintenance or servicing.

These objectives are not simple to achieve. At every cycle, the tool is clamped together under high loads and is subject to high injection pressures and high heat levels from the incoming polymer. During the cooling cycle, the moulding is cooled until it reaches ejection temperature, when the tool opens and the moulding is ejected. All these factors combine to make the mould tool a highly stressed dynamic heat exchanger.

It is important, therefore, to ensure that the mould design takes all these factors into consideration. Additionally, there are several other requirements that need to be considered, among which are the following:

- The number of impressions required
- The type of tool needed, e.g., two-plate, side core, split, multiplate, hot runner and so on
- The mould materials
- The cavity construction
- The required life of the tool
- Temperature control
- The moulding material

The purpose of this book is to address these (and many other issues) and each of these topics is discussed and examined in detail.

It is impossible to design a *successful* mould tool without some knowledge of plastics materials, the injection moulding process, toolmaking and basic injection moulding machine design. For example, it is necessary for the mould design engineer to know what type of gate is required for a particular moulding. This in turn will be dependent on both the material being used and the part geometry. Different materials behave differently and the material being used will frequently influence the mould design. Some materials are corrosive while others may be brittle, or very tough. All of these factors must be taken into consideration at the earliest stages of the design.

Similarly, mould bases and the mould cavities must be designed in such a manner that they can actually be made. The moulds must also be economic to make and operate reliably in production. Therefore, knowledge of basic tool room machining procedures is necessary so that the mould base and impressions are designed with specific machining processes in mind.

Clearly the mould designer must also be reasonably familiar with the injection moulding process and the basic moulding parameters such as runner sizing, gating, machine cycles and the fundamental processing variables such as melt behaviour and so on.

A good knowledge of the basic construction of moulding machines and their operation is also essential so that moulds can be mounted on machines and run successfully. In order to achieve this, the mould designer must be able to understand all the specifications and platen drawings provided by the machine manufacturer.

It is for these reasons that there are revision chapters dedicated to these topics so that that the mould designer has a full account of all the variables that need to be taken into account when designing successful mould tools.

All the major types of mould tools are covered including two-plate, three-plate, split, side core, stack and hot runner. Some less frequently used designs are also discussed including multiplate and rotary side core moulds.

There are additional chapters devoted to stress analysis and fatigue. These topics are not usually included in textbooks on mould design, but there are no apologies for including them in this book. Stress cracking of components and fatigue-induced failure are frequently encountered in production and cost the industry millions of pounds per annum. These chapters are included to try to invoke a more scientific approach to mould design so that a blend of science and experience may be applied for more reliable results. They also provide a means of determining the optimum mass size of the mould tool and its components for maximum economy of production and part quality.

The theme throughout the book is based on design simplicity. The simpler the design of the mould is, the more likely it is to provide trouble-free mouldings.

There are three golden rules in injection moulding:

- Good mould design
- Good-quality toolmaking
- Competent injection moulding

If all three of these can be achieved, all projects will result in success. If any one of them is missing, trouble will result.

The information contained in this book is based on over thirty-five years' experience in the injection moulding industry and on over 3000 successful mould designs. It therefore contains many tips, wrinkles and tweaks discovered over this period included in an effort to equip the reader with information that will contribute significantly to successful mould tool designs and avoid common pitfalls.

The book is essentially a data book that succinctly presents information in a logical, understandable reference form for mould designers, tooling engineers, production engineers and others associated directly or indirectly with injection mould tooling. Many examples of mould designs are included with notes, providing a complete understanding of the principles involved.

There are also many data tables, design examples and a gallery of full mould designs included so that useful information may be referenced quickly. Also included is a glossary of injection moulding terms with a full explanation in each case.

Throughout the book the term ***moulder*** represents the company or department carrying out the injection moulding and the term ***customer*** refers to the end user of the mouldings. The term ***toolmaker*** refers to the company or individual manufacturing the mould tool. The injection mould is variously referred to as ***mould, tool*** or ***mould tool***, all of which are commonly used in the industry.

Please note that this book uses the ISO system throughout except in a few cases where American examples are used that may be specified in the imperial system. It is important to note that the ISO system uses ***newtons***, ***metres*** and ***seconds***.

Consequently, as most mould designs are dimensioned in millimetres, the designer must be aware that all sizes used in calculations must be converted into metres first except where stated otherwise.

2 The Injection Moulding Process

2.1 Background

To produce moulded articles in thermoplastics it is necessary to heat the material to a liquid state, and then force the liquid 'melt' to conform to the shape of a mould. The liquid melt is then cooled, thereby returning it to the solid condition, and removed from the mould.

These operations can be fulfilled by the compression moulding process, but this process is wasteful of both heat and time and is better suited to thermosetting materials, where it is not necessary to cool the material before removal.

The injection moulding process was developed following the principle of pressure die-casting, in which molten metal is forced into a cool mould. JW and IS Hyatt used this principle in their 'stuffing machine', which was patented in the USA in 1872. However, the first machine actually used for production of thermoplastic parts was made in Germany in 1920. The machine was entirely manually operated with no automatic features. In 1927, again in Germany, a machine operated by pneumatic rams was developed, which was able to develop higher injection pressures.

Since then, development has been rapid, especially following the introduction of the reciprocating screw. Modern machines can operate completely automatically without human involvement and can also change moulds and materials automatically. They can also monitor and adjust the moulding parameters (to a limited extent) in an attempt to maintain component quality.

Further developments are taking place with the improvement of control systems. Tie-bar-less machines are now available, and modified injection moulding techniques such as gas-assisted moulding are becoming widespread.

2.2 Machine Design

2.2.1 Machine Base Unit

Often described as the machine 'bed', its function is to provide a rigid base to impart dimensional stability, accuracy and strength. Considering the need for accurate mould alignment and the high stresses during the moulding cycle, it is essential that both the clamp unit and the injection unit be held rigidly in position.

2.2.2 Clamp Unit

This is the part of the machine that carries, closes and opens the mould. It provides the force required to keep the mould closed during the injection phase and it ejects the moulding once the mould is opened.

The clamp unit consists of three plates or platens:

- A fixed, stationary platen on to which is mounted the half of the mould that contains the runner and sprue bush (the fixed or stationary half)
- A moveable platen on which is mounted the other mould half – the one containing the ejection system (the moving or ejection half)
- The tail plate

All three platens are connected through the tie bars. It is on these that the moving platen slides, carrying with it the ejection half of the mould tool. Housed between the tail plate and the moveable platen is the clamping mechanism.

The function of the clamping mechanism is to open and close the moveable platen thus opening, closing and clamping the mould.

The size of the mould tool that can be mounted on a machine is determined by the ***mould height***, the ***daylight*** and the ***distance between the tie bars***. These and other parameters are specified in the machine platen details supplied with the machine.

2.2.3 Mould Height

The thickness or height of mould that can be fitted into a machine is dependent on the amount of ***mould height adjustment*** that is available on the machine. This is the maximum amount of space with the machine toggles closed or the ram fully extended that is available between the fixed and moving platens. The mould height available is dependent on the type of clamping mechanism that is used.

2.2.4 Daylight

The amount of ***daylight*** on a given machine is the furthest distance that the machine platens can be separated from each other. The amount of daylight should be at least twice the depth of the moulding (*d*). This gives sufficient space for the mouldings to fall freely out of the tool.

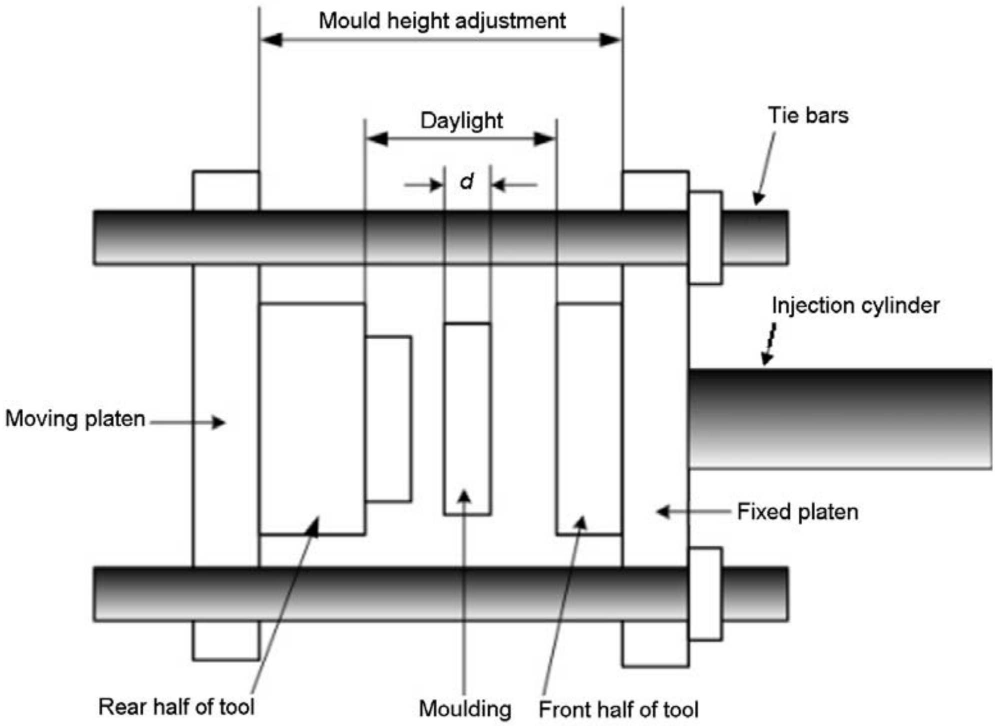


Figure 2.1 Mould Daylight

2.2.5 Distance Between Tie Bars

The internal horizontal or vertical distance between the tie bars also determines the maximum size of mould tool that can be mounted on a machine. Normally the mould is designed so that it will drop down between the tie bars from above. Once the mould has been located in the register ring hole in the platen, it can be secured to the platen directly with cap screws or indirectly with tool clamps.

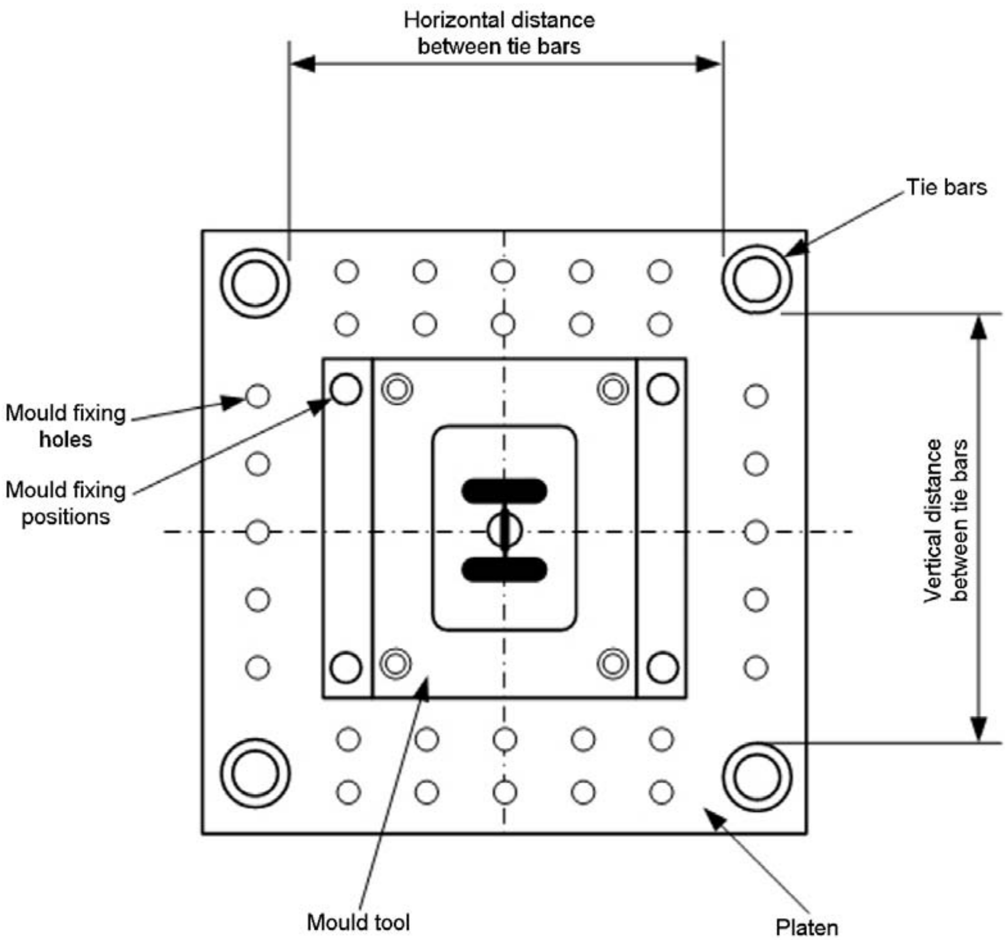


Figure 2.2 Platen drawing for mould fixing

2.2.6 Clamping Mechanisms

There are several types of machine clamping unit designs and each has to be capable of advancing and retracting the moveable platen so that the two halves of the tool can be brought into smooth contact. When the full lock is applied, the two halves of the tool are kept closed under pressure while the molten plastic is injected into the mould and allowed to set.

The most commonly used methods of machine clamping are:

- Toggle mechanisms (mechanical lock)
- Direct hydraulic lock
- Combined mechanical–hydraulic systems

2.2.6.1 Toggle Mechanisms

A toggle joint is essentially a system of links that multiplies the power that is applied to them to deliver the required clamping force.

Toggle mechanisms are divided into two types:

- Single toggle joint clamp
- Double toggle joint clamp

2.2.6.2 Single Toggle Joint Clamp

The single toggle joint, often called a collapsing strut or link, consists of a set of links that are directly actuated by a hydraulic cylinder through the central axis of the injection mould tool.

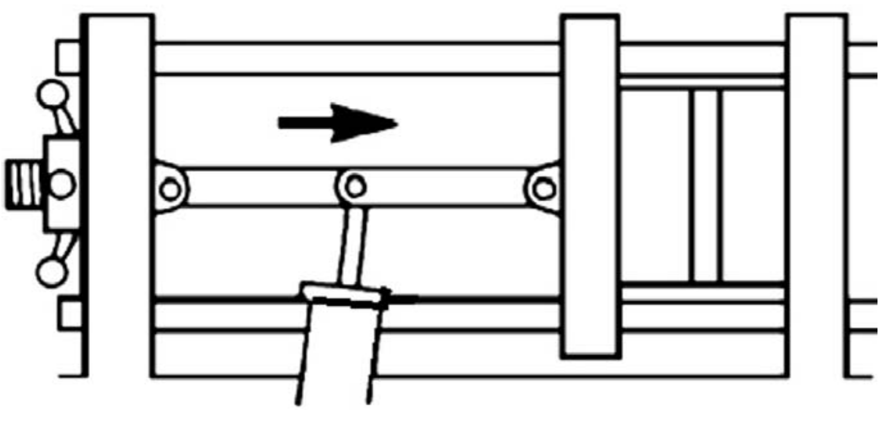


Figure 2.3 Single toggle design – mould closed

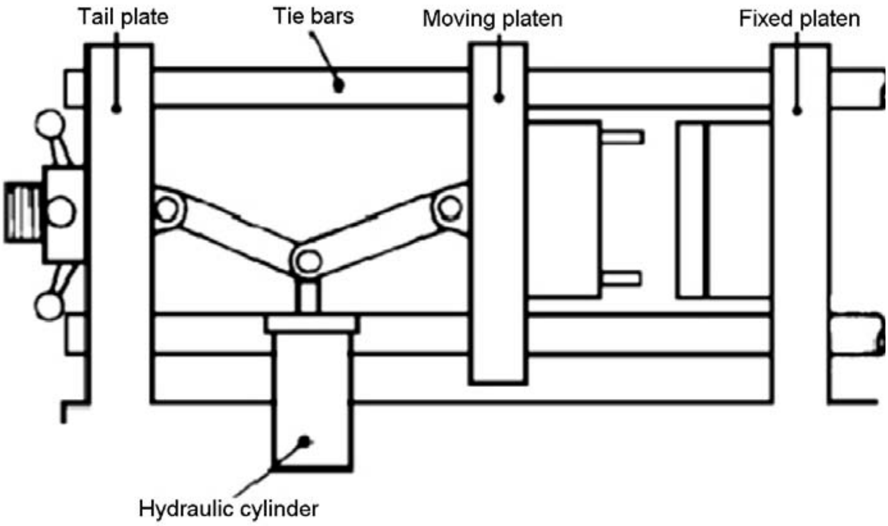


Figure 2.4 Single toggle design – mould open

Mould clamping is achieved by the mechanical locking of the toggles in the straightened position. As the mould is locked, the tie bars are designed to stretch slightly to maintain the clamped condition during the injection phase.

Because considerable forces are exerted on the platens during mould opening and closing, there is a tendency for the platen to tilt. Consequently, such a mechanism tends only to be used on smaller machines (70 tonnes or less).

2.2.6.3 Double Toggle Joint Clamp

The double toggle arrangement eliminates the platen-tilting problem and allows faster platen speeds to be achieved.

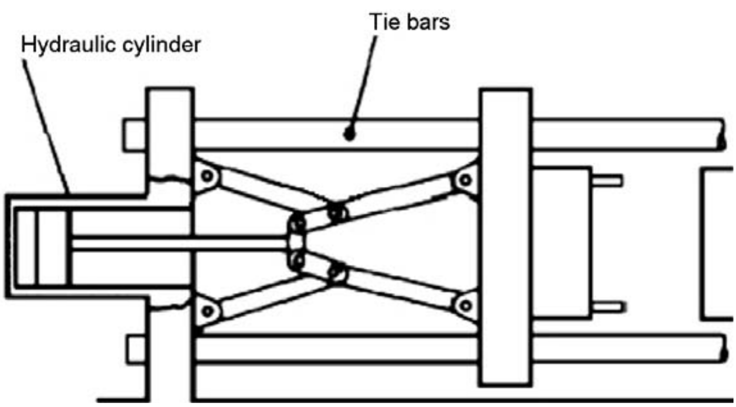


Figure 2.5 Double toggle design – mould open

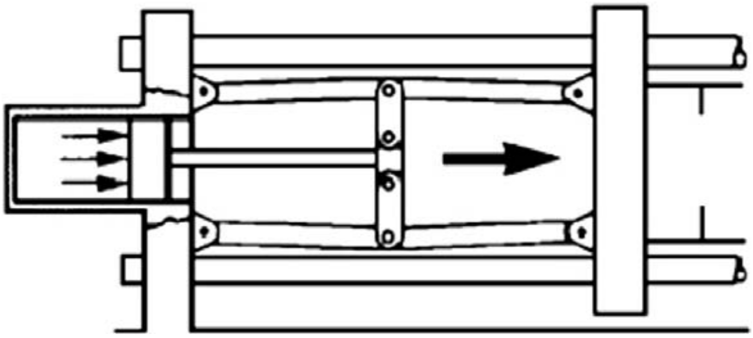


Figure 2.6 Double toggle design – mould closed

If the two main links of the toggles were of equal length then platen movement would be very restricted. In practice most machines have the linkage fixings offset, so that the toggle arms collapse inwards. This allows greater opening strokes than would otherwise be possible.

Variations of the double toggle design using five pivot points instead of the conventional four will give an even greater opening stroke. The double toggle clamp is the most commonly used in injection moulding for machines up to 1000 tonnes.

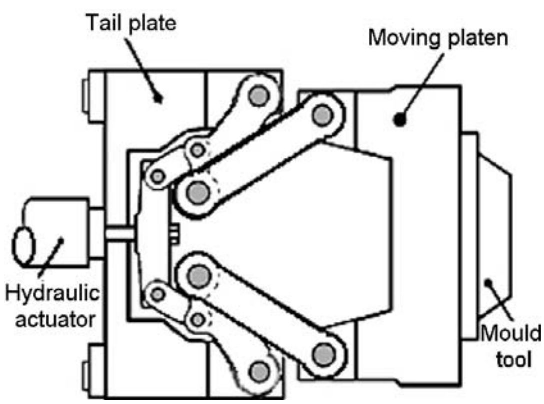


Figure 2.7 Five point toggle design

Owing to the high forces involved, one of the biggest problems with a toggle-actuated machine is mechanical wear, often made worse by poor machine setting. Problems caused by poor setting include setting too high a locking tonnage and running tools that are not parallel. Automatic and efficient lubricating systems are therefore essential to keep wear to a minimum.

Mould height adjustment on toggle machines is normally achieved by moving the whole of the locking assembly along the tie bars. Because the tie bars provide the final lock, it is important that the load on them is evenly distributed.

When tie bars are removed, it is essential that they be replaced correctly in relation to the fixed platen. They must also be correctly rotated in relation to the other tie bars or else die height and adjustment will be affected and undue strains will be placed on the tie bar that was re-fitted.

Tie bars should be checked regularly to ensure that the stress developed in each bar is the same when a mould is clamped. Failure to do this can result in out-of-balance clamping on the mould and premature tie bar failure.

The positioning of ejector mechanisms on toggle machines does not normally present any problems, as long as there are no ejectors in line with the toggles.

2.2.6.4 Direct Hydraulic Clamping

There are two main types of direct hydraulic clamping:

- Direct clamping
- Jack ram clamping

2.2.6.5 Direct Clamping

Direct clamping is usually achieved by means of a single ram or multiple rams that provide the opening, closing and locking functions.

The basic design shown below would be rather slow in operation. However, smaller jack rams can be added to speed up the platen movements.

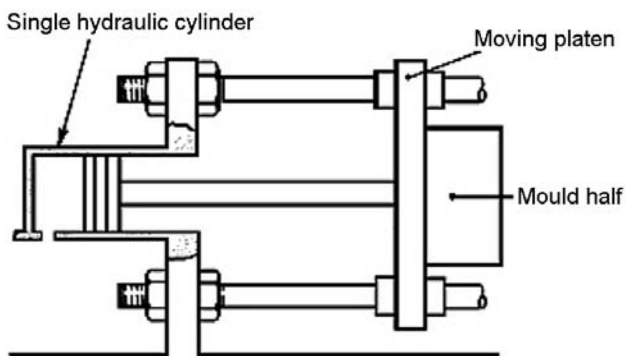


Figure 2.8 Direct hydraulic clanping design

2.2.6.6 Combined Mechanical–Hydraulic Systems

In a combined system the major movement of the platen and the final locking force are provided by different means. Such systems have become known as block and lock systems. The most common of these systems combines a toggle joint for mould opening, and closing with the final lock being provided by a small short-stroke hydraulic piston.

This gives a very smooth action and great flexibility to the moulder. Because the toggles are only used for movement they do not have to be as substantial as those in a straight mechanical system and lubrication is generally simpler. Methods of mould height adjustment vary between manufacturers and this is dependent on the actual location and design of the final pressuring cylinder.

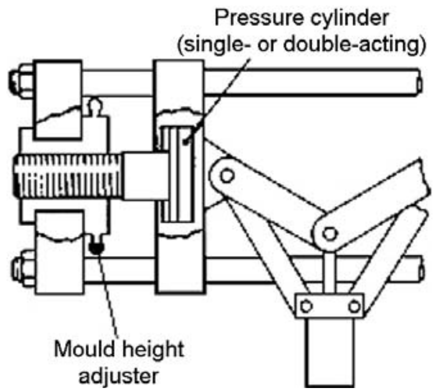


Figure 2.9 Combined toggle – hydraulic design

2.2.7 The Injection Unit

This is the part of the machine that stores and heats the material prior to injecting it into the mould tool. The injection unit has several functions:

- Metering the amount of material required for each shot
- Plasticising (or heat softening) the material
- Rotating an internal screw to transport the material via its screw flights to the front of the cylinder while moving backwards ready to pick up the next shot of material
- Advancing and retracting the injection carriage to bring the nozzle into contact with the mould sprue bush
- Providing a sufficient contact force between the injection cylinder and the mould tool to prevent material leakage
- Providing a variable speed of injection and variable injection and backpressure

- Maintaining a hold-on pressure to compensate for volumetric shrinkage of the material in the mould tool after initial mould filling has taken place

There are several other features that injection units may have, including:

- Hydraulic screw retraction on the nonrotating screw before or after screw rotation (***decompression*** or ***suck back***) to prevent material leaking into the mould cavities
- Profiled or stepped injection speed/pressure facilities
- Sometimes closed-loop computer-controlled systems are used to optimise part quality and cycle times by more accurately monitoring and controlling moulding parameters

2.2.7.1 Reciprocating Screw Design

The design of the screw is very important and will vary depending on the type of material being processed and the size of the shot.

Figures 2.10, 2.11 and 2.12 show the basic screw geometry and function of a standard screw unit. The compression ratio is the ratio $V_1{:}V_2$. The single screw plasticising design is the one that is used in the majority of injection moulding machines.

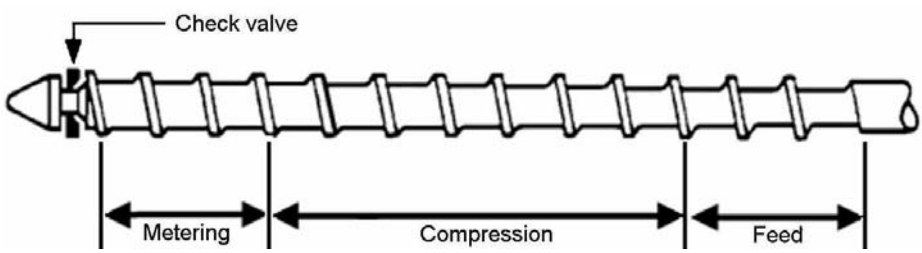


Figure 2.10 Screw design

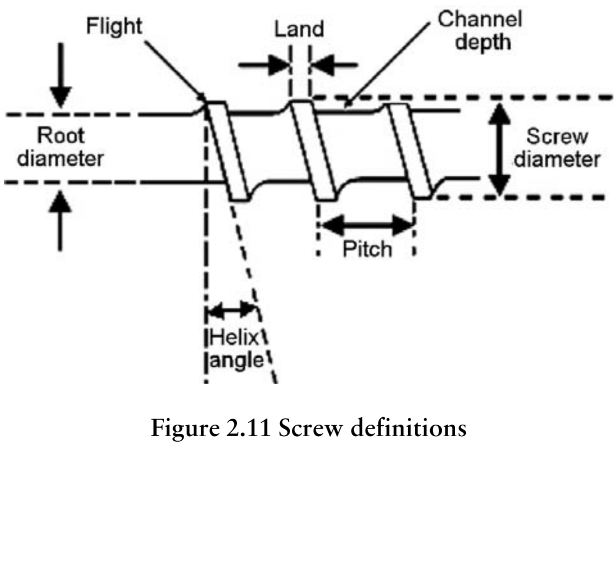


Figure 2.11 Screw definitions

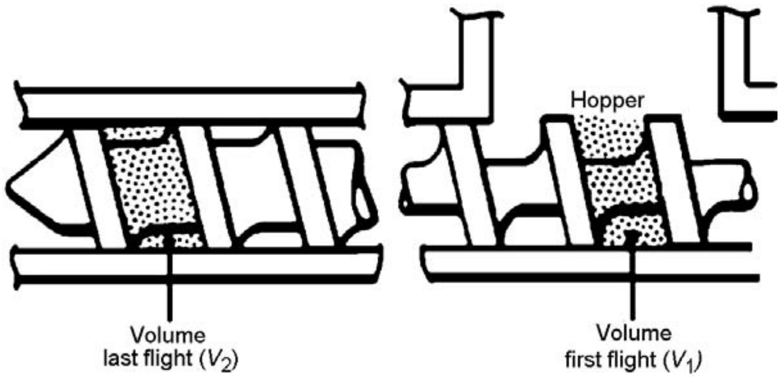


Figure 2.12 Screw compression ratio

In a typical injection unit (Figure 2.13), the raw material is fed from the hopper into the cylinder and then is transported along the cylinder by the rotation of the screw to the front of the cylinder. The pressure of the material at the front of the screw forces it backwards until the rear of the screw hits a stop to achieve the desired shot weight. At this point, the screw ceases to rotate. This phase is known as ***screw back***.

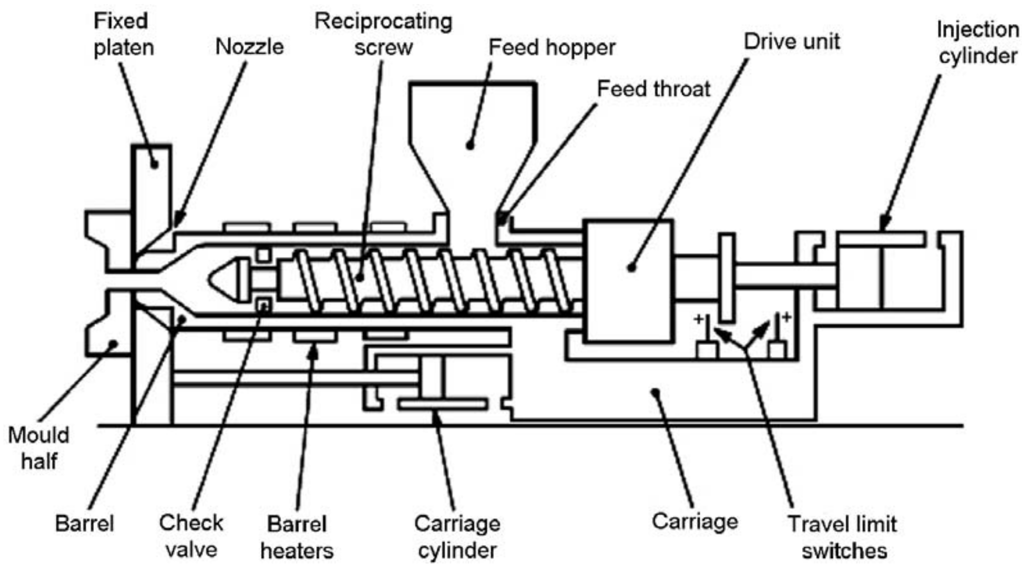


Figure 2.13 The injection unit

The region of the cylinder where the raw material is fed in is called the ***feed throat*** and this is usually kept cool by circulating cooling water. This stops the material from melting at the throat, which would prevent the material from feeding properly. However, if too much cooling is provided, condensation will form at the throat and can cause the adjacent section of the cylinder to lose heat.

Condensation in this area may also allow moisture to develop within the raw material. If the material being moulded is ***hygroscopic***, moulding difficulties are frequently encountered.

2.2.7.2 Screw Rotation

The material is softened or plasticised by means of frictional heat provided by the rotation of the screw and by external heater bands mounted on the cylinder. These two sources of heat, combined with the mixing effect of the screw, provide a homogeneous melt. As the screw rotates, pressure is built up within the barrel. This pressure forces material towards the nozzle and the screw backwards. This in turn forces back the hydraulic injection piston, moving the oil out of the cylinder to the tank. A valve is provided to restrict the oil backflow pressure, which enables the oil pressure to be increased or decreased. This regulates how much work the screw has to do in order to fully screw back. This pressure is commonly called ***back pressure***, but is sometimes called ***reaction pressure***.

The greater the amount of work the screw has to do, the greater is the amount of ***shear heat*** (frictional heat) that is put into the melt. When sufficient melt has been produced for a shot, the limit switch is tripped and screw rotation stops.

However, screw back pressure is also used to mix materials and additives more evenly and also to reduce any trapped air that may be present in the melt.

2.2.7.3 Screw Forward (Injection Phase)

At the end of the screw back phase, the screw ceases to rotate and the hydraulic cylinder then forces the screw forward, plunger-like, displacing the melt through the nozzle into the mould – hence the term injection moulding. For most materials a check flow valve prevents the melt from flowing backwards up the screw.

2.2.7.4 Injection Speeds and Pressures

Generally the injection phase is carried out in the shortest possible time to prevent the melt from solidifying before mould cavities are completely filled.

The total injection time varies with the material to be injected. Normally, ***stepped control*** is provided in order to give the requisite variation. The injection stroke is achieved at two main pressure levels:

- The first pressure and velocity is applied during the mould filling stage that represents 95% of the total injection stroke.
- At this point the second pressure, the packing or ***hold-on pressure***, keeps the injected material under pressure in the mould while the melt is cooling. This is to prevent shrinkage and ***cavitation*** in the mould.

As the force provided by the hydraulics to push the screw is constant, alteration of the screw diameter will give higher or lower specific pressure per square cm depending on the diameter of the screw. Table 2.1 below shows how the shot volume varies with screw for a typical range of cylinders.

Table 2.1 Variation of shot volume with screw diameter

	Injection unit		
	A	B	C
Screw diameter (mm)	60	70	85
Real injection volume (shot) (cm^3)	698	950	1,400
Maximum specific pressure on material (MPa)	196.8	144.5	98

2.2.7.5 Hold-on pressure

The hold-on pressure is normally lower than the injection pressure. Different machine manufacturers offer various numbers of stages for the holding phase, many of which may be programmed on more sophisticated machines.

The graph in Figure 2.14 shows a typical injection pressure curve throughout the screw stroke. This shows that the screw stops 5mm before the end of the stroke. This is necessary to provide a cushion of material to allow hold-on pressure to be maintained on the mouldings during solidification. At this point a limit switch is tripped to switch from the main injection pressure to the holding pressure.

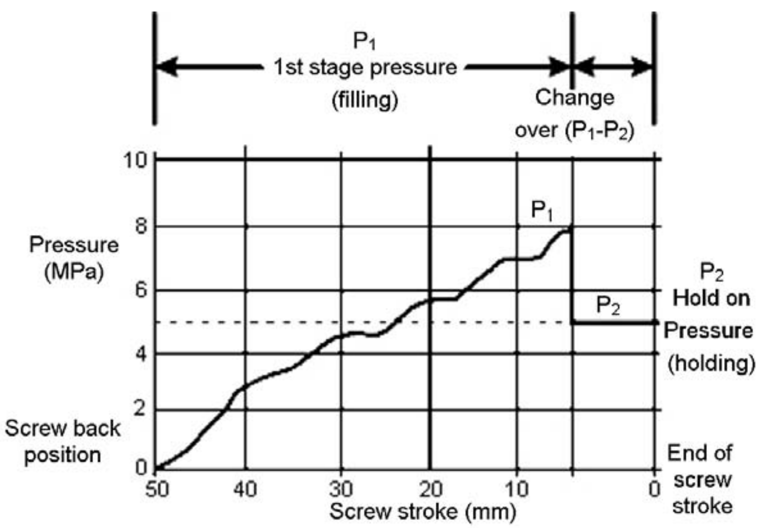


Figure 2.14 Injection pressure *versus* screw stroke

2.2.7.6 Screw Speed

It is important that the speed of rotation of the screw is kept constant from cycle to cycle. If this varies, the amount of ***shear heat*** put into the melt will vary. This would result in varying moulding conditions and, consequently, inconsistent results.

The screw speed that should be used will depend on the material being processed and other factors such as additives or difficult components such as acrylic lenses, etc. Generally speaking, the screw speed is determined so that it screws fully back and stops rotating just before the mould opens at the end of the cooling cycle. This avoids the material stagnating in the cylinder if screw rotation stops early in the cooling cycle. However, there are alternative theories that screw speed should be related to the screw/cylinder surface area.

2.2.7.7 Screw Stroke

The return stroke of the injection screw is determined by the amount of material to be injected (shot weight). The longest stroke is required for the largest volume.

The manufacturers of injection moulding machines for processing thermoplastics usually offer the choice of three different screw diameters:

- A small diameter, which will give a high specific injection pressure and a smaller maximum shot weight, often used for very thin-walled parts or other high-pressure applications.
- A standard diameter, which gives a specific pressure in the region of 1400 bar on the injected material. This is the commonly used version suitable for moulding a wide range of parts.
- A larger-diameter screw, which gives reduced specific pressure but increases the shot size proportionally. This is used for larger shot weights and sometimes for moulding thick wall parts and for screw injection of larger, thick-walled items.

There is a relationship between specific injection pressure, screw diameter and the maximum shot weight. Table 2.2 illustrates this relationship, assuming a standard injection stroke is being used. This relationship is important when selecting screw diameters for specific jobs.

Table 2.2 Specific pressure *versus* screw relationship

Screw		Piston		Ratio of piston to screw area	Hydraulic pressure (MPa)	Specific injection pressure (MPa)	Shot weight (g)
Dia. (cm)	Area (cm^2)	Dia. (cm)	Area (cm^2)				
3.5	9.62	15.0	176.71	18.4:1	14	252	198
4.5	15.9	15.0	176.71	11.1:1	14	154	323

The functions that are independent on the screw/cylinder combinations are:

- The maximum clamping force of the machine
- The maximum indicated injection pressure
- The maximum stroke of screw

2.3 Theoretical Mould Locking Force

During the injection phase the specific injection pressure acts on the projected areas of the cavities and runners. The product of this pressure and area generates a force, tending to open the mould. This has to be countered by the machine locking force.

The locking force must be at least equal to or preferably greater than the opening force to ensure the mould remains firmly clamped throughout the injection phase.

Note: The projected area of the mould tool is the total area of all cavities and runners at the split line, at right angles to the axis of the sprue bush.

Locking force = (Projected area of cavities and runners) × Injection pressure

Note also that this represents the limiting condition. That is the point at which the tool will only just remain closed.

In view of this a factor of safety must be used to ensure that the mould tool remains closed at all times. For example, any variation of the melt viscosity may result in an increase in the amount of injection pressure needed to fill the cavities properly. In this event the tool may very well flash. Therefore the above calculation should be modified to:

Locking force =
(Projected area of cavities and runners) × Injection pressure × Factor of safety

This topic is discussed in more detail later.

2.4 The Moulding Cycle

2.4.1 Mould Closing Phase

The mould should be closed as quickly as possible, without putting undue strain on the mould or the machine until the mould protection facility is tripped.

2.4.2 Mould Protection Phase

This is applied at the final stage of mould closing just before the two mould halves meet so as to avoid damage to the mould tool due to trapped mouldings or location of delicate shot off areas on either half of the mould. Both the distance and operating pressure must be set to suit the requirements on the machine control panel.

2.4.3 Injection (Mould Filling) Phase

In general, mould filling takes place rapidly, as previously discussed. However, care must be taken in order not to generate excessive shear stress in the material by excessively short fill times. An ideal fill time should prevent large reductions in melt temperature (less than 20 °C) and avoid the generation of high injection pressure (more than 100 MPa).

The injection speed should be adjusted to produce the required filling time and the injection pressure should be set to enable this injection speed to be achieved. For example, a large cavity may require a lower relative injection speed to give the air in the cavity time to be displaced to prevent compressed air being developed giving rise to ***shorts*** or ***burning***.

2.4.4 Holding Time and Pressurising Phase

During this stage, a little more material is forced into the mould before the gate freezes off. The pressure prevents the material in the mould from flowing back into the injection cylinder. The length of time required for holding depends upon the material being moulded, gate size, melt and mould temperatures. The setting of the hold-on stage is critical to the size and dimensional stability of components.

There are two aspects of this phase:

- Pressurisation, when the cavity pressure increases
- Compensation, when cavity pressure decreases

2.4.5 Cooling and Refill Phase

This starts after the hold-on time finishes. Should the component become cool enough to be ejected immediately after the screw back phase then no further cooling time is necessary and the parts may be ejected. In most case, however, the mouldings will require further cooling before ejection can take place.

The total cooling time required is largely dependent on the wall thickness of the component and the material used, and can be calculated accordingly.

2.4.6 Screw Back Phase

During the cooling time the screw rotates and is displaced backwards along the injection cylinder. This backward displacement takes place entirely during the cooling phase of the components as previously described. Once the screw has transported sufficient material to the front of the cylinder, the screw trips a limit switch and stops rotating.

2.4.7 Mould Open Phase

The same principles apply to the mould open phase as to the mould closing phase. Abrupt opening should be avoided, to prevent damage to the machine and mould. The distance of opening should be just enough to allow for the mouldings and any runners to be ejected cleanly. This will keep cycle time to a minimum.

2.4.8 Ejection Phase

Adequate time must be allowed for the ejection of the components from the mould. Ejection can be employed in a semi-auto or automatic mode.

Automatic ejection can be by mechanical, hydraulic or pneumatics systems, depending on the design of the ejector system. Air ejectors may be used to blow the component clear and can be set on a pulsating or continuous blow sequence. Timers can be used on both hydraulic and air ejectors.

Hydraulic ejectors may be used in a multistroke mode in certain circumstances to eject components that tend to 'stick' to the ejector pins. Alternatively, pick-and-place robots may be used where the cost is justified.

Many of these topics are discussed in more detail in the appropriate sections of this book. Figure 2.15 illustrates a summary of the moulding cycle.

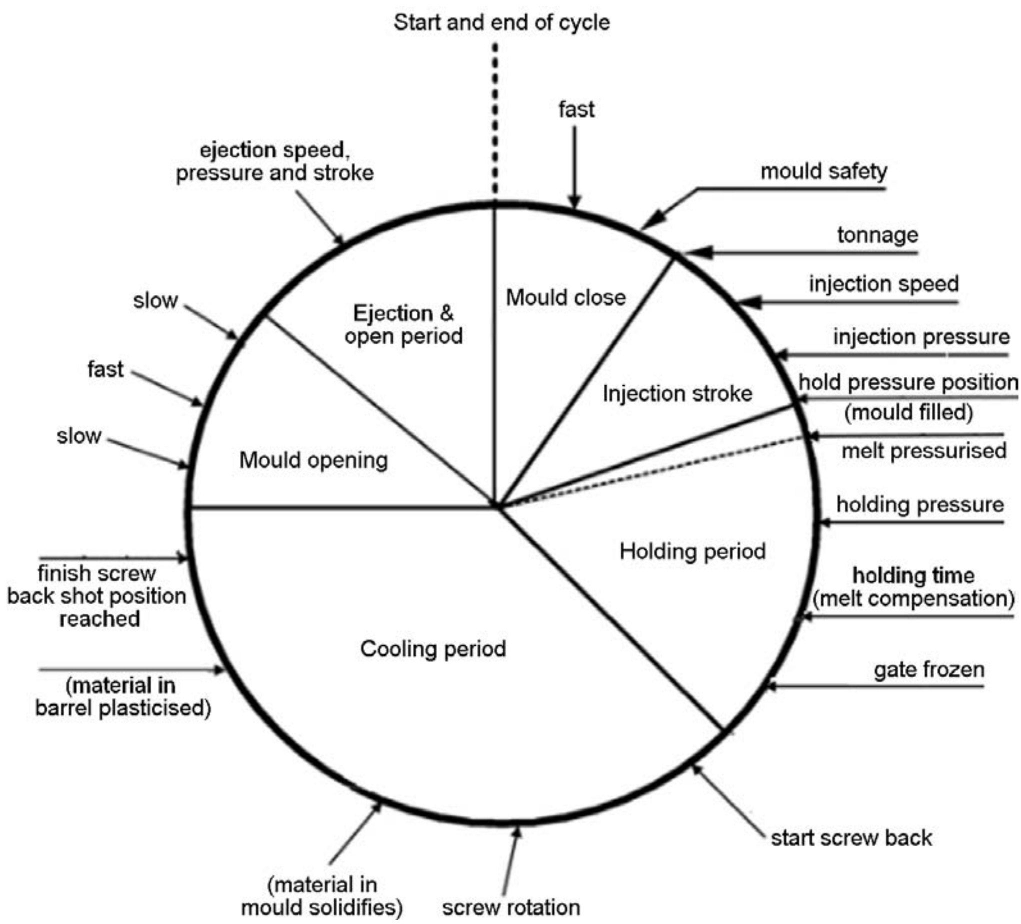


Figure 2.15 Summary of elements of the moulding cycle

3 Plastics Materials

3.1 Types of Plastics Materials

There are three main types of plastics materials:

- Thermoplastic
- Elastomer
- Thermosetting

3.2 Definition of Plastics

It is not easy to give a precise, clear-cut definition of plastics and perhaps the best definition is the one that a 'plastics' chemist may give, that plastics materials belong to a larger family of materials known as ***synthetic organic polymers.***

By 'synthetic' is meant man-made; the term 'organic' to a chemist signifies that they are carbon-containing compounds; and the term 'polymer' comes from the Greek word meaning 'having many parts'.

To summarise there are three terms commonly used in plastics technology:

- ***Synthetic*** (man-made)
- ***Organic*** (carbon based)
- ***Polymer*** ('many-units')

Understanding what a polymer is requires a modest knowledge of elementary chemistry, and this is given in the following discussion.

3.3 The Nature of Plastics Materials

Elements, Atoms and Molecules

All matter in the universe is made up of small particles called ***atoms***. There are over 100 different types of atoms constituting the chemical ***elements***. The ***atomic number*** of an element is the number of ***protons*** in the nucleus of an atom. This is also known as the ***proton number***.

The ***mass number*** or ***nucleus number*** is the number of ***nucleons*** in its ***nucleu***s: in other words it is the total number of protons + neutrons.

The elements most commonly found in plastics are:

Element	Symbol
Carbon	C
Hydrogen	H
Oxygen	O
Nitrogen	N
Chlorine	CL

Under normal circumstances the atoms of many of the elements do not occur singly. For example, the atoms of oxygen in the air we breathe occur in pairs, the symbol or formula for which is O_2. Atoms of different elements can also combine with others: for example, the carbon dioxide we expel from our lungs consists of pairs of oxygen atoms attached to a single carbon atom, the formula for which is CO_2.

These combinations of atoms are known as ***molecules***. Another example of a molecule has the formula H_2O, and is very well known as ice, water or steam. This example also demonstrates that the form in which a substance exists depends upon its temperature. In this case the water is a solid (ice) below 0 °C; between this temperature and 100 °C it is liquid (water); and above 100 °C it is a gas (steam).

The force which enables atoms to unite into molecules is known as ***chemical bonding***, and an assortment of different types of bonding exists. In many cases the bonding between the atoms is extremely strong and can only be broken by vigorous chemical attack or a large input of energy, as would occur when a substance is subjected to intense heat.

Bonds also exist between molecules, but these are usually considerably weaker than the chemical bonds between atoms within molecules. But with solid materials the bond between individual molecules is sufficiently strong to prevent one molecule from straying away from its neighbours. However, when the temperature is raised, the energy entering the material weakens these bonds until eventually individual molecules can escape their neighbours to a considerable extent and the material becomes a viscous liquid. If the temperature is raised further, an even greater amount of energy is put into this liquid. The individual molecules become largely separated from each other, the material degrades and a gas is produced.

It is not within the remit of this book to provide a comprehensive coverage of plastics materials technology or polymer chemistry. However, the following information may be useful to mould designers, engineers and technicians and is covered in a simple, non-chemistry-based manner. The information provided is primarily restricted to thermoplastic polymers.

3.4 Monomers, Polymerisation and Polymers

The molecules that make up plastics materials also consist of groups of atoms united by very powerful chemical bonds. However, in the case of plastics the number of atoms incorporated in each molecule is extremely high, often running into many thousands. This makes molecules of plastics very large compared with those other substances.

These very large molecules are made up of smaller units, repeated many times. In some plastics these units are joined together in a chain formation rather like beads on a necklace, whereas in other plastics a complex three-dimensional network is formed.

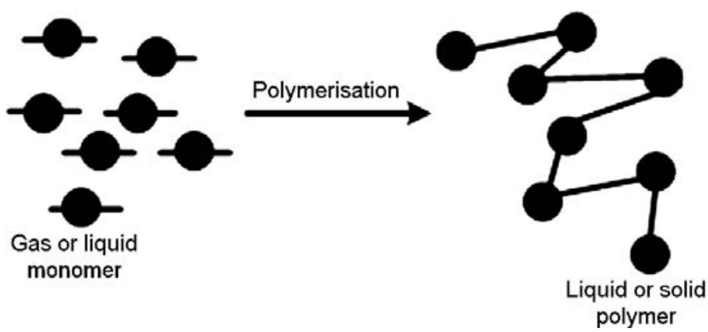


Figure 3.1 Polymerisation of monomers

One of the most well-known plastics materials is polythene, which more correctly should be named polyethylene. Polyethylene is produced from the gas ethylene by a chemical process called ***polymerisation***. The large molecules produced by the polymerisation reaction are known as the polymer. The small molecules that form the starting material are called the ***monomer***.

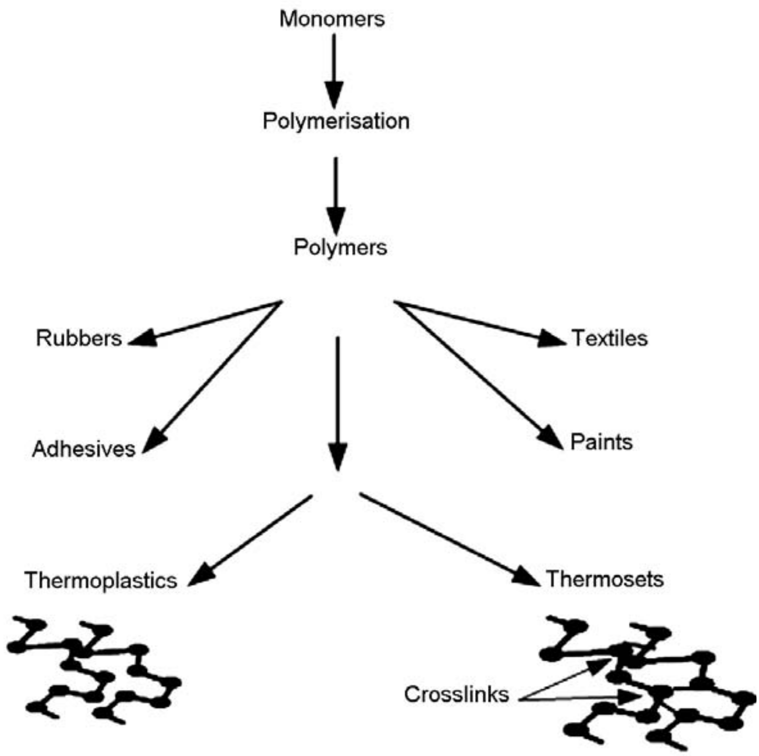


Figure 3.2 Products derived from polymerisation

In the case of polythene, ethylene is the monomer, which polymerises to form polyethylene; similarly, the monomer styrene polymerises to polystyrene and the monomer vinyl chloride polymerises to polyvinylchloride (PVC).

This type of polymerisation, known as addition polymerisation, is just one example of a range of polymerisation techniques used to produce the modern family of polymeric materials. Polymers (sometimes called resins), as well as being the major constituent of our plastics materials, also form the basis for natural and synthetic rubbers, adhesives, paints and synthetic textiles.

3.5 Classification of Plastics

3.5.1 Thermosets and Thermoplastics

This distinction is probably the most fundamental way of classifying plastics. Using this system the family of plastics materials is divided into two major branches, the ***thermosets*** (e.g. Bakelite) and the ***thermoplastics*** (e.g. Nylon, polythene or ABS).

The main difference between the products made from thermosets and those made from thermoplastics, apart from a few exceptions, is that thermoplastics components will always soften and eventually melt if subject to high temperatures, whereas the thermosets will not. There is also a major difference in the techniques used to process these two classes of plastics materials.

Thermoplastic materials have to be heated until they soften sufficiently to be moulded into the desired shape, after which they must be cooled in order to solidify and retain the required shape. If a thermoplastic product is reheated to its original processing temperature it will soften again. The thermoset materials also soften when first heated, which enables them to be moulded into shape, but instead of cooling, the material is then subject to additional heating. This additional heating causes a chemical reaction to take place within the material, which converts the hot, softened mass into an equally hot permanent solid. Further heating, even to a higher temperature, will not re-soften the thermoset product. The reason for the difference in behaviour between the thermoset and thermoplastic lies in the chemical composition of the molecular chains.

With the thermosets, the polymer in the moulding materials has roughly linear chain structure; this enables the material to behave rather like a thermoplastic when first heated, allowing it to soften and flow under pressure in order to take up the shape of the mould. However, the structure of the thermoset polymer contains chemically reactive positions at intervals along the molecular chains, which facilitate joining or cross-linking between adjacent molecules provided that sufficient heat is applied. The cross-linking (sometimes called curing) converts the linear structure into an infusible three-dimensional network.

With thermoplastics the long-chain molecules in the moulding compound do not have reactive positions within the chain, so under normal moulding conditions no crosslinking can occur. The material can only be solidified by cooling and of course it will soften and melt again if reheated.

3.5.2 Homopolymers, Copolymers and Polymer Blends (Alloys)

In the examples of polymerisation quoted earlier, a single monomer type (e.g., ethylene or styrene) was polymerised to produce a polymer (polyethylene or polystyrene) in which the molecular chain was made up of the same repeat unit throughout its length. Polymers of this type are known as ***homopolymers***.

It is possible, however, to produce polymers from a combination of two or more monomers, the final molecule chain then having a combination of repeat units corresponding to the monomers selected, rather like a necklace with different coloured beads along its length. This type of polymer is known as a ***copolymer***.

Examples of copolymers include SAN (e.g., Tyril from Dow chemicals), a copolymer based on styrene and acrylonitrile as monomers. ABS is a rather complex copolymer based upon three monomers, acrylonitrile, butadiene and styrene. Another widely used copolymer is based upon propylene and ethylene monomers and is usually called propylene copolymer, as distinct from polypropylene, which is the homopolymer based on propylene alone.

These copolymers have been developed mainly in order to overcome the specific shortcomings of the related homopolymers. For example, SAN is a much more heat- and solvent-resistant material than the homopolymer polystyrene. ABS has similar advantages over polystyrene, plus the additional benefit of greater toughness due to the butadiene content. With propylene copolymer, the presence of the ethylene-derived units in the polymer chain overcomes to a considerable extent the brittleness at subzero temperatures displayed by the homopolymer polypropylene.

The properties of individual copolymers can also be varied by altering the relative proportions of the monomers involved, or by arranging them in different patterns along the length of the molecular chain.

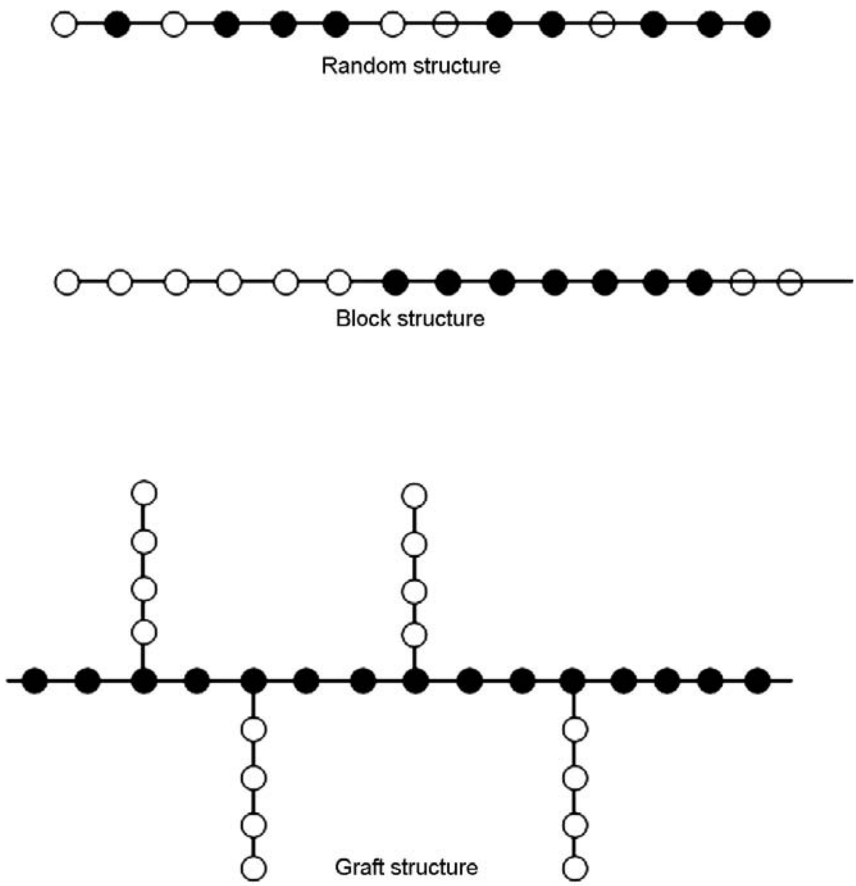


Figure 3.3 Molecular structure of monomers

The development of polymer blends, or alloys, has further expanded the range of materials for injection and other moulding processes. With this type of material, two or more polymers are produced separately and then blended or 'alloyed' together to form new materials having a combination of properties not possessed by the constituent polymers individually.

Examples of polymer blends include Noryl, from General Electric, a blend of polystyrene and polyphenylene oxide, or Bayblend, a combination of ABS and polycarbonate produced by Bayer.

3.5.3 Amorphous and Semicrystalline Thermoplastics

Thermoplastics can be subdivided into two distinct classes based upon differences in their molecular structure. These differences can have a significant bearing on the performance of mouldings in service, and have a marked effect on the behaviour of the material during processing.

Materials such as polystyrene, polycarbonate, acrylics, SAN, ABS and PVC are said to be ***amorphous*** thermoplastics. This signifies that in the solid state their molecular structure is random and nonordered, the long-chain molecules being all entangled rather like solidified strands of spaghetti.

Materials such as most of the Nylons, acetal, polypropylene, polythene and the thermoplastic polyesters, have a much more ordered structure in the solid state than amorphous materials. They have a considerable proportion of the long-chain molecules packed closely together in regular alignment. These materials are known as ***semicrystalline*** thermoplastics. It should be noted, however, that with both types of material the molecular structure is amorphous at melt temperature.

Most amorphous thermoplastics are transparent in their natural, unpigmented form, although ABS, for example, is an exception, while most semicrystalline thermoplastics in their solid unpigmented form are translucent or an opaque white colour.

It is interesting to observe (for example when 'purging' on injection moulding machines) that fully molten natural polypropylene or acetal are initially transparent, but as the melt cools it clouds over, becoming translucent in the case of polypropylene and opaque white in the case of acetal. This clouding is due to the material's molecular structure gradually rearranging itself from the tangled amorphous state in the melt to the more ordered semicrystalline state in the solid.

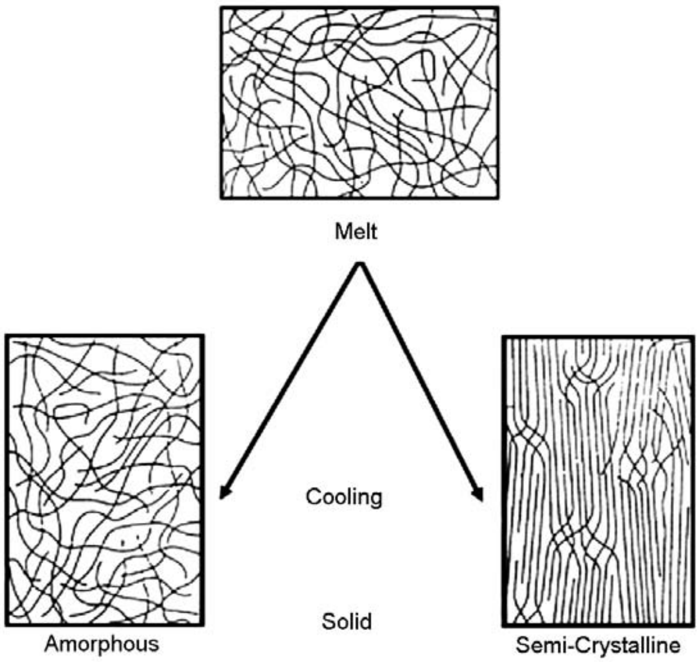


Figure 3.4 Cooling behaviour of materials

The main differences in behaviour between the amorphous and semicrystalline materials observed during injection moulding are discussed next.

3.6 Melting and Solidification

Amorphous thermoplastics exhibit a progressive softening over a wide temperature span, whereas the semicrystalline materials rapidly change from the solid melt condition over a quite narrow temperature band.

Conversely, when amorphous materials are cooled they solidify slowly over a wide range of temperature, in contrast to the semicrystalline plastics, which change from melt to solid over a narrow range of temperature.

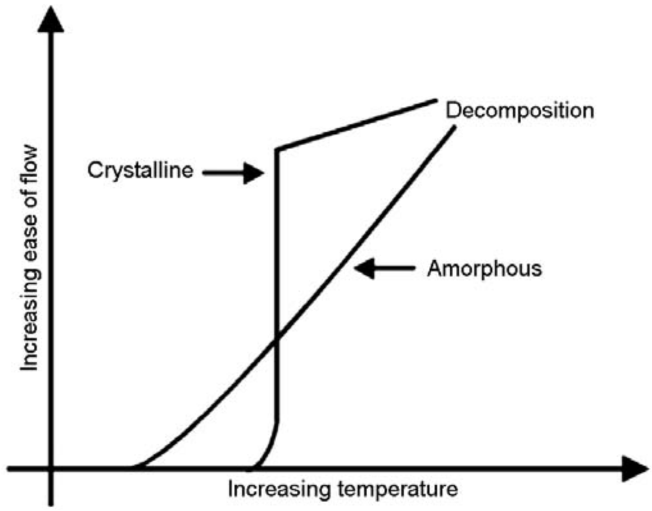


Figure 3.5 Behaviour of materials with increasing temperature

3.7 Shrinkage

Amorphous thermoplastics display very low shrinkage when they solidify, typically between 0.5% and 1%. Semicrystalline materials shrink very much more, usually between 1.5% and 5% depending upon the particular material.

The higher shrinkage with the semicrystalline materials is due to the repeat units along the molecular chains being of such a form that they can pack very closely together in an ordered manner depending on the moulding conditions being used.

For example, when semicrystalline thermoplastics are moulded in hot moulds, cooling rates are slow to allow more time for the molecular chains to disentangle themselves and take up their crystalline structure. This results in a greater proportion of the material being in its crystalline state (higher crystallinity), giving a product with superior mechanical strength and dimensional stability, but with relatively high shrinkage.

If the same material is moulded in a cold mould, the more rapid cooling will inhibit the formation of crystalline areas. The resulting lower level of crystallinity will give the product inferior physical properties, and lower shrinkage accompanied by a tendency for dimensional instability and distortion during later service due to continued after-moulding shrinkage.

3.8 Engineering and Commodity Plastics

Another method of classifying plastics is to refer to the physical properties of plastics. A plastic whose physical properties are adequate for, as an example, a DVD case, is not likely to be adoequate for an electric drill body.

Based on this method, ***commodity*** and ***engineering*** plastics can be identified. It is important to note that this system is not done on a scientific basis so there is no predefined list of commodity and engineering plastics. Indeed, some materials like polypropylene and polyacetal often fall into both classes.

3.8.1 Engineering Plastics

This term has evolved to describe those plastics that are used in place of metals for load-bearing applications (e.g., gear wheels) or plastics that must retain good physical properties at elevated temperature (e.g., in electric kettles).

3.8.2 Commodity Plastics

These plastics are not expected to be load bearing or to withstand elevated temperatures. They are more likely to be attractive housings, covers, etc., and are often produced on a very large scale, which affects their price.

Table 3.1 lists a range of commonly used commodity and engineering materials.

Table 3.1 Classification of common plastics

Amorphous	Semicrystalline
Acrylic	Acetal
PVC	Nylon
SAN	Polyester
Polystyrene	Polyethylene
Polycarbonate	Polypropylene
ABS	PTFE
Commodity plastics	**Engineering plastics**
Polypropylene	PET
HDPE	Acetal
LDPE	Nylon
Polystyrene	PBT
SAN	PC
Acrylic	PEEK
ABS	PAI

3.9 Material Additives

The actual materials used in the injection moulding process do not consist of just pure polymers. They frequently include numerous additives, some of which improve the processing characteristics of the material while others improve the performance of the final moulded product. Some additives modify the flow behaviour and shrinkage of the polymer. Described below are common additives and their effects on polymer processing behaviour.

Table 3.2 Common Additives
Nucleating agents
Flow promoters
Fibrous reinforcement
Antioxidants
Fungicides
Particulate fillers
Flame retardents
Blowing agents

With semicrystalline materials, particularly Nylon, grades are sometimes available which contain ***nucleating agents***. These additives promote the rapid and uniform development of the crystalline regions. This helps to reduce the cooling time needed to achieve solidification, and to give more consistent physical properties in the finished moulding.

Flow promoters are used by manufacturers in their materials to improve the flow of a material and in many cases a lubricant can be used for this purpose

Many materials are available with ***fibrous reinforcement***, glass fibre being the most popular, although carbon and asbestos are also used to a limited extent. This type of additive greatly improves the tensile strength, rigidity and heat distortion characteristics of the moulded product.

Different grades of fibre-reinforced materials are available with varying fibre content and fibre length. The addition of fibrous reinforcement frequently enables much shorter cooling times to be used owing to the moulding having much improved strength at high temperatures. However, glass fibres in particular are very abrasive and may cause rapid wear in the mould, barrel and screw assembly.

With all fibrous materials the final product may be subject to irregular shrinkage. This is caused by some of the fibres becoming highly aligned in certain directions owing to the flow of materials through the cavities.

Where this alignment occurs, the part will display a much higher shrinkage in directions at right angles to the fibre alignment, compared with the shrinkage parallel to the alignment. Materials that behave like this are said to be ***anisotropic***.

Certain materials require ***antioxidant additives*** to protect them from progressive deterioration when used for components that need to survive long-term exposure to elevated temperatures. Some plastics, plasticised PVC for example, are susceptible to attack by microorganisms when exposed to warm, humid atmospheres. Adding ***fungicides*** to the moulding compound can reduce this problem.

Particulate (or powder) fillers can also be incorporated. These improve the stiffness of the component and reduce overall shrinkage. Fillers of this type include talc, chalk, limestone powder and clay, and other additives are used to modify the surface characteristics of the material. Most polymers are not coloured, so that when coloured components are required, dyes or pigments have to be added. Despite the fact that these additives are used in very small amounts they sometimes have a marked effect on processing conditions. For this reason it is quite common to find that when moulding a component in one specific material, but in a range of colours, different processing conditions may be needed for certain colours.

The majority of plastics burn far too readily. In an attempt to overcome this problem, many materials are available with ***flame retardant additives***, which make the material more difficult to ignite, or less likely to burn so fiercely. Unfortunately, quite a number of additives of this type in use today cause considerable problems for the moulder in that they tend to accelerate degradation of the polymer as it passes through the cylinder and in some cases corrosive by-products are also released.

Some moulders are required to produce mouldings that have a cellular or microporous structure, for example, cushioning, thermal insulation or lightweight rigid thick-section components. There are several techniques that can be used to produce this type of component, some of which require a machine with special adaptations so that gas, under high pressure can be injected into the melt as it fills the mould. Similar results can be obtained on standard injection moulding machines if an appropriate ***blowing agent*** is added to the moulding material. This additive is a substance that breaks down to produce bubbles of gas as the melt undergoes a rise in temperature due to rapid flow of the melt through the restriction of the gate.

3.10 Flow Properties of Thermoplastic Materials

In Section 3.9 it was pointed out that substances known as ***flow promoters*** can be added to moulding materials in order to make them easier-flowing, but this is not the only way to manipulate the flow characteristics of the material.

Another method would be for the manufacturer to modify the average molecular weight of the polymer during the polymerisation process, and in some instances this would be preferable to the use of flow promoters. The following discussion explains the significance of molecular weight as it applies to polymer processing.

One way in which chemists indicate the size of a molecule is by quoting its molecular weight. A molecule of water, which is very small, has a ***molecular weight*** of 18, whereas for the somewhat larger molecule of ordinary alcohol the figure is 46, and for the sugar sucrose, which has quite a large molecule, it is 342.

By comparison, the molecules that make up plastics materials are gigantic. Nylon, for example, has a molecular weight of 15 000 or more, PVC has molecular weight 80 000, and polythene can range from perhaps 30 000 to several million.

3.11 Variable Molecular Weight

In addition to having exceptionally high molecular weights, the molecules of plastics also differ from those of most other materials in that their molecular weights are variable. This phenomenon is in sharp contrast with the invariability of molecular weight of other molecules, for example of ordinary water. This always has a value of 18 irrespective of the source the water came from, either on this planet or anywhere else in the universe.

The reason for the variability in molecular weight observed with the polymer molecules in plastics materials is that when a batch of polymer is made, the resulting molecular chains of the polymer are not all the same length. Usually a small number are very much shorter than the average and a similar number are considerably larger than the average. However, by altering the processing conditions during polymerisation it is possible to change the average length of the molecular chains. This has enabled materials manufacturers to produce special grades of polymer to suit specific applications. One of the characteristics of polymers, which is greatly affected by the length of the polymer chain, is its ability to flow in the molten state. In simple terms, reducing the average chain length will make the material easier-flowing, and increasing the chain length will make the material stiffer flowing.

3.12 Melt Flow Index (MFI)

One way in which the materials supplier can indicate the ease of flow of a material is by specifying its ***melt flow index*** (MFI) number. The MFI test consists of extruding molten polymer through a standard die orifice at a specified temperature and under a specified load, the load and temperature varying for different types of materials.

The quantity of material extruded in 10 minutes, measured in grams, is quoted as the melt flow index for the material. For example, an easy-flowing grade of polythene may have an MFI of 30 or greater, whereas the stiff-flowing grades as used for blow moulding may have an MFI of less than 1. Basically, the higher the MFI number, the more easily the material flows and *vice versa*.

The principal design features of the apparatus used to measure MFI are shown in Figure 3.6.

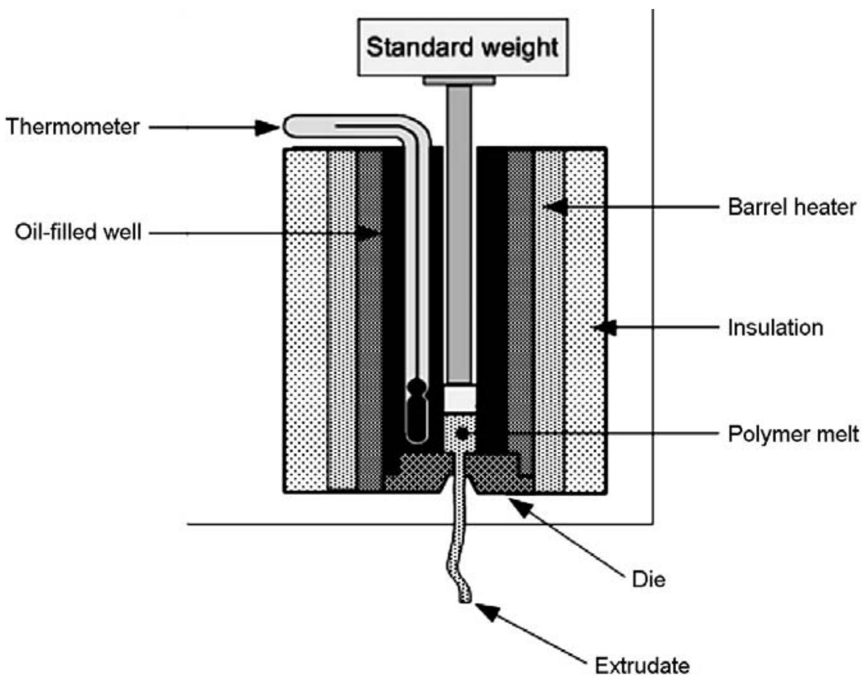


Figure 3.6 Melt flow index apparatus

3.13 Reprocessed Material

The average length of the molecular chains may also have an effect on the mechanical properties of the material; exceptionally short chains giving rise to inferior mechanical properties and a greater susceptibility to stress cracking. These changes in mechanical properties and flow characteristics can sometimes be observed when using material that has been reprocessed several times.

Every time the material passes through the cylinder of the injection moulding machine it is degraded to some extent. With many polymers this degradation takes the form of chain breakage, resulting in shorter molecular chains. The first indication of this reduction in average chain length is usually a noticeable increase in the ease of flow. Eventually, after repeated re-moulding, there will also be a marked deterioration in mechanical strength.

Clearly these factors should be taken into account when considering the use of reprocessed materials where the physical properties of the moulding are important.

A further discussion of this topic from another perspective is covered next.

3.14 Polymer Molecules

As far as the actual size and proportion of these long-chain molecules are concerned, it has been determined that some of the longer thermoplastic polymer molecules can be as much as one thousandth of a millimetre long, which on a molecular scale is gigantic. Molecules of this length should be visible under a microscope, except that they are far too thin, their thickness averaging out at about one five-thousandth of their length.

3.15 Material Names and Abbreviations

The chemical names of the various types of polymers are frequently quite long and complicated; therefore, in industry, simple abbreviations are used. Table 3.3 gives the abbreviations for the more popular plastics moulding compounds. For each abbreviation the commonly used chemical name is given, plus representative examples of trade names. Note the following:

- Some suppliers use the same trade name for several different materials: for example, Dow use the name Styron and Hoechst use Hostyren for both polystyrene and high-impact polystyrene.
- Material suppliers also use trade names, which clearly indicate the material type, e.g., Beetle Nylon 6, Beetle Urea (BIP Chemicals) or Bakelite Phenolic.
- For a more comprehensive list of abbreviations the British Standard 3502-3:1993 (*Symbols for plastics and rubber materials. Schedule for symbols for compounding ingredients*) should be consulted.

Subscripts may be added to the abbreviations to indicate modified grades: for example, GF for glass fibre-reinforced; FR for flame retardant.

Table 3.3 Abbreviations and trade names for common polymeric materials

Abbreviation	Chemical name	Trade names
ABS	Acrylonitrile-butadiene styrene terpolymer	Novodur, Cycolac, Lustran, Terluran
POM (Acetyl)	Polyoxymethylene (polyformaldehyde)	Delrin, Kematal, Hostaform, Ultraform
CA	Cellulose acetate	Tenite, Deval
CAB	Cellulose acetate butyrate	Tenite B, Cellidor B
EVA	Ethylene-vinyl acetate copolymer	Evathane
HDPE	High-density polyethylene	Lupolen, Rigidex, Vestolen A
HIPS	High-impact polystyrene	Hostyren, Styron, Lustrex, Lacqrene
LDPE	Low-density polyethylene	Alkathene, Lupolen, Hostelen, Stamylan
PA6	Type 6 Nylon (polyamide)	Akulon M 7 K, Ultramid, Maranyl B, Grilon
PA66	Type 66 Nylon (polyamide)	Rilsan B
PA11	Type 11 Nylon (polyamide)	Rilsan B
PA12	Type 12 Nylon (polyamide)	Grimalid, Vestamid, Rislan A
PBTP (PBT)	Polybutylene terephthalate (thermoplastic polyester)	Valox, Ultradur B, Pocan B, Celanex
PC	Polycarbonate	Makrolon, Lexan, Calibre
PEEK	Polyetherether ketone	Kalrez, Chemraz
PET	Polyethylene terephthalate (thermoplastic polyester)	Arnite A
PMMA (Acrylic)	Polymethylmethacrylate (acrylic)	Diakon, Lucite, Plexiglas, (Perspex)
PPO (PPE)	Polyphenylene oxide (ether) (modified with polystyrene)	Noryl, Luranyl
PP	Polypropylene	Novolen, Propathene, Stamylan P
PS	Polystyrene	Styron, Polystyrol, Hostren, Lustrex
PTFE	Polytetrafluoroethylene	Fluon, Teflon, Hostaflon
PVC	Polyvinylchloride (plasticised flexible)	Hyvin, Vinoflex, Vestolet, Lacqryl
SAN	Styrene-acrylonitrile copolymer	Luran, Tyril
UPVC	Unplasticised polyvinylchloride (rigid)	Hostalit, Welvic, Geon, Hyvin, Vestolit

Continued…

Thermosets		
DMC	Dough moulding compound (thermoset polyester)	Freemix, Polydur, Premiglas
Epoxy	Expoxide moulding compound	Araldite
MF	Melamine formaldehyde (amino)	Melmex, Ultraplas
PF	Phenol formaldehyde (phenolic)	Trolitan, Bakelite
SMC	Sheet moulding compound (thermoset polyester)	Flornat, Premiglas
UF	Urea formaldehyde (amino)	Polloplas, Beetle urea

3.16 Material Applications

Some of the main groups of polymers are identified below, with an indication of how these are used within the industry.

- *Acrylics:* Automotive lights, control knobs, dials and handles, meter cases, lenses, pens and pencils, hospital equipment, display material, signs, light fittings, inspection panel covers, windscreens, machine guards, skylights, some telephones, sanitary ware.
- *Acrylonitriles:* Butadiene styrene shoe heels, telephone handsets, housings for consumer durables, food containers, luggage, refrigerator liners, safety helmets, radio cabinets, tote boxes, car fascia panels, boat hulls, furniture.
- *Cellulose plastics (CA and CAB):* Packaging, sheeting, toothbrushes, windows in window cartons, moulded or extruded parts for metallisation, outdoor signs, tool handles, piping, safety glasses.
- *Epoxides:* Chemically resistant paints, adhesives, tools, PVC stabilisers, electrical insulation, chemical-and wear-resistant pointless flooring, road coatings, cements, laminates, powder coatings, spotting compounds, repair kits, printed circuits, filament-wound pipes, tanks and pressure vessels.
- *Ethylene-vinyl acetate (EVA):* Vinyl acetate flexible extrusions, tubing and hose, sachets, sheathing, cable covering, closures, gaskets, handle grips, shoe soles, teats, disposable gloves, box liners, packaging film, greenhouse film, inflatable toys.
- *Fluorinated polymers:* Polytetrafluoroethylene (PTFE) gaskets, packaging, valves, sintered metal bearings, rigid and flexible pipes, membranes, wire insulation, electronic engineering applications, nonstick coatings for kitchen utensils, heat-sealing equipment and confectionery machinery.
- Melamine formaldehyde: unfilled; usually occurs in laminate form as surfacing for tables, etc. Wood flour/cotton flock filled; bottle tops, electrical parts, fuse boxes, meter cases, heat-resistant close-tolerance mouldings, toilet seats (restricted in colours available) and dark-coloured plastic ashtrays.

3.17 The Behaviour of Thermoplastics During the Injection Moulding Process

3.17.1 Pretreatment of Materials Before Injection Moulding

The following sections describe how plastics melt (plasticise), flow and solidify as they pass through the injection unit and into the mould. It is not uncommon to find that certain materials may need some type of pretreatment before being moulded, for example reprocessed materials.

3.17.2 Reprocessed Materials

Ideally, reprocessed material should be sieved before moulding in order to remove any finely divided material to avoid it undergoing rapid ***degradation*** when heated to melt temperatures. In most instances reground material is mixed with an appropriate proportion of virgin material. The proportion of reground material that can be used very much depends upon the quality requirements of the component being produced, but can vary from as little as 5% right up to 100%.

It is usual for the customer, or the moulders' quality assurance department, to specify exactly how much ***regrind*** can be tolerated. The reground and ***virgin*** materials must always be uniformly blended together before being fed into the barrel of the moulding machine. In some instances it has been found necessary to incorporate a stirrer in the machine hopper to prevent the reground and virgin material from separating out.

For critical applications where the full physical properties of the material are important, reprocessed material should not be used at all.

3.17.3 Colouring Materials

Colouring of natural materials is achieved by the use of ***granular masterbatch***, liquid colour concentrate or powdered dye or pigment. To achieve a consistent colour it is essential that the concentrated colour is used in the correct proportions and to ensure that the mixing within the cylinder of the injection moulding machine is effective. It is usually recommended that back pressure be applied to the melt as previously discussed. This promotes more even dispersion of the colorant in the material.

3.17.4 Additives

Incorporation of other additives, to improve flow or to overcome mould release problems, is sometimes necessary and it is usual to incorporate additional lubricant such as zinc stearate. On occasions it is necessary to produce parts with a nonstandard filler or reinforcement content, and this can be achieved by blending the appropriate proportions of unfilled material with a more highly filled grade. For example, 60% glass fibre-reinforced nylon can be diluted with unfilled nylon of the same type to give lower levels of reinforcement. However, just as with colouring of materials, care must be taken to ensure uniform mixing of the correct proportions of the constituents.

3.17.5 Material Drying

Certain materials are ***hygroscopic***; i.e. they absorb moisture from the atmosphere. If appreciably damp materials are injection moulded, the resulting components will exhibit ***splash***, ***splay*** or ***mica*** marks caused by the bursting of bubbles of steam and other ***volatiles*** as the melt flows across the mould.

Some materials, for example polycarbonate or the thermoplastic polyesters, suffer severe embrittlement if processed even with very low moisture content that is insufficient to give any trace of splash marks. Hence these materials should always be thoroughly dried before moulding.

Table 3.4 gives an indication of the temperatures and drying times needed for a range of thermoplastics.

- Under adverse conditions, (i.e., when the material is exceptionally wet, or when the drying equipment is not particularly effective), drying times may need to be increased.
- Ideally Nylon should be dried in a vacuum oven to avoid the risk of degradation causing discoloration and possibly embrittlement due to reaction with oxygen in the atmosphere.
- When using air circulating ovens or driers it is strongly recommended that the air being circulated is pre-dried by passing it through a ***dehumidifier***.
- It should be borne in mind that some materials that, in theory, may need pre-drying may be used straight from the container. This is only true, however, when they are purchased from a reputable supplier in undamaged sealed containers, and providing they are used quickly and the humidity in the moulding shop is low enough. If in doubt about drying requirements, consult the material manufacturer for expert advice.
- Some filled grades of polymers, which do not normally absorb water, sometimes need drying before moulding.
- With materials such as ABS and the acrylics, drying may not be needed if a vented barrel machine is used.

Table 3.4 Drying times

Material	Temperature (°C)	Time (h)	Method
Nylon 6	80	3–4	Vacuum oven
Nylon 66	80	3–4	Vacuum oven
Nylon 11	80	2–3	Vacuum oven
Acrylic	70	3–4	Air circulating oven
Polycarbonate	120	4–8	Air circulating oven
ABS	75	2–3	Air circulating oven
PPO	90	2	Air circulating oven
GF PPO	110	2	Air circulating oven

3.17.6 Plasticising or Melting

When the screw within the barrel of the injection moulding machine rotates, it draws material from the hopper via the feed throat and propels it along inside the barrel. Once inside, and specifically as the material passes through the compression zone on the screw, it melts or plasticises. This is due to the combined heating effect of the heater bands around the barrel and the ***shear heating*** caused by the rotation of the screw. The actual temperature of the molten material is referred to as the ***melt temperature***.

Most thermoplastics can be processed over quite a wide melt temperature range, but the material supplier's data sheet should always be consulted in order to identify the recommended temperature range for the material. If such data sheets are not available, the temperature ranges indicated in Table 3.5 can be taken as a reasonable starting guide for the more commonly encountered materials. Note that these temperatures values are for the actual melt temperature, which may differ considerably from the set temperatures on the machine barrel temperature controllers.

Table 3.5 Table of melt temperatures

Material	Melt temperature range (°C)
ABS	190–290
Acetal	180–220
Acrylic	200–250
HDPE	210–270
HIPS	180–280
LDPE	180–240
PA6	230–290
PA66	270–300
PA11	220–250
PBTP	240–275
PC	280–320
PP	200–280
PS	170–280
PVC (Flexible)	170–190
PVC (Rigid)	160–210
SAN	200–260

3.17.7 Measurement of Melt Temperature

In order to measure the actual melt temperatures, about 150 cm^3 melt is purged out of the cylinder into a suitable container and measured with a pyrometer. [**Note:** This is a potentially dangerous operation, and must be carried out with extreme care.] A needle, or melt probe attached to a suitable pyrometer is then plunged into the melt and slowly moved around to search out the hottest spot. The maximum temperature indicated is taken to be the melt temperature.

3.17.8 Degradation of Materials During Plasticising

With any material it is inadvisable to exceed the maximum melt temperature as specified by the material manufacturer. If this happens the polymer may undergo degradation, leading to changes in flow characteristics, reduction in mechanical strength, and discoloration. Overheating of heat-sensitive materials such as PVC or the acetals can lead to very rapid degradation and the liberation of substantial quantities of noxious fumes.

It should also be remembered that molten polymers, even at temperatures within the recommended processing range, can also decompose quite considerably if they are held at such temperatures for an excessively long time in the cylinder.

The length of time a polymer can be held at a particular temperature without the risk of undue degradation is known as its ***maximum residence time*** at that temperature, and this time should never be deliberately or accidentally exceeded. For this reason, it is always good practice to ***purge*** the cylinder empty if a machine has to be stopped for more than a few minutes.

3.17.9 Selecting the Optimum Melt Temperature

The following are factors that should be taken into account when selecting the most appropriate melt temperature for a particular combination of material, mould and machine.

- The melt must be sufficiently fluid to enable it to flow easily to the farthest extremities of the mould cavity forms.
- Low temperatures (particularly in the case of amorphous thermoplastics) give rise to very viscous, stiff-flowing melts which, as well as making it difficult to fill the mould, can also give rise to mouldings with high levels of internal stress. This may cause distortion in the product during service.
- With some thermoplastics, for example high-impact polystyrene or ABS, too low a melt temperature will give components with a matt surface finish unless excessively hot moulds are used.
- High melt temperatures, particularly in the case of amorphous thermoplastics, usually necessitate extended cooling times to avoid distortion of the component on ejection.
- Excessively high melt temperatures can lead to a reduction in mechanical strength of the moulded part, although often the visual appearance is unaffected.

3.17.10 The Effect of Screw Rotational Speed and Back Pressure

The rotation of the screw creates shear heat within the material. Increases in screw speed and, to an even greater extent, the application of back pressure can cause an increase in melt temperature of as much as 100 °C in some instances. Conversely, very low screw speeds can generate so little shear heat that unmelted granules begin to appear in the melt.

This can occur when working with any material that is known to be prone to thermal instability (e.g., PVC and acetal). High screw speeds and the use of high back pressures should be avoided. Similarly, materials with glass or carbon fibre reinforcement should not be subject to high screw speeds and high back pressure as such conditions may cause the fibres to break down, producing a noticeable decrease in the mechanical strength of the moulded part.

With glass fibres these conditions can also give rise to rapid wear of the check ring that acts as a one-way valve at the front of the screw tip. However, with many modern machines a small amount of back pressure may be needed to ensure a consistent refill.

It is advisable to consult the materials supplier's data sheets for specific guidance on the selection of screw speed and use of back pressure for each material.

3.17.11 Flow Characteristics of the Melt During the Injection Phase

Ideally, immediately as the material has been plasticised it should be injected into the mould since its temperature begins to fall once the material has passed through the gate. Therefore, by minimising the residence time there is less chance for thermal degradation to take place.

To inject the material in to the mould, the hydraulic piston attached to the end of the screw is pressurised. As the screw starts to move forward, the melt between the screw tip and the inside of the nozzle and end cap also comes under pressure. This pushes the check ring into the closed position, preventing back flow over the screw. Note that a check ring should not be used with many PVC materials. Special cylinders and screws are usually required for processing PVC and as PVC normally corrodes steel the mould should be made from stainless steel to prevent this (see Chapter 16).

The screw now acts as a plunger or ram and injects the material through the sprue, runner and gate, into the mould cavities. The correct injection speed and the point where the changeover from injection to holding pressure occurs are both crucial to the success of the moulding operation.

3.17.12 Selection of Injection Speed

The material should flow rapidly and at a uniform speed throughout the mould runners and cavities. This helps to reduce problems such as short shots, weld lines, flow marks and moulded-in stress. As the melt flows into the mould it has to pass through the restriction of the gate. This causes an increase in both the melt temperature and the temperature of the gate itself. This increase in temperature will be proportional to the injection speed, with higher speeds giving a greater rise in temperature.

The way in which thermoplastics behave during flow is rather unusual, and is brought about by the long, thin shape of the polymer molecules. Low rates of flow due to low injection speeds result in the molecules in the melt tending to move along in a tangled amorphous mass. This will cause the material to have a higher ***viscosity***, that is, it will be stiffer-flowing.

As the rate of flow increases, the melt becomes progressively more fluid, i.e., its viscosity decreases but this is not due to any change in temperature. What in fact is happening within the melt is that the molecules are becoming progressively disentangled as the rate of flow increases. This movement causes the long-chain molecules to align or become ***orientated*** parallel to each other along the length of flow. With the majority of polymers this causes a substantial improvement in flow, enabling thin-walled components of complex shape to be moulded with relative ease.

Slow rates of injection should in most cases be avoided when moulding components having an average wall thickness of under 2 mm as they can result in difficulties in filling and can produce parts that are likely to distort in service owing to moulded-in stress.

We can examine how these stresses are induced if we consider what happens when a melt, at say 200 °C, flows through a mould with a surface temperature of 50 °C. At slow speeds of injection, the melt flows forward as a tangled mass of molecules. As the melt touches the relatively cold walls of the mould, the surface layer is rapidly chilled and solidifies, creating a frozen layer.

The rest of the melt continues to flow onwards past the frozen layer and between the core of still-moving melt there is a layer where partly solidified polymer is being dragged along by the material that is still molten and moving. The molecules in this boundary layer become highly stretched and orientated along the length of flow, and many of them become solidified in this state.

The presence of this stressed orientated layer of molecules will cause the moulding to distort in service if subject to high temperatures. Conversely, if the material is made to flow rapidly, a less pronounced frozen layer is formed, resulting in far less orientation being solidified into the moulding.

At first sight this appears to be illogical, since it is known that rapidly flowing polymer melts are highly orientated. However, this orientation only persists in the fluid melt while it is moving. Once the melt becomes stationary after the cavities in the mould are filled, the orientated molecules in the still-fluid melt will relax; the orientation disappears and an amorphous structure is re-established.

The effect of orientation can be exemplified by very thin-walled polystyrene cups used in vending machines tending to break very easily in the direction parallel to polymer flow in the mould, whereas it is quite difficult to break them in the circumferential direction. This is due to the long-chain polystyrene molecules being orientated by the very high injection speed that had been used and to the part being very thin with a very low mould temperature, causing the melt to solidify so rapidly that the orientation became frozen in.

If high injection speeds are attempted with thick-walled mouldings of over 3 mm, problems with gas trapping and jetting frequently occur. To avoid these problems, lower injection speeds should be employed. This enables the mould to be filled more slowly creating a thicker surface skin and a highly orientated boundary layer formed between the skin and the still-moving melt in the core of the moulding. However, once the mould has filled and the melt becomes stationary, the large reservoir of heat held in the thick molten core of the moulding is absorbed into the orientated layer. This allows the molecules to move again and take up more relaxed nonorientated positions. In effect, such thick-walled mouldings may be considered as ***self-annealing***, and for this reason relatively low injection speeds are quite acceptable.

The general rule for parts of average wall thickness 2 mm and under is to use higher injection speeds, but there are exceptions to this. One notable exception is material belonging to the acetal group, which suffers a considerable decrease in impact strength with high injection speeds. Wherever possible the material supplier's data sheet should be consulted to establish their recommendations for the appropriate injection speed that should be used.

In order to achieve the optimum injection speed it is essential that sufficient injection pressure is available. The pressure needed will depend upon the speed required, the melt viscosity, the section thickness and geometric complexity of the part together with the mould temperature. When sampling a new mould it is quite common to initially set the injection pressure to maximum, which will ensure that the highest injection speed can be achieved if necessary. However, this technique must be used with caution since high injection pressures may compact the mouldings in the cavities to the extent that will not eject properly.

Once mouldings of the required quality are obtained, the injection pressure should be set to a slightly higher value and a preproduction run should be undertaken to ensure these conditions are satisfactory for subsequent volume production. At this point all the moulding settings must be recorded for future reference. Preferably these settings should permit the widest possible operating window.

As a note of caution it should be remembered that if the injection pressure were subsequently changed, the injection speed would also be affected.

3.18 Initial Cavity Filling Phase

In addition to using the optimum injection speed, it is also very important to ensure that during the initial injection phase the mould is 99.999% filled with material. This is achieved by very careful adjustment of the change-over position control, which switches from the injection to the holding pressure phase. This can be achieved by position switch, timer, or pressure sensor depending upon the sophistication of the moulding machine. There are important reasons for ensuring that the change-over position is so precisely set:

- If too much material is injected, the mould may flash, or possibly the cavities will be overpacked.
- If insufficient material is injected, the cavities will not be fully filled during this first phase, with complete filling occurring in the holding pressure phase instead. As this pressure is usually lower than the injection pressure, it will cause a slowdown in the rate of flow of the melt into the cavity at this critical stage in the filling of the mould.

This can result in poor-quality mouldings exhibiting possible sinking, voiding and other problems.

3.19 Cavity Holding Pressure Phase

Once the complete injection phase is finished, the cavities are filled with material having a solidified outer skin and a molten core. As the mould is considerably colder than the melt, the temperature of the material begins to fall and shrinkage starts. The total amount of shrinkage varies between 7% and 18% of the volume of the mouldings depending upon the chemical composition and structure of the material. In the case of the semicrystalline materials, the cooling rate can also greatly affect overall shrinkage, which is usually quite high compared with amorphous materials.

3.20 Gate Freeze-off Phase

The material in the core of the moulding remains fluid for some time, as does that in the gates, runners and sprue. The gate itself will probably be hotter than the rest of the mould owing to the shear heat generated as the mould filled, as explained previously. As long as this fluid pathway through the gate remains open and the holding pressure is applied, the mould will be kept topped up with fresh material to replace the loss in volume as the melt cools.

The holding pressure can be effectively used in this way right up until the gate freezes off, and when making high-quality mouldings it is essential that the holding pressure time matches exactly the gate freeze-off time. Clearly, once the gates have completely frozen off, there is no point in any further pressure being applied as there is no pathway for material to enter the cavities.

3.21 Melt Compressibility and Shrinkage

The compensation phase provided by the holding pressure will substantially reduce the overall shrinkage of the mouldings. However, further reductions in shrinkage can be achieved by making use of the high melt compressibility property displayed by most plastics.

The compressibility of a polymer melt depends upon several factors including the chemical nature and structure of the polymer, the melt temperature, the mould temperature and the pressure being applied. The compressibility varies between 2% to 15% by volume; this means that by compressing the melt with sufficient holding pressure it is possible to force additional material into the mould, giving further reductions in shrinkage.

However, this technique should be used with caution and not applied universally or at too high a holding pressure as this may cause the parts to flash or overpack and induce ejection problems as described earlier. Additionally, too high a holding pressure can often lead to ***moulded-in stress***.

Generally, for most materials the holding pressure should be set at the lowest value needed to give mouldings of acceptable quality and be maintained until the gate freezes off. However, semicrystalline materials like acetal, Nylon, etc. do require high holding pressure to achieve required dimensions and mechanical performance.

3.22 Sinks and Voids

If the holding pressure is removed before the gate has frozen off, the compressed melt in the cavity will flow back through the gate into the runner system, causing the problems of sink marks and the formation of voids. In addition to maintaining holding pressure, it is essential that a small cushion or volume of material is held in front of the screw at all times. This ensures that that there will be sufficient materials available for pressurising the cavities through the complete injection cycle.

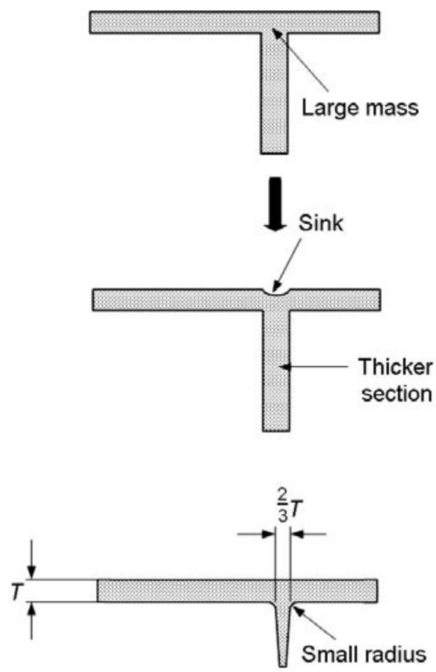


Figure 3.7 Sinking due to large mass of material

Figure 3.7 shows the classic problem at the junction of two sections of different thicknesses that creates a large mass of material, resulting in sinking. To avoid this, ribs and similar features should not be thicker than two-thirds of the main section of the moulding. Preferably they should also taper to a thinner section at the bottom, as shown.

Excessively thick sections are always prone to this problem but it may sometimes be disguised by introducing a surface texture on the affected area as shown in Figure 3.8. Figure 3.8(a) shows the original component; (b) shows a textured finish, which has reduced the effect; (c) shows a change to a lighter colour, which almost makes the sink disappear; and (d) shows a change of contour to a curved surface, which has reduced the problem a little. However, it is far better to avoid the problem completely by altering the part design where this is possible.

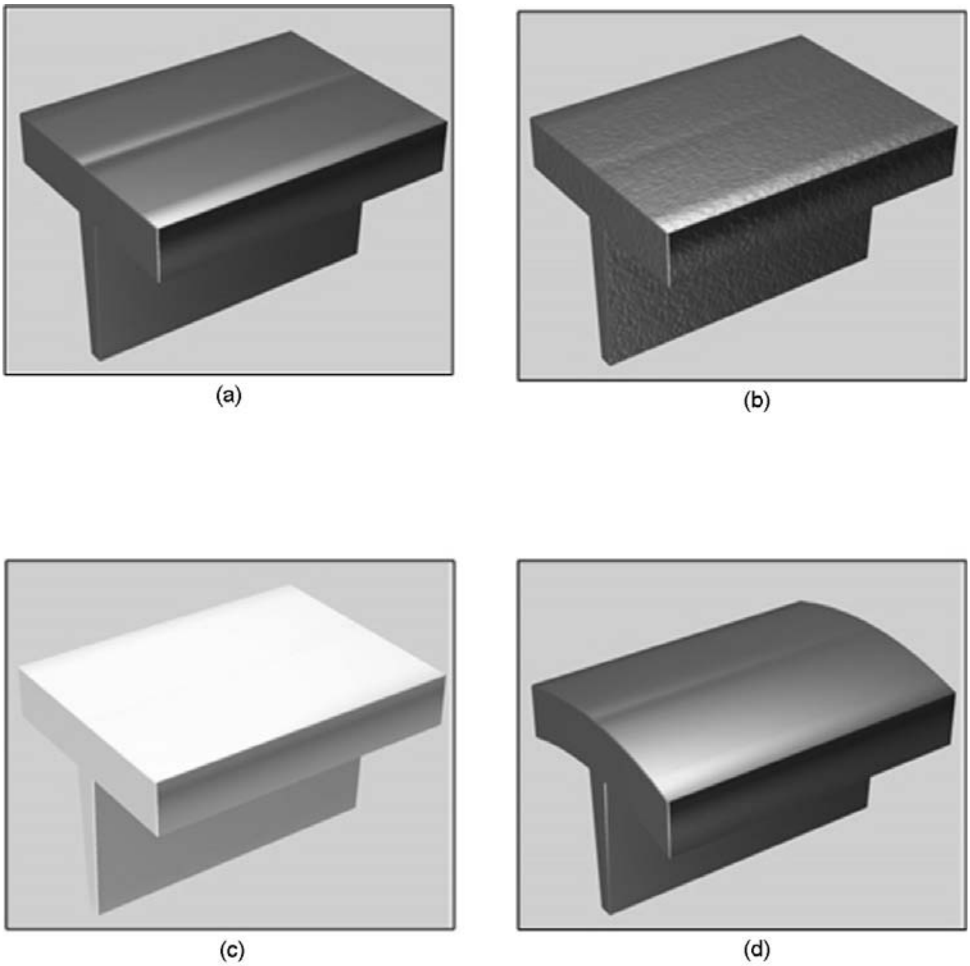


Figure 3.8 Disguising flow lines

Figure 3.9 illustrates voids occurring where excessively thick sections exist in a moulding. Although moulding technique can help reduce this problem, it usually cannot cure it completely. Once again, the design of the part is not suitable for injection moulding, where we require all sections to be reasonably uniform or reducing the farther away they are from the gate.

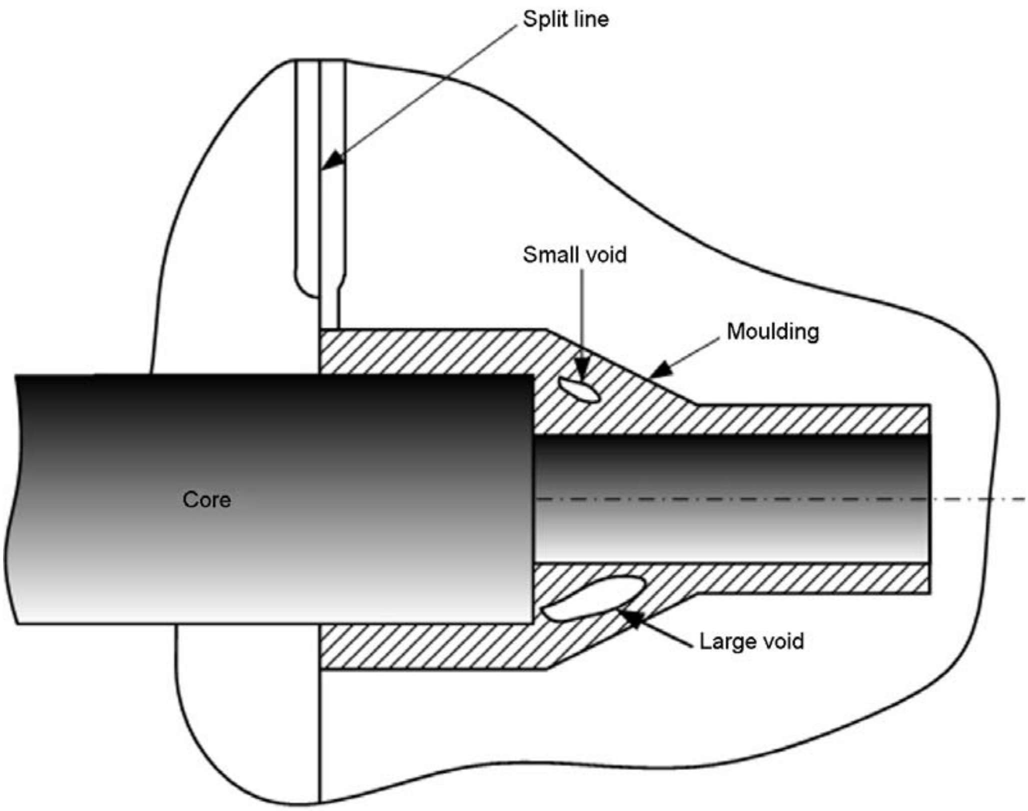


Figure 3.9 Thick sections causing voids

3.23 Weld Lines and Meld Lines

Typical weld lines are shown in Figure 3.10. These are prone to occur where the material flow separates around an obstruction. Where the material meets again, the material fronts have slightly cooled, and this prevents the two fronts joining together properly. This can result in a plane of weakness, sometimes leading to mouldings breaking.

Meld lines occur where a moulding has more than one gate these can also result in a similar plane of weakness where the material flow fronts join.

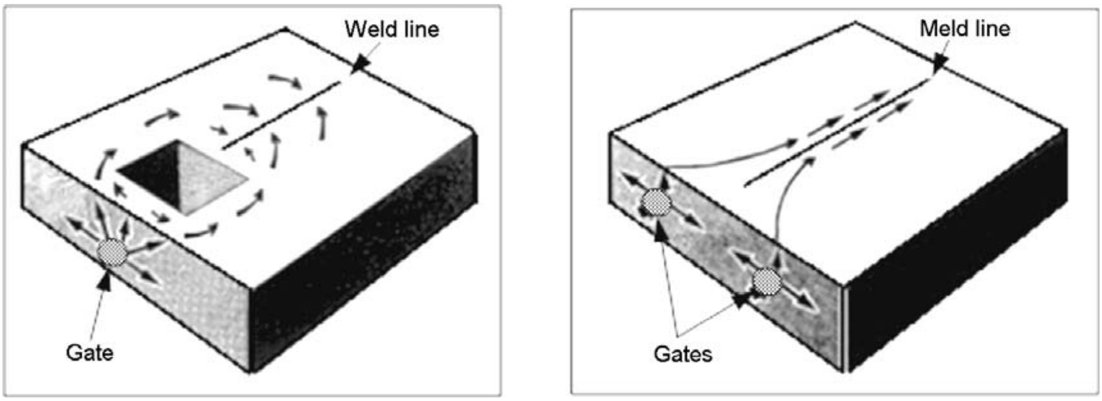


Figure 3.10 Weld lines and meld lines

The choice of gate position is important in minimising the weld lines as shown in Figure 3.10. Wherever the material flow meets an obstruction weld lines are very likely to occur and the position of the gate should be carefully considered to minimise this effect at the mould design stage. In critical applications it may be worthwhile carrying out a flow analysis to optimise the size and position of the gate (see Figure 3.11).

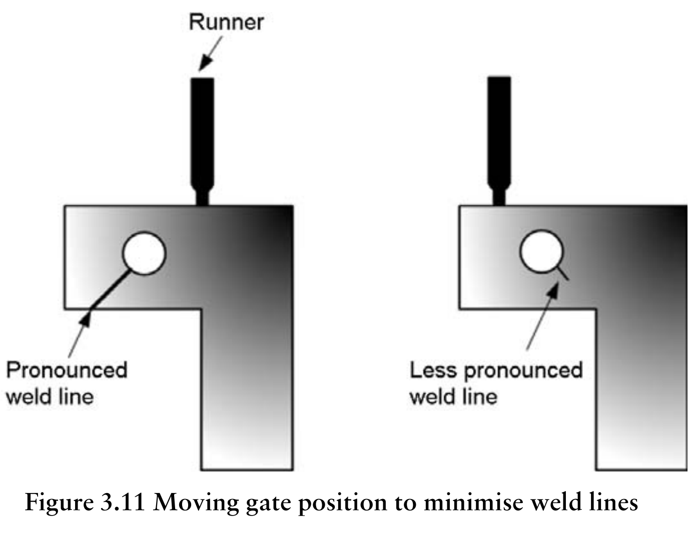


Figure 3.11 Moving gate position to minimise weld lines

3.24 Cooling and Solidification of the Melt

As discussed earlier, the outer skin of the melt solidifies rapidly, forming a frozen layer while the mould is filling. The remainder of the melt in the core of the moulding solidifies at a much later stage, well after the gate has frozen off.

The rate of cooling is a critical factor in the control of the injection moulding process. In order to keep cycle times as short as possible, rapid cooling is usually required, and this is often achieved by using low mould temperatures achieved with cool or sometimes chilled water. However, a cold mould can cause problems, such as difficulty in filling, poor surface gloss, pronounced weld lines and moulded-in stress. It is usual, therefore, to compromise and use a temperature that will produce a component of adequate quality in an acceptable cycle time.

Table 3.6 gives an indication of the mould temperature ranges for the more commonly moulded thermoplastics. It should be noted that these temperatures are intended for general-purpose and technical mouldings. For thin-walled parts, as used in packaging, very much lower temperatures are often used.

Whatever mould temperature is used, it is essential that the parts be held in the cavities long enough for them to cool to a stage where they can be safely ejected without damage or distortion.

Table 3.6 Mould temperatures for some common thermoplastics

Material	Mould temperature range (°C)
ABS	40–80
Acetal	50–120
Acrylic	50–80
HDPE	20–60
HIPS	30–80
LDPE	20–60
PA6	40–90
PA66	40–90
PAH	40–110
PBTP	60–90
PC	85–120
PP	50–80
PS	20–80
PVC (Flexible)	20–40
SAN	50–85
UPVC	20–60

4 Good Design Practice

There is an extremely wide variety of mouldings that have been produced, ranging in complexity from straightforward to highly technical, since the introduction of injection moulding. Advances in injection moulding technology, toolmaking and machining techniques have made it possible to produce mouldings of high complexity.

Not far behind these advances, the standard components industry has kept pace with an ever-increasing range of high-quality products. Making full use of these can greatly simplify designs and tool constructions and also reduce both design time and toolmaking time.

Many standard components are specifically designed to provide solutions to several different types of undercut or ejection problems. Clearly, where these can be successfully incorporated into a design, full advantage should be taken in using them. In most instances such components offer a self-contained solution for forming and releasing an undercut in the mould tool, such as collapsible cores, and are a considerable advantage for the designer and toolmaker.

Despite the wide range of geometric forms of mouldings that are produced, it is possible to classify the mould designs into two broad groups when a new component has to be moulded: those that may be based on existing proven mould designs and those that require a totally new design. It is clearly advantageous to use a previously proven design and adapt it to suit a mould design for the new part when this is possible, since with existing designs all the bugs have already been ironed out and their behaviour in production is fully known.

Inevitably, there are occasions when new designs have to be created to solve specific problems. In some cases existing design solutions can be extended but in others a totally new approach is required. In the latter case it is previous design experience that comes to the rescue in providing the designer with the insight to know whether a new departure is likely to succeed. However, the designer should always strive to ensure that the design represents the simplest possible solution to the problem.

If a sample moulding has been supplied when a new mould tool is required, this will often provide very useful information such as gate position and size and the position and size of ejector pins, etc. If a part has been successfully moulded before, the new mould design should be based on this unless, of course, the reason for laying down a new tool is that it was not successful.

Simpler designs always beat the complex, highly intricate ones for reliability and product quality. It is also good practice to use tried and tested designs and mould components as opposed to totally new and untried ones.

Gaining experience in mould design is largely a question of learning over a period of time and by achieving the following:

- To actually design as many mould tools as possible.
- To study and ***understand*** other existing mould general arrangement diagrams (GA).
- To become familiar with toolmaking procedures.
- To observe and ***understand*** how mould tools work while in production.
- To have an appreciation of the different type of material, particularly the difference between amorphous and semicrystalline materials.

4.1 Predesign Analysis

Generally speaking it is advisable to do some predesign analysis before embarking on the main design. This is an obvious statement to make and really needs some qualification. If you are not a mould designer (or even if you are), sketch out as many designs as you can first. Try to come up with at least three different approaches for split line positions, gate positions and type of ejection. At this stage the cavity construction must also be taken into consideration, as must water cooling and so on.

New designers should place the emphasis on solving the problems. Look at all the mouldings you can find and try and detect how they were moulded, where the split lines and gates are, where they were ejected and how any special features were formed.

4.2 Reading General Arrangement Diagrams (GA)

This is also invaluable practice. Contrary to common belief, most mould tool GAs cannot be read and ***understood*** in ten minutes, even by experienced designers. In many cases it can take hours rather than minutes to ***fully*** understand how the tool design actually works.

To illustrate this point, very often a toolmaker will contact the designer to query one or more aspects of the drawings that he does not understand. It could be that the drawing is ambiguous or even wrong. It can also be that the drawing is so complex that the toolmaker has some difficulty understanding it.

Whether the designer has made a mistake or the toolmaker is misunderstanding the drawing is not as important as the willingness of either party to resolve the difficulty. These discussions take place all the time in practice.

Neither toolmakers nor design engineers should be too proud to ask for clarification when something is not fully understood. As is (or should be) stated at the top of all drawings, the following statement is fundamental and necessary:

IF IN DOUBT – ASK

4.3 Understanding Toolmaking Concepts

Ideally, the mould tool designer should have had some toolmaking experience before embarking on mould design. Clearly it is a prerequisite that you have to know that what you are designing can actually be made.

For those that have not had any toolmaking experience, it is best to make a habit of regularly visiting a toolmaker to learn about the toolmaking techniques involved. Most toolmakers are reasonable people and normally quite willing to give a short 'teach in' in these circumstances. You do not have to be a highly skilled, accomplished toolmaker to design mould tools. However, you cannot possibly design mould tools with knowing whether what you are designing can be made.

It must also be noted that different toolmakers often have different plant and equipment, so the mould design must reflect this. Some toolmakers have highly sophisticated computer-controlled machining centres, while others have fairly basic operations. However, all toolmakers have a common core of plant and equipment as follows:

- Drilling machines
- Lathes
- Milling machines
- Surface and cylindrical grinding machines
- Electrodischarge machining facilities

4.4 Observing Mould Tools

Many mould designers never see the mould they have designed in production! This is a serious shortcoming. All designers should be compelled to attend the initial sampling trials for two reasons:

1. Moulds are often complex and need to be explained to the sampling technician. Many breakages have occurred when complex unscrewing mechanisms or phased latch controls have not been fully understood.

2. The mould designer can obtain valuable feedback on the design and can implement improvements or 'tweaks' that will help the mould run more efficiently.

It is also very instructive to look at and observe other mould tools while they are running to observe other people's designs. It is useful as well to go and look at mould tools while they are being stripped down for servicing or repairs. This can show pitfalls that can be avoided in the future: seized-up parts, excessive flash and wear, etc.

4.5 Summary of Good Design Practice

1. Use the simplest possible design.

2. Make full use of standard components.

3. Use tried and tested designs in preference to new, unknown designs.

4. Critically examine any existing samples that have been provided for gate positions, ejector positions, sinks, distortion, etc.

5. Check with the toolmaker that they have the equipment necessary for the design.

6. Attend sampling trials for essential feedback information and to advise the sampling technician on the tool function.

5 Design Checklist

Before starting a design, it is essential to have all the information necessary to enable a successful design to be achieved. Many problems occur when this simple rule is not followed, often leading to poor designs, misunderstandings, poor component quality and arguments between suppliers and end users.

An experienced designer will almost automatically make sure that all the steps necessary are followed, but even then the sheer number of potential pitfalls may catch out such a designer from time to time. It is therefore beneficial to have a checklist that that can be added to and can be ticked off point by point to ensure that nothing has been overlooked.

5.1 Predesign Checklist

- Original estimate details
- Component drawing
- Component geometry
- Component material
- Quantity required
- Component function
- Component tolerances
- Number of impressions
- Gating method
- Ejection method
- Component aesthetics

5.2 Original Estimate Details

1. It is essential that the original estimate details are available to the designer from the beginning. These should include all the information necessary to enable the design to be undertaken.

2. If these details are unclear or if any information is missing, this must be taken up with the estimator at the earliest opportunity. Without a clearly defined design brief, the mould tool design should not be started.

3. The fact that the estimator has made value judgements in preparing quotations does not mean that these are cast in stone. Estimates are often prepared very quickly and by definition they may not be as fully thought out as they would be if more time had been available. Therefore, the designer should not accept the estimate details automatically and should challenge any areas deemed to be dubious or indeed incorrect.

5.3 Component Drawing

1. A fully detailed component drawing must be available. It must be unambiguous, leaving no room for misinterpretation or doubt. All dimensions and tolerances must be present and the material clearly specified.

2. Any queries the designer may have should be taken up and discussed and agreed with the customer and a new drawing issued.

3. It is important that both supplier and customer are working to a single agreed drawing. This avoids confusion, delays, expensive mistakes and disagreements later.

5.4 Component Geometry

1. The drawing must be examined carefully until the designer is clear in his mind that he fully understands what the customer is asking for. This is absolutely vital. It is this analysis of the component form that will determine the type of mould tool that will be required. For example, two-plate, three-plate, multiplate, side core, split, stack, and so on.

2. It is not unknown for the component geometry to be impossible to make as a single injection moulding. If this is the case the customer must be informed immediately to discuss this problem. It may be possible to make the component by an assembly of different mouldings. Either way, this is a major point that must be resolved before any further work is undertaken.

5.5 Component Material

1. It is an absolute prerequisite to know the material characteristics for all designs. Therefore, the material must be fully specified without any ambiguity. If this material is outside the designer's experience, he should seek further information from both the customer, who may already have considerable knowledge of it, and the material supplier.

2. The material should be checked to see that it is suitable for the injection moulding process. For example, it may require very high moulding temperatures and pressures that the moulders cannot achieve with their plant.

3. Equally, the material may not be suitable for the intended application in terms of required performance. It may be too brittle, too soft, not strong enough, etc.

4. The material may be very expensive and a suitable, cheaper alternative may be available. It is also possible that the moulder may already hold another, equivalent stock material with which they have considerable experience. It is always worth enquiring whether such a material may be used if it will perform the same task satisfactorily.

5.6 Quantity Required

1. The quantity is another important factor as it often (but not always) determines the number of impressions the mould tool will have.

2. It may also determine the type of tool that will be used. For example, a runnerless or hot runner tool if the quantities are high enough.

5.7 Component Function

1. This term refers to the way in which the customer will use the component. The moulder should make sure that the material requested by the customer is compatible with the intended application.

2. In many cases, the customer may have selected a material that is unsuitable, leading to problems and even failure in operation.

3. In some cases a material manufacturer may have unduly influenced the customer. However, there may be another material that will perform the task better or there may be a cheaper alternative that will perform the task just as well.

5.8 Component Tolerances

1. The drawing must be checked to make sure that the tolerances required can be met in production by the moulder.

2. If the tolerances are small, the degree of difficulty of moulding increases considerably. Close tolerances should set off an alarm bell with the designer and guide him towards using fewer numbers of impressions than otherwise would be the case. See Chapter 6 on '*Determining the Right Number of Impressions*' for a further discussion.

3. It is a fact that during moulding the tolerance range of the mouldings will increase as the number of impression increases. Moulding on large numbers of impressions with closely toleranced dimensions frequently leads to many problems with out-of-tolerance parts.

5.9 Number of Impressions

1. In many cases the original estimates are based on quoting an alternative number of mould impressions to the customer. Clearly, the designer must be informed which of these alternatives has been selected by the customer before the design can be started.

2. If the designer feels the number of impression required is excessive, this should be challenged immediately.

3. The reasons for challenging the number of impressions range from tolerance considerations to machine clamping limitations. Both of these topics are discussed in more detail later.

5.10 Gating Method

1. This is another key factor in determining the success of a mould tool. The gating type and location should be selected with care (see Chapter 17).

2. The gate type and position should be selected so that the gate is in the best place to achieve a sound moulding. Unfortunately, there are many occasions when the gate has to be located elsewhere owing to functional or appearance requirements. If the gate has to be located in a position that the designer feels is dubious, this should be challenged at the earliest opportunity.

3. The same considerations also apply to the way in which the component is to be de-gated. Auto de-gating should always be employed wherever possible. If auto de-gating is not possible, the designer should include the design of appropriate de-gating jigs and fixtures.

5.11 Ejection Method

1. The method selected will depend upon the material and the component geometry as well as other factors like mould texturing drag, friction, and so on.

2. The designer should aim to achieve a positive balanced ejection of all the components from the mould tool. The type and number of ejectors used will vary with each design and will also depend on the facilities available on the designated moulding machine: for example, whether the machine has core-pulling or hydraulic ejection arrangements.

3. Ejection witness marks should be checked with the customer for acceptability. Witness marks should not be left on appearance faces or distort functional areas of the component, for example.

4. The component should be checked to see whether draft angles are present on the drawing. If they are not present and are deemed to be necessary, this should be negotiated with the customer.

5.12 Component Aesthetics

1. Many mouldings are used in situations where one or more faces constitute an important appearance area. If this is the case, the mould tool cavities will have to be constructed with this in mind to avoid potential undercutting and drag witness marks.

2. The cavity construction may have to be fabricated in order to allow textured areas to be achieved.

3. Consideration will also have to be given to preserving the appearance faces with regard to gate position, ejection and split lines. The combined split line/ejection system must be examined carefully to avoid drag and witness marks.

4. The appearance will also be influenced by the application and efficiency of the mould cooling design, which is also discussed in detail later.

6 Determining the Right Number of Impressions

The decision concerning how many impressions a mould tool should have is frequently given insufficient thought. The usual approach is as follows.

The production rate of any mould tool is given by the expression:

$$\text{Production rate per hour } = \frac{3600}{\text{Cycle}} \times \text{Number of impressions}$$

When a new mould tool is being considered, however, the expression is rearranged to estimate the number of impressions necessary to achieve a desired production rate:

$$\text{Number of impressions} = \frac{\text{Production rate per hour} \times \text{Cycle}}{3600}$$

If we take the example of a required production rate of 1800 per hour being necessary to meet production schedules, the number of impressions required to achieve this with an estimated cycle of 15 seconds is:

$$\frac{1800 \times 15}{3600} = 7.5$$

Clearly this result would be rounded up to 8 impressions or sometimes a higher number to accommodate rejections and provide buffer stocks.

Having established this, the next stage is to establish which machine the mould tool will run on. Apart from the physical size of the tool, the other main limiting factors are the shot weight and the projected area of the mould. Once these factors have been resolved, the mould tool may be designed to fit on the selected machine.

In many cases, this approach is satisfactory but a significant number of projects do not prove satisfactory in production when designed on this basis. This is often because the moulded parts do not meet the quality requirements. There are three main reasons:

- The mould tool design is unsatisfactory.
- The machine is not capable of producing the parts to the required quality.

- The machine is adequate but the number of impressions being used is too great for proper control.

If the mould tool design is incorrect, this can prove to be a very costly mistake. Major alterations to tools can be very expensive and time consuming. Worse than this, some tools that do not run properly due to errors in design cannot be rectified – new ones have to be made.

Putting the job on another more suitable machine, if one exists, may rectify the second reason. The third reason, however, is more difficult to resolve, and frequently even impossible.

6.1 Quality *Versus* Quantity

This is an age-old expression but it illustrates perfectly the situation described above. The term ***quality*** covers a wide range of conditions that a part may have to conform to in order to meet the customer's requirements. Among these are:

- The appearance of the part
- The part geometry
- The drawing tolerances

Assuming the mould design is not at fault, a frequent cause of failure to meet quality requirements is due to using too great a number of impressions. In general, the greater the number of impressions a mould tool has, the less the control over the individual impressions there is. Variations will exist between the impressions owing to differences in manufacture, pressure, temperature, gate sizes, and so on.

In order to minimise these differences, runner layouts and gate sizes may be balanced, but despite this there will still be finite variations in pressure, thermal gradients, impression sizes and other variations that make multi-impression tools sometimes difficult to run.

The three categories mentioned above are those which many moulders may have difficulty with through using too high a number of impressions.

6.2 Appearance

Many mouldings are required to fulfil an appearance role as well as a functional one. Any moulding that will finish up as part of a point of sale product has to be free of obvious blemishes: a substandard-looking part is clearly undesirable.

The greater the number of impressions, the more variation there will be in any sinking, voids and other internal and external defects. As the runner system gets longer, the more difficult it is to properly pressurise every cavity. As a result of this, pressures are often increased to try to eliminate sinking and to preserve special surface finishes.

This in turn can lead to some parts being overpressurised and perhaps flashed while others still exhibit problems. Carefully balanced systems will help reduce this effect, but inevitably unsatisfactory variations can remain with large-cavity-number mould tools.

Sometimes these variations are acceptable and will be deemed to be within specification by the moulder and the customer. This can only happen if both parties are clearly aware of the likely results and if these are fully defined and understood.

If the appearance requirements are critical or demanding, careful consideration must be given to using a smaller rather than a larger number of impressions.

6.3 Part Geometry

Owing to the same variations, mouldings with complex part geometry need a great deal of control during processing. To avoid warpage, distortion or shorts (with thin-walled parts), the same philosophy applies.

The fewer the number of impressions, the greater the control and the more the consistency between different impressions will be. Strict control of moulding conditions and the mould temperature is necessary for consistency.

6.4 Drawing Tolerances

If the tolerances required on the mouldings are very small, a high-quality mould tool and a good-quality machine with adequate closed-loop control are necessary. In addition, the mould tool cavities will have to be machined very accurately and as close to the same dimensions on all impressions where the close tolerances apply. In other words, for such parts it is necessary to get as near to identical cavity and core sizes as possible.

Again, the greater the number of impressions employed, the less control there will be and the greater the dimensional variance between mouldings from different cavities. Accurate mould temperature control is also essential for such parts and thermal gradients should be avoided. All of these requirements get increasingly difficult to achieve as the number of impressions increases.

6.5 Discussion

Much experimental evidence exists that illustrates the proposition that consistency of quality decreases as the number of impressions increase. Trials carried out in trade moulding shops also support this view.

The problem gets worse with high-shrinkage materials where greater variations are often experienced. The same is true of materials that are difficult to mould (those with high processing temperatures and certain filled materials). High-viscosity materials are always difficult to mould consistently and large numbers of impressions are to be avoided in many cases.

Using software to simulate the filling of mould cavities will help to achieve more balanced filling conditions, but the same principle applies.

6.6 More Cavities = Less Control

On the other hand, mould tools must have sufficient capacity to support production levels wherever this is possible. As the number of impressions on a tool is largely decided at the estimating stage, the number actually decided upon will clearly influence the part price and hence how likely a moulder will be to obtain the work.

The temptation when estimating is to select a higher rather than lower number of impressions to make the part price more attractive to the customer. The perennial problem is that when a moulder provides a quote to a customer, they do not know on what basis their competitors have quoted.

In many cases, where a moulder has responsibly decided on a low number of impressions for a part, another moulder may have based their quotation on using a higher number and this frequently leads to the responsible moulder losing the job. This is often due to the customer's lack of understanding of the relationship between large numbers of impressions and part quality.

Despite this, moulders in general should be more aware of the repercussions of basing quotations on tools with large numbers of impressions that will be unlikely to provide the required quality. This can lead to failure to supply parts to the quality required and to disaffection of the customer.

However, customers are increasingly becoming aware of some of the pitfalls in accepting superficially 'attractive deals' and are themselves becoming more knowledgeable. This has come about in 'self-defence' in trying to avoid costly failures and delays on their production lines.

The question arises: How is the correct number of impressions to be established? The answer is not straightforward. Much will depend upon the experience and expertise of the moulder, the nature of the part and what type of processing equipment and material is used.

Clearly, there are situations where the number of impressions is not so important. Open-tolerance washers, for example, can be moulded with large numbers of impressions quite happily. With this type of part the emphasis changes to finding a machine large enough to accommodate a large tool with a large number of impressions. On the other hand, there are some quite complex, closely toleranced parts that are very small. The shrinkage on these will be almost zero and the sizes of the moulding very close to the cavity sizes.

This is another case where larger numbers of impressions may be used. However, for the majority of typical 'trade mouldings' applications, the number of impressions used is important.

It is difficult to quantify the actual number of impressions that should be used, but Table 6.1 provides a rough guide based on past experiences. This table is based on a smallest tolerance of ±0.05. Amorphous materials have the designation **A** and semicrystalline materials have the designation **SC**.

Table 6.1 Recommended impression numbers

Part diameter (mm)	Material	Maximum number of impressions
≤5	A or SC	Unimportant
5–10	A	16
5–10	SC	12
11–20	A	8
11–20	SC	6
20–30	A	6
20–30	SC	4
>30	A	2
>30	SC	1–2

Clearly these figures are subjective and the actual number chosen will depend on the geometry and the complexity of the part, but beware if your chosen number of impressions starts to exceed these significantly. As a guide, but again a sweeping generalisation: as the tolerances double, the number of impressions can increase by 50%. If the appearance of the part is very critical, use the **SC** suggestions.

The following guidelines are suggested as a ‘checklist’ to avoid expensive mistakes.

1. If any of the following apply to a moulding, ***select a lower rather than higher number of impressions***. Decide on the maximum number of impressions for adequate control ***before*** calculating (2) below.
    - Close tolerances
    - Complex geometry
    - Very thin-walled sections
    - Demanding appearance requirements
    - High-shrinkage material
    - High viscosity material
    - High-melting-temperature material
    - A semicrystalline engineering polymer
    - Mouldings that may be difficult to eject
    - Materials with high levels of filler
2. Determine the number of impressions required to fulfil production requirements using the expression:

    $$\text{Number of impressions} = \frac{\text{Production rate required per hour} \times \text{Cycle (seconds)}}{3600}$$

    To allow for contingencies, increase this number by between 10% and 25% depending on the individual job.
3. If result (1) above is equal to or greater than result (2), choose (2) for the number of impressions.

    If result (1) is lower than result (2), choose the lower number of impressions indicated by (1). In this case, the potential customer should be given reasons why this is the case. There is little point in moulding high quantities of mouldings from mould tools with large number of impressions if they fail to achieve the necessary quality.
4. Once the number has been established, select a suitable machine to run the job.

6.7 Summary

Demanding parts are more difficult to mould than more straightforward ones and require more control.

Using fewer rather than a greater number of impressions achieves better control, quality and accuracy.

Using too high a number of impressions can lead to quality problems, incurring extra cost and possibly damaging customer relations.

7 Step-by-Step Design

7.1 Predesign Requirements

Before starting a mould design, the designer should be in possession of the following information (some items of which have been mentioned previously).

- An unambiguous fully detailed component drawing
- Specifications of the moulding material including grade and colour
- The moulding machine specifications
- All the estimating details including any sketches
- Tool specifications as follows:
    - Number of impressions
    - Type of mould e.g., two-plate, three-plate, split, side core, hot runner, etc.
    - Type of runner system
    - Type of gate
    - Method of de-gating
    - Use of robotics
    - Estimated cycle time

7.2 Golden Rules

1. Never start a mould design without all the necessary information.
2. If an established design works well, don't embark on a totally new design if you can base your design on the established one.
3. The simpler the design the more reliable and efficient it will be.
4. Always sketch two or three alternative approaches to the design before committing yourself to the first one you think of.
5. Draw a sufficient number of views so that the design can be understood fully.

7.3 Step-by-Step Design

It is very difficult to explain in words alone how a mould is designed; we will therefore follow through a step-by-step design of a typical mould tool from start to finish which illustrates the procedure. In order to do this, we will consider a moulding that has to be produced on an eight-impression basis.

Note that in Chapter 9 the two-plate tool design is discussed in more detail.

7.4 Design Example

For the sake of simplicity and clarity this example will be fairly basic; nevertheless, the principles involved are the same for any mould design (see Table 7.1).

Table 7.1 Specifications for design example

Component	Flanged housing
Type of tool	Two-plate
Gate type	Edge or sub gate
No. of impressions	8
Material	Polyacetal
Cycle required	20 seconds
Production rate required	50,000 per month

A component drawing has been supplied as shown in Figure 7.1. It consists of series concentric diameters with a hole through the middle.

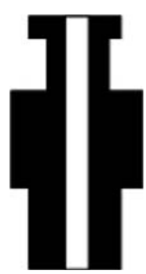


Figure 7.1 Flanged housing

The dimensions of the part have been omitted in this example but we will assume that we can mould them to the drawing tolerances on an eight-impression tool.

Among the first considerations we have to make is 'Have we ever moulded a similar shape before?' If we have, we should look up the design and find out whether the tool ran satisfactorily. We would then be able to use this design as basis for our new component. We will assume in this case that we cannot find a similar design and will have to design the whole tool from scratch.

Assuming we have all the information required to hand (as listed above) we can make a start. The first things we have to consider are the following:

- Where should the split line be located?
- Where will we gate it and what type of gate is required?
- Where we are going to eject it and how?
- Will venting be required?

7.4.1 STEP 1: The Split Line

This is always a crucial stage in the design process. If we get this wrong the repercussions will be severe in production. In fact there are only two possible places where this component can be split: at **B** or **C** in Figure 7.2. If we tried to split the component at **A** or **D** it would be undercut in the tool and it could not de moulded in a two-plate tool because it could not be ejected from the cavity.

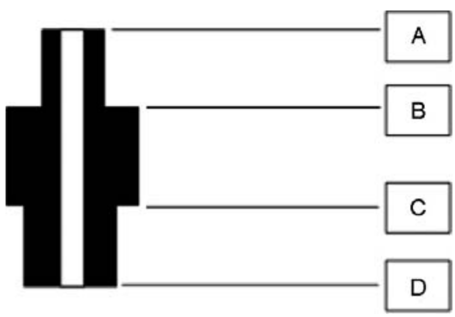


Figure 7.2 Possible split line positions

We could split the tool at position C as shown in Figure 7.3. If we were to select this position for the split line, this ***would*** work as the moulding will shrink away from the cavity walls and on to the pin that forms the central hole.

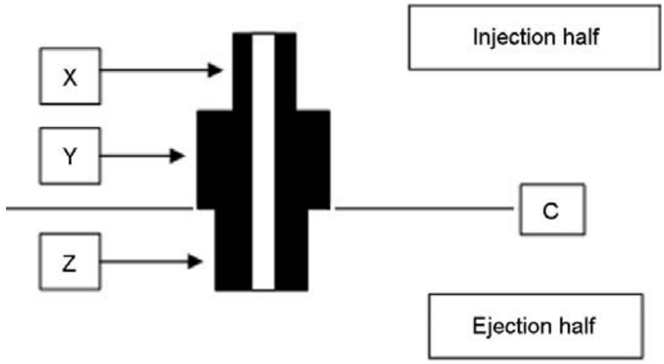


Figure 7.3 Part split at C

However, this is not the best method, especially from the point of view of accuracy and toolmaking, because the majority of the cavity form (**X+Y**) would be in the injection half or fixed half of the mould and it would be better if the majority of the form were in the ejection side of the tool. It is desirable to have as much cavity form in the ejection half as possible because the majority of the toolmaking work will be on this side of the tool. This is because the ejector system is also in this half of the tool and it would be sensible to have as much of the form as possible to be machined in this half in the same operation. This minimises the matching up of cavity forms in the two separate halves of the tool. If we split the tool at **B**, we will have achieved this with **X** in the injection half and **Y+Z** in the ejection half.

This is a good procedure to follow in general as, apart from toolmaking considerations, the greater the amount of component in the ejection half; the more likely it will be that the component stays on this side of the tool when it opens. This is clearly essential, as the component must stay on the ejection half of the tool after it opens in order to be ejected.

Therefore, we will split the tool at **B** as shown in Figure 7.4.

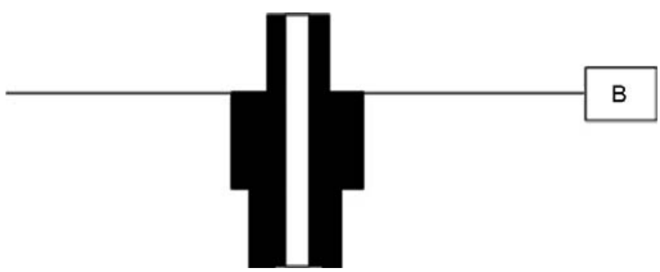


Figure 7.4 Mould split at B

7.4.2 STEP 2: Gating

If the relationship between the hole and all the diameters were important and subject to close concentricity tolerances, a two-plate tool might not be the best choice. This is because gating this part from the side might lead to differential shrinkage and warpage due to the unequal melt flow length. If this were important, a three-plate tool or hot runner tool would be preferred as the part could be gated at the top, providing more equal melt flow lengths.

In this example, this is not the case and we may therefore gate the part on the edge of diameter **Y** at the split line as shown in Figure 7.5 or with a sub gate shown in Figure 7.6.

As we require over half a million parts per year, sub gating is the obvious choice as the parts will be automatically de-gated.

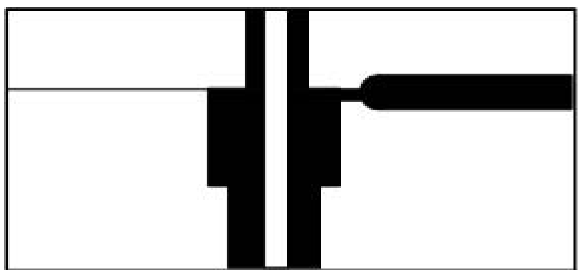


Figure 7.5 Edge gating

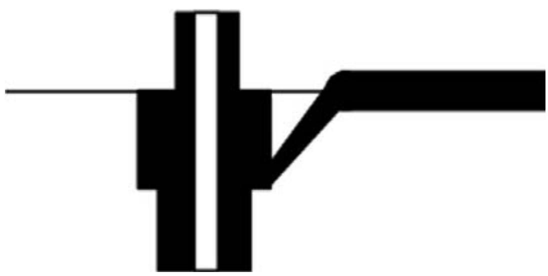


Figure 7.6 Sub gating

7.4.3 STEP 3: Ejection

We could eject this part with pins, with a stripper plate or with sleeve ejectors. It is always preferable to avoid pin gating if the options of stripping or sleeve ejection exist, for three reasons:

1. The ejection area of pins is smaller than in the other methods and we would achieve far greater ejection support with stripping or sleeve ejection. This eliminates the tendency of pins to hob or embed themselves in to the part.

2. For an eight-impression tool we would need 32 rather slender pins for ejection, which entails more toolmaking work and alignment.

3. The relatively slender pins may tend to deflect in the tool during ejection, causing premature wear and breakage.

This leaves the choice between stripper plate or sleeve ejection, so how do we choose between them? Basically the governing factor is the diameter of the part being stripped. Generally, smaller diameters should be sleeve-ejected and larger diameters stripped. In the opinion of the author, the cut-off point should be around 30 mm diameter. This is around the maximum comfortable size for toolmaking and for working with standard mould components.

In this case the diameter of the base of the moulding is 15 mm and therefore we will opt for sleeve ejection (Figure 7.7).

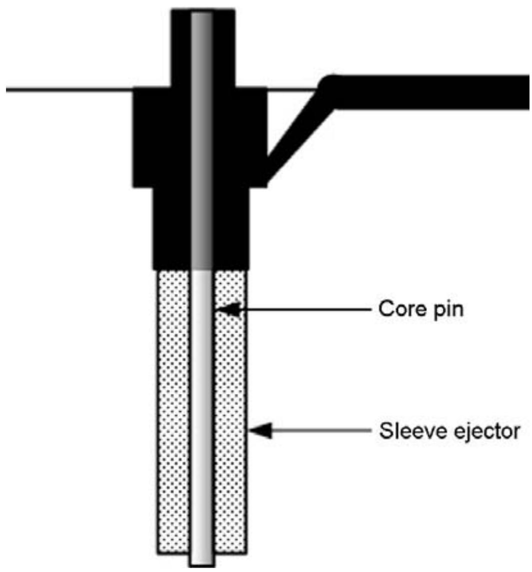


Figure 7.7 Sleeve ejector

7.4.4 STEP 4: Cavity Inserts

We can machine the impressions straight into a plate, but this has two disadvantages:

1. A plate that has cavities sunk directly into it may suffer form warping or distortion during the hardening process.

2. If a cavity suffers any damage during production, it can be very difficult to repair it.

It is therefore common practice to use cavity inserts to avoid these problems since:

(a) It is easier for the toolmaker to work on the inserts, as they are smaller.

(b) If any damage occurs it is much easier to replace an insert.

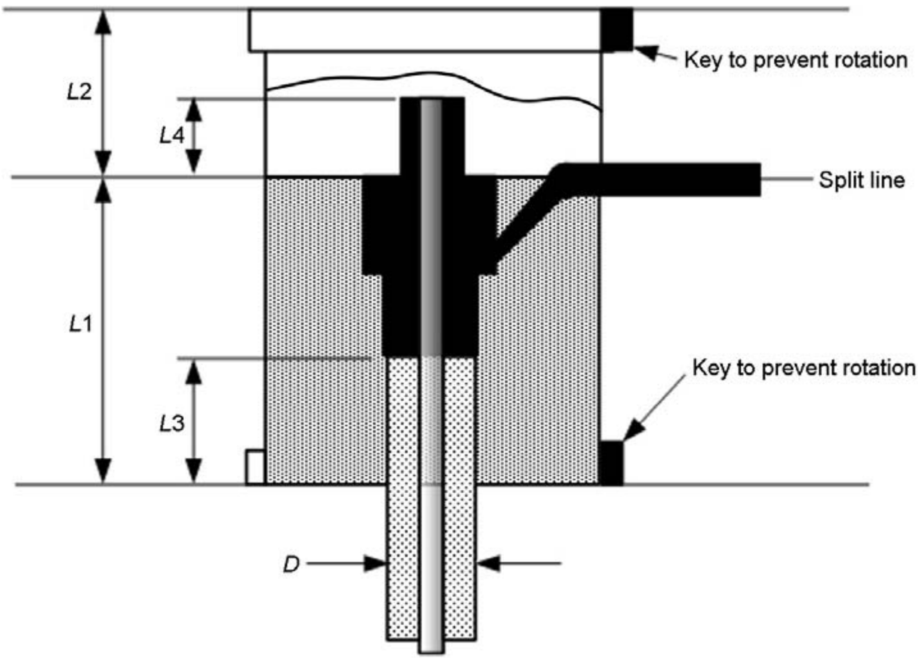


Figure 7.8 Designing the cavity insert

The diameter of the inserts should be large enough where possible to ensure that the whole of the sub gate form lies inside the insert as shown. This makes the spark machining of the sub gate easier and eliminates join lines that may prevent the gate exiting cleanly during ejection. As a rule of thumb, the following guidelines are suggested (see Figure 7.8). Further refinements come with experience.

The length of the lower insert L_1 should be the depth of the part below the split line + 1.5–2 times the length of the sleeve ejector diameter for adequate sliding location L_3.

The length of the upper insert L_2 should be 1.5–2 times the height of the form in the insert L_4.

Note that the lengths L_1 and L_2 automatically determine the plate thickness for the fixed half and ejection half of the tool. However, plates are only available in standard thicknesses from suppliers such as DME, DMS and Hasco. Therefore, the nearest standard plate sizes should be selected to determine final cavity depths.

7.4.5 STEP 5: Venting

If we look at Figure 7.8 we can try to visualise the flow of the melt into the cavity form. The material is initially directed down towards the bottom of the part and will then fill the cavity upwards from this point.

Any air in the cavity will be forced upwards and escape via the split line of the tool until the melt reaches the split line. Once the melt continues beyond this point, it seems that there is no exit path by which the air can escape. This means that the air may become trapped in the fixed half cavity and result in burning of the moulding.

Note that the actual fill pattern will depend on the gate size, speed of injection, injection pressure, tool temperature, and so on. To accurately simulate the most likely fill pattern a computer simulation is preferable.

In this case, however, we have identified the possibility of air entrapment and, if this possibility exists, we should do something about it before the event, and to counter this it is necessary to provide for a route for the air to escape.

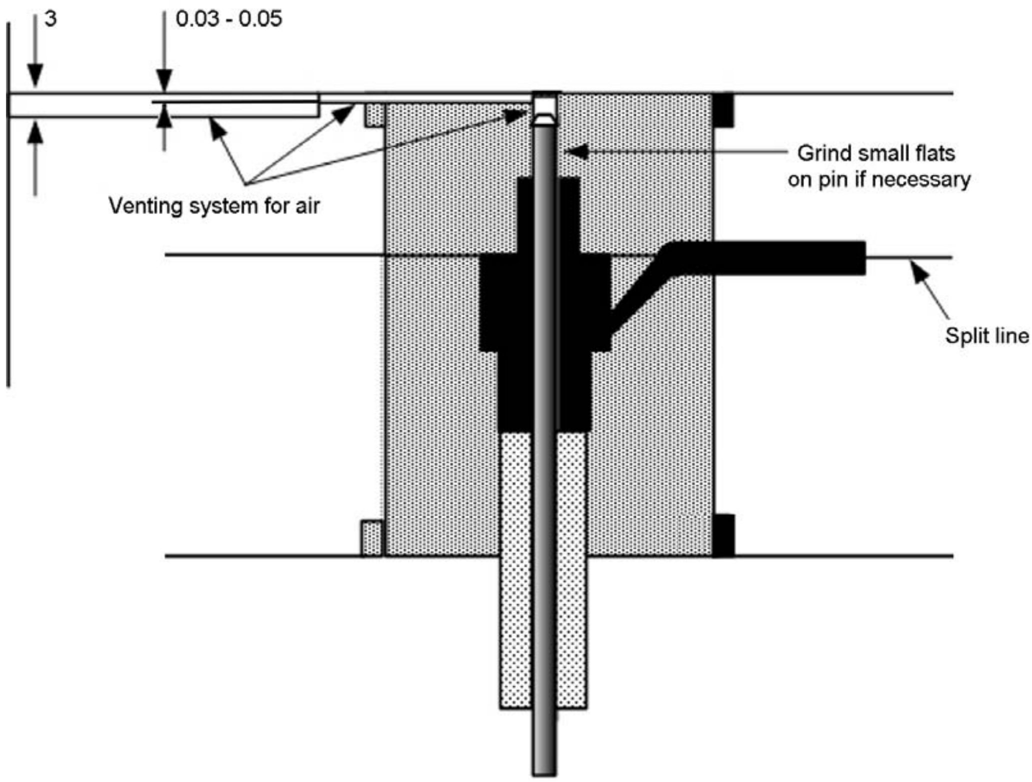


Figure 7.9 Providing venting

The solution kills two birds with one stone. If we extend the core pin upwards into the fixed half cavity insert, we will give extra support to the pin, preventing any tendency for it to deflect because of nonsymmetrical melt pressures. By extending the locating hole for the pin upwards to the top of the insert we also provide an escape route for the air. This ensures the air will exhaust along the top of the fixed half cavity and the cavity retaining plate.

This method works well for moderate injection speeds, but extra provisions will have to be made if high injection speeds are used. This can be achieved by grinding a flat channel approximately 0.03–0.05 mm deep along the cavity retaining plate as shown. The width of the channel is not critical and can be any width within reason. As soon as possible this vent should be opened up to allow the air to exhaust and expand into a larger space, because the air and gases being forced out of the cavity are very hot and can reach very high temperatures. By opening up the vent, the gases will be allowed to expand rapidly and thereby cool rapidly.

With high injection speeds it may also be necessary to grind small flats on the core pin where it locates in the top insert to allow the gases to escape more easily.

7.4.6 STEP 6: Water Cooling

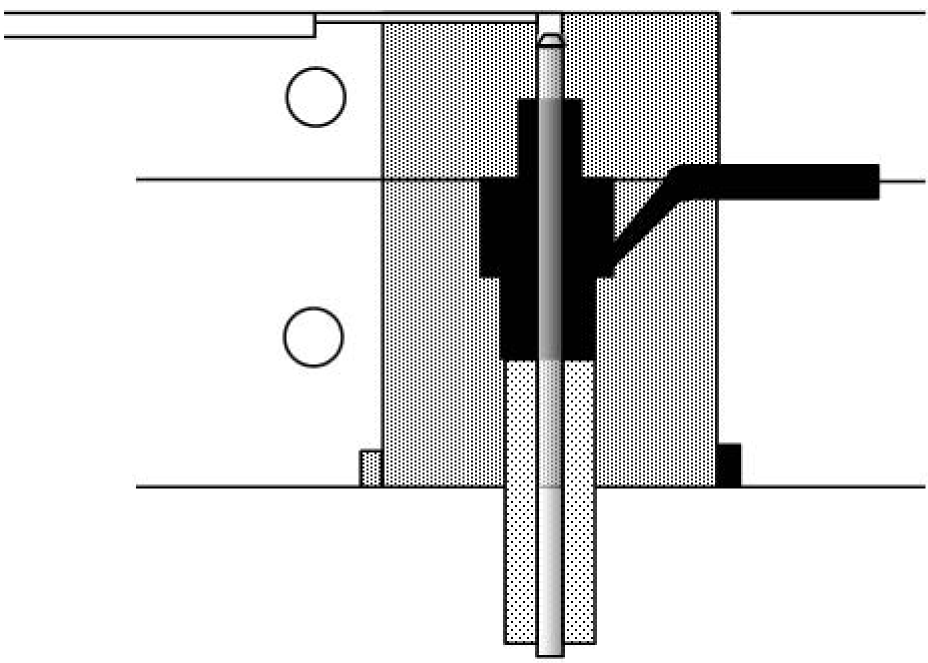


Figure 7.10 Adding water cooling

Temperature control is essential for all mould tools (see Chapter 11). We need to cool the moulding as soon as possible so that we keep moulding cycles within acceptable limits.

In this case we have two options: incorporating cooling channels into the cavity inserts if possible, or putting water channels through the mould plates next to the cavity inserts. Since locating cooling channels into the cavity inserts would be difficult in this case, we will use cooling channels through the mould plates (Figure 7.10).

7.4.7 STEP 7: Impression Centres

We are now in a position to start looking at the impression centres. The first stage is to establish the type of sprue bush we will be using. One is selected from a standard parts catalogue (Chapter 18) and from this we can establish the centre distance of the impressions. The minimum distance between the cavity insert and the sprue bush is around 10 mm (Figure 7.11).

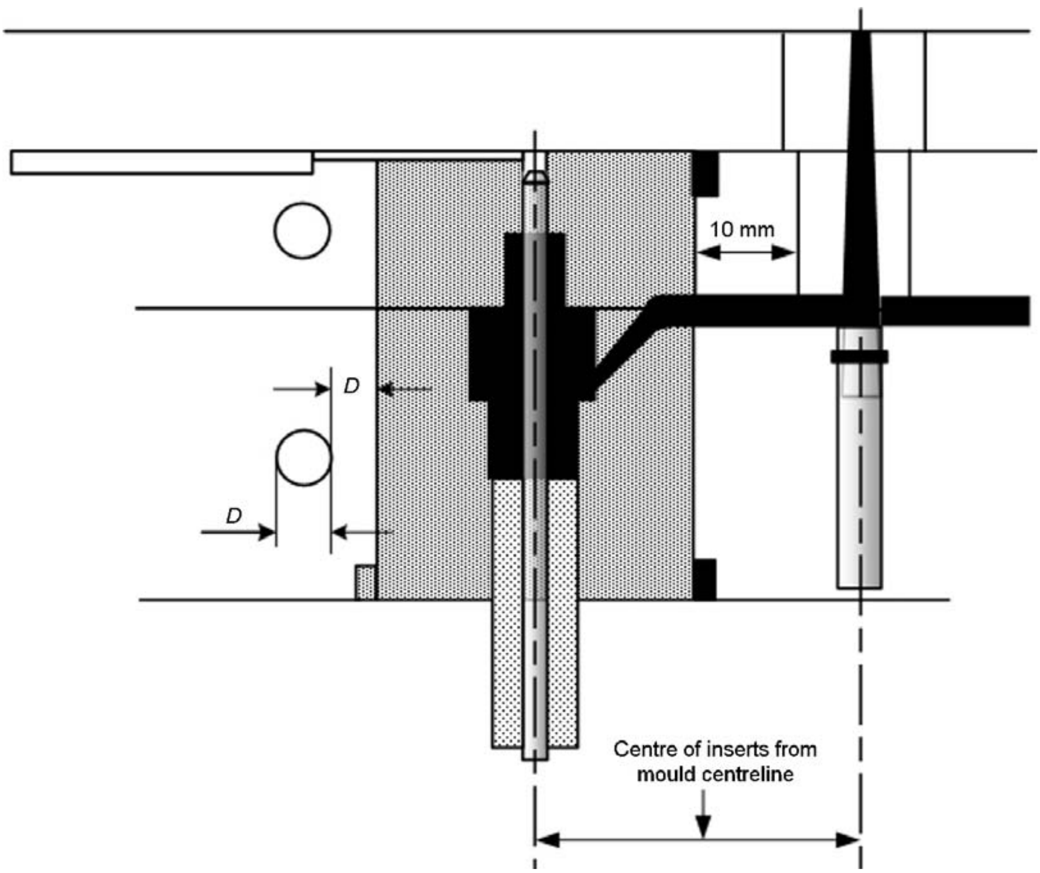


Figure 7.11 Establishing impression centres

7.4.8 STEP 8: Mould Layout

We have now reached the stage where we can determine the rest of the mould layout in plan view. The first stage is to lay out the impressions.

The view shown in Figure 7.12 is of the fixed half of the tool. This enables us to draw in the sprue bush and then arrange the cavity inserts around it. Note: the scale has been reduced for this view.

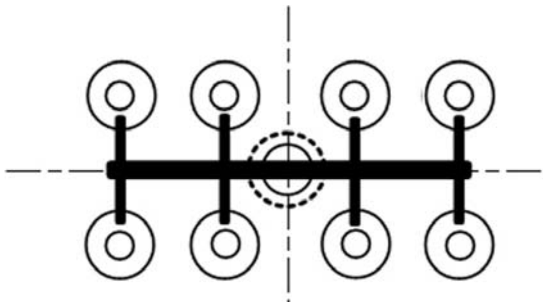


Figure 7.12 Impression layout – fixed half

We can now switch to completing the layout by looking at the ejection half of the tool. Figure 7.13 completes the picture. First the waterways are included as previously determined. Then the limits of the ejector plate can be established just outside the cavity inserts. Next the return pins are drawn in, followed by the guide pillars and screws. Just outside the guide pillars, the outside of the main tool can now be established (based on standard plate sizes). The platen drawing will have to be consulted to determine the positions of the mould fixing holes. A flange is drawn on the outside of the tool to accommodate these.

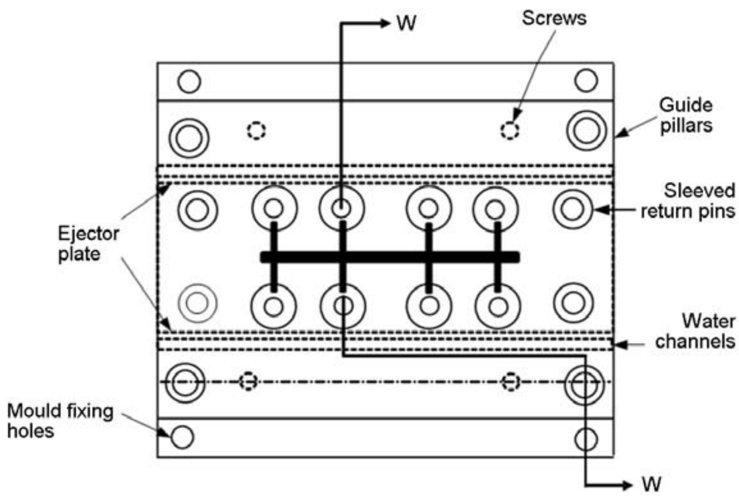


Figure 7.13 Mould layout – ejection half

7.4.9 STEP 9: Main Sectional View

Now that the plan views have been established we can turn our attention to the main sectional view that will complete the basic tool design (Figure 7.14).

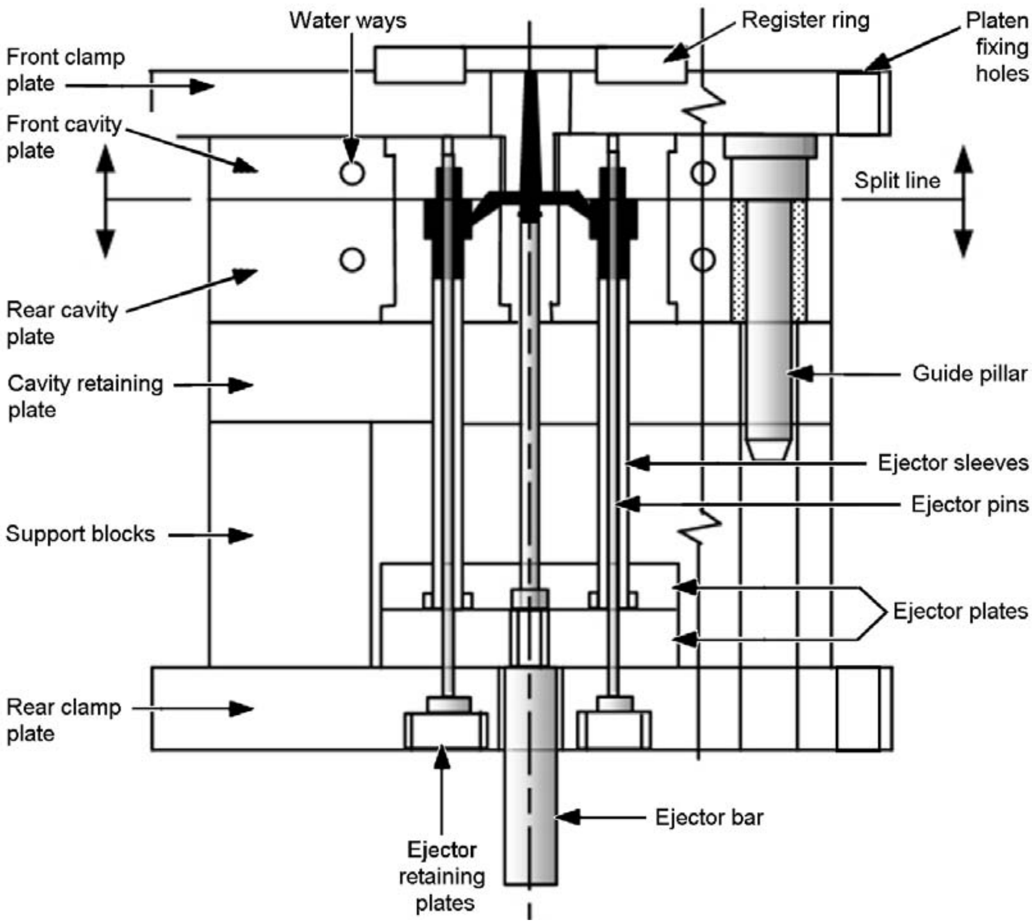


Figure 7.14 Sectional view W-W

This completes the step-by-step design for a basic component but the principles involved are very similar for all mould tools. This design is necessarily a subjective one and other designers may take a different approach, but it has served well for over 2000 designs so far.

Once experience has been gained in this field, designers naturally tend to develop their own personal approach. New designers should take every opportunity to study and understand as many mould general arrangement drawings (GA) as possible. Consult Chapter 9 for more details on two-plate mould refinements.

8 Mouldmaking

8.1 Discussion

Manufacturing an injection mould tool requires a high level of skill, and the success of an injection moulding tool depends jointly on the design of the tool, the skill of the toolmaker and the moulding technician. It is desirable, although not essential, for a tool designer to have had some experience of toolmaking. If the designer does not have direct experience, then at least an appreciation of toolmaking techniques and problems is necessary.

The same observation applies to toolmakers. Ideally, they should spend some time in an injection moulding production environment, to observe at first hand how tools perform and to observe the problems encountered. It is essential, however, for the mould designer to have both experience and knowledge of materials and injection moulding techniques.

In practice it is the combined design and toolmaking package that determines how well the tool will work in production. It is this combined package that we will now discuss.

8.2 General Mould Requirements

8.2.1 Mould Materials

All production tools should be made from high-quality steels manufactured to suitable BS, ASTM or DIN standards. This topic is discussed in more detail in Chapter 16.

Several different metals are sometimes used, but the majority of mould tool metals used fall into three groups:

- Nickel–chromium alloy steels (H13 ASTM or BS EN30B)
- Mild steels or low-carbon steels (BS EN8) or those of higher carbon content
- Beryllium-copper

See Chapter 16 for a full discussion of this topic.

8.2.2 Alloy Steels

Alloy steels are usually used for cavities and for any plates that come into direct contact with the moulding materials. Alloy steels may be used in their soft state or may be fully hardened depending on the application.

Generally all cavity components are fully hardened, as they have to withstand cyclical high loading, wear and thermal stresses. Cavity retaining plates and other shut off areas are normally made from the soft version. They do not need the higher strength and wear resistance that the hardened steel gives but they do offer a higher degree of protection against damage than would mild steel.

In some cases a pre-toughened form of this steel is used for cavities, cores and punches, especially for larger components where through-hardening may not be desirable or possible. This type of steel is tempered back to give a steel whose hardness lies between the soft and fully hardened versions.

8.2.3 Mild Steel

This steel is normally used for all other tool plates. Mild steel should not be used for cavity inserts or contact with the moulding material. It should never be used where it may be subject to excessive sliding conditions, etc. Sometimes designers prefer to use a higher-carbon-content steel on long-running jobs for greater resistance to wear and tear.

There is no reason why nickel–chromium steels should not be used throughout the tool – apart, that is, from cost. For large, expensive, long-running tools, however, this material may be preferable as the cost is small compared to the cost of the tool.

8.2.4 Beryllium-Copper

This material is an alloy of beryllium and copper. Beryllium is chosen for its strength and copper for its thermal properties. It will conduct heat away quickly and much more efficiently than steel.

Beryllium-copper is used when large quantities of heat have to be extracted from cavities or cores. Adequate provision for cooling must be provided to prevent excessive heat build-up.

8.3 General Construction

The following guidelines apply to all mould tools:

- All tool plates should be ground flat and parallel, and preferably the grade of steel and an identification number should be marked on them for future reference.
- Provision should be made for aligning the tool by means of extended guide bush systems or by separate alignment dowels. This enables the tool to be taken to pieces and then reassembled correctly.
- All sliding mating sliding surfaces should be fully hardened and should be of different degrees of hardness from each other
- All ejector pins should be hardened. Nitrided pins are used for most situations, but where any flexure is likely to occur Tuftrided pins are preferred.
- Tools should have a relief area ground around the cavity positions to concentrate the locking force on a smaller area. See Chapter 20 for a full discussion of this topic.
- Retaining catches must be used to hold side cores or splits in position after they have opened.
- Adequate provision must be made for water cooling (or oil heating).
- Lifting holes or bars should be provided.
- All surfaces with which the moulding material makes contact should be highly polished in the direction of flow. Cavities should be polished in the direction of draw unless a textured finish is required on the mouldings.

8.3.1 Cavity Construction

The way in which the tool is designed and constructed will depend on several factors including the following:

- The part geometry
- The length of the production run
- The degree of accuracy required
- Gating and ejection requirements
- Temperature control requirements
- The moulding material being used
- The split line
- The finish required on the moulding

All mould tool constructions normally require the use of turning, milling and grinding.

8.3.2 Turning

Many mould tools need turned parts. Cavities, cores, pins, screw threads and recesses are just a few examples.

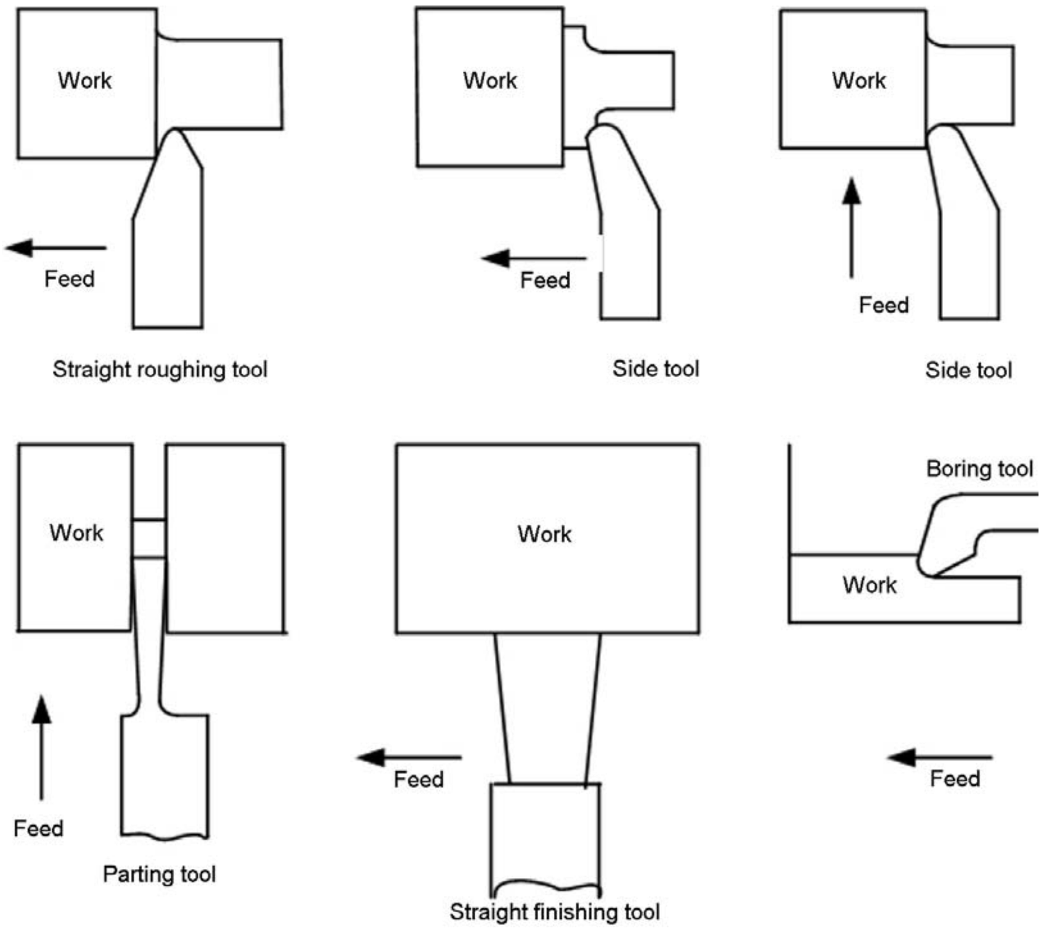


Figure 8.1 Turning operations

8.3.3 Milling

End milling can be used for machining out pockets into which cavity inserts will be located. Recesses are also made in this way. A number of other features may also be milled including screw threads. Very often, however, spark erosion is used for this purpose.

8.3.4 Grinding

Surface grinding is used to accurately grind flat areas such as the sliding areas for splits. Plates and parts of the cavity assembly are also ground. Cylindrical grinding is employed for accurately forming external and internal surfaces. Cavity diameters and cores are often finish-ground to size using this method.

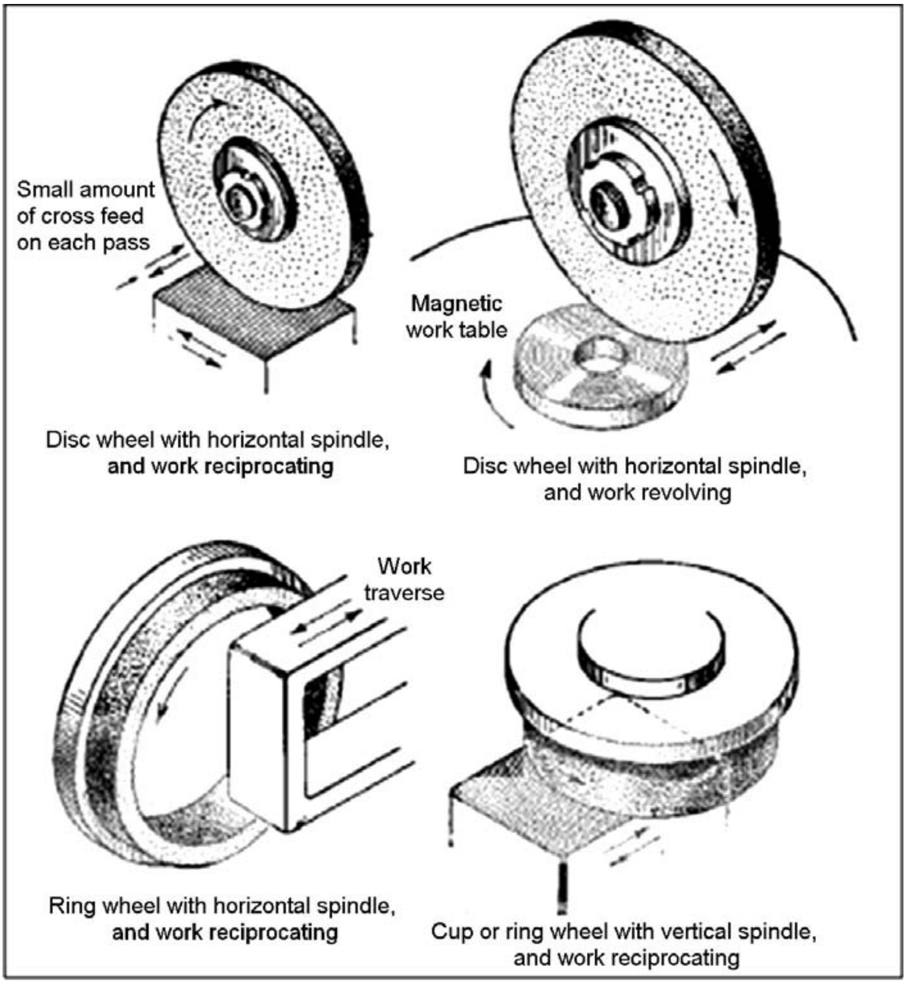


Figure 8.2 Surface grinding operations

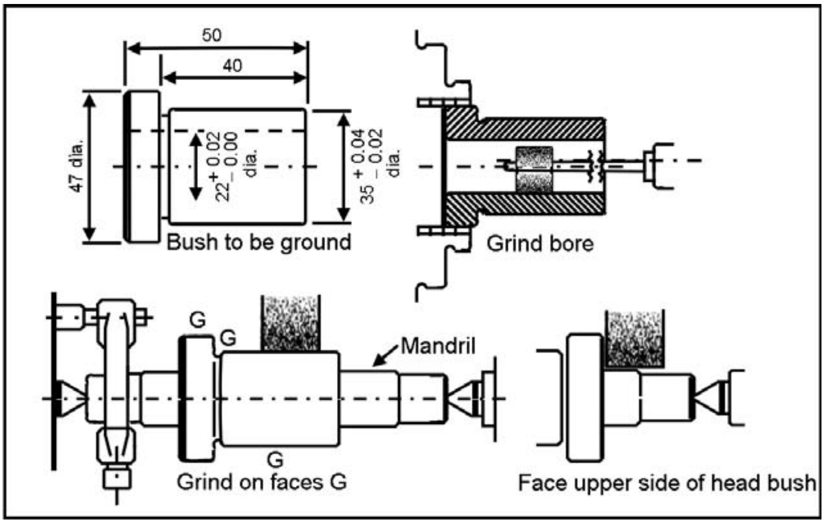


Figure 8.3 Cylindrical grinding operations

8.3.5 Fabrication

Fabrication is the breaking down of cavity forms into smaller, simpler parts. This method is sometimes used where complex cavity forms may be too difficult to machine in other ways or where hardening of the cavity or cores may otherwise pose problems.

The advantage of this method is that that it allows simpler machining operations to be carried out on relatively straightforward individual parts. It is also easier to harden these smaller pieces as the stresses in them are less and therefore they are less likely to distort.

These parts are left oversize to allow for grinding back to final size after the hardening process has been completed. Polishing if needed is also very much more straightforward as all areas can be accessed freely.

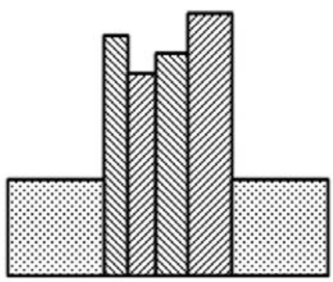


Figure 8.4 Fabricated assembly

8.3.6 Standard Electrodischarge Machining (EDM)

This method is often called ***spark erosion*** and is widely used in the manufacture of cavities, cores and punches. EDM allows the generation of complex cavity and punch forms to be achieved with relative ease compared with other methods.

To generate a female form, an ***electrode*** first has to be made. This would be the opposite form to the shape required. For example, to machine a cavity, the electrode form would have to be male as shown in Figure 8.5.

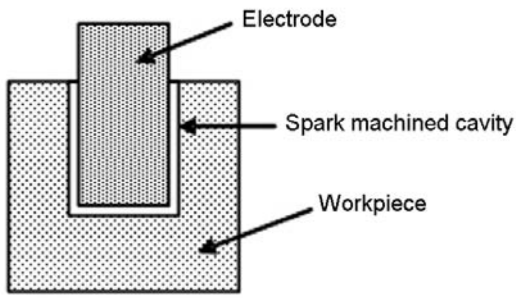
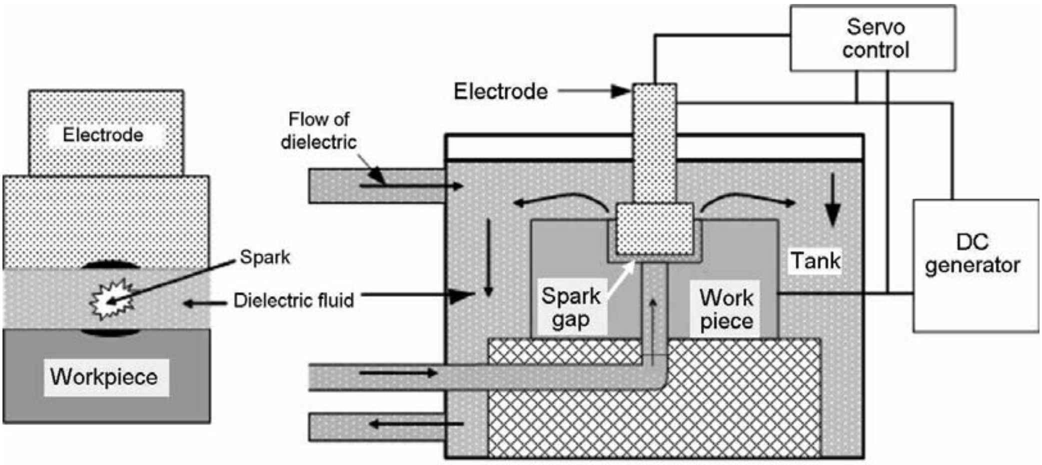


Figure 8.5 Cavity machining with EDM

The process consists of immersing the work piece in a ***dielectric fluid***, usually a form of refined paraffin or similar hydrocarbon. The electrode is lowered over the work piece until it is nearly touching it. A series of high-energy impulses are passed to the electrode and a high electrical potential is built up on it. This energy cannot pass to the work piece because the dielectric fluid electrically initially insulates the two parts from each other. However, when the electrode advances to within a very small distance from the work piece, the dielectric is broken down and sparks pass from the electrode to the work piece. Each impulse melts or evaporates a small portion of the work piece with temperatures reaching 100–500°C.



Medium	Dielectric fluid (Paraffin)	Operating voltage	40 – 200
Workpiece	Alloy steel	No load voltage	60 – 300
		Max current density	5 – 10 A/cm^2
Electrode wear		Spark frequency	0.2 – 100 khz
Copper (roughing)	<20%	Spark gap width	0.005 – 0.5 mm
Copper (finishing)	<5%	Rate of material removal	<2 mm/minute
Graphite (roughing)	<10%	Specific removal rate	8 mm^3/A per minute
Graphite (finishing)	<5%		

Figure 8.6 The EDM process

This distance is known as the ***spark gap*** and varies between 0.005 mm and 0.5 mm for most purposes. Lower energy levels permit smaller spark gaps with finer finishes, while larger gaps allow faster material removal but with a coarser finish.

Electrodes are made from materials that have the necessary electrical, mechanical and thermal properties. The most common materials used are copper and graphite. Unfortunately, these electrode materials wear away at the same time as the work piece is eroded; hence, alloyed electrodes such as copper–tungsten are often used to minimise electrode wear. The copper provides the electrical conductivity and the tungsten provides resistance to wear.

In practice, a cavity would be 'rough sparked' first to get rid of as much of the material as fast as possible. Then finishing electrodes would be used to machine out the cavity to the final size and finish. Very intricate forms may be machined by means of this process. Cams, spur gears, helical gears, worms and other complex geometric forms are typical examples.

For purely functional, nonappearance finishes, sparked finishes may be left as they are, but otherwise polishing may be necessary. EDM is also used to impart a variety of finishes to the cavity surface. Leather grain, stipple and fine matt finishes are examples. Specialised suppliers make electrodes for these finishes.

8.3.7 Wire Electrodischarge Machining

This method is an adaptation of the standard process. The principle is shown in Figure 8.7.

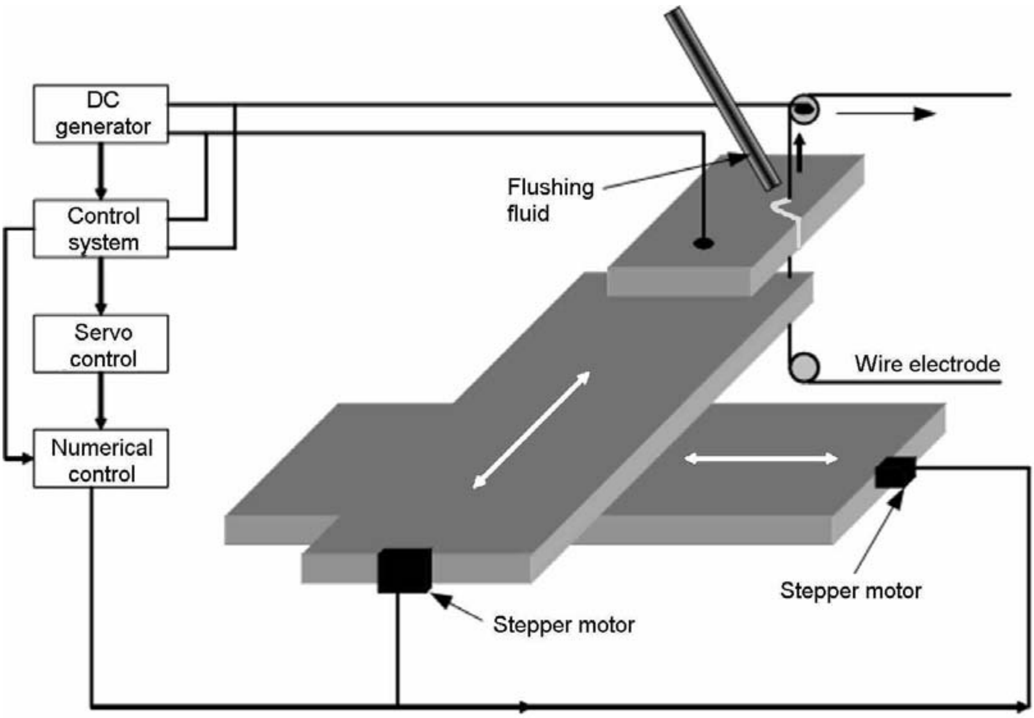


Figure 8.7 Wire EDM process

While standard EDM is used for sparking 'blind forms', wire EDM is used for eroding completely through the work piece. Wire EDM is also used for machining complex forms with the electrode path being controlled via a computer through precision stepper motors.

This method may be used to advantage where 'blind' corners are unsuitable and particularly where blind cavities may give rise to air entrapment and burning (Figure 8.8).

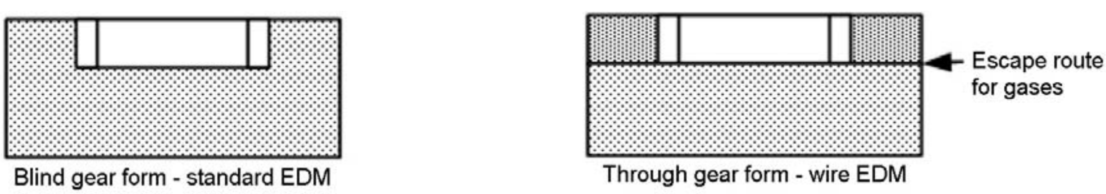


Figure 8.8 Comparison of standard and wire EDM

Wire electrodes are usually made from copper, molybdenum, brass and special alloy steels with diameters varying from 0.02 to 0.5 mm. Owing to the fragile nature of the wire, demineralised water is used as a dielectric. This permits a larger spark gap, making removal of debris easier and minimising the risk of ***arcing*** leading to wire breakage.

8.3.8 Cold Hobbing

This technique was used before the introduction of EDM. It consists of forcing a hardened, polished punch into an annealed blank work piece (Figure 8.9). The hobbing force is continuously increased until the required depth of form has been achieved.

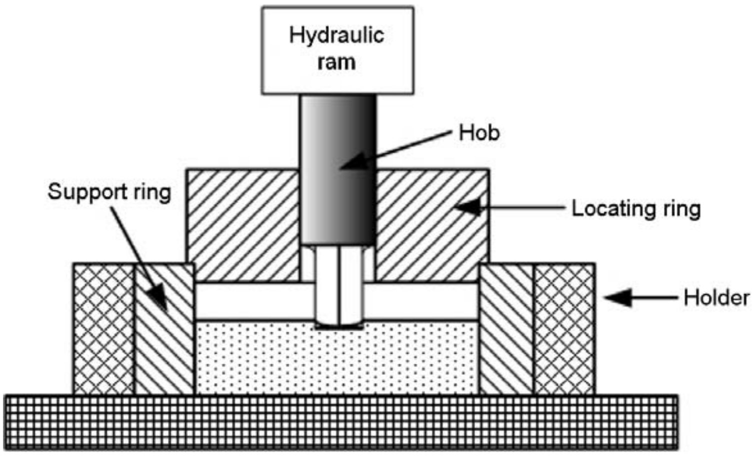


Figure 8.9 Cold hobbing process

During penetration of the hob, the work piece may become work hardened and need re-annealing several times until the full form depth is achieved. To assist the hobbing process and to avoid the hob and work piece welding together, extra-high-pressure lubricants are used. Following hobbing, material is forced up on the top surface of the work piece and this has to be machined away. The work piece is then hardened, tempered and polished.

This procedure is regaining its previous popularity where large numbers of simple forms are required. For shallow, simple forms, the technique is faster than EDM.

8.3.9 Beryllium-Copper

Some impressions cannot transfer the heat away quickly enough, leading to extended cooling cycles and often distorted mouldings. Beryllium-copper may be used to advantage in such circumstances. The copper is used for its high thermal conductance properties and the beryllium for its high mechanical strength.

The usual composition of this alloy is 1.7% beryllium, which gives a tensile strength of about 1200 MPa. Lower percentages of beryllium make the alloy too soft to use as cavity components, while higher levels impair the thermal conductance.

In its soft state, the material is readily machineable using most machining techniques including EDM. It will harden quite well up to around 30° Rockwell but with ion implantation this may be increased by 15%. For extra durability the alloy may be hard nickel-plated; this is preferred to chrome, which tends to flake away.

This alloy may also be hobbed and pressure or gravity cast, although cold hobbing usually requires the alloy to be preheated to around 60–75 °C. Specialist suppliers carry out these casting processes.

Where the alloy is not in direct contact with the moulding material, it may have a much lower beryllium content. Typical usage would be as a heat exchanger inside a steel punch or cavity.

Beryllium-copper is extremely useful for short-cycling jobs where rapid heat removal is essential for short cooling cycles. For more intricate mouldings its properties are useful where rapid heat removal and better temperature control is required, often giving better quality mouldings.

8.3.10 Electroforming

This is a very similar process to (but not the same as) electroplating. Whereas with plating a deposit of about 25 μm is the norm, electroforming can be millimetres thick.

Nickel or cobalt–nickel is deposited onto a former, which is made from an inert material, often acrylic. Other former materials may be used but if they are not electrically conductive they have to be made conductive by coating with chemically reduced silver.

The process consists of depositing a layer of cobalt–nickel up to 5 mm deep onto the former. Next a further layer of copper is deposited to increase the cavity wall thickness. At the end of the procedure the former is withdrawn and the composite cavity is inserted into a steel chase for support.

The advantage of this process is that a component accuracy of 1 micron can be achieved and there is no shrinkage involved, unlike in casting. The great disadvantage of this process is the time scale involved, which can be up to 10–12 weeks.

A scheme of the electroforming process is given in Figure 8.10.

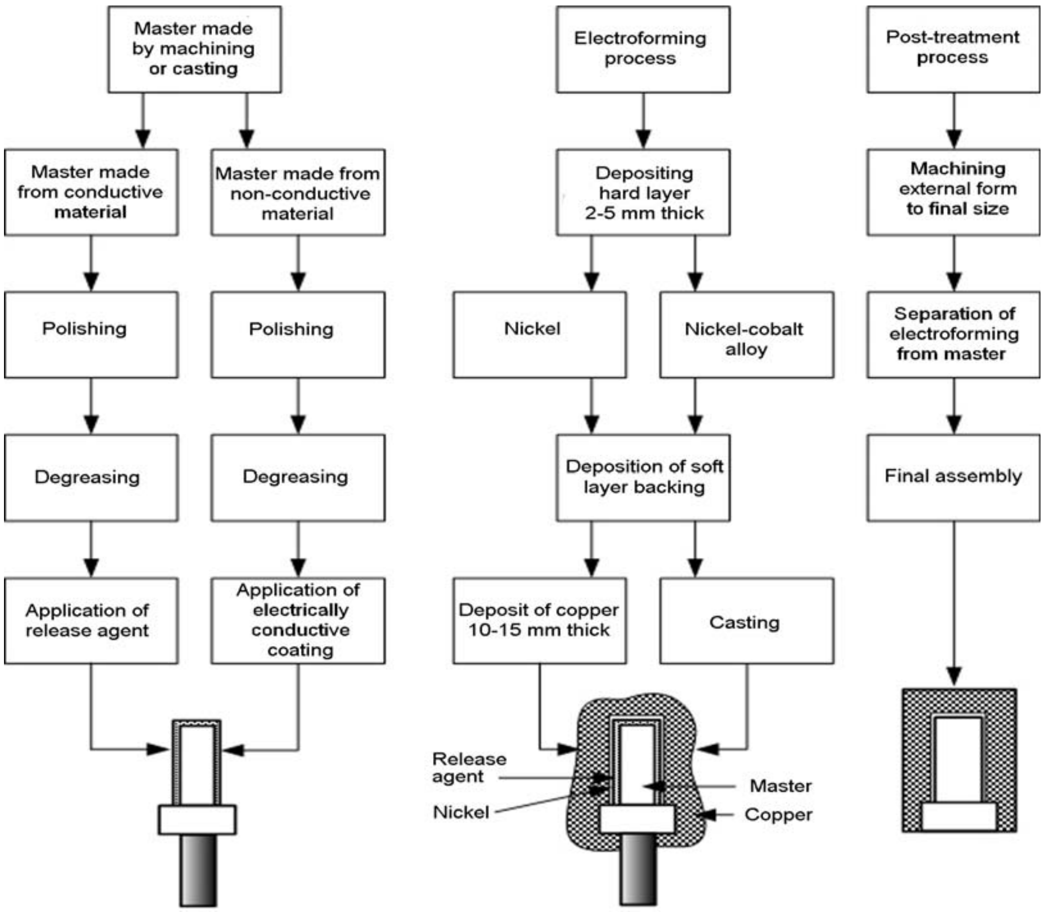


Figure 8.10 The electroforming process

8.3.11 Cavity Corrosion and Erosion

When abrasive or corrosive materials such as glass-filled Nylon or PVC are being used, there is a danger that erosion or corrosion of the cavity will occur. These problems can severely damage the tool, which may then need expensive repairs.

The answer for both problems is to hard chromium-plate or nickel-plate the cavities. This gives a good level of protection to the cavity against both problems. When the plating begins to wear away it may be stripped off and the surfaces re-plated.

It should be remembered that, when using corrosive or abrasive materials, not only the cavity should be protected but also the runner and sprue bush as well.

8.3.12 Gassing and Burning

When the melt enters the cavity, it has to displace the air in front of it. Often this presents no problem, as the air will escape through the split line or ejector pins or down the sides of core pins.

There are some situations, however, where the air cannot escape easily. This often occurs with blind cavities or when high injection speeds are used. In these cases the incoming melt will compress the air in front of it, causing the material to burn. The problem is worse when large volumes of air have to be displaced when using high injection speeds.

To overcome this, vents have to be included to provide an easier path for the air to escape, as shown in Figure 8.11. These vent channels have to be very shallow, usually 0.015 to 0.025 mm to avoid the possibility of flashing. The ***land length*** of the channels has to be kept short, to allow the air to expand and cool as quickly as possible.

For more minor gassing and burning problems, venting can be provided by grinding very small flats on the sides of ejector pins. Alternatively, special ***venting pins*** can be located at trouble spots.

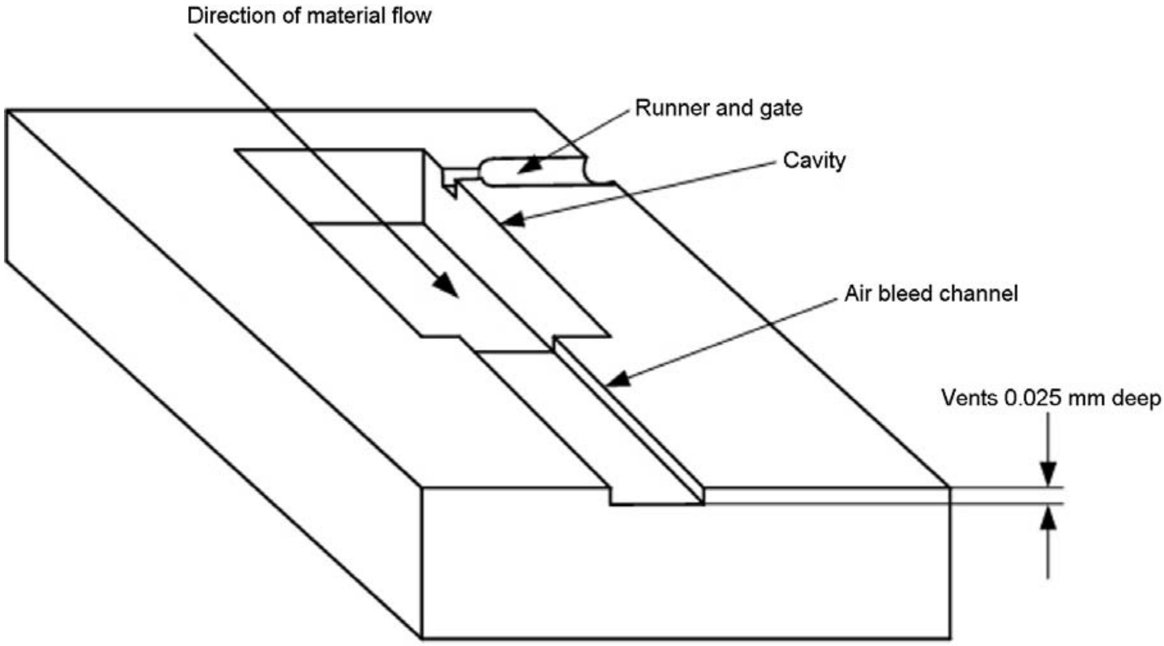


Figure 8.11 Venting cavities

8.4 Differential Shrinkage

Accurate shrinkage prediction is one of the many problems faced by the designer. This becomes a greater problem when precision mouldings are required with close dimensional tolerances.

This shrinkage is due to the volumetric contraction of the material as it changes state from the melt to solid as it cools. Additionally, the molecular orientation of the material is important, which is greater in the direction of melt flow than at right angles to it. This means that the application of a global shrinkage factor to a cavity is very unlikely to result in the moulding being dimensionally correct. It is even more difficult to predict the cavity sizes for high-shrinkage crystalline materials. Unfortunately, owing to their desirable physical properties such materials are more likely to be used for precision applications.

Among the many variables that will affect shrinkage are:

- Part geometry
- Gate position and size
- Injection pressure and speed
- Part thickness
- Melt temperature and tool temperature

In order to accommodate unexpected shrinkage, resulting in out-of-tolerance mouldings, the designer should make sure the tool is adjustable on critical sizes. This is discussed in the next section.

8.5 Maximum Metal Conditions

It is good engineering practice to make sure that mould tool cavities can be adjusted if necessary after the first sampling trials. Critical snap-fit features or features that have to mate with other parts are examples of where such adjustment may be necessary. Failure to ensure this can result in very expensive changes or replacements in the tool.

It makes sense to dimension the tool cavities and cores so that small amounts can be machined away from them if the moulding dimensions are incorrect. In fact, it is better to systematically make sure that critical sizes are slightly out of tolerance from the start, so that they be can adjusted after moulding trials, thus eliminating the possibility of re-makes being necessary. This method is called using maximum metal conditions (MMC).

It consists of making all female cavity sizes too small and all male core sizes too large. If the drawing size is A and the shrinkage factor is B%, this can be achieved by applying the following method:

Female forms:

$$A \times \{1 + [(B/100) \times 0.95]\}$$

Male forms:

$$A \times \{1 + [(B/100) \times 1.05]\}$$

In words, this means for female forms apply 95% of the shrinkage and for male forms apply 105% of the shrinkage.

8.6 Example

The drawing diameter of a disc is 100 mm and the shrinkage is 2%. This would be a female feature in the tool. Here $A = 100$ and $B = 2$. Hence the cavity size is:

$$100 \times \{1 +[(2/100) \times 0.95]\} = 100 \times \{1 + [0.02 \times 0.95]\} = 101.90 \text{ mm}$$

Alternatively: shrinkage is 2%, therefore use 2% × 95% = 1.9%. Hence the shrinkage size is:

$$100 + 100 \times 0.019 = 100 + 1.9 = 101.90 \text{ mm}$$

instead of 102 mm. This ensures that the cavity will be slightly undersized and can be accurately adjusted after moulding trials to the correct size.

Use of this technique can save a lot of unnecessary cost: if this diameter came out too large, it could not be made smaller very easily.

The same procedure would be applied to cores, only in this case they have to be left too large and hence the shrinkage factor percentage would have to be multiplied by 1.05 as described above.

MMC techniques can be used to great advantage with components having multiple holes in them that are tightly toleranced with respect to each other or from a datum line. Each core pin may be individually adjusted for diameter and position within the hole array, allowing accurate repositioning. Clearly this avoids possible expensive re-makes of the cavity form.

9 Two-Plate Mould Tools

9.1 Design Details

The simplest and most reliable mould design is the two-plate tool. This is because it normally has the fewest number of moving parts and is more straightforward to manufacture and run in production. Because of its simpler construction it is usually cheaper to manufacture than more complex designs.

Given the simplicity of its design and manufacture, mould design engineers should make sure that all possibilities of using a two-plate design have been exhausted before other more complex designs are considered. This means that the component should be examined carefully to see whether any undercut features could be designed out of the part. Screw threads are a prime example of this point. Threads normally require split tools, collapsible cores or more complex automatic unscrewing devices, but sometimes they can be ***jumped*** out of the cavity.

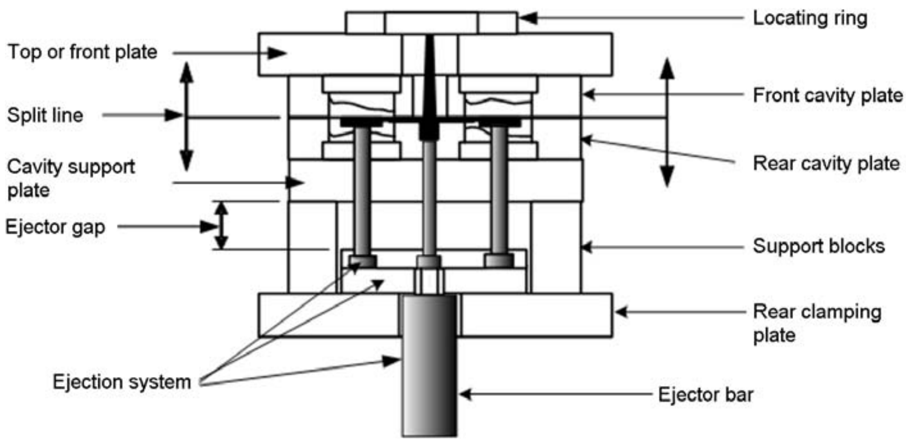


Figure 9.1 Basic two-plate construction

A typical two-plate mould tool is shown in Figure 9.1. Figure 9.2 shows a typical full (but deliberately simplified) general arrangement (GA) drawing of a two-plate mould tool. In practice, the general arrangement drawing would be considerably more detailed than this. However, this simplified version illustrates more clearly, the basic construction of a typical two-plate mould tool.

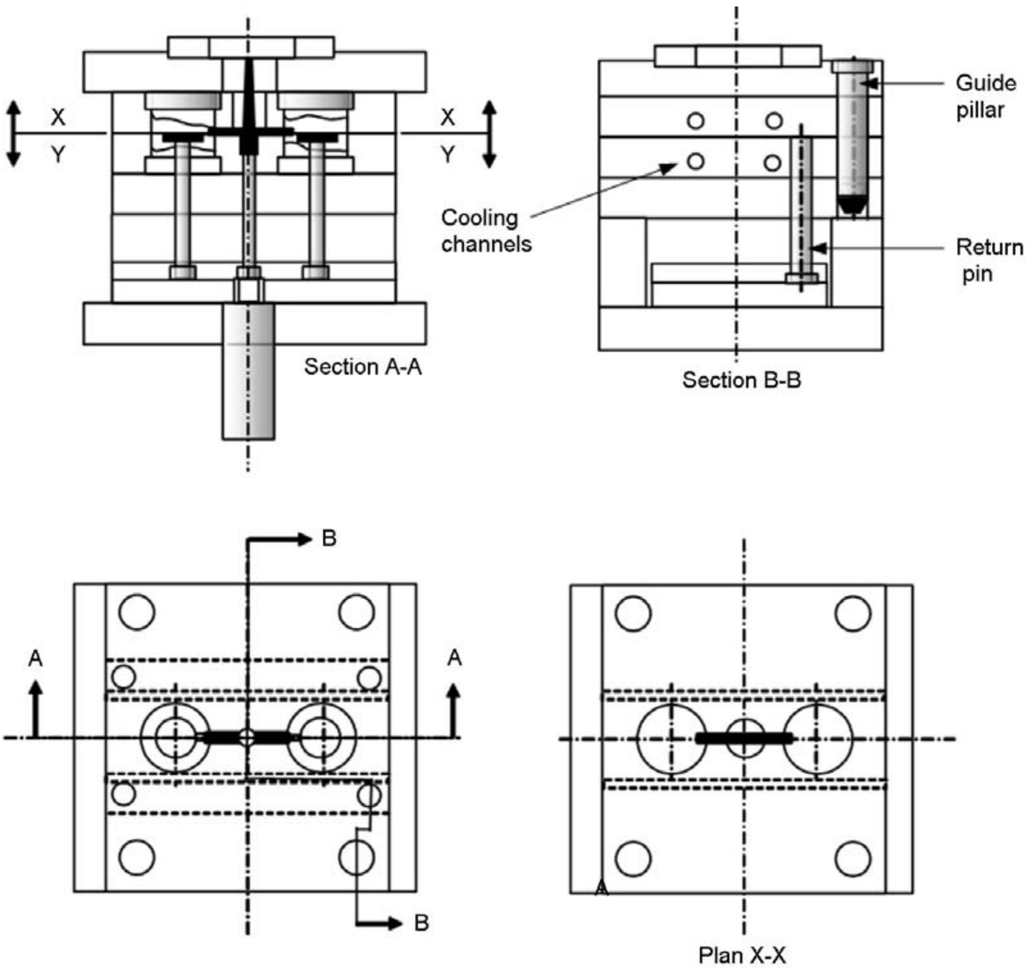


Figure 9.2 Basic two-plate tool general arrangement

Since some of the components in this design are common to the vast majority of all injection mould tool designs, we will look at some of these individually. Terms in frequent use in the industry are shown in bold italic type.

9.1.1 Locating or Register Ring

This is a circular ring, screwed to the front clamping plate. It enables the tool to be centred on the injection cylinder axis by locating it into a machined hole in the fixed platen. It is usually made from good-quality low-carbon steel.

9.1.2 Top Plate

There are alternative names for this plate:

- Front plate
- Fixed half front plate
- Fixed half clamping plate

Its function is to allow the tool to be secured to the ***fixed platen*** with cap screws to hold it in position. It is usually made from low-carbon steel or perhaps alloy tool steel for very long-running jobs. Tools are also frequently clamped to the platens with tool clamps. The rear half of the tool may be secured in a similar manner.

However, the more secure system for clamping tools on to the machine is to use direct cap screw fixing that entails providing clearance holes in the clamping plate to secure the tool to tapped holes in the platens.

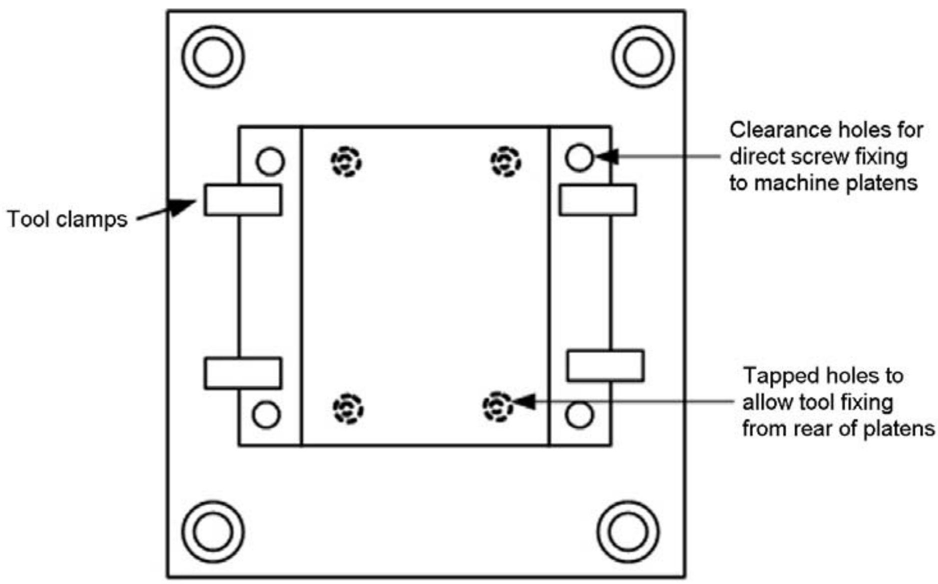


Figure 9.3 Mould clamping arrangements

Another method for tool clamping is to provide tapped holes in the top and rear plates of the tool. Screws are passed through clearance holes in the platens and then screwed into the tool from the rear of the platens.

9.1.3 Split Line

This is the plane or position at which the tool separates into two distinct parts – the ***fixed half*** and the moving or ***ejection half***. After the tool has split at this point, space is created for the mouldings to be pushed or ***ejected*** from the tool.

9.1.4 Cavity Insert

This is a circular or rectangular piece of alloy tool steel that carries the ***form*** of the moulding in it. Such inserts are inserted into the front and rear retaining plates as described below. Using inserts avoids machining the ***cavity forms*** directly into the cavity plates, which is more difficult. It also avoids having to harden the cavity plates, which can lead to the plates distorting. This is discussed in more detail in the toolmaking and mould materials sections.

Figure 9.4 Cavity insert

9.1.5 Front Cavity Plate

Another name for this is the fixed half cavity plate. Its function is to hold the front half cavity inserts in position in the ***fixed half*** of the tool. The cavity inserts cannot move because the inserts have a shoulder on them to make them captive between the top and front half cavity plates. The plate in which they are fitted is either low-carbon steel or, for very long-running jobs, alloy steel.

9.1.6 Rear Cavity Plate

This serves the same function as the front cavity plate. It makes the rear half inserts captive between it and the cavity support plate. The materials used are the same as the front cavity plate.

9.1.7 Cavity Support Plate

This plate has to withstand the force generated by the injection pressure of the melt that is exerted on the actual ***cavity forms***. This force is given by:

No. Imps. × (Projected area of cavities and runner) × Injection pressure of the melt

This plate must be made from an alloy tool steel to resist the cavity inserts being embedded (or hobbed) into it. It must also be of sufficient depth to prevent excessive plate deflection taking place.

9.1.8 Ejection System

After the parts have been moulded and have solidified sufficiently, they have to be pushed out of, or ***ejected*** from, the mould tool after it has ***opened*** at the ***split line***.

The ejector assembly carries a number of ***ejector pins*** that push or ***eject*** the parts from the cavities (Figure 9.5). The parts usually fall into a bin or onto a conveyor for packaging or for further operations to be carried out on them.

As well as ejector pins, the ejection system may use sleeve ejectors and blade ejectors or may also operate stripper plates, double ejection systems, collapsible cores or other more complex devices. These are discussed in more detail in Chapter 10.

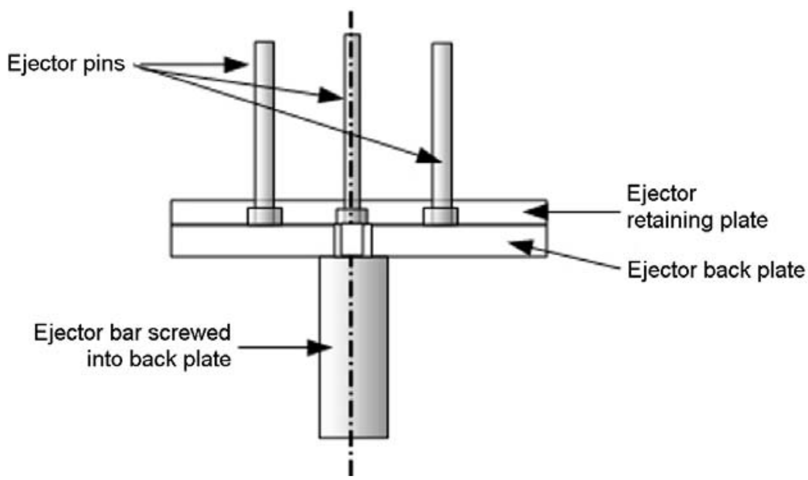


Figure 9.5 Typical ejection system

9.1.9 Ejection Gap

This is the amount that the ***ejector system*** or ***assembly*** can move towards the cavity support plate from its rest position. It must be large enough to permit the whole ***form*** of the component to be fully ***ejected*** from the tool. It is essential that the parts are cleanly ejected from the tool to prevent them becoming trapped in the tool.

9.1.10 Support Blocks

These are also sometimes called ***risers***. They connect the cavity support plate to the rear clamping plate or back plate. The material used is usually good-quality low-carbon steel.

9.1.11 Guide Pillar

Guide pillars are used to accurately align the front and rear halves of the tool. This is necessary because the moulding machine cannot be relied on to do this consistently. Unless the two mould halves are aligned accurately there could be mismatches of the cavity forms and cores in the front and rear mould halves.

Guide pillars are also used in toolmaking to align and register the complete tool so that it may be stripped down and reassembled accurately. This is discussed in more detail in Chapter 8.

Guide pillars are normally made from hardened alloy tool steel.

9.1.12 Return Pins

They are used, as the name implies, to return the ejection system to its initial or rest position when the tool closes. They stand proud of any other ejector pins and therefore as the tool closes they make contact with the front half first and thus prevent any damage to the more fragile ejector pins through contact with the front half of the tool.

Return pins are also quite often called ***push backs*** for obvious reasons. They are made from either hardened silver steel or hardened alloy steel.

9.1.13 Fine Tuning the Mould Tool

Although Figure 9.2 illustrates the basic elements and construction of a two-plate mould tool, it would not operate very satisfactorily as a production tool. There are several tweaks and wrinkles that are used to ensure that the tool runs as reliably in production as possible. For example, it is important to include appropriate clearances for certain sliding parts and bushes to prevent excessive wear on guide pillars and return pins. Figure 9.6

shows a more complete mould tool design that would be suitable for use as a production tool.

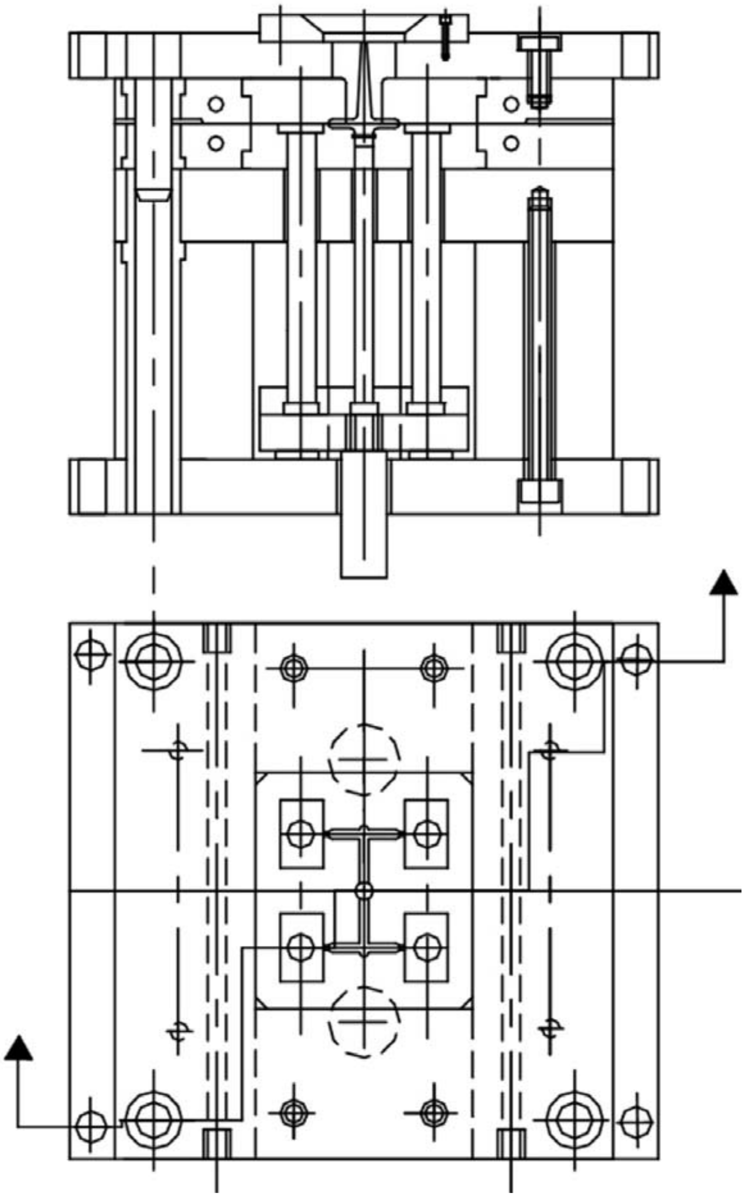


Figure 9.6 More complete two-plate mould design

The additional features included in this more complete design are as follows:

- Clearances around the ejector pins, ejector return pins and ejector bar
- Bushes on guide pillars and return pins
- Screws to hold the tool together
- Support pillars
- Taper tapped holes on water cooling channels
- Stand-off buttons beneath the ejector system
- Chamfers on rectangular cavity insert
- Guide pillar and bush system completely aligns the tool

9.1.14 Clearances

These are necessary to avoid undue wear on sliding surfaces. A good guide is that the sliding surface contact length between mating sliding diameters should be around 2–3 times the diameter of the pin.

9.1.15 Bushes

Most mould plates are often soft mild or alloy steel and repeated sliding of hardened components in them would lead to early wear. To prevent this, hardened bushes are used as inserts in the soft plate.

9.1.16 Screws

High-tensile steel cap screws are used to secure the tool together, the number and size of these being dependent on the size and nature of the mould tool.

9.1.17 Support Pillars

These are used to provide extra support and stiffness to the cavity support plate. They prevent this plate from excessive deflection that may give rise to flashing at the split line and a variety of other associated problems including leaking water systems.

Support pillars should be included in a design whenever possible for these reasons. However, in some designs this may not be possible where the presence of large numbers of ejector pins prevent this. In such cases, the designer should ensure that the cavity support plate is of sufficient thickness to minimise any deflection.

9.1.18 Taper Threads

These are tapped in the ends of the water cooling channels. They are designed to provide a secure fixing for water connections and to prevent leaks.

9.1.19 Stand-off Buttons

These are circular steel components screwed into the underside of the lower ejector plate to create a clearance between it and the back plate of the tool. This prevents small scraps of material accumulating at the back of the ejector system and stopping it returning fully.

9.1.20 Chamfers and Radii

Wherever possible, all sharp edges should be chamfered or radiused. The rectangular insert shown in Figure 9.6 is also chamfered to allow it to fit into the rectangular hole machined into the cavity retaining plate. It would be difficult, unnecessary and time consuming to try to fit a sharp-cornered insert into a rectangular hole.

9.1.21 Guide Bushes

Note that these have been extended right through the tool to allow for it to be removed from the tool and reassembled accurately.

10 Ejection Systems

10.1 Requirements

It is very important to give careful consideration to the way in which a component is going to be ejected from the tool. The design of the ejection system is one of the major factors in determining how efficient the tool will be in production.

The paramount requirement is that all components are ejected positively, without exhibiting any tendency to twist, distort or hang-back. In determining a satisfactory system, a number of factors have to be taken into account, including:

- The part geometry
- The material
- Gating
- Ejection balance
- Machine specifications
- Component finish requirements

10.1.1 Part Geometry

The component geometry will often restrict where ejectors may be placed. Features on the part may make it impossible to eject on certain faces. For example, they may be stepped, or perhaps a face may have several holes all grouped closely together. This type of feature means the face cannot easily be used for ejection.

10.1.2 Draft Angles

The component drawing should be checked for suitable draft angles being present in the line of draw. Draft angles are often an essential requirement. Deep drawn parts in particular may tend to scuff or score up when ejecting from parallel-sided cores.

If draft angles are not present on the drawing, the designer should pursue this problem with the customer with a view to obtaining a concession. At the least the customer should be warned of the consequences of continuing in such cases. A draft angle of at least 1° is required for most mouldings, but for deep drawn components with long sides 2° or more is preferable.

Precision mouldings with close tolerances often mean that draft angles cannot be used, as they may take the part out of tolerance. In such cases, it may be possible to provide a small amount of draft by using the maximum and minimum tolerance conditions of the dimensions. If this method is employed, however, sufficient tolerance should remain to allow for variations in sizes from part to part during moulding.

In some cases, where quite small parts are being moulded, it is sometimes possible to mould the parts without any draft angle at all on the cavities. This is more likely to succeed with high-shrinkage, semilubricated material like Nylon and acetal where they shrink away from the cavity form. However, it is still preferable to include draft angles wherever possible.

10.1.3 Tolerances

Tightly toleranced parts also need extra attention when designing the ejection system. The prime requirement, in this case, is to avoid the possibility of distorting the part and resulting in out-of-tolerance dimensions during the ejection phase.

Flatness tolerances can easily be exceeded if the part is not supported during ejection or if the cooling cycle is too short. Insufficient cooling is often the cause of distortion on many mouldings, as the moulding will not be stable enough to maintain its form owing to the presence of excessive heat.

10.1.4 Material

The type of material being used will influence the choice of ejectors and the number of ejectors required. For example, with brittle materials like polystyrene, the part would have to be supported a great deal more than would tough materials like Nylon. Brittle materials are easily prone to cracking or even breaking during ejection unless sufficient attention has been paid to this point.

On the other hand, it is often possible to get away with much less ejection support with the stronger self-lubricated materials, as they are stiffer and tough enough to transmit the ejection force to all parts of the moulding.

Some soft materials can lead to the material compressing and ‘bellying out’ at the point of ejection, resulting in the moulding resisting being stripped from the core.

Flexible materials, like flexible PVC or certain grades of polyurethane, pose considerable ejection problems and require a lot of thought in designing the ejection system. Figure 10.1 shows a typical example. In this arrangement, the moulded, flexible PVC tube is extremely likely to buckle when ejection takes place. The reason is that the ejection force is not transmitted through the entire length of the tube and tends to concentrate at the point of ejection. In fact it may not be possible to eject this component at all, because of this problem. In such cases, it may be necessary to use a stiffer grade of material before satisfactory ejection can take place.

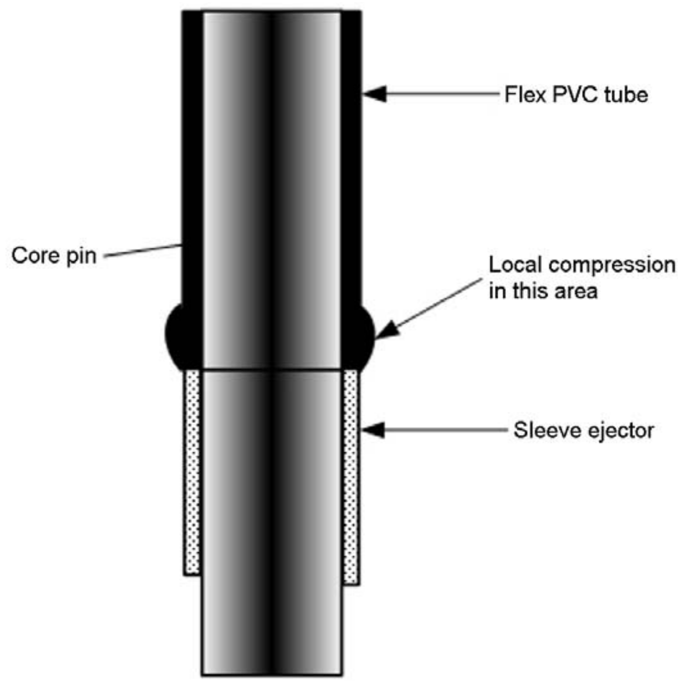


Figure 10.1 Compression of flexible materials

10.1.5 Gating

Special support may be necessary near the gate position. A classic example of this is with tunnel gates. An ejection position must be chosen so that the gate is sheared off cleanly and ejected without any tendency to hang-back.

Similar problems can occur with tab-gated components, which may shear off and tear into the part, resulting in a reject. This is more likely to happen with brittle materials, and accordingly adequate ejection support must be provided for such parts.

Overfeed gates, used in three-plate moulds, are also a potential source of problem. Often, this type of gate is substantial in size and difficult to break off. In these cases the ejection must be phased in, with a sequenced opening of the tool. Sequenced opening ensures the gate is broken away from its runner before ejection takes place. This problem is discussed in more detail later in this chapter.

10.1.6 Ejection Balance

An ejection system can contain many ejector pins and often these can be quite slender. Such pins can easily buckle or start to score if the ejection system is not balanced or guided (see Figure 10.2).

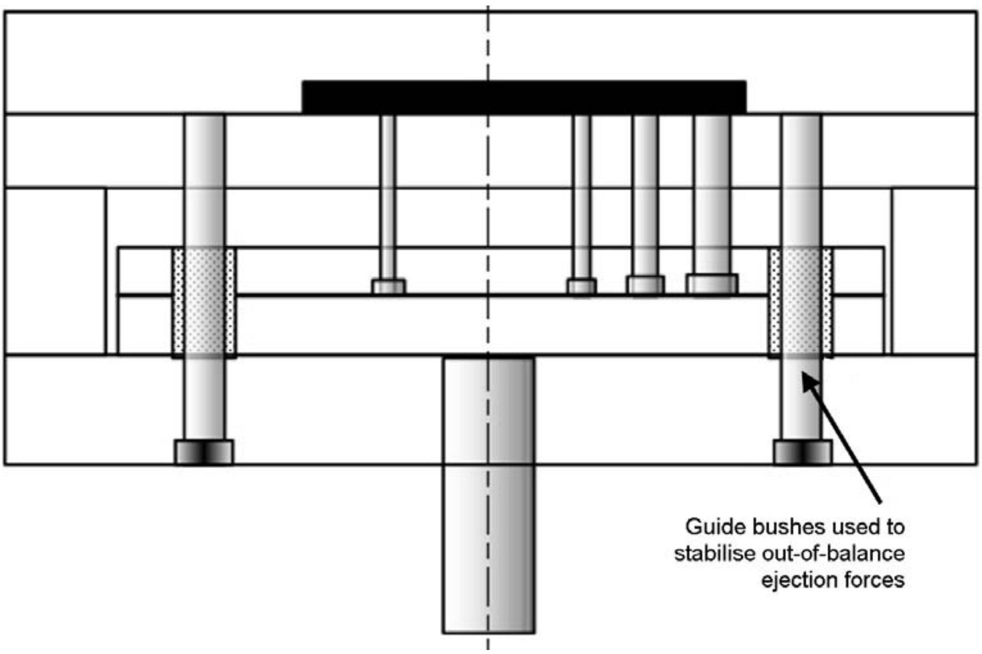


Figure 10.2 Out-of-balance ejection system

Family tools (tools that produce parts with different geometry from each other, e.g., a lid and a base on the same tool) invariably lead to an out of balance ejection system, as the ejectors are not symmetrically positioned. In these cases, it is good design practice to guide the ejection system with bushes to avoid any problems occurring.

10.1.7 Machine Specifications

As soon as the basic mould design has been decided, the machine specifications should be consulted to determine the features available. The major things specific to ejection that need checking are listed below.

- Opening stroke
- Machine ejection features
- Core pulling
- Movement control features

10.1.8 Mould Opening Stroke

Sufficient opening stroke needs to be available on the machine to ensure correct operation of multisequence opening ejection systems. A classic case of this is with three-plate tools, which require a large opening stroke. Double ejection or multistage ejection tools also require longer than normal opening strokes.

Any tool that involves multistage ejection or multiple openings generally needs longer opening strokes. In addition to this, the machine must be consistent and accurate in its mould opening stroke. Any variations usually cause incorrect operation of the tool or, worse, tool breakage.

10.1.9 Machine Ejection Features

All moulding machines provide a mechanical dead stop on the crosshead of the clamping unit. In many cases this is sufficient and a very wide variety of tools use this system as their primary means of ejection, as it is cheap and simple.

However, most modern moulding machines are equipped with hydraulic ejection facilities and where possible, advantage should be taken of this. Hydraulic ejection is much more controllable than a mechanical stop and also more versatile.

Occasionally, with large ejection systems it is better to provide machine ejection nearer the ends of the ejector plate assembly. Larger machines are usually provided with tapped hole positions at the ends of the crossheads, into which ejector bars can be directly screwed.

It is important to select the best system and examine each case on its merits. Ideally any system chosen should be reliable, consistent and as simple as possible.

10.1.10 Movement Control Features

Wherever sequential opening of a tool is required, catches, finger cams and latches may be necessary to control the plate movements. Proximity switches or additional microswitches may be used to directly actuate such devices.

Die halt facilities may also be needed to enable loading of moulded-in inserts either by hand or by robot.

10.1.11 Component Finish Requirements

Clearly, it would be inappropriate to eject a component on one of its appearance faces, which would leave an undesirable witness mark. Sometimes it is actually possible to make a feature of an ejector witness mark by incorporating a logo on the top of the ejector pin. This could, of course, only be incorporated with the express agreement of the customer, but this technique is a very useful alternative where ejection may otherwise be very difficult.

In all such cases the possibility of using alternative forms of ejection should be considered to avoid ejecting on appearance faces. Other possibilities include stripping or ejection from the front half of the tool.

10.2 Ejection Methods

The most common forms of ejection are as follows:

- Pins and blades
- Sleeve ejectors
- Stripping actions
- Valve ejectors

10.2.1 Ejector Pins and Blades

Ejector pins are the most common method of ejecting parts from the cavity. These should always be hardened for production tooling. Three variations are normally used:

- *Nitrided pins*. These are pins that have been heat-treated in a molten salt ferritic bath or gas to introduce nitrogen into the surface of the pin. They have good wear resistance and are used for all normal ejector pin applications.
- *Tuftrided pins*. Tuftriding introduces nitrogen and extra carbon into the pin surface, giving a harder surface and leaving a softer core. This has distinct advantages where slender pins have to be used that may be subject to flexing during operation.
- *Through-hardened pins and blades*. These are hardened in the same way as cavity parts, using nickel–chrome steels. This technique is used for larger core pins and pins that form the core of a sleeve ejector.

Figure 10.3 shows a variety of commonly used ejector blades and pins.

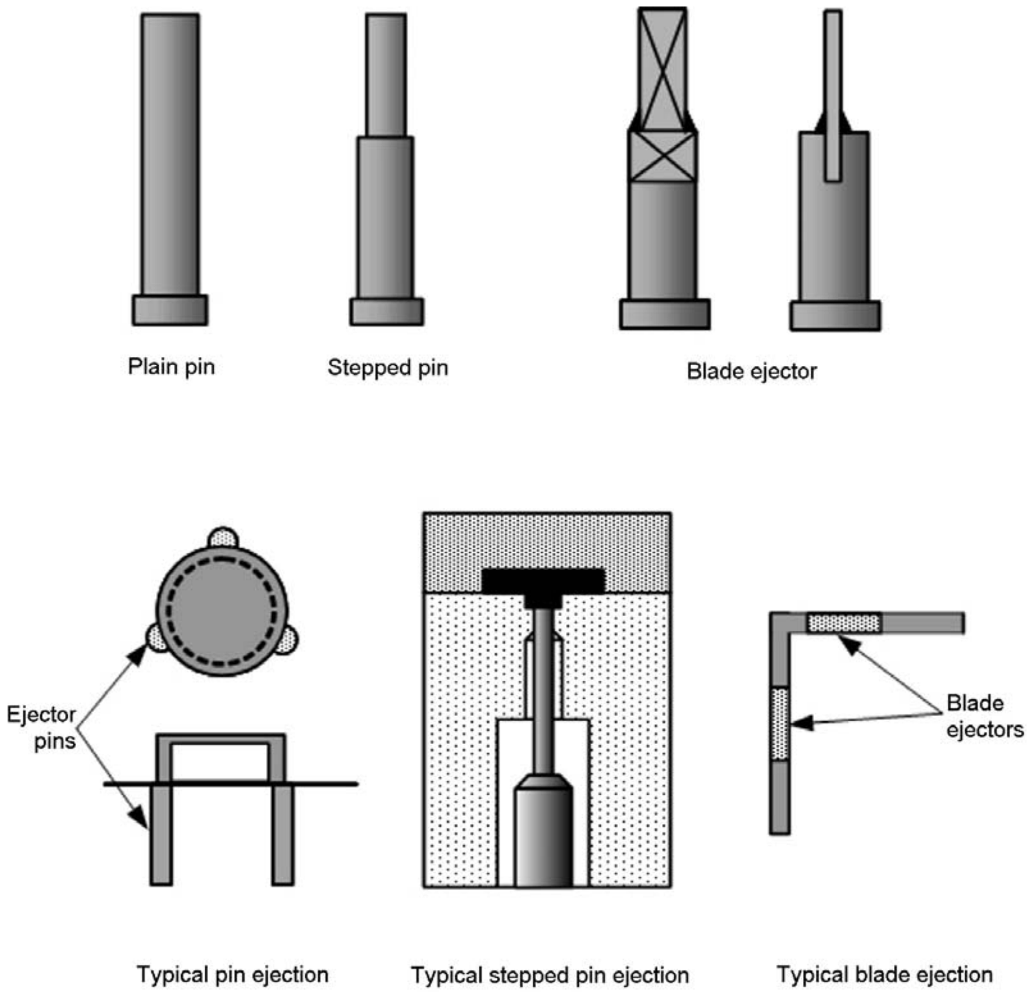


Figure 10.3 Pin and blade ejectors

10.2.2 Sleeve Ejectors

Sleeve ejectors are used to eject on circular features such as circular pads, bosses or recessed holes. Like ejector pins, sleeve ejector assemblies are available as standard components in a wide variety of sizes. Nonstandard sleeves can be made by adapting standard ones; failing this, they will have to be specially made.

A typical sleeve application is shown in Figure 10.4.

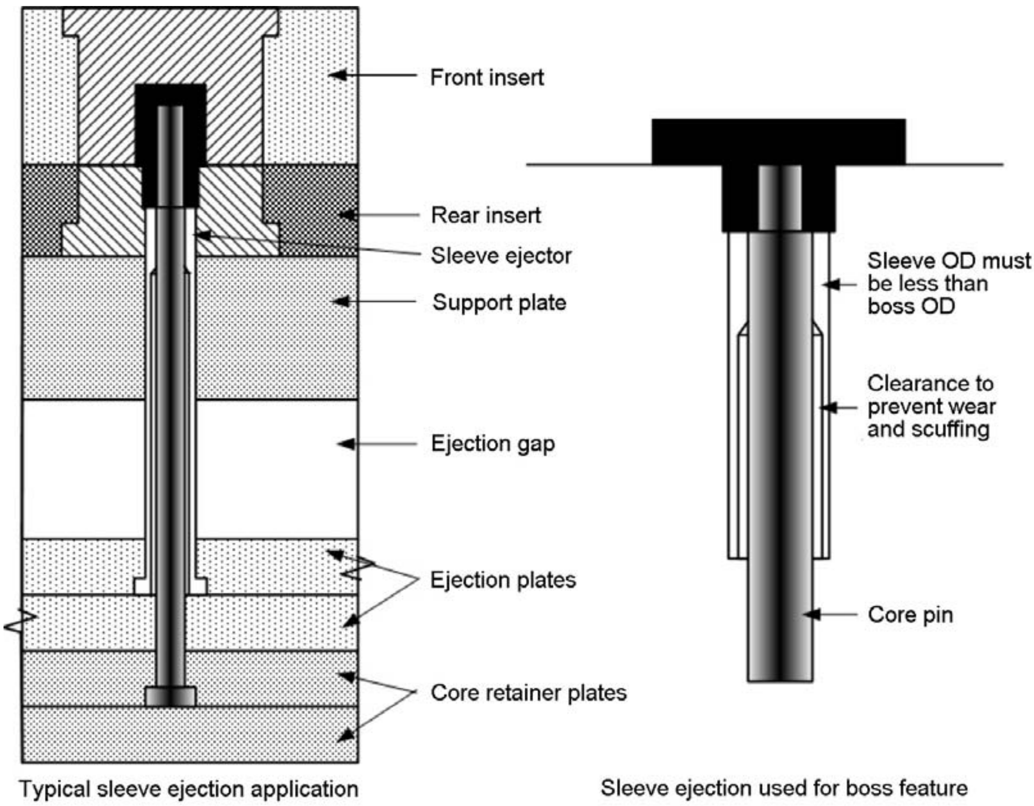


Figure 10.4 Sleeve ejection

10.2.3 Stripper Plate Ejection

Stripper plate systems are very effective and usually more efficient than pins wherever they can be used as they support the maximum area possible during ejection (Figure 10.5). Typical applications are for tubular parts and circular, square or rectangular boxes.

Stripper plate systems are also often used in conjunction with other forms of ejection. They are used with pins, sleeves and blade ejection, and sometimes with compressed air.

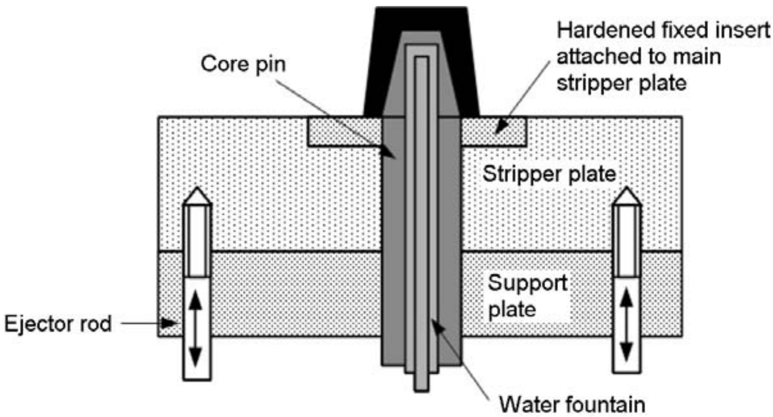


Figure 10.5a Stripper plate with integral hardened insert

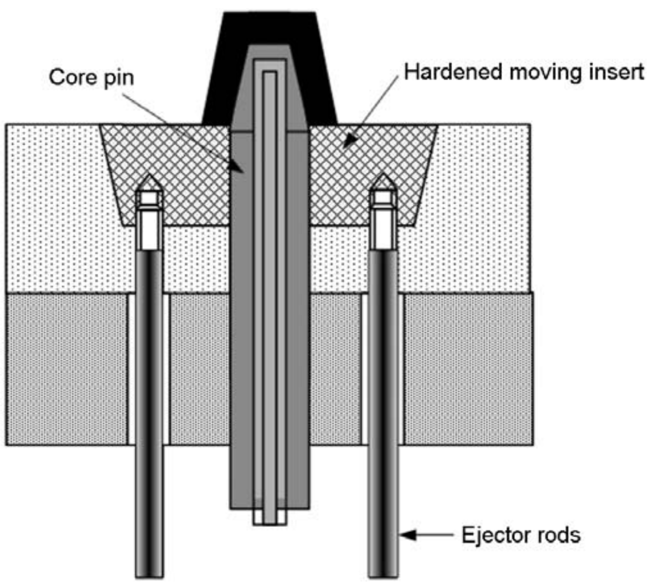


Figure 10.5b Stripper plate with moving hardened insert

10.2.4 Valve Ejection

This ejector is used to provide a large area of support that is particularly useful for supporting the top surfaces of thin-walled boxes. Such components, especially those in brittle materials, can be prone to breakage if not supported in this way.

Valve ejection is also useful for releasing a vacuum in enclosed components such as boxes. Examples of the use of valve ejectors are shown below.

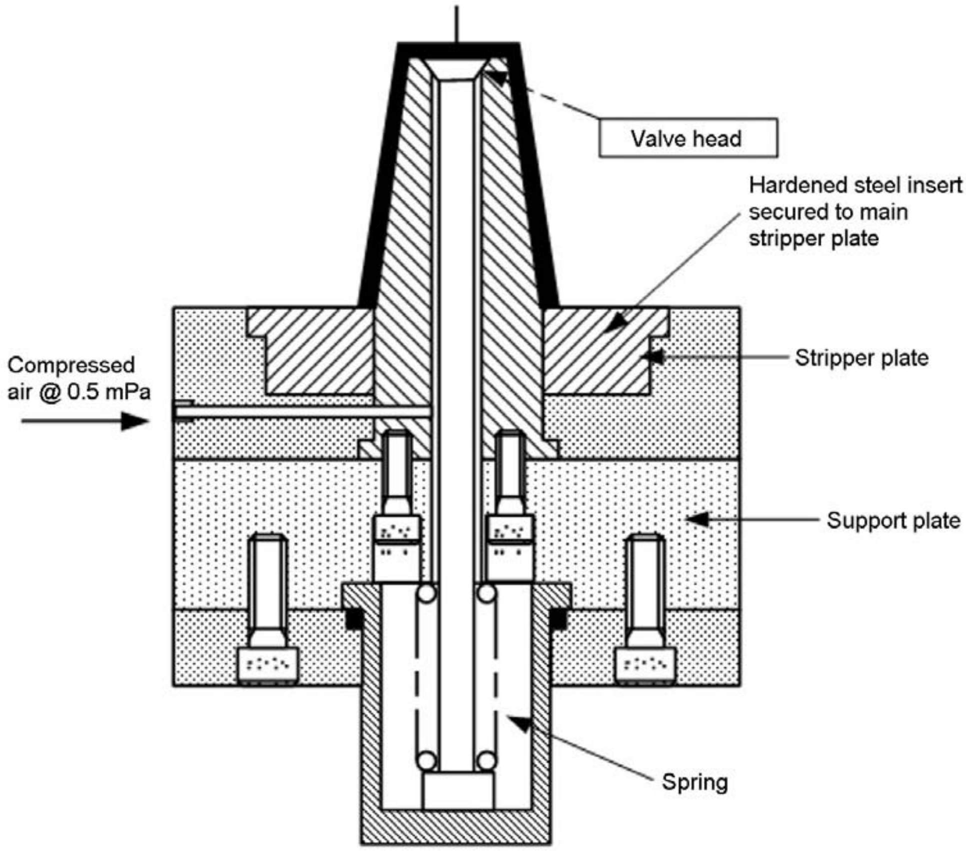


Figure 10.6 Air-assisted valve ejection

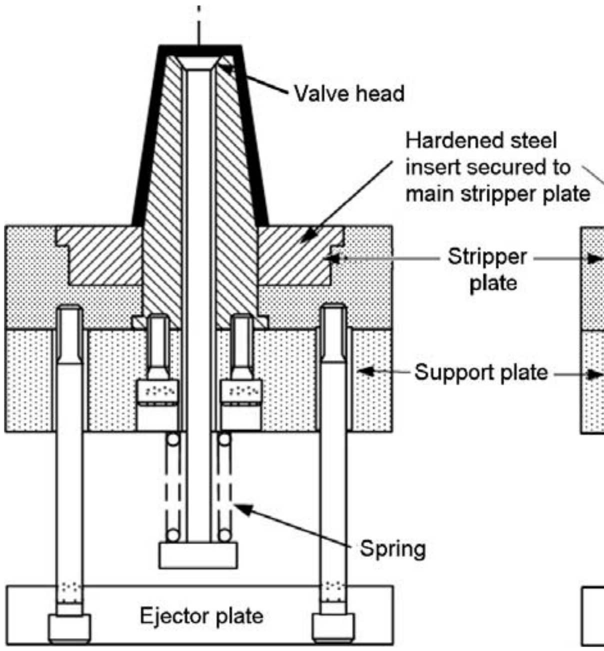


Figure 10.7a Spring-return mechanical valve ejection

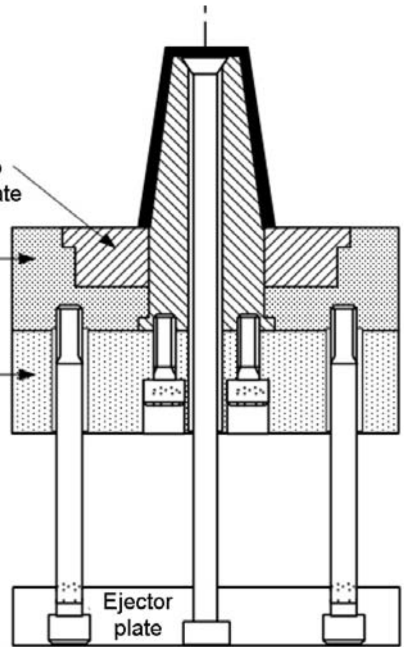


Figure 10.7b Direct mechanical valve ejection

10.2.5 Ejection Forces

It is becoming increasingly important to determine the amount of force necessary to eject all the parts out of the tool. This is because economic factors are tending to force moulders to run jobs on the smallest machines possible in order to keep the prices they charge as low as possible.

With ever-increasing competition from the rest of the world, the pressure is on to mould more and more efficiently in an effort to remain competitive while retaining the desired quality. It is becoming evident that this trend is resulting in moulders operating ever closer to the machine limits in terms of shot weight, plasticising capacity, projected area and ejection force. It is for this reason that machine manufacturers include the maximum available ejection force in the machine specifications.

Calculation of the ejection force is quite straightforward, and we will now examine the process.

10.3 Ejection Force Calculation

Primer

The basic SI unit of force is the newton, which has the symbol N. One newton is defined as the force necessary to give a mass of 1 kg an acceleration of 1 m/s^2. The acceleration due to gravity is normally taken as 9.81 m/s^2. This is the acceleration imparted to a 1 kg force by its own weight (1 kg-force). Hence:

1 kg-force = 9.81 N

1 tonne-force = 9810 N or 9.81 kN

Note: For less precise calculations the value of *g* is often taken as 10 m/s^2.

The SI unit of pressure and stress is the pascal, which has the symbol Pa.

1 Pa = 1 N/m^2

1 MPa = 1 MN/m^2 or 1 N/mm^2

1 GPa = 1 GN/m^2 or 1 kN/mm^2

Note: The SI system actually uses the designation 9/81 ms^{-2} for the acceleration of gravity (*g*) and a similar system for other units. However, to avoid confusion the traditional designation is being used here.

10.4 Formulae

The following formula may be used for calculating the ejection force:

$$F_p = \frac{EA\mu\alpha\Delta_t}{\frac{d}{2t} - \frac{d}{4t}m}$$

This is the way the formula is usually written in scientific texts but a slightly easier form for computational purpose is:

$$F_p = \frac{EA\mu\alpha\Delta_t}{\frac{d}{2t}\left(1 - \frac{m}{2}\right)}$$

where:

F_p = the ejection resistance force (N)

E = Young's modulus of the polymer (N/cm^2)*

A = total surface area of moulding in contact with cavity or core, in line of draw (cm^2)*

μ= coefficient of friction, polymer on steel

m = Poisson's ratio

d = the diameter of a circle whose circumference is equal to the total projected perimeter of the moulding (cm)*

α= the coefficient of linear expansion of the polymer (cm/°C)*

Δ_t= (polymer softening temperature) – (mould tool temperature) (°C)

t = average wall thickness of part (cm)*

*Note that the units of length here are all in cm.

10.4.1 Example

A two-impression thin walled box-shaped component is to be moulded on a 275 tonne press. The machine has an ejector force rated at 40 kN. Calculate whether this is sufficient given the following data:

Material:	Polystyrene (PS)
Young's modulus of elasticity:	30×10^4 N/cm^2
Poisson's ratio:	0.35
Coefficient of friction (PS on steel):	0.4
Softening temperature of PS:	80 °C
Mould tool temperature:	20 °C
Coefficient of linear expansion (PS):	7×10^{-5} cm/°C

The dimensions of the box are shown in Figure 10.8: all dimensions are in cm.

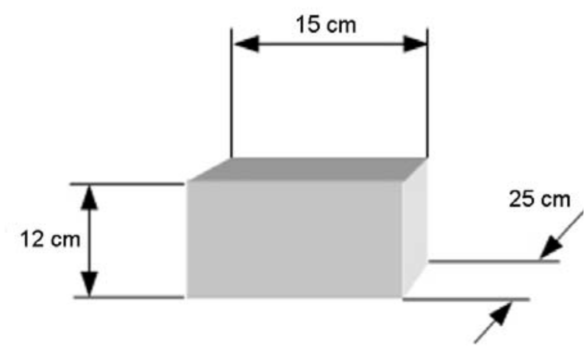


Figure 10.8 Polystyrene box

Total area of resistance = 2 × (12 × 15) + 2 × (12 × 25) = 360 + 600 = 960 cm^2

Total projected perimeter = 2 × 15 + 2 × 25 = 80 cm

Hence:

$d = 80/\pi = 25.46$ cm and $\Delta_t = 80 - 20 = 60$ °C

Therefore,

$$F_p = \frac{30 \times 10^4 \times 960 \times 0.4 \times 7 \times 10^{-5} \times 60}{\frac{25.46}{0.6}\left(1 - \frac{0.35}{2}\right)} = \frac{483840}{35} = 13\,824 \text{ N, or } 13.8 \text{ kN}$$

Hence for a two-impression tool we require 2 × 13.8 kN = 27.6 kN. This is well within the machine specification of 40 kN; however, in practice the machine ejection force will also be subject to the sliding resistance of the ejector system and sometimes to force exerted by any return springs used in the ejector assembly.

A good rule of thumb is to apply a factor of 1.25 for nonspring systems and 1.5 for spring return systems. Therefore, in this case the total ejection resistance force is:

1.25 × 27.6 = 34.5 kN for nonspring systems, or

1.5 × 27.6 = 41.4 kN for spring return systems

This demonstrates that the machine ejection force is satisfactory for the first case but unsatisfactory for the second case.

10.5 Ejection Assembly Actuation

The ejector pins, sleeves or stripper actuators, together with their retainer and backing plates, form the ejection assembly.

As discussed previously, it is desirable, wherever possible, for the complete assembly to be symmetrically balanced to avoid out-of-balance forces that may create premature wear or damage.

10.5.1 Mechanical Ejection

A typical mechanical ejection system with a spring return is shown in Figure 10.9. In this case the ejectors are symmetrically positioned and a bushed guide system has not been used.

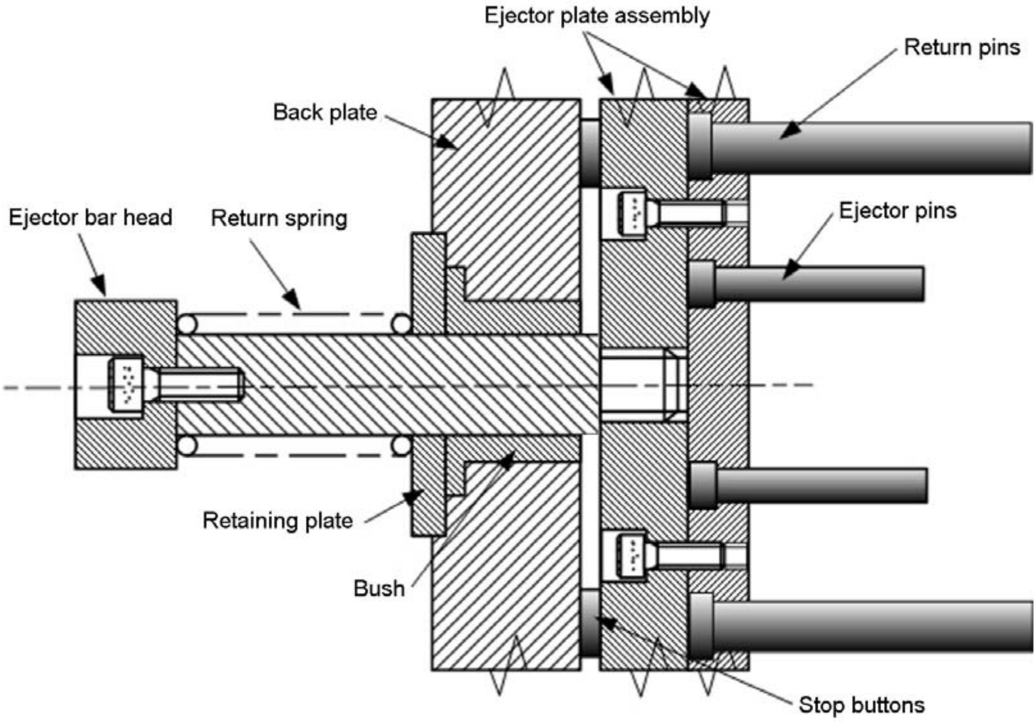


Figure 10.9 Typical mechanical ejection system

Sometimes it is advantageous to strip components by pulling a stripper plate from the front half of the tool. A basic system is shown in Figure 10.10.

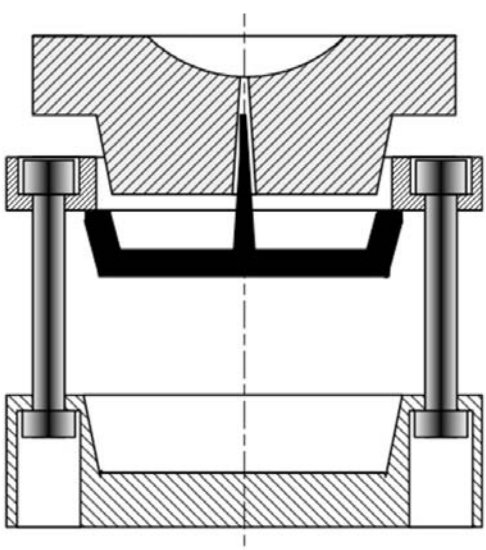


Figure 10.10 Ejection by stripping from front half of tool

The mechanically operated bar ejection, shown previously, is very widely used. However, this method is not very controllable and imparts a high initial force on the ejection system. For more fragile components this approach may be too severe and a more controlled method is preferred.

A method that is frequently used for such cases involves the use of toggle systems, which apply more controllable and gentler forces. Examples of this approach are shown in Figures 10.11 and 10.12.

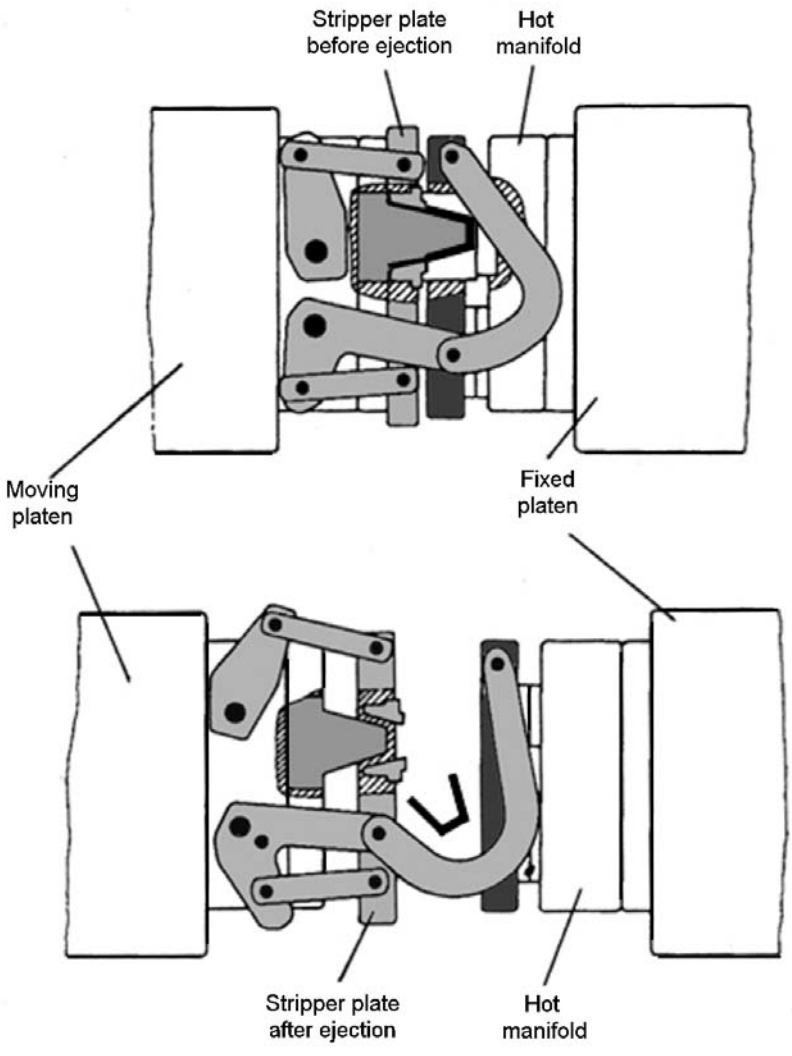


Figure 10.11 Toggle-operated ejected system

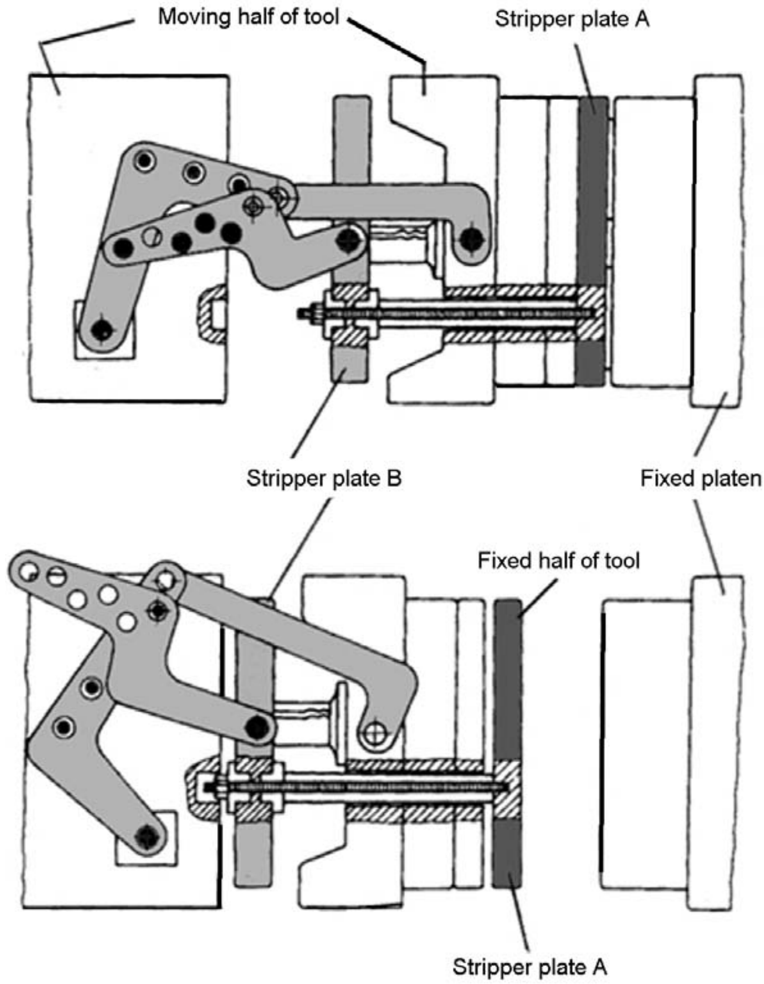


Figure 10.12 Toggle-operated system operating two stripper plates

10.5.2 Hydraulic Ejection

Most modern moulding machines are equipped with hydraulic ejection facilities and advantage should be taken of this wherever possible. Hydraulic ejection is much more controllable than a mechanical stop and also more versatile. It also can provide a much greater force than a mechanical dead stop.

A hydraulic ejector can be adjusted for speed and force, allowing fine control over the ejection phase. Some systems also permit staged speed ejection, which can be quite useful with certain jobs: double ejection can also benefit from this. Such systems can be very useful where the ejector assembly needs to be returned before the tool closes, eliminating the need for springs. Another advantage of hydraulic systems is that the tool ejection assemblies may be multi-stroked. This feature is useful for parts that refuse to drop after normal ejection has taken place. In effect, the ejection system is shaken to force the parts to fall.

Finally, hydraulic ejectors are self-lubricating and do not create any significant wear or damage to the mould tool. However, caution is needed when moulding food, drug or medical related products owing the possibility of oil contamination.

10.5.3 Pneumatic Ejection

Compressed air is a very inefficient and limited choice for general ejection purposes. The main disadvantages are:

- Low available force. Most systems can only provide 0.05–1.0 MPa.
- As the name implies, air compresses easily, giving erratic performance.
- Oil from the compressor can cause contamination and spoil mouldings. This occurs even when using breathing standard filters.
- Perhaps the single biggest disadvantage is that owing to the low pressure available, large cumbersome cylinders may have to be used to gain sufficient force.

Nevertheless, compressed air is widely used because it is readily available, cheap and for smaller light-duty work can be very useful.

10.5.4 Hybrid Ejection Systems

Many ejection systems require a high degree of ingenuity, on the part of the mould designer, to solve ejection problems. Several factors may combine together to create difficulties in designing suitable systems. These include the cavity form and geometry, the material and the type of cavity construction. In practice, a mixture of methods may be used. Mechanical, pneumatic and hydraulic systems may be combined in difficult cases.

Figure 10.13 shows a stripper plate system with a direct mechanical valve ejector. This may also be combined with compressed air ejection if necessary as described earlier.

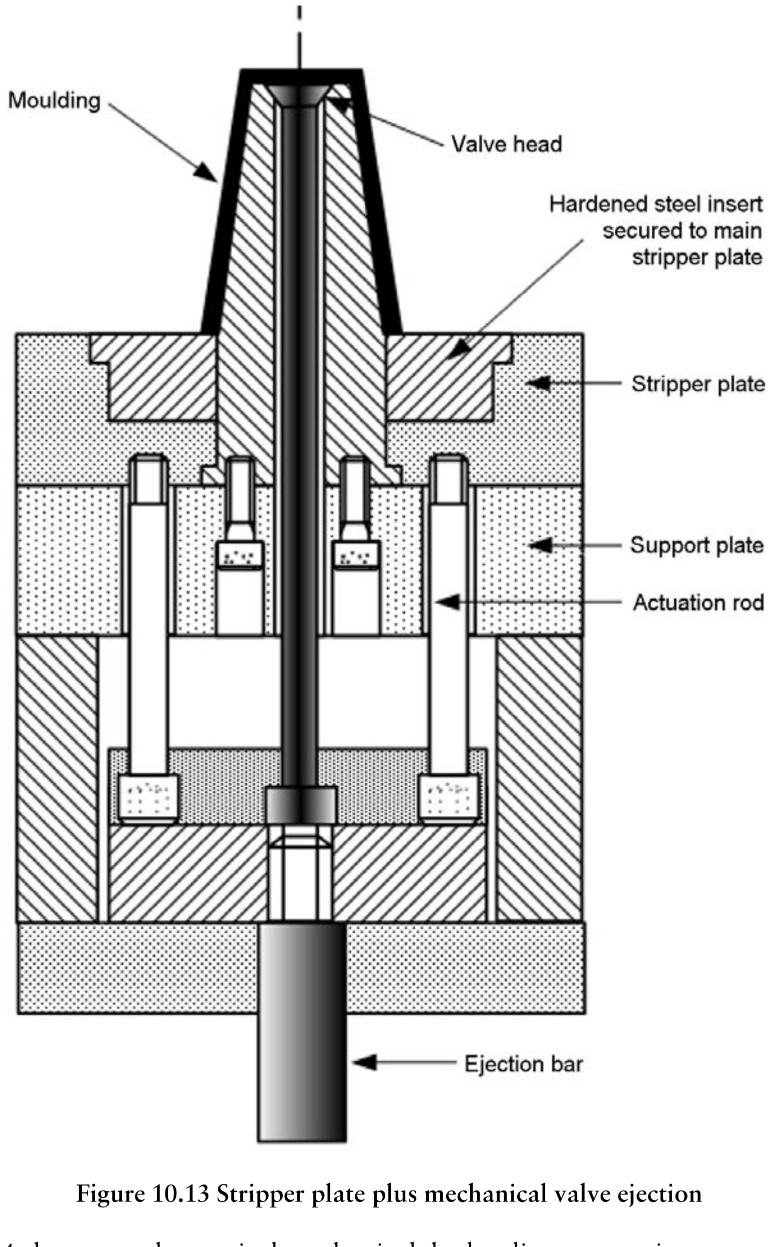


Figure 10.13 Stripper plate plus mechanical valve ejection

Figure 10.14 shows another typical mechanical–hydraulic–pneumatic system. In this case a threaded part is being moulded. A hydraulic or pneumatic motor drives the pinions during the unscrewing phase. After this has been completed, the part is ejected by means of a mechanically operated ejector pin.

In other cases, the unscrewing phase is often sufficient to push the part clear of the cavity with a final air blast is used to ensure complete clearance. These systems are described in more detail in Chapter 13 on 'Automatic Unscrewing Mould Tool Design'.

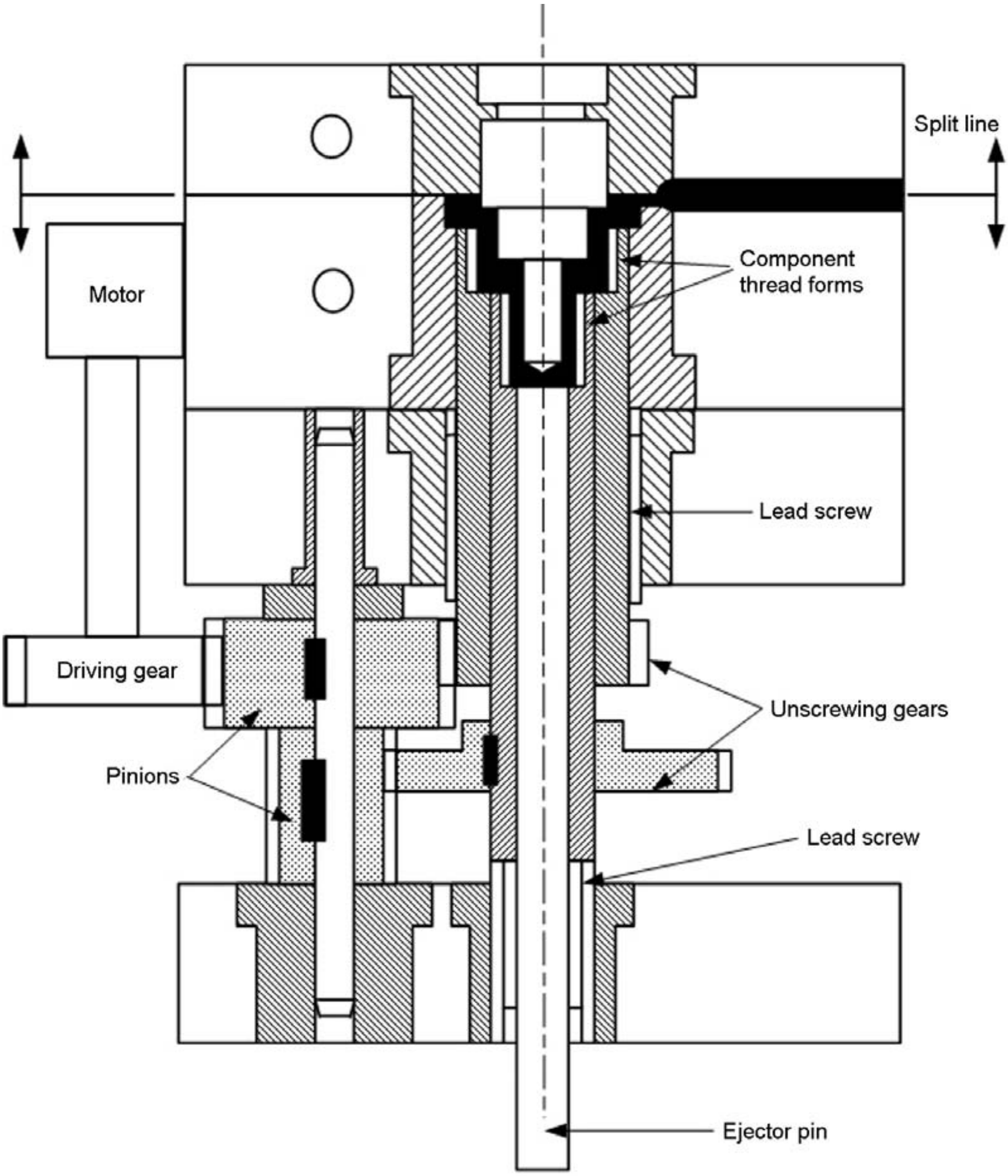


Figure 10.14 Unscrewing combined with mechanical ejection

10.5.5 Double Ejection

Deep drawn box mouldings often have wall thicknesses that are too thin to eject on directly. The solution is usually to use a single large ejector, a series of ejectors or perhaps a valve ejector under the top of the part. Unfortunately, this leaves the moulding resting on top of the ejector pins, so another stage of ejection is needed to clear the parts. The usual solution is to use double ejection. This can be a mechanical system driven or supplemented by air or hydraulics. A typical solution for a cap component is shown in Figure 10.15.

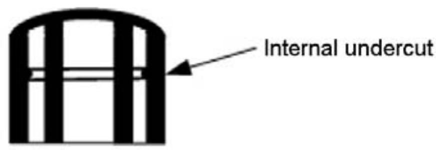


Figure 10.15a Component drawing

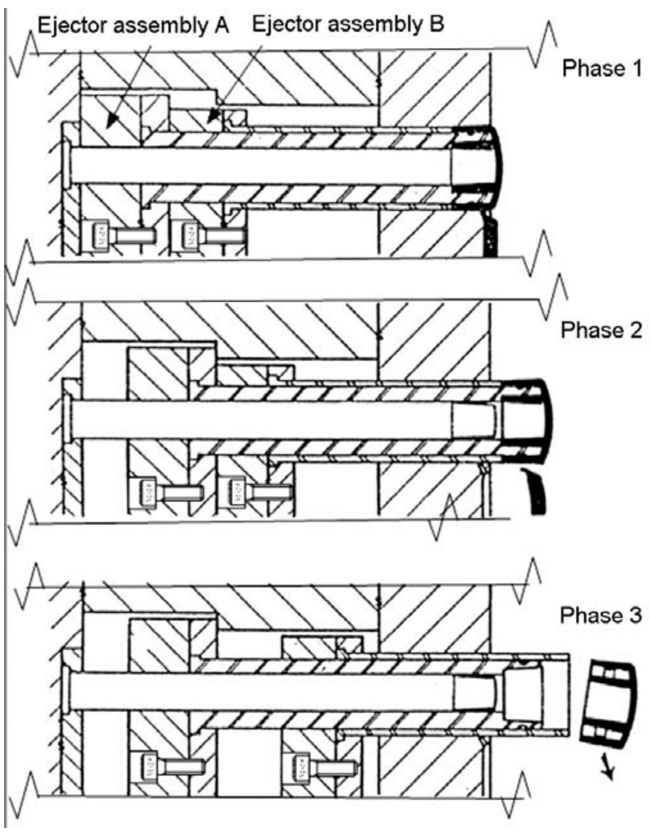


Figure 10.15b Standard double ejection system

In this design, phase 1 shows the mould tool closed. In phase 2 a hydraulic ejector pushes forward both ejector assemblies **A** and **B** together as a single unit to free the outer wall section so that the moulding may be able to deflect. Once this has occurred, the first-stage ejection assembly **A** hits a fixed stop and cannot move any further forward to complete phase 2. In phase 3 the second-stage ejector assembly **B** moves further forward, leaving the first stage behind, thus completely clearing the moulding from the cavity.

The key to the operation of this type of double ejection design is the module that connects the two ejector plate assemblies together. A spring-loaded collet ensures that the two systems move forward together as a single unit to complete the first stage. The lower assembly then hits a mechanical stop, the collet disengages, and the upper assembly continues forward, completing the second stage.

Figure 10.16 shows a very basic but nevertheless effective method of achieving double ejection for noncritical applications. After the tool opens, both ejector assemblies **A** and **B** move forward distance **Z** together as a single until assembly **A** is forced to stop by the cavity support plate above it. As the ejection stroke continues, the die springs compress, allowing assembly **B** to continue forward until they in turn hit the stops **C**.

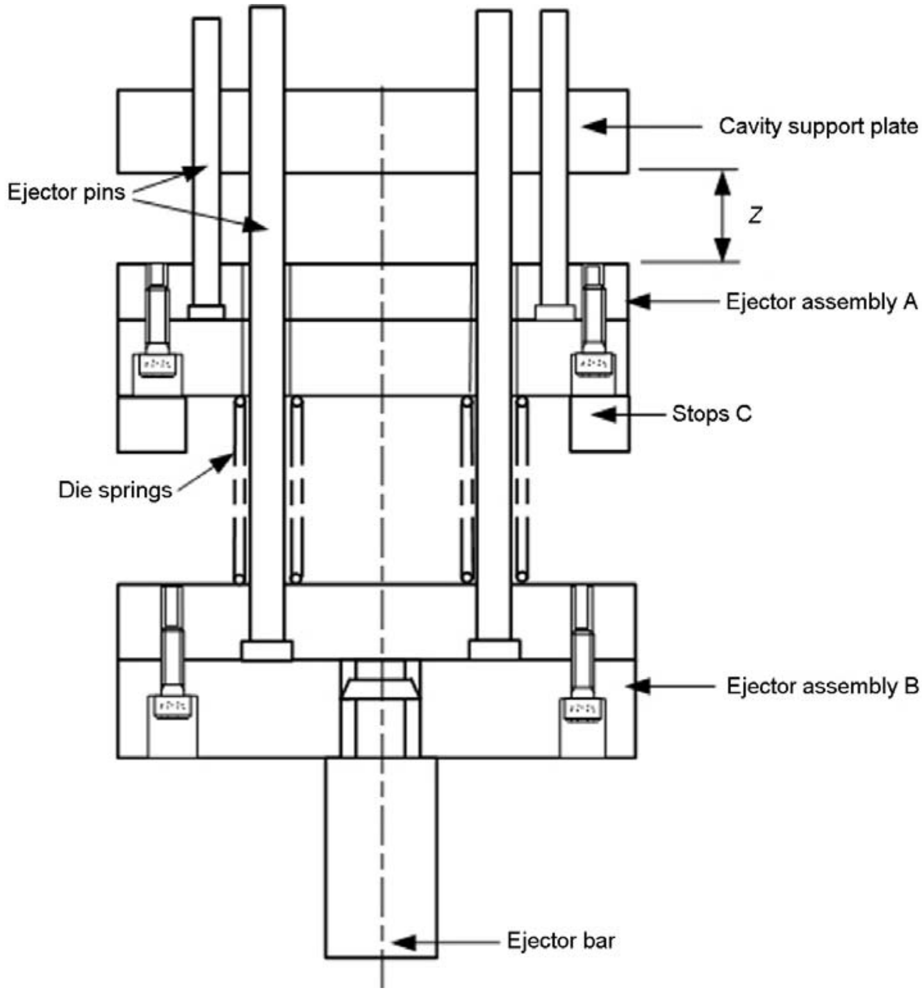


Figure 10.16 Simple spring-operated double ejection system

Clearly the whole success of the operation depends on the stiffness of the die springs being selected to allow this to take place. To avoid premature fatigue of the die springs, they should not be allowed to become coil-bound when they are compressed for the second stage ejection: hence the need for the dead stops **C**.

10.6 Unsatisfactory Systems

By definition, unsatisfactory systems are those that do not work reliably in production. Unreliable systems are invariably due to the following:

- Overcomplicated designs
- Out-of-balance forces
- Nonguided assemblies
- Insufficient ejection stroke
- Insufficient opening of the tool
- Insufficient number of ejector pins
- Ejection pin diameters too small
- Incorrect positioning of ejectors
- Flash causing mouldings to hang in cavity
- Scoring of ejector pins due to poor maintenance or design

This list is by no means exhaustive and can be added to by almost all designers during their careers.

11 Mould Temperature Control

11.1 Discussion

Some of the heat supplied to the material during the plasticising and injection phase must be removed from the tool before ejection of the parts can take place. However, not only is it unnecessary it is also wasteful to continue cooling the tool until the part has reached ambient temperature, as many materials may be safely ejected at temperatures up to 50 °C or more.

The cooling phase can be up to 80% of the overall cycle and often the most expensive cost component of the moulding. Clearly it is highly desirable to minimise the cooling cycle, and in order to do this it is essential to pay sufficient attention to the design and efficiency of all cooling systems.

The overall requirement is to cool the moulding as quickly as possible while preserving the physical properties of the material and the required quality of the moulding. When molten material is injected into the cavities of a mould it has to be allowed to solidify before the resulting mouldings can be ejected. As the ejection temperature may be 200–300 °C lower than that of the molten material, heat must be removed from the mould to reach ejection temperature as soon as possible.

A mould tool, is in effect, a highly stressed heat exchanger and the cooling phase of the injection moulding cycle is extremely important. The overall objective is to cool the polymer as quickly as possible to a temperature at which the moulding can be safely ejected. In general terms, amorphous materials that have a random structure may be cooled quickly in most cases without any ill effect on the properties of the material.

Crystalline materials are different. They have a preferred almost linear molecular chain structure and in this state they are stable and have their full physical properties. However, when the molten polymer is first injected into the cavity these molecular chains have a random orientation similar to amorphous materials. If this material is prematurely frozen while it is still in this state, the result will be far from satisfactory. The properties will be impaired and the moulding will strive to achieve its preferred structure after it has been ejected. Over a period of time the moulding will warp and distort and suffer dimensional changes.

As crystalline materials are frequently used for technical applications, this situation is clearly undesirable as the mouldings will be in an unsuitable state for use. To avoid this problem, heat must be supplied to the mould tool rather than cold water.

While all mouldings require cooling it is the *rate* of cooling that is most important. With the supply of heat to the mould tool instead of cold water, the crystalline polymers do not suffer such a high degree of thermal shock. The material is given more time for its preferred structure to form, which results in less internal stress being set up.

The temperature of the mould tool should be:

- High enough to allow the cavities to fill without premature freezing of the material
- As uniform as possible to ensure the moulding is cooled equally in all areas
- High enough with crystalline materials to avoid an unsatisfactory structure

11.2 Heat Transfer Fluids

11.2.1 Water

Water is the most commonly used fluid for mould cooling because it has good heat transfer and flow characteristics.

For very fast-cycling jobs like teaspoons or disposable cups, refrigerated water may be used at quite low temperatures, down to –5 °C. At these temperatures, antifreeze has to be used. In the majority of cases water is used for mould cooling over the temperature range from 5 to 80 °C. Water may occasionally be used at much higher temperatures, up to 200 °C, but in such cases the whole system must be pressurised.

Scale and algae accumulate in the pipework and cooling channels and this can rapidly diminish the efficiency of the cooling system. Periodic water treatment is essential to keep the system in good order. The alternative is to use demineralised water in a closed-circuit system.

11.2.2 Heat Transfer Oil

For higher mould temperatures (above 100 °C), oil is normally used as a coolant. It avoids the dangers of superheated steam. It also has the spin off advantage of not corroding the waterways and cavities.

11.3 Chillers

For many applications it is necessary to supply very cold water to the mould to achieve rapid cooling. Chiller units are supplied in two distinct types:

- Air cooled
- Water cooled

Both systems use pumps to circulate the water and the water-cooled versions often draw their supply water from water-cooling towers. Additionally, chillers may be dedicated to a specific machine or may be a part of a centralised system supplying cooling water generally to all machines.

11.4 Temperature Controllers

At higher temperatures, control of the mould temperature is not only used for straightforward cooling of the plastic but also to control surface finish, sinks, voids and shrinkage, and in most cases the actual temperature used is based on the results of sampling trials and previous experience.

It is necessary to ensure that the selected mould temperature is maintained and hence temperature controllers are used. These vary in sophistication from basic reactive models to expensive solid-state predictive computer-controlled models.

Most models have a heat exchanger in them through which the mould cooling fluid passes. Cooling water is normally used to cool the heat exchanger, which in turn is controlled by valves coupled to the electronic circuitry. Additionally, temperature controllers have integral heaters to supply heating fluid at the required temperature.

11.5 Cooling Channels

The simplest method of supplying cooling fluid to the mould is to drill holes in the mould plates around the cavities. These should be of standard drill sizes and of sufficient diameter to permit an adequate flow of cooling fluid.

The most basic circuit, shown in Figure 11.1, consists of two drilled holes running parallel to the longest sides of a rectangular moulding. This is not a good design as the cooling effect will be greater adjacent to the cooling channels than it is on the other two sides of the component. This inefficient design leads to over-long cooling cycles and frequently, loss of part quality.

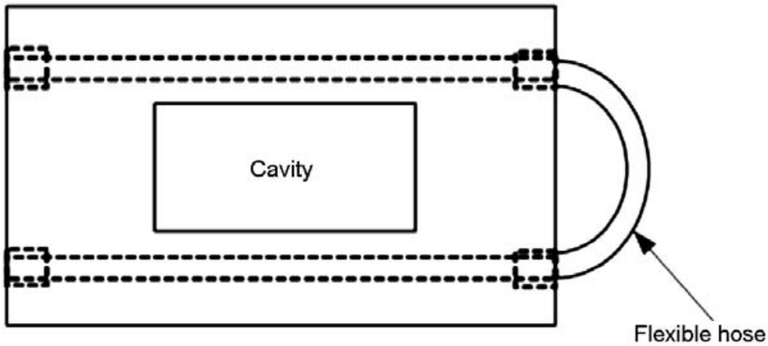


Figure 11.1 Basic cooling circuit

Figure 11.2 shows a more efficient circuit giving more uniform cooling around all four sides of the moulding.

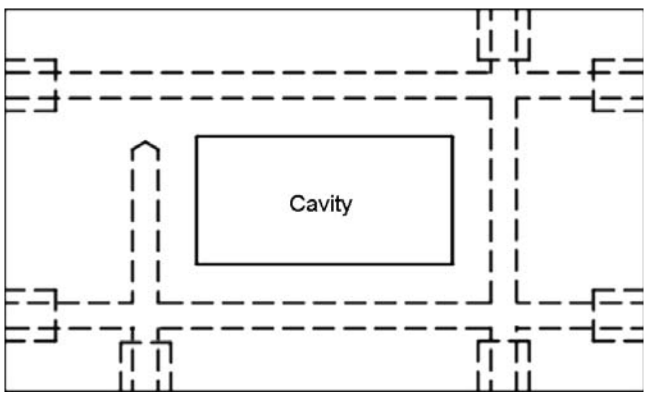
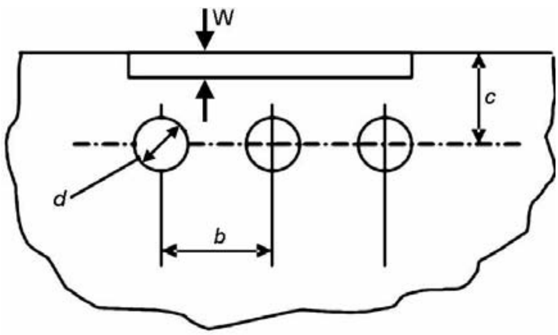


Figure 11.2 A more efficient cooling circuit

The location of channels around larger areas is important for efficient cooling. A guide to cooling channel positioning is shown in Figure 11.3. If the channels are too far apart, there is danger of an uneven thermal gradient developing between them. If the channels are too close together, there is a danger that the thickness of steel between them may become too low. If they are too close to the cavity surface, an additional problem may occur with localised ‘over-cooling’, resulting in irregular temperature control.



Part thickness W	Channel Diameter d
2 mm ········	8–10 mm
4 mm	10–12 mm
6 mm	12–15 mm
c = 2*d* to 3*d*	*b* = 3*d* to 4*d*

Figure 11.3 Guide to cooling channel positioning

11.5.1 Core Cooling

It is often desirable and sometimes essential to provide cooling inside core pins. In many cases core pins will get very hot if no cooling is incorporated in them, resulting in prolonged cooling cycles. In extreme cases, lack of cooling can prevent satisfactory production, as the moulding remains too soft to eject for many minutes.

Several different methods are used for cooling cores and cavities depending on their size and construction:

- Baffle system
- Fountain system
- Angled hole
- Stepped hole
- Spiral cooling
- Heat rods
- Heat pipes
- Beryllium copper cores and cavities

11.5.1.1 Baffle System

This is a simple method of cooling smaller cores, although arrays of baffles may be used in larger cores. A hole is bored into the core and a strip of copper is inserted into it. It must be a good fit in the hole so that fluid does not leak past it.

To ensure unrestricted flow, the cross-sectional area of the gap each side between the baffle and the hole must be numerically equal to at least half of the bore diameter. Figure 11.4 shows a typical multiple baffle system inside a large core. With a series circuit no more than four baffles should be interconnected to avoid an undesirable increase in fluid temperature.

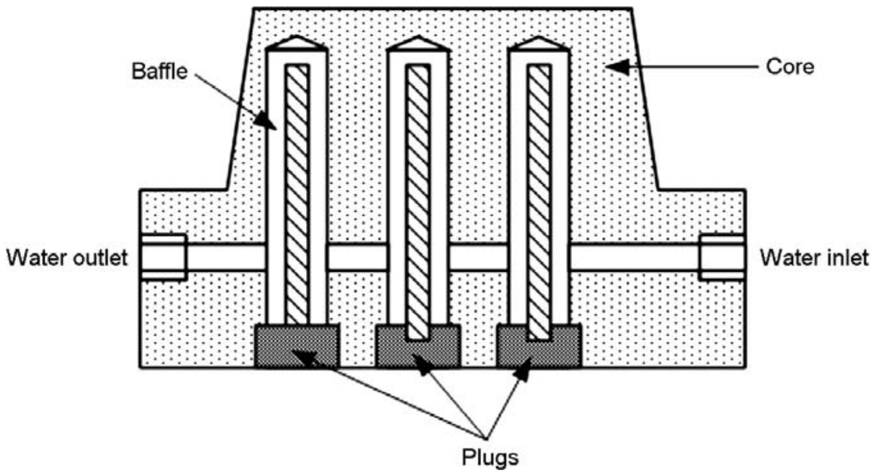


Figure 11.4 Baffle design

11.5.1.2 Fountain System

Fountain designs are more efficient than baffle systems because the cooling circuitry is usually in ***parallel*** not ***series***. This gives a more uniform temperature control over the entire moulding area. With this design a tube is fitted into the centre of a hole in the punch or core pin.

Fountain designs are not restricted to multiple-array use in a single large core but may also be used to cool core pins in individual cavities.

Figures 11.5 and 11.6 show constructional details for a typical fountain design and the system used for an array in a larger punch.

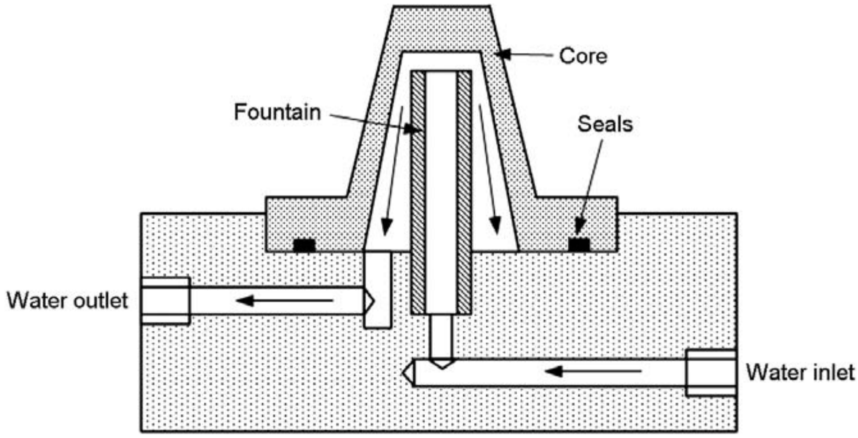


Figure 11.5 Single fountain design

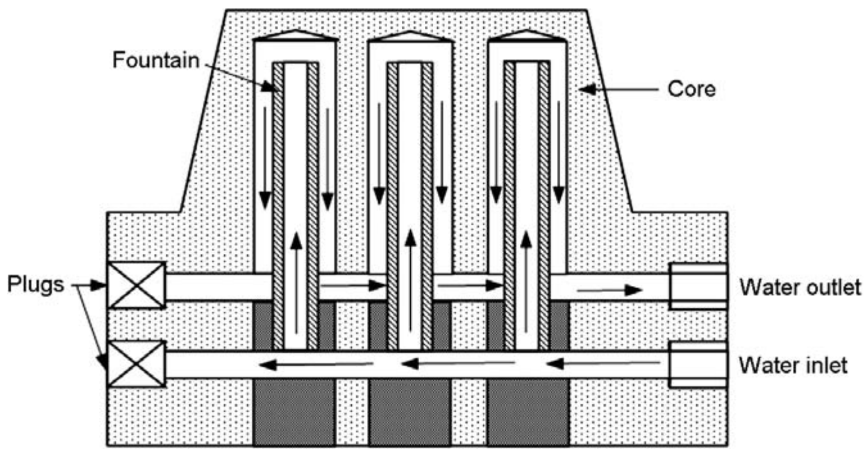


Figure 11.6 Multiple fountain design

11.5.1.3 Angled Hole Design

As the name implies, this method consists of drilling holes at angles in larger punches so that they intersect each other to create a path for the cooling fluid to flow through. The main difficulty with this method is that the drilled holes must intersect each other on a full diameter. This becomes increasingly difficult to achieve as the length of the drilled holes increase, owing to the tendency of the drill to wander off course. In practice the length of the holes is restricted to a maximum of about 150 mm to ensure full-diameter intersection.

With this design, there is a danger that swarf from the drilling operation may be trapped at the intersections of the holes, thus restricting the flow of coolant through the core. It is good practice to check the waterways to make sure they are clear of any obstructions before running the tool in production.

Small-bore deep holes may be machined with EDM techniques. This is a more expensive option but is well worth the cost for installing cooling channels in smaller, more intricate cores.

Figure 11.7 shows a typical angled drilled hole design used in larger cores and punches.

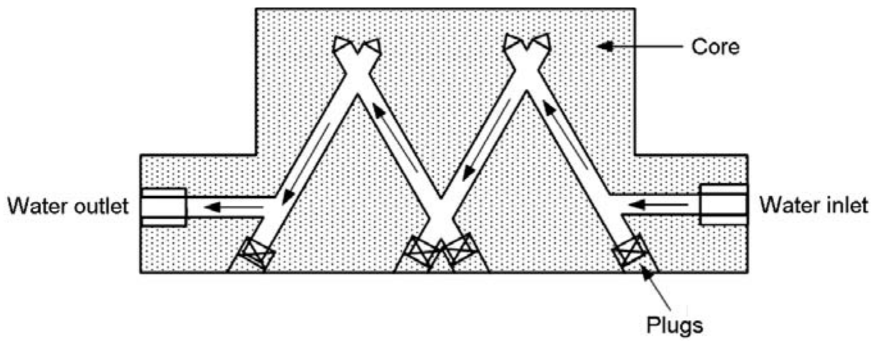


Figure 11.7 Angled hole design

11.5.1.4 Stepped Hole Design

This is an easier system for toolmakers to make than the angled hole design, as it is not so difficult to match up the drilling. Where drilled holes break through into the punch surface they have to be plugged and then brazed or welded over. This witness is then ground away to match the punch form. ·················A problem associated with this system is that owing to the injection pressure and continued cyclic expansion and contraction, the plugs are sometimes prone to leak.

This system can cause problems where the job is of a critical appearance nature. A witness can often be seen on the moulding where the plugs are positioned, either in the form of a ring or sometimes a ***blush mark***. The blush mark effect is due to a differential cooling effect through the plug to the moulding surface, which occurs if the plug is made from a different material from the core. To avoid this, the plug should be made from the same material as the core, usually alloy tool steel. This is obviously more expensive than using a standard bronze plug but may be justified on critical appearance parts.

Figure 11.8 is typical of a stepped hole design, but more than one circuit may be used in a single punch where necessary.

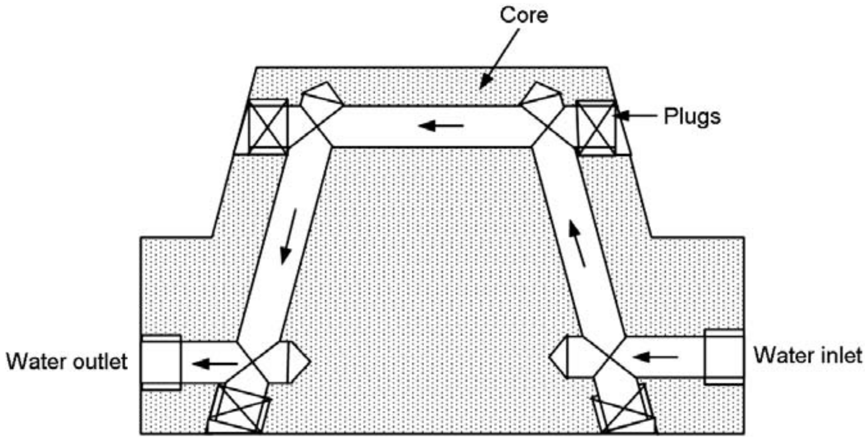


Figure 11.8 Stepped hole design

11.5.1.5 Spiral Cooling

For larger cylindrical cores above 50 mm diameter, spiral cooling systems provide more uniform and efficient cooling permitting quite good temperature control.

A variety of different designs can be used depending on the sizes of the cores and the space available. The basic design uses a channel that is machined down the outside of a centrally inserted tapered diameter and follows the path of a helix (Figure 11.9).

Seals have to be used to prevent leakage in this type of design. Where space permits, a double helix may be used to provide two cooling channels that run next to each other. The single-channel and double-channel systems are very similar to a single-start and two-start screw thread respectively. The remaining wall section of the core must also be thick enough to withstand the forces generated during injection of the polymer. Cooling channels must also be far enough away from the core surface to prevent excessive chilling of the polymer too quickly.

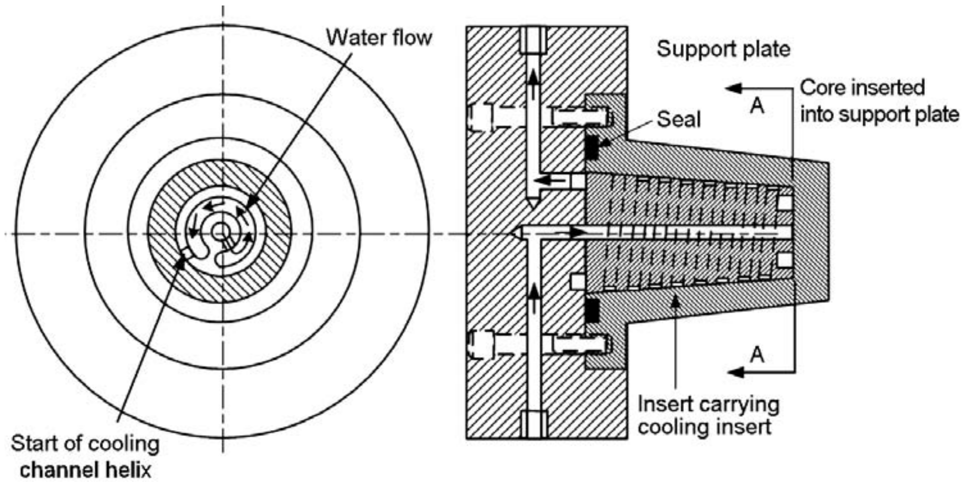


Figure 11.9 Spiral cooling insert design

11.5.1.6 Heat Rod

For smaller punches and core pins it can be difficult to fit fountains or baffles. In these cases heat rods are often used. These consist of high thermal conductivity materials that are inserted into the core pin. The material most frequently used is copper, which is both ductile and an excellent conductor of heat.

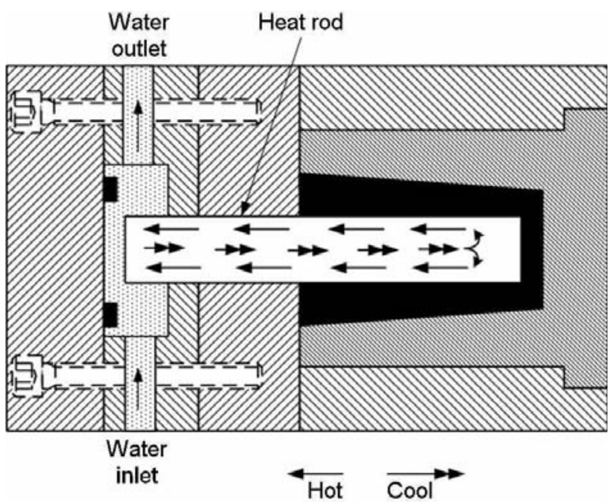


Figure 11.10 Heat rod operation

The principle of operation is that the copper conducts the heat away from the core pin into the path of a cooling fluid. It is important to ensure that there is intimate contact between the heat rod and the core pin for efficient heat transfer. The ductility of copper is very useful in this respect as it can be lightly tapped into the core pin and will spread out to give the good contact as required. Figure 11.10 illustrates the principle of the use of heat rods.

11.5.1.7 Heat Pipe

Heat pipes are also used for cooling small core pins. They act as heat exchangers just like a heat rod but operate on a different principle. A heat pipe consists of a copper tube sealed at both ends with a fine 'wick' running along the length of the inside wall of the tube. The tube is filled either with water or with a low-boiling-point alcohol. The liquid vaporises as it picks up heat from the moulding and travels to the other, cooler, end of the tube that is placed in the flow of a cooling fluid. The vapour at the cool end of the tube condenses back into fluid and is drawn back up to the hot end by capillary action. Figure 11.11 illustrates the principle.

Once again, the efficiency of heat transfer depends on the contact between the outside of the heat pipe and the inner wall of the core pin. In order to assist in this respect, a heat transfer paste is normally spread over the heat pipe before it is inserted into the core pin.

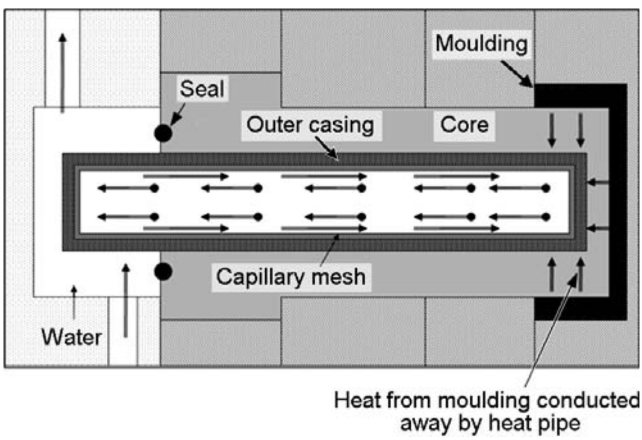


Figure 11.11 Heat pipe

Figure 11.12 gives a summary of the types of core cooling that can be used with increasing core diameters.

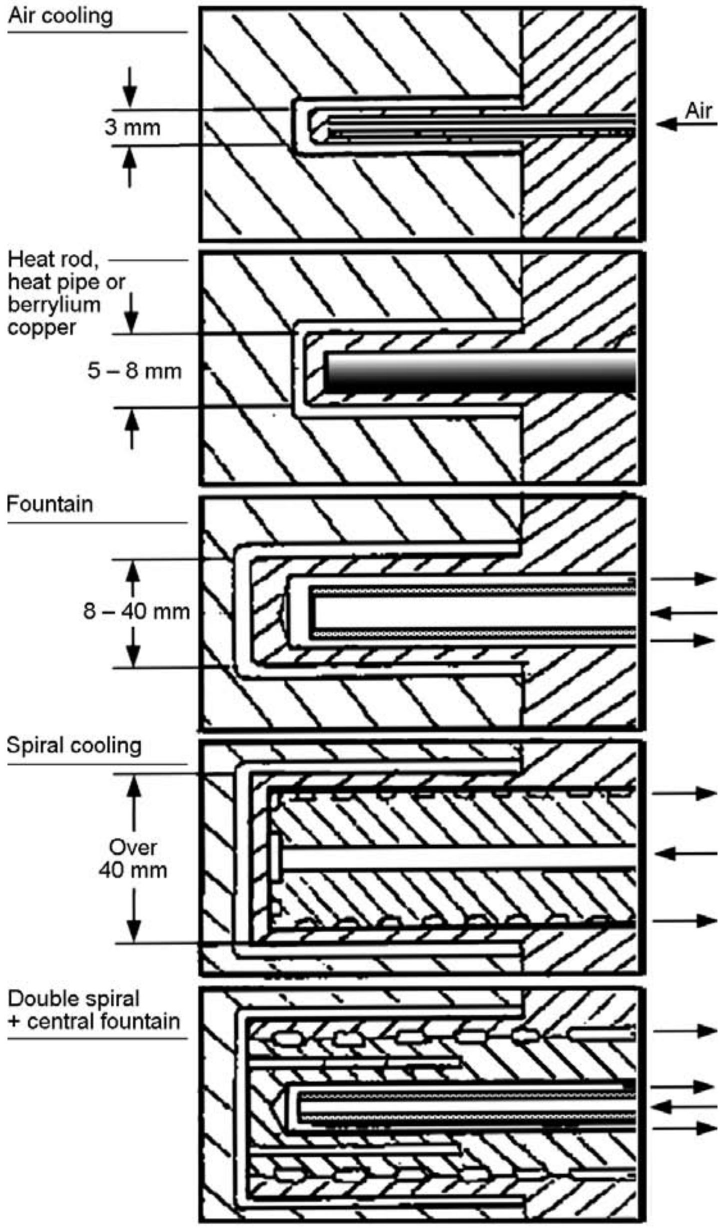


Figure 11.12 Summary of cooling designs

11.6 Cavity Cooling

It is also necessary to introduce cooling into cavity inserts wherever this is possible. On many jobs, cooling the cores without cooling the cavities can lead to nonuniform cooling of the component, resulting in lack of control.

With larger cavity inserts it may be possible to incorporate circular channel systems by using drilled holes systems like the angled hole or stepped hole designs. Alternatively, arrays of parallel straight holes may be used where the size and construction of the cavity permits. In many cases, however, more complex arrangements are necessary owing to limitations in size or complexity of cavity construction.

Depending on how the cavity has been designed, cooling may be introduced around or beneath the insert. Figures 11.13, 11.14, 11.15 and 11.16 illustrate different methods that are commonly used for cavity insert cooling.

In all these systems, O-rings or gaskets have to be used to prevent cooling fluid leaking from them. Careful attention has to be paid to sealing, as water leaks are quite common and can have disastrous consequences. Any water leaks inevitably tend to find their way into the cavities, often resulting in rust damage.

As cavity inserts are usually situated deep inside the mould, the normal method of supplying cooling fluid to them is to machine channels from the outside of the mould, which also have to be sealed. An alternative is to use copper pipe with a BSP taper thread, which passes through a clearance hole in the mould and is directly screwed and sealed into the insert.

As with most mechanical designs, the best design is the simplest one. Therefore, the design that uses the least complex construction and the least amount of sealing is to be preferred.

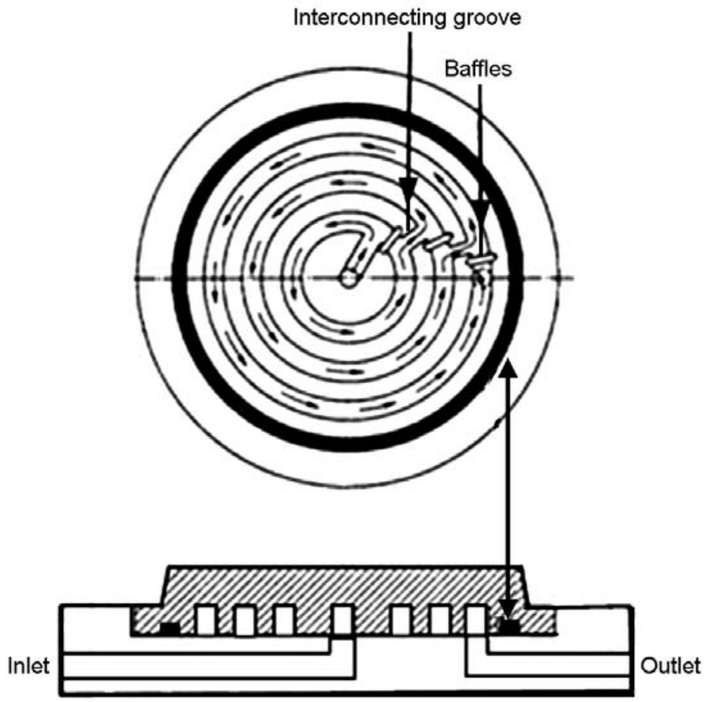


Figure 11.13 Cooling system for circular cavities

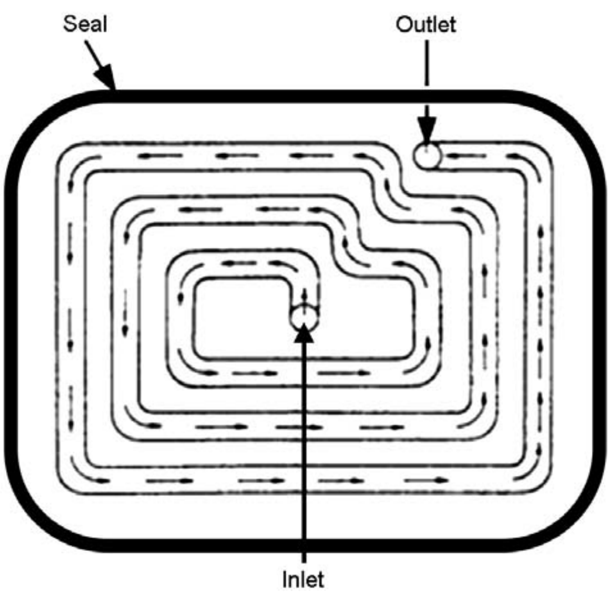


Figure 11.14 Cooling arrangement for rectangular cavities

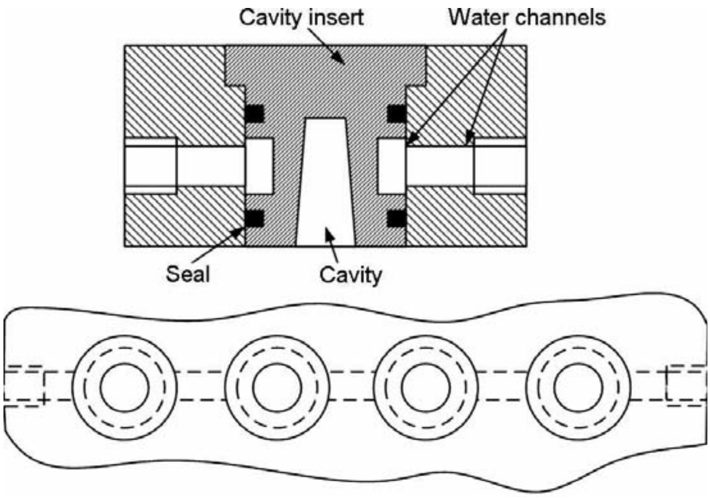


Figure 11.15 Annular groove cooling

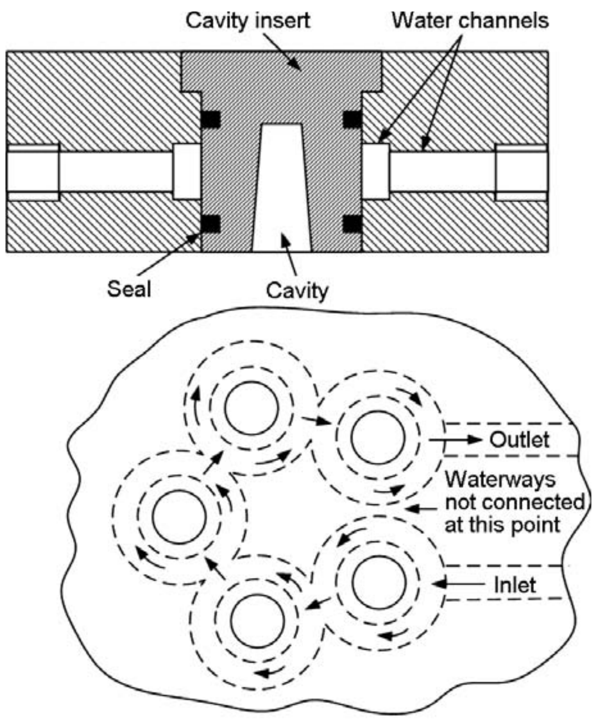


Figure 11.16 Annular groove cooling

11.7 Circuit Efficiency

There are two basic ways of arranging cooling circuitry: in series and in parallel. Both of these have advantages and disadvantages, but wherever it is possible parallel systems are preferred because of their greater efficiency. The main features of each system are as follows.

11.7.1 Series Cooling

In this system there is only one inlet and one outlet. The coolant flows through each cooling circuit in turn picking up more and more heat as the coolant flows from inlet to outlet. This system is called a ***series circuit***.

This means that there is a high temperature differential between inlet and outlet. The consequence of this is that all cavities or cores are cooled at different temperatures.

Because there is only one circuit there is a high pressure drop in the circuit, but blocked cooling channels are easily detected as the coolant flow is restricted or stopped completely.

Summary

- All coolant flows through one connected circuit.
- There is a high temperature differential between inlet and outlet.
- There is a high-pressure drop between inlet and outlet.
- Any blockage in the circuit is easily identified.

Figure 11.17 shows a typical series circuit used with a baffle system.

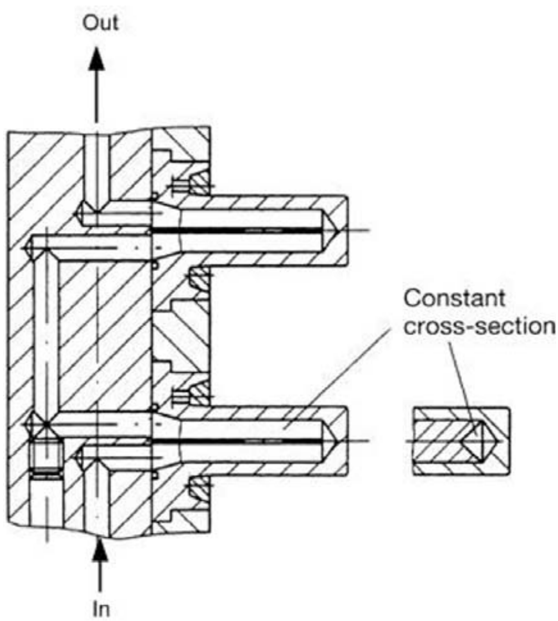


Figure 11.17 Baffle system in series

11.7.2 Parallel Cooling

In this system the coolant is simultaneously supplied to each individual cooling unit. Each core, cavity or array is supplied with coolant at the same temperature. This means that there is more uniform heat extraction from the mould, with all cavities and cores being maintained at the same temperature.

In order to obtain maximum benefit from this system it is important that all circuits within the mould should have similar lengths and diameters to preserve equal flow through all circuits.

Additional benefits from this system are that there is a lower temperature differential across the mould and a more uniform overall mould temperature. As each circuit within the mould is served independently, there is less chance of detecting any blockages. This system is called a ***parallel circuit.***

Summary

- All circuits are fed by a common supply at a similar temperature.
- There is a lower temperature differential across the mould.
- There is a lower pressure drop between inlet and outlet.
- The mould temperature is more uniform.
- Circuit blockages are less easily detected.

Figure 11.18 is typical of a parallel circuit. In this case a parallel system is feeding a fountain or bubbler design.

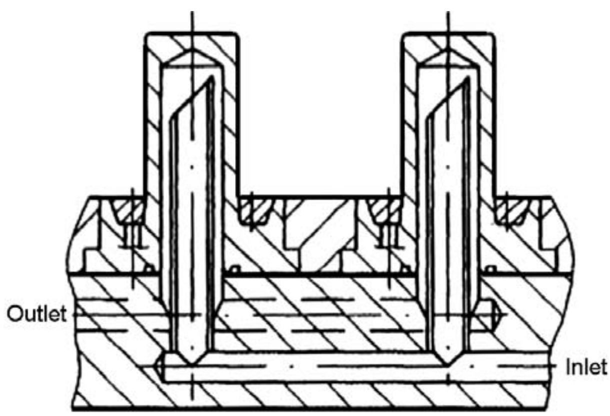


Figure 11.18 Fountain system in parallel

11.8 Beryllium-Copper Cores and Cavities

There are occasions when cores and cavities may be difficult to cool by any of the methods so far described. There are two principal reasons for this:

- Long, slender, round core pins that cannot be cooled owing to the difficulty of incorporating fountains or heat rods or heat pipes in them.
- Cavity inserts or core inserts that have complex constructions that prohibit conventional cooling techniques.

In the first case it is possible to construct the entire core pin from beryllium-copper, albeit with a loss of mechanical strength. However, it is quite possible to increase the beryllium content to 3–5% or more to increase the strength to around 75% of that of alloy tool steel with induction hardening.

This is often the only way these types of cores can be cooled satisfactorily in production. In fact they will permit much faster cooling cycles than would alloy tool steel. Note, however, that the normal beryllium content of beryllium-copper is around 2.7%, so the standard material may not be able to be used. The specification should be discussed with the manufacturer of the beryllium-copper in conjunction with the toolmaker.

Cavity inserts can be made from this material with great success and perform well in production if reasonable care is taken. In this case the material may be machined or cast by a specialist casting company. Again cooling cycle times are considerably improved.

It must not be forgotten that, when using this material, provision must be made for removal of the heat from it. Therefore, part of the cavity or core must be in contact with a suitably placed water-cooling channel (like the heat rod previously described).

11.9 Factors Affecting the Cooling Cycle

Although we have to cool the moulding in order to make it solidify, it can be safely ejected at a suitable temperature that is normally well above ambient. The temperature at which a moulding can be safely ejected depends upon a number of factors, notably:

- The part geometry
- The wall sections
- The material
- The type and size of the gate and runner
- The mould material

11.9.1 Part Geometry

The shape and nature of the part can often influence the length of the cooling cycle. If the moulding is complex with fragile, thin section features, premature ejection may cause distortion or even breakage. Such components often need longer cooling cycles, so that the tool acts like a jig, supporting the shape until it is stable enough to be ejected.

With some crystalline engineering materials, the natural crystalline structure must be able to form. If the material is frozen before this takes place, the material quality will be impaired, as previously discussed. In order to prevent this, heat must be supplied to the tool, rather than taken away from it. With such materials, it is very important that sufficient time is given for the material to achieve its preferred natural crystalline structure to preserve the physical properties of the material.

11.9.2 Wall Sections

The thickness of the wall sections will also influence the cooling cycle. Thick wall sections require prolonged cooling cycles, as they can remain molten for a considerable time. They will influence thin sections adjacent to them and this situation often leads to distortion or warpage.

It is both desirable and good design practice to make sure all wall sections are of a reasonable size. Not only will excessively thick sections require extended cooling cycles but they can also exhibit unsightly sinking and voiding.

11.9.3 Moulding Material

The type of moulding material has a direct influence on the cooling cycle. Materials with a high ***specific heat*** value will take longer to heat up and cool down and *vice versa*. Therefore, materials with high specific heat values should warrant more effective cooling arrangements within the tool.

If this is not taken into account during the design phase, any deficiencies will be very difficult to remedy later, after the tool has been made. So the watchword here is to provide adequate cooling channels in the tool from the start.

Certain crystalline materials will, for reasons already stated, require heat to be supplied to the tool. This in turn will mean a longer cooling cycle than with other materials. Such factors should be taken into account during the estimating stage, when the component costs are being established.

11.9.4 Influence of the Gate and Runner

Sometimes it is the gate, runner or sprue that determines the cooling cycle on a cold runner tool. If any of these is thicker than the thickest wall sections of the moulding, the cycle will have to be extended until these have solidified. In this respect, hot runner tools have a distinct advantage.

Also, certain types of gates may not shear off cleanly to permit automatic de-gating if the cooling cycle is too short. Certain types of ring gates and tab gates fall into this category. Thick runner sections can be troublesome to cool and may not eject satisfactorily without substantial cooling times.

11.9.5 The Mould Material

For efficient heat removal, the cavity steel should have good thermal conductance. Most production mould tools are made from nickel–chromium alloy tool steels. These are used for their overall suitability in terms of their machineability and physical properties, but their thermal conductance is only average.

For increased thermal conductance, other materials such as copper or beryllium-copper should be used, either directly in the case of beryllium-copper or indirectly in the case of copper. Using these materials will often dramatically reduce the cooling period and they are frequently used as heat exchangers in a cooling system.

If stainless steel is being used, it should be realised that the higher chromium content will reduce the thermal conductance and therefore extra cooling will be needed.

11.10 Mould Temperature Control

For consistency of operation and moulding quality it is essential to control the mould temperature. The rate at which a moulding cools affects the surface finish, cycle times, tolerances, distortion and internal stress of the part.

In general, higher mould temperatures tend to improve surface gloss and minimise voids. On the other hand, they tend to increase the possibility of flashing and sink marks; but if the mould temperature is too low, the gate may freeze off before the moulding has filled properly.

In most cases the actual temperature used will be determined by previous experience and by a certain amount of trial and error. Table 11.1 gives guide temperatures for a range of common materials. These represent the temperature in the tool and not the temperature of the cooling medium being supplied to it. These figures offer a starting point for mould temperature but they may be refined during moulding trials. However, if the physical properties of the material are not important, different temperatures may be (and often are) used.

Table 11.1 Mould Temperatures

Material	Mould temperature (°C)
Low-density polyethylene	30–50
Ethylene vinyl acetate	25–40
Polypropylene	40–80
Nylon 6,6	85–100
Acetal	70–110
Polyvinylchloride	20–50
Acrylic	60–80
Polycarbonate	85–120
ABS	50–85
Polystyrene	55–70

High-speed moulding cycles are necessary for cheap disposable parts such as teaspoons, for example. It is usual for such parts to employ large numbers of impressions and cycles as low as 5 seconds. For single impression, very thin-walled plastic cups, cycles of 3 seconds are not unusual. In either case, very low water temperatures are used to promote rapid cooling.

11.11 Cooling Efficiency

The major factors that influence cooling efficiency are:

- The cavity material and construction
- Channel geometry
- Number of channels
- Rate of coolant flow

11.11.1 Cavity Material and Construction

If large quantities of heat need to be extracted from a tool, suitable materials must be used.

Large cavities and cores need substantial cooling; therefore, either multiple channels are needed around the cavities, or fountain coolers in the cores. Alternatively, a 2% beryllium copper alloy can be used for the core and cavity. This material can be ion implantation-hardened to give a hardness of around 30 °C.

Good-quality toolmaking is necessary for efficient heat transfer. Close fits are needed to ensure good contact between mating parts, particularly in fabricated cavities. Any gaps, however small, will insulate parts from each other and inhibit heat conduction between adjacent components.

11.11.2 Channel Geometry

The larger the surface area of the cooling channels, the greater the cooling effect will be. Channels with rough surface finishes give more efficient heat transfer than smooth ones. Rough finishes promote turbulent flow and increase transfer by a factor of 2–3.

Generally, round channels are more efficient than rectangular ones and are in most cases easier to machine. A drilled or bored finish is satisfactory unless the core is going to be subjected to potentially high fatigue stresses, in which case a smooth hole may be needed.

11.11.3 Number of Channels Required

A sufficient number of cooling channels is necessary in all moulds. These should be spaced no nearer to each other than $2D$ apart, where D is the channel diameter. Channels should not be closer than $2D$ to the cavity or core surface.

In general, as many channels as possible should be included at the design stage. If over-cooling occurs, some of these can be closed, but if not enough channels are provided it might not be possible to provide more after the tool has been made.

11.11.4 Rate of Coolant Flow

The higher the rate of flow, the better the heat transfer will be. The heat transfer will also be greater if the linear flow rate is greater than 2.5 m/s. This is the minimum rate necessary to induce the more efficient turbulent rather than laminar flow.

11.12 Coolants

The most commonly used coolants are shown in Table 11.2.

Table 11.2 Common coolants

Medium	Working range (°C)
Antifreeze (glycol/water)	–20 to 0
Inhibited chilled or heated water	0 to 90
Heat transfer oil	90 to 200
Electrical heating	150 to 450

11.12.1 Thermal Conductance of Metals

The thermal conductance values of common mould metals are shown in Table 11.3.

Table 11.3 Conductivities of common mould metals

Mould Material	Conductivity (W/mK)
Nickel–chromium steels	30 to 60
Stainless steel (12–18% Cr)	13 to 18
Aluminium	197
Beryllium-copper	160
Brass	94

11.13 Cooling Calculations

It is useful to be able to calculate the amount of heat required to be removed per shot, given the maximum permissible cooling cycle. In practice this cooling period will already have been established at the estimating stage before any tool design work is undertaken, and if this estimate is exceeded in production the job will not return the estimated profit. Some basic calculations will ensure that this estimated cycle is not exceeded.

11.13.1 Specific Heat

Specific heat is the amount of heat required to raise the temperature of 1 kg of material by 1 °C. The units are kJ/kg/°C.

11.13.1.1 Heat Requirements – Amorphous Materials

For amorphous materials the amount of heat required to raise 1 kg of material from ambient to melt temperature is given by:

Heat (kJ) = Specific heat (kJ/kg/°C) × (Melt temperature – Ambient temperature) (11.1)

Table 11.4 lists some common amorphous polymers.

Table 11.4 Amorphous polymers

Polymer	Melt temperature (°C)	Specific heat (kJ/kg)	Heat required (kJ/kg)
Rigid PVC·	180–200	1.05	168
Polystyrene	210–250	1.34	268
HIPS	210–250	1.40	280
ABS	210–260	1.40	308
Noryl	240–300	1.34	308
Polycarbonate	280–320	1.26	353

11.13.1.2 Heat Requirements – Crystalline Materials

For crystalline materials an additional factor has to be included. This is the amount of heat necessary to melt 1 kg of the polymer crystals at their melting point. This effect is the same as that of ice changing to water, in that additional heat is required to achieve this change of state, without any increase in temperature occurring. This effect is known as the ***latent heat.*** The units are kJ/kg.

Crystalline materials are not completely crystalline, varying between 30% and 80% crystallinity, depending on the material and the previous thermal history of the material.

Heat due to latent heat effect (kJ) = Latent Heat (kJ/kg) × % Crystallinity (11.2)

Total heat requirement = Heat required from Eq. (11.1) + Heat required from Equation (11.2)

Table 11.5 lists the thermal properties of semicrystalline polymers.

Table 11.5 Thermal properties of semicrystalline polymers

Polymer	Melt Temperature (°C)	Specific heat (kJ/kg/°C)	Latent heat (kJ/kg)	Crystallinity %	Heat required (kJ/kg)
LDPE	190–200	2.30	150	50	489
HDPE	210–240	2.30	209	80	627
Acetal	180–215	1.45	163	80	420
PP	210–250	1.93	100	75	499
PA 6	240–280	1.59	130	50	423
PA 66	275–285	1.67	130	50	491

11.13.1.3 Enthalpy Curves

The main drawback of Equations (11.1) and (11.2) is that the specific heat varies with the temperature of the material. This means looking up the specific heat value for each calculation. To simplify things, material manufacturers that allow these figures to be read directly publish enthalpy curves. A typical example is shown in Figure 11.19.

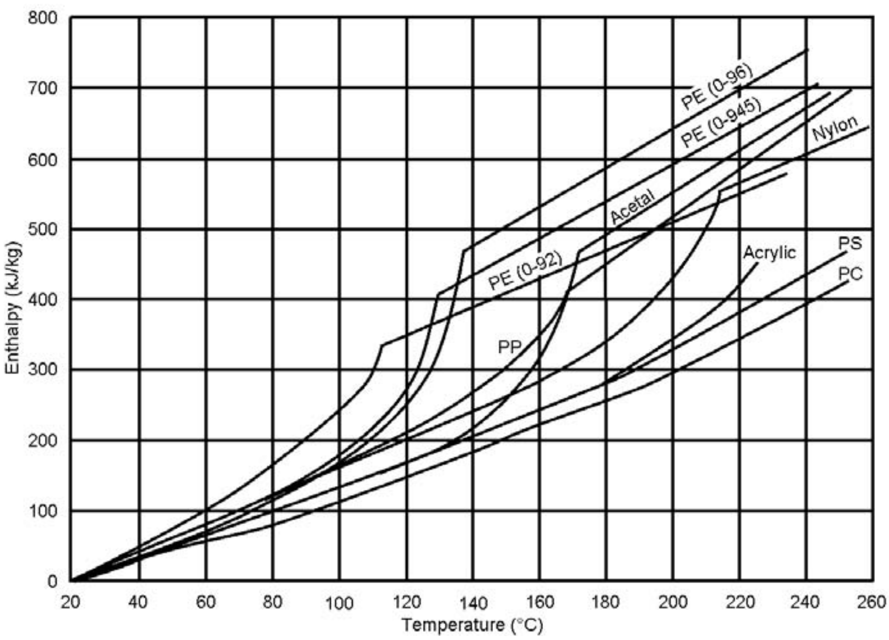


Figure 11.19 Enthalpy curves for common materials

To use these curves, first locate the material curve and then locate the required temperature on the horizontal axis. Project a vertical line up from this point to intersect the curve. From this point of intersection, project a line to intersect the vertical axis to read off the ***enthalpy***.

The object here is to determine the amount of heat Q that we need to extract per cycle. Bearing in mind our earlier comments, this quantity is the difference in enthalpy between the melt and ejection temperatures. This is written as:

$$Q = \text{Mass} \times (\text{Enthalpy at melt temperature} - \text{Enthalpy at ejection temperature})$$

or

$$Q = M \times [\text{Enthalpy}(T_m) - \text{Enthalpy}(T_e)] = M \times (H_m - H_e)$$

where:

M = the shot mass in kg

T_m = material melt temperature in °C

T_e = moulding ejection temperature in °C

H_m = enthalpy at the material melt temperature in kJ/kg

H_e = enthalpy at the moulding ejection temperature in kJ/kg

The cooling capacity Q' required is then this value divided by the moulding cycle C (in seconds), i.e.,

$$\text{Cooling capacity } Q' = \frac{M \times (H_m - H_e)}{C}$$

For maximum cooling efficiency there should be a difference of 5 °C between the cooling inlet and outlet temperatures. This is a result that has been established by research experiments.

The specific heat of water is 4.19. Therefore, it takes 4.19 kJ of energy to increase the temperature of 1 kg of water by 1 °C. Hence to raise it by 5 °C we would need 5 × 4.19 = 20.95 kJ.

The volumetric flow of water required to remove the heat in the mould is given by:

$$V_f = \frac{Q}{20.95} \text{ kg/s}$$

$$\frac{Q}{20.95} \text{ litres/s (since 1 litre of water weighs 1 kg)}$$

We also need a linear flow rate of 2.5 m/s to promote turbulent flow, hence the volumetric flow can also be expressed as V_f = 2.5 × cross-sectional area of channel. If the channel is circular we can write this as:

$$2.5 \times \frac{\pi d^2}{4} = \frac{Q}{20.95} \quad \text{(Note that } d \text{ is in metres here)}$$

Transposing for *d* gives

$$d = \sqrt{\frac{76.37 \times Q}{\pi}} \text{ mm (converted to mm for convenience)}$$

11.13.1.4 Example

The details of a mould tool are as follows:

No of impressions:	4
Material:	Polypropylene
Cycle:	12 s
Shot weight:	45 g
Melt temperature:	240 °C
Ejection temperature:	40 °C

From the enthalpy curves, the enthalpy at 240 °C is 650 kJ/kg and at 40 °C is 40 kJ/kg.

Note: Be careful with the units – the mass is in kg and not g. Hence,

$$Q = \frac{\frac{45}{1000} \times (650 - 40)}{12} = 2.287 \text{ kJ/s}$$

and

$$d = \sqrt{\frac{76.3 \times 2.287}{\pi}} = 7.45 \text{ mm}$$

This would, of course be rounded up to the next standard drill size; say 8 mm in this case.

Using $V_f = Q/20.95$, the volumetric flow = 2.287/20.95 = 0.1092 litres/s.

Knowing the diameter of the channel allows us to calculate the maximum length of the channel by using ***Poiseuille's*** equation:

$$F = \frac{P\pi r^4}{8\eta L}$$

where:

F = flow rate in m^3/s

P = pressure in Pa

r = radius of channel in metres

η = viscosity of coolant in Pa-s

L = length in metres

We can transpose this equation to obtain:

$$L = \frac{P\pi r^4}{8F\eta}$$

We can now calculate the maximum length of cooling channel for an 8 mm drilled hole. Assuming a pressure of 70×10^3 Pa and knowing that the viscosity of water is 0.001 Pa-s, substituting these values into the equation gives:

$$L = \frac{70 \times 10^3 \times \pi \times (4 \times 10^{-3})^4}{8 \times 1 \times 10^{-3} \times 1.092 \times 10^{-1} \times 10^{-3}} = 64.44 \text{ m}$$

Clearly this length would be long enough for any mould tool. However, if the pressure dropped to 1000 Pa, this length would reduce to 0.92 metres. This value may be too small for many larger moulds.

Alternatively, if we wish to calculate the maximum diameter of a channel given a maximum length, Poiseuille's equation can be transposed to give us this:

$$r^4 = \frac{8F\eta L}{P\pi}$$

$$\Rightarrow r = \sqrt[4]{\frac{8F\eta L}{P\pi}}$$

$$d = 2 \times \sqrt[4]{\frac{8\pi\eta L}{P\pi}}$$

Note: Be careful with the units: length L is in metres not mm.

Wherever long channels are needed, it is advisable to use a delivery hose of larger bore than the cooling channel diameter in the mould tool.

11.14 Pulsed Mould Cooling

Everything we have discussed so far has been based on the coolant being pumped through the mould tool continuously. Although this approach is used almost universally, it is not the most efficient as research has shown that a substantial amount of energy can be lost in this way.

Continuous cooling means that the cavity is being cooled during the injection period as well as the cooling period. This means that the polymer has to be injected at higher temperatures and pressures than it otherwise would.

If cooling took place only during the time the moulding was cooling after the injection phase, cavities could be filled at lower temperatures and pressures. The only disadvantage of this is that proportionally more cooling must be provided during the shorter cooling phase. This in turn means that more attention needs to be paid to the design of the cooling system to achieve maximum efficiency. However, this disadvantage is far outweighed by the overall energy savings that this technique achieves.

The increased cooling can be achieved by using lower coolant temperatures, but where this is not possible the cooling channels can be increased in size to obtain the same effect. To demonstrate the effect of this, we can use the previous example.

In the previous example we will assume that the injection phase is 2 seconds and the closing time is 3 seconds, leaving a cooling phase of 7 seconds. Then:

$$F = \frac{\frac{45}{1000} \times (650 - 40)}{7} = 3.921 \text{ kJ/s}$$

and

$$d = \sqrt{\frac{76.3 \times 3.921}{\pi}} = 9.76 \text{ mm}$$

As expected, this shows that more heat must be extracted from the mould per second, and to achieve this we need larger-diameter cooling channels, say in this case 10 mm. This possibly introduces a further disadvantage, in that larger-diameter channels may be more difficult to incorporate in the mould tool. However, the big advantage is that that a lower melt temperature may be used, resulting in reduced energy costs.

A bonus is also achieved in terms of the length of the channel. The larger-diameter channel allows a greater length to be used. In this case, if we substitute a 10 mm diameter channel in Poiseuille's equation we get:

$$L = \frac{70 \times 10^3 \times \pi \times (5 \times 10^{-3})^4}{8 \times 1 \times 10^{-3} \times 1.092 \times 10^{-1} \times 10^{-3}} = 171.81 \text{ m}$$

Clearly we would never need a length anywhere near this, but the principle is clearly demonstrated. For many larger mouldings, the value of *Q* can be quite high. In these cases, the calculations confirm that increasing the channel diameter does not pose a problem.

11.14.1 Selective Pulsed Cooling

This is a method of selectively cooling the cavity areas of a mould by supplying coolant to the cavities only when needed. Probes are inserted into the cavity to monitor the surface temperature of the moulding.

Coolant is supplied if the surface temperature exceeds the desired level, and conversely is switched off when it falls below this value. Figure 11.20 illustrates the principle.

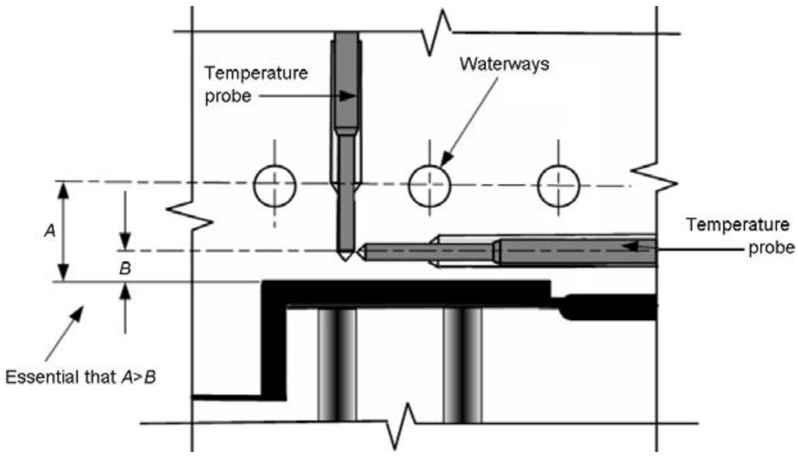


Figure 11.20 Position of probes for monitoring moulding temperature

Temperature sensors normally measure the temperature over the first 10–15 mm of their length. In order to correctly monitor or control injection moulds it is necessary to locate the sensor closer to the moulding surface than the cooling channels, as shown in the diagram. This is essential to avoid monitoring or controlling the mass of the mould and not the surface of the moulding.

This method of cooling has only recently been introduced following extensive development, mainly in the USA. It is clearly more expensive to incorporate this system in mould tools, but for long-running jobs it can significantly reduce cycle times and improve moulding quality.

11.15 Mould Cooling Variables

Adequate mould cooling is a vital factor in injection moulding. With inadequate or badly designed systems the quality of the moulding will be adversely affected. Without sufficient provision for cooling, cycle times will increase, lowering the production rate and thus increasing manufacturing costs.

The design of the cooling system has to take into account the widely different thermal properties of polymers. As we have seen, specific heat capacity and melt flow behaviour will vary markedly and, in this respect, the cooling system should be tailored to the polymer used. The greater the ***specific heat capacity*** of a polymer, the greater the amount of cooling required.

Large cavities and cores will absorb correspondingly large quantities of heat and will need substantial cooling. The cooling effect should be at a maximum where the moulding is the hottest or where large sprues and runners are used. Other critical areas to look at are:

- Restrictions to polymer flow, such as gates or where small sections feed larger ones. In both cases the polymer temperature will rise owing to such restrictions. The polymer will also experience a shearing effect at the gate areas that also leads to hot spots.
- Thick wall sections, protruding bosses, intersecting wall sections and similar features are all potential trouble spots. Very thick wall sections should be cored out to avoid sinking, voids and excessive cooling times.
- Particular attention should be paid to delicately fabricated cavity or core designs. The cooling arrangements must be a major consideration in such cases. If such designs will not permit the inclusion of water channels, then cool pins or heat pipes should be used to conduct the heat away to suitable water-cooling channels.

11.16 Summary

- Adequate mould cooling is essential for economic cycle times and part quality.
- Wherever possible, cores and cavities should incorporate cooling channels.
- If part quality is important then semicrystalline engineering-grade materials will require mould heating rather than cooling.
- If stainless steel is being used for cores or cavities, more cooling will be needed owing to the poorer thermal conductivity of the material.

12 Undercut Injection Mould Tools

12.1 Introduction

Vast numbers of injection mouldings are produced in an ever-increasing variety of materials. Of these a very large number of components have some sort of undercut form on them. These can range from simple holes and projections to highly complex undercut forms that require more demanding design solutions and toolmaking skills.

Whatever the application or part complexity, the mould design and construction should conform to the following requirements:

- It must be reliable in production.
- It must produce components of the required quality.
- It must achieve the agreed tool life.
- It must be economic.

The last point is an important one. It is easy to over-engineer some undercut tool designs with the consequence that the tool is too expensive (and possibly has an increased cycle as a result). As stated previously, the simplest design is the most elegant one, but despite this the tool must be designed and manufactured to a standard that will satisfy the first three conditions.

In other words, we require all designs to be as simple as possible but also of high design and constructional quality. In general, the simpler the design the more reliable it will be and, equally importantly, the smaller the tool, the smaller its mass will be. The smaller the mass of the tool, the faster heat may be conducted away from it, enabling faster cycles and hence reduced cost of production.

The theme of this book is to promote the fact that the simplest design is the best, and this important point must be particularly adhered to when designing mould tools for undercut components, where considerable effort must be made not to generate an over-complex design.

Therefore, this chapter will concentrate on the following key points:

- Design simplicity
- Tool reliability
- Product quality
- Designing for wide operating windows
- Minimum cycle times

The following topics keep these points in mind while discussing all the mainstream mould design solutions for moulding undercut features.

The major designs discussed in this chapter are as follows:

- Loose inserts
- Split tooling
- Side cores
- Collapsible coring
- Angled lift splits
- Angled form ejector pins
- Multistage ejection
- Radial side core designs
- Latch and finger cam design
- Jump undercuts
- Hybrid designs

A large number of practical designs are discussed and these should provide designers with a good database of ideas and design solutions for new designs of their own.

The contents of this section will also equip the non-designer with good background knowledge for assessing and commenting on undercut mould designs.

12.1.1 Undercut Components

We will define any component that cannot be moulded and ejected in a conventional two-plate tool to be undercut in some way. Many components have undercut features and some typical cases are shown in Figure 12.1.

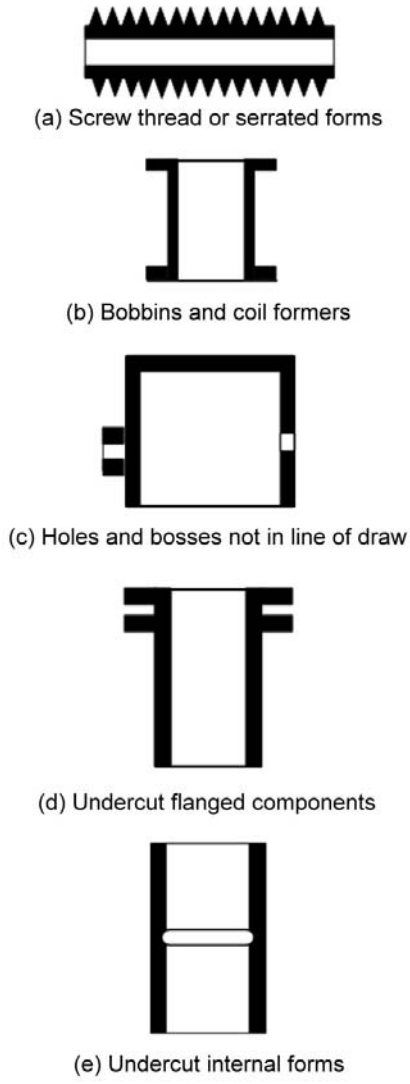


Figure 12.1 Typical undercut features

12.1.2 Basic Undercut Mould Designs

There are several basic design techniques for enabling the moulding of straightforward undercut components that have stood the test of time:

- Loose inserts
- Moulding in splits
- Use of side cores

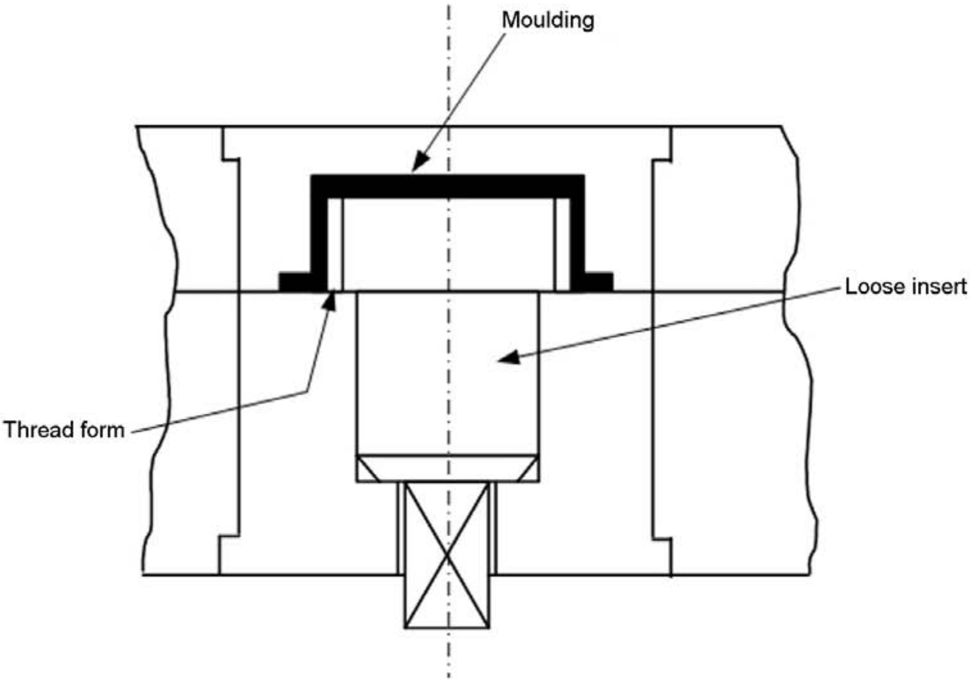
12.1.3 Loose Inserts

Not all components are required in vast quantities. For example, the aircraft industry, the military and other similar industries may only require a few dozen parts. However, to those industries, this level of production may involve capital investment of many millions of pounds.

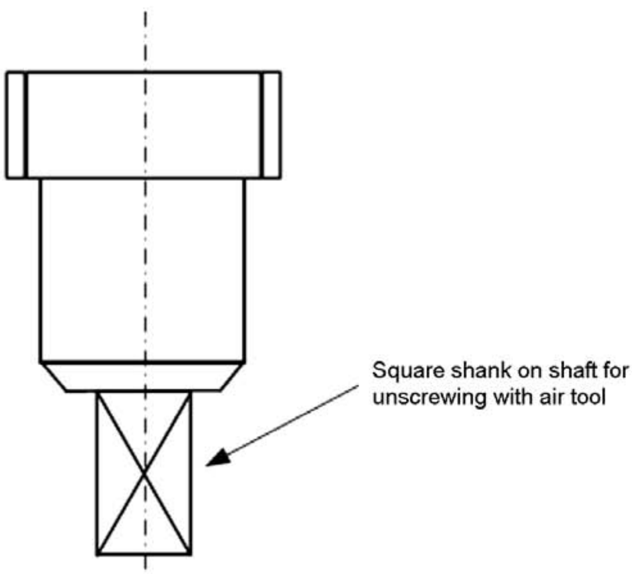
Clearly, for these quantities expensive fully automatic tooling would not only be unnecessary but also unjustified. The use of loose inserts can easily accommodate such small quantity requirements. The disadvantages of using loose inserts are:

- Longer cycle times, hence greater part cost
- Slight loss of quality due to a more variable cycle time

However, for most small-quantity applications, loose inserts will quite adequately provide satisfactory components with relatively straightforward undercuts. Most loose insert designs can be achieved by using a variation of the design for producing a screw thread shown in Figure 12.2



(a) Using loose insert to produce thread form



(b) Loose insert detail

Figure 12.2 Loose insert

Other, more complex undercuts may be produced by this method; for example, by using split cores. However, the greater the number of separate parts a loose insert has, the more difficult it is to handle. Split loose inserts also have the disadvantage of promoting early flash problems.

12.1.4 Moulding in Splits

This method of producing undercut components is very widely used. It is ideally suited to moulding a wide range of undercuts in variety of materials where the split line witness is acceptable.

The use of split tooling is generally less expensive than using alternatives such as automatic external unscrewing tooling. Splits are also very versatile and can accommodate a wide variety of undercut forms (not just screw threads). This method, therefore, should be the first-choice design for parts where split line witness is not a problem. Note that for production moulding both the splits and the angle dowels should be made from hardened alloy tool steel.

Most splits operate using:

- Straight angle dowels, or
- Offset angle dowels

12.1.5 Straight Angle Dowels

This design uses a dowel pin, located at an angle to the axis of the mould tool to create a sideways sliding motion in a pair of splits.

An example of a typical design is shown in Figure 12.3.

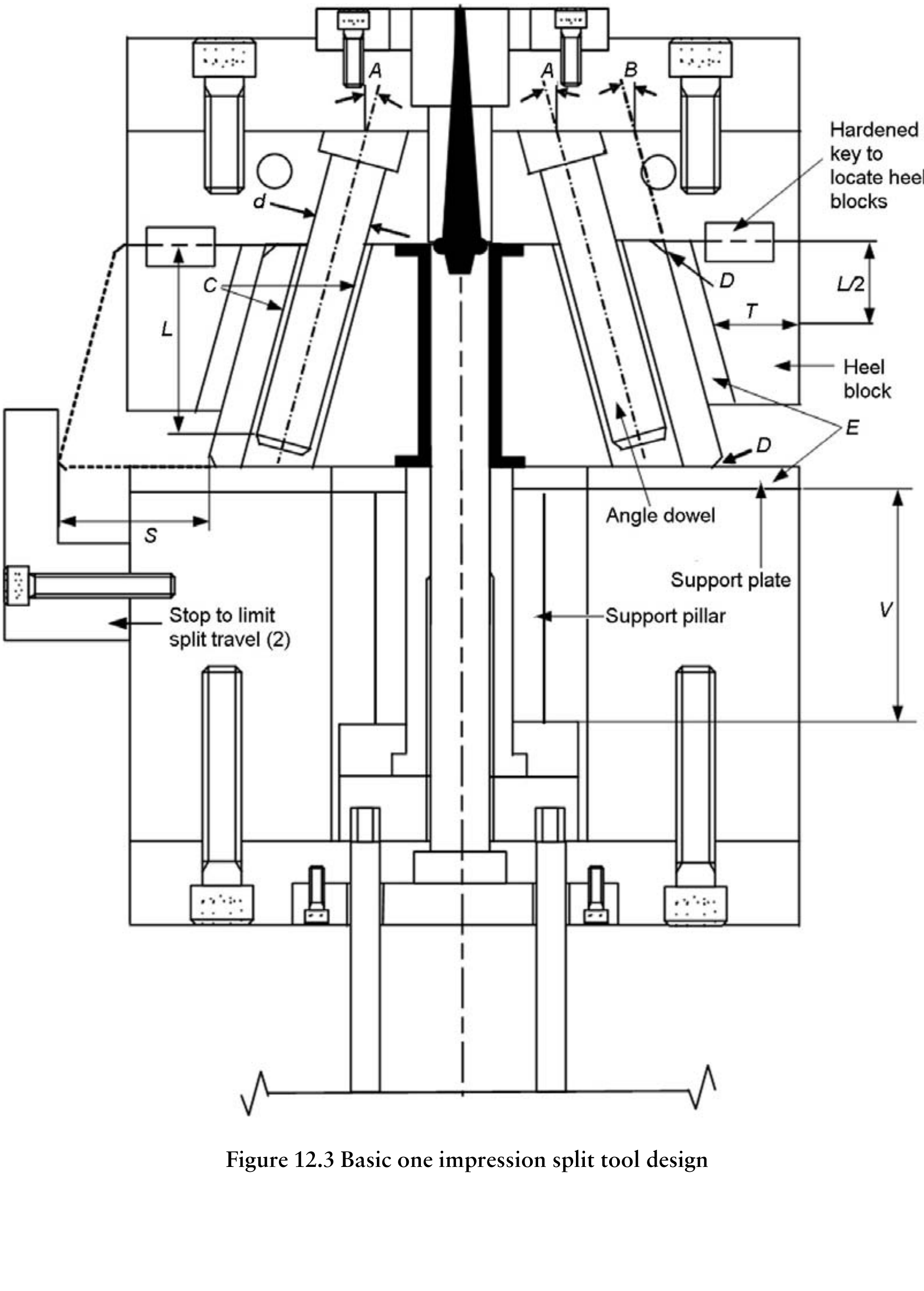


Figure 12.3 Basic one impression split tool design

12.2 Key Design Features

- Angle A must not exceed 26° for all normal purposes.
- Angle B should be 2 – 5° greater than angle A.
- Sideways movement $S = L \times \tan A$ + clearance.
- Ejection travel V must be greater than the depth of the component.
- Distance S must clear all undercut depths.
- Clearance must be provided at **C**.
- Radii must be provided at **D**.
- The angle dowels may be circular or square (for the same dimensions the square type is stronger).
- Angle dowels should be made from hardened tool steel or case-hardened steel. Tuftrided dowels are also gaining in popularity.
- Wear strips are required at **E** for long-running tools.
- The lateral force W on the split should be calculated to ensure heel block thickness T (Figure 12.4) is adequate using the formula:

  W = Lateral projected area of cavity (m^2) × 0.75 × Maximum injection pressure of machine (N/m^2)

See Chapter 19 'Deflection and Stress in Mould Components' for a full discussion of this topic.

$$T = \frac{1.5}{4.6} \times \sqrt[3]{\frac{6WL}{b}} \quad (12.3)$$

Where:

W is expressed in Newtons

L and b are in metres

T is then given in mm

An alternative rule of thumb gives $T = 1.5d$.

In all but the lowest loading conditions it is extremely important that the angle dowels are ***not*** used to lock the splits in place. This practice invariably leads to early failure of the angle dowels. It is the task of the heel blocks to provide support to the splits against the opening force due to injection pressure.

The heel blocks are, of course, screwed to the front tool plates. These are not shown for purposes of clarity of the overall design.

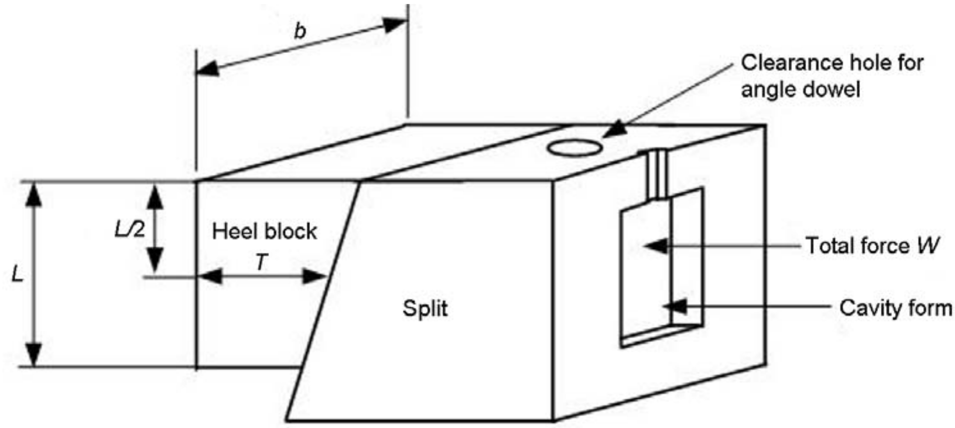


Figure 12.4 Heel block dimensions

12.2.1 Example

The following example illustrates the use of the formula (12.3)above to establish the heel block thickness (Figure 12.5). In this case, the angle dowel is 20 mm diameter (*d*). All dimensions in this equation are in metres; however, the value *T* is given in mm for convenience. The maximum injection pressure is 150 MN/m².

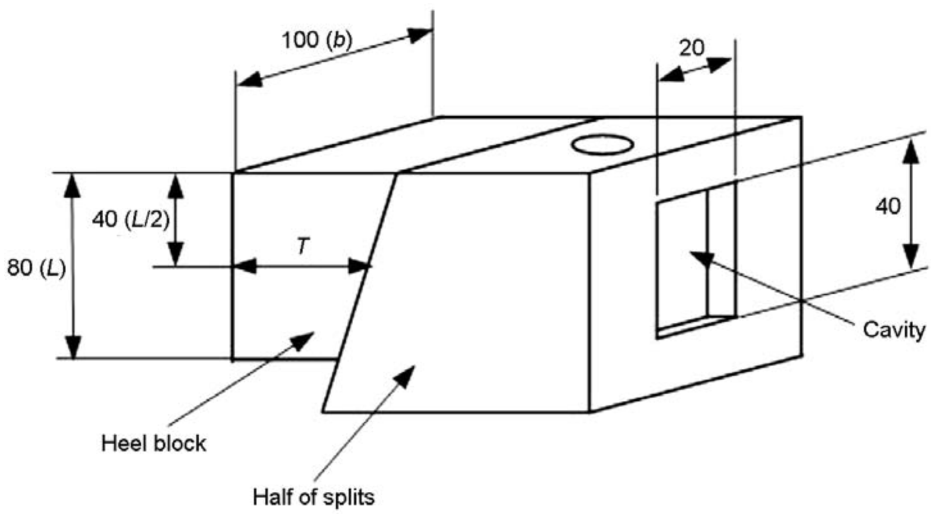


Figure 12.5 Calculating the value of *T*

Here the projected area = 0.02 × 0.04 = 0.0008 m². Hence, for the force,

$$W = 0.75 \times (150 \times 10^{6}) \times (8 \times 10^{-4}) = 6 \times 150 \times 10^{2} = 90{,}000\ \text{N}$$

Substituting the values into Equation (12.2) above, we get:

$$T = \frac{1.5}{4.6} \times \sqrt[3]{\frac{6 \times 9 \times 10^4 \times 80 \times 10^{-3}}{100 \times 10^{-3}}}$$

$$= \frac{1.5}{4.6} \times \sqrt[3]{432{,}000}$$

$$= \frac{1.5 \times 75.6}{4.6} = \text{ 24.65 mm minimum}$$

In practice this would be rounded up to standard diameter of, say, 25 or 30 mm. This compares with the rule of thumb minimum of 1.5 × 20 = 30 mm.

Note. All sizes must be converted to metres before substituting values in the formula.

Split Location

It is important that the splits are constrained to slide in an inward and outward direction only. Figures 12.6 and 12.7 show the normal construction for retaining splits in position.

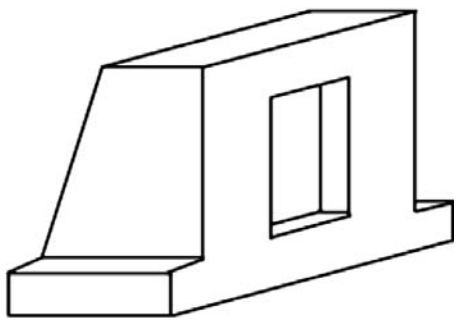


Figure 12.6 Typical design of split

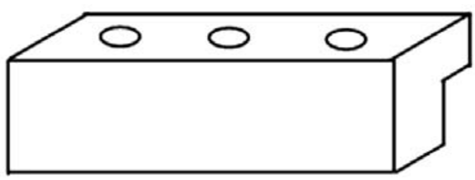


Figure 12.7 Retaining feet blocks for splits

It is also essential that the splits are held in their outermost position after the mould tool has opened. This is necessary to prevent the possibility of them moving inwards before the guide pillars have located in them when the tool closes. This can happen if the splits are in line vertically when the mould is mounted on the machine, with the possibility that the upper split can fall downwards due to gravity. It can also happen due the jerky movement of the mould during the opening or closing cycle. Figure 12.8 shows a typical design for a retaining system that is frequently used. With this design the splits move outwards until the spring-loaded ball catch locates with the machined indentation as shown.

There are other standard components that can also be used for this purpose that screw to the splits and the main tool. At least one of these systems must be used to prevent possible damage.

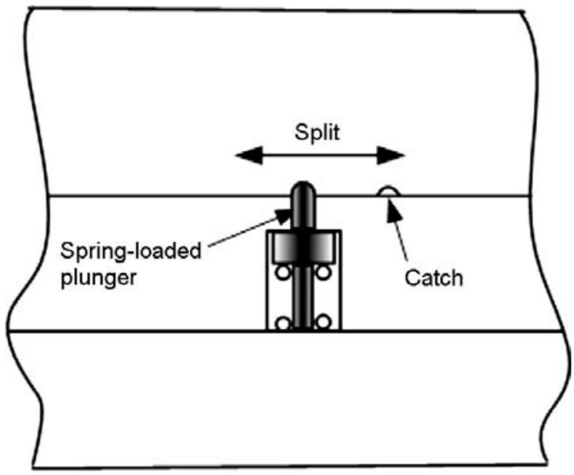


Figure 12.8 Ball catch system

12.3 Offset Angle Dowels

As the name implies, this design makes use of an ***offset*** or ***dog leg*** dowel to actuate the sliding motion of the splits. This design is used for creating some ***lost motion*** as the tool opens.

In the straight angle dowel design the side cores are forced to open immediately the tool starts to open. By contrast, the offset dowel allows the tool to open a given distance ***before*** any sideways movement of the splits takes place. Figure 12.9 shows the operation of this design.

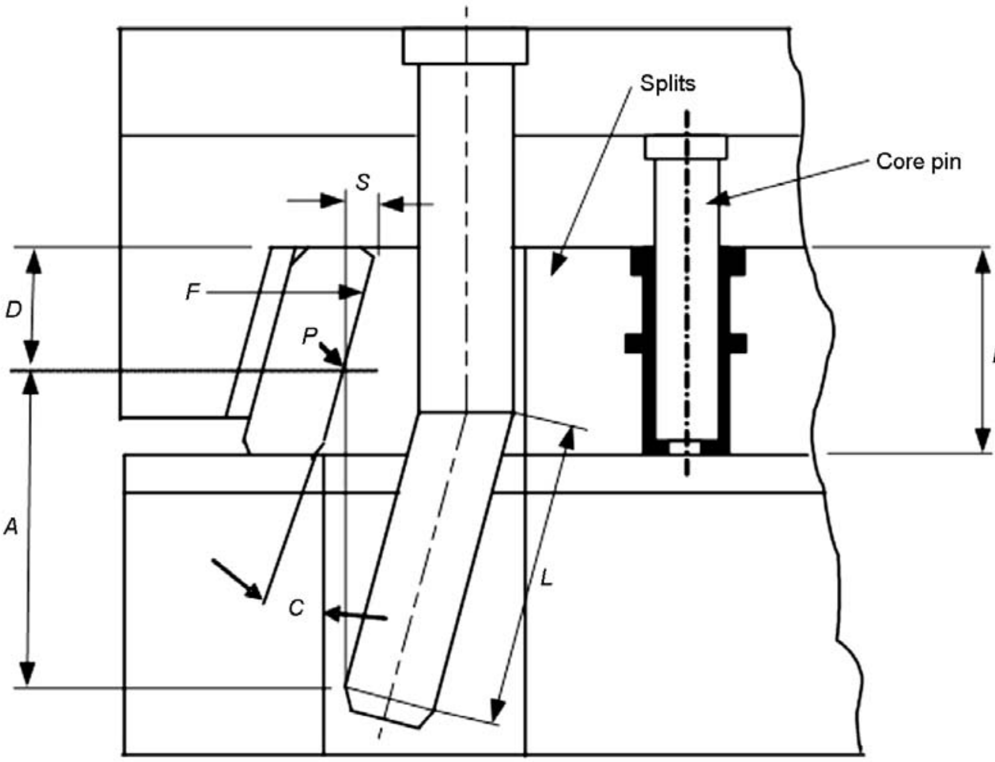


Figure 12.9 Offset dowel design

In this arrangement, the angle dowel will not contact the splits until the tool has opened distance ***A***. The dowel then strikes the splits at point **P** and opens the splits distance ***S*** after the tool has fully opened.

One of the main reasons this design is used is where a core pin is located in the fixed half of the tool. The lost motion effect ensures that the pin is completely withdrawn from the part ***before*** the splits fully open, thus preventing the part from remaining on the core pin.

Note, however, that some other means of ejection may be necessary with this type of design to prevent the mouldings 'hanging up' in the opened splits.

12.3.1 Key Design Features

- If the part cannot be guaranteed to fall freely from the splits when the tool is fully open, the part would have to be inverted and a conventional ejector used.
- Distance A must be greater than distance B.
- Distance S must be greater than the maximum depth of undercut.
- The offset dowel is usually of square section as this is easier to make.
- $S = D \times \tan C$ + clearance.
- Other design features are the same as those for the straight angle dowel design.

12.3.2 To Establish Point P

1. Draw the component in position.
2. Draw in the vertical portion of the angle dowel.
3. Draw the angled portion of the dowel such that distance L is 1.5 times the length B.
4. Project a line upwards from the bottom of the angled part of the dowel.
5. Draw in a line to represent face **F** to pass through **P** and position this such that distance $S = D \times \tan C$.
6. Continue with the rest of the construction.

Another example of the use for an offset dowel design is shown in Figure 12.10. In this case face **A** is too small to eject from and face **B** is selected for sleeve ejection.

This component has to have core pins in both halves of the tool and is moulded in splits with both core pins carrying a small undercut. The lower undercut **Y** is designed to be more severe that the upper one **X** to make sure the moulding will be retained on it.

The undercut on the lower core pin, **Y**, holds the moulding back after the splits have opened beyond the point where the external undercut form has been released. As the opening phase continues, the undercut on the upper core, **X**, is then jump-stripped from its core pin via the sleeve ejector. After the splits fully open, the lower undercut **Y** is freed as ejection takes place.

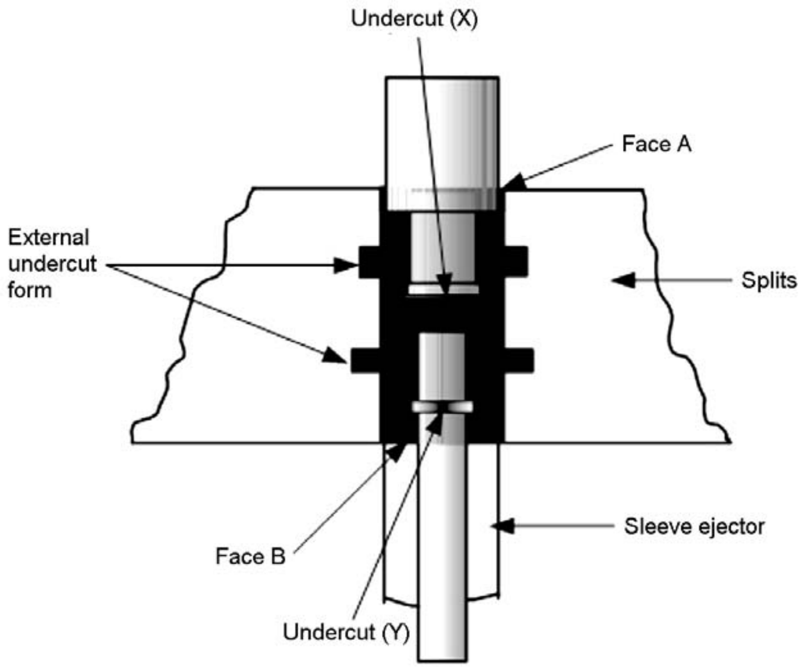


Figure 12.10 Enlarged cavity details

12.4 Use of Side Cores

12.4.1 Discussion

Not all components have an undercut form that necessitates the use of splits. Many undercuts are locally positioned on the part and can be released by means of a localised side core. Key design features are similar to those for angled dowels discussed earlier.

The component shown in Figure 12.11 is typical of such an undercut form.

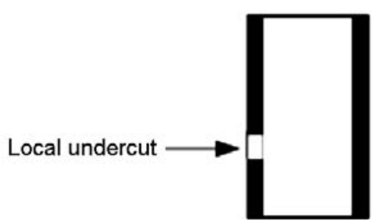


Figure 12.11 Local undercut on tubular moulding

Figure 12.12 shows the basic design method for releasing this and similar types of undercuts.

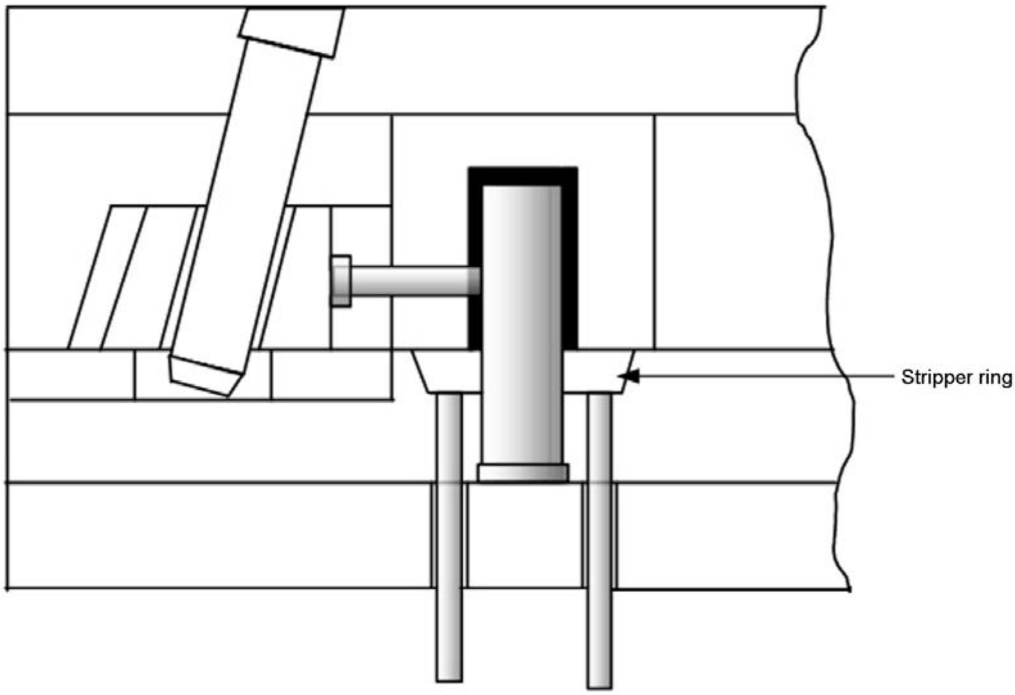


Figure 12.12 Typical side core design

12.5 Angled Lift Splits

12.5.1 Discussion

Angled lift splits designs are basically a simplified, cheaper version of the normal splits design discussed earlier for external undercuts. In most cases they are used for less critical components. Figure 12.13 shows a common design for an externally threaded component.

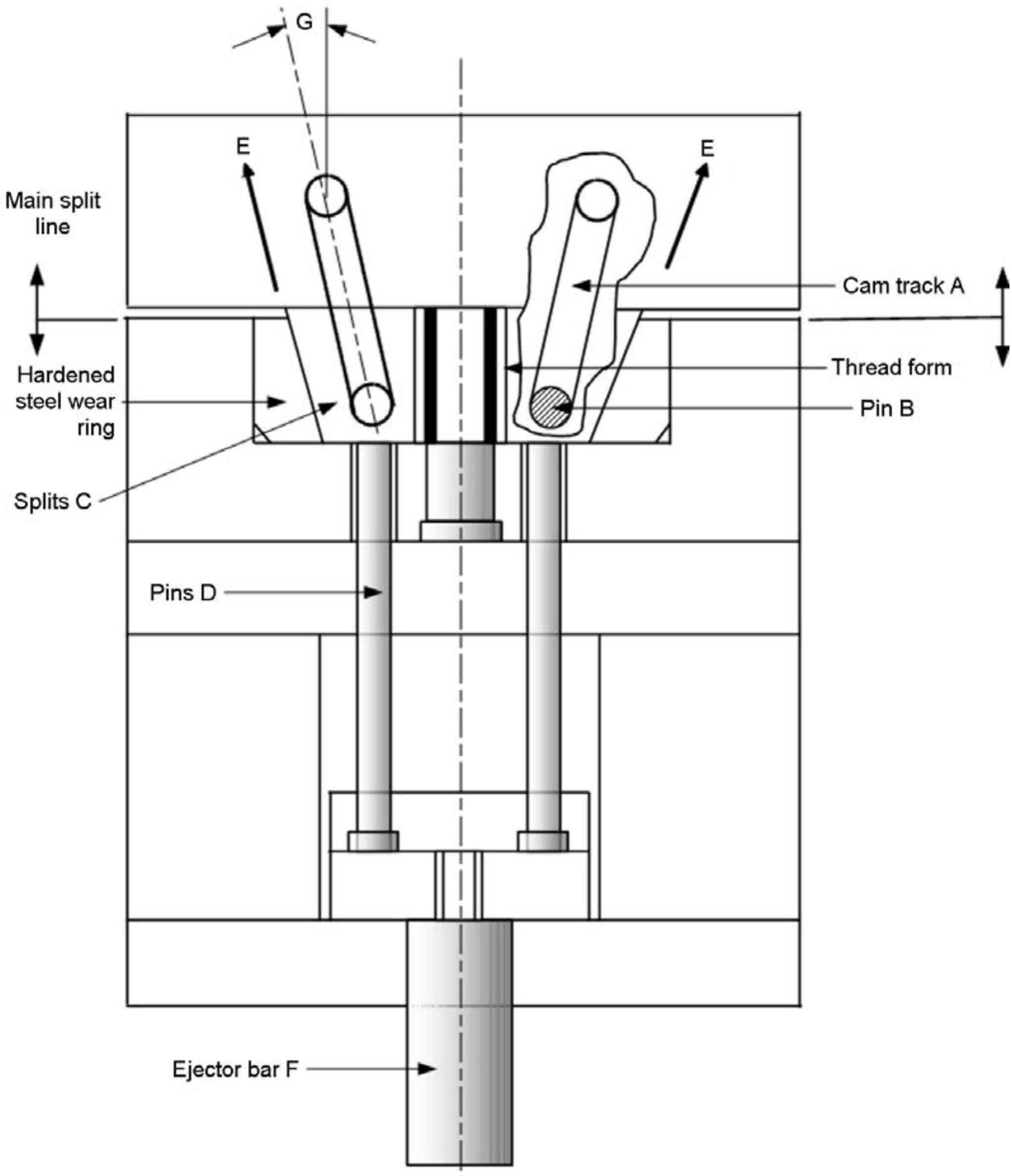


Figure 12.13 Angled lift splits

12.5.2 Description of Operation

1. The tool opens and ejector bar **F** strikes the machine crosshead.
2. As the tool continues to open, ejector bar **F** forces pins **D** forward.
3. This in turn forces the lift splits **C** to move forward.
4. As pins **B** are secured to the splits, these are forced to follow the cam track **A** into which the pins are located, thus forcing the splits upwards and outwards in direction **E**.

12.5.3 Key Design Features

- Pins **D** are ***not*** connected to the splits **C**. The pins must be free to slide laterally across the splits.
- The splits **C** must be hardened.
- A hardened wear ring is required for the splits to locate into.
- The outward movement of the splits must be greater than the maximum depth of undercut.
- The cam track plate and pins **B** must be hardened to avoid wear.
- The maximum angle *G* should not exceed 10°.

12.5.4 Formulae

Refer to Figure 12.14. The sideways movement of each split is given by

$$S = L \times \sin G$$

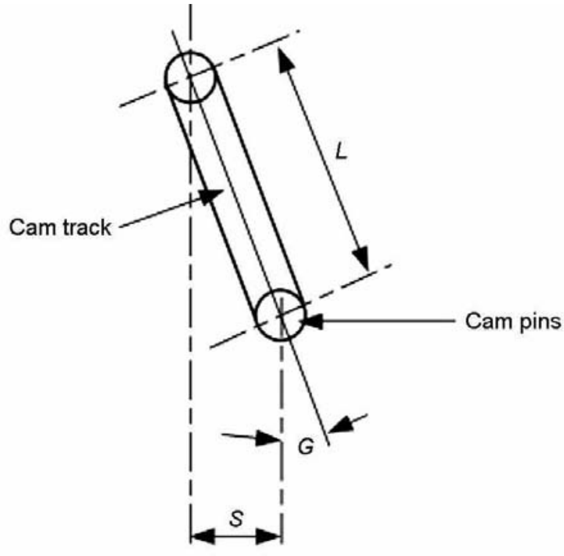


Figure 12.14 Cam track geometry

12.6 Form Pins

12.6.1 Discussion

Whereas angled lift splits are used for external undercuts, form pins are used to release local internal undercuts. Clearly, form pins are only used where the undercut cannot be jump stripped.

There are two basic designs for form pins:

- Straight action
- Angled action

12.6.2 Straight Action Form Pins

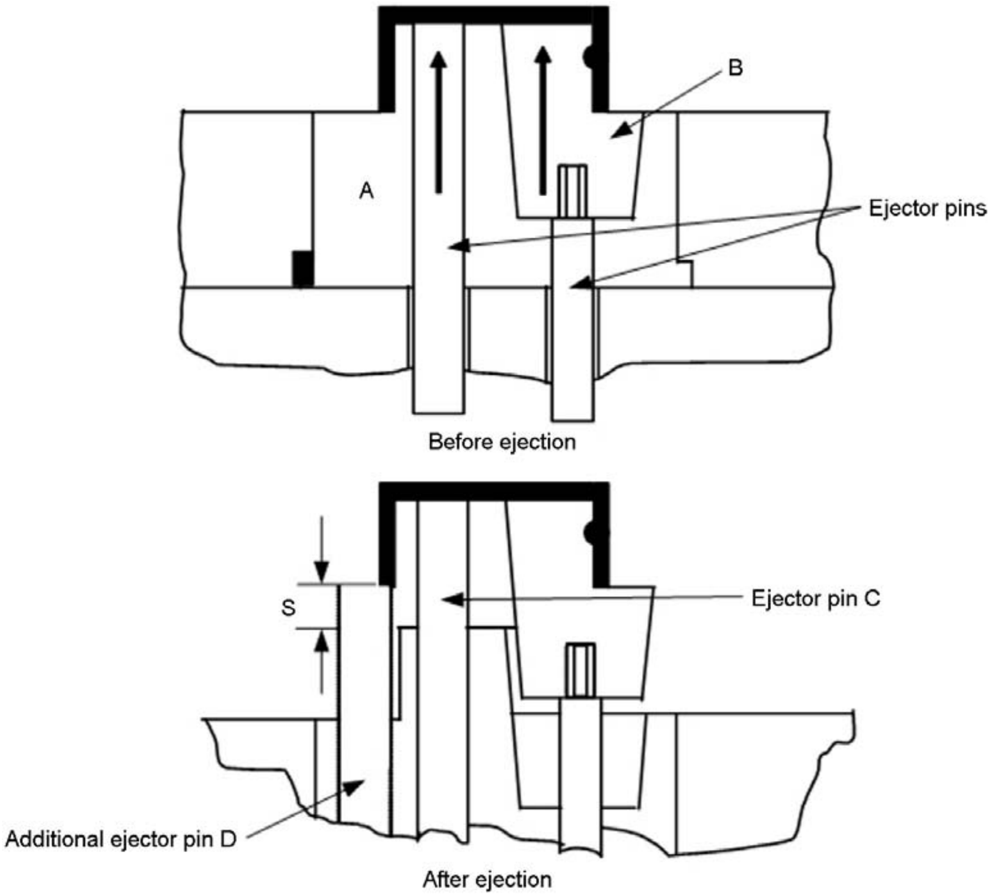


Figure 12.15 Straight action form pin

This type of pin is constrained to move parallel to the main tool axis only. No angled movement relative to the tool axis takes place. Figures 12.15 and 12.16 show the usual design for this type of action form pin.

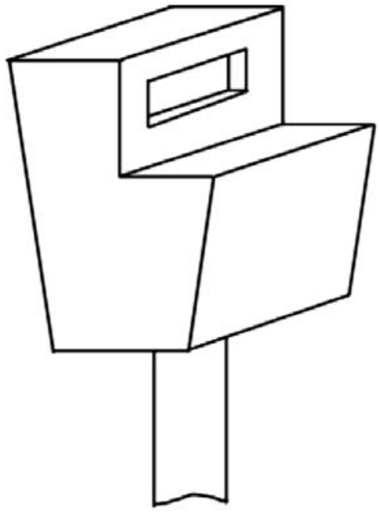


Figure 12.16 Form pin

12.6.3 Key Design Features

- Used for localised internal undercuts only.
- Lift split must locate on a taper.
- Main core **A** and lift split **B** must be hardened.
- The forward movement of the lift split should normally be sufficient to allow the moulding to be clear of the core (distance *S*).
- Unless the part will fall freely from the tool, a secondary-stage ejection will be necessary to ensure complete ejection from the tool.
- Air ejection is often used for secondary ejection purposes.

Note: In the example shown, the moulding is very likely to rest on ejector pin **C** after ejection takes place. The other possibility is that it remains firmly stuck in the undercut in the form pin, refusing to fall free.

It is bad design practice to assume the moulding will fall free in such circumstances. In any design, the designer must never design on the basis of such assumptions.

There are three options available prevent the moulding sticking in the undercut:

- Two-stage ejection as described in Chapter 10 and shown as pin **D** in Figure 12.15
- An air blast at the end of the normal ejection stroke
- Removal by robot

Two-stage or secondary ejection would guarantee that the part is positively ejected from the form pin. This is the more expensive option but the most positive.

The air blast option is by far the cheaper option but cannot be guaranteed. This option may entail several tweaks (including design changes) and possibly more polishing on the undercut before it works.

The robot option will also guarantee effective removal from the form pin but again this can be expensive and is usually restricted to high-volume production.

Whatever option is chosen the designer must be certain that the moulding will be freed from the mould and not assume that the moulding will fall free from the lift split without assistance.

12.6.4 Angled Form Pins

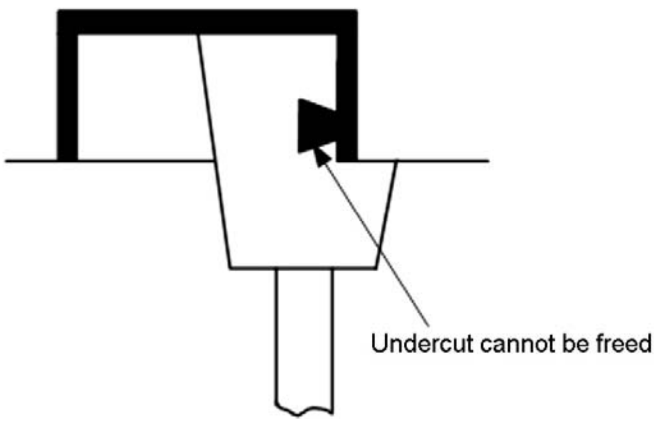


Figure 12.17 Incorrect undercut design

With a straight action form pin, there is always the danger that the moulding may not free itself from the form pin when ejection takes place. To recapitulate, there are two conditions in which satisfactory ejection may not take place with a straight action form pin, as previously discussed:

- Moulding left hanging on to form pin undercut and refusing to fall free
- Moulding left hanging on ejector pin

Non-freeing is certain to happen with a straight action form pin if the form of the undercut is as shown in Figure 12.17. Although the secondary undercut shown here is exaggerated, it can be clearly seen that it would be impossible for a moulding with this feature to fall free without a significant change to the mould design. These problems are overcome by using an angled action form pin.

12.6.5 Angled Action Form Pin

The action of this pin is very similar to the action of the angled lift splits discussed previously. The difference is that the angled form pin uses an ejector pin placed at an angle in the tool to provide the necessary sideways motion to clear the undercut.

Figure 12.18 illustrates the use of an angled form pin, which will clear both categories of undercut.

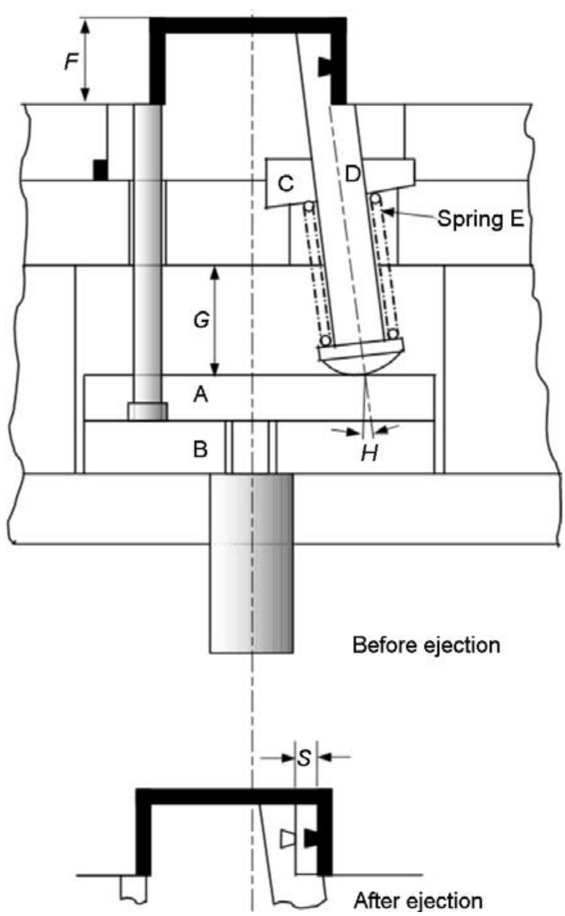


Figure 12.18 Angled action form pin

12.6.6 Description of Operation

1. As the tool opens, the ejector bar strikes the machine stop and pushes the ejector assembly **A** and **B** forward.

2. This action causes angle pin **D** to move forward at angle *H*.

3. The radiused end of **D** sliding on ejector plate **A** accommodates the sideways motion of the pin.

4. As the tool closes, spring **E** keeps **D** in contact with ejector plate **A**.

5. Spring E returns the form pin to its starting position as the ejection system is returned

12.6.7 Key Design Features

- Form pin **D**, spring pressure plate **C** and ejector plate **A** should be hardened.
- If the ejector plate assembly is relatively large, a hardened insert should be let into ejector plate **A** instead.
- Distance *G* should be greater than distance *F*.
- Angle *H* should not exceed 10° to avoid excessive wear, friction and bending stresses on the form pin.
- Distance $S = G \tan H$.
- Distance *S* must be sufficient to clear the depth of undercut.

Some variations on the design method employed at the base of the form pin are also used. One of these variations is shown in Figures 12.19 and 12.20 (Figure 12.20 is the transverse section through Figure 12.19). In this design the form pin is held underneath a retaining plate by means of a shaft. This design does not generate as much friction and wear as that shown in Figure 12.18. Consequently, the angle *H* can be greater but not normally greater than 15°.

This design is often used for longer-running jobs but is more expensive to fabricate and fit than the previous design. It is also used where the maximum amount of sideways movement is required.

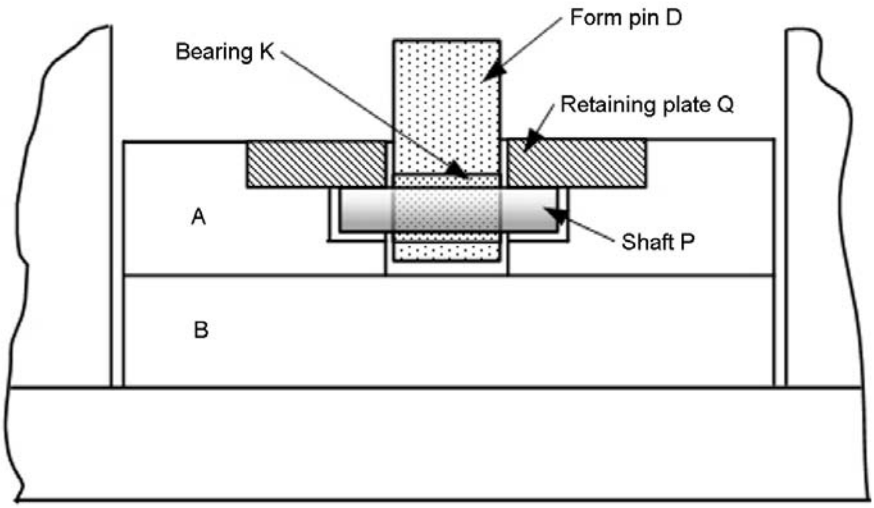


Figure 12.19 Alternative design for actuation of form pin

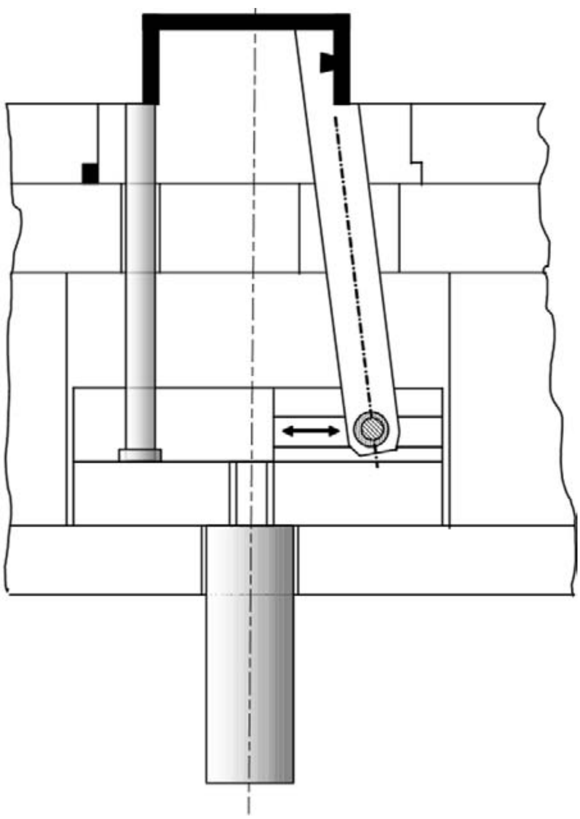


Figure 12.20 Alternative design for actuation of form pin (transverse section through Figure 12.19)

12.6.8 Description of Operation

- As the tool opens, the ejector bar strikes the machine stop and pushes forward the ejector assembly **A** and **B**
- This action causes angle pin **D** to move forward at an angle *H*.
- The shaft **P** at the end of **D** rotates beneath the retaining plate **Q** allowing the form pin to move sideways and upwards as ejection takes place, clearing the undercut.
- As the tool closes, retaining plate **Q** pulls the form pin back as the ejection assembly is returned.

12.6.9 Key Design Features

The following features refer to Figure 12.18:

- Form pin **D**, retaining plate **Q**, plate **C** and shaft **P** should be hardened.
- It is advisable to use an oil-impregnated bearing **K** (Figure 12.19) or similar to reduce friction to a minimum.
- The retaining plate **Q** is let in as a separate insert.
- Distance *G* should be greater than distance *F* as before.
- In this case angle *H* should not exceed 15° to avoid excessive wear, friction and bending stresses on the form pin.
- Distance $S = G \ \tan H$ as before.
- Distance *S* must be sufficient to clear the depth of undercut.

Note: If the core is large enough, and other design restrictions permit, it may be possible to incorporate a local internal side core.

12.7 Nonstandard Side Core Designs

Sometimes situations occur where an undercut has an unusual form that has to be approached in a slightly different way from that shown in previous designs.

In these cases, each design will have to be developed specifically to accommodate the undercut form. However, there are three type of undercut that occur frequently enough for a general analysis here:

- Undercuts at an angle to the main tool axis
- Curved undercuts
- Continuous radial undercuts

12.7.1 Undercuts at Angle to Tool Axis

Figure 12.21 shows a typical undercut that lies at an angle to the tool split line. Basically, the design is exactly the same as the side core design that is parallel to the split line except that it is rotated through the angle that the undercut makes with the split line.

In this design, the undercut lies at an angle of *H* to the split line. Hence the whole side core assembly has to be rotated through the same angle *H*.

12.7.2 Description of Operation

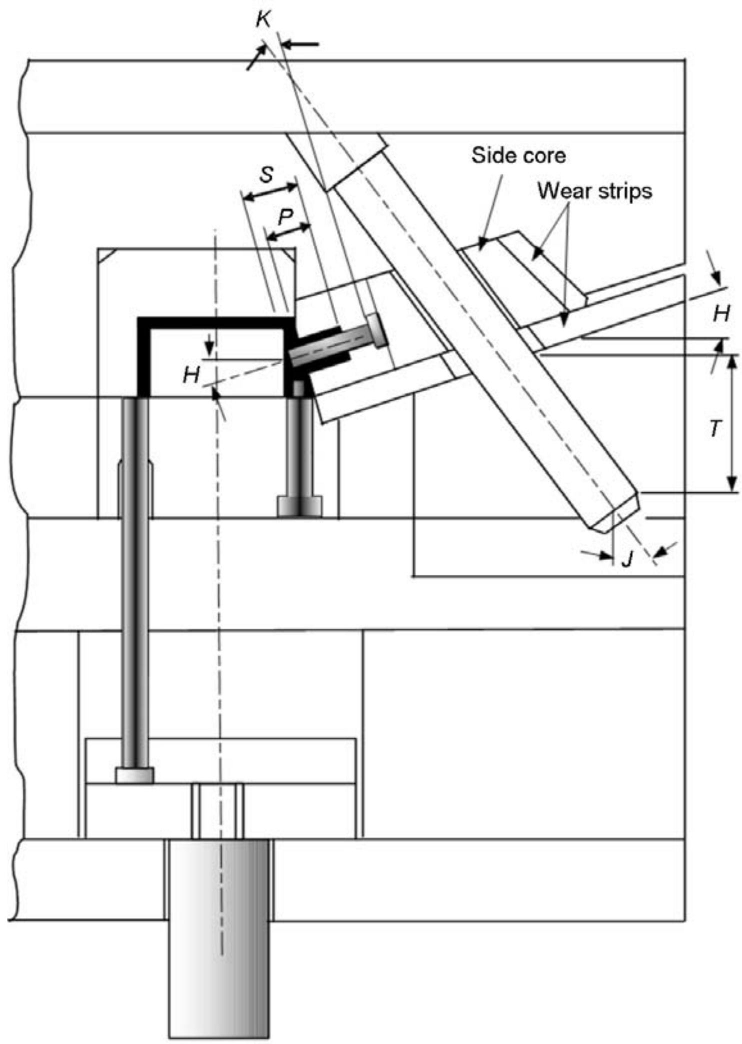


Figure 12.21 Angled undercut side core design

The operation of this design is exactly the same as for any normal side core design except that it has been rotated through the angle of the undercut.

There are two features that are undercut on this component: the hole formed by the side core pin and the boss surrounding it formed by the main side core. Clearly, the amount of movement of the side core relative to the component must exceed the longest length undercut – in this case the hole formed by the pin. To this distance, clearance must be added for safety.

12.7.3 Key Design Features

These are generally the same as those given previously, with the following differences:

- Angle K must not exceed 26°.
- Angle J = sum of angles ($H + K$).
- $S = T \times \sin J$.
- In this case S is greater than P, hence the side core must be withdrawn a distance S + clearance.

12.8 Curved Undercuts

Components with curved undercuts are often required in medical and laboratory applications. Once more, the principle of releasing them in the mould tool is exactly the same as with a normal side core. In this case, however, we have to 'bend' the side core assembly into a curve that matches the form of the undercut.

Figure 12.22 shows the tool design for a component with a curved hole. The curved nature of the part is a typical of suction devices used in operating theatres.

12.8.1 Description of Operation

1. Hydraulic cylinder **D** actuates rack **A**, which operates pinion **B.**
2. Pinion **B** is rigidly attached to the drive arm **E.**
3. As cylinder **D** operates, drive arm **E** rotates through angle H.
4. This in turn causes the side core carriage **C** to rotate through the same angle.
5. It is important that angle H gives sufficient movement to clear the core pin from the cavity.
6. When the actuating arm is in the fully open position, ejection takes place

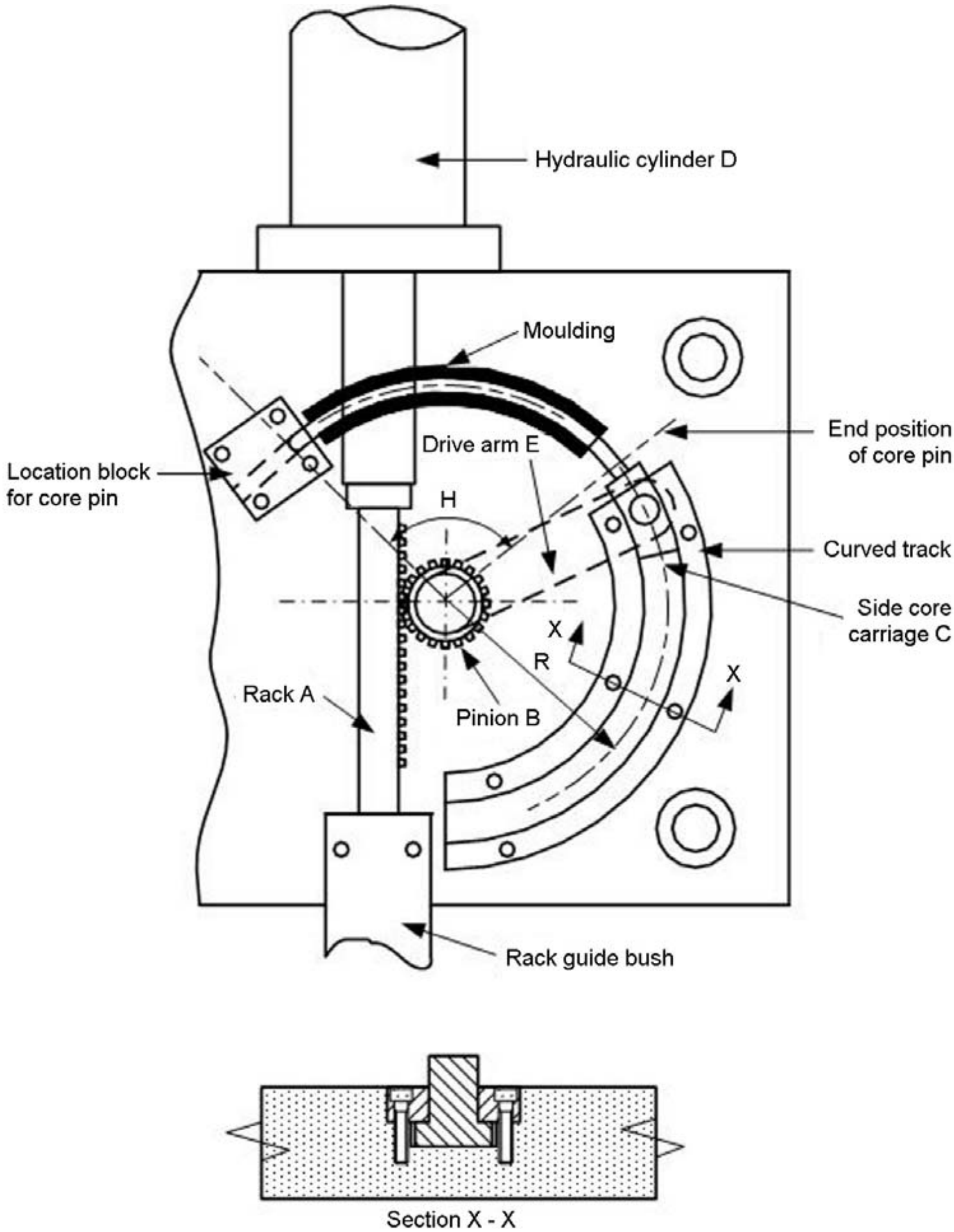


Figure 12.22 Curved side core design

12.8.2 Key Design Features

- The side core carriage **E** must follow the same curve as the core pin.
- With long core pins, the free end should be supported to prevent deflection by the polymer during injection.
- Rotation of the actuating arm must be sufficient to clear the moulding + clearance.
- Actuating arm **C** moves through angle H + clearance.
- Length of arc = $R \times H$, where H is in radians (number of degrees × π/180).

12.9 Radial Undercuts

Print wheels and similar components have raised characters all around the periphery of the part. This means that the entire circumference of the part is undercut. Figure 12.23 shows an eight-sided component with external undercuts on each face.

The part cannot be moulded in a two-plate tool because of the sunken undercuts (where a special clip has to be fitted) and no split line witness is permitted on the print wheel characters.

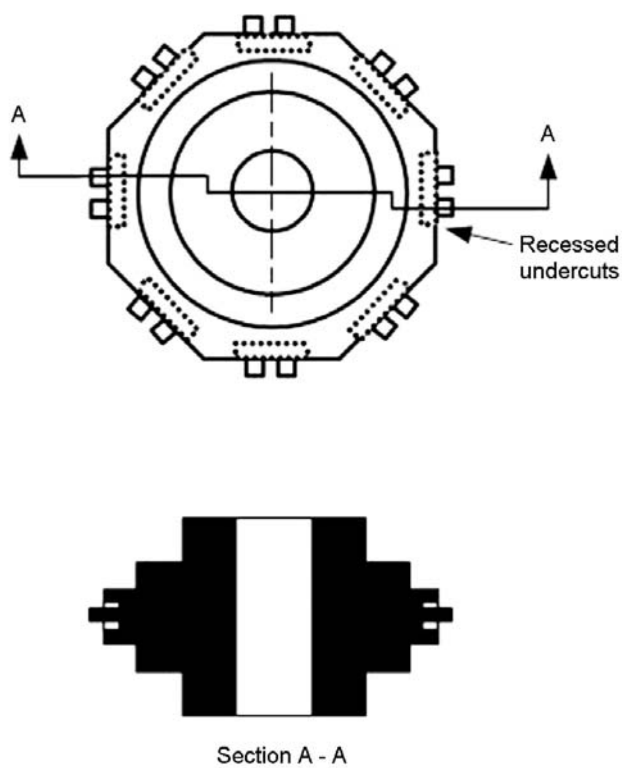


Figure 12.23 Component details

To be able to mould these components, the tool has to be designed with eight separate side core units. Figures 12.24(a) and (b) show the basic tool design for this part. This type of design is also frequently used for other components with raised engraving on their edges, where the same restrictions apply.

Note that this design uses eight spring-loaded side core units. Only two of these have been shown for the sake of brevity. Spring-operated side core designs like this are restricted to relatively small undercut features.

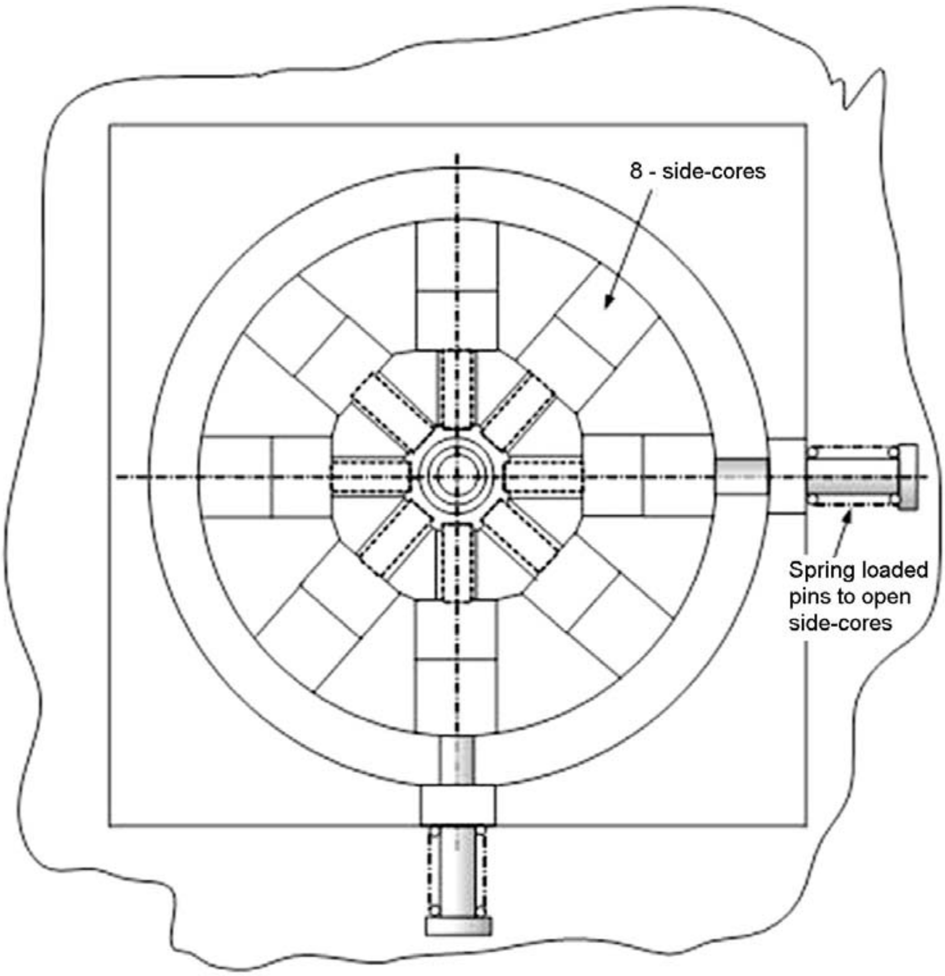


Figure 12.24a Plan view of print wheel mould

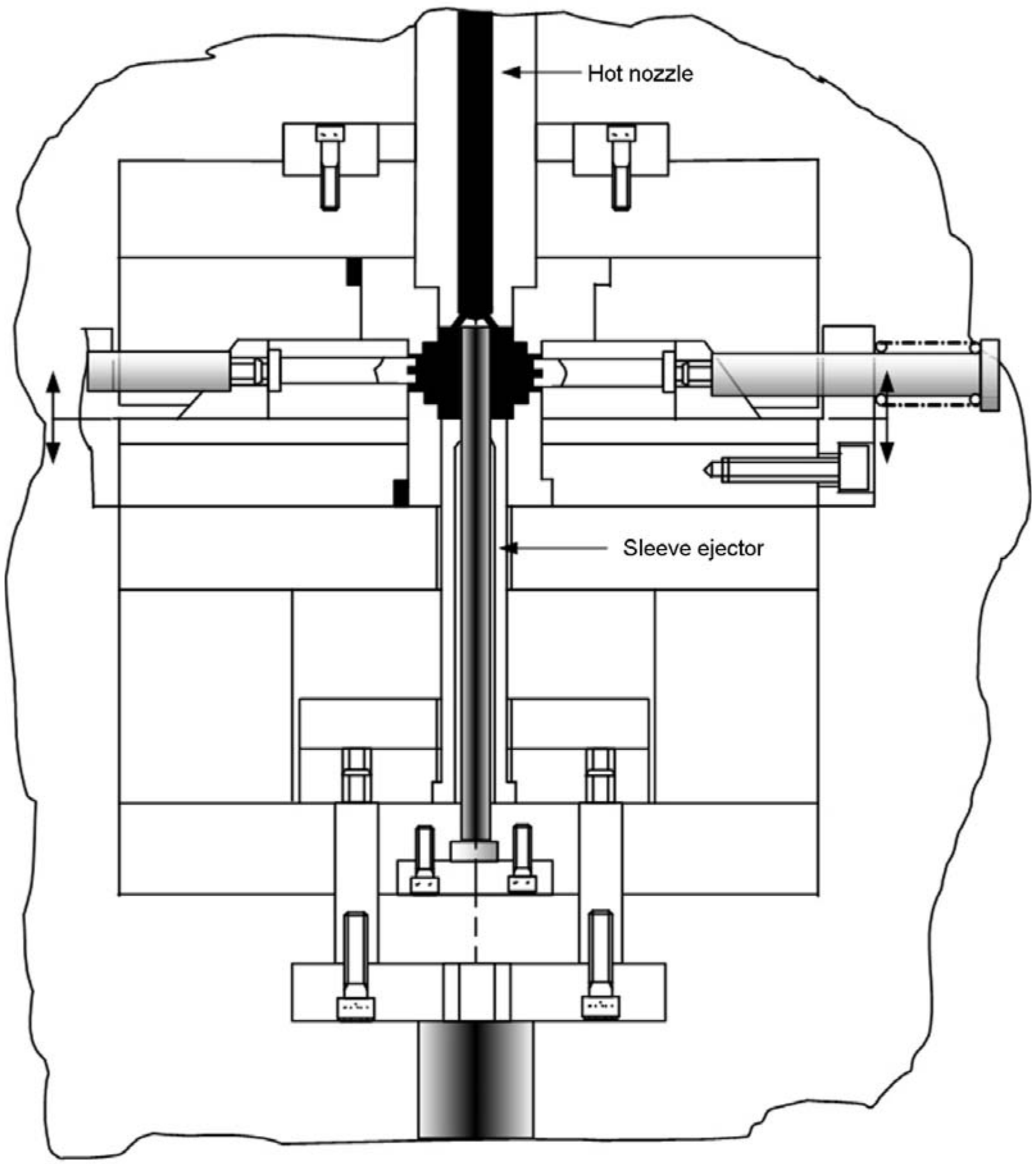


Figure 12.24b Design for radially undercut part – sectional view

12.9.1 Description of Operation

The operation of this tool is quite straightforward. Basically it operates in exactly the same way as a normal side core tool. The only difference is that there are eight separate side core units arranged around the periphery of the part. All the side core units are made such that their outside form is circular. The springs must be strong enough to open the side cores during tool opening.

When the tool opens, each side core is opened by means of die springs. In this example, springs are sufficient to withdraw the side cores from the moulding, but in other cases, where springs may not have the necessary power, individual angle dowels would have to be used.

To clamp the side cores in place when the tool is closed, the fixed half of the tool has a circular sloping face machined in it to lock the side cores in position. In this case the part is subsequently sleeve ejected.

12.9.2 Key Design Features

Most of the comments made for side core tools also apply here, but there are some additional requirements as listed below.

- The design layout of the side core units should be symmetrical for economy of tool manufacture.
- The design presupposes that a very high-quality toolmaker is being used. In this case, for example, all eight individual side cores must shut off accurately without any hint of flash. This requires high-precision toolmaking.
- The undercuts on this type of part are usually quite small and therefore springs are normally sufficient to actuate the side cores.
- For more substantial undercuts, springs may be inadequate and small individual angle dowels may have to be used.
- All main sliding surfaces in the tool should be hardened.
- The degree of difficulty increases as the number of individual side cores increases.
- The maximum number of side cores will depend on the size of the component, but seldom exceeds 12.
- Use of individual side cores is only valid if:
  - The part cannot be moulded with split-line witnesses using a two-plate tool.
  - Any undercuts cannot be jump ejected.

Note: This type of tool design is likely to be more prone to flash than normal side core tools because of the large number of side cores being used. This fact should be taken into consideration when estimating tool life and the maintenance required and the quality of the toolmaker.

12.10 Undercuts on Helical Gears and Pump Impellers

Some parts have more difficult undercut forms that require special mould design and tool construction techniques. Helical undercuts are a good example of these. Undercuts of this type usually fall into two categories:

- Parts that can be ejected with normal ejection techniques
- Those that require special ejection designs to enable satisfactory release from the tool

The example in Figure 12.25 shows a straight tooth form gear with the teeth set at an angle to the gear axis. As can be seen, the gear form creates a continuously increasing undercut that is not necessarily straightforward to eject from the cavity.

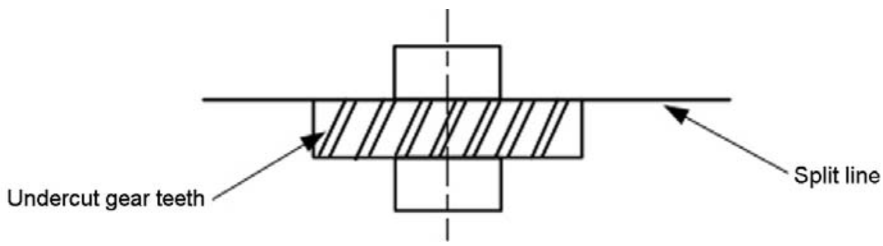


Figure 12.25 Helical gear form

The same problem occurs with water pump impellers, propellers and similar components. These parts have blades that are set at an angle to the shaft and are sometimes undercut in two planes.

It is very important that careful analysis of the undercut form is carried out ***before*** any design work is undertaken. It must be established at the earliest stage that it is possible to release the undercut. This may sound obvious, but some forms are quite complex in nature and need careful thought and analysis to establish this possibility.

12.11 Normal Ejection Techniques

With some forms it is possible to eject parts with this type of undercut by carefully adjusting the ejection speed and force. The helical gear is a good example of this. However, to fully establish the success or otherwise of normal ejection there are ***two*** variables that need to be assessed:

- The form and nature of the undercut
- The material in which the part is being moulded

12.11.1 Form of Undercut

- It must either be of a constant cross-section or increase in section as the undercut approaches the split line of the tool.
- The angle of the form should not normally exceed 45° with respect to the component axis.
- The material must be compatible with this technique.

The first point is critical. Figure 12.26 shows a helical undercut form and a straight blade undercut form. The form cross-section must either remain constant ***or*** increase in section towards the split line as indicated by sections A–A and B–B if this can be tolerated.

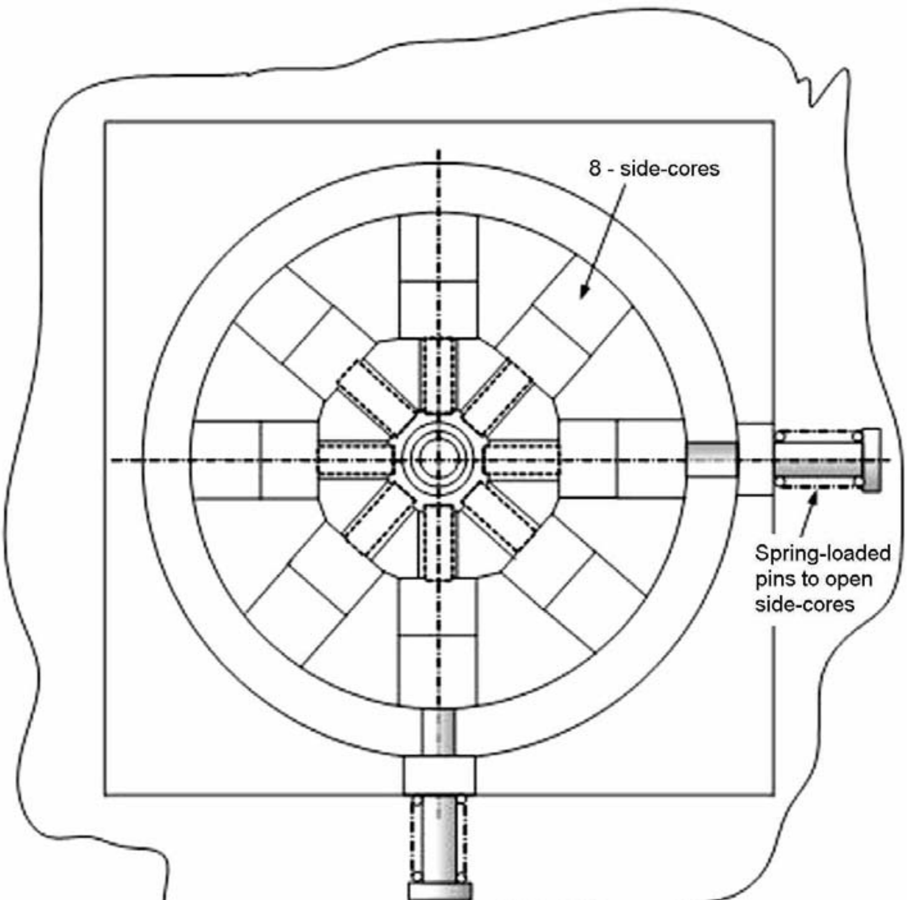


Figure 12.26 Conditions for release of undercut

12.11.2 Component Material

The component material has an important part to play in the success or otherwise of axial ejection. The main requirements are:

- It must not be brittle.
- It should be quite tough and durable.
- It should be fairly rigid but not totally inflexible.
- It should resilient.
- Ideally it should be self-lubricating.

Some of these requirements sound rather vague but it is difficult to quantify exactly, the minimum properties required. For example, brittle materials like polystyrene and styrene acrylonitrile are not suitable for this technique: they do not have the mechanical strength or resilience to absorb the slight deflection of the form that takes place during ejection.

Rigidity is also a requirement. More flexible materials such as low-density polyethylene or flexible PVC can distort on ejection, making the part out-of-specification. Very rigid materials, on the other hand, are also not suitable since a degree of flexibility is normally necessary to accommodate a little deflection throughout the ejection phase.

12.11.3 Satisfactory Materials

- Most grades of Nylon – an added lubricant is ideal
- Most grades of polyacetal
- Higher density polyolefins
- Acrylonitrile-butadiene-styrene
- Most polyesters, preferably with a lubricant and reduced form depth

12.11.4 Unsatisfactory Materials

- Any very flexible materials like LDPE
- Any very rigid materials, especially those with a glass filler

This guide is not exhaustive but it does reflect direct experience by the author of using these materials for normal axial ejection. This is a general guide only and it is possible to mould most materials, providing provision is made for them in the design.

However, by breaking these design guides the designer may be entering uncharted territory and consultation with the material manufacturer is recommended. For example it ***is*** possible to mould rigid glass-filled materials but extreme care must be taken during the ejection phase otherwise the part may not eject or, worse, damage to the cavity may occur.

Warning: If this method of ejection is selected, the rate of ejection *must* be slow compared with normal. If ejection is carried out at speed, there is a danger of the part becoming jammed in the cavity or the undercut form being damaged.

During initial moulding trials, the ejection speed should be set as low as possible and then slowly increased to reach the optimum conditions.

12.12 Special Ejection Designs

With deep drawn components or those with high helix angles, it can be unsafe to attempt normal in-line axial ejection. Components with both of these features are more difficult to eject from the tool and more complicated designs may be necessary. Parts with undercuts in two planes are also cases that need special attention. In this section three cases are considered:

- Splitting the component into one or more parts and assembling after moulding
- Moulding in one piece for enclosed impellers
- Helical ejection for non enclosed helical gear and impellers

12.12.1 Splitting the Component

The component shown in Figure 12.27 illustrates an impeller component that has a totally enclosed series of undercuts that can be moulded by splitting the impeller into two parts.

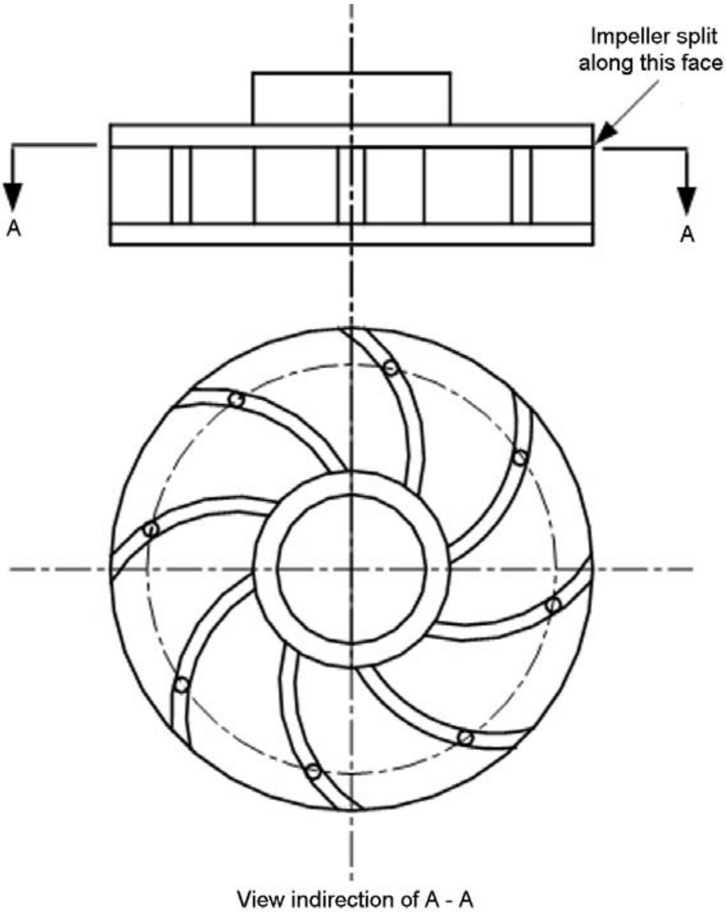


Figure 12.27 Pump impeller

If the component could be split into two parts along line A–A, both parts could be moulded quite easily in a two-plate tool. The two parts are then assembled together by locating spigots and heat-sealing together if necessary.

Figures 12.28(a) and (b) show the two separate mouldings and the locating spigots and holes for subsequent assembly. The parts may also be glued together or they may be an interference fit.

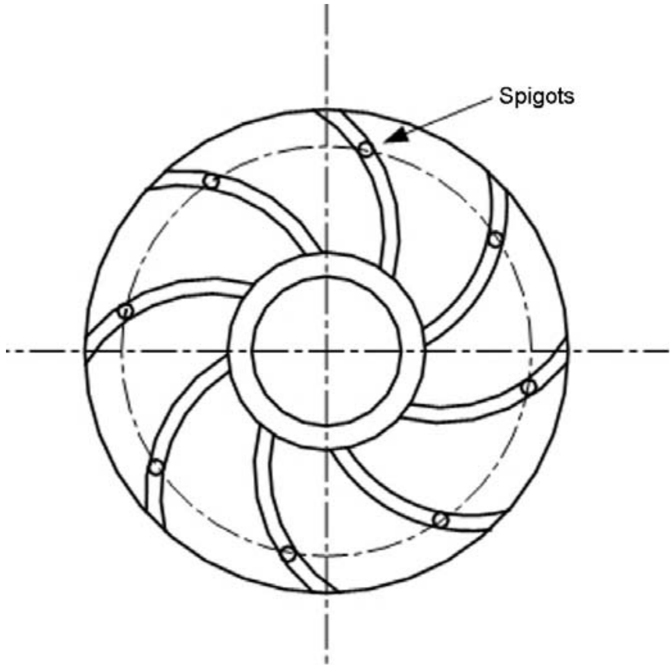


Figure 12.28a Main body

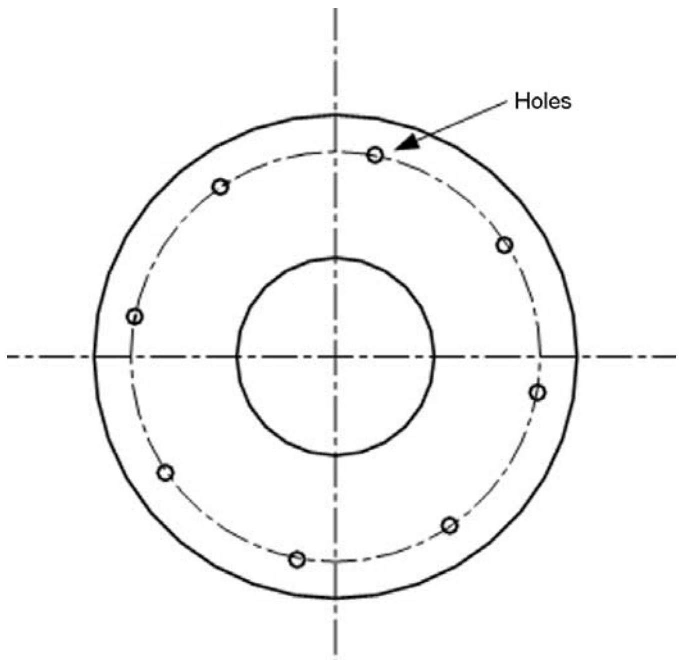


Figure 12.28b Cover plate

12.12.2 Moulding in One Piece

If it is not possible to split the component in this way, it may be possible to mould the component as a one-piece moulding.

This may look difficult and it certainly is not easy. The method of attack would be to design a series of independent side core units. These would follow the internal form of the impeller and be actuated by means of guides that withdraw the side cores on a curved track similar to that for the curved component shown earlier.

It should be evident from these designs that the standard of toolmaking involved will be of a very high order. Consequently, only the best-quality toolmaking companies should be used.

12.12.3 Helical Ejection

Where a nonrotating ejector cannot eject helical undercuts, they may be helically ejected. This entails using an ejector that is guided to rotate by using a sleeve in the tool, which has the same helix angle as the form being ejected (Fig 12.29)

Small drive keys are added to the base of the part to enable the ejector to 'grip' the moulding while ejection takes place. The ejector then 'rotates' the moulding out of the cavity in a similar manner to unscrewing a very steep-angle screw thread out of a cavity.

If necessary, a secondary ejection system or air ejection may be included to avoid the possibility of the moulding sticking to the driving keys after the primary ejection phase has been completed.

As with the nonrotating ejection system, the speed of ejection should be fairly slow to avoid the possibility of damaging the driving keys or distorting the moulding.

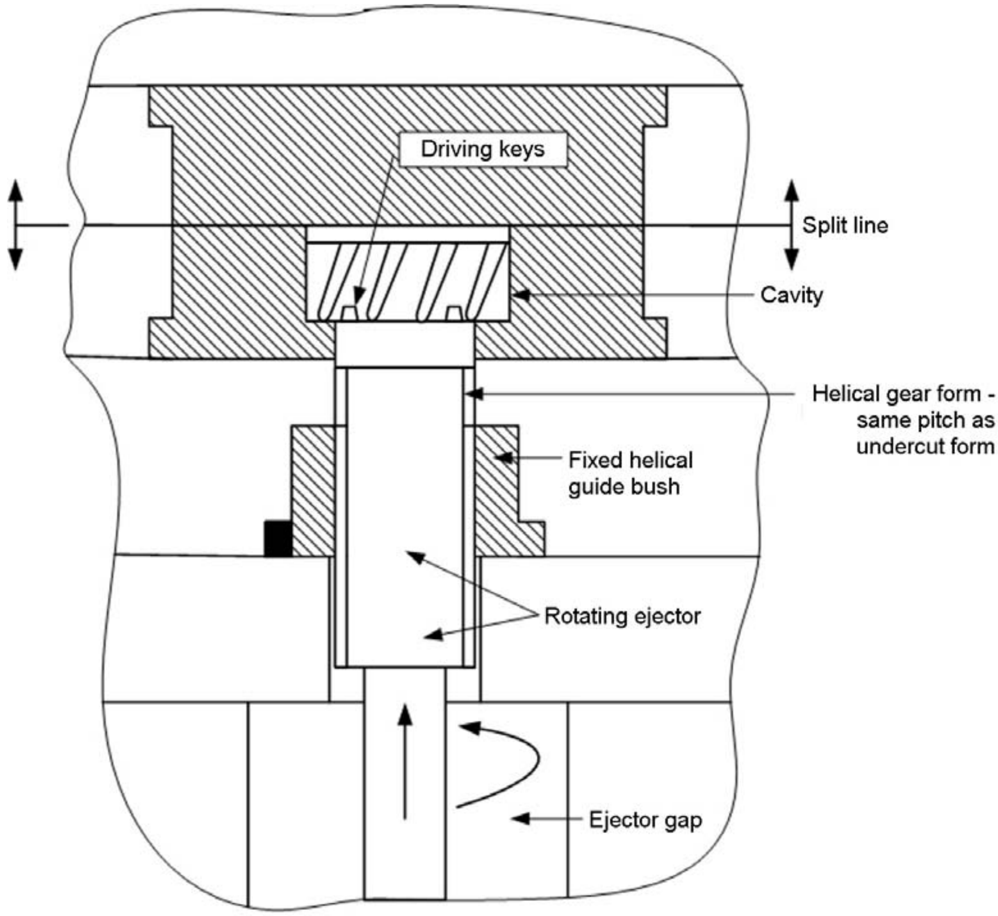


Figure 12.29 Helical ejection with rotating ejector pin

13 Automatic Unscrewing Mould Tool Design

13.1 Introduction

The invention of the screw thread is arguably second in importance only to the invention of the wheel. Although there have been many developments in fastening technology since the invention of the screw thread, it remains as the primary method of securing parts in countless applications in almost every walk of life.

Screw threads cut by die plates and threaded holes cut by longitudinally grooved screws have been known for centuries. Primitive taps were cut by hand with no standardisation of pitch being possible. An attempt to try to standardise thread pitches and diameters was made by Holtz Apfel, a mechanic who was in business in the Charing Cross area of London in the nineteenth century.

Others also became involved in trying to standardise thread forms, but it was left to Sir Joseph Whitworth in a paper read before the Institution of Civil Engineers on 15 June 1841 to introduce a formal standardisation system based on a 55° flank angle. In 1864 an American, William Sellars carried this standardisation procedure further by proposing the 60° flank angle, which was then adopted almost universally.

A major step forward in unification of screw threads was taken in 1898 by the International Conference held in Geneva resulting in the formulation of the Système International (SI) metric thread.

However, many different national thread standards have emerged since that time for various applications. These have today polarised into two main standards: The metric thread for Europe and the unified system in the USA and Canada.

The older British Standard forms such as the Whitworth and British Standard Fine have now largely been superseded by the metric standard in the UK, but certain old British threads systems are still in use today, notably the British Standard Pipe thread system, which is used not only in the UK but also on mainland Europe. The other notable exception is the British Model Engineering screw thread, which is still in use throughout the world.

Apart from these two main groups, specialist thread forms for specific purposes such as horology, instrumentation and bottle and closure threads have also evolved to suit these and other specialist applications.

13.2 Injection Moulding Thread Forms

Plastics are such versatile materials that they have found screw thread applications from the domestic products field right through to hi-tech medical and electronic high-precision parts. Many of these parts contain screw threads that are required to be produced in a variety of different materials. These threaded components can be used in wide-ranging environments and range in application from simple, basic noncritical forms right through to highly precise instrument components.

It is important for the mould designer to ensure that the correct mould design solution is employed for each threaded component. This in turn means that the mould designer should have a thorough understanding of the working environment of the part and the tolerances and other standards that the part will have to conform to.

Basically, thread forms may be moulded by the following methods:

- Using loose tool inserts
- Using splits
- Using collapsible cores
- Using automatic unscrewing techniques

Readers should already be familiar with the first two topics, which were discussed in Chapter 12. These two categories are simply another type of undercut that may be produced by using the methods described there.

This section concentrates on discussing the last two methods in some depth. It is hoped that this will provide the mould designer, toolmaker or technician with sufficient knowledge of current design solutions to extend to new designs of their own. In particular, the following topics are discussed:

- Producing thread forms with collapsible cores
- Axially moving and static unscrewing cores
- Axially moving and static unscrewing cavities
- Internal and external unscrewing design solutions
- Double internal and external thread designs
- Combined internal/external designs thread designs

In addition to the examples on the following pages, further unscrewing designs are included in Chapter 24 ‘Integrated Design Examples’.

13.3 Thread Geometry

Screw threads may be classified into two basic groups:

- Parallel threads
- Taper threads

13.3.1 Parallel Threads

A parallel screw thread is a continuous helical ridge of uniform section and uniform axial spacing formed around the exterior of a solid circular cylinder or tube or on the interior of a circular hole. The thread formed is such that the axial displacement of a point that travels along a helix connecting corresponding points of successive ridge profiles is always proportional to its angular displacement about the axis.

When formed on the exterior, the thread is termed an ***external*** or ***male thread***; an interior thread is termed an ***internal*** or ***female thread***.

13.3.2 Number of Starts

13.3.2.1 Single-start Threads

A single helical ridge is called a ***single-start thread*** as there is only one thread running down the length of the cylinder. With this type there is only one place of engagement on the periphery of the cylinder for mating thread forms.

13.3.2.2 Multistart Threads

A single-start thread is not convenient for many applications, especially where ease and speed of engagement of mating threads is important. Many closure threads incorporate a system whereby engagement is effected at more than one point on the cylinder.

This is achieved by forming a number of parallel helical ridges or threads running down the cylinder. This enables thread engagement at more than one point around the periphery of the cylinder. The number of separate threads reflects the number of starts of the thread. Thus two threads are called a ***two-start thread*** and in general *n* threads are called an ***n-start thread.***

13.3.3 Thread Form

The thread form or sectional profile of the thread is normally defined in its axial section and comprises one complete contour of the thread between adjacent ridges. The bottom of the groove between the ridges is called the ***root*** and the top of the ridge or thread is called the ***crest***. The thread root and crest may be either flat or curved in axial section.

The straight part of thread between the root and crest is called the ***flank***. A complete thread form has two thread flanks that are either inclined equally to the axis in the metric or unified form or inclined at unequal angles as in the buttress thread.

The included angle between adjacent flanks is called the ***thread angle*** and the angle between the flank and a plane perpendicular to the axis the ***flank angle***. The axial distance between adjacent thread forms is termed the ***axial pitch*** or more commonly the ***pitch***.

The relative axial displacement of two threaded parts when engaged with each other when one part is rotated one complete revolution relative to the other is known as the ***lead***:

Lead = pitch for a single-start thread

Lead = n × pitch for an n-start thread

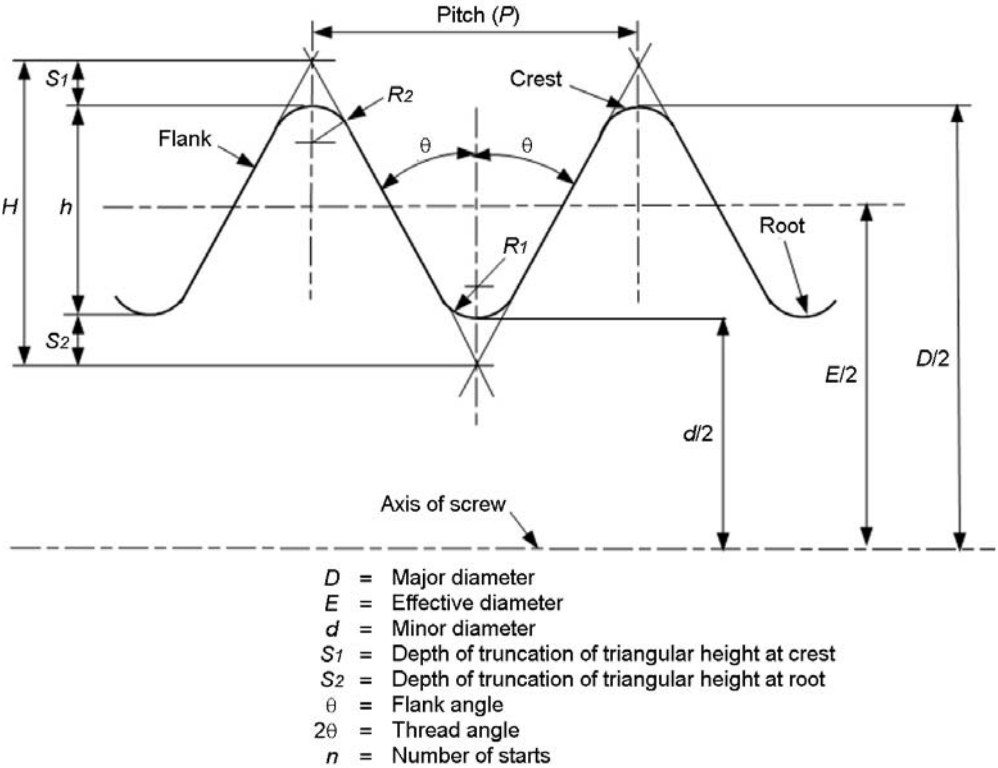


Figure 13.1 Basic screw thread geometry

13.3.3.1 Thread Formulae

The relationship between the elements defined in Figure 13.1 for a thread having equal flank angles is given by:

$$D = E + \frac{1}{2} P \cot\theta - 2S_1$$

$$d = E - \frac{1}{2} P \cot\theta + 2S_2$$

$$h = \frac{1}{2} P \cot\theta - (S_1 + S_2)$$

Dimension H is known as the triangular height and is given by:

$$H = \frac{1}{2} P \cot\theta$$

where S_1 and S_2 are specified in terms of fractions of the triangular height and where $S_1 = k_1H$ and $S_2 = k_2H$. Then

$$D = E + (1 - 2k_1)H$$

$$d = E - (1 - 2k_2)H$$

$$h = (1 - k_1 - k_2)H$$

The ***helix angle (λ)*** at any point along the flank of the thread at a distance q from the axis is given by:

$$\tan\lambda = \frac{1}{2\pi q}$$

This angle is sometimes also known as the ***rake angle***.

The ***mean helix angle*** ***(***λ_m***)*** is the helix angle at the effective diameter E and is given by:

$$\tan\lambda_m = \frac{1}{\pi E}$$

A good approximation for finding the mean helix angle is given by:

$$\lambda_m = 1094 \times \frac{1}{E}$$

Note: The resulting angle is given in minutes of arc and is correct to within 2 minutes for all value of λ. For values of λ between 0° and 3° it is correct to the nearest minute.

13.3.3.2 ISO Metric Thread Form

Although many thread forms are still in use worldwide for specific application, the UK is now standardised on the ISO metric thread standard. The basic geometry for this thread form is shown in Figure 13.2.

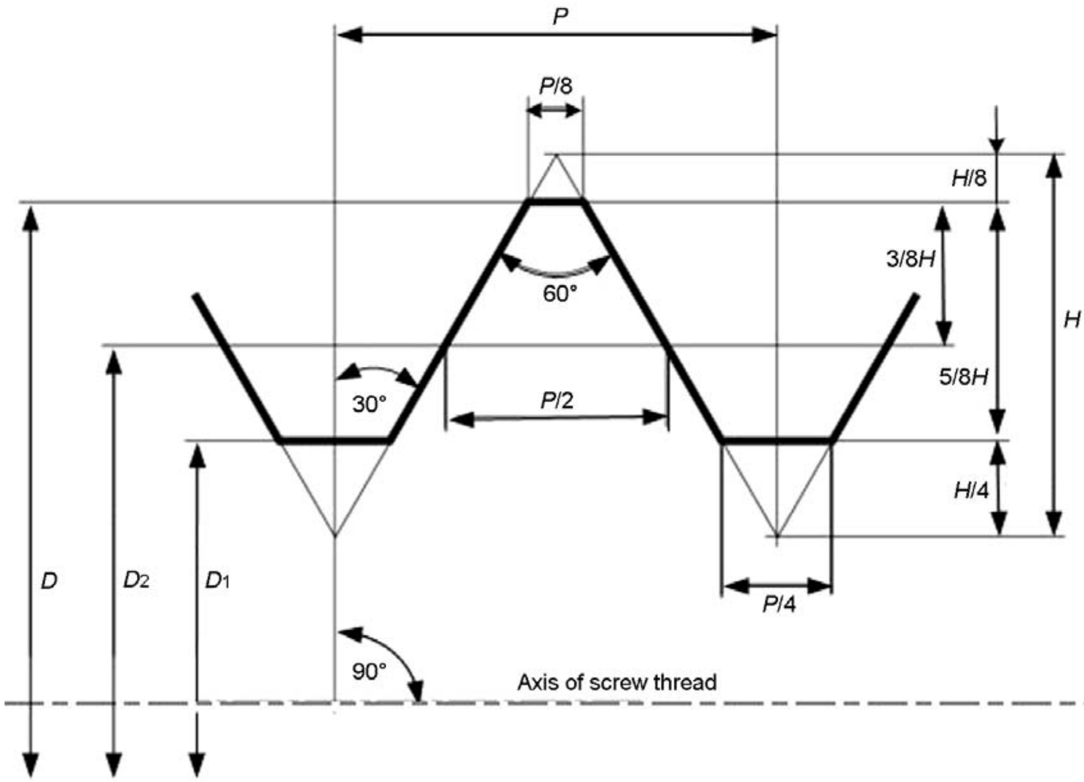


Figure 13.2 Basic form of ISO metric screw thread

It can be seen from these proportions that there are just two variables: pitch and diameter. These are related as follows:

$$H = \frac{\sqrt{2}}{3}P = 0.866035404 \times P$$

$$D_1 = D - 1.23P$$

$$D_2 = D - 0.65D$$

The letter M followed by the diameter designates a metric thread and pitch specified in millimetres, e.g., M6 × 0.5

The relevant British Standard BS3643 allows for two classes of fit:

- **Fine:** The pitch must be specified from a limited available range, e.g. M6 × 0.5.
- **Coarse:** The pitch is directly related to and varies according to the diameter.

For coarse threads it is only necessary to refer to the thread diameter (e.g., M8). With fine thread sizes, however, the diameter ***and*** pitch must be specified (e.g., M6 × 0.5).

BS 3643 (ISO metric screw threads - principles and basic data) also specifies three classes of fit:

- **Medium fit:** This is the most widely used fit suitable for a wide variety of general engineering applications. The BS hole/shaft classification is H6/g6.
- **Close fit:** This fit is used only for more precision engineering applications and is more expensive to produce. The BS hole/shaft classification is H5/g4.
- **Free fit:** This fit is used for quick mating of threaded parts that will still mate even when the threads are damaged or dirty. The BS hole/shaft classification is H7/g8, which gives a wider clearance condition between screw and hole.

Table 13.1 lists commonly used sizes for ISO metric coarse and fine threads.

Table 13.1 Shortened list of ISO thread sizes

Nominal diameter, D (mm)		Pitch, P (mm)		
1st Choice	2nd Choice	Coarse	Fine	
1		0.25		
1.2		0.25		
	1.4	0.3		
1.6		0.35		
	1.8	0.35		
2		0.4		
2.5		0.45		
3		0.5		
	3.5	0.6		
4		0.7		
5		0.8		
6		1		
	7	1		
8		1.25	1	
10		1.5	1.25	1
12		1.75	1.5	1.25
	14	2	1.5	

Continued…

1st Choice	2nd Choice	Coarse	Fine	
16		2	1.5	
	18	2.5	2	1.5
20		2.5	2	1.5
	22	2.5	2	1.5
24		3	2	
	27	3	2	
30		3.5	2	
	33	3.5	2	
36		4	3	
	39	4	3	
42		4.5	3	
	45	4.5	3	
48		5	3	
	52	5	4	
56		5.5	4	
	60	5.5	4	
64		6	4	

13.3.4 Taper Threads

A taper thread is a thread form where the minor, effective and major diameters progressively increase (or decrease) along the axis of the thread.

The principal use of taper threads is to ensure a positive lock between mating male and female thread forms. An example of this type of thread is the British Standard Taper threads for pipe (BSTP). The taper in this case ensures that the thread will not unlock easily and that water leaks are minimised.

The terminology and thread geometry of the taper thread are generally the same as for the parallel thread, but the point along the axis of the thread where these parameters apply must be stated. For taper threads forms the following additional information must be supplied:

- The cone angle of the thread
- The position along the thread axis at which the effective diameter is measured
- Whether the pitch is measured along the thread axis or along the pitch-cone generator

13.3.5 British Standard Pipe Thread

The British Standard Pipe thread (BSP thread) is a system of standard screw thread forms that has been adopted internationally for connecting and sealing pipe ends by mating an external (male) with an internal (female) thread.

This type of thread is used almost universally on mould tools for connecting water fittings to the tool to prevent leaking. It is usual also to use PTFE tape wrapped around the male thread for extra resistance to leaking. Two of the most frequently used types of threads are discussed here:

- Parallel threads, which have a constant diameter (*G*)
- Taper threads, whose diameter increases or decreases along the length of the thread (*R*)

13.3.6 Jointing Threads

These are pipe threads for joints made pressure-tight by the mating of the threads. They always use a tapered external thread but can have either parallel or taper internal threads. (In Continental Europe, taper internal pipe threads are not commonly used.)

13.3.7 Longscrew Threads

These are parallel pipe threads used where a pressure-tight joint is achieved by the compression of a gasket on to the surface of the external thread by tightening lock nuts.

For both the taper and the parallel pipe threads, the Whitworth thread form is used, which has the following characteristics:

- A symmetrical V-form thread with an angle between the flanks of 55° (measured in an axial plane) with one-sixth of the V form truncated at the top and bottom of the thread
- The thread form is rounded at the crest and root, blending tangentially with the flanks
- The depth of the thread is 0.640327 times the nominal pitch

The size designation of BSP threads were originally based on the inner diameter of a steel tube which was required to be threaded, measured in inches. The modern metric designation is based on a number system ranging from 1/16 to 6.

The major diameter shown in Table 13.2 is the outer diameter of the external thread. For a tape thread it is the diameter at the ***gauge length*** from the smaller end of the thread. The taper is 1 to 16, which means that for each 16 mm measured from the smaller end, the diameter increases by 1 mm.

The designation used to specify a pipe thread is shown in the following examples:

Pipe thread EN10226 Rp ¾ (based on BS EN 10226, Pipe threads where pressure tight joins are made on the threads, 2004)

Pipe thread ISO 07 Rc 21/4 (based on ISO 07)

Pipe thread ISO 07 R 21/2 (based on ISO 07)

where:

Rp is internal parallel thread

Rc is an internally tapered thread

R is an externally tapered thread

Table 13.2 British Standard Pipe Thread

Thread size	Threads per 2.5 cm	Pitch (mm)	Major diameter of the thread		Gauge length (mm)	Corresponding pipe			
			(mm)	(in)		DN	OD (mm)	OD (in)	Thickness (mm)
0.0625	28	0.907	7.723	0.304	4				
0.125	28	0.907	9.728	0.383	4	6	10.2	0.40	2
0.25	19	1.337	13.157	0.518	6	8	13.5	0.53	2.3
0.375	19	1.337	16.662	0.656	6.4	10	17.2	0.68	2.3
0.5	14	1.814	20.995	0.825	8.2	15	21.3	0.84	2.6
0.75	14	1.814	26.441	1.041	9.5	20	26.9	1.06	2.6
1	11	2.309	33.249	1.309	10.4	25	33.7	1.33	3.2
1.25	11	2.309	41.910	1.650	12.7	32	42.4	1.67	3.2
1.5	11	2.309	47.803	1.882	12.7	40	48.3	1.90	3.2
2	11	2.309	59.614	2.347	15.9	50	60.3	2.37	3.6
2.5	11	2.309	75.184	2.960	17.5	65	76.1	3.00	3.6
3	11	2.309	87.884	3.460	20.6	80	88.9	3.5	4
4	11	2.309	113.030	4.450	25.5	100	114.3	4.5	4.5
5	11	2.309	138.430	5.450	28.6	125	139.7	5.5	5
6	11	2.309	163.830	6.450	28.6	150	165.1	6.5	5

13.3.8 Moulded Thread Forms

When designing core pins and cavities containing screw thread forms, it is important to avoid incorporating features that are difficult to machine during toolmaking. In particular, it is important to avoid the creation of ***feather edges*** at the ends of threads (Figure 13.3). Equally, sufficient clearance must be left at the bottom of thread forms where they adjoin core pins. Failure to attend to these problems can often result in toolmaking difficulties and also in the failure of the moulded screw thread in use.

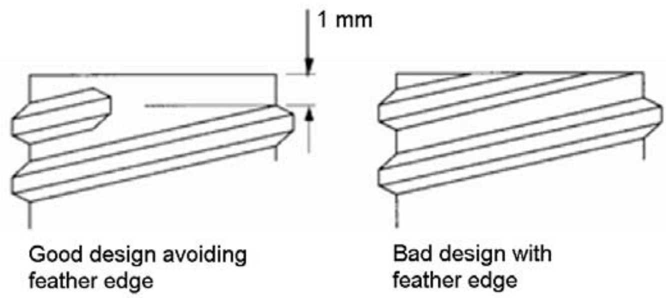


Figure 13.3 Avoiding feather edges on thread forms

Figure 13.4 below shows the recommended practice, which should be applied, to all cores and cavities.

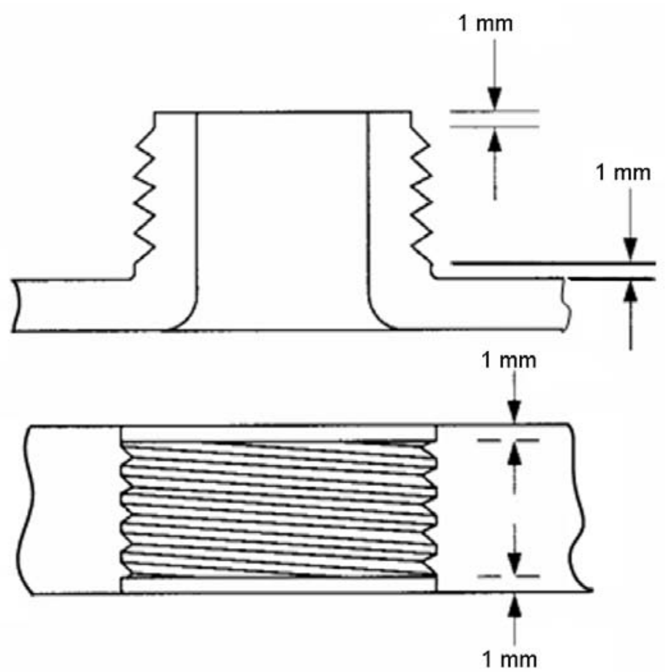


Figure 13.4 Recommended design for internal and external moulded thread forms

13.4 Thread Shrinkage Compensation

13.4.1 Discussion

In common with other plastics components, it is necessary to apply a shrinkage allowance to the cavity and core sizes. This ensures that after volumetric shrinkage of the polymer has taken place, the moulded thread form will be correct.

If a shrinkage allowance is not applied, this can result in the moulded thread failing to mate correctly with other parts. This is particularly true when semicrystalline materials are being used. The relatively high level of volumetric shrinkage that takes place with these materials makes it essential to compensate for this in the mould tool.

In particular, high-performance engineering materials like acetal and Nylon have large shrinkage values. Threads moulded in these materials are often used for more precise applications; hence, special attention must be given to shrinkage. In addition, such applications require extra attention to ensure moulding consistency so as to minimise dimensional variation.

Great care must be taken with this class of component to make sure that the unscrewing operation does not distort the thread form. This can often be the cause of precision components failing to meet quality standards or failing to mate satisfactorily with other threads.

The overriding requirement in any injection moulding enterprise, however, is to be competitive and profitable. In view of this, where applications call for a simple noncritical fit, there is no point in applying expensive shrinkage compensation techniques or control devices.

Also, on very small thread forms or when using materials with low shrinkage values, it may be equally unnecessary to apply shrinkage compensation as virtually no shrinkage may take place.

13.4.2 The Effect of Incorrect Shrinkage on Thread Forms

All of the dimensions shown in Figures 13.1 and 13.2 will be affected by shrinkage taking place on the component. In particular, the following problems can occur if the shrinkage allowance is incorrect, whether too small or too large:

- Pitch inaccuracy
- Thread form inaccuracy
- Inaccurate thread diameters

13.4.3 Pitch Inaccuracy

This can result in a progressive, cumulative pitch error causing the thread to jam in the mating part after initial engagement.

13.4.4 Thread Form Inaccuracy

This condition gives rise to two problems. The first is that the thread will enter the mating part but result in a loose fit owing to the thread form being undersize. The second problem is the reverse of the first. In this case the thread form is too large and will also jam in the mating part.

13.4.5 Inaccurate Thread Diameters

Similar problems occur with oversize or undersize effective and outer diameters as those mentioned above, ranging from too loose a fit to an interference condition.

13.5 Application of Shrinkage Allowance on Thread Forms

Clearly, in general, the higher the material shrinkage, the larger cavity and core sizes have to be to compensate. However, account has to be taken of impression structure and form before applying a global shrinkage allowance to all dimensions.

Often there are cavity or core forms that will restrict the full amount of shrinkage taking place, and moulding a screw thread gives a perfect example of such a restriction – the actual thread form itself. The thread form is a continuous helical undercut and as such it will prevent free, unrestricted shrinkage that would otherwise take place.

This suggests that a lower shrinkage factor should be applied to the pitch than to the thread diameters, where such restrictions do not exist. This becomes increasingly important as the thread accuracy requirements increase.

For such applications it is suggested that a reduced shrinkage allowance of 0.75 of the normal shrinkage allowance be applied.

13.5.1 Shrinkage Formulae

The following two formulae will assist in establishing the shrinkage sizes for basic thread forms for most purposes. In these formulae, the symbols have the following meanings:

CS = Cavity and core sizes

DS = Drawing sizes

SA = Shrinkage allowance in %

Thread diameters

$$CS = DS \times \left(1 + \frac{SA}{100}\right)$$

Thread Pitch

$$CS = 0.75 \times DS \times \left(1 + \frac{SA}{100}\right)$$

For more critical requirements the full range of shrinkage compensation formulae are listed below:

$$D = \left(E + \frac{1}{2} P \cot \theta - 2S_1\right)(1 + SA/100)$$

$$d = \left(E - \frac{1}{2} P \cot \theta + 2S_2\right)(1 + SA/100)$$

$$h = \left(\frac{1}{2} P \cot \theta - (S_1 - S_2)\right)(1 + SA/100)$$

$$H = \left(\frac{1}{2} P \cot \theta\right)(1 + SA/100)$$

$$D = (E + (1 - 2k_1)H)(1 + SA/100)$$

$$d = E - (1 - 2k_2)(1 = SA/100)H$$

$$h = (1 - k_1 - k_2)(1 + SA/100)H$$

$$\tan \lambda = \frac{1}{2\pi q}(1 + SA/100)$$

$$\tan \lambda_m = \frac{1}{\pi E}(1 + SA/100)$$

$$\lambda_m = 1094 \times \frac{1}{E}(1 + SA/100)$$

13.6 Injection Moulding Considerations

It is beyond the scope of this book to embark on a comprehensive discussion on injection moulding technique. However, it is very relevant to discuss the effect of certain injection moulding conditions and techniques on the production of screw threads.

It is pointless to have carefully designed mould tools constructed if the moulding conditions vary widely or are wrongly set. Difficulties with the production of screw threads are often encountered because of such problems.

13.6.1 Moulding-related Problems

The main causes of difficulty are briefly discussed next.

13.6.2 Injection Pressure

High pressures are necessary for the production of precision components, particularly those in crystalline materials. However, if this pressure is set too high it can lead to extreme difficulty in unscrewing thread forms from the impression. Material is packed far too tightly into the cavity, making heavier-duty unscrewing motors necessary and promoting the distinct possibility of the occurrence of flash.

13.6.3 Injection Speed

Too high an injection speed has a similar effect to too high a pressure in promoting unnecessary flash, again making unscrewing difficult.

13.6.4 Unscrewing Speed

While a reasonable unscrewing speed it necessary for an economic cycle, too high a speed can be counterproductive. This can often lead to inaccurate thread forms and can leave a 'trailer' of thread at the bottom of the thread form as the component clears the cavity or core.

13.6.5 Ejection Speed

Many unscrewing systems have lead screws that move a stripper plate forward at the same rate at which the thread is unscrewed. If this type of system is operated too quickly, the end thread form can be damaged. In extreme cases the end of the thread can become separated from the main thread, resulting in rejection.

13.6.6 Operating Window

Clearly, the moulding conditions should be consistent. Wide variations in conditions will produce similar variations in the size and quality of the mouldings. Therefore, if a precision thread is being moulded, the conditions should only be allowed to vary within a narrow range. Computer control is an obvious advantage for such parts.

13.6.7 Tool Temperature Control

There are two basic groups of materials each with different molecular structures:

- Amorphous
- Semicrystalline

Each needs to be moulded in different ways to ensure satisfactory results.

13.6.7.1 Amorphous

An amorphous material has no real preferred structure. Molecular chains are distributed at random during the injection phase, rather like a plate of spaghetti. As the moulding cools and then solidifies, it keeps this random structure and remains relatively stable thereafter.

Most of these types of materials are moulded with tool temperatures in the range 5–80 °C depending on the material requirements. Water-cooling is normally employed for these materials.

13.6.7.2 Semicrystalline

Semicrystalline materials also have a randomly oriented molecular structure during the injection phase. As the moulding cools, however, the structure tries to change into a more linearly oriented one. This linear structure is its preferred natural structure and it is important that it be given time to form properly before solidification takes place.

If the material freezes before the natural orientation has had time to form, then the material will suffer from a distinct loss in physical properties. In particular, the mechanical strength can be significantly reduced. This can lead to mechanical failure of the part and to dimensional distortion over a long period of time. For precision and load-bearing applications this can lead to failure in use.

In order to allow the formation of natural structure to take place, the part must be given the right conditions for this to happen. In practice this means supplying heat to the mould tool rather than cold water. Temperatures in the range 80–140 °C or higher are used so that the material is not cooled too rapidly.

In view of the higher temperatures involved, it is usual to employ oil as the heat transfer medium for added safety. However, it is not uncommon to see water heater systems running at these temperatures. If water heaters are used, they should be closed-system types, as superheated steam may otherwise be produced.

13.7 Basic Screw Thread Mould Designs

There are four basic methods that can be used for the production of moulded threads:

- Split tooling
- Thread jumping
- Collapsible coring
- Rotary unscrewing

13.7.1 Split Tooling

A very large number of screw-threaded components are injection moulded by this method. It involves machining half the thread form in each half of a split die as shown in Figure 13.5. The details of split tool construction were discussed in Chapter 12 for a variety of undercut components. The use of splits for moulding threads forms follows exactly the same method.

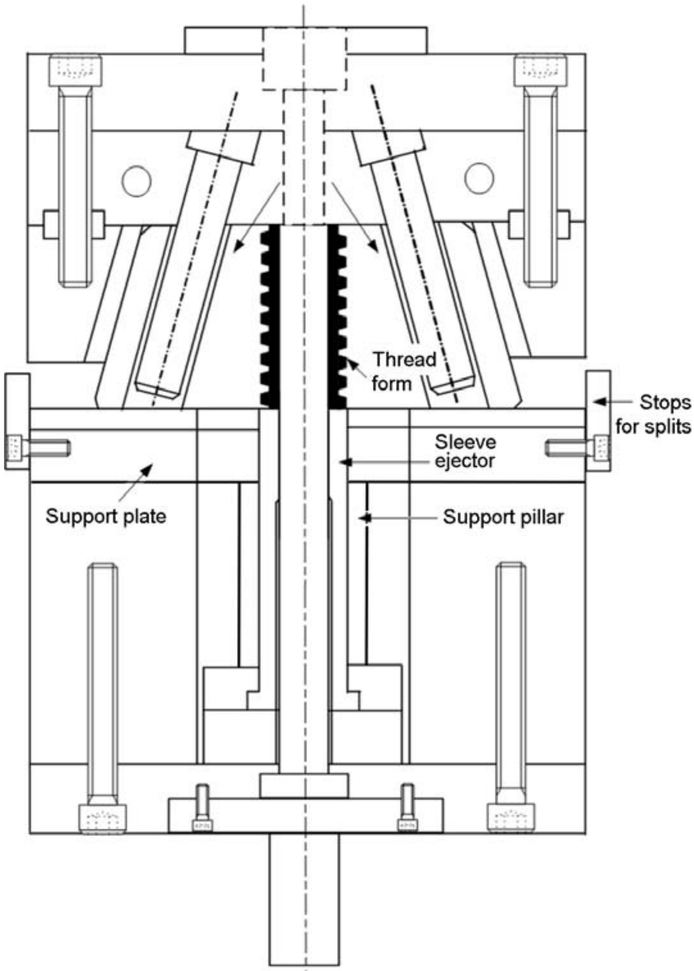


Figure 13.5 Basic two-impression split tool design for moulded thread

13.7.2 Thread Jumping

This is the cheapest method of all for the production of screw thread and is very widely used for the manufacture of closure threads. Figure 13.6 illustrates a typical jump undercut.

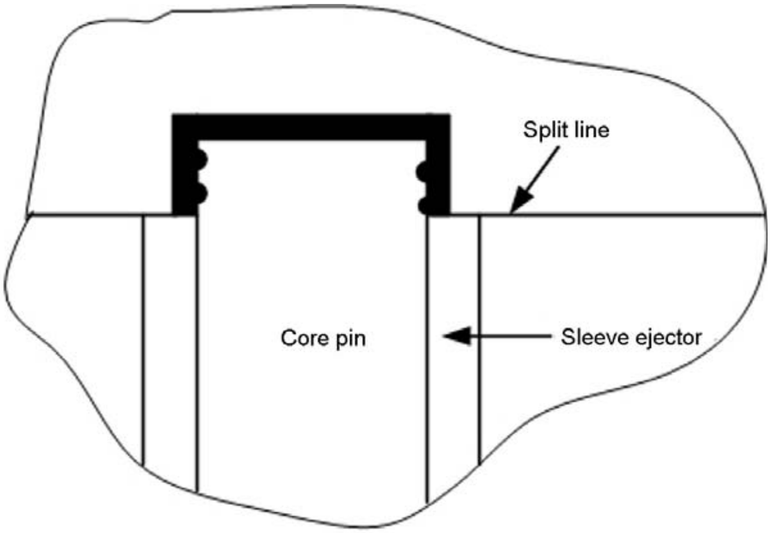


Figure 13.6 Typical jump undercut design

To jump eject a screw thread, it must have the appropriate form. Ordinary screw thread forms cannot be ejected by this method as the flanks and top and bottom of the thread present too great an undercut.

The form for jump ejecting a thread must be a well-rounded one such as a bottle thread. Before ejection takes place the undercut must have the freedom to expand and distort into a clear space. Thus, any restraining cavity walls must be moved away to permit this.

13.7.3 Collapsible Coring

This is another very widely used method for producing screw threads and a very convenient one as the basic collapsible core can be purchased as a standard component. The thread form is machined on to the core and the whole unit inserted into the tool.

Collapsible cores come in two basic forms:

- Two-segment
- Multisegment

Both types of core work by collapsing internal segments, thus freeing the thread (or other undercut form), usually as ejection takes place. Often a secondary-stage ejection may be required to ensure that the part is fully ejected from the tool. A typical two-segment collapsible core is shown in Figure 13.7.

With this system the central core is withdrawn, thus forcing the outer small side cores to move inwards. Two-segment cores are sufficient for many applications and are very widely used. This type of core is discussed in more detail later.

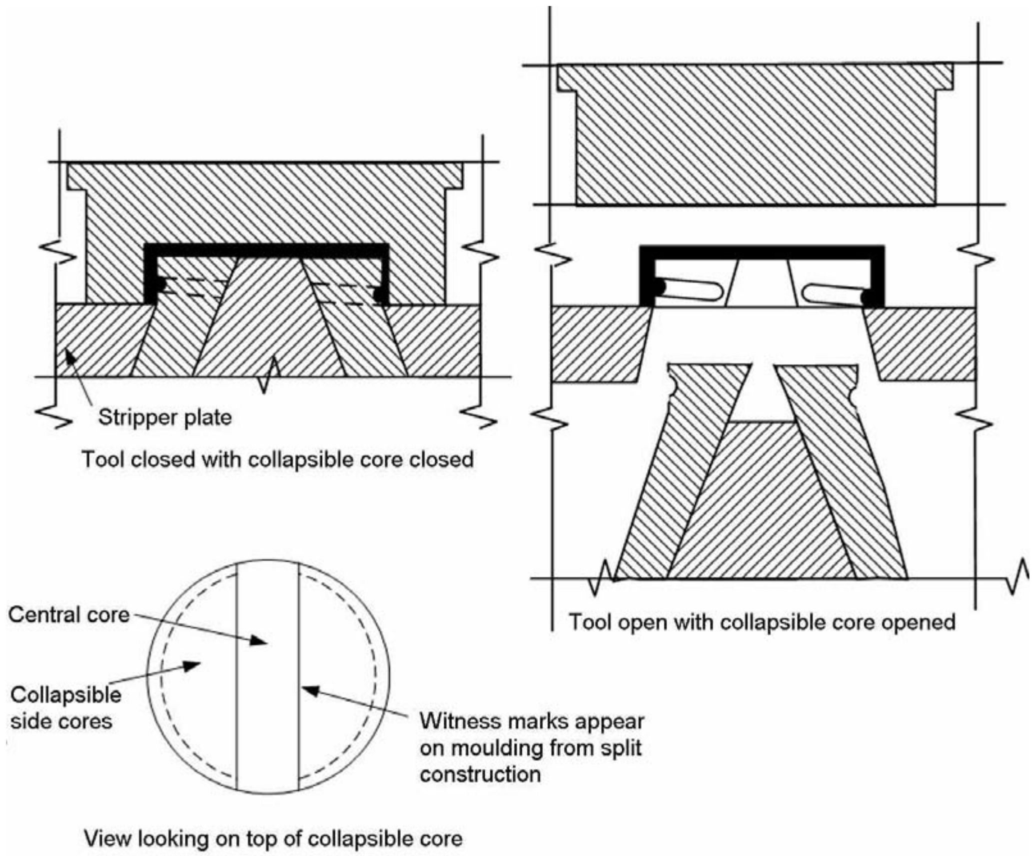


Figure 13.7 Two-segment collapsible core

The other type of core has a multisegment structure enabling complete a thread form to be moulded. These are more expensive but are still widely used for many screw thread applications. Split line witness lines are also visible with this system, but for many applications this does not matter.

A typical multisegment collapsible core is shown in Figure 13.8. Most of the standard components suppliers sell this type of core. The one illustrated is the DMS version; its operation is shown in Figure 13.9.

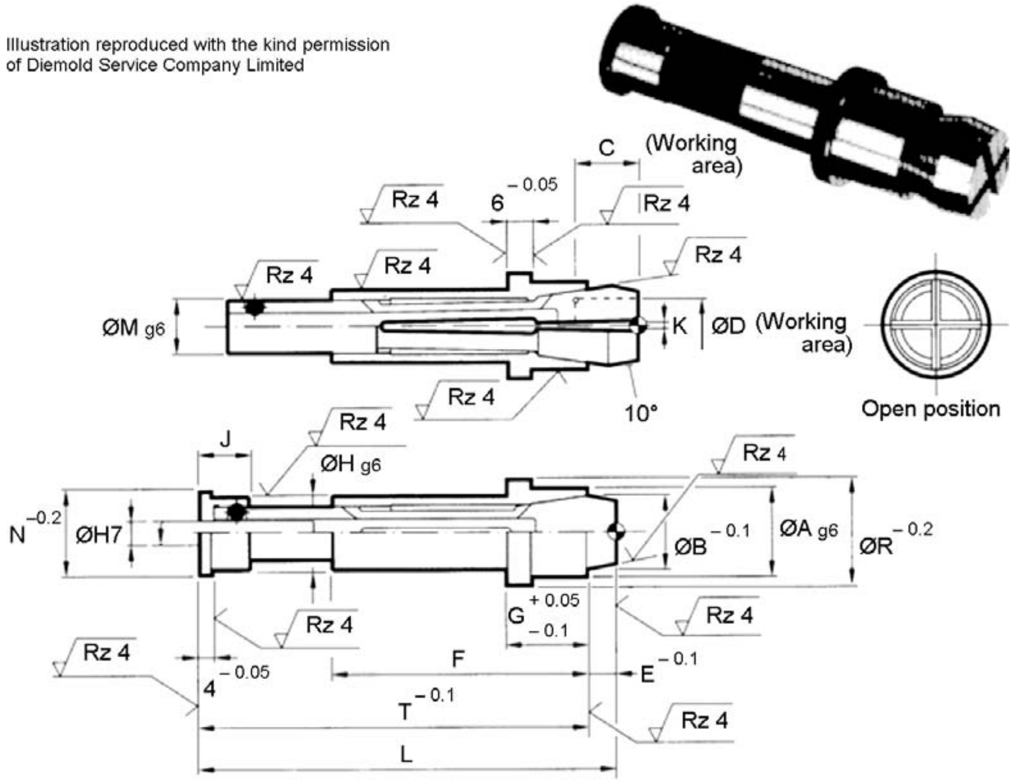


Figure 13.8 DMS Multi-segment collapsible core (reproduced with permission)

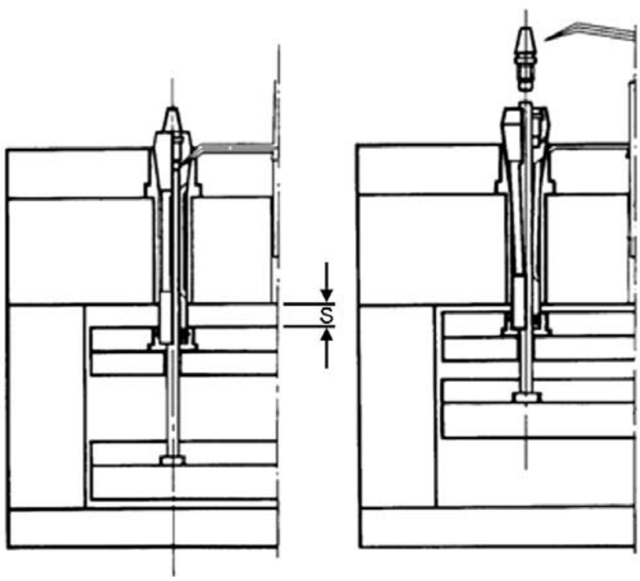


Figure 13.9 Operation of DMS collapsible core

13.7.4 Operation of Multisegment Cores

- As the mould opens the upper ejector system moves forward by releasing the external core mechanism and hence the moulding.
- The upper ejection assembly now stops and the lower ejection system continues forward to eject the moulding.
- Mould closing is the reverse operation.

13.8 Rotary Unscrewing

Rotary unscrewing is used where split line witness cannot be tolerated or often when larger numbers of impressions are required.

There are many different ways of automatically unscrewing threaded parts, which will be discussed in more depth later. The basic method for rotary unscrewing is either to unscrew the part from the core or to unscrew the core from the part. Figure 13.10 shows a typical basic arrangement.

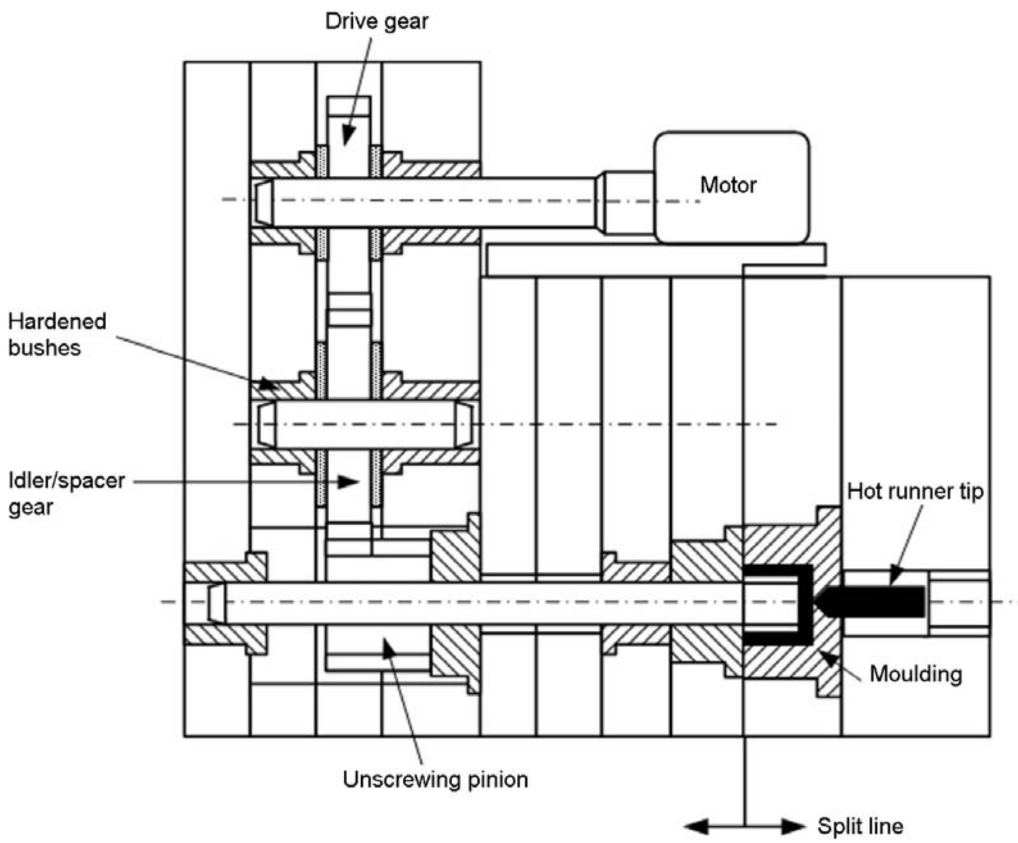


Figure 13.10 Rotating core unscrewing tool

Rotating cores or cavities can be actuated by a rack-and-pinion system, with a rotating core or with a rotating cavity.

13.8.1 Collapsible Coring Details

Collapsible cores are in wide use for producing thread forms and justifiably so. Collapsible coring has the following advantages and disadvantages:

13.8.1.1 Advantages

- Available as a standard unit.
- Available in a reasonable range of sizes.
- Undercut forms up to 5 mm are possible.
- Ease of location into tool.
- Cost-effective for small numbers of impressions.

13.8.1.2 Disadvantages

- Limited thread length.
- Expensive for larger numbers of impressions.
- Can require frequent maintenance.
- Cooling the cores can be difficult.

13.9 Types of Collapsible Core

As mentioned previously there are two basic types of collapsible coring:

- Two-segment cores
- Multisegment cores

13.9.1 Two-segment Core Details

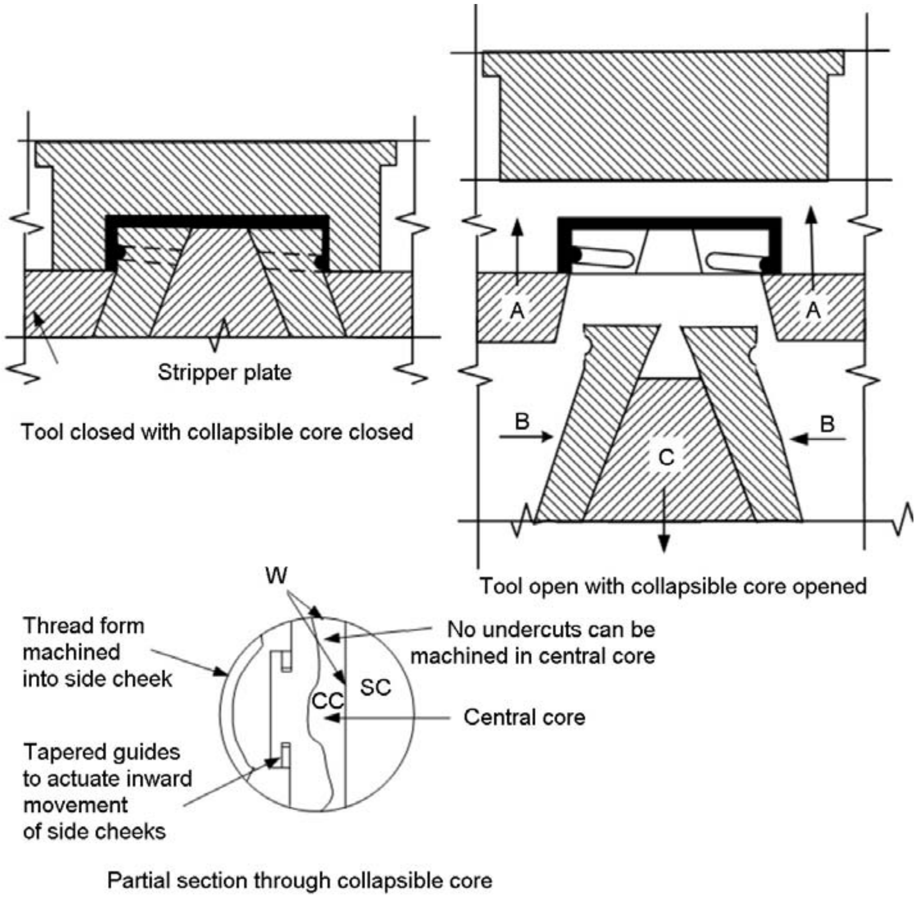


Figure 13.11 Two-segment collapsible core details

There are many applications for which a complete thread form is unnecessary. Bottle closures, for example, only use the simplest of thread forms, often consisting of partial threads.

If they cannot be made using two-plate tools (as they often can be, where perhaps a longer thread length is required), two-segment cores may be used. Figure 13.11 is a more detailed view of the two-segment core shown earlier in Figure 13.7.

Collapsible cores are like mini side core units but placed at an angle to the axis of the core. In Figure 13.11 the central core is withdrawn downward (action **C**) away from the moulding. As it moves it forces the two small side cores **SC** to move inwards (action **B**). This clears the cores from the moulded thread. Finally, the part is stripped off the tool face (action **A**).

Clearly an undercut form cannot be placed on the non-side core areas, as it would not be released when the central core withdraws.

13.9.2 Multisegment Collapsible Cores

As the name implies, multisegment collapsible cores consist of a number of segments, which are constrained to move inwards or outwards by the action of a tapered sleeve expanding and collapsing all the individual segments. This system is very similar to the two-segment system but in this the undercut thread form cut be machined in all the way round the core.

Just as with the two-segment cores, this type of core will show split line witness marks. In this case, however, several split line witnesses will be evident owing to the extra number of segments. For highly accurate or other sensitive applications these witness marks may be unacceptable.

Figure 13.12 below shows a typical collapsible core construction.

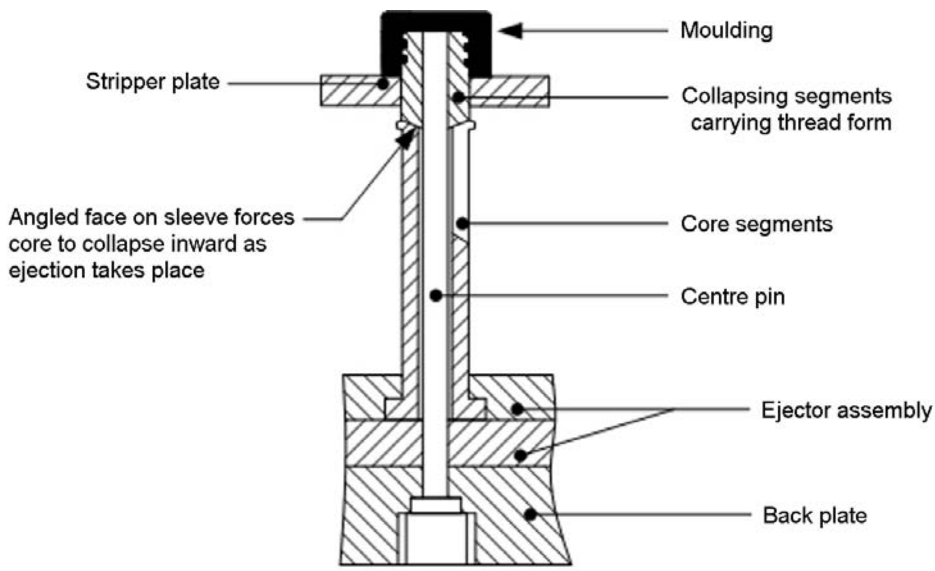


Figure 13.12 Multi-segment collapsible core

While collapsible cores are used quite widely and successfully for many different applications, the following points should be taken into account when deciding and before using them.

- The core assembly can be quite complex. This consists of at least three elements and up to eight.
- Difficulties can occur with the locking and opening of the segments.

- Wear on the sliding surfaces will promote flash conditions earlier than in an unscrewing design. This can result in high maintenance costs.
- It can be quite difficult to incorporate water-cooling in the core. This becomes an increasingly important factor when moulding certain types of components where large quantities of heat must be removed from the core and becomes even more of an issue when moulding heat-sensitive materials.
- For straightforward nonsensitive applications, collapsible core mould tools may be simpler to construct than auto-unscrewing types. They can, however, be a more expensive option when larger numbers of impressions are being used.
- Moulding cycles are often slower than when using auto-unscrewing tools.

13.10 Using Silicone Rubber Sleeve Cores

Silicone rubber sleeve cores are a more recent development and can be quite useful for noncritical applications.

This system again uses a split core similar to the conventional collapsible core or a tapered pin construction depending on the severity of the undercut form. In this case the core pin carries a silicone rubber cap or sleeve at its tip, which has the thread form incorporated into it. When the mould tool is in the closed position, the rubber sleeve is kept stressed by the core pin. With a collapsible core design the tool opens and the core pin retracts and collapses, allowing the silicone sleeve to distort and permit the moulded thread form to be stripped off over it.

This is a cheap alternative system for use with simple, straightforward thread forms where thread form accuracy is not particularly important.

13.10.1 Advantages

- It is a simple alternative method for noncritical thread forms.
- It avoids split line witnesses associated with segment-type cores.
- Maintenance costs are lower as flash is less likely to form.
- It is considerably cheaper than split segment cores.

13.10.2 Disadvantages

- Not recommended for accurate thread forms or large production runs.
- Silicone sleeves need regular replacement.
- Heat conduction from silicone is not very good.
- Cooling cycles are longer.

Although the silicone sleeve has to be replaced regularly, the sleeves are very cheap. However, the mould tool would have to be stopped to permit replacement on a regular basis. Silicon sleeve inserts would not normally be a candidate for volume production, but they can be useful for prototyping or smaller production runs.

Figure 13.13 shows a basic tool design using a silicone sleeve core.

In operation, this tool opens with the simultaneous opening of the moving plate **C** and the ejection assembly **D**. As the mould opening continues, the moulding is ejected from the silicon core by virtue of it flexing out of the way and being forced off the end of the tapered pin **E**.

For deeper undercut forms the central pin is withdrawn before ejection takes place. For a severely undercut form a collapsible core may be used to allow more deflection of the silicon rubber.

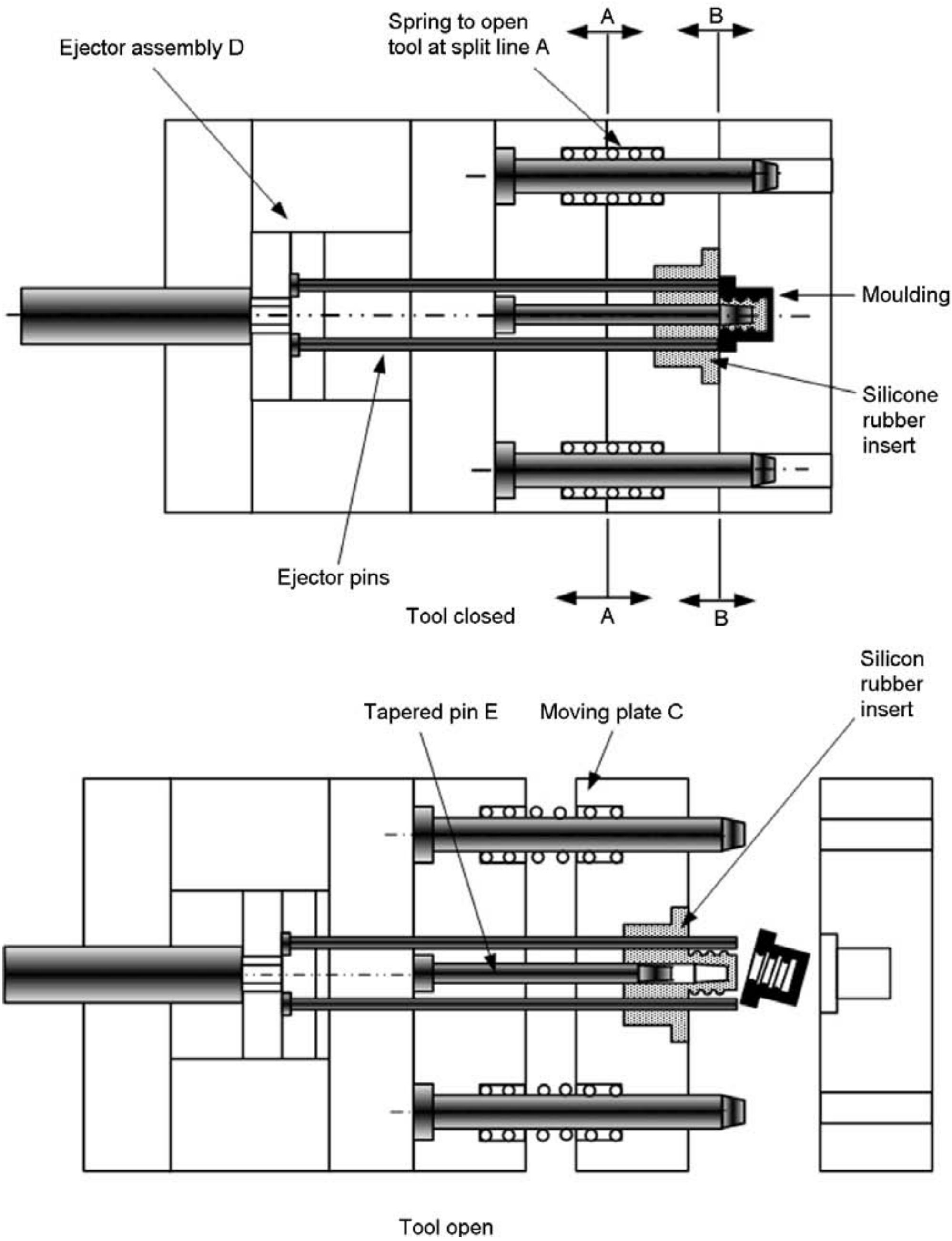


Figure 13.13 Silicone rubber core mould design

13.11 Core Unscrewing

Core unscrewing is used to free internal screw thread forms and falls into two broad categories:

- Core remains fixed with respect to the mould
- Core moves axially with respect to mould

The method selected will depend upon the application and on the geometry of the component. In both categories, a system of gearing is used to transmit the rotary motion to the unscrewing core from the driving source. Driving sources are discussed later in this section.

13.11.1 Fixed Core Systems

Fixed core systems are the most widely used method for automatic unscrewing. With this system, the core rotates in a static plane, simply revolving with no axial displacement of the core relative to the mould tool.

13.11.2 Cavity in Moving Half

In operation, as the core rotates, the component is driven upwards out of the cavity until the part is completely unscrewed from the core. In order for this to occur, however, the component must be prevented from rotating with the core. This is achieved by effectively keying the part so that it cannot rotate. This is most usually arranged by providing a series of splines or serrations around the periphery of the part. This allows the part to move up the splined cavity as the unscrewing process takes place. Figure 13.14 shows a basic arrangement for this design.

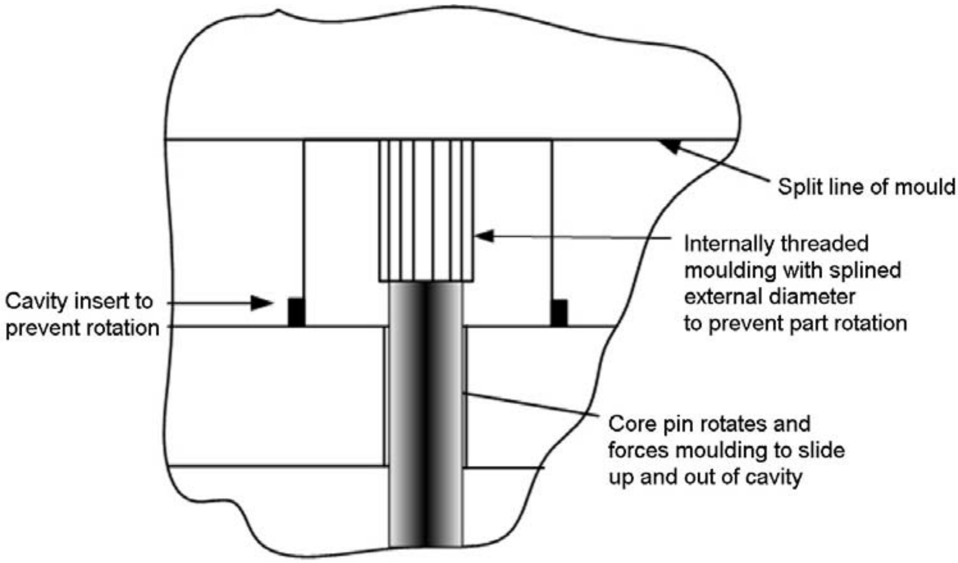


Figure 13.14 Basic design for rotating core – cavity in moving half

The basic design shown is one of the simplest types of core unscrewing designs, but the unscrewing phase must be delayed until the tool has opened. This ensures that the moulding has a free space to move into as unscrewing proceeds.

13.11.3 Cavity in Fixed Half

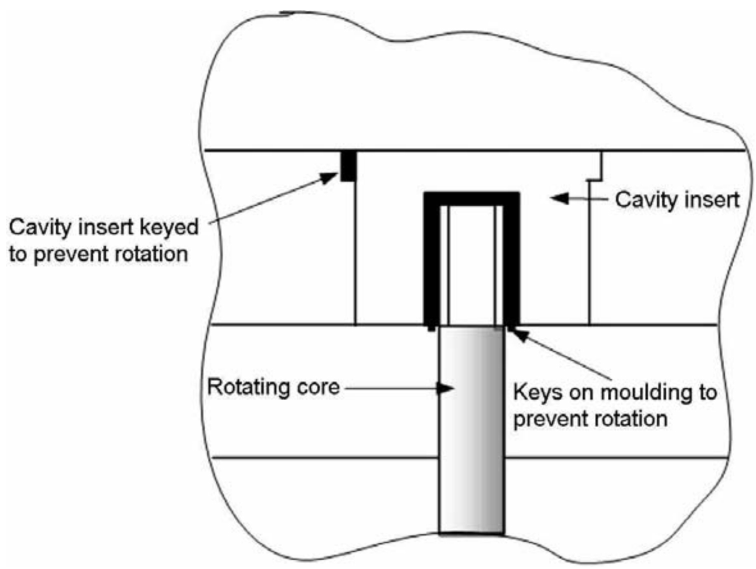


Figure 13.15 Basic design for unscrewing core – cavity in fixed half

This alternative design may be used to prevent part rotation by placing some small keys at the base of the moulding and placing the cavity in the fixed half as shown in Figure 13.15.

With this design, the moulding has been keyed from rotation by the introduction of small projections around the base of the moulding. Similarly, this design requires that core rotation does not take place until the tool has opened.

This design may only be used for very short thread form lengths, possibly on one or two complete threads at the most. This is because, as unscrewing progresses, the keys at the base of the moulding will progressively move out of the plate they are machined into. Clearly, if the thread length were longer than the depth of the keys, the keys would move out of location and the moulding would then spin freely as the unscrewing action takes place.

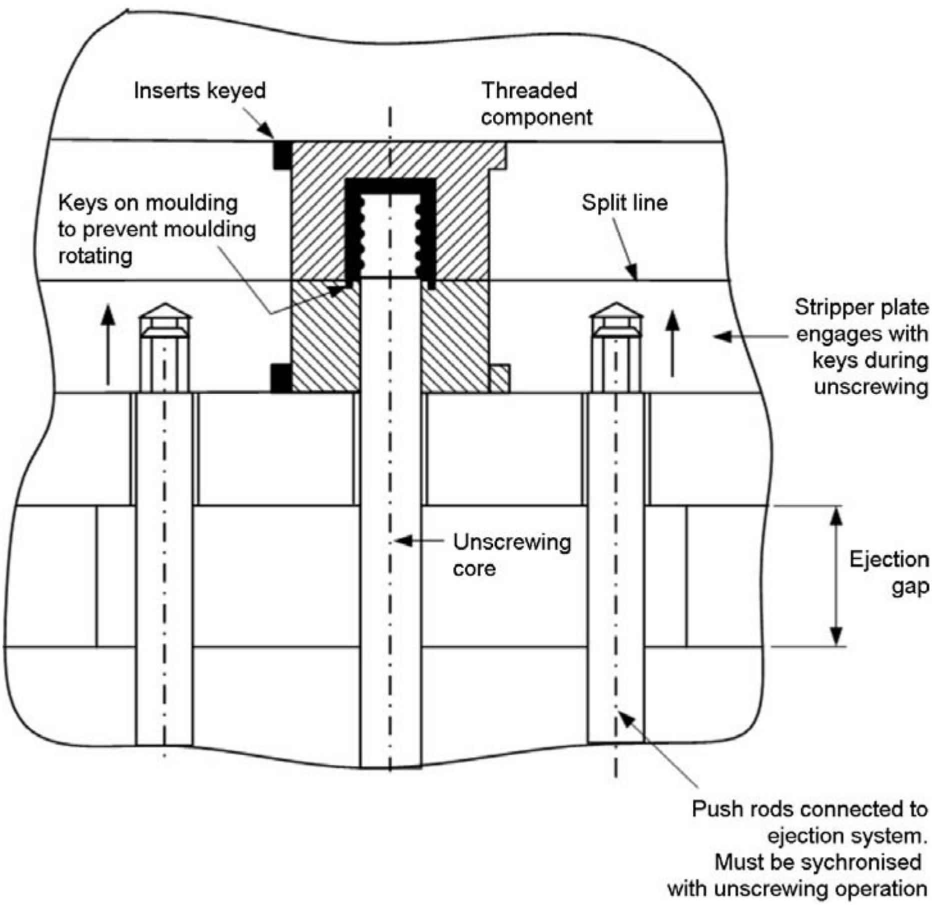


Figure 13.16 Unscrewing with synchronised stripper ejection

Although this design works for some parts, it is usually desirable to incorporate a stripper support plate to maintain contact at the base of the component. This ensures that the keys are kept in secure location as unscrewing progresses and allows a greater thread length to be moulded. The basic system for this design is shown in Figure 13.16. Note also that it is essential to key all cavities where the unscrewing action may try to rotate the cavity insert.

With this design the mould opens first and then unscrewing takes place with a stripper plate supporting the moulding throughout the unscrewing phase. This may be achieved by spring loading the stripper plate or using a lead screw to actuate the stripper plate. When using the lead screw or jackscrew design it is essential they have the same pitch and form as the part being unscrewed to synchronise the movement of the stripper plate with the unscrewing operation. The spring loading and jackscrew designs are shown in Figures 13.17 and 13.18.

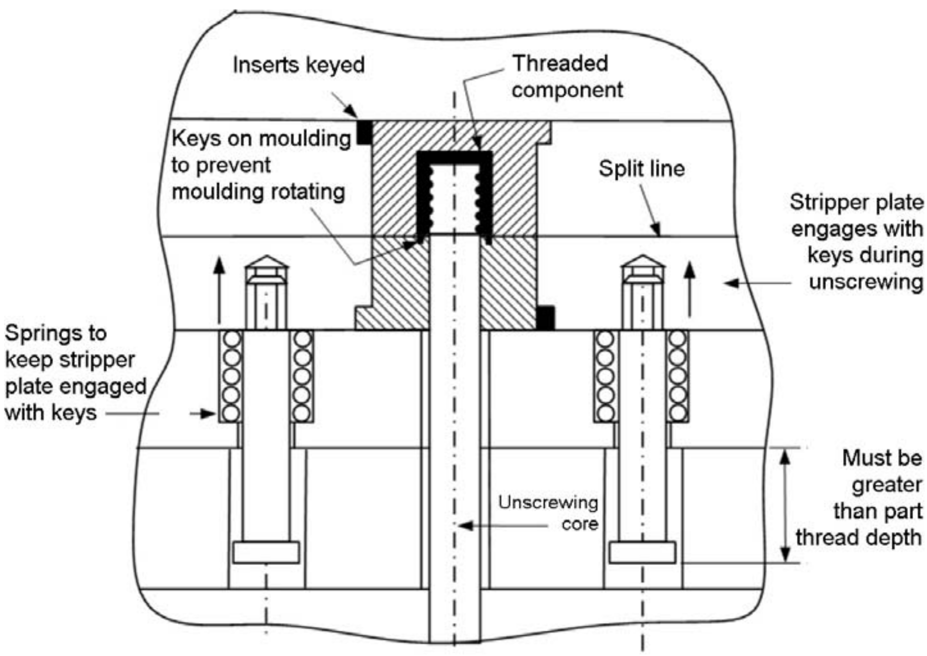


Figure 13.17 Unscrewing with spring-assisted stripper ejection

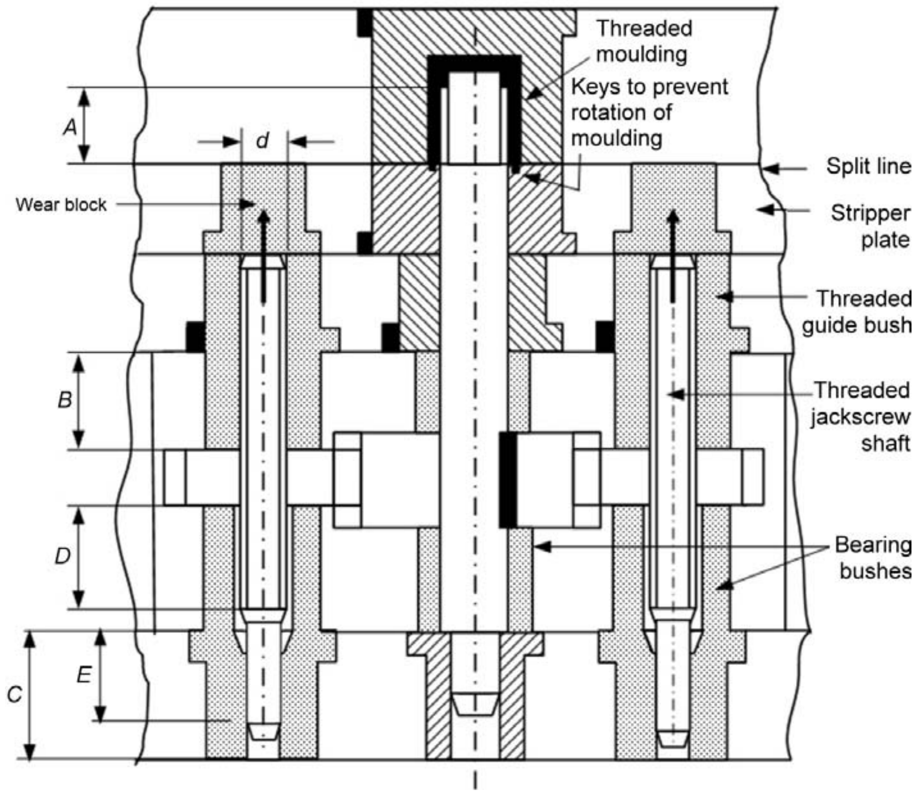


Figure 13.18 Unscrewing design with jackscrew actuating stripper plate

13.11.4 Key Design Features of Figure 13.18

- Dimensions *B* and *C* must be greater than dimension *A*.
- Dimension *C* should be greater than dimension *B*.
- Dimensions *D* and *C* should be greater than dimension *B*.
- The lead screw must be the same thread form and pitch as the moulded thread.
- The unscrewing gear meshes with lead screw gears to ensure synchronisation.
- The stripper plate moves forward in synch with unscrewing to ensure keys are kept engaged throughout unscrewing operation.
- A microswitch or similar device will be needed to stop the unscrewing motion to prevent the lead screw running out of location.

For most application the following guidelines are useful:

$B = A + 5$ mm

$C = B + 1.5d$

$D = B + 1.5d$

$E = A + d$

13.12 Anti-Rotation Keying

13.12.1 Base Key Geometry

Where the mould opens before the unscrewing operation, the component will be left on the moving half of the mould. In this case it is necessary to shape the keying features on the base of the moulding as shown in Figure 13.19. The keys must combine two essential functions:

- Maximum resistance to rotation
- Ease of final removal from mould

The key face that opposes the direction of unscrewing should be vertical (or slightly off vertical). The trailing face must be angled to assist with subsequent ejection.

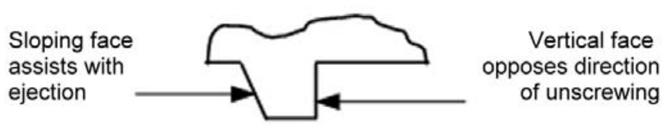


Figure 13.19 Unscrewing key geometry

For applications where unscrewing takes place before mould opening, any form that provides a keying feature will be satisfactory, including that shown above. This may be either an existing feature or one that will have to be specially introduced. If a keying feature is not already available as part of the existing design, then a suitable design will have to be agreed with the product design engineer. A simple square or triangular form running down the outside of the moulding is frequently used, as shown in Figure 13.20.

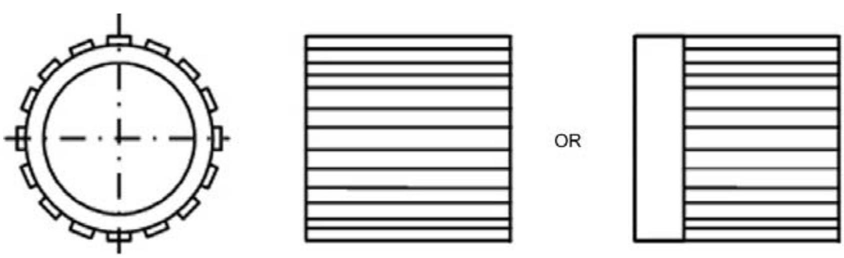


Figure 13.20 Typical serrated form on part to prevent part rotation

The golden rule is to examine the mould design carefully to establish what kind of keying is required and incorporate it into the design so that it will resist the unscrewing operation without any damage occurring.

13.13 Moving Core Systems

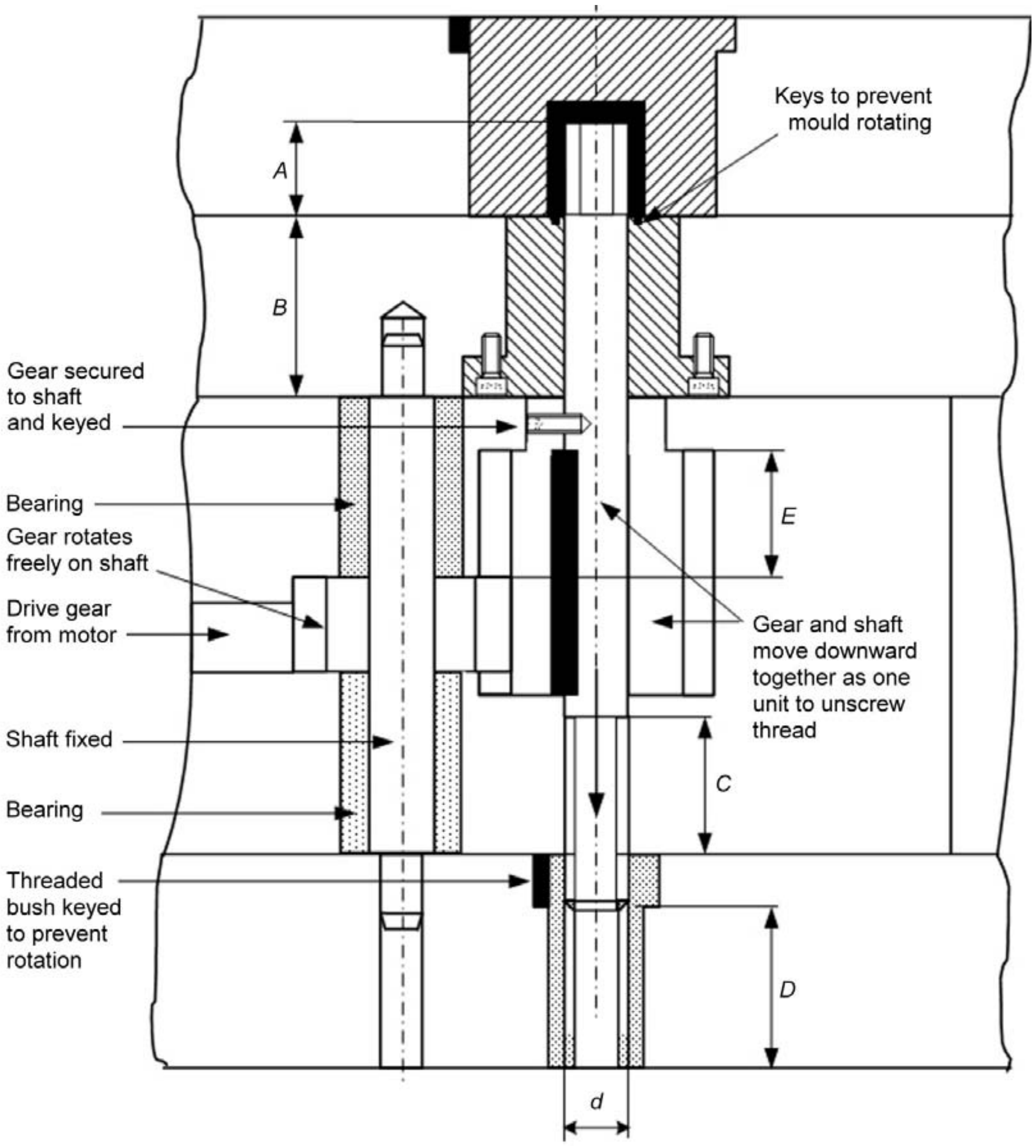


Figure 13.21 Unscrewing with moving core

With this type of design, the unscrewing core moves axially away from the moulding to release it. According to the design, this leaves the moulding sitting either on top of the split line or in the cavity. Depending on the part geometry and the general tool design, some additional ejection facility may be needed. Longer screw threads may be unscrewed with this design than with the floating stripper plate method. Figure 13.21 shows a typical moving core arrangement.

In this design, it is normal to include keys around the base of the moulding as discussed previously. This again provides resistance to the moulding turning during the unscrewing phase, but in this case a supporting stripper plate is not necessary. This is because the core is unscrewing downwards, out of the moulding, and hence the keys are not forced out of location as in the fixed core design.

An alternative that is sometimes used is to unscrew the moulding before the mould opens. This would require that splines or other keying features be machined into the cavity. However, this poses another difficulty in that the moulding remains in the cavity after the unscrewing phase. This in turn means that some form of fixed-half ejection would be needed to extract the moulding from the cavity. While this type of design is sometimes necessary for parts with complex geometry features, it is advisable to ensure that the moulding remains on the moving half. This simplifies the design and construction of the mould tool.

13.13.1 Key Design Features

- The mould tool opens before unscrewing takes place.
- The core moves downwards as unscrewing takes place.
- The moulding has to be keyed.
- A microswitch or other device is necessary to prevent overrun.
- Dimension B should be greater than dimension A.
- Dimension C should be less than dimension B.
- Dimension D should be greater than dimension A.
- Tool components must be keyed against rotation where shown.
- Similar guidelines apply as for static core systems:
    - $B = A + 1.5d$
    - $C = A + 2d$
    - $D = A + 2.5d$
    - $E = A + d$

13.14 Cavity Rotation

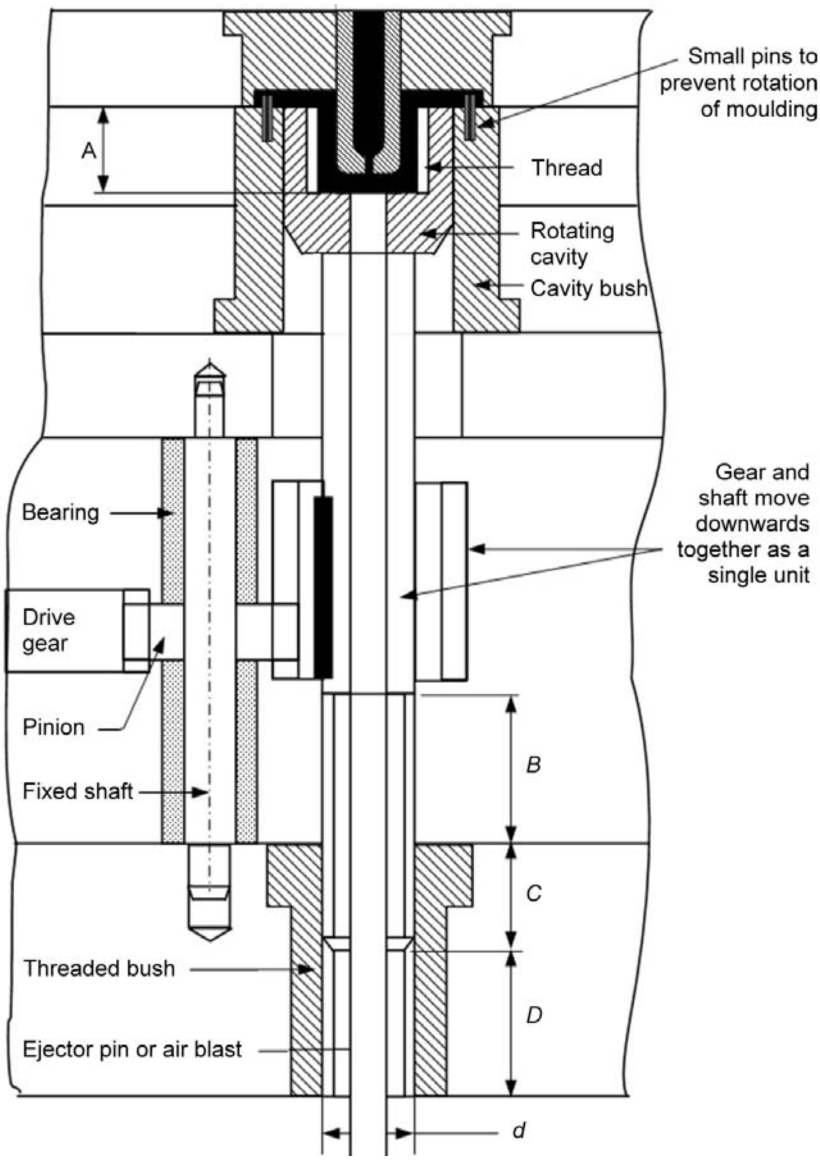


Figure 13.22 Cavity unscrewing design

Cavity unscrewing is normally used for unscrewing external threads where the use of splits has been discounted, and on more complex components in conjunction with core unscrewing where the part has more than one thread. Cavity unscrewing may also be used for unscrewing internal threads where the thread form is located in the fixed half of the tool.

The principles involved are similar to those already described for a moving core. Figure 13.22 shows a typical arrangement for cavity unscrewing a precision external thread form where split line witnesses resulting from using splits is undesirable. The moving cavity insert must be fully hardened and be a good rotary fit in the mating insert, which also is fully hardened.

In this case, two keys are provided in the form of two small pins in the rear half-cavity bush to prevent rotation of the moulding during unscrewing. The inclusion, form and positioning of anti-rotation keys may have to be agreed with the product engineer if there is no suitable geometry on the part that can be used for this purpose.

This design is based on the unscrewing operation taking place ***after*** mould opening to ensure the moulding is pulled off the core pin on the front half of the mould. This may leave the moulding resting in the unscrewing cavity. To make sure this does not happen, an ejector or air blast should be provided to make sure the mouldings clear the mould tool.

It is also necessary to close the mould ***before*** the moving cavity is screwed back to the split line. This is to allow the moving cavity to butt up against the fixed-half insert, enabling it to shut off properly. This is the safest method to prevent overrun and underrun of the cavity, which could cause damage or flashing. A micro switch can be included if considered necessary to prevent the threaded gear shaft over running into its threaded guide bush.

Figure 13.23 shows the mould after unscrewing operation has finished and ejection about to begin.

Cavity rotation systems are more expensive to design and construct than rotating core designs. Always use rotating core designs in preference to rotating cavity designs for internal threads where this is possible for this reason.

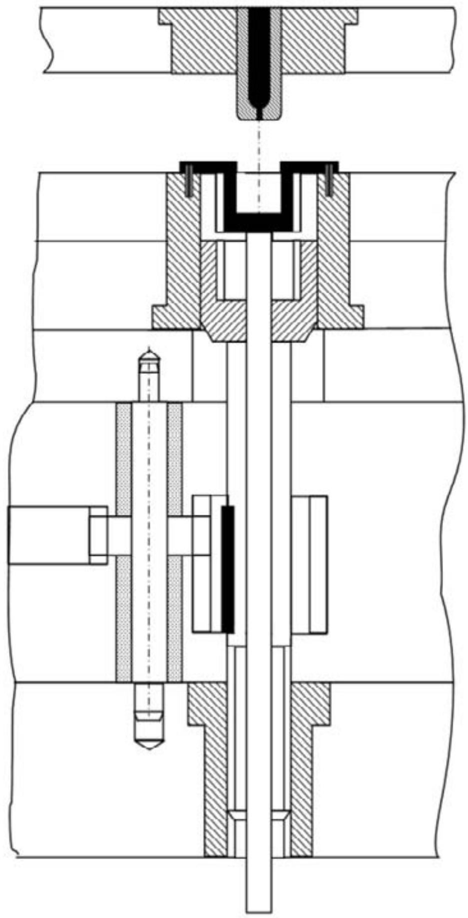


Figure 13.23 Cavity unscrewing design

13.14.1 Key Design Features

- The cavity moves downwards as unscrewing takes place.
- It can be used for internal threads in fixed half or external threads.
- The cavity may be in the fixed or the moving half of the tool.
- The moulding may require keying against rotation.
- Dimension $B = A + d$.
- Dimension $C = 1.5d$.
- Dimension $D = A + d$.

13.14.2 Guidelines

- Always use a rotating core design in preference to rotating cavity designs for internal threads where this is possible. Rotating core designs are less expensive and more reliable.
- For external threads always choose to mould a thread in splits over a rotating cavity where a split line witness can be tolerated along the thread form. Moulding threads in splits is significantly lower in cost.

13.15 Two-thread Unscrewing Designs

13.15.1 Discussion

In many applications multithreaded components are required, often with different pitches and thread forms. Such components can present challenging design problems for the mould tool designer. To accommodate such requirements it is necessary to incorporate and combine features drawn from the preceding sections on static and moving cores and possibly rotating cavity designs as well. The main difficulty is in achieving a design that will be reliable in production and that will not be prone to breakdowns or require frequent servicing. With so many potential sliding/rotating elements, flash is an ever-present possibility.

In view of these difficulties, considerable thought must be input at the design stage and, of course, for such designs a first class toolmaker will have to be used.

13.15.2 Key Design Features for Two External Threads

Figure 13.24 shows a design using unscrewing cavities for two external threads with different pitches. This design centres around two threaded sleeves, one rotating within the other and moving downwards at different rates.

It is important to control the start and finish phase of unscrewing to avoid damage.

Key Design Features (Figure 13.24)

- Two rotating sleeves one inside the other and moving at different rates relative to each other.
- Each sleeve carries the moulding thread form and the unscrewing thread.
- Each sleeve must the have same the pitch for unscrewing as the moulding thread.
- High quality screw threads must be used for unscrewing.
- Minimum backlash in the gears system is required.

- Close tolerance sliding fits and rotary fits are required.
- Dimensions *E* and *F* must be greater than dimension *A*.
- Dimensions *C* and *G* must be greater than dimension *B*.
- Dimension *D* must be greater than the larger of (*A* or *B* + clearance).
- Dimension *D* should be greater than dimension *F*.

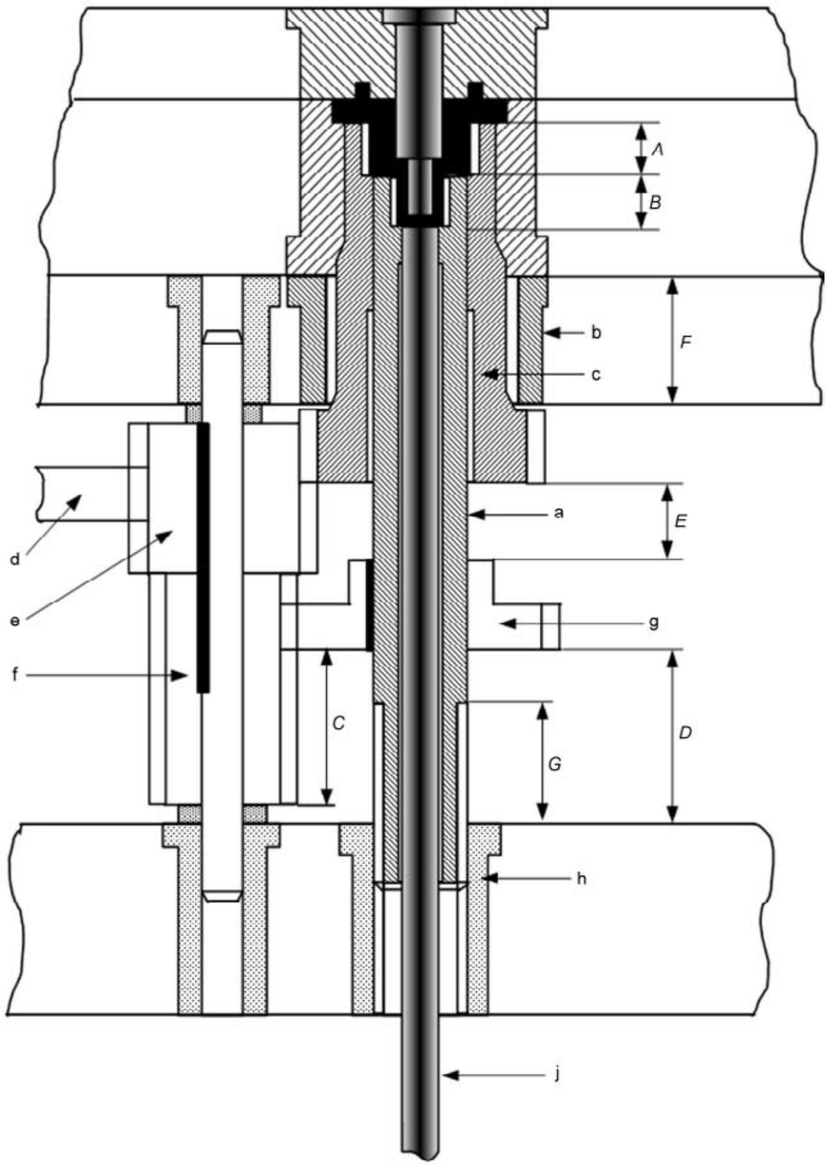


Figure 13.24 Double cavity unscrewing design for two threads with different pitches

Key to Figure 13.24

- *A* Length of the larger-diameter thread.
- *B* Length of the smaller-diameter thread.
- **a** Threaded sleeve (moulded thread at one end, unscrewing thread at other; must be same pitch).
- **B** Threaded sleeve (same pitch as outer moulded thread).
- **c** Outer unscrewing cavity (mates with b).
- **d** Driving gear.
- **e** Pinion gear (mates with gear c).
- **f** Pinion gear (mates with gear g).
- **g** Gear keyed to shaft a (mates with gear f).
- **h** Threaded bush for sleeve a (must be same pitch as moulded thread).
- **j** Ejector pin.

13.15.3 Operation

After the tool opens at the main split line, the unscrewing operation starts with the driving gear **f** driving gears **c, e, f** and **g.**

As **c** is unscrewed, **a** also starts unscrewing at the same time. In this scenario, the pitch of **a** is greater than the pitch of **c**. Therefore as **c** moves down, **a** will also move down but will move a greater distance in the same time. However, sleeve **c** must unscrew at least distance *A* and sleeve **a** must unscrew at least a distance *B* whatever the pitch of either thread.

Hence, dimension *D* has to provide clearance for the downward movement of **c** plus any downward movement of **a** relative to **c.** The safe option here is to make *D* greater than the larger of ($A + B$) plus the amount of overrun of each sleeve).

Once the unscrewing phase has finished, ejector pin **j** is actuated to eject the component out of the tool.

If this scenario were reversed and thread **A** had a larger pitch than **B**, then the relative movement between **a** and **c** would also be reversed. That is **c** would unscrew faster than **a**. However, apart from this, the general principle of operation would remain the same.

Unscrewing One Internal and One External Screw Thread

Designs to accommodate unscrewing an internal and external thread simultaneously are often similar to the design in Figure 13.24 with some modifications. There are many design variations on this theme that differ in detail, but the fundamental requirement is a rotating cavity that unscrews the external thread and a rotating unscrewing core running inside it.

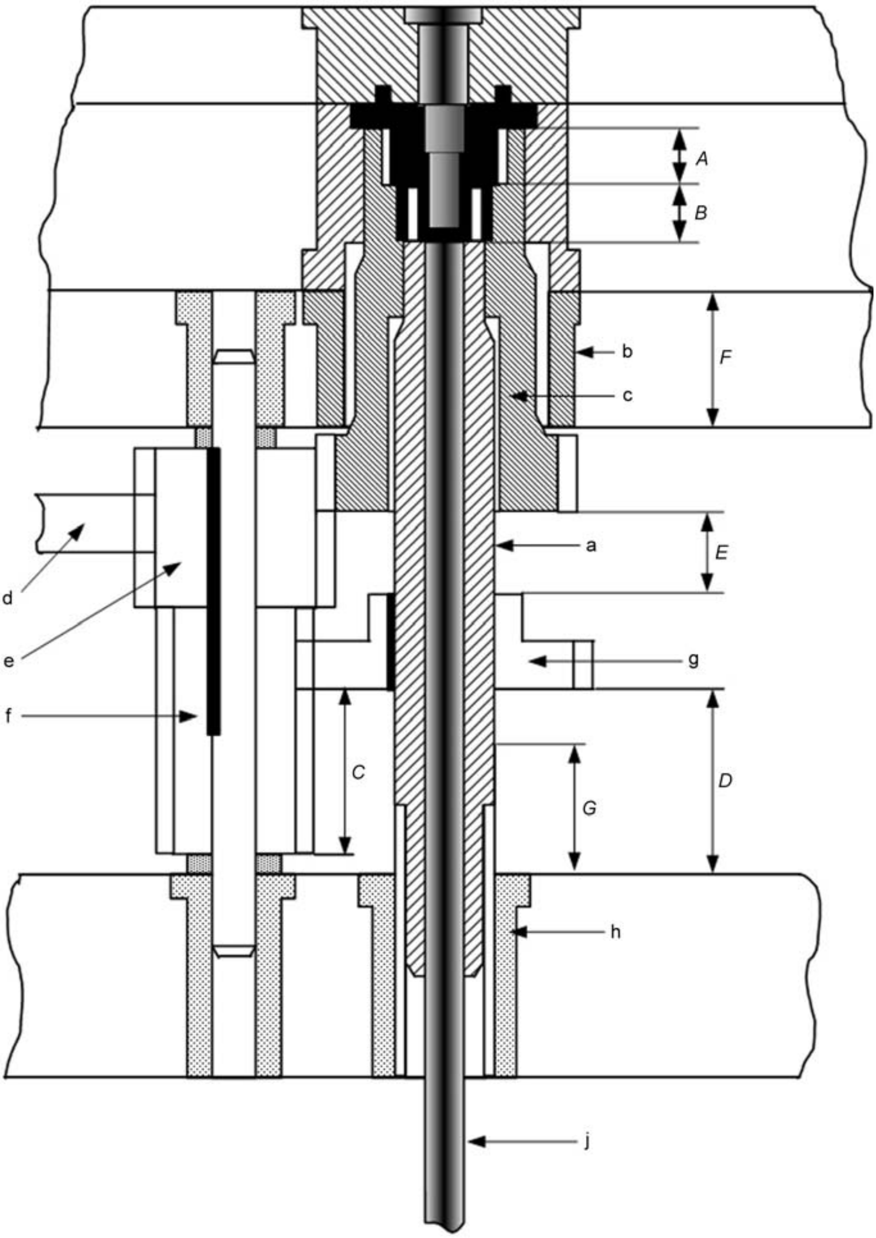


Figure 13.25 Unscrewing design for one external and one internal thread with different pitches

Figure 13.25 shows a design using an unscrewing cavity and core for one internal and one external thread with each having a different pitch. This design also centres on a threaded sleeve rotating around a rotating core, one within the other and moving downwards at different rates.

It is important to control the start and finish phase of unscrewing to avoid damage.

13.15.4 Key Design Features

- One rotating sleeve running on one rotating core and moving at different rates relative to each other.
- The sleeve and core carries the appropriate moulding thread form and the unscrewing thread.
- Each of these must the have the same pitch for unscrewing as the moulding thread.
- High quality screw threads must be used for unscrewing.
- Minimum backlash in the gears system is required.
- Close tolerance sliding fits and rotary fits are required.
- Dimensions *E* and *F* must be greater than dimension *A*.
- Dimensions *C* and *G* must be greater than dimension *B*.
- Dimension *D* must be greater than the larger of dimensions (*A* or *B* + clearance).
- Dimension *D* should be greater than dimension *F*.

Key to Figure 13.25

A Length of external thread.

B Length of internal thread.

a Threaded shaft (moulded thread at one end, unscrewing thread at other; must be same pitch).

b Threaded sleeve (same pitch as outer moulded thread).

c Outer unscrewing cavity (mates with **b**).

d Driving gear.

e Pinion gear (mates with gear **c**).

f Pinion gear (mates with gear **g**).

g Gear keyed to shaft **a** (mates with gear **f**).

h Threaded bush for shaft **a** (must be same pitch as moulded thread).

j Ejector pin.

13.15.5 Operation

After the tool opens at the main split line, the unscrewing operation starts with the driving gear **f** driving gears **c, e, f** and **g**.

As **c** is unscrewed, **a** also starts unscrewing at the same time. In this scenario, the pitch of **a** is greater than the pitch of **c**. Therefore as **c** moves down, **a** will also move down but will move a greater distance in the same time. However, sleeve **c** must unscrew at least distance *A* and sleeve a must unscrew at least a distance *B* whatever the pitch of either thread.

Hence, dimension *D* has to provide clearance for the downward movement of **c** plus any downward movement of **a** relative to **c.** The safe option here is to make *D* greater than the larger of (*A* or *B*) plus the amount of overrun of each sleeve).

Once the unscrewing phase has finished, ejector pin **j** is actuated to eject the component out of the tool.

If this scenario were reversed and thread **A** had a larger pitch than **B**, then the relative movement between **a** and **c** would also be reversed. That is **c** would unscrew faster than **a**. However, apart from this, the general principle of operation would remain the same.

An alternative design for unscrewing an internal and external thread is to internally thread sleeve **c** and externally thread shaft **a** with the same thread which has the same pitch as the internally moulded thread form so that **a** will screw up and down **c.**

13.16 Gearing Geometry

13.16.1 Introduction

In order to design gear unscrewing mechanisms it is necessary to have a basic understanding of gear geometry. This will enable the designer to select and specify appropriate gears, lead screws and gear ratios.

There are several types of gear forms in use that cover a wide range of applications from clock making to heavy plant and machinery. However, the only type of gear form that is used for gear unscrewing purposes is the involute form. For these purposes a sufficient definition of the involute curve is: 'The path traced by the end of a piece of string being held taught, as it is unwound from a drum' (Figure 13.26).

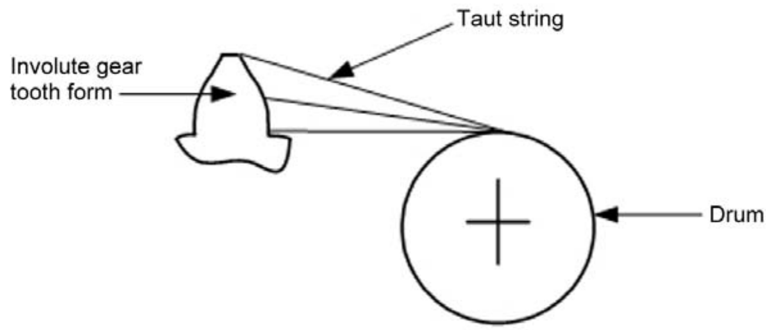


Figure 13.26 Generation of involute gear tooth form

Involute gearing is used for relatively smooth transmission of power and motion and is used for a very wide range of straightforward and precision applications. The basic geometry is shown in Figure 13.27.

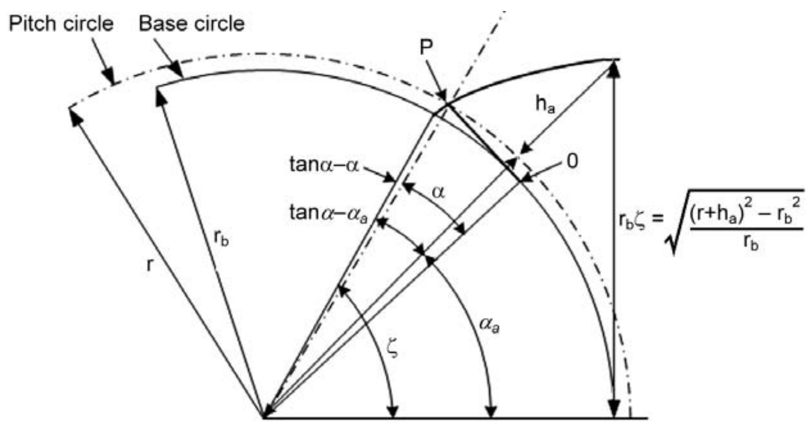


Figure 13.27 Geometry of the involute form

Key to Figure 13.27

h_a = height of addendum

r = radius of pitch circle or reference circle

r_b = radius of base circle

α = pressure angle at reference circle

ζ = total curvature of involute from base circle to tip

α_a = pressure angle at the tip

PO = $r \sin \alpha$

$r_b = r \cos \alpha$

$$\frac{PO}{r_b} = \tan\alpha$$

$$\cos a_a = \frac{r_b}{(r + h_a)}$$

$$\zeta = \tan\alpha = \sqrt{\frac{(r + h_a)^2 - r_b{}^2}{r_b}}$$

The angle subtended between the start of the involute and point P on the reference circle is the involute function of the angle α and is expressed as **inv α**, where:

$$\text{inv}\ \alpha = (\tan\alpha) - \alpha$$

Similarly, the angle subtended between the start of the involute and its outer extremity is the involute function of the angle α_a and is given by:

$$\text{inv}\ \alpha_a = \tan\alpha_a - \alpha_a$$

where angles α and α_a are expressed in radians.

There are two types of involute gearing that are used for the transmission of power and motion:

- *Spur gears:* These are gears in which the teeth are parallel with the axis of the gear. This type of gear is suitable for a very wide range of applications and used for nearly all unscrewing designs.
- *Helical gears:* These are gears in which the teeth are set at an angle to the axis of the gear and follow the form of a helix. They provide better continuous tooth-to-tooth contact and are used for more precise and heavier load bearing applications.

As the vast majority of geared unscrewing systems use spurs gearing we will restrict our analysis to these.

13.16.2 Basic Spur Gear Definitions

Number of teeth	The total number of teeth the gear has
Pitch circle diameter (PCD)	The pitch circle is the effective (imaginary) working circle of a gear which would be obtained if a pair of gears were replaced with disks that transmitted the same motion through contact friction
Diametral pitch (DP)	The number of teeth per inch of the PCD (Imperial)
Module	The number of mm of PCD per tooth
Addendum	The height of the tooth above the PCD

Dedendum	The depth of the tooth below the PCD
Pressure angle	The angle between the common normal of the two mating tooth surfaces and the common tangent plane of the pitch cylinders

13.16.3 Basic Spur Gear Formulae

For mould design purposes only one relational formula is normally necessary.

13.16.3.1 DP Gears (Imperial)

Diametral pitch gears are the older imperial specification, but as they are still in use the formulae are given here. All measurements are in inches.

$$DP = \frac{No.\,of\ teeth}{PCD}$$

13.16.3.2 Module Gears (ISO)

$$Module = \frac{PCD}{No.\,of\ teeth} \quad (13.1)$$

The PCD and the Module are expressed in millimetres.

13.16.4 Conversion Between ISO and Imperial Systems

$$Module = \frac{25.4}{DP}$$

$$DP = \frac{25.4}{Module}$$

13.16.5 Example Gear Calculations (ISO)

Let us suppose we wish to design a gear train for an unscrewing operation. Firstly, the motor speed is too high as supplied and must be geared down from 100 rpm to 60 rpm for this particular job. Secondly, we have to increase the distance between the drive gear and the driven gear to accommodate the diameter of the motor body. The diameter of the rotating core is fixed at 10 mm. We also want to have the same direction of rotation on driving and driven gears.

In order to meet the first condition we must have a gear ratio between driving and driven gears of 60:100.

To meet the second condition we need to introduce an idler gear between the driving and driven gears. An idler gear is a gear placed between two gears to increase the distance between them and to preserve the direction of rotation between driving and driven gears. It has no other effect (see Figure 13.28).

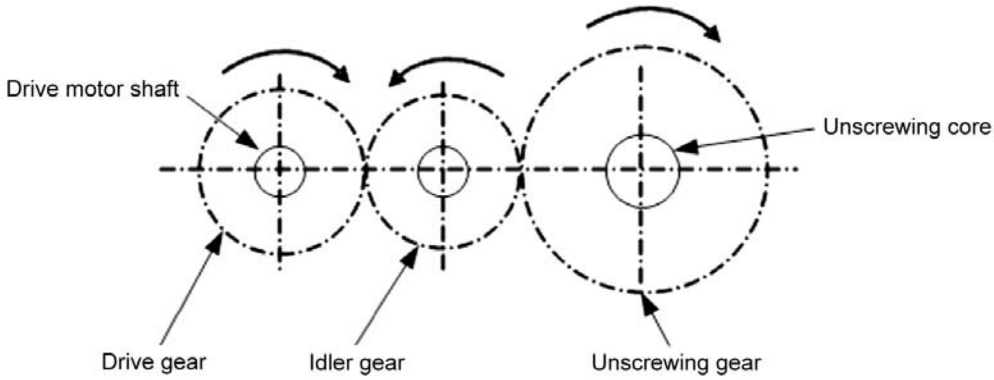


Figure 13.28 Unscrewing gear layout

Clearly we do not want the gear system to take up too much space, so we will assume in this case that the unscrewing gear will have a PCD of 40 mm. This leaves enough meat in the middle of the unscrewing gear for the unscrewing core to pass through.

The next stage is to decide the module of the gear, which we will choose to be 1. From formula (13.1) we have:

$$Module = \frac{PCD}{No. of\ teeth}$$

Hence, we have:

$$1 = \frac{40}{No. of\ teeth}$$

Giving number of teeth = 40.

Now to gear down the motor speed we need the driving gear to have 60/100 × 40 = 24 teeth.

The idler gear is needed to preserve the direction of rotation between driving and driven gears and may have any number of teeth providing it has the same module; however, we might as well choose this to have 24 teeth like the driving gear. Thus we have the result shown in Figure 13.29.

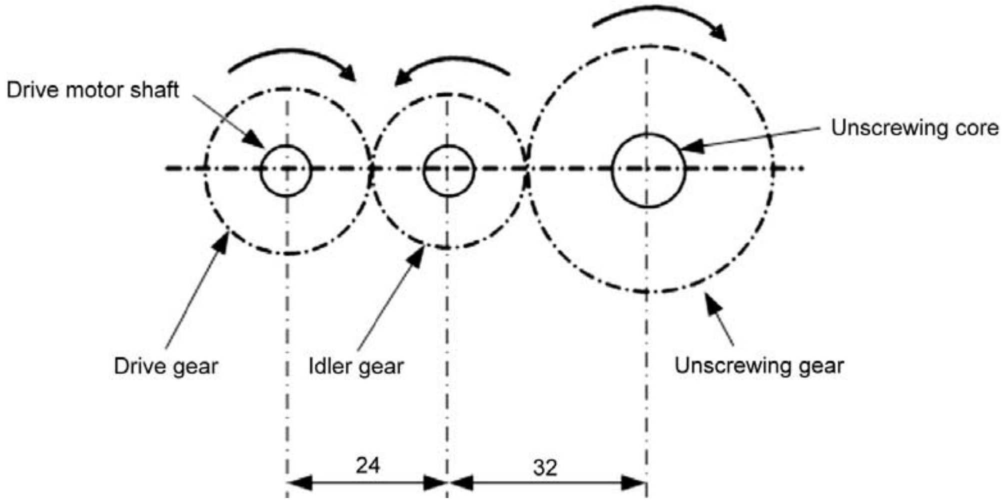


Figure 13.29 Unscrewing gear centres

The PCD of the driving and idler gears is 24, hence the centres between the idler and driven gears will be 0.5 × (PCD idler + PCD driven gear) = 0.5 × (24 + 40) = 32.

13.16.6 Guidelines for Gear Selection (ISO)

Module	Values in the range 0.5 to 2 are generally suitable. All gears in the train must have the same module.
No. of teeth	Must have at least 12 teeth; fewer teeth than 12 = problems.
PCD	The smallest gear must be large enough to accept a shaft to run on.
Idler gears	Can have any number of teeth (greater than 12).
Material	Good-quality steel. Should be hardened for long-running jobs.

13.16.7 Guidelines for Gear Train Design (ISO)

This guide is suitable for most gear trains. However, there may be occasions on which a different approach may be necessary depending on the circumstances.

1. Choose a motor of sufficient power and speed.

2. Determine a suitable PCD for the drive gear, large enough to enable the motor shaft to be secured and keyed in it. (Also see (6) below.)

3. Choose a module for the drive gear. This will determine the number of teeth on it as described above.

4. If the motor speed needs reducing, calculate the number of teeth required on the driven gear (60–180 rpm is the norm for most unscrewing operations).

5. If the distance between the centres of the drive gear and the driven gear is not large enough and you want to have the same direction of rotation on the driving and driven gears, introduce an idler gear between them.

6. If you want the driven gear to rotate in the opposite direction to the drive gear, then mesh the drive and driven gears directly together. The gears will have to be large enough to give sufficient distance between their centres depending on the tool design and the size of the motor and where it is mounted. This is best effected by using a higher number of teeth on each gear.

13.17 General Mould Design Guide for Threads

The following notes are intended to provide a checklist for deciding the method of approach when designing injection mould tools for components having integral thread forms in them.

13.17.1 Observation

Although it has been mentioned repeatedly before, it cannot be emphasized enough that the most reliable and trouble-free mould tools are those that have the simplest possible design and construction. This is particularly true for threaded parts and it pays dividends to ensure that intricate unnecessary designs are avoided by spending sufficient time to establish a simple, reliable, robust design.

13.17.2 Stage 1

13.17.2.1 Preliminary Considerations

- Perform critical analysis of thread forms on the component.
- Establish the method of machining thread forms in the mould.
- Decide the driving source.

13.17.2.2 Thread Form

- Study the thread form requirements.
- Analyse for suitability of manufacture.
- Avoid thread design that have feather edges.
- Discuss the operating environment with the product engineer.

13.17.2.3 Method of Thread Production

- Determine whether a split line witness along the axis of the thread can be tolerated. If the answer to this is yes, then producing the thread in splits should be a front-runner for external thread forms.

  Don't forget that this method still requires using a high-class toolmaker. Polishing the thread form with the splits clamped together can result in a barely perceptible split line witness.

- If the thread form is not critical and split line witnesses from a collapsible core would be acceptable, then consider this method for internal thread forms.
- If split line witnesses are unacceptable, then choose an auto-unscrewing design.
- Given that an auto-unscrewing design is to be used, the method of unscrewing has to be decided:
  1. Axially moving or axially static rotating cores for internal threads.
  2. Axially moving or static designs for rotating cavity designs.

13.17.2.4 Driving Source

- Decide the driving source method.
- Rack-and-pinion is cheapest and simplest.
- Hydraulic motor is more expensive but very reliable and controllable.
- Pneumatic motor is cheaper than a hydraulic motor but has less power and is less controllable.
- Electric motor is less controllable and has less power than a hydraulic motor. Stepper designs are a possibility for difficult shut-off problems.

13.17.3 Stage 2

13.17.3.1 Predesign Phase

- Produce alternative design sketches.
- Establish basic mould tool design.

13.17.3.2 Basic Mould Design

Spend sufficient time in establishing the correct basic design features of the tool:

1. Split lines
2. Method of cavity design and construction
3. Type of ejection
4. Method of gating
5. Material-related requirements
6. Cooling requirements
7. Expected tool life

13.17.3.3 Alternative Design Sketches

- Spend some time examining alternative ways of designing and constructing the mould tool. Sometimes this exercise will produce a better design than the 'obvious' one. This becomes more advantageous the more complex the design is.
- Critically appraise the cavity and core design. Look at the cavity construction from a toolmaking point of view.
- Try to reduce the number of moving parts to a minimum.

13.17.4 Stage 3

13.17.4.1 Integrating the Design Features

- Once all the individual design elements have been decided, look at the design as an integrated whole and amend if necessary.
- Incorporate as many standard items as possible.
- Do the gearing calculations and establish the movements necessary. This will quantify these parameters for the final tool design.

13.17.5 Stage 4

13.17.5.1 Main Design Phase

- Establish the number of views necessary to fully describe the design.
- Design the tool.

13.17.5.2 Number of Views

- It is important to establish this at an early stage, as it can be difficult to include more views at a later stage. If necessary use additional drawings to fully explain the design and include detail drawings of the cores and cavities where the design is complex.
- It is important to make sure sufficient views are included to enable the reader to understand clearly what is going on. Unscrewing tools in particular can get quite complicated and more views and information may be necessary with these designs.

13.17.6 Stage 5

13.17.6.1 Design Review

- Check the design ***again*** for correct operation and function.
- Make sure the correct materials have been used.

13.17.6.2 Correct Function

- Run through the entire opening, unscrewing, and closing sequences and other features of the tool to ensure everything functions and works correctly. This can save having to rectify expensive mistakes after the tool has been made.
- A lot of sliding/rotary motion takes place in these types of tools, so double check that compatible materials have been used and clearly specify any hardening requirement.
- The mould is almost always drawn in the closed position and this can make it difficult to visualise the unscrewing sequences in complex moulds. It is recommended that the main sectional view of the mould also be drawn, showing the mould open and after the complete unscrewing operation has taken place. It is surprising how frequently this shows up fundamental errors of design and is well worth doing.
- It is a good practice to get another designer to check your design for errors wherever this is possible. A fresh pair of eyes can often pick up problems that have been missed by the original designer.
- Alternatively, leave the design for a couple of days and then look at it critically again for errors or possible improvements. It is surprising how this ‘fresh look’ will highlight any deficiencies or possible improvements.

13.18 Driving Systems

All automatic unscrewing mould tools need some type of driving device to provide the necessary rotary motion. Although a wide variety of novel approaches have been tried over the years, there are four main driving systems that are in normal use today:

- Rack-and-pinion systems
- Pneumatic motors
- Hydraulic motors
- Electric motors

13.18.1 Rack-and-Pinion Systems

Rack-and-pinion systems are a cheap, convenient method of driving unscrewing systems. There are two basic ways in which they are used:

- Via the opening movement of the mould tool
- Actuation by a pneumatic or hydraulic cylinder

13.18.2 Opening Movement of Mould Tool

This is the simplest of all the systems. Figure 13.30 shows a typical arrangement, with unscrewing taking place through a rack **A** secured to the tool turning a pinion and another rack **B** through to the unscrewing components.

There can be backlash in this arrangement, so it should be used for relatively noncritical applications; it is used for a wide variety straightforward work.

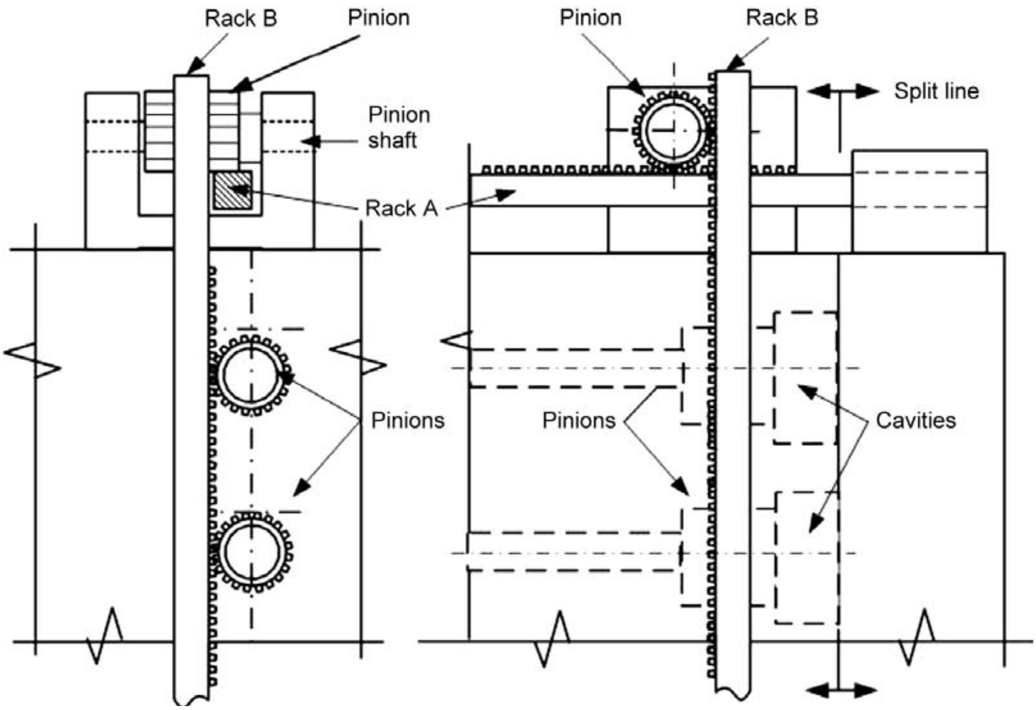


Figure 13.30 Unscrewing actuated by opening of mould with rack and pinion system

13.18.3 Actuation by Cylinder

The most frequently used design is based on connecting a number of racks to a common manifold and then using a cylinder to actuate the rack/carrier plate system. For this approach to work it is necessary to place the impressions in line as shown in Figure 13.31.

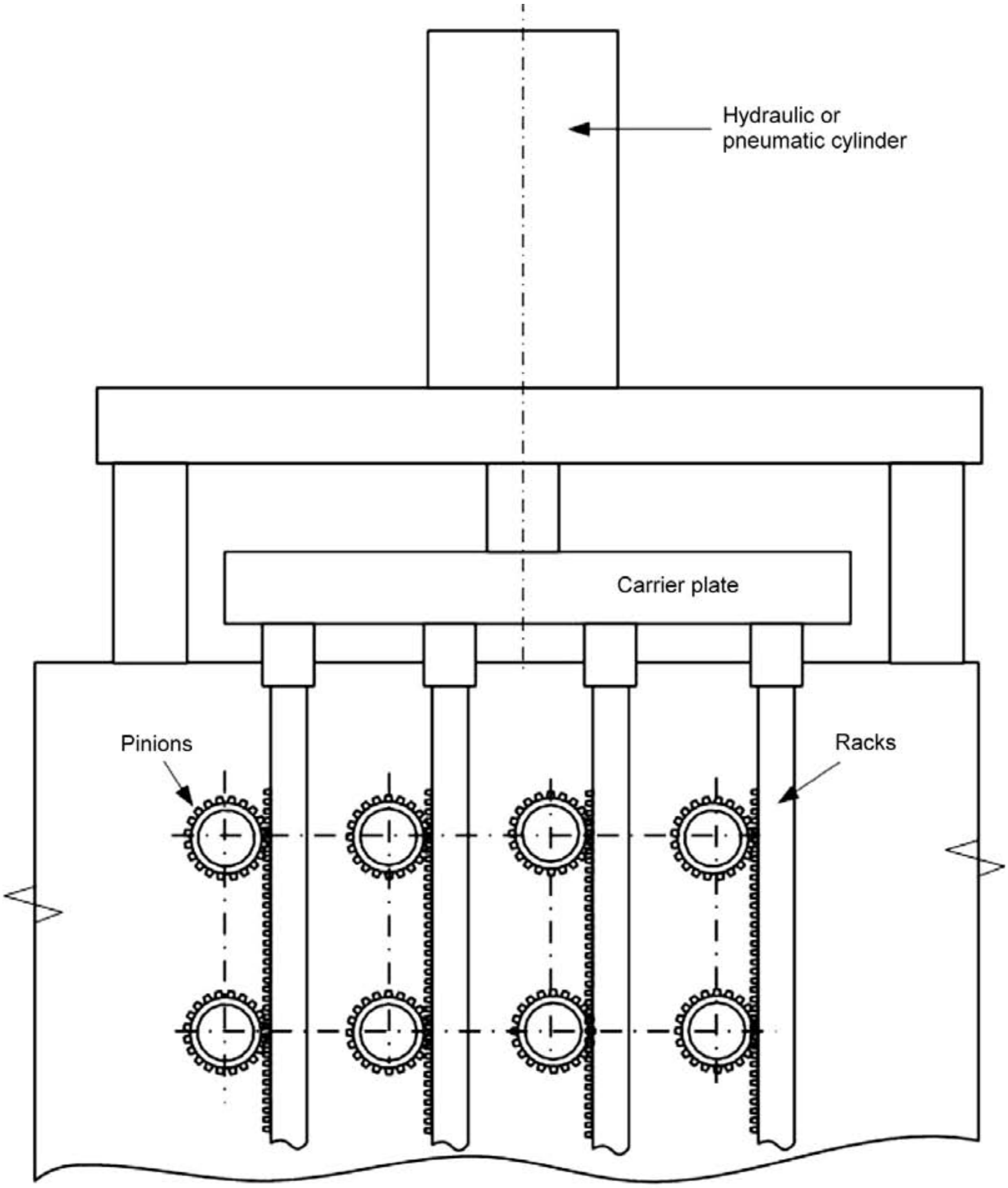


Figure 13.31 Unscrewing operated by rack manifold system

This system is used for many unscrewing operations but perhaps may be unsuitable for precision applications where the backlash associated with racks may not be acceptable. However, this design is more accurate, direct and positive than the previous system as the rack transfer pinion is omitted and hence there is less backlash.

13.18.4 Pneumatic Motors

Pneumatic motors are relatively cheap and readily available. They are used widely for unscrewing purposes and are quite satisfactory for a number of lighter-duty unscrewing applications.

Pneumatic motors have lower power than electric motors and particularly hydraulic motors. This is because the operating pressure is limited to the line pressure available in the factory distribution system. Air pressure is usually limited to around 0.05–1 MPa in most systems and the amount of force this generates is relatively small.

Another disadvantage of air is that it is compressible; hence stalling can happen if increased loading occurs.

13.18.5 Hydraulic Motors

These are probably the best all-round choice for a large number of mould actuation applications. They are ideal for unscrewing purposes, giving much greater driving power than pneumatic or electric motors.

The motor can easily be phased in to the machine hydraulic supply line and suitable control valves can conveniently actuate and stop the unscrewing phase. They may also be used in conjunction with machine core pulling systems. Another advantage is that they can easily be adjusted for speed without loss of power.

Line pressures of 0.7 MPa or more are available and will generate very high forces in cylinders or torque on motors. With a line pressure of 10 MPa, a torque of 170 N-m is available, sufficient for almost all jobs.

Additional advantages are that hydraulic motors are self-lubricating and clean, and operating pressures are continuously variable.

A typical hydraulic unscrewing unit is shown in Figure 13.32.

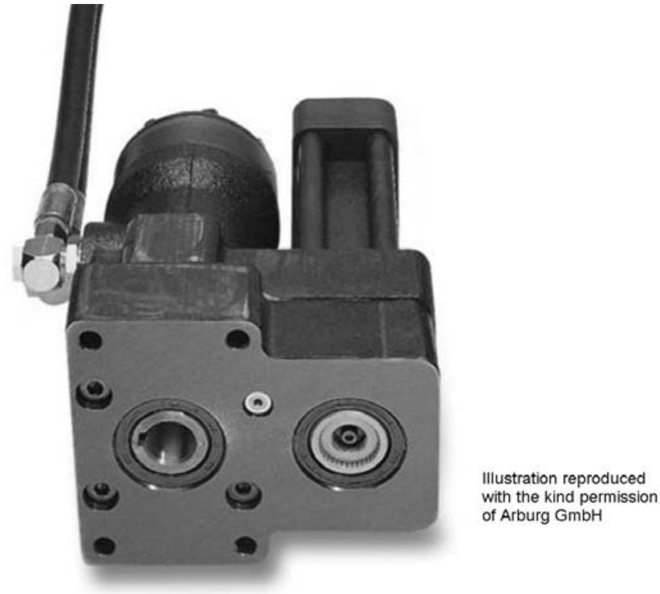


Figure 13.32 Arburg hydraulic motor

There are also a number of self-contained hydraulic unscrewing modules available from the standard mould parts suppliers. Figure13.33 shows the DMS Exaflow module. Incorporating modules like this into the design where possible can save on design and toolmaking time. Similar modules are available from other suppliers.

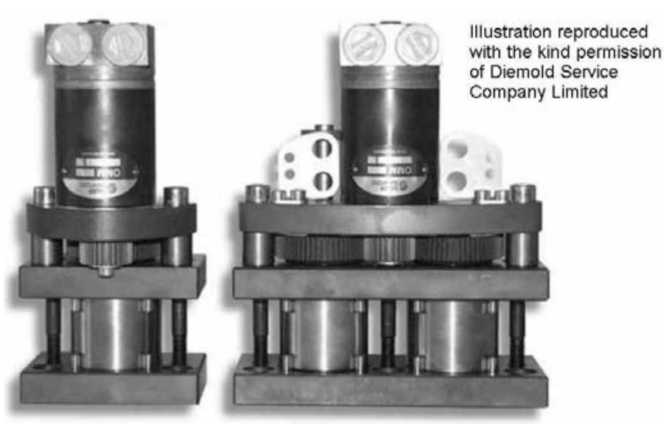


Figure 13.33 DMS exaflow system available from DMS in UK

13.18.6 Electric Motors

Although electric motors can be quite powerful, they are only suitable for lighter-duty applications when used ***inside*** a mould tool. This is because the physical size of electric motors makes it difficult to include high-power types in internally powered unscrewing designs.

Typically, electric motors are limited to a maximum power of around 10 watts if they are to be small enough to be incorporated within the tool in an unscrewing design, with models of around 5 watts being most common. Normally, high-power models are restricted to external mounting. However, with advances in electronics, the situation is constantly improving in this respect and more compact higher-power motors are now being introduced onto the market.

In particular, ***stepping motors*** are a quite useful introduction that allows control of rotational movement to within 0.5°. This feature can be used to great advantage when a moving rotating core has to butt off against another tool face. It avoids the core screwing up too tightly against the mating surface, which can result in it being very difficult to unscrew.

With this system, the number of revolutions of the rotating core can be counted electronically and the final revolution can be ***phase stepped.*** The system allows for precision rotational accuracy with an electronic control that sets the ***pulse width modulation.*** By modulating the pulse width, very small angular increments can be achieved without the loss of power.

Stepping motors using pulse width modulation are used frequently for precision control of rotary positioning, including many precision scientific and engineering applications where positional accuracy is of paramount importance.

13.18.7 Clutches and Rotation Control

There are many designs where a rotating core has to butt off against another face on the fixed half of the tool. With rotating cores that do not move axially, this is not normally too great a problem, as the core should remain in the same position relative to the split line.

With rotating cores that do move axially, however, this scenario can present a difficulty where the core must shut off against another face ***before or after*** the tool has closed. The main problem is controlling the final movement of the core so that it does not wring or jam itself against the face it shuts off against. If this does happen it can be almost impossible to unscrew the core before the tool opens owing to the very high torque required.

There are a number of ways in which rotation can be controlled to avoid this problem:

- Using clutches
- Using stepper motors
- Using torque limiters
- Using specialised designs

13.18.8 Using Clutches

Slipping clutches are an obvious solution to this problem. Small units are available that can be incorporated internally into the unscrewing mechanism. These will perform quite successfully for a wide variety of applications. They are normally located just after the motor where there is more room to accommodate them.

Suitable clutches are available from the suppliers to the manufacturers of automatic drilling and tapping machines and similar equipment. Their incorporation into the design is straightforward, being simply a matter of ordinary mechanical design. Figure 13.34 shows a basic configuration.

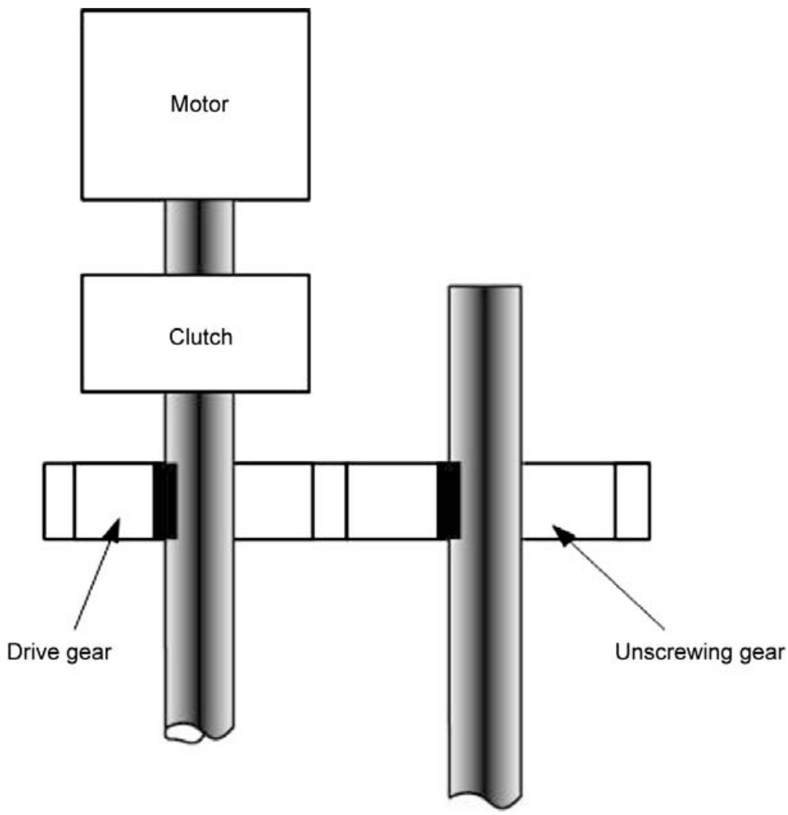


Figure 13.34 Unscrewing system using a clutch

13.18.9 Using Stepper Motors

These motors have a rotor containing a number of permanently magnetised radial teeth that rotate inside a stator that also contains teeth. Depending on how the teeth on the stator are energised, the rotor will align itself in a particular orientation relative to the stator.

A stepper motor will contain a stator that typically has four windings that energise the various teeth. Switching the current from one winding to the next winding continuously drives the motor. At each full step the motor aligns itself with the winding that is energised.

When two adjacent winding are energised, the rotor positions itself between the two windings, creating a half-step effect. By extending this principle, the current to each winding can be phased and controlled by pulse width modulation, thus enabling microstepping to take place.

The number of whole steps available can be up to 360 or more depending on the motor specification. By microstepping, fractions of these whole steps can be created, enabling control to be achieved to fractions of a degree of rotation.

Figure 13.35 shows the arrangement for using a stepper motor.

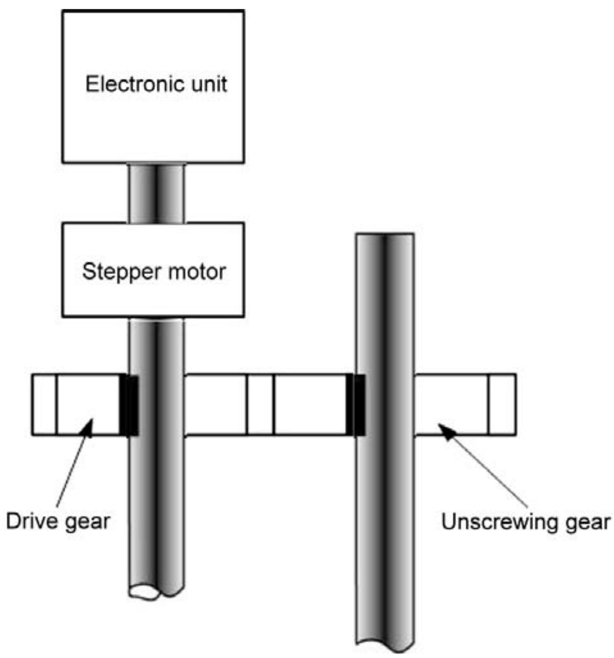


Figure 13.35 Unscrewing system using a stepper motor

13.18.10 Using Torque Limiters

Torque controllers or limiters can also be used to prevent overtightening rotating cores on mating faces.

In effect these are similar to a clutch except that they can be set to a specified torque. They operate via springs creating a force on steel balls pressing onto a ratchet. When this pressure is exceeded, the balls will slip over the ratchet.

The system is exactly the same as a torque wrench used for tightening screws. Cylinder head screws on cars, for example, have to be tightened to a specific torque using a torque wrench. The torque is usually specified in foot-pounds or in newton-metres.

The arrangement for including this internally is similar to the clutch mechanism shown in Figure 13.34.

13.19 Special Designs

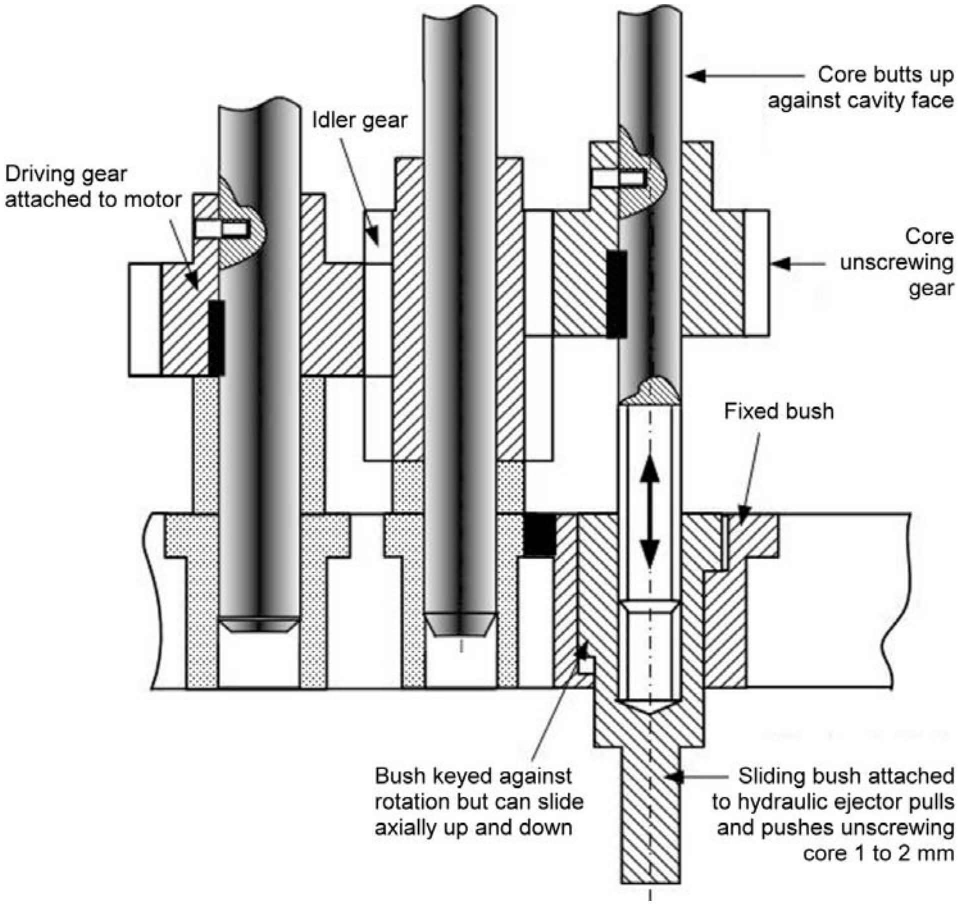


Figure 13.36 Use of hydraulic ejector to lock core against cavity face

Before embarking on a special design to resolve this type of problem, it is advisable to eliminate all the previous options first unless a simple, cost-effective alternative design can be achieved.

One design that can be used in the right circumstances is to allow the core to unscrew until it has some clearance beneath the moulding thread form. When the core is screwed up again, it stops short of its final position by 1–2 mm.

Core rotation is stopped at this point and is moved into its final position by means of a hydraulic ejector. This system is shown in Figure 13.36. Where the core is not subject to high downward forces exerted by the polymer, sometimes heavy die springs and a mechanical ejector are used instead.

If the moulding requires ejection to clear it from the mould, this will have to be provided in addition, perhaps using double ejection techniques. Remembering our theme of keeping the design as simple as possible, this may start to become overcomplex and one of the previous designs should be used. However, it works well for mouldings that free themselves after the unscrewing operation has been completed.

13.20 Commercial Unscrewing Systems

There are standard commercial unscrewing units available that are worth consideration as they can eliminate the need to design unscrewing systems made up of several different parts.

14 Multiplate Tool Systems

14.1 Three-Plate Tools

The most familiar example of a multiplate mould tool is probably the three-plate tool. These are used when an over feed gate is necessary, either for multipoint feeding parts or for gating parts to achieve balanced flow. Figure 14.1 shows the basic design requirements for this type of mould tool.

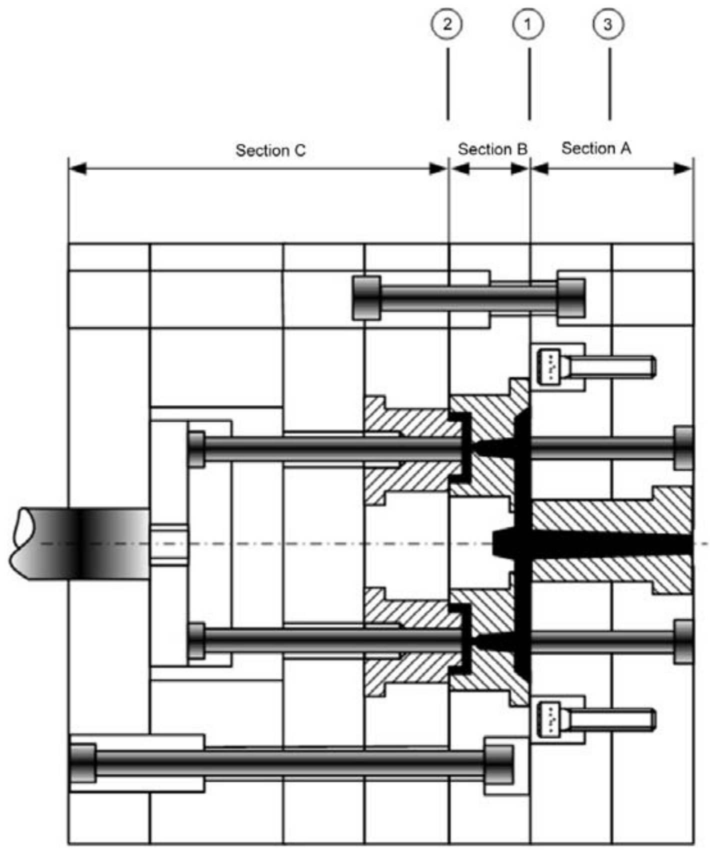


Figure 14.1 Basic three-plate tool in closed position

This design is so named because the tool splits into three distinct modules on opening – sections **A**, **B** and **C**. The first opening is usually at the runner position (**1**). This makes sure the runner is held back onto the snatches ready for subsequent stripping.

The second opening occurs at the main split line to provide clearance for the moulding to be ejected or stripped (**2**). The third opening (**3**) occurs when the runner stripper plate is actuated to allow the runner to be ejected from the tool. This type of tool is more expensive to make than a two-plate tool owing to the extra plates and opening movements necessary.

However, there are many three-plate tools that do not split at the runner position first, which can lead to problems with the mouldings sticking back into the cavities as the mould opens. If no control over the opening sequence of the mould opening is provided, the design engineer must be certain this cannot happen.

Hot runner tools are used in preference to three-plate tools wherever this is possible because of the more efficient nature of these systems. However, there are certain circumstances where the three-plate tool is used in preference to the hot runner tool:

- They are suitable for medium-length production runs, where the relatively higher cost of the hot runner tool would not be economic.
- They are often more reliable owing to their simpler nature and do not require expensive heating and control systems.
- Changing material and/or colour is easier since this type of tool clears its complete feed system every shot.
- The thermal sensitivity of certain material such as PVC or acetals may prohibit the use of hot runner systems.

See Chapter 15 for hot runner tooling.

14.1.1 Three-Plate Tool Operation

Figures 14.2, 14.3 and 14.4 show the typical operation of a three-plate tooling during different stages of mould opening. In this case, two circular parts are being moulded with a central gate, selected for balanced flow.

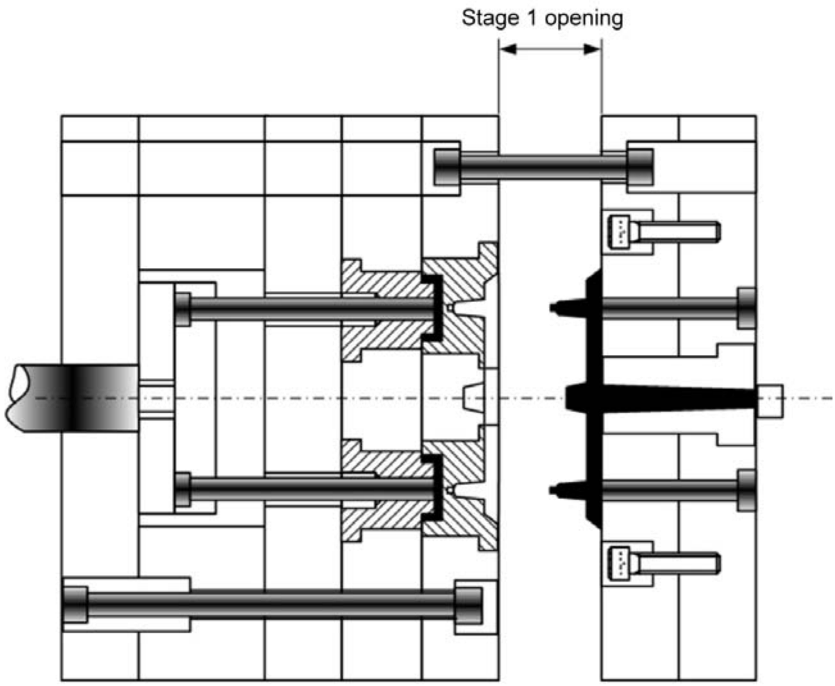


Figure 14.2 Basic three-plate tool: stage 1 opening

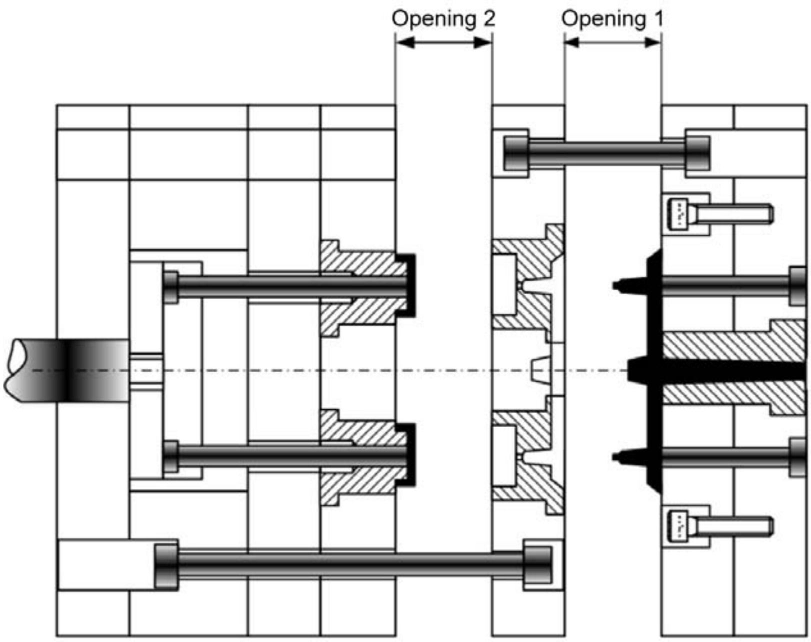


Figure 14.3 Basic three-plate tool: stage 2 opening

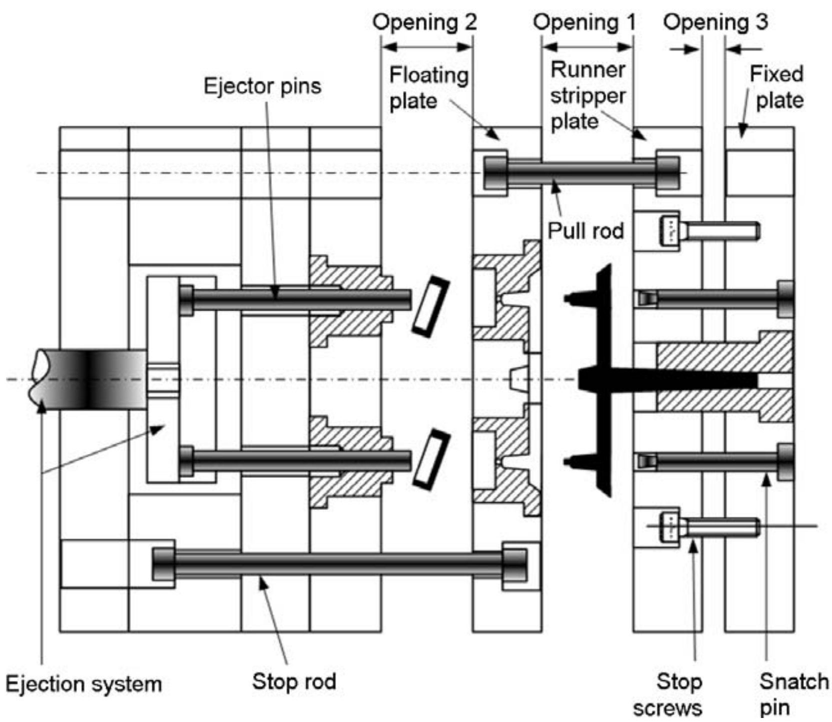


Figure 14.4 Basic three-plate tool: stage 3 opening

The guide pillars have been omitted here for clarity but these should be a little larger than those in a two-plate tool owing to their length and the floating plate they have to support. Shoulder bolts attached to the moving half usually control the openings. Alternatively, latches may be used if there is sufficient room for them on the outside of the tool.

The operation of the tool consists of four separate stages as follows.

14.1.1.1 Stage 1

As the machine opens, sections **B** and **C** move away as a combined unit from section **A**. This ensures that the gates are broken away from the mouldings, leaving the runner sitting on the runner stripper plate. This is known as the gate breaking stage.

14.1.1.2 Stage 2

As the tool continues to open, puller rods start to pull the runner stripper plate forward to strip the runner from the tool. The movement of this plate is limited by the limit bolts in the front half of the tool to avoid the possibility of the plate being pulled out of the tool.

14.1.1.3 Stage 3

By this stage, the feeding assembly is fully open. Further opening causes the stripper puller bolts to pull section **B** away from the core pins and ejection assembly (section **C**). This ensures there is enough clearance for the mouldings to be safely ejected from the tool.

14.1.1.4 Stage 4

Continued opening of the tool actuates the stripper puller bolts in the front half of the tool that pull the main stripper plate forward and strip the mouldings off the cores.

This rather complex opening sequence of the tool illustrates one of the main disadvantages of this system. Firstly, a long opening stroke is necessary to accommodate all the different openings. Secondly, both the speed and accuracy of the mould open stop must be good as variations in either can results in the failure of the tool to operate or, worse, in a breakage. The limiting factor on most mould tools is nearly always the length of opening stroke required. This is critical in the case of deep drawn mouldings such as boxes and tubular components.

The closing sequence is straightforward. As the platen moves forward, all the section modules are progressively collected until the tool closes.

Several different arrangements may be used for the construction and operation of three-plate tools depending on part geometry and gating requirements but the ones shown here are the most frequently used.

Although some moulds open at the main split line first, the danger is that the mouldings may stay attached to the gates and remain in the cavities. If the designer suspects this may be a possibility, then the tool must be split at the runner first. Figure 14.5 shows a typical result of an incorrect opening sequence where the main split line has been allowed to open first.

Frequently not only the mouldings stick into the cavities but the runner can also remain connected to the mouldings having been stripped from the snatch pins as shown. If this happens, the parts and the runner system can be difficult to remove and carry the risk of subsequent damage to the tool. Figure 14.5 illustrates this problem. However, if the moulding does stick into the cavities, the cores could have shallow undercuts ground on them, forcing the mouldings to stay on the cores if this is allowable.

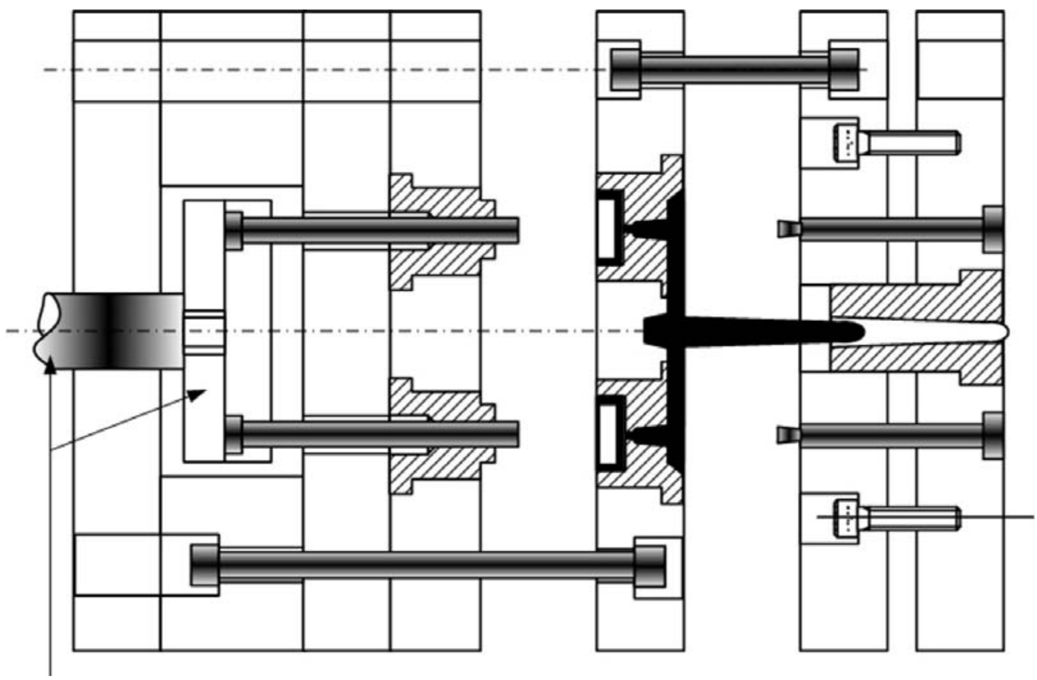


Figure 14.5 Result of incorrect opening sequence

There are three main requirements for a three-plate tool:

- It must open in such a way that all possibilities of the moulding sticking in the cavities are avoided.
- The openings must be sufficient to ensure the runner, sprue and the parts have sufficient room to fall freely from the mould.
- The moulding machine must have an accurate opening stroke, otherwise the pull rods and limit bolts may be broken. Another likely problem is that the parts and the runner system may not be stripped and ejected properly.

Figure 14.6 shows a Nylon drive gear component required in modest quantities but to a high degree of accuracy. Consequently, a single-impression three-plate mould tool was selected since any kind of side gating would induce ovality in the part. A twin overhead gating system was selected as direct central gating was ruled out because de-gating the part would be difficult and expensive.

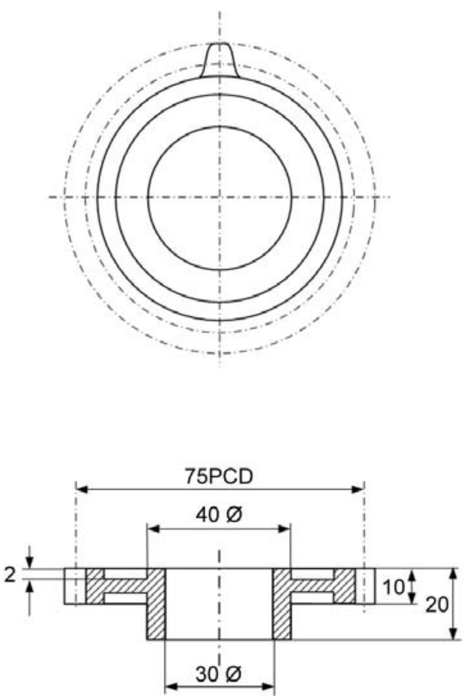


Figure 14.6 Drive gear

Figure 14.7 shows a section through the GA (general arrangement) drawing and illustrates all the normal features that would have to be included on a full production mould tool. Note the spring washers that force the mould apart on opening to ensure that the mould splits at the runner position. The tapered sprue bush is also an added refinement to avoid any scuffing due to continued movement. Note also the cooling channels that are essential as the mould needed to be heated up with heat transfer oil to around 80°C.

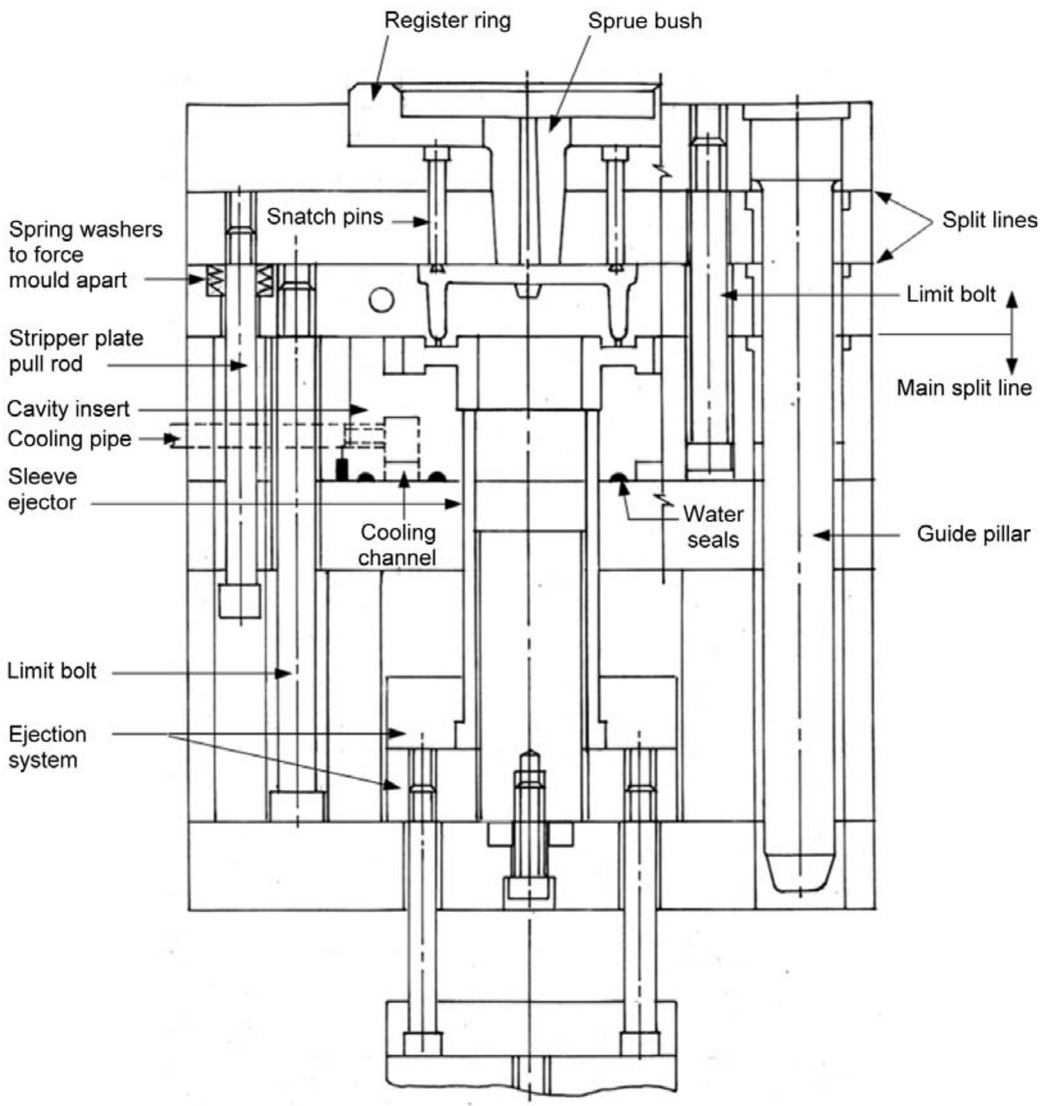


Figure 14.7 Single impression three-plate mould for drive gear

14.2 Multiplate Undercut Tools

Some components have several undercuts on them, making the tool design considerably more complex. Multiplate undercut tools are used to mould such components, where the material is capable of being jump ejected. Polypropylene and polyethylene are two of the most commonly used materials for this purpose, although others are occasionally used.

Figure 14.8 shows a polypropylene valve housing that has undercuts that require a tool with five openings shown at split lines **1**, **2**, **3**, **4** and **5** as shown in Figure 14.9 to Figure 14.13 . The design of the tool and the sequence of openings are shown at each stage. The control of the mould opening sequence is usually achieved with external latches that sequence the release of the openings at the correct phase.

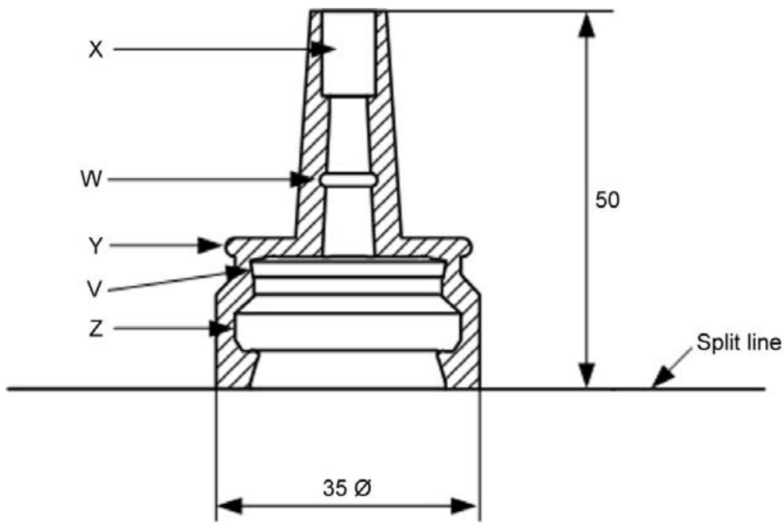


Figure 14.8 Valve housing

This part has a hole **X** that must be formed by a core pin in the front half of the tool, an external undercut at **Y** and an internal undercut at **Z**, and an internal undercut at **W** and **V**. Before these features can be freed, they must have space to deflect into made available by removing the steel surrounding them. This is accomplished by opening the tool sequentially to arrive at this condition.

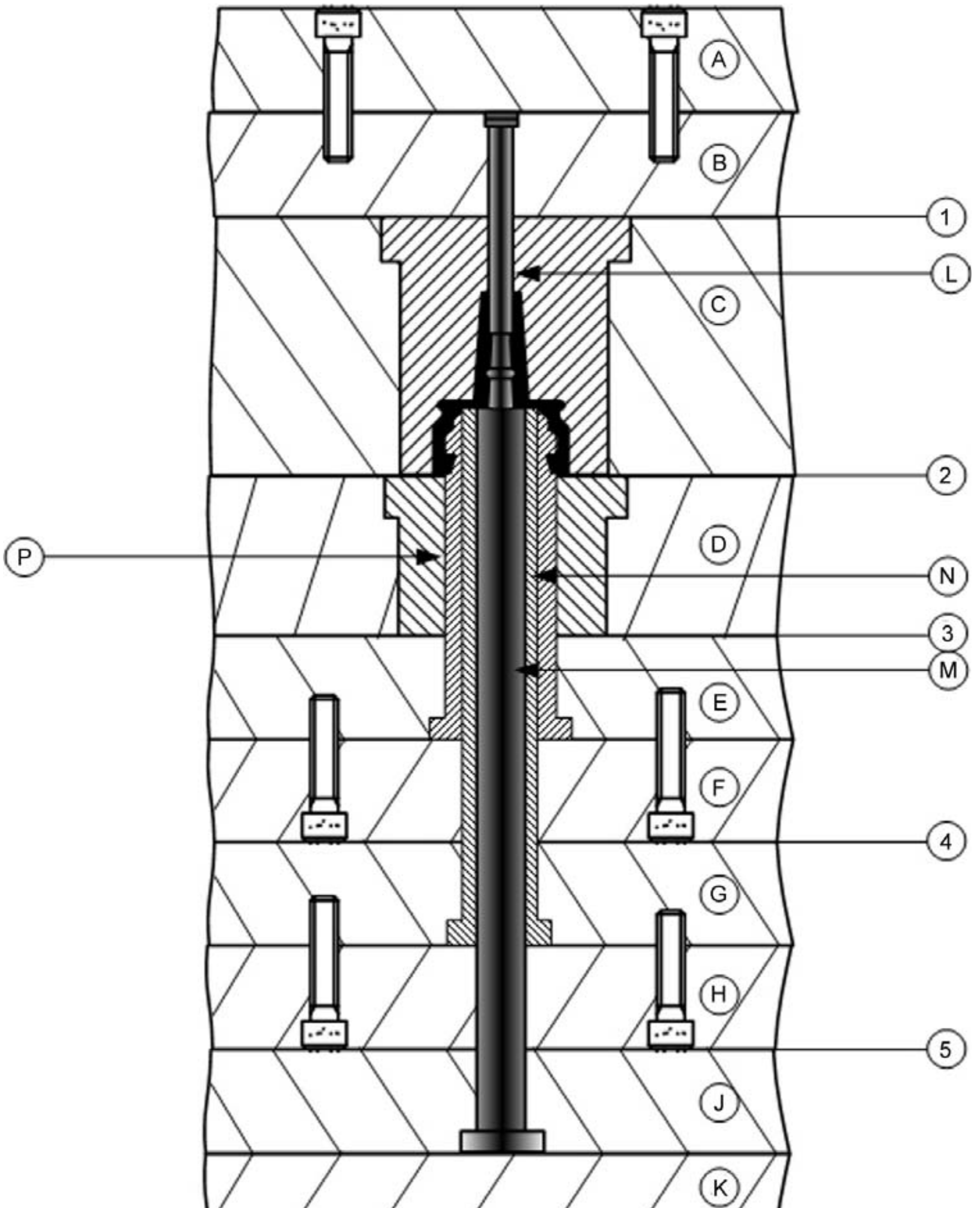


Figure 14.9 Valve housing tool closed

14.2.1 Sequential Opening

14.2.1.1 Phase 1 opening

As the tool starts to open, split lines **1** and **5** open first simultaneously to withdraw the two central core pins **L** and **M**. This releases core pin **X**. Plates **A** and **B** are screwed together and move as a single unit (Figure 14.10). This also releases undercut **W**.

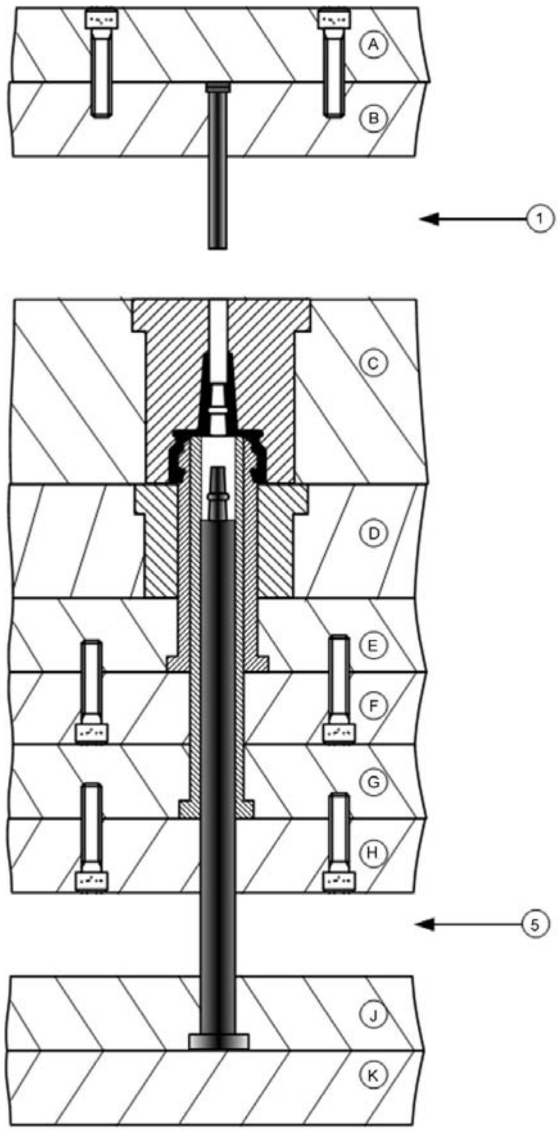


Figure 14.10 Valve housing tool opening 1

14.2.1.2 Phase 2 opening

Next the tool opens at split line **4**, withdrawing sleeve **N**. This releases undercut **V**.

Note that plates **G** and **H** are screwed together and move as a single unit (Figure 14.11).

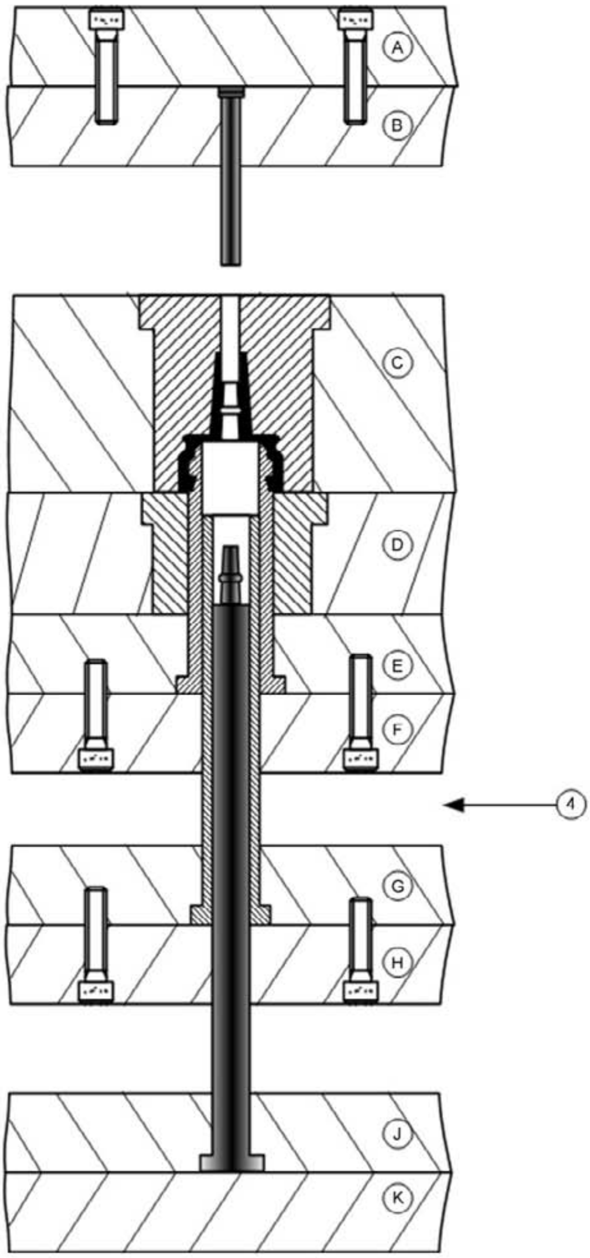


Figure 14.11 Valve housing tool opening 2

14.2.1.3 Phase 3 opening

In this phase the tool opens at split line **2**. This is the main split line of the tool and it is important to note that the opening must be sufficient to allow the moulding to fall free after ejection takes place (Figure 14.12). This is the stage at which undercut **Y** is freed owing to the internal undercut form **Z** on sleeve **P** holding the moulding in position.

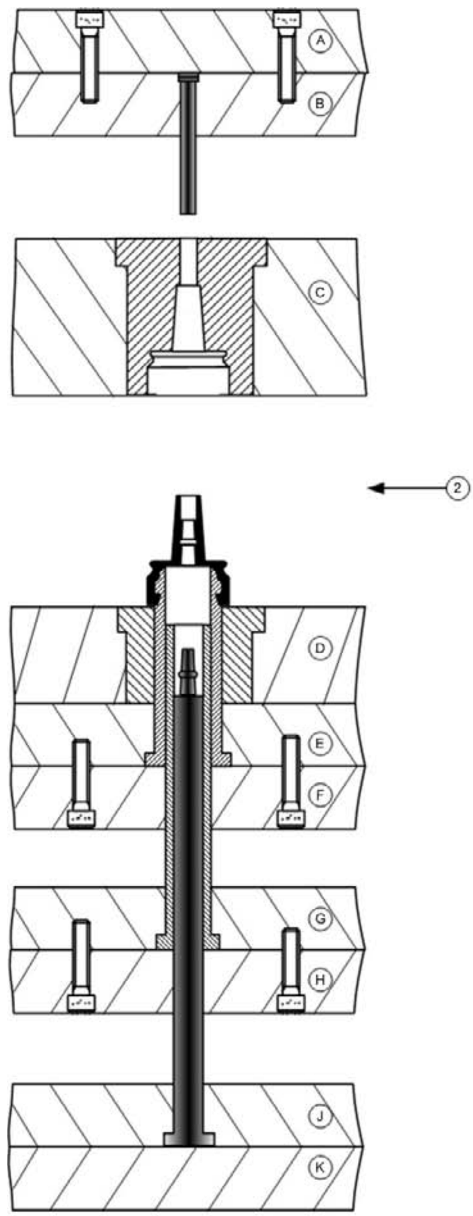


Figure 14.12 Valve housing tool opening 3

14.2.1.4 Phase 4 opening

This is the final opening of tool at split line **3** (Figure14.13). This is the stage at which the stripper plate **D** moves forward to strip the internal undercut **Z** of the moulding from the sleeve **P.**

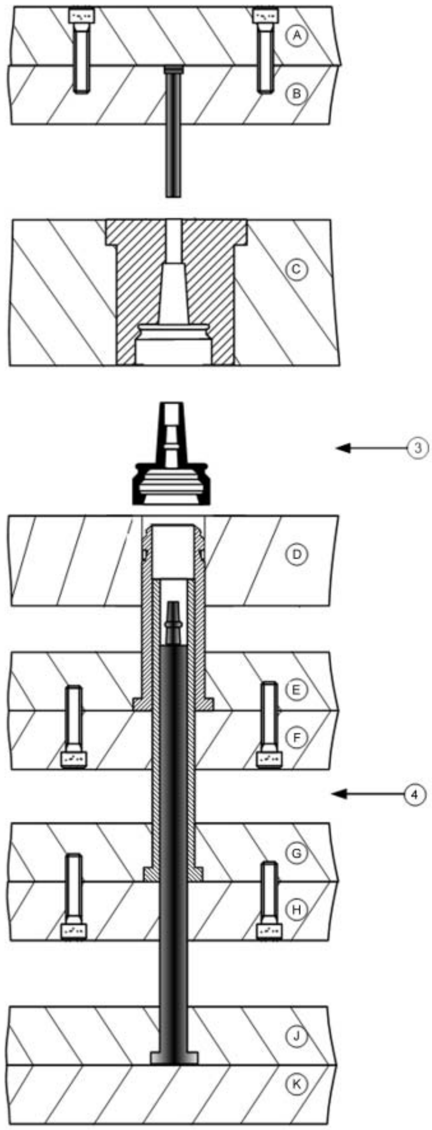


Figure 14.13 Valve housing tool opening 4

The latches that control the opening sequence are normally mechanical or sometimes have proximity switches or microswitches.

14.3 Stack Moulds

Many noncomplex standard components are sold in tens or even hundreds of millions and consequently there is a great deal of competition to mould and sell them. In view of this, the moulder has to adopt a highly efficient, cost-effective production method to stand any chance of succeeding.

Shallow boxes, cassette cases, video cases and Petri dishes are examples of this type of part. Such components often have large projected areas that would mean having to use large machines to produce them. Clearly it would be a distinct advantage if the moulder could mould these on a smaller machine, thus lowering the cost of production considerably.

In normal circumstances the machine locking force is determined by multiplying the projected area of the parts by the injection pressure. In Figure 14.14 we examine what happens when one component is placed directly beneath the other, to see how this affects the locking force requirements.

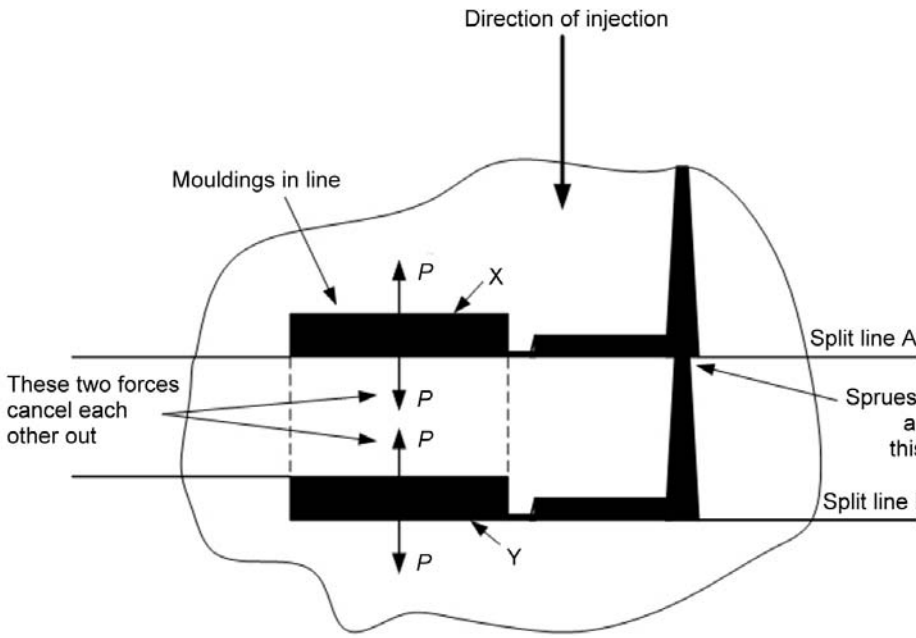


Figure 14.14 Alignment of projected areas in stack moulds

By definition, the projected area is the area of the moulding seen when looking down on the tool in the direction of injection. Here we can see that the two projected areas of mouldings **X** and **Y** coincide; thus the projected area for moulding two components in line is the same as for moulding one.

Looking at the situation from the point of view of simple physics, we can consider the forces acting on the tool. We can see that the forces *P* trying to open the tool are the same for both cavities. Adding these forces algebraically, the resultant force is simply *P*. This is the result of equal and opposite forces cancelling each other out.

Either way, the net result of moulding two parts having the same in-line projected areas is that the total projected area is the same as for moulding one part. Note that the only requirement here is that the projected areas are in-line and of the same value: different parts may be moulded in this way provided these conditions are met.

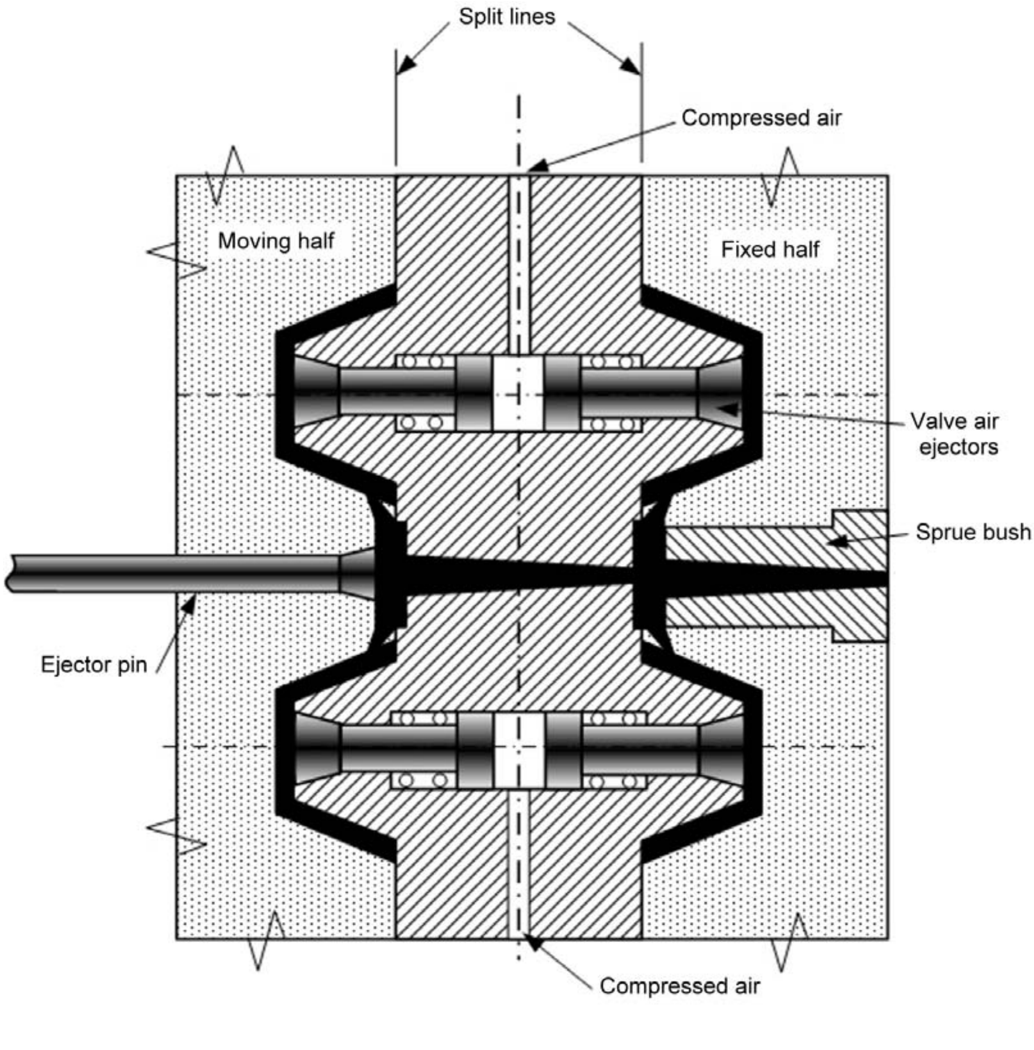


Figure 14.15 Basic principle of stack tool design

Figure 14.15 shows the basic construction of a typical stack tool. In this case, the tool design is based on a cold runner system where the upper set of cavities is fed via a sprue in the normal way, while the lower set of cavities is fed by a sprue extension. The interface between the two sprues is designed so that the lower one breaks away from the upper one as the tool opens as shown. In this design, the components are placed so that they may be ejected by means of air ejectors placed in the plate carrying the common cores. These are returned to their starting position via springs.

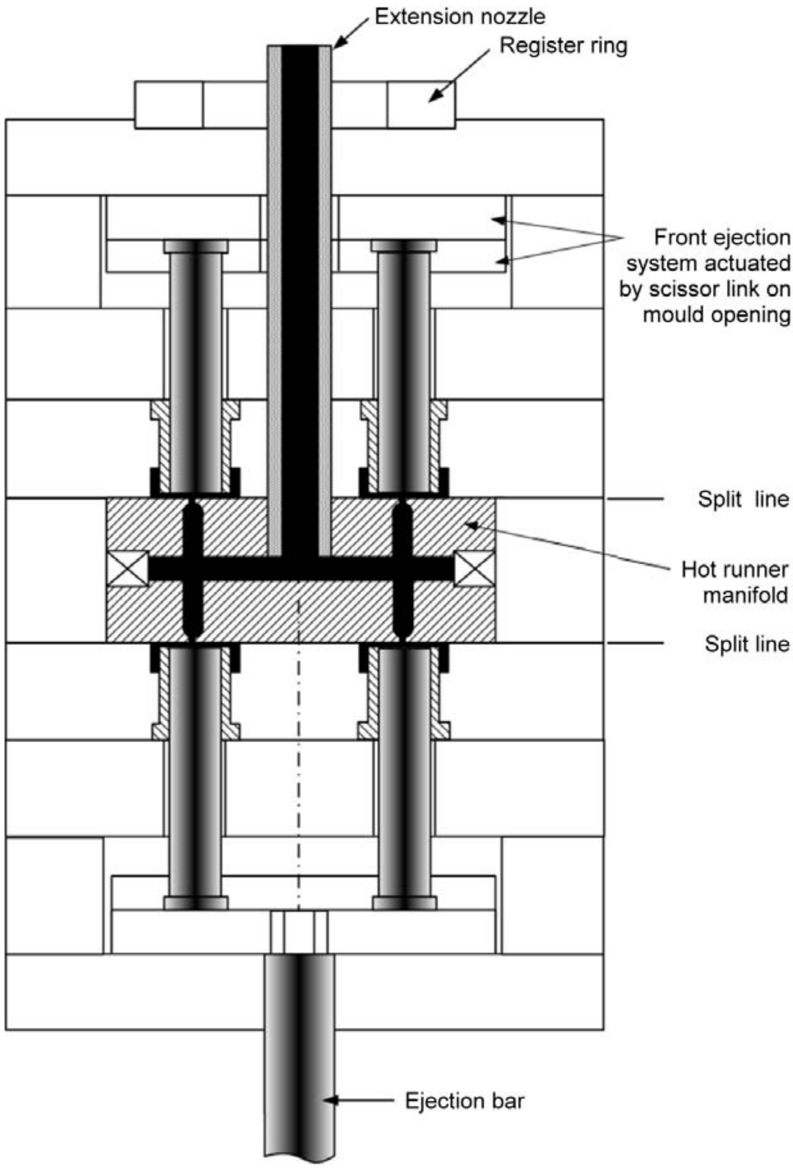


Figure 14.16 Basic hot runner stack mould

In practice it is far more usual to use a hot runner approach on stack moulds for obvious reasons. With such large quantities, the hot runner offers advantages of faster cycling, fewer rejects and more consistent production. Figure 14.16 shows a basic stack tool design with a hot runner system.

Figures 14.17 and 14.18 show an eight-impression stack mould moulding polypropylene cover components with a full hot runner system. In Figure 14.17 the scissor links are screwed to the tool plates where indicated at **A**, **B** and **C** but are free to rotate as the tool opens and closes. The remaining joints are also free to rotate but not attached to the tool. Note also that the position of the scissor link is reversed on the other side of the tool to prevent out-of-balance forces and ensuring a more even actuation of the stripper plates.

Note the very long guide pillars that are required to provide location for the mould throughout its long opening stroke (Figure 14.18). Since stack moulds are used for producing very large quantities of components, high-quality alloy tool steels should be used throughout the construction. Additionally as these tools normally run continuously, provision must be made for an adequate lubrication system – preferably automatic.

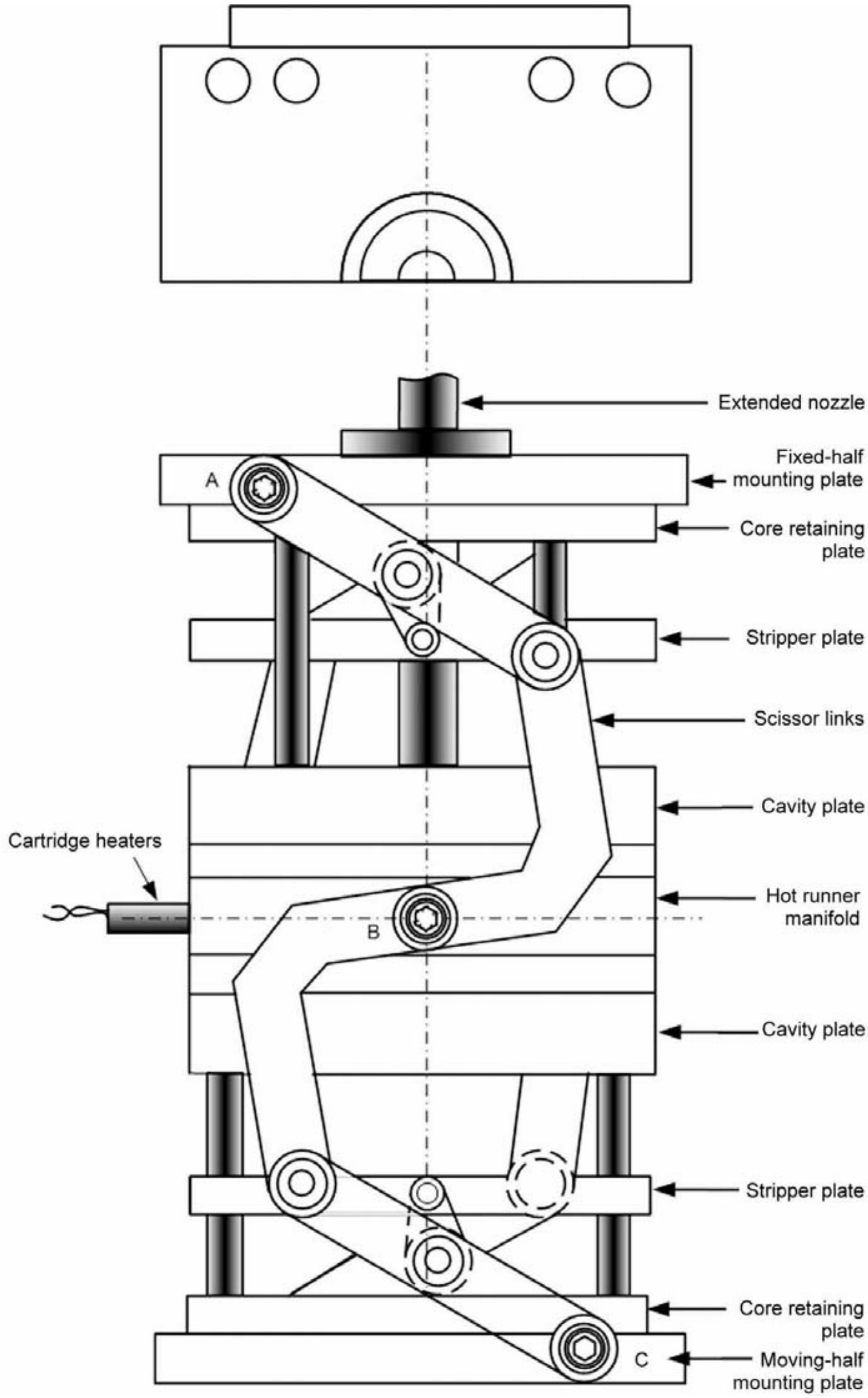


Figure 14.17 Eight impression cover stack mould

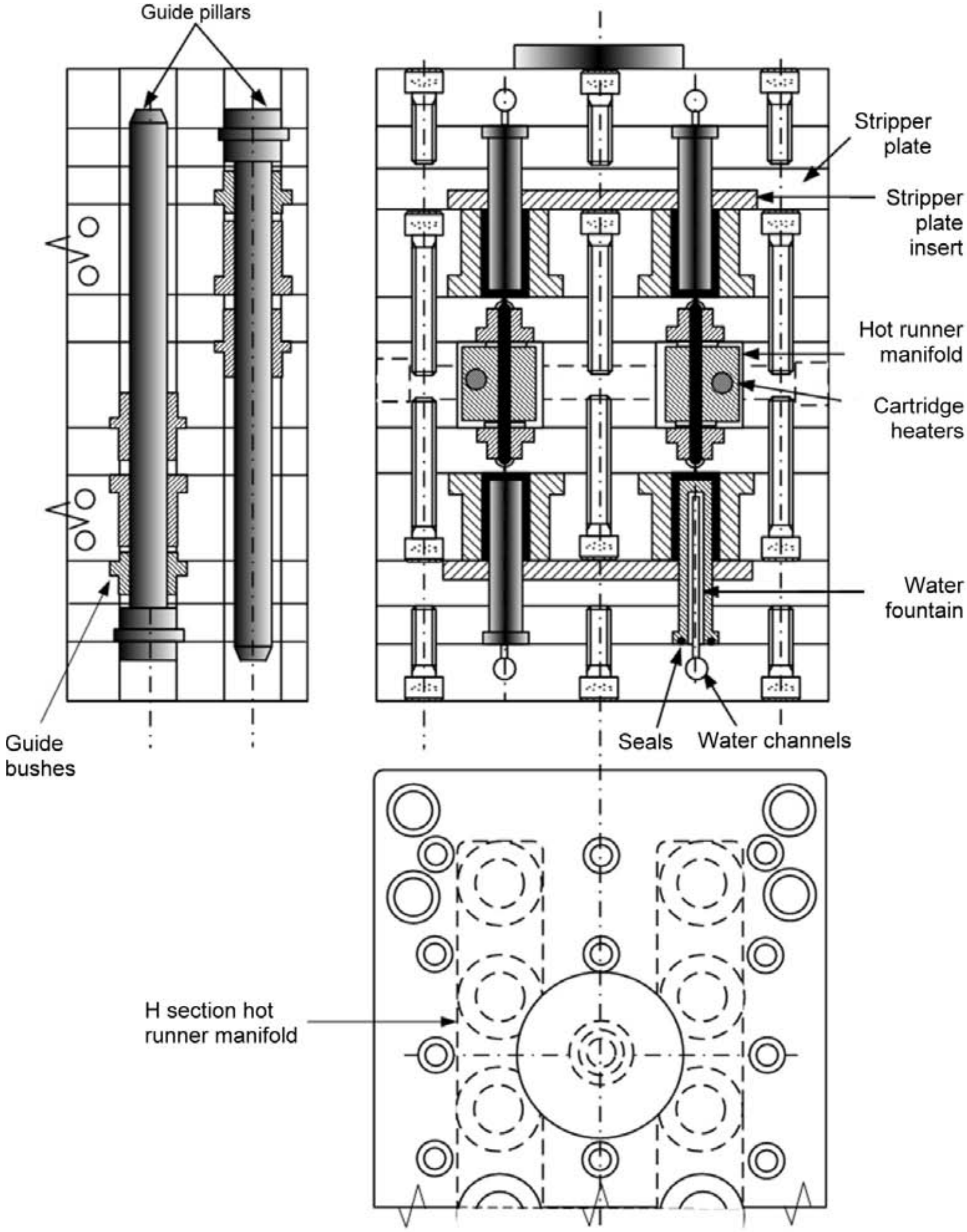


Figure 14.18 Eight-impression cover stack mould

All the major components shown in this design can be purchased as standard parts including the nozzle extensions, the H-type layout of the hot runner manifold and the guide pillars and bushes, etc.

15 Runnerless Moulding

The term ***runnerless moulding*** is used to describe any mould tool where a conventional cold runner and sprue is not produced:

- Sprueless moulding
- Insulated runner systems
- Hot runner systems

15.1 Sprueless Moulding

There are two main categories for sprueless moulding:

- Basic antechamber designs
- Heated hot sprue bushes or nozzles

15.1.1 Basic Antechamber Type

Sprueless moulding is frequently used for fast-cycling single impression tools producing thin wall components in non-heat-sensitive materials such as PE, PP and PS.

This method usually consists of a specially formed machine nozzle, which is designed to fit into a recessed feature in the mould tool. The most basic designs incorporate an ***antechamber*** feature. With this arrangement, a thin skin of colder material insulates a molten central core between the nozzle and gate.

Figure 15.1 shows three typical designs of antechamber type nozzle. The design shown in Figure 15.1(b) has the advantage that if the melt in the nozzle solidifies to a cold slug, the undercut form on the nozzle permits easy withdrawal from the tool. Figure 15.1(c) shows an antechamber feed system without a cold slug well.

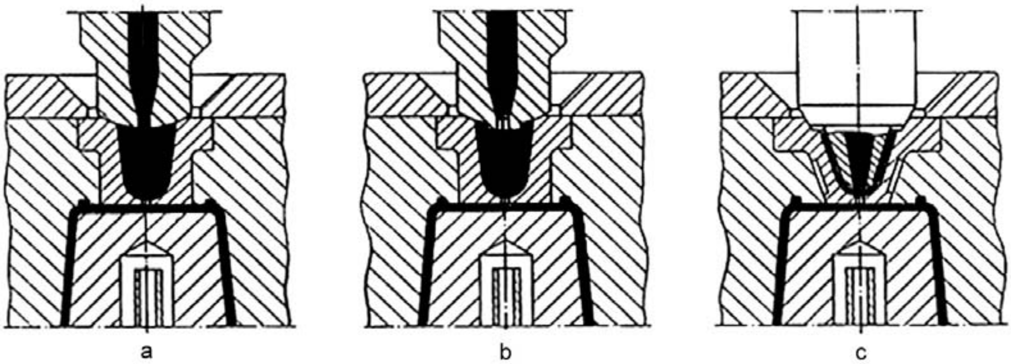


Figure 15.1 Antechamber nozzle design

This approach may also be used for larger mouldings running on a single-impression basis where maximum control and quality are required.

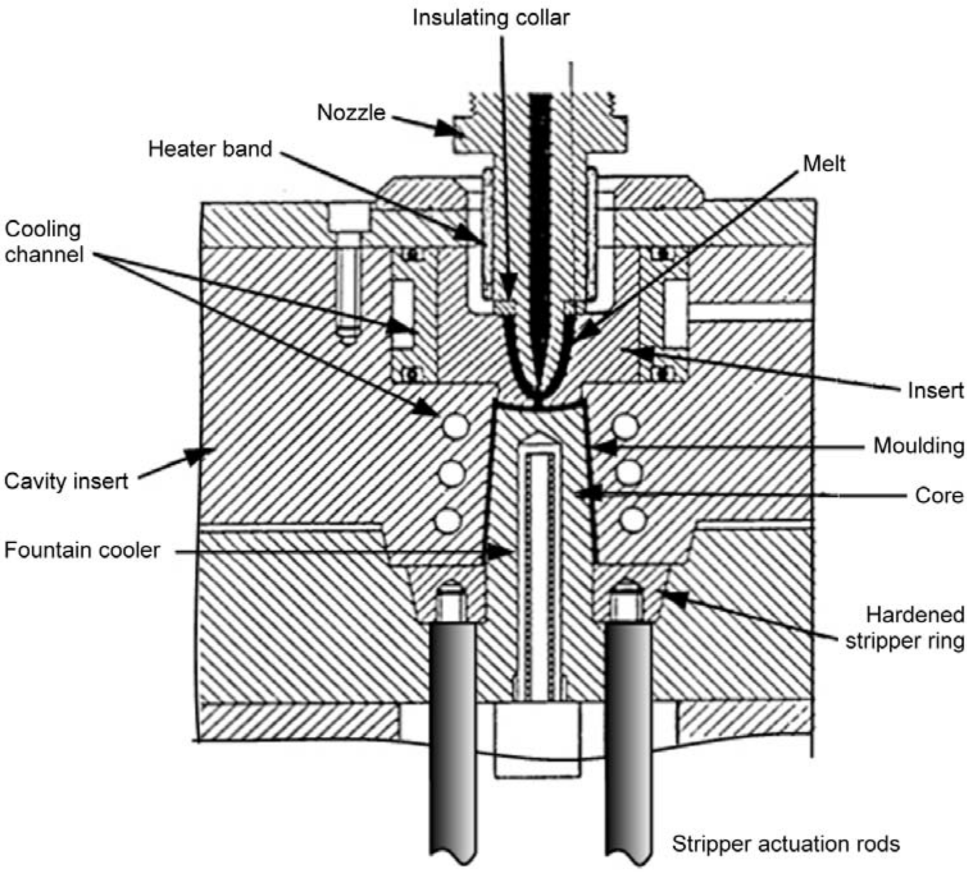


Figure 15.2 Details of a typical antechamber design

Sprueless moulding techniques may also be employed for more heat-sensitive materials. In these cases it is preferable to extend the nozzle as far as the gate, as in Figures 15.2 and Figure 15.3. The serrated undercut on the nozzle in Figure 15.3 usually takes the form of a screw thread. This permits the cold plug to be simply unscrewed after the cylinder is retracted from the tool.

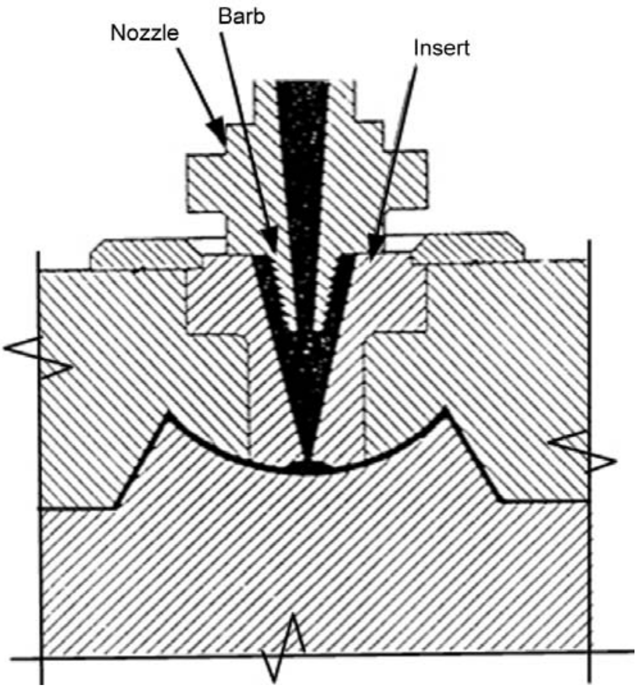


Figure 15.3 Antechamber design with snatch feature

Apart from the obvious saving in eliminating the sprue, extended nozzles are used in three-plate or multiplate designs to reduce the opening stroke. Since no sprue is moulded, the opening required to allow the runner (if any) to be stripped is much less.

15.1.2 Heated Hot Sprue Bushes

There are two methods of heating hot sprue bushes:

- Internal
- External

15.1.2.1 Internally Heated Hot Sprue Bushes

The construction of this type of hot bush consists of three basic units:

- An outer body
- An inner body
- A torpedo

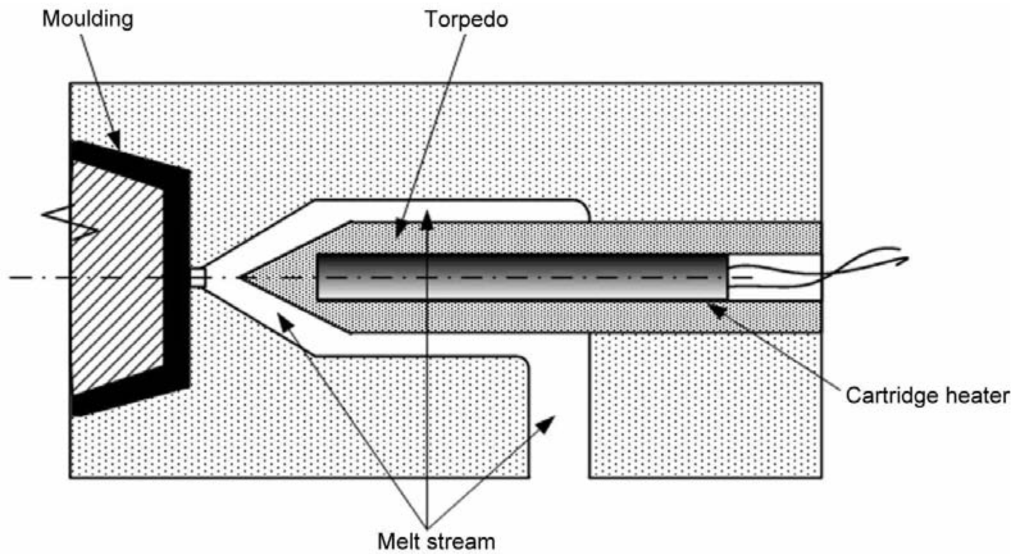


Figure 15.4 Internally heated bush

A typical internally heated hot nozzle is shown in Figure 15.4. The purpose of the torpedo is to push the melt towards the outer walls of the melt channel. This avoids too large a mass of material accumulating, which would result in an unequal melt temperature and uneven plasticising due to a thermal gradient across the melt.

The torpedo carries a series of fins, which extend through the melt to touch the outer walls of the nozzle. This provides a location for the torpedo and a path for the melt to pass through.

With this system there can still be considerable temperature fluctuations and the pressure drop can be high. In view of this, internally heated nozzles are not recommended for heat-sensitive materials.

The main advantage of an internally heated nozzle over an externally heated one is that a better gate witness mark may be achieved. Colour changing may be more difficult than with the external type, however.

Figure 15.5 shows a more complete design for a typical internally heated bush.

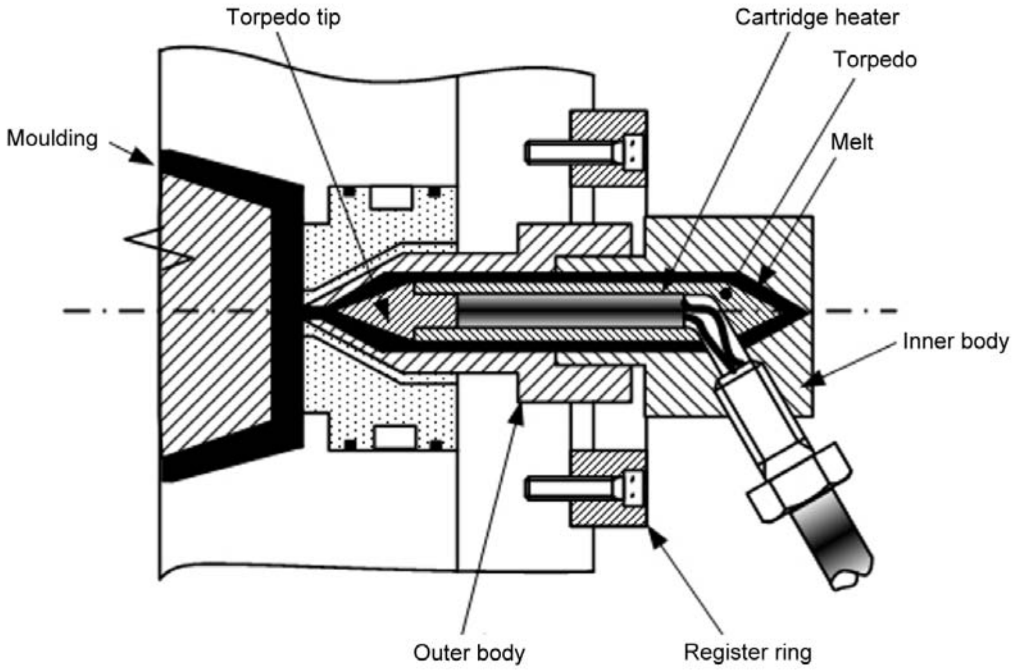


Figure 15.5 Internally heated bush

15.1.2.2 Externally Heated Hot Sprue Bushes

By comparison, the construction of an externally heated nozzle is very straightforward. It consists of a nozzle with a central tubular hole through which the melt passes. The outside of the bush is heated by means of external heater bands, usually using a coil-type heater.

Direct gating is possible but only with small tip diameters up to 2 mm. Since there is a high degree of heat transfer from the bush to the cavity with direct gating, it can be difficult to achieve a good surface finish in these areas. To avoid this problem, a short sprue tip (10 mm) is normally used to minimise gate pip height and stringing; a short torpedo tip may also be used.

The great advantage of externally heated systems is that they may be used with most thermoplastics. They are also much easier to maintain and heater replacement is easy. Colour changes are also easier.

Figure 15.6 shows the basic construction of an externally heated bush. Figure 15.7 shows a more complete design for a typical externally heated bush.

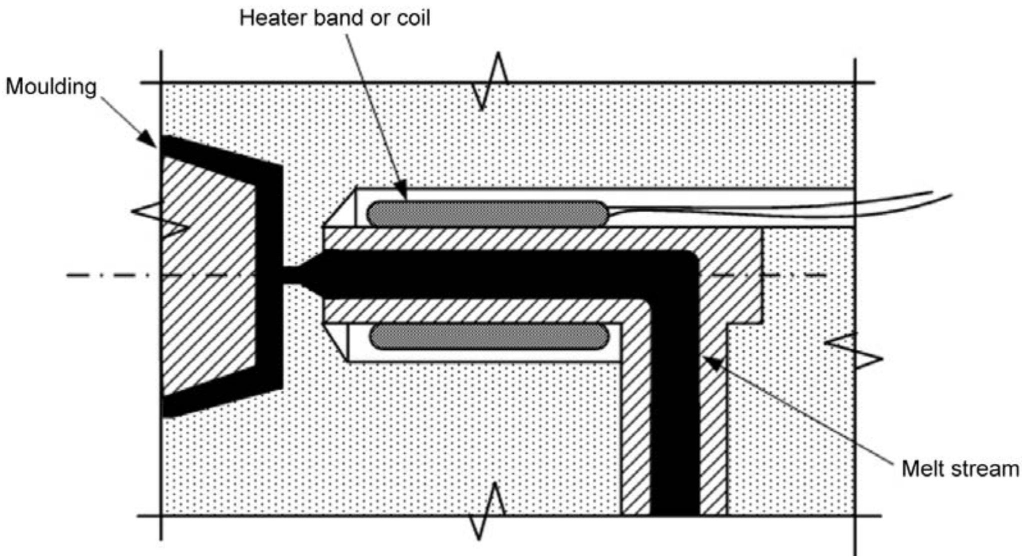


Figure 15.6 Externally heated bush

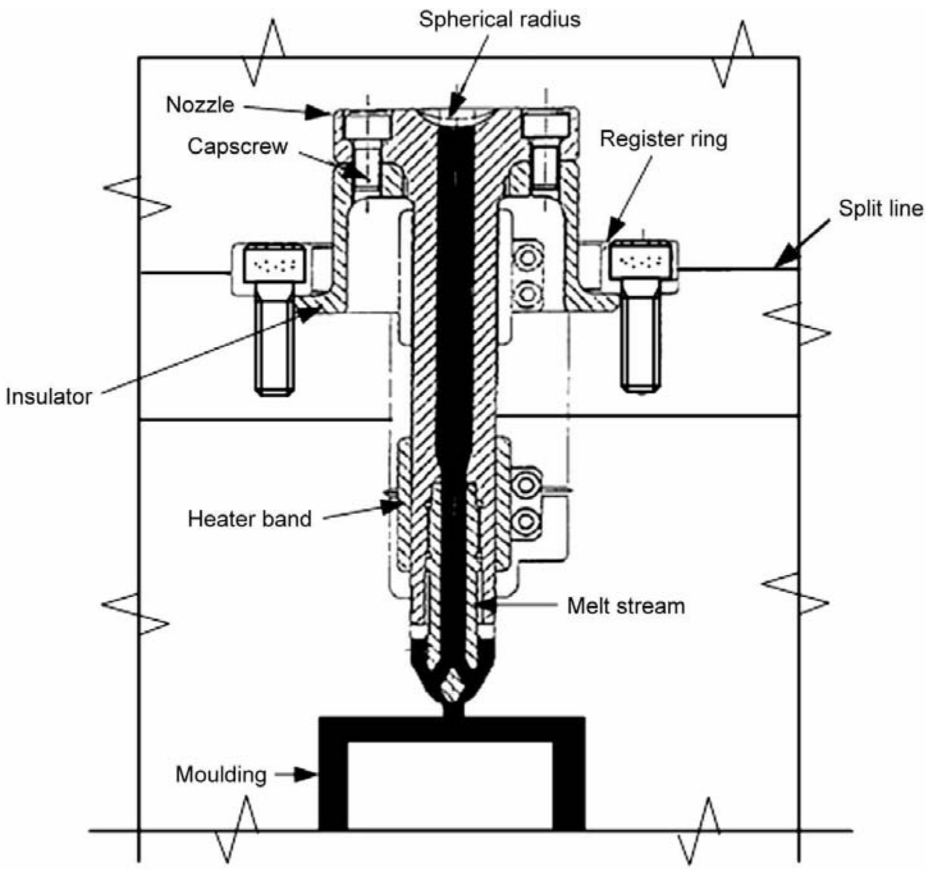


Figure 15.7 Typical hot nozzle

15.1.3 Summary

There are two basic systems in use:

- The antechamber design: melt flows through an insulated cold slug well.
- The heated sprue bush: heating may be internal or external.

A summary of the advantages and disadvantages of internally heated and externally heated types is given in Tables 15.1 and 15.2.

Some internally heated systems use low-voltage control that provides better temperature control than 240-volt systems.

Internally heated systems are more suited to less heat sensitive materials like PE, PP and PS, whereas externally heated systems are suitable for almost all materials.

Table 15.1 Advantages and disadvantages of internally heated systems

Advantages	Disadvantages
Better control of height of gate pip	Poorer temperature control
Lower energy costs	Requires higher injection pressure
Longer heater life	Poorer material and colour changing
Lower installation cost	More chance of material degradation
Less heat transfer to mould	Shorter heater life
Cooler mould	Heater replacement more difficult

Table 15.2 Advantages and disadvantages of externally heated systems

Advantages	Disadvantages
Lower injection pressures	Higher cost
More streamlined flow = no dead spots	Poorer control over gate pip height*
Better material and colour changing	Heat is transferred to end of bush
Easier maintenance	Larger body diameter requires greater spacing on multi-impression tools

* Some externally heated bushes have a special integrated tip that provides better control over the gate pip height. For materials with a higher processing temperature a shorter sprue bush is required to help reduce gate pip height.

15.2 Insulated Runner Systems

Insulated runner systems evolved from the three-plate tool design. The runner stripper plate was integrated with the rest of the fixed half of the tool and larger heated runner channels were used.

There are two types of insulated runner tool designs:

- Insulated
- Semi-insulated

15.2.1 Insulated

By maintaining the fixed half of the tool at a high enough temperature, a central core of material in the runner system remains at melt temperature between cycles. An example of this type of design is shown in Figure 15.8.

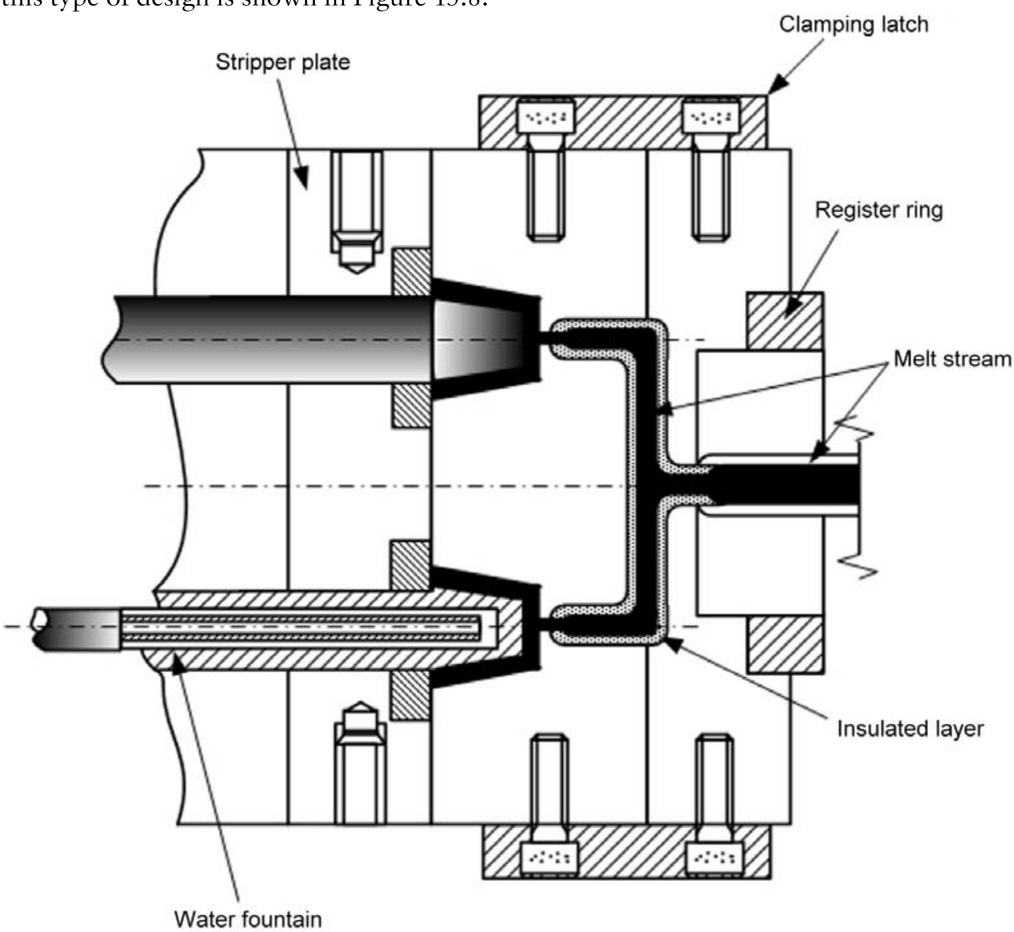


Figure 15.8 Basic elements of insulated runner design

With this type of design it is necessary to provide a means of removing the runner system when it solidifies. In this design a clamping latch system has been used to achieve this. This system was largely used with PE and PP and was the origin of the modern hot runner mould tool. This design has largely been superseded by full hot runner systems and is rarely used now for new tools even if they are for straightforward applications. There are still, however, several tools of this type in existence that are producing many millions of parts annually.

15.2.2 Semi-insulated

This design is also referred to as 'modified insulated runner'. It was introduced to avoid the problems of the fully insulated type, which were prone to gates and runners freezing off. This was particularly problematical with high-temperature materials and heated probes were located in the runners near the gates. A typical design is shown in Figure 15.9.

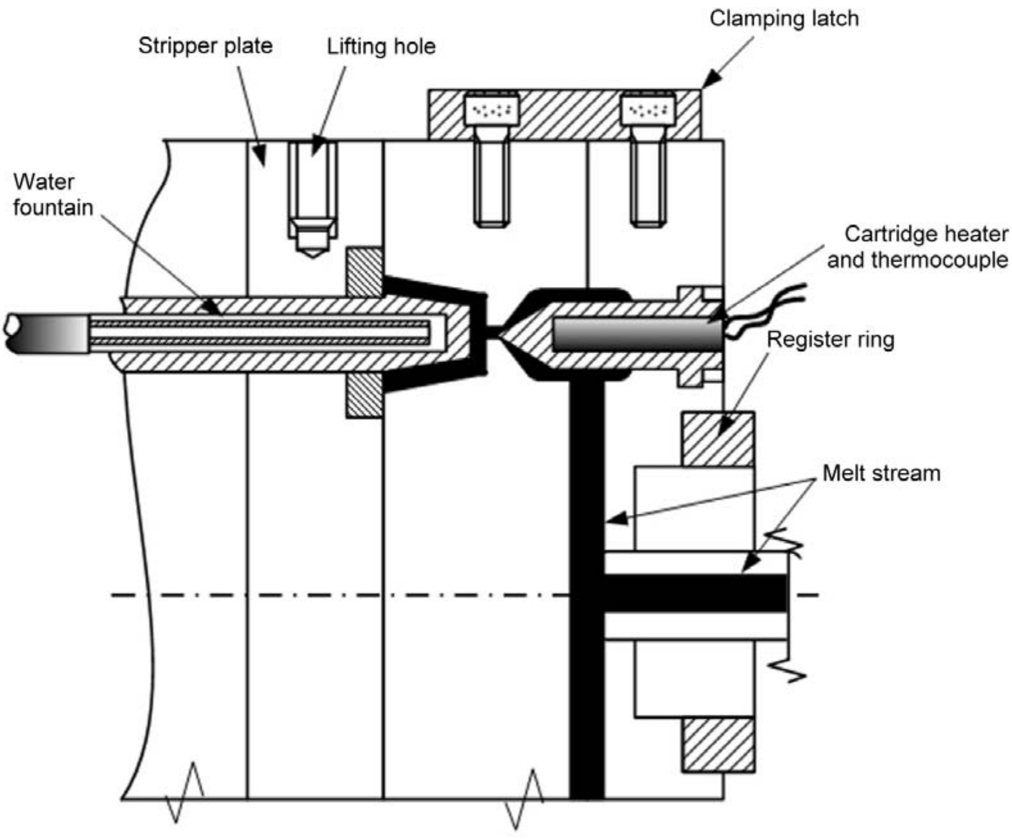


Figure 15.9 Basic elements of semi-insulated runner design

This modified design allows better temperature control and more consistent and reliable production. Problems still exist of difficulty with colour changes and high pressure drops throughout the runner system.

This system was the direct forerunner of the modern hot runner tool following on from the fully insulated hot runner tool and has also been largely superseded. However, just as with the previous design there are still many of these types of tool in existence. It is also used still used occasionally for very cheap simple components in PE and PP where the expense of a full hot runner tool would be prohibitive.

15.3 Full Hot Runner Systems

15.3.1 Advantages Over Cold Runner Moulds

There are numerous advantages in using a hot runner mould as opposed to a cold runner mould. A selection of the most obvious ones is listed below:

- There is no runner system to be removed from the tool.
- With no cold runner to be cooled, there is a shorter cycle time.
- Mould opening stroke is reduced.
- Cost of storing and regrinding runners is eliminated.
- Risk of material contamination is lower as no reground material is used.
- Gates may be balanced more easily.
- Hot runner diameters can be larger than cold runners; thus lower injection pressures may be used.
- Cooling times are reduced.
- Better part quality can be achieved owing to a more consistent cycle.
- A greater number of impressions may be used, as less injection pressure is necessary.
- Smaller shot weight means shorter metering times and injection times.
- Lower injection pressure means that smaller machines may be used.

These are powerful reasons for using hot runner moulds but these moulds are significantly more expensive than equivalent cold runner moulds. In view of this they are normally used for large quantities of at least 500 000 parts but, exceptionally, smaller quantities are sometimes produced.

The disadvantages are few but worth mentioning:

- 24-hour operation is required for maximum economic production.
- Heat-sensitive materials may be difficult to process.
- Gate blockages can be time consuming and expensive to remedy.

Full hot runner systems have almost universally replaced the older insulated runner designs where high volume production is required. With only minor design changes it is possible to obtain much better temperature control, less pressure drop, and higher quality of parts moulded.

The modern designs make use of heated ***manifolds***. These are separate units that carry the runner and nozzle gating systems. They are separate units insulated from the main body of the tool by ***stand-off buttons*** or ***feet***. Note that the manifold does not touch the main tool at all, to prevent heat transfer from the manifold. The stand-off buttons and the lock screws are the only contact between the two. These types of tool are also sometimes referred to as ***hot runner unit tools***.

Cartridge or tubular heaters are used to maintain melt temperature in the manifold and thermocouples are used to monitor it. These are connected to temperature controllers that switch the heaters on and off at predetermined values.

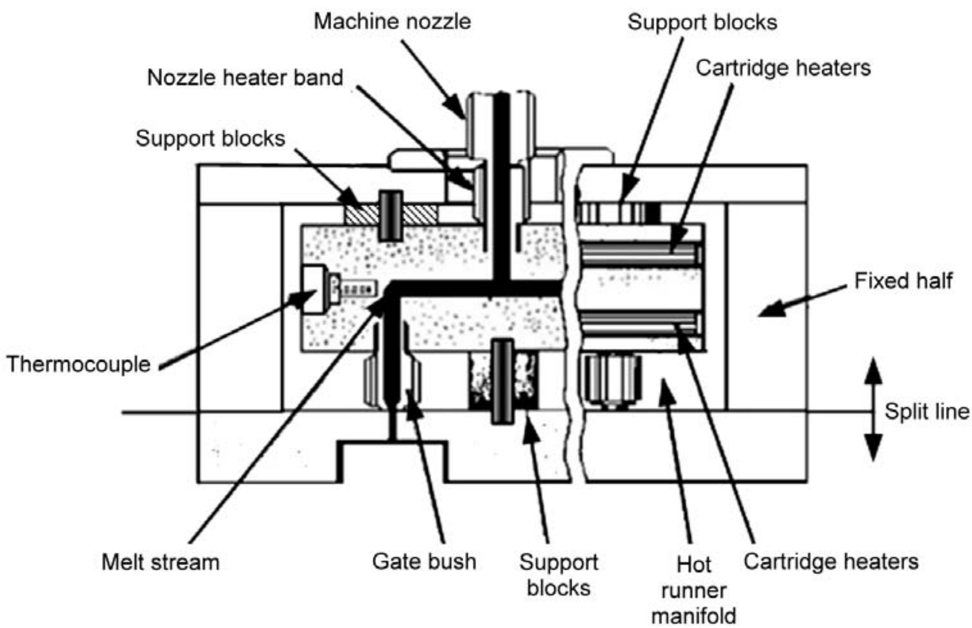


Figure 15.10 Hot runner manifold

This design is ideally suited to moulding in non-heat-sensitive materials and is very widely used where the quantity requirements justify the cost. Once melt temperatures have been reached after start-up, very little additional energy is required to maintain the material temperature at this level owing to the insulating properties of plastics materials in general. Figure 15.10 illustrates the basic design of a modern manifold design hot runner tool.

Figure 15.11 shows a more detailed full hot runner tool moulding two different components. This clearly shows the manifold located into the tool at the top and insulated from the rest of the tool by stand off buttons. Note also that the tool is equipped with adequate water-cooling both in the cores and the cavities. This is important with hot runner tools to counter the inevitable transfer of heat from the manifold to the rest of the tool.

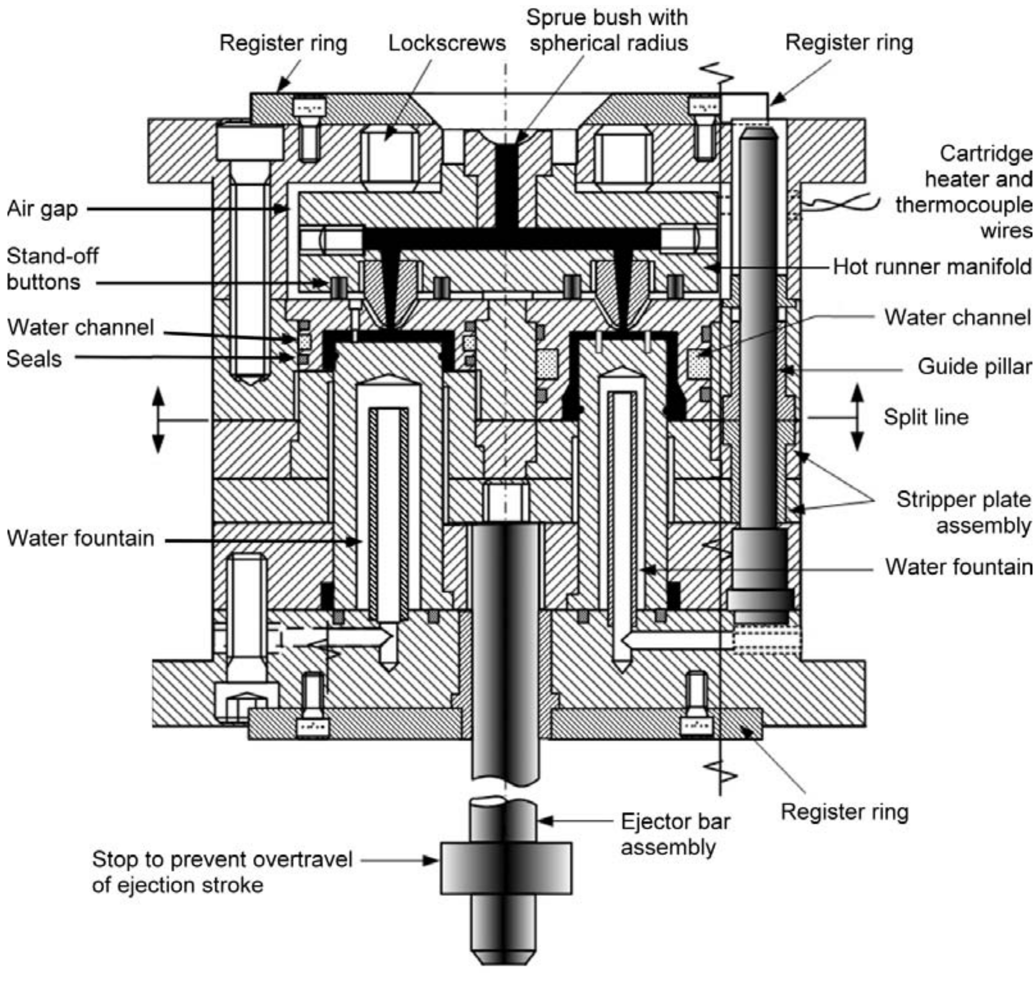


Figure 15.11 Two-impression hot runner tool

The mould incorporates a stripper plate, which gives maximum support to the two mouldings during ejection. This is important in this case to provide even, all round support for stripping the undercuts on the mouldings as ejection takes place. Another important feature of this tool is the length of the guide pillars, which must be long enough to guide the stripper plate throughout the ejection stroke. In this design, the length of the ejection stroke is controlled either mechanically with a stop as shown or with a hydraulic ejector.

When large components are being moulded, these may require a hybrid hot runner/cold runner system. Figure 15.12 shows such a design for a suitcase half, which uses a flash gate along most of the length of the moulding. This ensures that the melt stream is directed uniformly through the cavity with even flow. It also ensures that the relatively large volume of air is progressively displaced towards the split line furthest away from the gate. The direction of flow is very important to achieve this displacement of air to prevent burning and to prevent distortion associated with multipoint overhead pin gating.

Note in particular the position of the moulding with respect to the mould centre line of the mould tool. It is positioned dead centre on the mould. This ensures that the main projected area and hence the force is evenly spread with respect to the mould centre, thus avoiding out-of-balance forces on the machine platens.

To achieve this, the hot runner manifold has to be placed off centre. This does create a small out-of-balance force but it is very small compared to that of the cavity area.

As both the cavity and punch are both quite large, they will require a large number of cooling channels, as shown, to conduct away the heat generated.

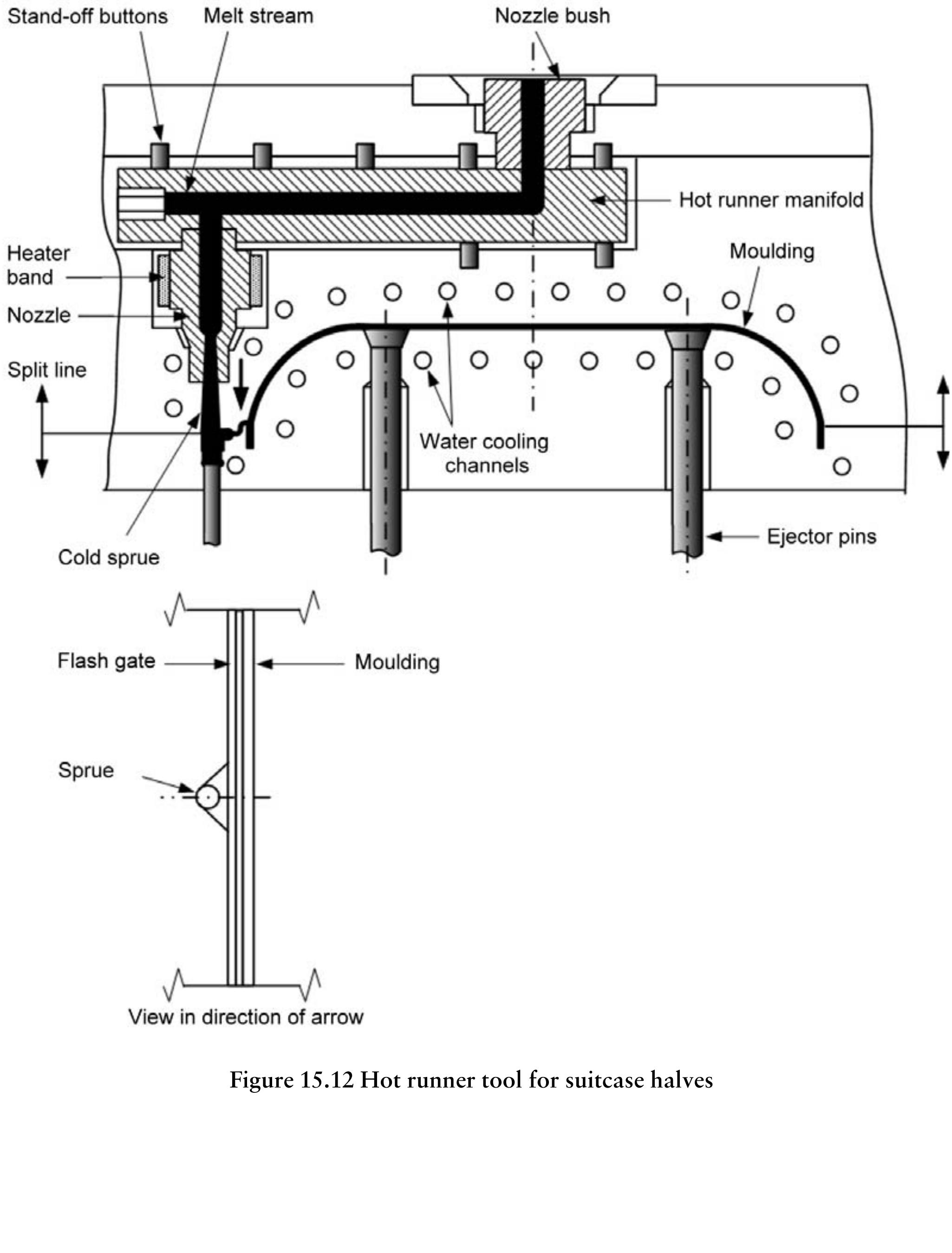


Figure 15.12 Hot runner tool for suitcase halves

15.3.2 Nozzles and Gate Bushes

There are many different designs of nozzles available for use in hot runner tools. They are heated in a similar way to standard heated nozzles with band, coil and cartridge heaters depending on whether they are internally or externally heated types. They are marketed in mains voltage and low-voltage models.

There are several gating options and associated control systems available to cover a very wide range of conditions based on mains and low voltage. These include:

- Internal or external heating
- Edge or pin gating
- Valve gating
- Multigating
- Straight-through designs
- Integral tips

15.3.3 Open Gate Nozzles

The open cylindrical gate shown in Figure 15.13 has a short land length L that provides an excellent break point above the component. Although a small gate vestige remains, the break-off point is consistent. The land length L and the gate diameter D will vary according to the material being used and the sizes of the parts being moulded, but usually have a minimum value of 1 mm for L and 0.5 mm for D. The junction of the two radii R_1 and R_2 provide for a more efficient flow of the melt, as does the chamfer.

The designer should consult the material manufacturer for actual recommended gate sizes for their materials, but empirical values can be calculated (see Chapter 17).

The big advantage of open gates is that they can be very small and they are frequently used for more heat-sensitive materials as they have fewer restrictions to the flow of the melt. They are less expensive to make and allow for easier processing than other types of gates.

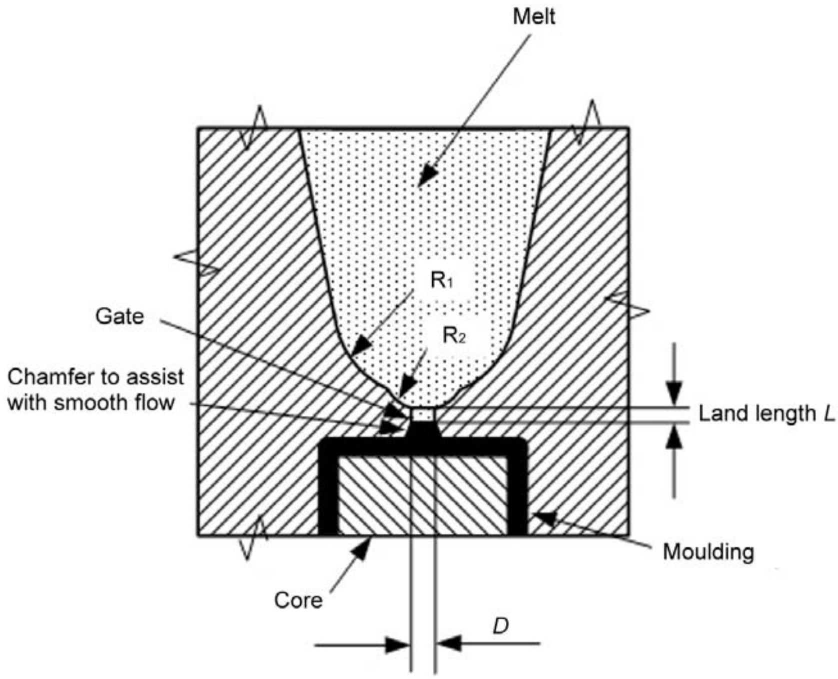


Figure 15.13 Design of open gate for hot runner nozzles

15.3.4 Spring-Operated Needle Nozzle

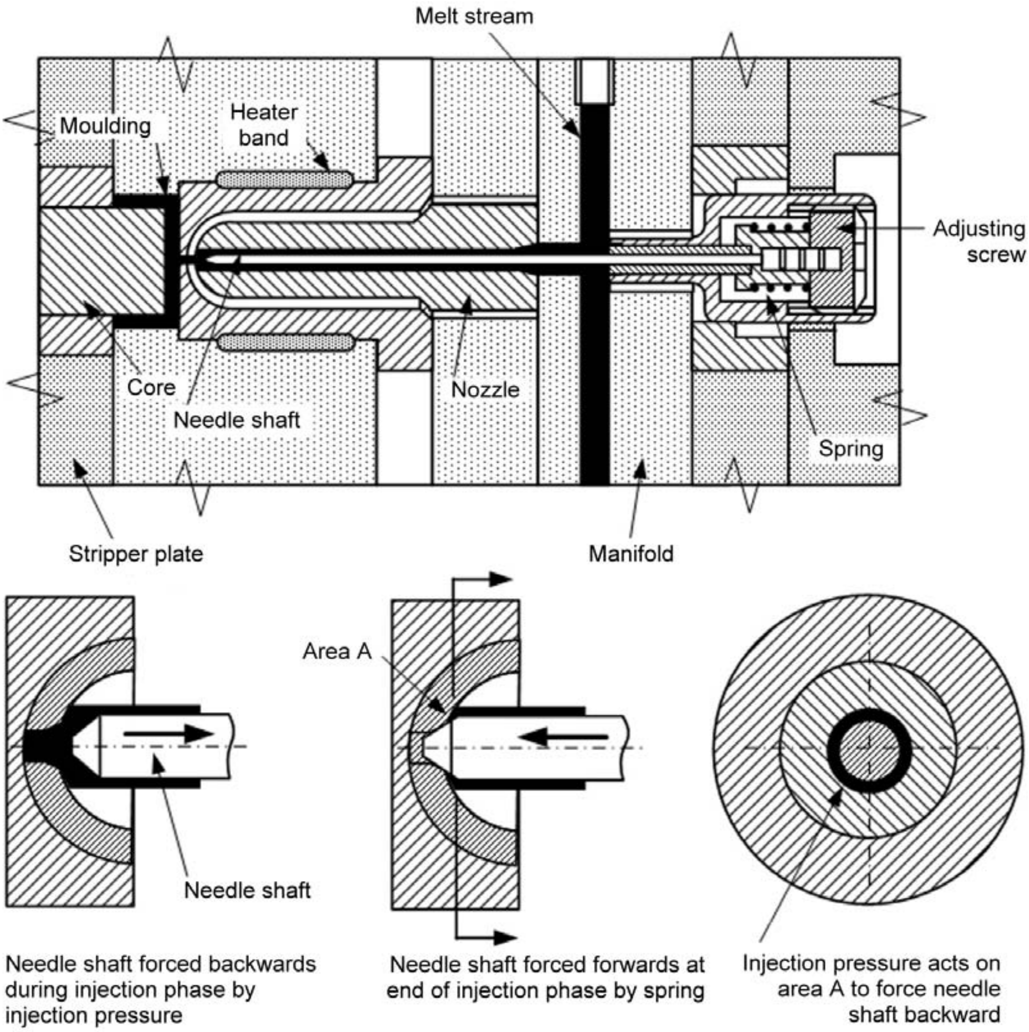


Figure 15.14 Spring-controlled needle valve

Figure 15.14 shows the basic construction of a spring-operated needle valve. In operation, the needle is forced backwards, overcoming the spring pressure when the melt pressure increases during the pressurisation phase when injection of the polymer takes place. This happens because the melt pressure acts on the projected area of the end of the needle at the gate position, creating a backward force on the needle that is greater that that exerted by the spring. When the melt pressure decreases at the end of the injection and follow-up phase, the spring forces the needle forwards and seals off the gate. An adjusting screw is provided for fine adjustment of the spring pressure.

15.3.5 Hydraulically Operated Needle Valve Nozzle

An alternative to the design in Figure 15.14 is the hydraulically operated needle valve nozzle shown in Figure 15.15. With this design a linkage connected to a hydraulic cylinder to open and shut off the melt stream operates the needle shaft.

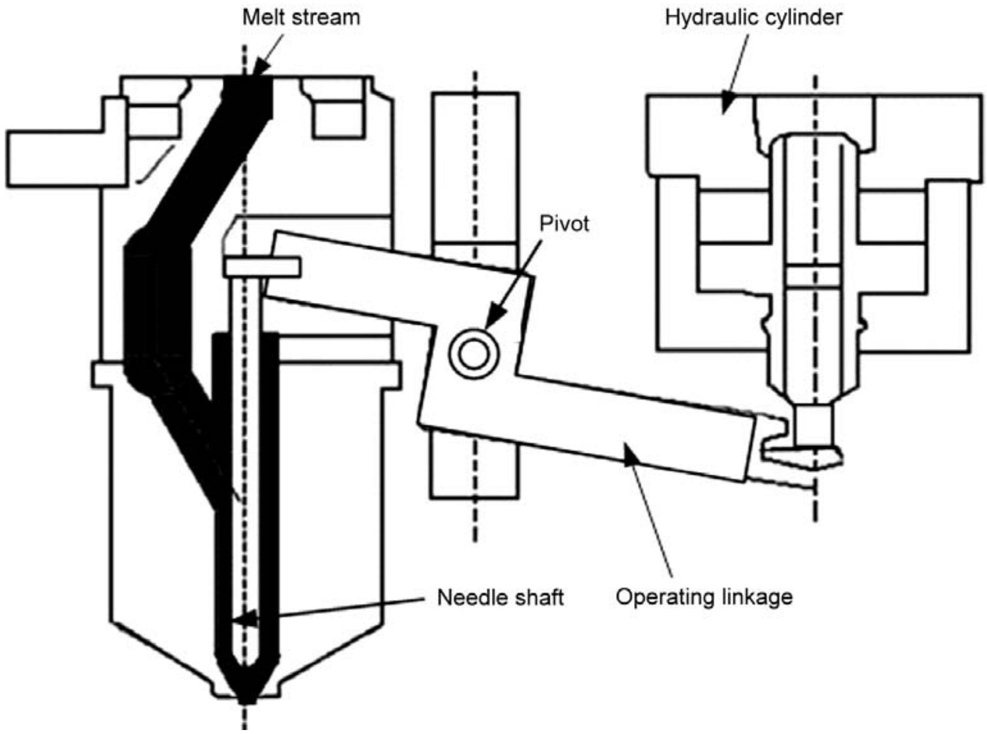


Figure 15.15 Hydraulic needle valve nozzle

15.3.6 Multipoint Gating

Multipoint gating is used to feed larger mouldings, such as beer crates, for which single gating would be insufficient. It is also used to feed multiple mouldings in mould tools with high numbers of impressions. Figure 15.16 illustrates the types of nozzle designs that are used for this type of application.

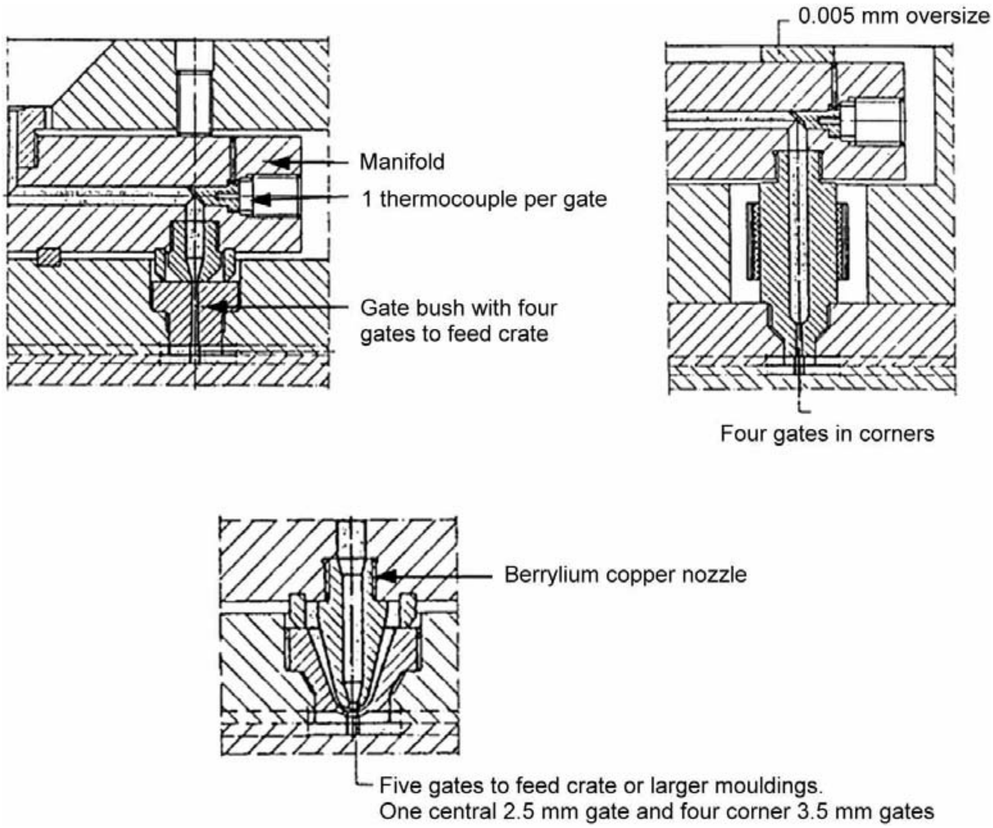


Figure 15.16 Multiple-gate nozzles

Multiple gating is frequently used for feeding several smaller components at a time on moulds with large numbers of impressions. Figure 15.17 shows the gating arrangement for a mould tool producing 64 tea/coffee spoons each shot. These are arranged with 16 inserts each with four spoon impressions in them.

With large numbers of impressions like this, maximum control is needed over all the moulding conditions to ensure consistent results.

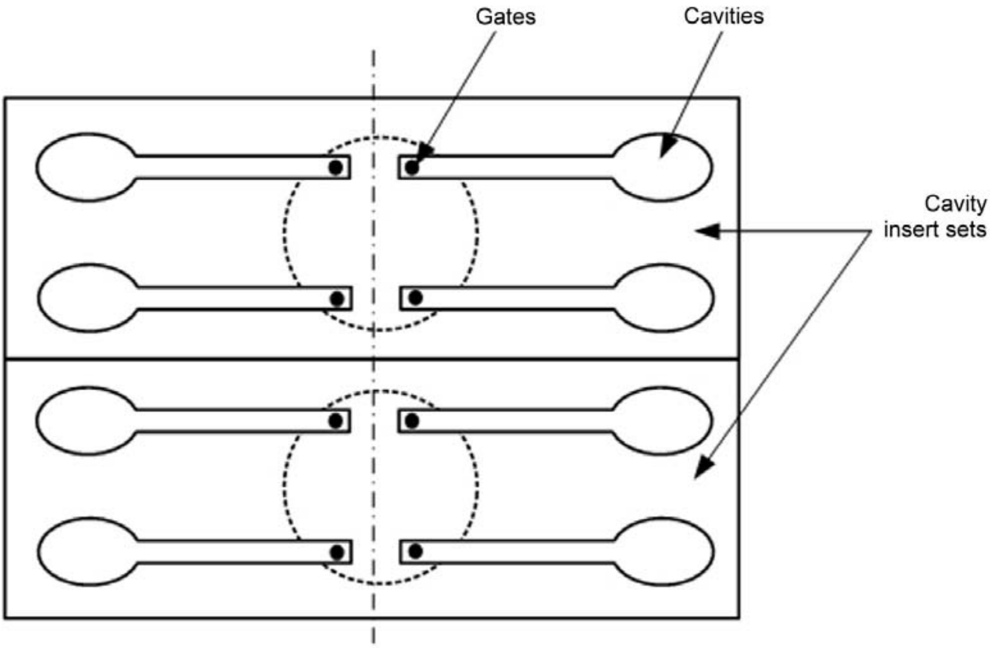


Figure 15.17 Multiple gating system for teaspoon mould

A selection of DME multigate nozzles are shown in Figure 15.18.

Figure 15.18 A selection of DME multi-gate nozzles (reproduced with permission of DME)

15.3.7 Summary

- Insulated runner tools have largely been superseded.
- Full hot runner tools keep the material at melt temperature and eliminate the production of cold runners and sprues.
- Most modern hot runner tools have a separate manifold that maintains melt temperature.
- Temperature controllers and thermocouples must be used to control the melt correctly.
- Open gates are preferred wherever possible, but where the melt tends to leak with lower-viscosity materials like Nylon, valve-operated gates need to be used.
- Hot runner moulds should always be used where high volume production is required whenever this is possible.

15.4 Heating

The correct heating of hot runner manifold systems is very important and is crucial to the success of the tool in production. There must be good heat transfer between the heater and the surface being heated or the heater will fail prematurely. Heater channels in the manifold should be smooth in order to achieve this and must not be left rough machined.

There are six types of heating systems that are commonly used in hot runner tooling:

- Band heaters
- Coil heaters
- Cartridge heaters
- Tubular heaters
- Integral heaters
- Hybrid heater/heat pipe systems

15.4.1 Band Heaters

This is the most common method of heating external cylindrical surfaces such as barrels, nozzles and tubular manifolds. Band heaters give good uniform heating right across their width and are available in a wide range of wattages and sizes. Mica and ceramic insulation are usually used.

Mains voltage operation is most common, although low-voltage systems are available at higher cost. Sizes up to 100 mm diameter by 150 mm long are available as standard but specials are available to order.

15.4.2 Coil Heaters

These are normally used to heat cylindrical surfaces where it is not necessary or sometimes not desirable to have uniform heating along its length. Coil heaters achieve this by having a varying heating capacity along their length.

Depending on the actual heating requirements, the coils may be progressively spaced further apart to provide a thermal gradient. This type of heater is most frequently used for obtaining thermal gradients on nozzles.

Operation at 240 volts is most usual. A reasonable range of sizes is available but the range is more restricted than that available for band heaters.

15.4.3 Cartridge Heaters

These are mainly used to heat hot runner manifolds and internally heated nozzles, although they are also used for heating non-hot runner tools when processing at high temperatures.

Cartridge heaters are available in a wide range of diameters, lengths and wattages. Sizes range up to 20 mm diameter by around 350 mm length. Special sizes are available to order.

It is important that cartridge heaters are not operated at full power when heating up from cold as this can also lead to premature heater failure. To avoid this problem a low voltage (or temperature) should be applied for the first 15 minutes before switching over to full working temperature.

As mentioned above, good surface contact between the heater and the manifold is essential to avoid premature failure problems. Inefficient heat transfer will also result with poor surface contact. Cartridge heaters are particularly prone to this problem.

With existing tools that have poor surface contact problems, a heat transfer paste may be used. This will greatly improve heat transfer and prolong cartridge heater life but is not as effective as properly machined smooth channels.

15.4.4 Tubular Heaters

These are very similar to cartridge heaters except that they are semiflexible. This allows them to be carefully bent into shape to fit into non-straight-line channels. They are available in diameters of 6–8 mm and in lengths up to 1000 mm and are usually 240 volts.

The same precautions regarding surface contact and low-power start-up apply to tubular heaters. If these precautions are observed, heater life is quite good.

15.4.5 Integral Heating

This is a different method of heating from any of the methods previously described. It consists of heating elements made from high-resistance wire which is electrically insulated on the outside. The wire can be cast into heated manifold systems or into torpedoes to form the source of heating in internally heated nozzles and bushes.

Integral heating is less frequently used than the previous methods but can be useful for more specialist applications.

15.4.6 Heat Pipes

The principles of heat pipes and heat rods have already been discussed in Chapter 11 on mould temperature control.

Conventional heaters can only be located in easily accessible areas in a manifold, resulting in some areas of the manifold not being heated sufficiently. To combat this, heat pipes can be used to transfer the heat to these less accessible areas. This has the distinct advantage of greater simplicity of heater location and easier maintenance if the conventional heaters fail. Once again, it is essential to have very good surface contact between the heat pipe and the surface with which it is in contact.

Heat pipes are very useful for reaching more remote areas of the manifold. As they can be obtained in smaller diameters than cartridge heaters, they can also reach areas that would otherwise be inaccessible.

15.5 Temperature Control in Manifolds

Temperature control in manifolds is very important for reliable and consistent operation of hot runner mould tools. Without adequate heating, control and heat transfer, many problems will be experienced during production.

There are two systems available for temperature control of manifold assemblies:

- Closed-loop control
- Open-loop control

15.5.1 Closed-Loop Control

A temperature sensor, usually a thermocouple, measures the temperature of the heaters or the hot runner channel. The positioning of the thermocouple is important for accurate control of the melt. Precise control is essential for heat-sensitive materials and, usually, the sensor is located midway between the heater and the melt channel.

With small internally heated nozzles it is often not possible to place sensors in this position and they may have to be placed within the heater itself. To compensate for this it is necessary to set the temperature 20–30 °C above the melt temperature for the material. This takes account of the thermal gradient that exists between the heater and material in the melt channel.

With closed-loop systems, the sensor sends back information to the temperature controller, which either adjusts or switches voltage to maintain preset conditions. Closed-loop systems are required for processing heat-sensitive materials, as accurate temperature control of the melt is essential for these.

The temperature controllers may be predictive where they continuously adjust the temperature rather than simply switching on and off, as is the case with the simpler, cheaper reactive types.

15.5.2 Open-Loop Control

Open-loop control is used in tools where accurate control of the melt temperature is not critical. Thermocouples are not used and hence there is no control on temperature.

In these circumstances, temperatures within the manifold are established by experimentation. Once the correct conditions have been found, however, consistent production can be achieved with straightforward non-heat-sensitive materials.

Open-loop control systems should not be used for heat-sensitive materials or for difficult applications where melt temperature may be critical.

15.5.3 Other Factors

As mentioned previously, good heat transfer is essential for consistent production and good surface contact is required between heaters and the surfaces they are heating.

Premature failure of heaters can also occur by switching them on to full power when the manifold is cold. To avoid this, a ‘soft start’ facility on the temperature controller is recommended. This system provides a low-power start to the heaters by supplying a reduced voltage or temperature for the first 15–20 minutes after the heaters have been switched on.

In manifold assemblies where more than one nozzle is used, separate zone control for each nozzle and/or manifold branch is usual. In large manifolds with long extended nozzles, more than one control zone for each nozzle or manifold branch may be needed.

Temperature controllers range in sophistication from simple on–off types to high-tech multizone programmable or predictive computer-controlled models. The latter are quite expensive and are usually reserved for large multi-impression tooling where maximum control is essential.

In very straightforward multi-impression applications where all nozzles are the same and the heaters are matched, a single temperature controller is often sufficient for the complete system.

15.6 Gating

We have already discussed types of gates used on nozzles for hot runner tools, but here the merits of some of the major gates types are discussed for suitability. Gating on hot runner systems falls into three basic categories:

- Pin point or edge gating
- Valve gating
- Thermal sealing

15.6.1 Pin and Edge Gating

This type of gating is very similar to that used in conventional cold runner tools. Hot tips may have one or more gates machined into them and these may be used for feeding a single component or feeding several parts from one nozzle. These types of gates rely on the material freezing and forming a seal, preventing the gate from leaking or dribbling when the tool opens to eject the part.

Where direct gating is employed on large mouldings or where difficult flow materials are used, large gates may be required. These can be difficult to seal and often leave a large unsightly gate witness. They can also leave a relatively large gate pip, which has to be removed as a secondary operation.

15.6.2 Valve Gating

To avoid leakage problems and the gate blemishes referred to above, valve-gated systems may be used. These are similar in operation to a needle nozzle unit on a machine cylinder.

Basically, a metal pin is moved within the melt stream to block off the gate after the injection phase and to open it again prior to injection. Several operating systems are used as follows:

- Mechanical
- Pneumatic
- Hydraulic
- Self-actuating

The self-actuating type relies on the injection pressure forcing a spring-loaded pin backwards away from the gate during injection. As the injection pressure drops, the spring returns the pin to block the gate off again. This type of nozzle was discussed earlier.

15.6.3 Thermal Sealing

This is a system originated by Seiki Spear and known as 'the Seiki Spear System'. The gate is kept at a nominal temperature just below melt temperature so that material cannot leak from it when the tool is open.

A small probe is located into the gate area of the nozzle and just before injection; the probe is heated by a low-voltage supply that raises the material temperature in the gate to melt temperature.

A control system is used to detect the point at which injection is about to occur and the voltage is applied throughout the injection and holding pressure phase of the cycle. At the end of this period the voltage is removed and the gate temperature reverts to its nominal sub-melt value, thus sealing the gate again.

This system is very impressive in operation and very reliable, with gate melting time being less than 1 second from the moment the voltage is applied. It is quite expensive, but for some difficult and critical applications it can prove a justifiable investment.

15.7 Thermal Expansion

When a hot runner tool is being designed, careful attention must be paid to potential difficulties associated with thermal expansion. Frequent failures of gate bushes and nozzles can be attributed to temperature changes and consequent stresses occurring in these components if care is not taken.

Whenever a manifold is heated from ambient to operating temperature, the manifold will expand in accordance with the relationship

Expansion = length × α × temperature rise

or

$E = L\alpha t$

where

E = the change in dimensions or expansion

L = the initial length

α = the coefficient of linear expansion

t = the temperature rise in °C

The coefficient of linear expansion of steel is 13×10^{-6}. Hence a manifold with an operating temperature of 250 °C and a distance between nozzle centres of 300 mm would expand by

$300 \times (13 \times 10^{-6}) \times (250 - 20)$ (assuming ambient temperature is 20 °C)

= 0.9 mm

In this example it may be necessary allow the gate bushes or nozzles to slide in the cavity plate by other means as discussed next. This would ensure the nozzle centres would be free to expand to match those in the cavity plate at the operating temperature of the manifold.

Designs must incorporate provision for this expansion and this is accomplished by providing sliding interfaces in two ways:

- Manifold/nozzle
- Nozzle/mould

15.8 Manifold/Nozzle Interface

In this design the nozzle is located into a bored diameter in the rear of the cavity plate and the manifold slides over the nozzle during expansion. The rear face of the nozzle and the manifold must be ground flat to achieve a good sliding seal. In some designs a stainless steel 'O ring' is located in an annular groove at the top of the nozzle to improve sealing.

15.8.1 Nozzle–Mould Interface

The nozzle is screwed to the manifold in this design. As expansion takes place, the front of the nozzle slides across the rear of the cavity plate. An insulated antechamber is often used with this design to assist sealing.

When relatively long nozzles are being used, sometimes no expansion allowance is made. Instead, the nozzle body is allowed to flex to accommodate the expansion.

15.8.2 Heating Capacity Requirements

The actual heating capacity for heaters used in manifold and nozzle application must be calculated for each tool design. Failure to do this will result in either inadequate heating or premature failure of heaters.

For most general-purpose materials the following guide may be used:

Melt Temperature 220–250 °C

200–250 W per kg of steel in the manifold

Or approx. 1–1.2 W/cm^3

Melt Temperature 250–300 °C

250–300 W per kg of steel in the manifold

Or approx. 1–2 W/cm^3

In both cases the amount of heating required will be dependent on how well the manifold system is insulated from the rest of the tool.

15.8.3 Wattage Density

Once the overall amount of heating capacity has been established, the next stage is to ensure that the wattage density is kept within certain limits as follows:

Cartridge heaters:	6 W/cm^2
Band heaters:	10 W/cm^2

If these values are exceeded, premature heater failure can result. To calculate the values to be used, the number of heaters that are going to be used must be established. This is often determined by the design of the manifold, but the heater layout should provide for uniform heating throughout the manifold.

15.8.3.1 Example calculation

To illustrate the method, consider the following example: A hot runner tool is manufacturing components in polypropylene with a melt temperature of 230°C and has manifold dimensions of 30 cm × 15 cm × 10 cm. The design allows eight cartridge heaters to be used.

- In this case, the manifold has a volume of (30 × 15 × 10) cm^3 = 4500 cm^3.
- From the above information it is decided to use 1 W/cm^3 of the manifold to maintain melt temperature.
- We therefore require 1 × 4500 W or 4.5 kW total heat capacity.
- Eight heaters are being used, hence we require (4500/8) W = 562.5 W cartridge heaters.
- For this design, 15 mm diameter × 20 cm heaters are selected.
- We now require each heater to provide a maximum of 6 W/cm^2.
- The surface area of this heater is πDL= 3.142 × 1.5 × 20 = 94.25 cm^2.
- Hence the wattage density will be 562.5/94.25 = 5.97 Wcm^2, which is satisfactory since it is below our limit of 6 W/cm^2.

If this calculation had resulted in a wattage density of more than 6 W/cm^2, one or more of the following would have to be chosen:

1. A larger-diameter heater
2. A longer heater
3. A larger number of heaters

Options (1) and (2) would increase the surface area of the heaters. Option (3) would decrease the wattage of each heater. Any of them would reduce the wattage per square cm.

In cases where the design will not allow the used of heaters below 6 W/cm^2, special heaters may be available to order.

15.8.4 Manifold Heat-Up Time

A further consideration that needs to be taken into account when deciding heating capacity, is the time taken for the manifold to reach working temperature from ambient.

The following formula gives a good rule of thumb guide for the heat-up time in minutes for 'average' conditions:

$$\text{Heat-up time} = \frac{16 \times Manifold\,mass\,in\,kg \times (T_o - T_a)}{Total\,heater\,capacity\,in\,Watts}$$

where T_o is the operating temperature of the manifold and T_a is the ambient temperature. The density of steel may be taken as 7.85 g/cm^3.

16 Mould Materials

16.1 Introduction

It is very important to ensure that the correct materials are specified in all new injection mould designs. Use of incorrect or inappropriate materials can lead to poor mould performance in production and to early failure of the tool.

In all mould materials we are looking for certain characteristics for ease of toolmaking and good performance during production from the mould tool. Ideally we would prefer the material finally selected to have the following properties:

- Good machining properties
- Ease of heat treatment where hardening is required
- Good toughness and strength
- Polishes and accepts texturing well
- Good resistance to heat and wear
- Good fatigue resistance
- High thermal conductivity for effective water cooling
- Good corrosion resistance

Unfortunately, in practice no single material will exhibit all these characteristics and therefore a compromise has to be reached depending on the type of tool design being employed. Among the major governing factors that should be considered are:

- The tool life in terms of the quantity of parts required to be produced from the tool
- The moulding material being used (e.g., abrasive or corrosive)
- Texturing and polishing requirements
- Whether hardening is required (e.g., for long running tools or for side cores and splits, etc)
- Whether high thermal conductivity will be required
- Exceptional requirements like the use of very high injection pressures or speeds

16.2 Selecting the Material for the Application

For most normal applications steel is used because it has most of the properties we require. There are several other applications, however, where alternative materials may be used. The following sections discuss the materials used for most normal situations encountered. Table 16.1 gives an overview of the materials most often used.

Table 16.1 Mould materials

Application	Materials Used	Process
Preproduction runs	Epoxy resin	Casting
Prototypes	Low-melting-point alloys, e.g., Kirksite	Casting and metal spraying
Small quantities	Mild steel or low-carbon steel	Machining
Medium production runs for straightforward parts	Mild steel Aluminium Pretoughened alloy tools steels Unhardened alloy tool steels	Machining
Medium production runs for technical or high-performance parts	Aluminium alloy Pretoughened alloy tool steels Unhardened alloy tool steels	Machining
High-speed production and close tolerance work	Hardened alloy tool steels	Machining
Large-volume production	Hardened alloy tool steels	Machining
Texturing, high polished finishes for:		
Low/medium volumes	Aluminium alloy Unhardened and pretoughened alloy steels	Photo-etching Chemical etching EDM
High volumes	Pretoughened alloy steels Hardened alloy tool steels	Photo-etching Chemical EDM
High heat transfer	Beryllium copper	Casting and machining
Poor heat transfer	Ceramic titanium	Casting and machining

In practice certain applications may fall outside the groupings shown owing to individual preferences or special requirements. For example, some companies use aluminium alloys for all their mould tools irrespective of whether the application is a long- or short-run job. The groupings given in the table are those used for most general-purpose mould tools.

16.3 Materials Characteristics

This section discusses the major properties and characteristics of the majority of the materials used for injection mould tools.

16.3.1 Steel

Steel is the industry standard material for the manufacture of mould tools. It is considered a good all-round material embodying many of the desirable characteristics that we are looking for.

There are many different types of steel available for a wide range of general-purpose applications and many specialist steels for more extreme applications. For our purposes, however, we will restrict our discussion to those steels commonly used for the manufacture of injection mould tools.

A number of steels are used for the construction of mould tools. All steels contain ***carbon*** and, in general, the higher the level of carbon, the tougher and stronger the steel will be. Sometimes plain or ***mild*** steel is used with low carbon content, and on other occasions higher carbon content steel is used, often alloyed with other elements to improve the properties of the steel. Carbon steels that have been alloyed with other elements to increase their performance, are usually called ***tool steels*** or ***alloy tool steels.***

For nearly all mould steels the most common alloying elements are ***chromium***, ***nickel***, ***molybdenum***, ***tungsten, cobalt*** and ***vanadium.*** For most mould steels, four of these elements are normally used.

Chromium: Improves surface resistance to wear and corrosion.

Nickel: Improves low-temperature toughness and increases fatigue resistance.

Vanadium: Increases strength, hardness and impact resistance.

Tungsten: Increases strength, toughness and higher temperature performance.

Although these alloying elements are designed to improve certain properties, it must be noted that they can also have adverse effects on other properties. For example, with increasing chromium content the thermal conductivity of alloy steel decreases.

16.3.2 Plate Steel

Table 16.2 lists the different types of steel available for mould plates together with a brief account of their properties and uses.

Table 16.2 Mould steel applications

Category	Uses	Standard	Comments
Low-carbon, also known as plain plates, carbon or mild steel	Backplates, support locating rings	BS907 (EN8) AISI 1020 DIN 1.1805	Used for economy in noncritical applications
Prehardened or pretoughened alloy tool steels	Cavities, punches and cores	BS4569 BP20 AISI P20 DIN 1.2713	Alloy tool steel used unhardened. Can be locally heat-treated
Fully hardening alloy tool steels	High volumes where high quality, strength and hardness are required for cavities and cores	BS4569 (EN30B) AISI H13 DIN 1.2343	High-quality tool steel. First choice for long-running jobs
Stainless steel	Used for corrosion resistance to protect against corrosive materials such as PVC	BS (EN57) AISI 420 SS DIN 414 SS	Stainless steels contain up to 18% chromium and hence have worse heat transfer
High-carbon–high-chrome	Cavities and cores where high levels of hardness are required	BS (EN308) AISI D2 DIN1.2601	Very hard when heat treated. Used for small parts. Prone to stress cracking
Nitriding steels	Areas of high wear. Sliding surfaces, ejector pins and sleeves	BS907 722M24 AISI H13 DIN 1.2307	Extensively used for small sliding parts

The most frequently used standard is the AISI, which stands for the American Iron and Steel Institute. By international agreement the AISI designatory system has been adopted and hence literature will increasingly refer to this standard. All AISI specifications have an initial identification letter, which helps to identify steel types as shown in Table 16.3.

Table 16.3 AISI steel designations

Identification letter	Type of steel
A	Air hardening steels
C	Carbon steels
D	High-carbon–high-chrome steels
F	Carbon–tungsten steels
H	Hot work die steel (H1–H19 chromium base) (H20–H39 tungsten base) (H40–H49 molybdenum base)
L	Low alloy steels
M	Molybdenum base steels
O	Oil hardening steels
P	Mould steels (P1–P19 low-carbon) (P20–P39 other types)
S	Shock-resistant steels
T	Tungsten-base steels
W	Water hardening steels

The most commonly used steels for injection moulding tools are as shown in Table 16.4. The alloy steels listed will machine readily (conventional machining and EDM) and will support high levels of polish. They are also suitable for texturing using EDM and photo-etch techniques.

These are not the only steels used for injection mould tools but they do represent those used for the majority of applications. Specialist steels may be used for more demanding applications, e.g., stainless steel for corrosion resistance, and high-carbon–high-chrome to achieve ultra-hard cavity inserts.

Table 16.4 AISI designated mould steels		
Type of steel	**AISI No.**	**Comments**
Mild Steel	AISI 1020	For backplates, support plates, support register rings and ejector bars
Nickel Chrome Alloy	AISI H13	Used unhardened for cavity backing plates where high loads are likely and for medium-quantity jobs for cavities and cores, or for plates likely to suffer bruising, e.g., runner system plates and stripper plates on multiplate tools. Used hardened for high-quality, long-running jobs for all cavities, cores and punches. Hardness value 48–52 Rc
Nickel Chrome Alloy	AISI P20	Pretoughened steel used for medium-volume work. Material can be machined in this state. It is about halfway between the unhardened and hardened grades of H13 in toughness and hardness. Used for cavities and cores. Hardness value 28–32 Rc

16.3.3 Cast Steel

For large mould tools, plate steel from rolled or forged stock is often not available in the sizes that may be required. Even when plate steel is available in these sizes it is seldom economic to machine cavity forms directly into such large pieces of metal.

Deep drawn forms would also be extremely difficult to machine on components like refrigerators, wheelie bins and TV surround cases. Additionally, to machine such large forms would result in up to half of the original steel billet being machined away, making it an uneconomic process. To overcome this problem, large mould tools would be cast from suitable steel, which is usually very similar to the plate steels previously discussed for smaller tools.

The cavity form is cast in a similar manner to other metal casting techniques using a pattern in a sand mould. It is common practice to incorporate during the casting process complete water temperature control channels and cored ejector pinholes and similar features that would be difficult or expensive to machine in the finished casting. A specialist foundry would carry out such casting work.

Although the steels used for casting are similar to those used for plates, there are slight differences because the structure of cast steel makes it not quite as strong as that of rolled or forged steels. Casting-grade steels are therefore selected to give as fine a crystal structure as possible for maximum quality and strength.

An important factor is that the cast steel should easily weldable, as pits, blowholes and shrinkage holes frequently occur in the surface of the casting. Long-term damage from thermal shock is common in cast steels and results in surface cracks appearing. Welding also normally repairs these.

The sand casting process is used for producing large mould tools of up to about 4 tonnes per casting (per mould half) resulting in finished moulds of up to 10 tonnes in weight.

The basics of the sand casting process are shown in Figure 16.1. A pattern (usually wood) is placed on a bed of sand and further sand is packed around it until the sand reaches the parting line. Special parting sand is dusted over the surface of the sand at this point to enable the two halves of the mould to be separated more easily. The top box is then placed on top of the lower box and also filled with sand.

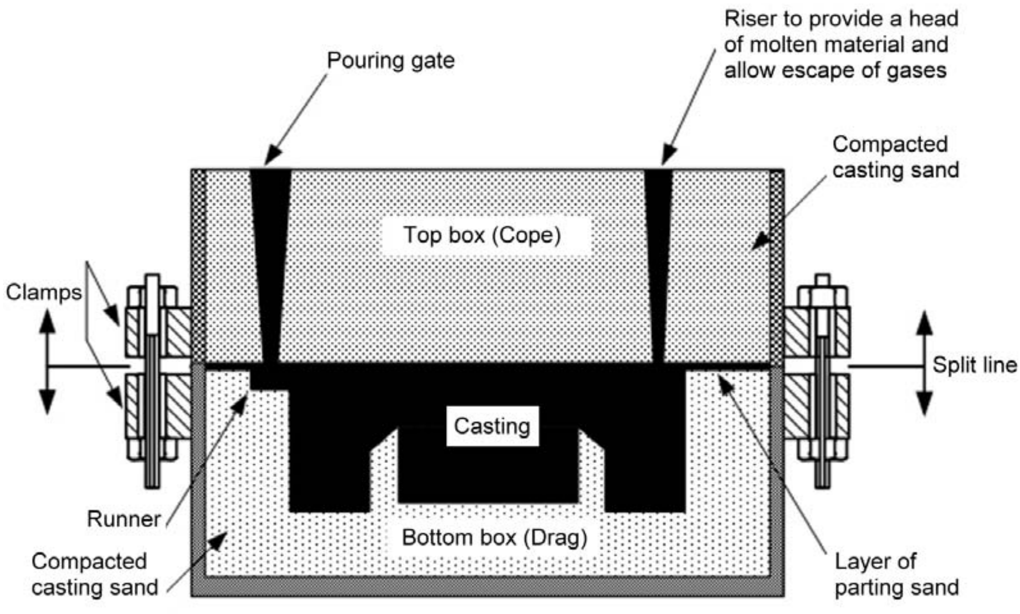


Figure 16.1 Sand casting process for cast steel moulds

The runner and riser are inserted into the top box and the molten metal is poured into the gate. After the steel has cooled, the box is split at the parting line and the casting is removed. It is from this casting technique that the terms used in injection moulding originated.

Table 16.5 gives details of the steels normally used for casting.

Table 16.5 Steels used for casting

Steel	Specification	Details
Carbon steels	AISI 1020	0.18–0.23% C; 0.30–0.60% Mn; 0.04% P; 0.05% S; annealed BH 122; normalised BH134. Welding is readily done by most arc and gas processes. Preheating is unnecessary unless parts are very heavy.
	AISI 1040	0.37–0.44% C; 0.60–0.90% Mn; 0.04% P; 0.050% S; normalised and annealed BH 175; normalised and oil quenched BH 225. Welding can be done by arc, resistance and gas processes. Decreased cooling rate and subsequently hardness preheating to above 150°C, preferably 260°C. Final heating to 600–650°C restores ductility and relieves stress.
Alloy steels	AISI 1330	0.28–0.33% C; 1.60–1.90% Mn; 0.20–0.35% Si; 0.035% P; 0.04% S; normalised BH 187; normalised and tempered BH 160. Can be relatively easily welded with mild steel filler metal
	AISI 4130	0.28–0.33% C; 0.40–0.60% Mn; 0.20–0.35% Si; 0.80–1.10 Cr; 0.15–0.25% Mo; 0.035% P; 04% S; annealed BH 175. Welding the same as for AISI 1330.

Continued…

Steel	Specification	Details
Alloy steels (continued)	AISI 4340	0.38–0.43% C; 0.60–0.80% Mn; 0.20–0.35% Si; 1.65–2.001% Ni; 0.70–0.90% Cr; 0.20–0.30% Mo; 0.035% P; 0.04% S; normalised and annealed BH 200; quenched and tempered BH 300. Welding calls for pre- and postheating and filler metals of the same mechanical properties as the base metal. Stress relieving is desirable, especially in repair work.
	AISI 8630	0.28–0.30% C; 0.70–0.90% Mn; 0.20–0.35% Si; 0.40–0.70% Ni; 0.40–0.60% Cr; 0.15–0.25% Mo; normalised BH 240; annealed BH 175. Welding preferably with filler metal of the same chemical analysis. No preheating needed for sections up to 0.5 inch but stress relieving after welding is necessary.
Heat-resistant steel	AISI 501	0.10% C; 1.00% Mn; 1.00% Si; 4.00–4.00% Cr; 0.40–0.650% Mo. Welding similar to 8630.

16.3.4 Nonferrous Materials

There are certain situations where nonferrous materials are used in mould tool construction. In some cases these materials are used for specific purposes within a steel mould base. In other cases they may used as the main mould base material.

16.3.5 Aluminium Alloys

There is a noticeable trend towards the use of aluminium alloys for medium- to high-volume production in the UK, the USA and increasingly in mainland Europe.

The principal advantages of this material are:

- It costs less than steel.
- It has good machineabilty: it machines up to 5–10 times faster than steel.
- Distortion from machining is minimal compared to steel owing to a special heat treatment of the material during production.
- The thermal conductivity is excellent, much higher than that of steel, which promotes rapid and efficient heat removal from the mould during moulding.
- Cavity forms can be made using EDM techniques at a rate of up to six times faster than steel.
- The weight of aluminium alloys is less than that for comparable sizes of steel.
- It may be chrome plated or anodised to reduce wear and corrosion.
- It can be polished and etched in the same way as steel.

The main disadvantages of this material are:

- The modulus of elasticity is only 30% that of steel.
- It cannot achieve the same levels of hardness as steel.
- As it is mechanically weaker than steel, plate thickness' have to be around 40% greater than with steel.
- Wear is greater and the material bruises more easily.

The service life of aluminium alloy mould tools can quite readily achieve around 200 000 shots depending on the moulding conditions. There are a few notable exceptions to this where longer service lives of up to a million shots are achieved for straightforward parts, although certain mould parts may have to be replaced because of damage and wear.

There is also an increasing use of hybrid aluminium–steel mould tools in which the advantages of both materials are used to best effect – steel for high-wear areas and aluminium for less critical areas and where high rates of mould cooling are desirable.

Table 16.6 shows two of the main grades of aluminium alloy used for mould tool applications and Table 16.7 shows comparisons between aluminium alloys and other commonly used materials.

Table 16.6 Properties of aluminium alloy for moulds

AA No.	7075-T6	7029-T6
Composition	Al, Zn, Mg, Cu, Cr	Al, Zn, Mg, Cu
Treatment	Solution treated, artificially aged	Solution treated, artificially aged
Density (kg/dm^3)	2.80	2.74
Coefficient of thermal expansion	23.3×10^{-6}	24.7×10^{-6}
Thermal conductivity (W/(kg-m))	140	126
Ultimate tensile strength (Mpa)	572	537
Yield strength (Mpa)	503	469
Brinell hardness (BHN)	150	125

Table 16.7 Comparison of aluminium with other mould materials

Mould material	Additional description	Coefficient of expansion[1]	Thermal conductivity[2]	Density (lb/in^3)	Hardness[3]	Yield strength (KSI)	Weldability[4]
QC-7	Aluminium Alcoa	12.8	91	0.102	167 HB	74–79	A
7075-T651	Aluminium	13.1	75	0.101	150 HB	48.73	A
6061-T651	Aluminium	13.1	96	0.098	95 HB	40–42	B
P20	Mould steel	7.1	20	0.284	28–37 Rc	130–135	
S7	Alloy tool steel	6.99	21	0.283	59–61 Rc	210	C
H13	Hotwork die steel	6.1	14.4	0.28	52–54 Rc	228	C
420	Stainless steel	5.7	20	0.28	52 Rc	215	C
MOLDMA X	Beryllium–copper brush Wellman	9.7	60.75	0.302	30–40 Rc	140–155	C
AMPCO	Copper Ampco metal	9.7	125	0.315	210 HB	75	D

[1] Values are in in/in °F: a higher number indicates increased expansion.
[2] Values are in btu/[(ft^2-h-°F)/ft] at 68°F: higher numbers indicate greater thermal conductivity.
[3] HB = Brinell hardness; Rc = Rockwell hardness. Higher numbers indicate increased hardness levels.
[4] Weldability: A: Moderately weldable, large repairs shoul be avoided.
B: Readily weldable.
C: Moderately weldable, preheat and postweld heat treatment required.
D: Weldable with proper technology.

16.3.6 Zinc Alloys

Zinc alloys have poor mechanical strength and are unsuitable for production tooling. They are, however, often used for prototype tooling where only a relatively small number of parts are required for preproduction evaluation purposes.

They have a low casting temperature of around 400–450 °C and are therefore well suited to casting from patterns of plaster, wood, steel and aluminium. Zinc alloys can also be cast by sand moulding as described above or by using ceramic moulding techniques. The resulting castings reproduce intricate pattern detail extremely well, giving a smooth nonporous surface that ultimately produces good-quality plastic mouldings.

Premium-grade zinc alloy is also suitable for cold hobbing, usually with a rotating hob (for circular components), to impart undercut forms into the cavity insert. Many undercut forms can be replicated in this way (helical gears, for example), giving a cheap accurate method for producing accurate undercut forms.

In view of the poor mechanical strength of this material, normally only the cavity forms are made from it. The resulting casting or hobbed cavity would be inserted into a steel bolster to support it. Two of the best-known zinc alloys are ***Mazak*** and ***Kirksite***. A summary of their properties is listed in Table 16.8.

Table 16.8 Properties of Mazak and Kirksite

	Density (g/dm^3)	Melting point (°C)	Shrinkage	Thermal expansion ($10^{-6}/K$)	Tensile strength (Mpa)	Elongation (% in 50 mm)	Brinell hardness (BH)	Compressive strength	Shear Strength (Mpa)
Mazak	6 700	390	1.1	27	220–240	1–2	100	600–700	300
Kirksite A	6 700	380	0.7–1.2	27	226	3	100	420–527	246

16.3.7 Beryllium–Copper Alloys

Pure copper is a very soft, ductile material and is unsuitable for use as cavities or cores. Copper is used in mould tools only as a heat exchanger, usually inside core pins. Its excellent thermal conductivity makes it ideal for conducting heat away from smaller core pins where direct water-cooling is not possible.

When copper is alloyed with beryllium, the resulting beryllium–copper alloy is a much stronger, tougher material and is used for cavity and punch applications. With increasing beryllium content, the mechanical properties improve but the thermal properties worsen.

At least 1.7% beryllium content is required for direct cavity and punch applications, with around 2% being the norm. Cavities made from this material may be heat-treated to around 400 °C, giving a hardness of about 40 Rc. The surface hardness may also be increased by about 15% by the use of ion implantation techniques.

Beryllium copper may be cast and machined and will accept chromium and nickel plating. Cold hobbing is used for shallow forms and hot hobbing at temperatures of 600–800 °C, followed by solution annealing.

Unlike steel, this material is totally resistant to thermal shock and therefore highly suitable for cavity inserts where large amounts of heat have to be removed. This can result in significantly shorter cooling periods, thereby reducing the overall moulding cycle. Table 16.9 gives a summary of the principal properties of beryllium–copper.

Table 16.9 Properties of beryllium–copper

Property	Designation				
	C17200	C17300	C1700	C17510	C17500
Composition	Be: 1.80–2.00% Co/Ni: 0.20% min. Co/Ni/Fe: 0.6% max. Cu: balance	Be: 1.80–2.00% Co/Ni: 0.20% min. Co/Ni/Fe: 0.6% max. Pb: 0.20–0.6% Cu: balance	Be: 1.60–1.79% Co/Ni: 0.20% min. Co/Ni/Fe: 0.6% max. Cu: balance	Be: 0.20–0.60% Ni: 1.40–2.20% Cu: balance	Be: 0.40–0.75% Co: 2.40–2.70% Cu: balance
Density (kg/m^3)	8 250		8 610	8 610	8 775
Thermal expansion W/(m-K)	130		130	260	260
Thermal expansion (10^{-6}/K)	17.50		17.50	17.60	18
Specific heat capacity (J/(kg-K))	420		420	420	420
Electrical resistivity (10^{-8} Ω-m)	7.7		7.7	3.8	3.8
Modulus of elasticity (Gpa)	131		128	138	138

Continued…

Property	Designation				
	C17200	C17300	C1700	C17510	C17500
Tensile strength (Mpa)	I: 415–585 II: 620–895 III: 1 140–1 310 IV: 1 275–1 480		I: 415–585 II: 620–895 III: 1 035–1 310 IV: 1 170–1 450	I: 415–585 II: 620–895 III: 1 035–1 310 IV: 1 170–1 450	
Yield strength (MPa)	I: 140–415 II: 515–725 III: 1 000–1 200 IV: 1 140–1 380		I: 140–205 II: 515–725 III: 860–1 070 IV: 930–1 140	I: 140–310 II: 340–515 III: 550–690 IV: 690–830	
Elongation (%)	I: 35–60 II: 10–20 III: 3–10 IV: 2–5		I: 35–60 II: 10–20 III: 4–10 IV: 2–5	I: 20–35 II: 10–15 III: 10–25 IV: 10–20	
Rockwell hardness	I: B45–80 II: B88–103 III: C36–41 IV: C39–44		I: B45–85 II: B91–103 III: C32–39 IV: C35–41	I: B25–50 II: B60–75 III: B92–100 IV: B95–102	

I: Solution heat-treated.
II: Cold drawn.
III: Solution heat-treated and age hardened.
IV: Cold-drawn and age-hardened.

16.3.8 Bismuth–Tin Alloys

These alloys are more commonly known as 'Cerro alloys'. When subject to shock loading they are quite brittle, but under constant loading conditions they exhibit some plasticity. Unusually the mechanical strength of these alloys increases with ageing. Even so their moderate mechanical strength makes them suitable only for prototype mouldings.

Bismuth–tin alloys have low melting points, ranging from 40 °C to 180 °C. They are well suited to conventional casting techniques and for die and vacuum casting. Frequently they are used with a special-purpose spray gun, which is used to spray a coating of the alloy onto a master to form a cavity that can be inserted into a bolster

Table 16.10 summarises the properties of some Cerro alloys.

Table 16.10 Properties of Cerro alloys

Designation (registered trademark)	Cerrotru	Cerrocast
Density (kg/dm^3)	8.64	8.16
Melting point or range (°C)	1.38	138–170
Specific heat (kJ/kg)	1.88	1.97
Thermal expansion (10^{-6}/K)	15	15
Thermal conductivity (W/(K-m))	21	38
Brinell hardness (BHN)	22	22
Ultimate tensile strength (MPa)	56	56
Elongation (slow loading) (%)	200	200
Max. constant load (MPa)	3.5	3.2
Composition (%Bi)	58	40
Composition (%Sn)	42	60

16.3.9 Epoxy Resin

This material is frequently used for making cavity forms because of the ease with which it can be done. A resin and hardener are mixed together and then a finely divided aluminium powder is added to the mixture. The aluminium is an essential additive to help with heat conduction, as the resin itself is a poor conductor of heat.

The resulting mixture is thoroughly mixed under a high vacuum to obviate the inclusion of air bubbles. Once a homogeneous mixture is achieved, the resin may be carefully cast over a master to achieve a cavity insert, which is then loaded into a bolster (usually steel).

Owing to the low mechanical strength of the material and its poor thermal conductivity, its use is limited to prototype work only. However, many very intricate prototypes have been successfully moulded from moulds with epoxy resin inserts. Several major car manufacturers use this technique to obtain good-quality small plastic mouldings for evaluation. It is a cheap and quick method of making cavity inserts from suitable master forms.

16.4 Heat Treatment

Heat treating is a science in itself and should be left to specialists. One of the reasons the designer should stay with a minimum selection of tool steels is to avoid the many heat treatment specifications, which are usually different for each type of steel; this way both the designer and the heat treatment company both become familiar with particular steels and know what to expect.

Nearly all mould toolmakers use outside suppliers for heat treatment because it is a specialist process and also because of the investment that would otherwise be required for the necessary plant and equipment.

Sometimes two steels, even with an identical AISI number, may require significantly different heat treatment (as shown in the steel supplier's specification sheets) to achieve the optimum properties required from the steel. The designer need only specify the required hardness of the part, as it is not necessary for the designer to have a deep knowledge of the heat treatment process. It is desirable, however, that the basic procedures are understood so that the designer will be aware of the results that different hardening procedures give.

Where the same degree of hardness can be obtained by using alternative hardening procedures, the designer should specify which process is required since these may affect, wear, toughness and mechanical strength.

There are several different hardening techniques available for mould tools, the main ones being listed next:

- Through-hardening
- Pretoughening or prehardening
- Carburising or case hardening
- Nitriding
- Tuftriding
- Ion implantation

16.4.1 Through-Hardening

This technique is used for most cavities, punches, core pins, side cores and other items that come into contact with the moulding material. Through-hardening consists of heating the steel to a given temperature and then quenching it in air, water or oil. The usual steel selected for this purpose is ***AISI H13 alloy*** or equivalent.

The cavity, punches and core pins need to be hardened for medium- to long-run jobs to avoid them becoming bruised, scuffed or worn during repeated cycling of the tool. If these items are not hardened, the tool will quickly deteriorate, resulting in damage and possibly seizure on mating sliding parts. Unhardened tools are also prone to early signs of flashing, which can rapidly worsen with continued production.

Through-hardening in mould tools is restricted to nickel–chromium, high-carbon–high-chromium or similar alloy tool steels. To through-harden steel it must have at least 0.35% carbon content. Steels with a lower carbon content than this will not through-harden and other methods of hardening have to be used.

Most through-hardening processes involve the work piece being heated to a high temperature followed by quenching. During this procedure the steel undergoes a high degree of thermal shock, which induces a very brittle structure in it. Subsequent tempering procedures have to be carried out to change this structure, otherwise the steel will remain too brittle and fracture easily.

The combined procedures of hardening and tempering can result in the work piece distorting. In view of this it is standard practice to leave a small grinding allowance on the work piece so that the part may be ground to final size before fitting to the tool.

It is also usual to carry out EDM machining after hardening rather than before to avoid delicate cavity forms becoming distorted or damaged during hardening. However, there may be occasional exceptions to this rule as discussed in Chapter 20 on 'Fatigue'.

16.4.1.1 The Through-Hardening Process

- Heat above the critical temperature to about 800 °C.
- Allow temperature to equalise throughout the work piece.
- Quench in oil or air.
- Temper the work piece by heating it to between 200 and 500 °C.
- Allow temperature to equalise throughout the work piece.
- Allow the work piece to cool slowly in air.

The higher the tempering temperature, the lower will be the final hardness of the work piece. Where heavy machining, EDM, grinding and welding have been carried out, the material should be stress-relieved as follows.

- Heat the work piece to about 200 °C below the hardening temperature.
- Allow temperature to equalise throughout the work piece.
- Cool slowly in air or in a furnace.

The hardness of the steel is measured using a Rockwell testing machine. It consists essentially of a very hard steel ball that is forced into the work sample under a standard load. The resulting indentation is measured with a microscope and this measurement directly relates to the hardness of the material. With steel, the Rockwell C scale test is used and the value comprises a number followed by Rc. For example most through-hardened steels have a Rockwell value of 50–60 Rc.

16.4.2 Pretoughening

The process of through-hardening steels and then finish machining them is time-consuming and expensive; to avoid this, prehardened or pretoughened steels have been developed. In effect the steel is heat-treated in a similar way to normal through-hardened steels but it is tempered back to a lower hardness.

For example, tempering at a temperature of 200 °C gives a hardness of approx. 50 Rc, while tempering at 600 °C gives a hardness of around 30 Rc. The big advantage is that while steel at 50 Rc cannot be milled or turned, material at 30 Rc can be. This means that all machining can be carried out without any need for further heat treatment. A commonly used version of pretoughened steel is ***AISI P20***.

The main reason for using pretoughened steel is that it does not have to undergo subsequent heat treatment hence avoiding the risk of distortion from a full hardening process. Clearly, however, the through-hardened AISI H13 at 50 Rc is much better suited to long-running tools than the pretoughened AISI P20 at 30 Rc. The lower the hardness of the steel the quicker it will wear and suffer damage. P20 steels can, however, be subsequently treated with ion implantation to increase ***surface hardness*** by up to 15%.

Pretoughened steels would normally be chosen where the risk of distortion on delicately machined forms is unacceptable. It would also be selected for medium-run jobs where the cost does not justify full hardening and finishing operations.

16.4.3 Carburising or Case Hardening

This process is a carry-over from the days when suitable alloy steels were unavailable. It consists of heating low-carbon steel (mild steel) in a carbon-rich gas, in a liquid (cyanide salt bath) or in a container filled with a form of carbon material. The carbon ingresses into the surface of the steel, where a hard structure is formed giving a component with a hard surface and a tough, more flexible interior.

Modern hardening techniques have largely superseded carburising but there is a trend towards the use of this technique in recent years where the advantages of the hard skin and soft core are attractive. Carburising may be used to advantage where any deflection of components is taking place such that through-hardened parts may break much earlier.

A disadvantage of carburising is that it is quite prone to distort parts, so that subsequent machining is required to combat this effect. Carburised parts are not suitable for heavy direct loading applications where they will fail. For such loading conditions, through-hardened alloy steels should be used.

Carburising is used frequently for surface hardening of cavities and punches for very large mould tools where through-hardening would not be possible. This process is also used for hardening cavities that have been hobbed.

16.4.3.1 The Carburising Process

- The work piece is heated to 850–900 °C in a carbon-rich gas, a cyanide salt bath or a carbon-rich powder.
- The temperature is allowed to equalise throughout the part.
- The work piece is quenched in oil or water.
- The part must be tempered back to give the required degree of hardness.

16.4.4 Nitriding

With this procedure the surface hardness of steel can be increased by the formation of iron nitrides in the surface. The part is heated in a nitrogen-rich environment, usually a gas (ammonia) or a powder bath (the Tenifer process).

The Tenifer process is normally preferred as the process time is much shorter (3–5 hours) than for the gas method (up to 100 hours). Nitriding has several advantages over carburising as follows:

- Most alloy tool steels can be used, apart from stainless steel.
- There is less risk of distortion as lower temperatures are used.
- Hardness is maintained at high temperatures, which is very useful for hot runner manifolds, nozzle blocks, cylinders and cylinder screws, etc.

This process will yield hardnesses up to 70 Rc with the surface having a very brittle layer. This means that shock-loading conditions must be avoided.

16.4.4.1 The Nitriding Process

- The work piece is heated to 500–550 °C in a nitrogen-rich environment, either ammonia or a powder bath.
- The part is allowed to cool slowly to avoid the formation of undesirable stresses.

16.4.5 Tuftriding

This method is similar to nitriding except that nitrogen and carbon are introduced into the surface of the work piece. This is achieved by heating the part in a molten salt bath for 2–4 hours. The result is a very hard but thinner layer, which is more resistant to shock loading conditions. Its chief advantages are:

- A very hard but less brittle surface
- Resistance to shock loading conditions
- Short process times
- Cost-effectiveness

16.4.5.1 The Tuftriding Process

- The work piece is heated to 500–550 °C in a nitrogen- and carbon-rich powder bath.
- The part is allowed to cool slowly to avoid the formation of undesirable stresses.

16.5 Mould Finishing

Nearly all cavity and punch forms require a finish to be applied to them. This may be a polished finish, a photo-etched finish or a plated finish. However, for some technical components the surface finish is not important and they are often left with a fine EDM finish.

Where special finishes are required, there are several processes available including:

- Polishing
- Chromium plating
- Photochemical etching
- EDM
- Bead blasting
- Vapour blasting

16.5.1 Polishing

The correct steel must be selected if a very high surface finish is required on the core/cavity. It must be free of impurities and stresses and have low content of sulfur (often added to improve machinability).

Electro slag refining (ESR) is a process used by suppliers of mould steels to reduce the amount of impurities in the steel. Vacuum de-gassed steels are also used in an effort to prevent the formation of localised impurities or pits in the surface of the steel, which can spoil a polished finish.

The polishing process is a slow laborious procedure, which involves three distinct stages:

- Coarse: using abrasive papers, carborundum paste or a mechanical reciprocating polishing device such as a Diprofile.
- Intermediate: using fine abrasive stones.
- Finish: hand polishing with diamond paste and orange sticks or with a powered mechanical reciprocating hand tool.

All moulding surfaces should be highly polished in ***line of draw*** for cavities and punches unless an alternative finish is required. The sprue bush and runners should also be highly polished in ***line of flow*** to assist streamlined flow of the polymer and to prevent any tendency for these to 'stick back'.

16.5.2 Chromium Plating

Chrome plating can be used to improve hardness and corrosion resistance and improve release of mouldings. The degree of finish is very much dependent on amount of polishing prior to plating. Plating will never improve a surface, it will only accentuate a poor finish.

With very corrosive materials like PVC and certain types of thermoplastic rubbers it is usual to use stainless steel to combat the corrosion. Unfortunately even the best stainless steel alloys have impurities and localised ferrous (iron) areas in them. These will soon be attacked by corrosive materials, resulting in pitting on the surface of the steel. With long-running tools it advisable to chromium plate the cavity areas made from stainless steel to protect against this possibility. If a non-stainless mould tool is to be used for moulding corrosive materials, the moulding surfaces must be chrome plated and the rest of the tool flash chrome plated to protect it.

16.5.3 Photochemical Etching

Many products require a textured finish to enhance sales appeal. The product designer in consultation with the sales and marketing department of the company selling the final product normally chooses the actual finish required.

There are many standard finishes available from specialist companies. These are selected from a sample book of plaques supplied by the photo-etching company. Good imitation effects may be achieved, including leather grain and stipple, etc.

The finish is achieved by applying a chemically resistant coating in the form of a pattern produced by photochemical means to the moulding surface of the steel. Suitable acid-based chemicals are then applied to the coating, which results in selective etching of the steel.

There are few companies specialising in this process and much secrecy exists as to the details of producing the many different surface patterns.

Care should be taken to ensure that if an etched surface is to be used, it does not interfere with the ejection of the moulding from the cavity. Sufficient draft angles must be used to assist in the efficient removal of the moulding from the tool.

16.5.4 EDM Finishes

Increasing use is being made of EDM techniques to apply finishes to moulding surfaces instead of using photochemical etching. This is a relatively new departure that has come about in an attempt reduce the time and cost associated with the photo-etching process. Electrodes are becoming available from specialist suppliers in a limited number of patterns and textures for this purpose.

There is much debate at the moment about which process gives the better result, but EDM is gaining in popularity and will probably become a major rival of photo-etching in the future.

16.5.5 Bead Blasting

This procedure involves firing small beads of plastic and other materials in a high-velocity air stream at the surface of the area to be textured. The results vary from a quite coarse sand-blasted effect to a very fine almost polished finish. Plastic bead blasting is beginning to be used to impart a ‘grip free’ surface to EDM fine sparked finishes to assist in part removal from the cavity.

16.5.6 Vapour Blasting

This process consists of directing high-velocity liquids, with or without any particles being present. Again, as a specialist process this is not usually undertaken by the mould manufacturer.

Vapour blasting is not new but it can be useful in imparting a very fine matt finish to surfaces and is sometimes preferred to EDM finishes. It can be used successfully to disguise poor moulding defects such as sinking and flow lines.

16.6 Mould Maintenance

All mould tools are expensive and easily prone to damage and corrosion if they are not maintained properly. In most injection moulding shops, the mould storage area often houses a considerable capital investment, often running into millions of pounds.

Before a mould is stored it should be checked for any repairs that are necessary and these should be carried out ***before*** the next time the mould is used. A few simple precautions will make sure the mould is in good order for the next time it is required. A basic checklist is as follows:

- The mould should be cleaned and serviced.
- Waterways should be blown out with ***low***-pressure air.
- The mould should be lubricated.
- Vents should be cleaned.
- All moulding surfaces should be sprayed with a mould protective.
- All safety switches should be checked for damage and correct function.
- All electrical circuitry should be checked for safety and function.
- Moulds should be stored closed if possible. If this is not possible, the two mould halves should be protected with a wooden or similar cover to prevent damage.

17 Runner and Gate Design

17.1 The Feed System

The feed system of an injection mould tool comprises four main components (see Figure 17.1):

- The sprue (for a cold runner tool)
- Cold slug well (for a cold runner tool)
- The runner
- The gate

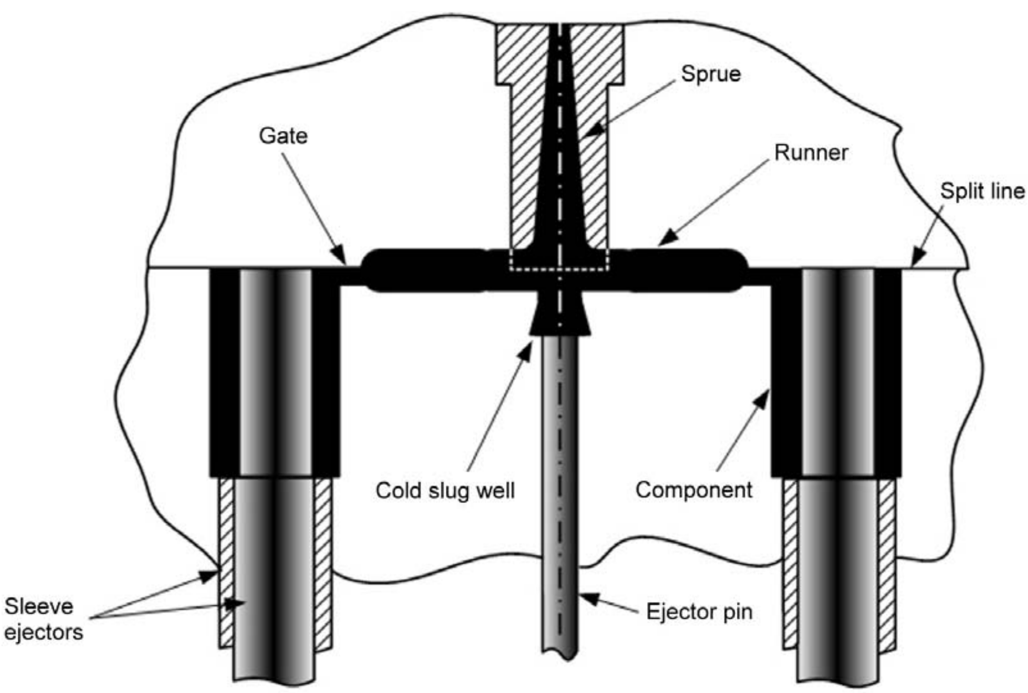


Figure 17.1 Basic feed system

17.1.1 The Sprue

This should be tapered 3–5° inclusive angle in order for it to be pulled out of the tool more easily. It should also be highly polished in the line of draw to assist withdrawal and in the direction of flow of the melt for more efficient flow. The diameter at the narrow end should be larger than the machine cylinder nozzle opening.

17.1.2 Cold Slug Well

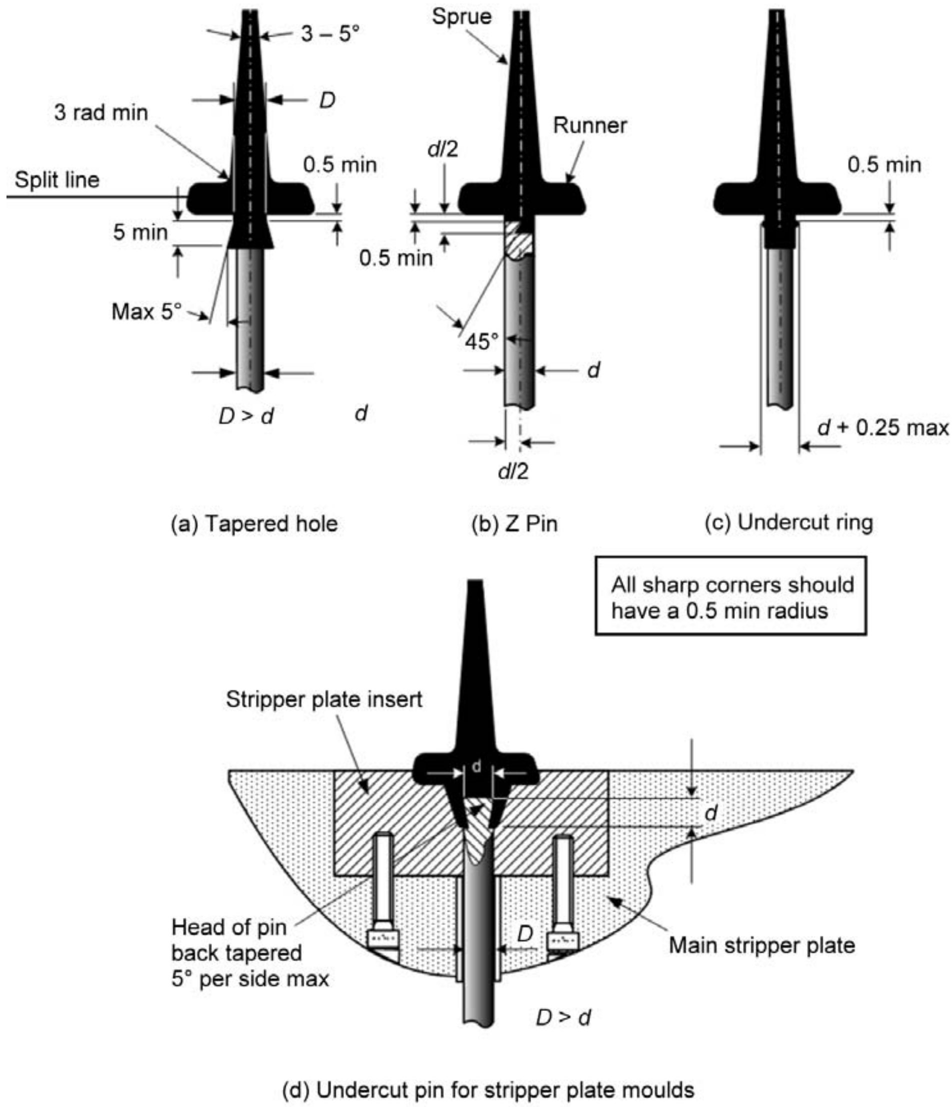


Figure 17.2 Snatch pins for cold runners

This is designed to trap the cooler advancing front of the melt, thus permitting hotter melt to reach the cavities and gates. It usually has a ***snatch*** or ***pull pin*** or ***sucker pin*** underneath it to positively pull the sprue out of the sprue bush. Three basic designs are used for ejection pin systems and a slightly different system with an undercut pin for stripper plate ejection, as shown in Figure 17.2. The diameters of each design are based on the diameter of the sprue where it meets the runner. It is important to avoid any obstruction to the melt flow; therefore, the pins should always be designed to avoid its protruding into the runner area.

Figure 17.2(a) shows a basic back-tapered hole design. Figure 17.2(b) shows a Z-type snatch and Figure 17.2(c) is an undercut ring snatch. Each design should have an ejector pin beneath the cold slug well to eject it out of the tool when the tool opens.

In each case the pin should be based on a standard diameter ejector pin size. The pin should also slide in a hardened bush to minimise wear from continued movement.

The undercut ring design is the one normally preferred as the snatch and ejection is positive and not likely to 'hang up'. The undercut ring need only be around 0.25 mm deep by 0.5 mm wide but this may vary with the material being used.

The tapered hole design is the least desirable as it usually has the largest mass and therefore the longest cooling time. However, this design does capture the colder advancing front of the material very well.

The Z snatch shown in Figure 17.2(b) sometimes tends to 'hang up' when it 'refuses' to fall away from the Z shape, although this design may be preferred for brittle materials such as PS and SAN as the undercut ring and tapered hole versions may break off on ejection.

17.1.3 Runner Design

The purpose of the runner is to transport the melt from the sprue to the gates. There are three basic parameters for runner geometry:

- The cross-sectional shape
- The diameter
- The cavity layout

17.1.3.1 Runner Cross-Section and Layout

The most efficient runner section is the full round and this should be used wherever possible. For three-plate tools the trapezoidal runner has to be used (see Chapter 14). The semi circular or half round runner severely restricts flow and should be avoided although it is frequently seen in production mould tools. Square section and rectangular section runner should never be used.

Figure 17.3(f) shows the behaviour of the melt as it flows through a trapezoidal cross-section runner. The melt stream will always revert to a circular cross-section, leaving areas of slow-moving melt in the corners. However, the trapezoidal runner is the only choice for certain applications such as three-plate moulds. Figure 17.3(f) shows the basic design for this type of runner, which is frequently used, but the design in Figure17.3(g) is preferred as there are fewer 'dead zones' as can be seen.

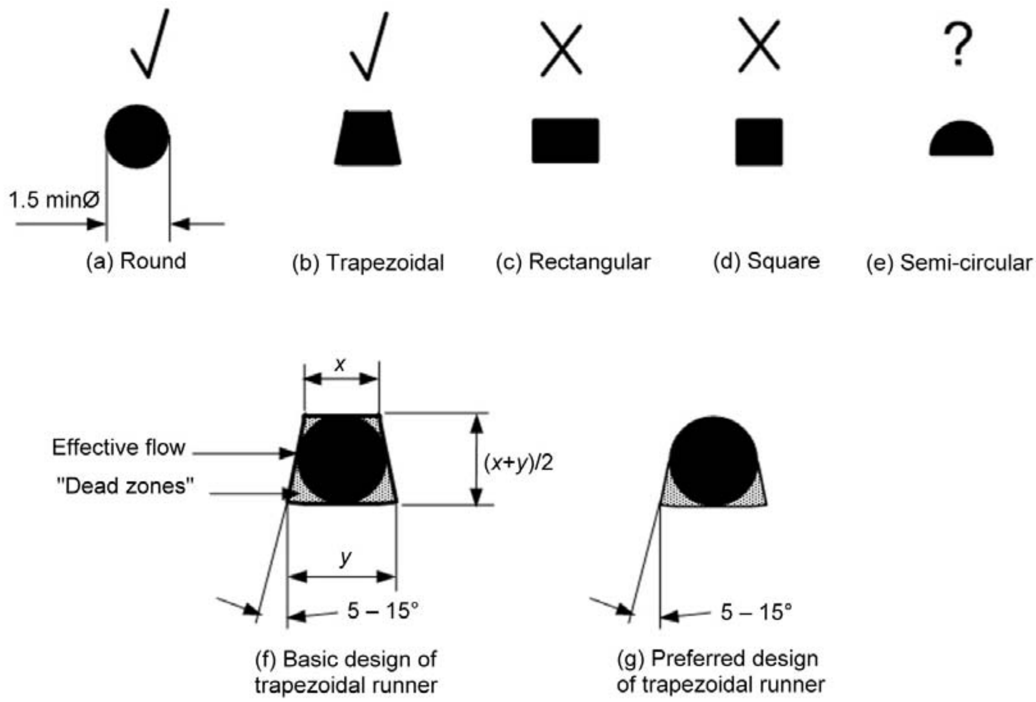


Figure 17.3 Runner cross-sections

The rectangular, square and semicircular cross-sections present similar problems with melt flow efficiency and should never be used. Even though many existing runner systems employ these undesirable designs they are rheologically inefficient and wasteful on material and energy.

The size of the runner should be based on the thickness of the moulding wall section. It must be large enough to provide adequate pressure to all the cavities. This ensures that there will be no packing pressure shortfall and thus permit adequate control over the moulding conditions to achieve satisfactory mouldings. An alternative method is to calculate the runner cross-section based on an appropriate pressure drop along the length of the runner.

All runner intersections should have a cold slug well beneath each intersection and preferably have an ejector pin beneath them. The cold slug well helps the flow of material through the runner system and into the cavity. The length of the well is usually equal to the runner diameter. Figure 17.4 shows the correct design for including cold slug wells in runner systems. A cold slug well must also be placed at the end of each runner after it intersects with another runner. This ensures that, as the runner cools, the advancing cool front is trapped at each stage. Note also that the runner diameter decreases at each branch as shown at **1**, **2** and **3**.

Figure 17.5 shows a frequently used incorrect rectangular layout design and Figure 17.6 the correct design. Figure 17.7 shows the similar correct and incorrect designs for circular layouts.

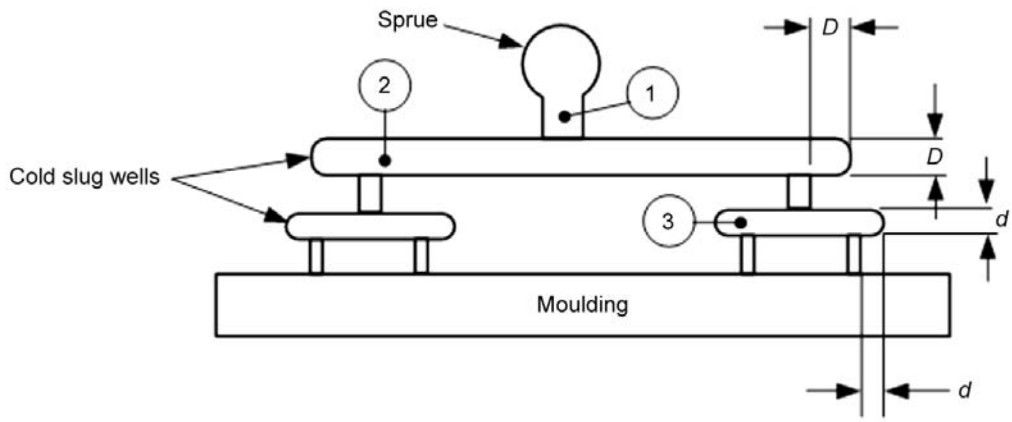


Figure 17.4 Correct runner design

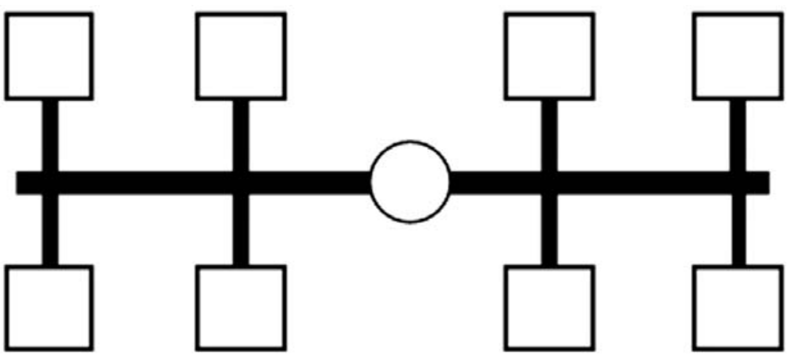


Figure 17.5 Incorrect runner layout

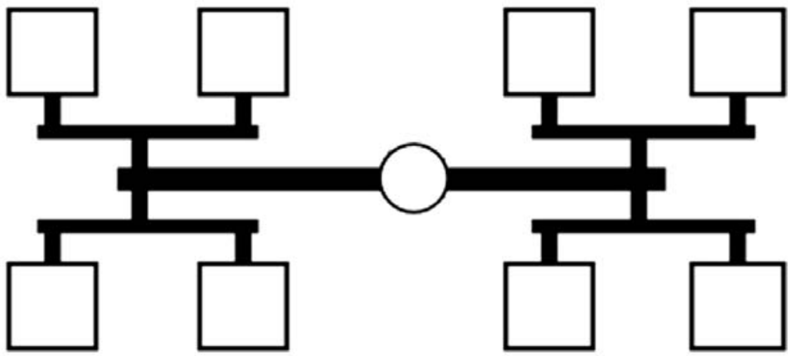


Figure 17.6 Correct runner layout

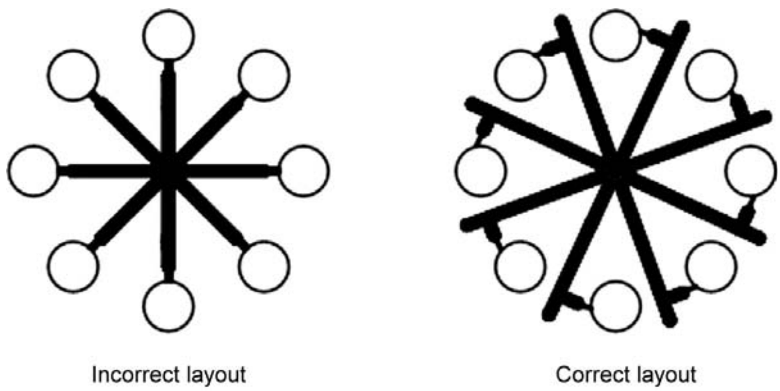


Figure 17.7 Radial runner layout

17.1.4 Runner System Design Rules

- Runners must be designed to fill the cavity rapidly.
- Runner design must provide for easy ejection and easy removal (de-gating) from the moulded part.
- For a multicavity system, balanced runner layout is preferred for the best uniformity and part quality. Runners may be balanced either naturally or artificially.
- Runner balancing may be achieved by changing the runner size and length. Changing the gate dimensions may seem to give a reasonably balanced fill but this will affect the gate freeze-off time, which is detrimental to part uniformity.
- Smaller runner sizes are preferred to larger ones in order to minimise scrap volume and generate viscous (frictional) heating. Viscous heating generated in the runner system is an effective way to raise the melt temperature as opposed to using high cylinder temperatures, which may cause material degradation.

- The cross-sectional area of the runner should not be smaller than that of the sprue, to permit rapid, unaltered flow of material to the gating areas.
- Each time a runner is branched, the diameter of the branch runner should be smaller than that of the main runner. This is because less material flows through the branch runners and it is economically desirable to minimise the amount of material in the runner system. Where *N* is the number of branch runners, the relationship between the main runner diameter (*D*) and that of the branch runner (*d*) is given by:

$$D = dN^{\frac{1}{3}} \quad \text{or} \quad d = \frac{D}{N^{\frac{1}{3}}}$$

- The depth of a trapezoidal runner is approximately equal to its width with a 5–15° taper or draft angle on each side wall.
- The minimum recommended runner diameter for most materials is 1.5 mm (0.06 in).
- For most materials, the runner surface and sprue should be polished in the line of material flow. Cavities and cores should be polished in the line of draw unless an alternative finish has been specified.
- It is desirable to have multiple sprue pullers and ejection locations in extended runner systems.
- The selection of a cold runner diameter should be based on standard machine tool cutter sizes.
- When designing hot runner systems, it is advisable to consult the suppliers for availability and recommendations for the correct manifold and drops.

Typical runner diameters for various unfilled generic materials are shown in Table 17.1.

Table 17.1 Runner diameters for common materials

Material	Diameter in mm
ABS, SAN	4.8–9.6
Acetal	3.2–9.6
Acetate	4.8–11.2
Acrylic	8.0–9.6
Butyrate	4.8–9.6
Fluorocarbon	4.8–9.6
Impact acrylic	8.0–12.8
Ionomers	2.4–9.6

Continued….

Material	Diameter in mm
Nylon	1.6–9.6
Phenylene	6.4–9.6
Phenylene sulfide	6.4–12.8
Polyallomer	4.8–9.6
Polycarbonate	4.8–9.6
Polyester (thermoplastic)	3.2–8.0
Polyethylene	1.6–9.6
Polyamide	4.8–9.6
Polyphenylene oxide	6.4–9.6
Polypropylene	4.8–9.6
Polystyrene	3.2–9.6
Polysulfone	6.4–9.6
PVC (plasticised)	3.2–9.6
PVC (rigid)	6.4–16.0
Polyurethane	6.4–8.0

17.2 Calculating the Runner Length

Although modern moulding machines can generate injection pressures in excess of 150 MPa, most average mouldings in unfilled materials with a wall thickness of 1–3 mm need only around 30 MPa injection pressure to fill.

For filled materials, this may rise to pressures in excess of 50 MPa, but if we allow for a maximum pressure of 100 MPa this normally covers most conditions that are likely to be encountered.

If we therefore base our calculations on a maximum pressure drop along the length of the runner of 70 MPa (50 MPa for filled material), this should represent a safe working figure with which to calculate runner lengths.

There are three equations that may be used which give a sufficiently accurate result for most moulding conditions:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi r^3} \quad (17.1)$$

$$\tau = \eta \dot{\gamma} \quad (17.2)$$

$$P = \frac{2\tau L}{r} \quad (17.3)$$

where:

$\dot{\gamma}$ = shear rate (s^{-1})

$\dot{Q}$ = flow rate (m^3/s)

r = runner radius (m)

η = viscosity of material at melt temperature (Pa-s)

P = pressure drop (MPa)

τ = shear stress (MPa)

L = runner length (m)

The use of these formulae is best demonstrated with an example.

17.2.1 Example

Mouldings are to be produced from polycarbonate using a melt temperature of 310 °C and a flow rate ($\dot{Q}$) through the runner of 2.85 cm^3/s. The runner length is 120 mm and the diameter is 4 mm. The viscosity is 1000 Pa-s.

Note: Remember all SI calculations use kg, metres and seconds.

Using:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi r^3}$$

we get:

$$\dot{\gamma} = \frac{4 \times 2.85 \times 10^{-6}}{\pi \times \left(2 \times 10^{-3}\right)^3}$$

$$= \frac{11.4 \times 10^{-6}}{25.13 \times 10^{-9}} = 0.454 \times 10^3 = 454 \text{ sec}^{-1}$$

Hence, using $\tau = \eta \dot{\gamma}$,

$\tau = 1000 \times 454 \text{ Pa} = 0.454 \text{ MPa}$

The pressure drop across the runner is then given by Equation (17.3):

$$P = \frac{2\tau L}{r}$$

$$= \frac{2 \times 0.454 \times 120 \times 10^{-3}}{2 \times 10^{-3}} = 54.48 \text{ MPa}$$

As this figure is well below the maximum allowed figure of 70 MPa, the runner length is satisfactory. Table 17.2 shows the shear rates for several common materials.

Table 17.2 Maximum shear stress and shear rate values for common materials

Material	Max. shear stress (MPa)	Max shear rate (s^{-1})
PP	250,000	100,000
HDPE	80,000	40,000
LDPE	80,000	40,000
PS	250,000	40,000
HIPS	300,000	40,000
SAN	300,000	40,000
ABS	300,000	50,000
PPS	345,000	50,000
Nylon	500,000	60,000
PET	500,000	6,000
PUR	250,000	40,000
PBT	400,000	50,000

17.3 Gate Design

A gate is a small opening (or orifice) through which the polymer melt enters the cavity. Gate design for a particular application includes selection of the gate type, dimensions and location. The gate design is largely determined by:

- The part geometry (wall thickness, etc.)
- Part specifications (appearance, tolerances, etc.)
- Material used
- Fillers used
- Cycle time
- De-gating requirements

Unless it is necessary to use multiple gates (e.g., the length of melt flow exceeds practical limits), a single gate is generally preferred. Multiple gates always create problems of ***weld*** and ***meld lines***. The cross-section of the gate is typically smaller than that of the runner and the part, so that the part can be easily ***de-gated*** (separated from the moulding). Gate thickness is usually two-thirds of the part thickness.

Technically speaking, the material freezing off at the gate indicates the end of the cavity packing phase. Hence there is no point in maintaining pressure after this point is reached. This in turn means the gate must be large enough to make sure that the moulding is properly filled before gate freezing occurs.

A larger gate dimension will reduce viscous (frictional) heating, permit lower velocities, and allow the application of high packing pressure to increase the density of the material in the cavity. If low stress is a requirement, owing to concerns of aesthetic appearance or dimensional stability, a larger gate may be necessary.

Figure 17.8 defines the terms used to describe gate geometry.

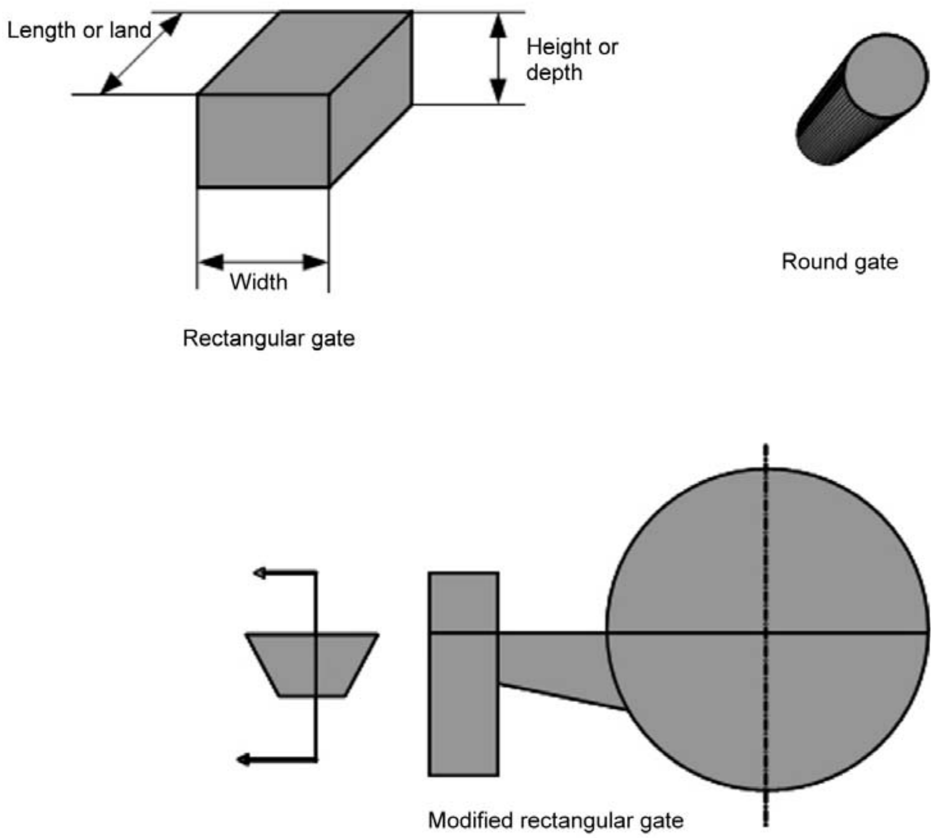
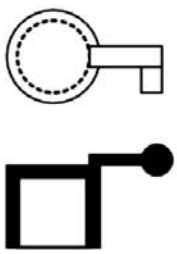
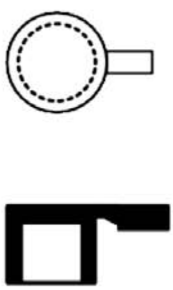
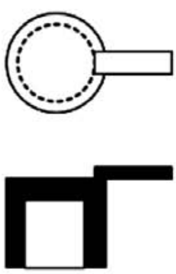
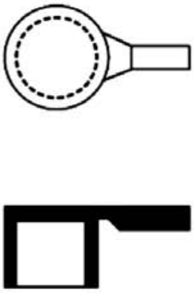
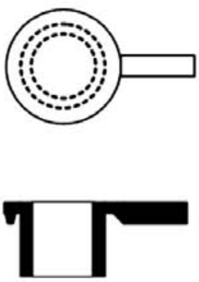


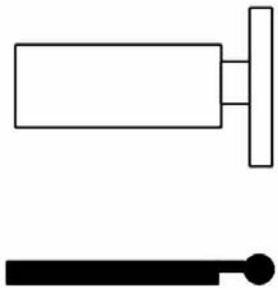
Figure 17.8 Gate terminology

The gate location should be selected in such a way that rapid and uniform mould filling is ensured and the weld/meld lines (if any) and air vents are positioned properly. The gate should be positioned away from load-bearing areas. This is because the high melt pressure and high velocity of flowing material at a gate causes the area near a gate to be highly stressed.

Figure 17.9 shows the most common types of gates. Gates may have a variety of configurations.

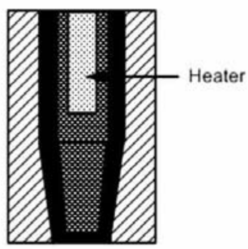
	**Direct or Sprue Gate** Usually used for single cavity moulds where the sprue feeds the material directly into the cavity rapidly and with minimum pressure drop. The disadvantage of this system is that the gate has to be trimmed off and a large gate witness is left on the part. The sprue diameter at the point of entry to the cavity should be approx twice the thickness of the moulding at that point. Gate diameters range from 1.5 to 6.5mm and 1.6 to 12.5mm in length with a minimum taper of 1° per side.
	**Tab Gate** Typically used for flat, thin parts to reduce the shear stress in the cavity. The high shear stress is confined to the tab which is trimmed off after moulding. Tab gates are used frequently for moulding PVC, Acrylic, SAN, ABS materials. The minimum effective tab width is 6.4mm and the minimum thickness is 75% of the cavity depth.
	**Edge or Side gate** Located at the parting line of the the mould and fills the cavity from the side, top or bottom of the part. Typical gate size is 0.4 to 6.4mm, thick and 1.6 to 12.5mm wide.
	**Overlap Gate** Similar to the the edge gate except the overlaps the wall or surfaces. Typical gate sizes are the same as the edge gate above.

	**Fan Gate** A gate similar to a wide edge gate with a variable thickness. It permits rapid filling of large parts or fragile mould sections through the large entry area. It is used to create a a uniform flow front into wide parts where warpage and dimensional are the main concerns. Typical gate sizes range from 0.25 to 1.6 mm thick and the width 6.4 mm to 25% of the cavity length.
	**Disc or Diaphragm Gates** Frequently used for gating cylindrical or round parts that have an open inside diameter. Used when concentricity requirements are important and weld line unacceptable. Typical gate thickness is 0.25 to 1.27mm
	**Ring Gate** A ring gate is sometimes used for gating round or cylindrical parts. The material flows freely around the core before it flows down as a uniform front to fill the cavity. Typical gate thickness is 0.25 to 1.6mm.
	**Spoke or Spider Gate** This is also called a four point or cross gate. It is used for tubular parts and offers much easier de-gating than the ring gate. Disadvantages include the possibility of weld lines and out of roundness. Typical gate sizes range from 0.8 to 4.8mm thick and 1.6 to 6.4 wide.



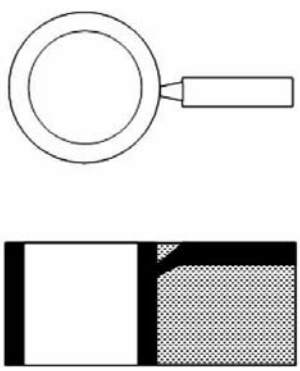
Film or Flash Gate
This is similar to a ring gate but is used for flat, straight parts.
It consists of a straight runner and a gate land across either the entire length or width of the cavity or a portion of it.
It is often used for Acrylic parts and large flat areas to keep warpage to a minimum.

Gates are typically 0.25 to 0.63mm long.



Hot Probe Gate
A hot probe gate or a hot runner gate is normally used to deliver material directly into the cavity through heated runners resulting in runnerless mouldings.

Pin Gate
A pin gate is generally used in three plate and hot runner tools to permit rapid gate freeze off and easy de-gating. The runner is automatically trimmed from the moulding with a stripper plate as the mould opens.
Gate sizes typically range from 0.25 to 1.6mm diameter.



Submarine or Tunnel Gate
A sub gate is mainly used in two plate moulds. They consist of a tapered, angle hole machined from the main runner to the cavity below the split line. It enables automatic de-gating of the part from the runner during the ejection phase.

Typical gate sizes are 0.25 to 2mm in diameter at the point of entry in the cavity.

Figure 17.9 Common gate designs

They are classified into two categories, based on the method of de-gating:

- Manually trimmed gates
- Automatically trimmed gates

17.3.1 Manually Trimmed Gates

Gates that need to be manually trimmed should be used only after all other possibilities have been exhausted, because of their extra cost. If they have to be used, then as much attention should be paid to this as to the mould design. Jigs and fixtures will be required to hold the mouldings securely and quickly and an automated electric or air tool should be used to cut, mill, drill or saw the gates away cleanly. Failure to do this often results in the whole process becoming uneconomic.

17.3.2 Automatically Trimmed Gates

Clearly, automatically de-gated parts should be used as much as possible and the best of these are those on hot runner moulds. For cold runner moulds, the sub (submarine) or tunnel gate is very good and used extensively for higher-quantity production. However, if the gate is designed incorrectly, it will run erratically during production and for this reason the sub gate is shown in more detail below.

It is preferable to start with a fairly small gate since the gate can be increased with EDM using a slightly larger electrode if necessary. Too large a gate can be difficult to shear off, leading to ejection difficulties and premature wear of the mould steel.

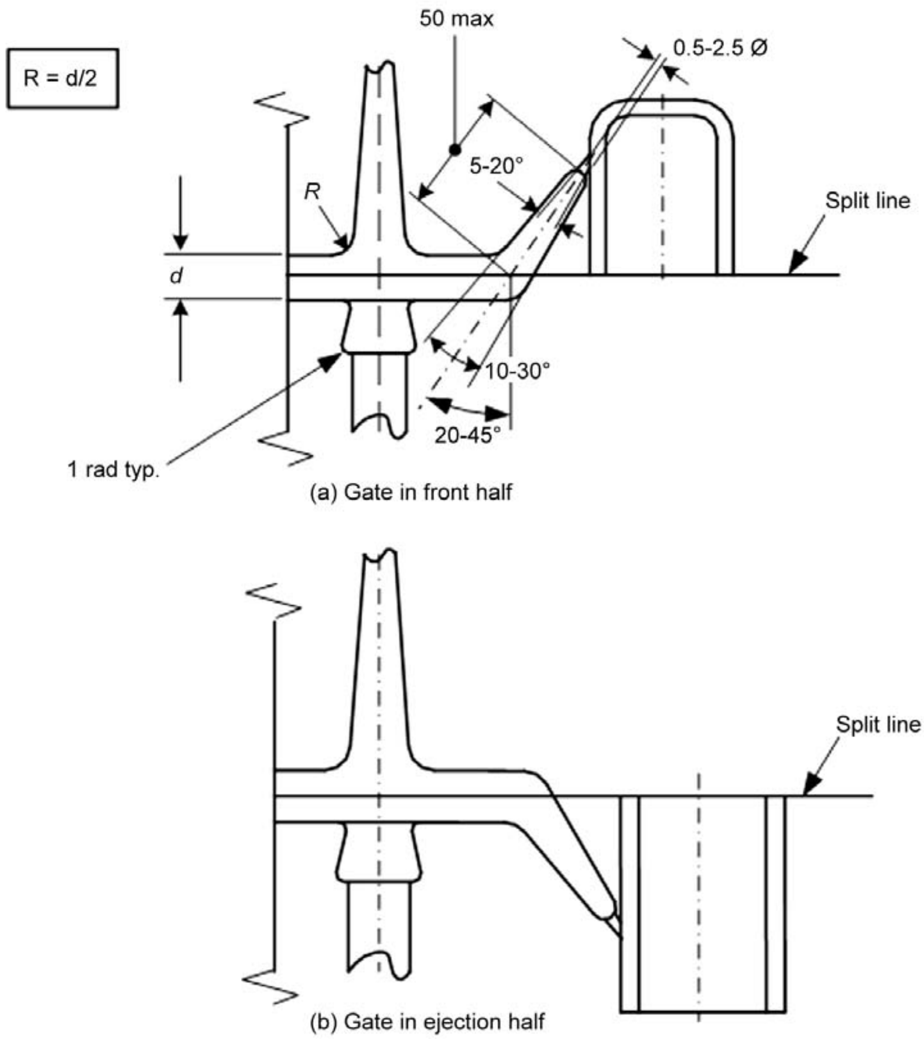


Figure 17.10 Submarine gate details

Note that the sub gate may be positioned in the front half or the ejection half of the tool as necessary. Figure 17.10 shows both versions. The dimensions are the same for either version.

Occasionally, gating onto the top surface or side of a component is not acceptable because of an undesirable witness mark left on the appearance face. When no other option is available, the hook gate may be used, which gates into the underside of the part (Figure 17.11). However, this type of gate is difficult and expensive to make and, owing to the geometry of the gate, the material being used must be flexible to enable it to be ejected satisfactorily. The gate is enclosed within two inserts, the main cavity insert **C** and a separate additional insert **B** as shown.

The gate must decrease in cross-section as it approaches the moulding to achieve a sharply defined weaker section where it meets the moulding. This ensures a clean positive break at the moulding surface.

A very important requirement for this gate design is that the runner must be extended downwards a distance *A*, which must be sufficient to enable the full length of the gate to be withdrawn from the tool.

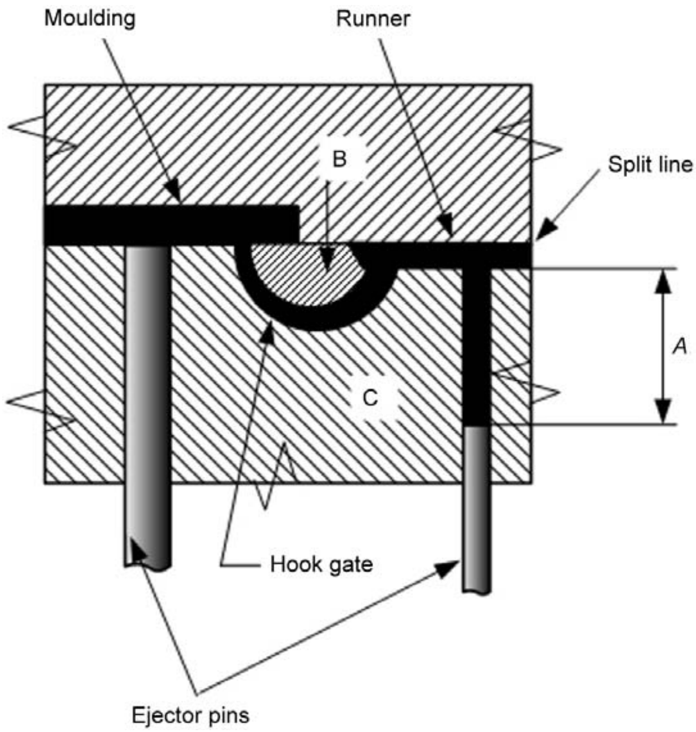


Figure 17.11 Hook gate design

17.3.3 Gating Design Rules

- The gate design should deliver a rapid, uniform and preferably unidirectional mould-filling pattern.
- The gate location should allow the air present in the cavity to escape during the injection phase. Failure to vent the air will result in short shots or burn marks on the moulding.
- If the gate location is likely to cause weld or meld lines, it should be positioned so that these will occur at appropriate positions to preserve part quality and appearance.

- Gate location and size should avoid the possibility of jetting (the string appearance or spaghetti strands on short shots). Jetting may be prevented by enlarging the gate or by locating the gate in such a way that the melt is directed against a cavity wall.
- The freeze-off time at the gate should ensure maximum cavity packing time. A well-designed gate freeze-off time will also prevent back flow of the injected material.
- The gate location should be at the thickest area of the part, preferably at a point where the function and appearance of the part are not impaired.
- The gate length should be as short as possible to avoid an excessive pressure drop across the gate. A suitable gate length ranges from 1 mm to 1.5 mm (0.04–0.06 in).
- Normally the gate thickness is 50–80% of the gated wall section thickness. For manually trimmed gates, the gate section can occasionally be the same as the gated wall section thickness. For automatically trimmed gates, the gate thickness is typically 80% of the gated wall section thickness to avoid part distortion during degating. Typical diameters at the gate end for pin and submarine gates are 0.5–2.5 mm for the former and 0.25–2.0 mm for the latter.
- Fibre-filled materials require larger gates to minimise breakage of the fibres when they pass through the gate. Using small gates such as submarine, tunnel or pin gates can damage the fibres in filled materials.
- Gates should always be machined smaller when the mould tool is first made, so that they can be enlarged later if necessary. Enlarging gates is relatively easy but reducing them can be both difficult and expensive.

17.3.4 Computer Simulations of Gate Designs

Computer simulation is an effective tool for comparing the implications of different gate designs. For a given mould tool, one can test the effects of all possible gate designs and gating positions before finalising the mould design.

17.3.5 Number and Location of Gates

The following example compares three possible gate designs for a large rectangular part. For each gating design, computer simulation predicts the resultant filling pattern, as well as any potential warpage, weld lines or air entrapment. Figure 17.12 shows three different gating arrangements with their corresponding filling patterns. It is possible in many cases to visualise the filling patterns of straightforward parts, and this ability increases with experience.

With potentially complicated flow paths, however, this becomes increasingly difficult and, if the application is a critical one, a computer simulation should be run before the gate position and geometry are finalised.

Upon examining the computer predictions, one can make the following observations:

- The centre-gated design, shown in Figure 17.12, produces a ***radial*** filling pattern consisting of both ***shear*** and ***elongational*** flows. Such a filling pattern introduces molecular orientation in both radial and tangential directions. If the volumetric shrinkage in these two directions is different, then ***warpage*** will occur. Figure 17.13 shows the predicted part warpage for the centre-gated design.
- The double edge gated design results in a weld line at the centre of the part. This could be undesirable from an appearance or functional point of view.
- The single edge gated design is the best of the three designs because it produces a unidirectional filling pattern with uniform molecular and fibre orientation.

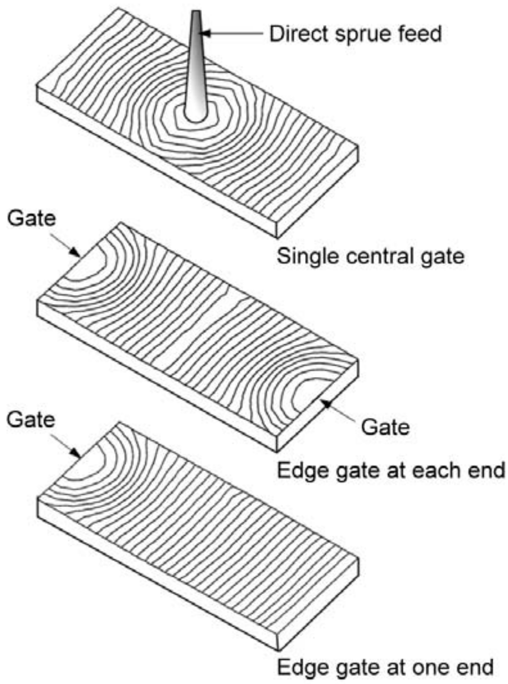


Figure 17.12 Material flow patterns

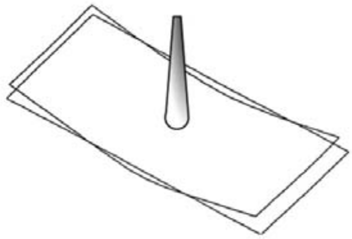


Figure 17.13 Predicted part warpage for centre-gated part

17.3.6 Gate Sizing

Factors Affecting Gate Size and Shape

All plastics materials are non-Newtonian fluids (**n-Nfs**). The difference between n-Nfs and Newtonian fluids (**Nfs**) (e.g., water) is that viscosity (resistance to flow) η, of a flowing Nf is unchanged across the flow path within a round channel, but the viscosity of an n–Nf changes greatly with temperature and in relation to a shear rate $\dot{\gamma}\left(\eta = f\left(\dot{\gamma}, t\right)\right)$

This can be expressed with the following formulas:

$$\dot{\lambda} = \frac{dv}{dr}\sec^{-1}$$

where:

$\dot{\lambda}$ = shear rate ($\sec^{-1}$)

v = velocity (cm/sec)

r = radius of runner channel (cm)

Shear rate is also dependent on:

1. Type of plastic – material being processed
2. Processing variables (injection pressure, speed, temperature)
3. Surface finish, and temperature of gate and runner channels

As before, a convenient approximation for average shear rate is:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi r^3} \quad (17.4)$$

The shear rate $\dot{\gamma}$ increases with the volume (flow rate) of the material ($\dot{Q}$), as it would when higher pressure pushes the same amount of plastic (per time unit) through the channel; but $\dot{\lambda}$ increases significantly with any reduction of the channel diameter (2*r*).

An example will illustrate an interesting result.

17.3.7 Example

A product has a mass of 108 g PS, corresponding to a volume of 100 cm^3. This will be injected in 1.0 seconds, so:

$$\dot{Q} = 100\ cm^3/sec$$

The selected gate size has a cross-sectional area of 1 mm^2, corresponding to a diameter (2*r*) of 1.25 mm = 0.125 cm. Therefore, r = 0.0625 cm.

The speed of injection is, therefore:

$$\frac{100{,}000}{1} = 100{,}000\ mm\ sec^{-1}$$

$$\text{or } 100\ m\ sec^{-1}$$

This speed is about one-third the speed of sound (Mach 1 = 344 m/s). If the volume Q were three times that of this example, the plastic would theoretically pass through the gate at about the speed of sound. Considering these high velocities it is no surprise that gates can wear rapidly, particularly if the gates are small and the material is abrasive.

Using equation (17.4), the maximum shear rate is:

$$\dot{\lambda} = \frac{4 \times 100}{\pi \times (0.0625)^3}$$

$$= \frac{400}{\pi \times 0.000244}$$

$$= 521{,}519\ sec^{-1}$$

$$\textit{or approx } 522{,}000\ sec^{-1}$$

This is an extremely high value for most materials and strongly indicates that one or both of the following changes should be made to bring the shear rate closer to the permitted value for the material (in this case, for PS, a maximum of 40,000 s^{-1}):

1. Increase the gate size.

2. Increase the injection time (reduce injection speed).

In several optimisation software programs, the gate size will be determined using an equation to determine the gate diameter (2*r*) based on the wall thickness in conjunction with the maximum shear rate allowed for the material as follows:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi r^3}$$

Hence,

$$r^3 = \frac{4\dot{Q}}{\pi\dot{\gamma}} \quad \text{or} \quad r = \sqrt[3]{\frac{4\dot{Q}}{\pi\dot{\gamma}}}$$

In this case we know $\dot{Q}$ and $\dot{\gamma}$, hence we can obtain r as follows:

$$r = \sqrt[3]{\frac{4 \times 100}{\pi \times 40{,}000}}$$

$$= 0.147\,\text{cm}$$

$$= 1.47\,\text{mm}$$

To work safely below the maximum shear rate limit, a diameter ($2r$) of 4 mm would be suitable.

17.3.8 Gate Land Length

The gate land should be as short as possible to achieve lower pressure for filling and to improve de-gating by minimising the height of gate vestige. The only reason for not using very short lands is the loss of strength of the steel at this area, which may cause the steel to bruise or fracture. In the author's experience, land lengths should be from 0.25 to 1.0 mm for the average moulding.

17.3.9 Gate Diameter

Too small a gate can be recognized by blemishes at the gate and by surface imperfections. However, even before it affects the resin, it dramatically affects the available injection pressure so that the product will not be filled, and the gate will freeze off too soon. Too large a gate often results in an unsightly vestige. It will affect the mould-closed time, and requires an increase in cycle time. While too small a gate can easily be corrected by increasing the gate size, too large a gate will require a new gate insert, or even a new cavity if there was no insert.

17.3.9.1 Shearing in Gate Diameter Sizing

High shear rates can raise the local melt temperature at the small gate significantly, thus reducing the viscosity and allowing the material to flow easily within the cavity space. High shear rates can also significantly improve the surface finish of the product, especially its gloss. If the gate is too large, there is no temperature rise as a result of shear in the gate, which may result in premature gate freeze-off and sinks in the product. This can be explained with an example, as shown in Figure 17.14.

The gate in Figure 17.14(a) creates about four times as much shear as the gate in (b). The gate in (c) is so large that the shear and therefore heating of the resin through the gate is small. Note that this example applies to a specific combination of resin, product mass, injection pressure, etc. It only shows that a smaller but sufficient gate may be better than a larger one, because it will freeze more easily and will create a smaller, cleaner gate vestige. Factors influencing the actual gate size are now discussed.

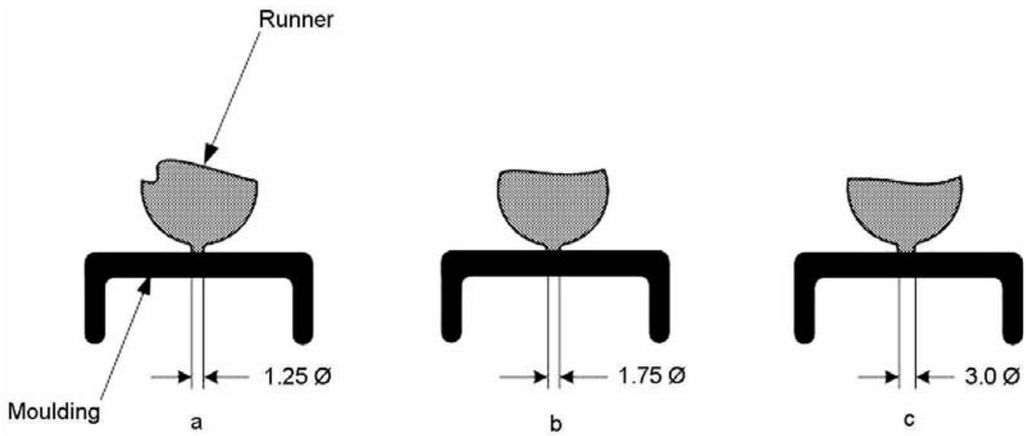


Figure 17.14 Effect of gate diameter on shearing

As discussed, we know that the shear rate at the gate must be greater than 1000 s^{-1}. In thin-wall moulding, shear rates of 100,000–1,000,000 s^{-1}, dependent on the material, may be needed for best results (i.e., to be able to use the lowest possible moulding temperatures). This reduction of viscosity by shearing is often essential.

Reduction in viscosity achieved through high velocities and sheer rates may be the most effective way to mould otherwise difficult-to-process, high viscosity materials. However, there is a limit to the amount of shear a resin can take before it starts to degrade.

What happens at shear rates greater than 1,000,000 $s^{-1}$is not fully known. There is a point at which the molecules can no longer slide against each other in response to an applied shear stress. In other words, the material can only be stretched so far before it starts to be torn apart.

In a fully stretched condition, the material viscosity is as low as it can be, because the molecules have aligned as much as possible in the direction of flow. If this condition occurs at 100 000 s^{-1}, there is no point in shearing the material any further, because it will not provide any more viscosity reduction. If we could determine the limit to viscous stretching, we would obtain a physical limit to the amount of shearing.

All materials have a maximum permissible shear rate at which they degrade. The more heat-sensitive they are, the lower the permissible shear rate. Note, however, that it is difficult to find the maximum shear rate; because degrading is also affected by the length of time the material is subjected to that shear rate.

17.3.9.2 Effect of Time on Shear and Viscosity

In general, it is the length of time of exposure to shear that has the most effect on the material. This must be carefully considered.

For example, a remote disturbance (restriction), upstream of the flow will be remembered by the material, even though the resin has subsequently passed through a viscous flow length. Additionally, the short time the plastic has been sheared at an extremely high rate at the gate is not as significant as the long duration for which the resin is exposed to shear in the manifold or in the nozzle tip. It is more difficult to overshear a resin in the gate if it is subjected to the high shear stress for a short time only.

Large variations in viscosity can also lead to moulding difficulties (e.g., surface imperfections, uneven fill, high stress, warp, differences in shrinkage). In general, it is suggested that it is best to mould in the region where changes in shear rate do not significantly affect the viscosity (i.e., shear rates in the range of 1000–2500 s^{-1}).

17.4 Establishing the Correct Gate Size

There are five methods available to us for estimating gate size:

1. Using past experience from earlier designs.
2. Consulting the material manufacturer for their recommendations.
3. Using hot runner systems supplied by a specialist manufacturer.
4. Using a sophisticated computer analysis, as described below.
5. An empirical approximation, as described below, is based on experimental evidence as described by R.G.W. Pye [1]. This method yields a close enough gate size and is frequently used.

17.4.1 Computer Analysis

The gate is part of the hot runner (HR) and should be designed together with the rest of the hot runner system. The complete system can then be modelled, and pressure, shear stress and temperatures can be checked for the entire system.

The following limitations apply when determining the correct channel sizes in the HR manifold, although these vary accordingly to the programme used for analysis:

Pressure drop (Δ_p)	$\Delta_p < 45$MPa ($\Delta_p < 35$MPa for general purpose (GP) plastics)
Melt temperature rise (Δ_t)	$\Delta_t < 15$ °C, but less for shear-sensitive plastics
Shear rate ($\dot{\gamma}$)	$\dot{\gamma} = 1000\ s^{-1}$ ($-1500\ s^{-1}$ for easy colour changes)
Shear stress (τ)	See Table 17.2 below for gate and manifold data.

The critical fill rate of the cavity must not exceed the maximum permissible shear stress (or shear rate) for a material. If this value is reached, flow-induced brittleness (melt fracture) may result, causing moulding difficulties and poor product quality. These values can be calculated for the entire hot runner system using computer flow analysis for hot runners.

17.4.2 Empirical Analysis

Equation (17.5) below may be used to determine gate diameter d:

$$d = NC\sqrt[4]{A} \quad (17.5)$$

where A = total surface area of the product (not the projected area) in mm^2, and N and C are empirical factors, as described in Table 17.3. In many cases this method provides a fairly good gate size approximation.

Table 17.3 Empirical factors for *C* and *N*

Wall thickness of product (mm)	0.75	1.00	1.25	1.50	1.75	2.00
Value of C	0.178	0.206	0.230	0.242	0.272	0.294
Value of *N*: 0.6 (PE, PS) 0.7 (PC, PP, acetal) 0.8 (Nylon) 0.9 (PVC)						

17.4.2.1 Example

A moulding in PP has a total surface area of 5000 mm² (not the projected area) and a wall thickness of 1.5 mm. Find the gate diameter.

$$d = 0.7 \times 0.242\sqrt[4]{5000}$$
$$= 0.1694 \times 8.409$$
$$= 1.42\text{mm}$$

References

1. R.W.G. Pye, Injection Mold Design: Manual for the Thermoplastics Industry, Fourth Edition, 1989, Halstead Inc., New York, USA.

18 Standard Mould Parts

Standard mould parts are used extensively in almost all modern injection mould tools. Only a few special-purpose tools are constructed from 'scratch' without taking advantage of all the standard components available. Even these tools would have a small number of standard parts in them such as guide pillars, ejector pins and liner bushes.

The advantages of using standard mould parts are considerable. Some of the major advantages are listed below:

- Components are usually available ex stock.
- Quality is guaranteed.
- Parts are made to close tolerances, so accurate interchangeability is assured.
- A wide variety of sizes and materials is available.
- Standard parts cost less to buy than they would to make in a toolroom.
- Using standard parts enables toolmakers to concentrate on making the cavity inserts and other custom parts.
- Using standard parts cuts down delivery times for tool manufacture.
- Toolrooms can produce more mould tools than they could otherwise.
- Replacement parts are easy to obtain and fit, making maintenance easier.
- CAD-compatible software from standard parts suppliers is available for reducing design times.

18.1 Standard Parts Available

There is a vast array of standard components that may be purchased 'off the shelf'. A few of the major items are listed next.

18.1.1 Mould Base Units

Complete bolster sets are available over a wide range of different sizes and materials. Ejector and stripper plate versions can be purchased and, recently, mould base sets with integral sets of splits and three-plate tools have been added to the range.

18.1.2 Mould Plates

A very large range of these is marketed in different sizes and thicknesses. If required, individual plates can be supplied with insert pockets premachined into them. Additionally, plates are available with screw holes, guide pillar holes and many other features premachined.

18.1.3 Location and Alignment Components

Among the many components available are:

- Guide pillars and bushes
- Liner bushes
- Ejector plate guidance systems
- Register rings
- Side core slides

18.1.4 Ejection Components

- Ejector pins
- Blade ejectors
- Return pins
- Ejector plate early return systems
- Angled lift pins
- Blank form pins
- Spring ejectors

18.1.5 Feed Systems

- Hot sprue bushes
- Runnerless systems
- Full hot runner systems

18.1.6 Cooling Components

- Baffles
- Fountains
- Cool pins
- Heat pipes
- Plugs
- Manifold connectors

18.1.7 Unscrewing Components

- Racks, pinions, gears
- Bearings, leadscrews
- Motors (hydraulic, electric and pneumatic)

18.1.8 Miscellaneous

- Nozzles, gate bushes, thermocouples, limit switches, proximity switches, instrumentation, side core stops, screws, chain, etc.

18.2 Mould Tool Designing Using Standard Parts

While the use of standard parts in mould tools has many advantages, it can take a long time to incorporate them in to mould tool designs as a great deal of information has to be looked up in the catalogues. This applies whether a CAD system is being used or not. Each of the parts used must be listed accurately on the drawing, referring to correct codes and subcodes used to identify individual components.

The situation changes dramatically, however, when the standard mould parts CAD software is used. This permits the whole library of parts in the catalogues to be quickly viewed on screen and automatically drawn in for the designer. This represents a great saving in time and is by far the most efficient way of incorporating standard items into a design.

Despite the effort involved with manually incorporating standard parts into designs, the overall mould design/toolmaking cost-effectiveness cannot be disputed.

All tools should be designed using the maximum number of standard parts that can be incorporated (sensibly) into the mould tool design.

18.3 Toolmaking Using Standard Parts

Toolmakers are very highly skilled individuals and all toolmaking operations are expensive. It makes sense, therefore, to maximise the use of toolmaking skills in producing the cavity forms and punches rather than in simple machining operations. Using parts that are manufactured to guaranteed quality allows toolmakers to concentrate on these more 'demanding areas' of the tool construction.

It also allows expensive plant and equipment to be used to greater cost-effectiveness and permits a greater throughput of tools with shorter deliveries.

Figures 18.1 and 18.2 show typical mould tool components and illustrate the range of standard parts available.

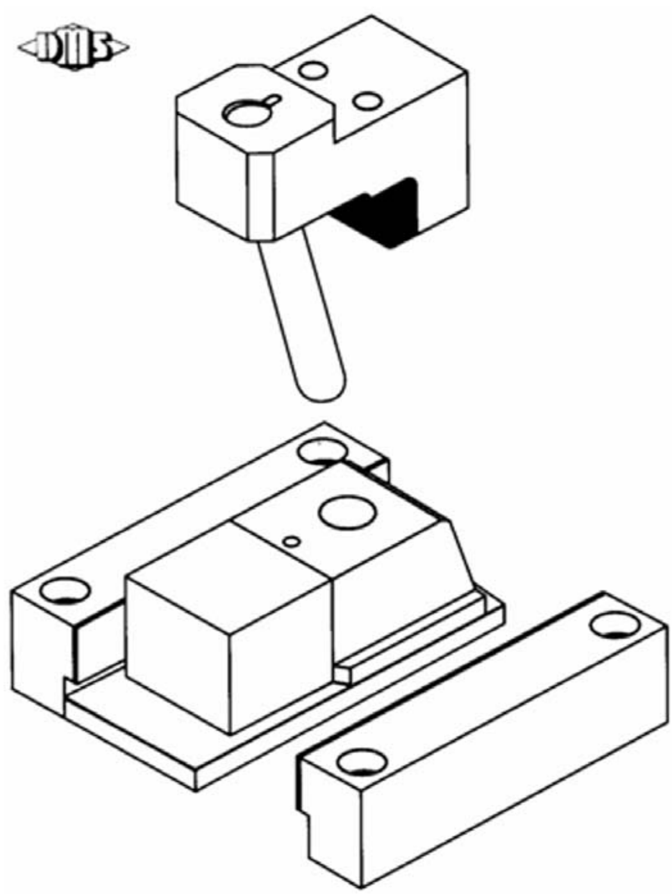


Figure 18.1 DMS standard side core assembly (available from DMS in UK; reproduced with permission of Diemould Service Company Limited)

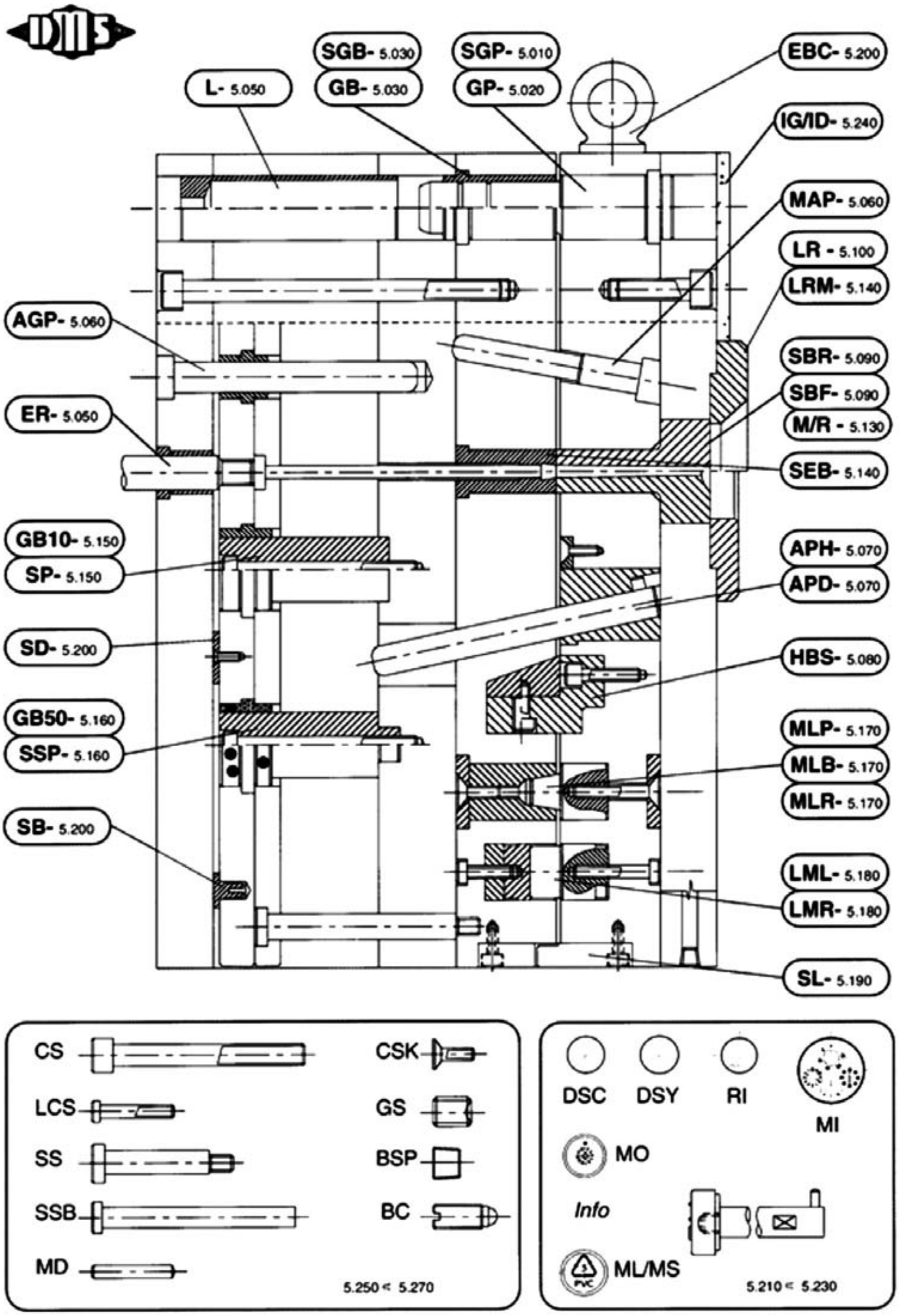


Figure 18.2 Typical range of standard parts available
(DMS; reproduced with permission of Diemould Service Company Limited)

18.4 Summary

- Standard mould bases, plates and ancillary components make tool manufacture more cost-effective.
- Tool lead times are reduced.
- Toolmaking skills may be concentrated on the impressions.
- Tool costs are reduced.
- Quality is guaranteed.

19 Deflection and Stress in Mould Components

19.1 Discussion

Historically, the sizes of plates and other components in an injection mould tool have been established purely on the basis of previous experience. In many cases this has been sufficient for mould designers to establish designs that work in production – but not always. This practice is still in wide use today, with very little emphasis being placed on any scientific approach to establishing more efficient mould tool geometry.

Almost no attempt has been made to take advantage of any scientific or engineering developments that would enable mould design parameters to be established more accurately apart from flow analysis. Very few engineering industries rely solely on previous experience only and base their products and manufacturing design processes on a blend of science and experience.

It is reasonable to ask why it would be desirable to develop any kind of scientific approach for mould design if experience has served so well in the past. One answer to this question is becoming apparent, as more companies are experiencing increasing competition both within the UK and overseas.

While experience is an invaluable asset, it is when this is combined with well-established scientific principles that the best of both worlds is available to the designer. Some of the major reasons for applying a basic scientific analysis to mould construction are discussed next:

- Competition
- Energy costs
- Breakage of mould components
- Deflection of mould plates and core pins
- Bending, fracture or stress cracking of components

19.1.1 Competition

As competition increases there is a tendency to maximise the number of impressions used in tools and to run them on the smallest possible machines. This practice tends to make production costs lower but it also means tools and machines are operating ever closer to the limit of their capability.

Although this approach will tend to lower prices, it also results in increasingly higher forces being generated within the tool. As this philosophy gains momentum it inevitably leads to approaching limiting factors, in terms of machine locking capacity, shot weight capacity and the physical size of the mould tool and its component parts.

19.1.2 Energy Costs

The larger the mass of the mould tool, the greater the amount of energy needed to operate it. With increasing mould tool mass, moulding temperatures are higher, cooling cycles are longer and machine energy consumption is greater.

Therefore, keeping the mass of the tool to a minimum makes sound economic sense. It reduces cycle times and energy costs and reduces machine wear.

19.1.3 Breakages

It is not uncommon for parts of the tool to suffer damage owing to undersize components or overstressed parts. Cavity parts can crack, leading to flashing or water leaks. Core pins may stress crack or bend or, worse still, parts may fracture completely. In such cases repairs can be very expensive.

It is not generally realised that very large forces are generated in the mould during the injection phase of the cycle. For example, if a press of 500 tonne lock is needed for a job, the reason a 500 tonne machine is required is to keep the tool closed during injection. This amount of locking force is required to prevent the tool being forced apart by the force exerted by the incoming molten material. This clearly means that the mould opening force generated during injection is approaching this figure.

It would not be unreasonable to assume that a mould tool on this size of machine might be subject to a force of around 350–400 tonnes trying to force it apart. Such high forces can easily fracture or crack components if they are not properly designed or supported.

19.1.4 Deflection

Deflection takes place on all loaded components and injection mould tools are no exception. If a mould tool is observed during the injection phase, no deflection can be seen with the naked eye but it will be deflecting. Transducers, attached to the tool, will demonstrate this very clearly. The effects of deflection are easily seen, however, with long, slender core pins that may be forced out of position during injection, resulting in rejects.

If the level of deflection is high it can cause water leaks and flashing, factors that are frequently attributed to faulty mould manufacture. Continued high deflection of core pins also leads to fatigue, resulting in their eventual failure.

For all these reasons, it is advantageous to carry out a few simple checks to prevent these problems occurring.

19.2 Force and Stress

Checking the stress and deflection levels in mould tools is a fairly straightforward process and if programmed into a computer or calculator takes only a few minutes. This is a small price to pay for ensuring correct functioning and reliability of the tool.

19.2.1 Definitions of Forces

Figure 19.1 demonstrates the most common (but not all) of the forces that the mould tool may be subject to during the moulding cycle.

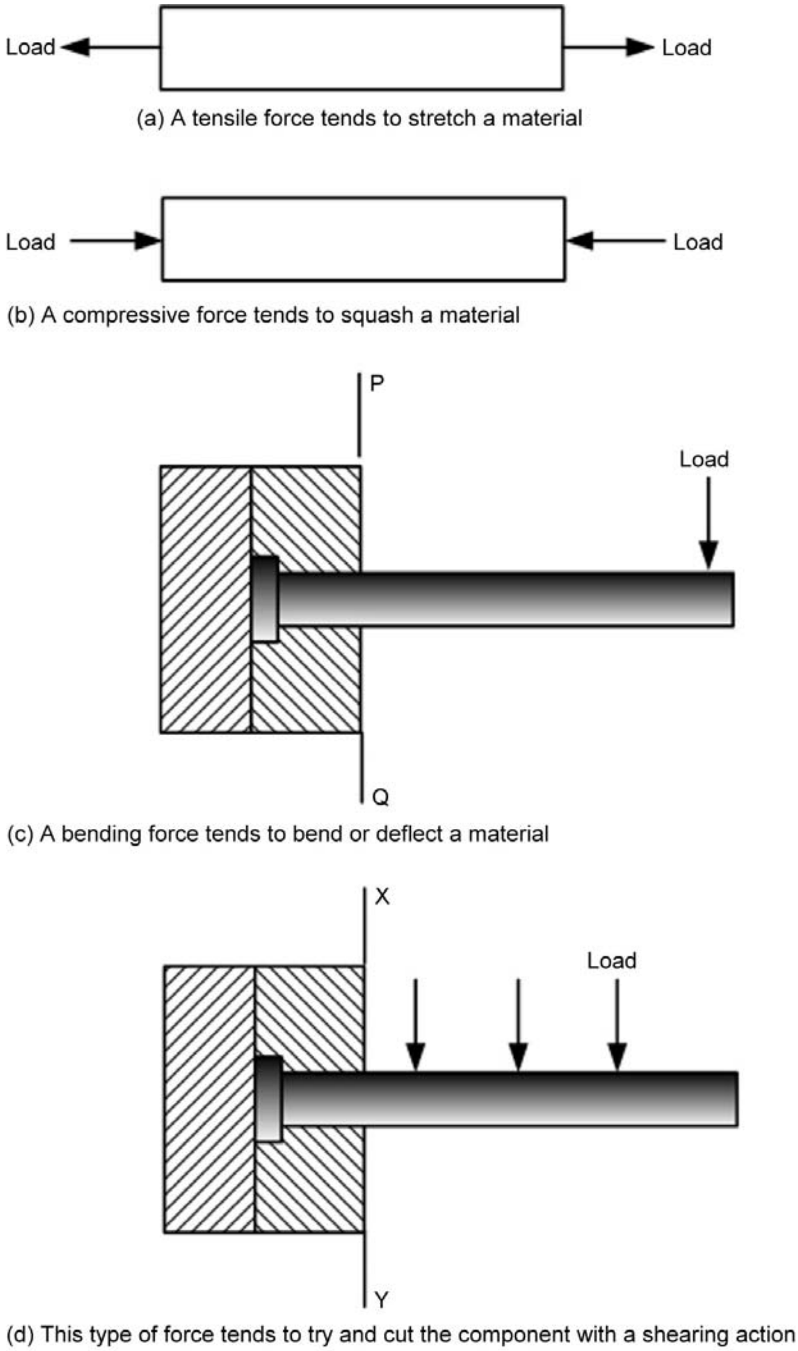


Figure 19.1 Common forces in mould tools

19.2.1.1 Tensile Force

Figure 19.1(a) shows a tensile force that occurs whenever materials are stretched. Examples of this are:

- Cavity support plates
- Cavity inserts
- Guide pillars
- Pull rods in multiplate tools
- Cap screws for clamping mould to platen

19.2.1.2 Compressive Force

A compressive force tends to compress a material as shown in Figure 19.1(b). Mould parts that this applies to include:

- All the cavity plates during clamping
- Cavity inserts
- Return pins

19.2.1.3 Bending Force

Bending forces tends to deflect or bend long core pins as shown in Figure 19.1(c). Other examples are:

- Cavity support plates
- Guide pillars
- Ejector pins (if not supported)

In the example shown, the shearing force occurs along line **P–Q**.

19.2.1.4 Shear Force

This type of force tends to try to cut the component with a shearing action as illustrated in Figure 19.1(d).

In this example, the shearing force takes place along line **X–Y**. Other examples include:

- Guide pillars
- Ejector pins
- Mould clamping screws

As can be seen from the above examples, a component can be subject to more than one type of force, which can make analysis quite complex. However, it is not proposed that every last component should be critically analysed to ensure it has adequate strength. Instead, it is suggested that those parts of the mould subject to the greatest stresses be checked:

1. To establish that the main mould tool plates have adequate strength to prevent excessive deflection.

2. To make sure the mould is not 'over engineered', which can result in more energy being required to operate the mould.

Both of these are important and the former is often the reason for flashing, leaking and distortion or uneconomic production.

19.3 Stress

When a material is subjected to an external force such as those that tend to bend, stretch or twist it, the material sets up internal forces to oppose them. Up to a limit, the material will behave like a spring, compressing or stretching when a load is applied and recovering when it is removed.

If this limit is exceeded, permanent deformation or fracture of the component will follow. It is therefore essential not to exceed the ***elastic limit*** for any material.

A measure of the intensity of the internal forces opposing an external force is stress. This is defined as the external force acting per unit area. It is measured in pascals (Pa):

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

19.4 Strain

When a component is subject to an external tensile or compressive stress it will increase or reduce its length. Strain has no units, being a ratio of lengths. It is defined as:

$$\text{Strain} = \frac{\text{Change in length}}{\text{Original length}}$$

19.5 Stress–Strain Graph

By subjecting a specially made specimen to an increasing tensile force, a stress–strain graph can be produced. As the force is increased, the change in length of the specimen is measured. Figure 19.2 shows a stress–strain graph for a ***ductile*** material, in this case steel.

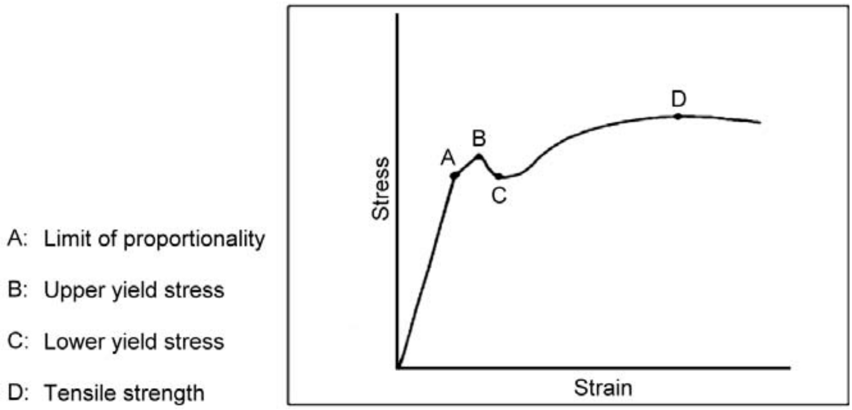


Figure 19.2 Stress-Strain graph for steel

19.5.1 Young's Modulus of Elasticity

A stress–strain graph for carbon steel is shown in Figure 19.2. The linear section of the graph shows the range over which stress is proportional to strain. In other words, a component subjected to a stress that lies on this line will recover its original dimensions once the stress has been removed.

The gradient of this linear section of the graph is known as ***Young's modulus*** but is also known as the ***elastic modulus*** and ***tensile modulus***. Therefore, by definition,

$$\text{Young's modulus} = \frac{\text{Stress}}{\text{Strain}}$$

Young's modulus is expressed in pascals (Pa) and is a measure of the rigidity of the material. The higher the value, the greater the rigidity of the material. It is designated by the symbol *E*.

19.5.2 Limit of Proportionality

At the top of the linear section (point **A**), the stress ceases to be proportional to the strain. Consequently it is known as the ***limit of proportionality***. Beyond this point the material will not recover when the applied stress is removed. Permanent deformation will result if this point is exceeded. Units are pascals.

19.5.3 The Elastic Limit

This is roughly the same value as the limit of proportionality. Again it indicates the point beyond at which permanent deformation will occur. Units are pascals.

19.5.4 Yield Stress

Once the limit of proportionality has been exceeded, permanent deformation will result and with some materials the strain will continue to increase without any increase in stress.

The point on the graph (point **B**) indicates the maximum tensile stress a material can withstand before breaking is inevitable. This is called the ***upper yield stress***. Units are pascals.

Point **C** is called the ***lower yield stress*** and is termed the ***yield point***. The corresponding stress that produces it is called the ***yield stress***. Units are pascals.

19.5.5 Tensile Strength

The maximum stress the material can withstand is at point **D** and is referred to as the ***tensile strength*** of the material. However, this point is far beyond the amount of stress within which the material can recover. If further stress is applied, the material will fracture shortly after this point.

19.6 Factor of Safety (FOS)

In any engineering design it is essential that stress levels do not exceed the limit of proportionality, for the reasons explained above. In order to keep working stress levels safely within the linear portion of the graph, a factor of safety is applied. As this is a ratio, it has no units.

19.6.1 Brittle materials

$$\text{Factor of safety} = \frac{\text{Tensile strength}}{\text{Maximum working stress}} \quad (19.1)$$

19.6.2 Ductile materials

$$\text{Factor of safety} = \frac{\text{Yield stress}}{\text{Maximum working stress}} \quad (19.2)$$

Nearly all materials used in mould tool construction are ductile; hence, expression (19.2) would be used for mould analysis. In practice, a suitable factor of safety is allocated depending on the circumstances and the maximum working stress level obtained. For injection mould analysis, a suitable FOS would be 1.5; hence, the following expression would be used:

$$\text{Maximum working stress} = \frac{\text{Yield stress}}{1.5}$$

Thus, knowing the yield stress from the manufacturer's specification, the working stress can be obtained.

19.6.2.1 Example

Calculate the minimum diameter of a circular steel bar subject to a tensile load of 500 kN. The yield stress of the steel is 200 MPa and FOS is 1.5. If d is the diameter of the bar, then:

$$\text{Maximum working stress} = \frac{200}{1.5} = 133.33 \text{ MPa}$$

$$\text{Stress} = \frac{\text{Load}}{\text{Area}} \quad \text{so that} \quad \text{Area} = \frac{\text{Load}}{\text{Stress}}$$

Hence:

$$\frac{\pi d^2}{4} = \frac{500 \times 10^3}{133.33 \times 10^6} = 0.00375 \text{ m}^2$$

So that:

$$d = \sqrt{\frac{4 \times 0.00375}{\pi}}$$

$$= 0.0691 \text{ m} = 69.10 \text{ mm}$$

19.7 Poisson's Ratio

Whenever steel is subjected to a ***tensile load*** it will extend in the longitudinal direction of the load and reduce in width in the transverse direction, at right angles to it. This effect can clearly be seen when an elastic band is stretched. This is demonstrated in Figure 19.3. Figure 19.3(a) shows the steel bars under no load. Figure 19.3(b) shows the effect of applying a tensile load to the same bar. It can be seen that the length L has increased to L_1 and the diameter D has *decreased* to D_1.

Figure 19.3(c) shows the corresponding effect for a ***compressive load***. In this case, L has *decreased* to L_2 and D has *increased* to D_2.

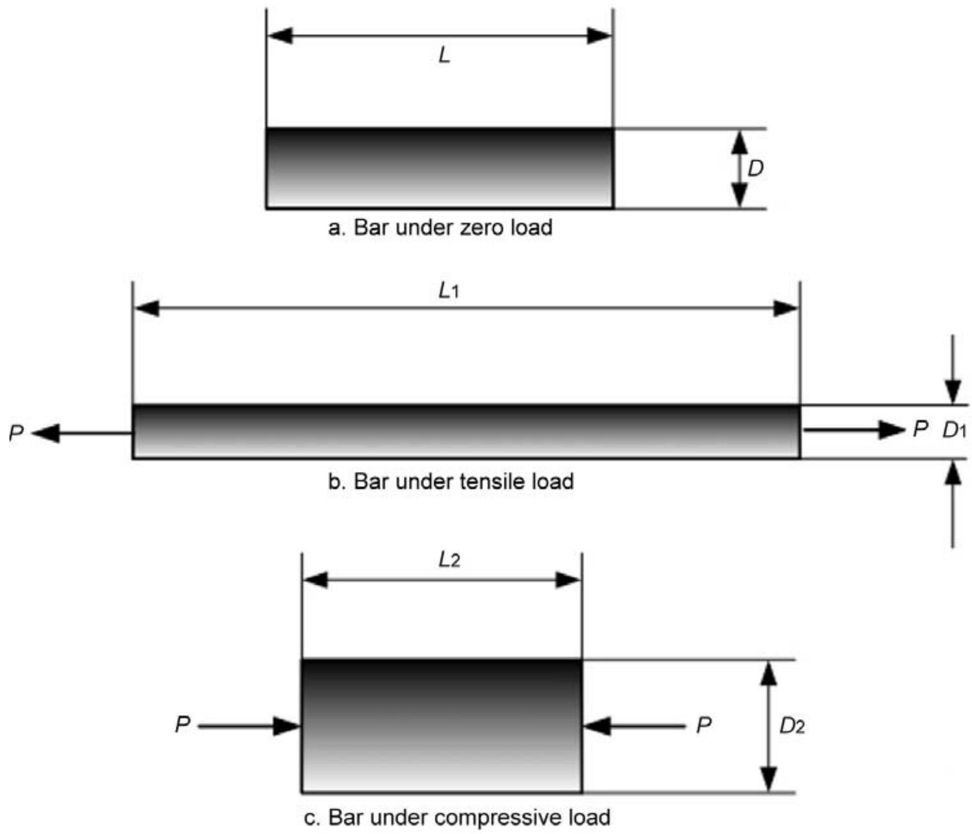


Figure 19.3 Poisson's ratio

The ratio of the transverse strain to the longitudinal strain under a tensile load or stress is knows as ***Poisson's ratio*** and has a value of approximately 0.3. Being a ratio, Poisson's ratio has no units:

$$\text{Poisson's ratio} = -\frac{\text{Transverse strain}}{\text{Longitudinal strain}}$$

The negative sign indicates the reduction in size in the transverse direction from D to D_1 when the bar is subjected to a tensile load.

Note also then when steel is subjected to a change in temperature with zero load applied, the material will be subject to strain with zero stress.

19.7.1 Example

A steel bar of length 150 mm and width 20 mm is subjected to an axial tensile load that increases the length of the bar by 0.015 mm. If Poisson's ratio is 0.3, calculate how much the width of the bar will reduce:

$$\text{Strain} = \frac{\text{Increase in length}}{\text{Original length}}$$

$$\text{Longitudinal strain } \frac{0.015}{150} = 0.0001\,\text{mm}$$

Transverse strain = Poisson's ratio × Longitudinal strain

$= -0.3 \times 0.0001 = -0.00003$

$$= \frac{\text{Change in width}}{\text{Original width}}$$

Hence:

Change in width = $-0.00003 \times 20 = -0.0006$ mm

The negative sign indicates the width has decreased.

19.8 Temperature Stresses

Most materials will expand when subjected to an increase in temperature and contract with a decrease in temperature. If the ends of the material are fixed so that they cannot expand, a temperature-induced stress will occur. This occurs frequently in hot runner mould tools.

The change in length due to a change in temperature is given by $L\alpha t$, where L = length and α = coefficient of linear expansion. Since Strain = Change in length/Original length,

$$\text{Strain} = \frac{L\alpha t}{L} = \alpha t$$

The stress associated with temperature change = Strain × E; hence:

$$\text{Stress} = E\alpha t$$

19.8.1 Example

A steel bar is subject to a temperature rise of 10 °C and it is prevented from expanding by rigid supports at its ends. Calculate the stress induced if the coefficient of linear expansion is $11 \times 10^{-6}\ K^{-1}$ and the modulus of elasticity is 225 GPa.

$$\text{Stress} = E\alpha t$$

$$= 225 \times 10^9 \times 11 \times 10^{-6} \times 10$$

$$= 225 \times 11 \times 10^4$$

$$= 24.75 \text{ MPa}$$

19.9 Beam Theory

There are several methods, used by engineers, to analyse the stress levels and deflection of metal components. In this book we will be using beam theory to model components for analysis. This is one of the least involved methods of stress analysis but very suitable for mould tools.

A beam is defined as a structural member that carries loads at different points along its length. These loads cause the beam to bend and curve (or deflect) causing one surface of the beam to be in tension and the other to be in compression.

Figure 19.4 shows an exaggerated caricature of what happens to the mould tool when it is under load. To analyse these effects we need to look at the following models.

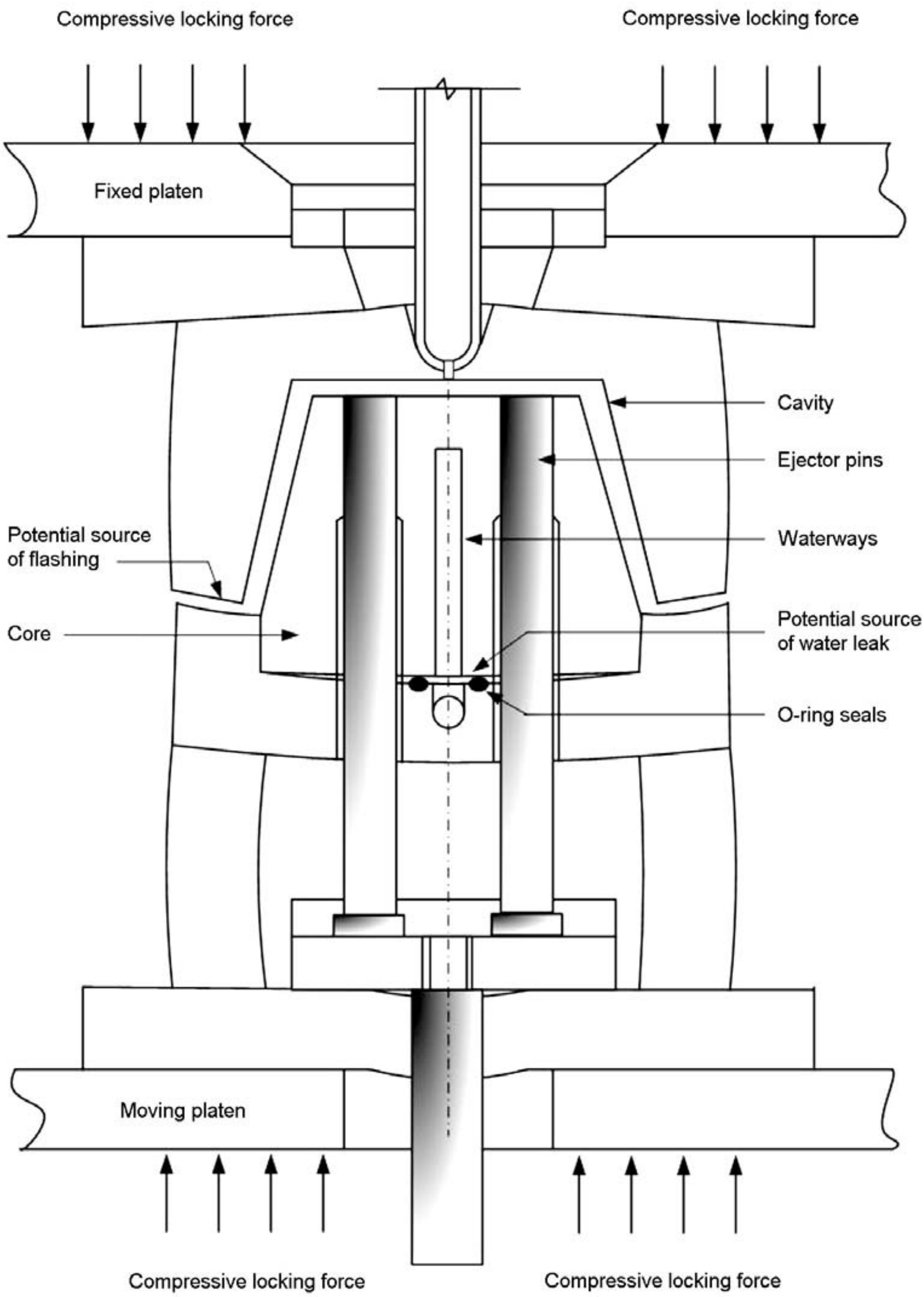


Figure 19.4 Exaggerated effect of mould tool under load

19.9.1 Beam Models

For mould analysis, six beam models will be considered (Figure 19.5): in all cases the load *W* is the *total* load on the beam, which may be a point load or a uniformly distributed one.

These six models cover almost all conditions of loading that would occur in a mould tool. Each of these cases will now be considered.

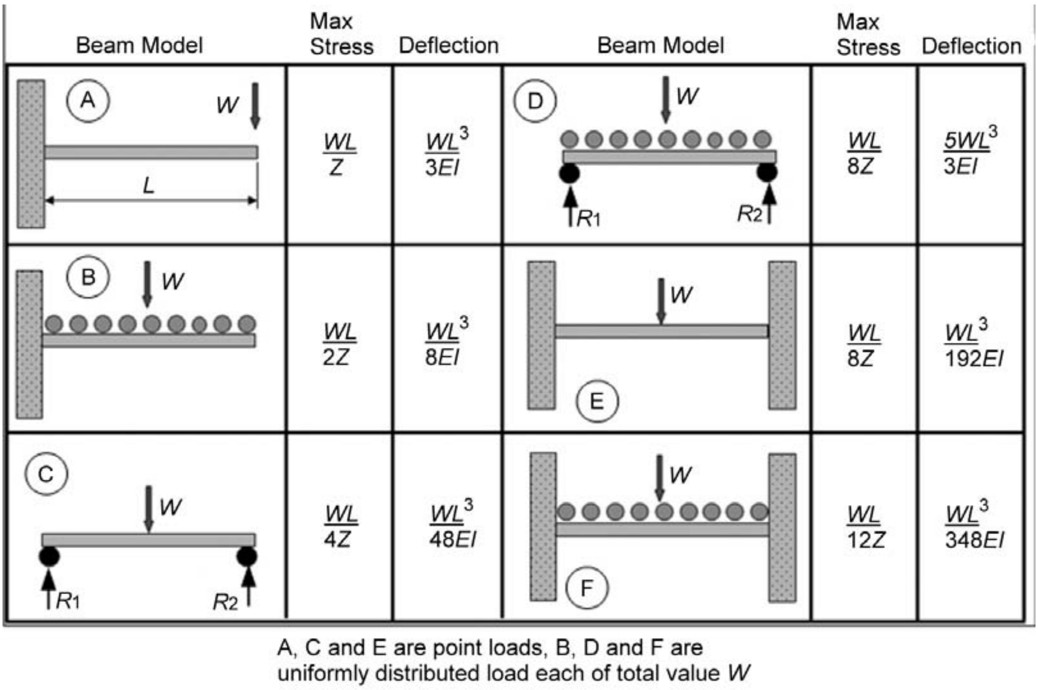


Figure 19.5 Beam models

Models B, D and F all have uniformly distributed loads that have a total value of *W*. The remainder are all loads of value *W* acting at a single point. These models may be split into three broad groups:

19.9.1.1 Simply Supported Beams

This type of beam (C and D) is supported freely at two points. There are *reactions* at the supports (R_1 and R_2) but no resisting moments.

19.9.1.2 Cantilever Beams

Cantilevers (A and B) are rigidly fixed at one end and free at the other. Under load there is a reaction and bending moment at the fixed end.

19.9.1.3 Beams with Both Ends Fixed

With this model (E and F), both ends are firmly fixed. This is also referred to as an ***encastre*** beam. There are reactions and ***bending moments*** at both ends of the beam.

19.10 Bending Moments

The bending moment (*M*) in Figure 19.6 is the algebraic sum of all moment acting on the beam at a specific point or section on it.

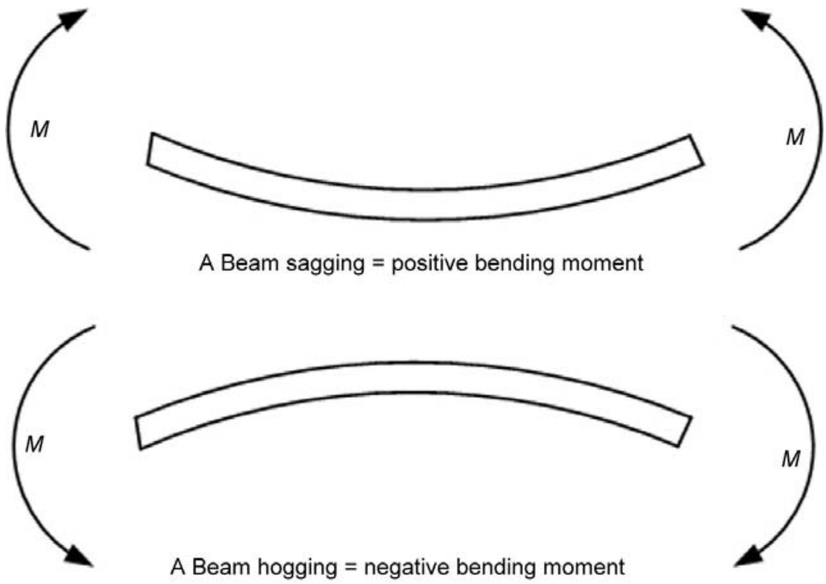


Figure 19.6 Bending moment conventions

By convention, beams that deflect downwards are said to be *sagging* and have a positive bending moment. Conversely, beams that are deflected upwards are said to be *hogging* and have a negative bending moment.

19.10.1 Neutral Axis

When a beam bends, as shown in Figure 19.7, the upper surface is being stretched and is in tension, while the lower surface is in compression.

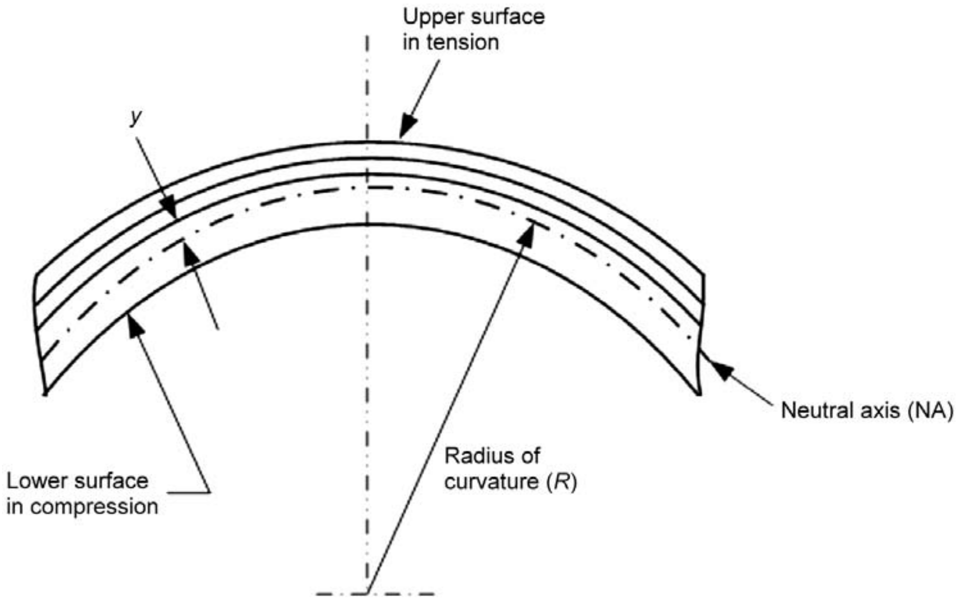


Figure 19.7 Behaviour of a beam during bending

The position of the neutral axis passes through the ***centroid*** of the beam.

19.10.2 Second Moment of Area

If a strip of width y has an area of δA (Figure 19.7), then the moment of force about the neutral axis is:

$$\text{Force} \times y = \frac{Ey\ \delta A\ y}{R}$$

$$= \frac{Ey^2\ \delta A}{R}$$

But each layer of the beam exerts a moment about the neutral axis and therefore the total moment is the sum of all these moments:

$$\text{Total moment } M = \sum\left(\frac{Ey^2\ \delta A}{R}\right)$$

$$= \frac{E\sum y^2\ \delta A}{R}$$

The expression $\sum y^2\ \delta A$ is called the ***second moment of area*** (I) about the neutral axis. The units are m^4.

For mould analysis purposes there are two shapes that are of interest: rectangular and circular (Figure 19.8). In both cases a force *P* is being applied in the direction shown.

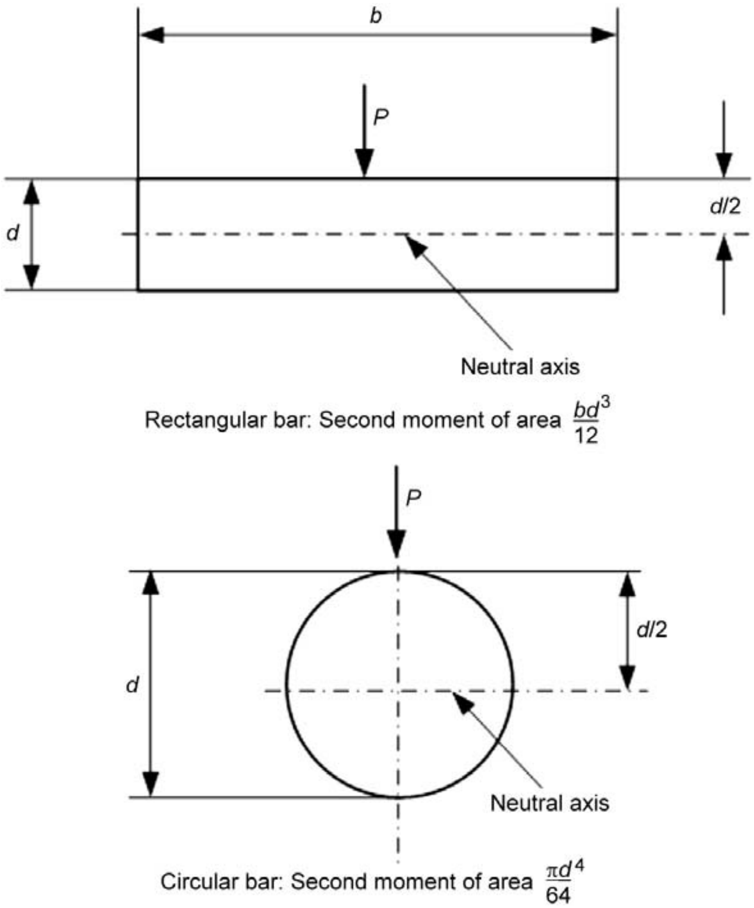


Figure 19.8 Second moments of area for rectangular and circular bars

19.10.2.1 Second Moment of Area for a Rectangular Bar

$$\text{Second moment of area} = \frac{bd^3}{12}$$

The second moment of area is a measure of the stiffness of the beam; therefore to reduce deflection either *b* or *d* would need to be increased. Clearly it is more effective to increase *d* as this term is cubed in the formula.

19.10.2.2 Second Moment of Area for a Circular bar

Second moment of area = $\frac{\pi d^4}{64}$

Again stiffness and consequently reduction in deflection is achieved by increasing *d*.

19.11 Bending Formula

All the above may be combined in the well-known general bending formula:

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

where:

M = bending moment (N-m)

I = second moment of area (m^4)

σ = bending stress (Pa)

y = distance from neutral axis at which fibres are subjected to stress σ (m)

E = modulus of elasticity (Pa)

R = radius of curvature (m)

19.12 Section Modulus

In a beam under load the maximum stress σ_m occurs where the distance from the neutral axis is a maximum σ_y.

From the bending formula we can then establish:

$$M = \frac{I \times \sigma_m}{y_m}$$

The quantity I/y_m is purely geometric, being dependent only on the shape of the cross-sectional area. This quantity is known as the ***section modulus*** *Z*. The units are m^3. Hence,

$M = Z\sigma_m$

For a rectangular bar, $Z = \frac{bd^2}{6}$

For a circular bar, $Z = \frac{\pi d^3}{32}$

19.13 Deflection of Beams

Whenever a beam is subjected to a load, it will tend to bow or deflect because of the resulting bending moment.

In many applications excessive deflection would be highly undesirable and mould tools are no exception. It is therefore very important to be able to predict the amount of deflection of a component at the design stage. Figure 19.5 lists all the beam models we have been discussing together with simple formulae for the maximum stress and deflection for each case.

19.14 Analysing Mould Tools

We can now apply these formulae to carry out analyses of mould plates, cores and other components. It is important, however, to be aware that the accuracy of the results depends on the tool being of good quality and that a correct model has been selected.

19.14.1 Two-Plate Example

Figure 19.9(a) shows a simple single impression mould. Area *A* is the area over which the injection pressure is acting and therefore *A* is the projected area.

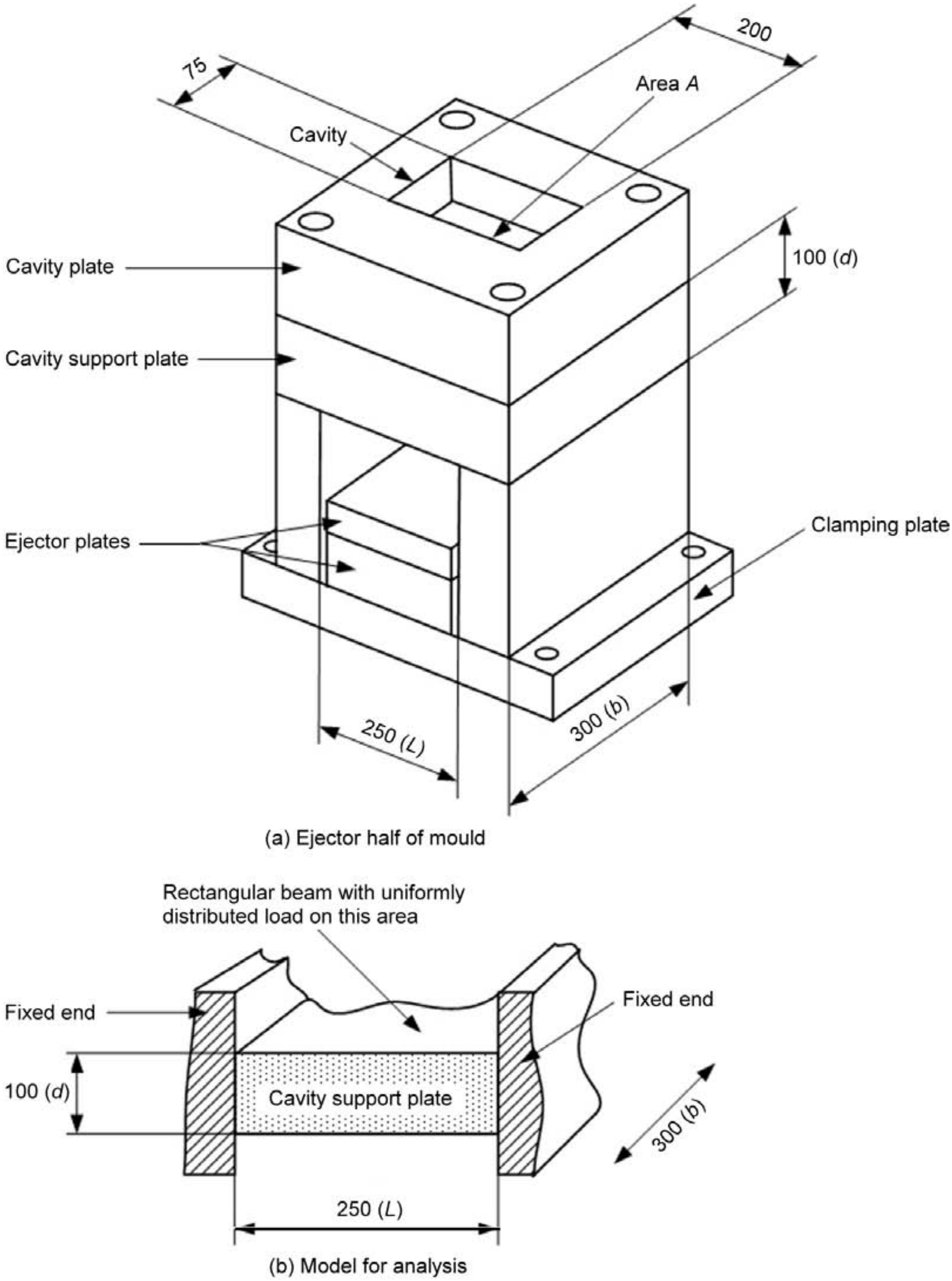


Figure 19.9 Modelling a two-plate tool

Figure 19.9(b) is the model we can deduce from the mould design. While it does not quite represent the actual conditions, it is close enough for an analysis of this type. In this case the cavity support plate is rigidly held captive by the clamping force exerted on the mould tool, so we can use the model of a beam with both ends fixed (model F in Figure 19.5). This makes the effective length of the beam 250 mm. If the following parameters apply, we can calculate the deflection as follows:

Melt pressure = 150 MPa

Young's modulus of elasticity = 200 GPa

Projected area of cavities = 0.015 m^2 (200 mm × 75 mm)

The model here is a beam with a uniformly distributed load and fixed at both ends. Hence from Figure 19.5:

$$\text{Max. stress} = \frac{WL}{12Z} \quad \text{and} \quad \text{Deflection} = \frac{WL^3}{384EI}$$

Hence:

$$\text{Total load } W = 150 \times 0.015 = 2.25 \text{ MN}$$

$$I = \frac{bd^3}{12} = \frac{0.3 \times (0.1)^3}{12} = 0.000025\ m^4$$

$$Z = \frac{bd^2}{6} = \frac{0.3 \times (0.1^2)}{6} = 0.0005\ m^3$$

Then the deflection is:

$$\frac{WL^3}{384EI} = \frac{2.25 \times 10^6 \times (0.25)^3}{384 \times 200 \times 10^9 \times 2.5 \times 10^{-5}} = 0.000018\,\text{m}\ or\ 0.018\ \text{mm}$$

The maximum stress is:

$$\frac{WL}{12Z} = \frac{2.25 \times 0.25}{12 \times 0.0005} = 93.75\ MPa$$

While the stress level is satisfactory, this level of deflection may be undesirable if a low-viscosity material, like Nylon, is being used with high pressure.

To combat this we can either increase the depth (*d*) of the support plate or, if possible, introduce support pillars under the cavity backing plate (Figure 19.10).

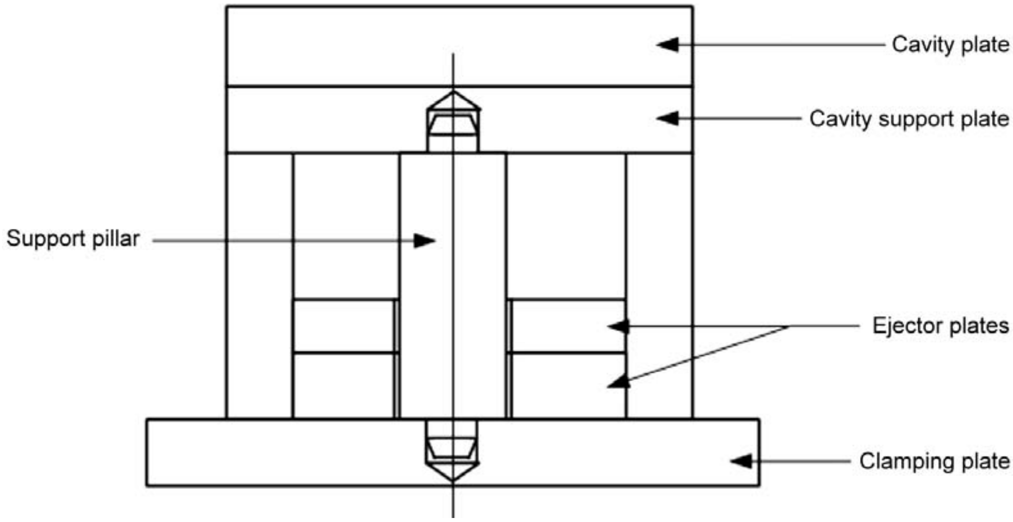


Figure 19.10 Use of support pillars

If it is not possible to introduce support pillars, the plate thickness will have to be increased if this level of deflection is unsatisfactory. In order to do this we need to choose a maximum allowable deflection. Here we will take the allowable deflection to be *x metres*.

The equation Deflection = $WL^3/384EI$ can be transposed to isolate I as follows:

$$I = \frac{WL^3}{384Ex}$$

Hence:

$$\frac{bd^3}{12} = \frac{WL^3}{384Ex} \quad \Rightarrow d = \sqrt[3]{\frac{12WL^3}{384Ebx}} \text{ metres}$$

Note that to decrease deflection, it is far more effective to increase dimension *d* than dimension *b*, as any increase of the value of *d* is cubed.

19.14.2 Split Tool Example

The same principles of analysis apply to split tools as to two-plate tools. The example below shows the method used to analyse a typical split tool. In this case we are analysing the *heel blocks* to determine whether they are within acceptable limits with regard to deflection and stress. The projected area we require in this case is that shown in Figure 19.11 by the shaded area and the opposite face to it. It is over these areas that the force *W* generated by the injection pressure acts. It is this force that the heel blocks have to withstand.

To simplify the analysis it is sufficient to take the depth *d* of the heel blocks as the average depth: in this case 50 mm. In this case a cantilever beam, fixed at one end with a uniformly distributed load, models the heel blocks (model B in Figure 19.5).

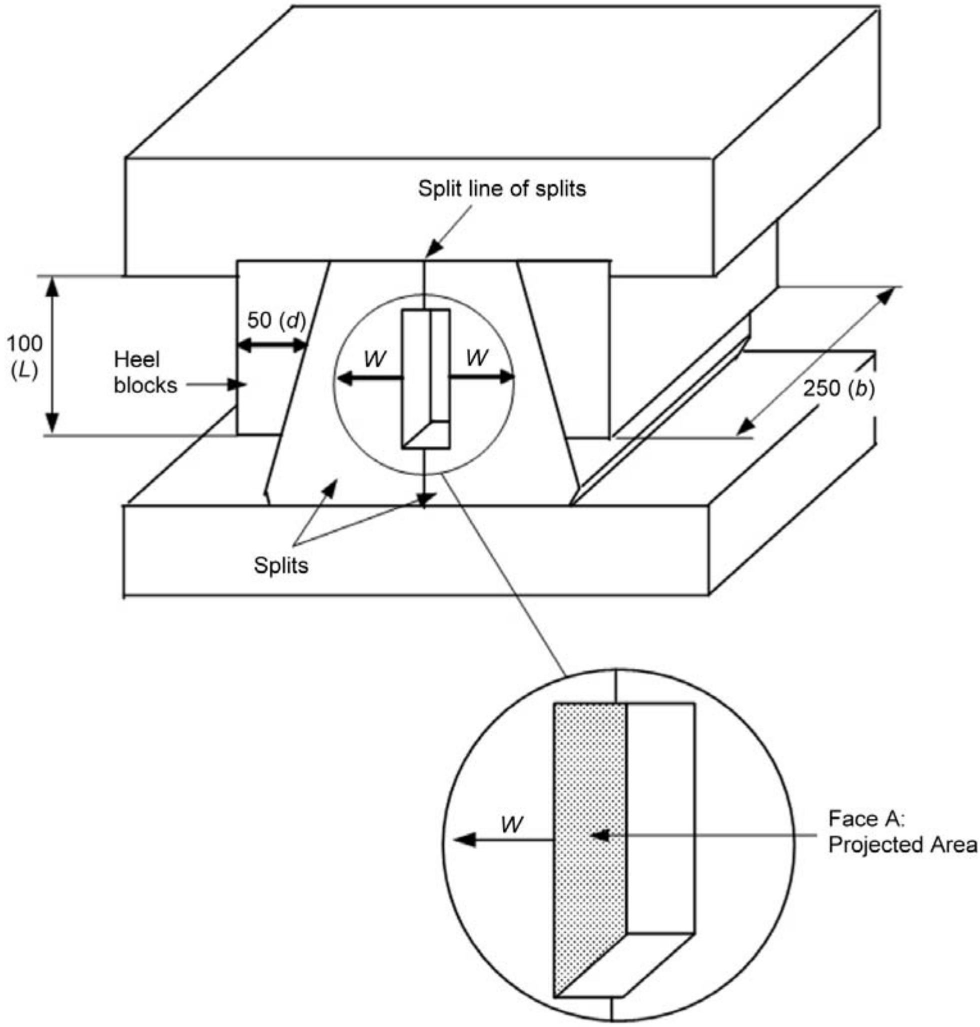


Figure 19.11 Split tool example

The parameters for this are as follows:

Melt pressure = 150 MPa

Young's modulus = 200 GPa

Projected area of cavities = 75 × 50 mm = 3750 mm^2 = 0.00375 m^2

L = 100 mm

b = 250 mm

d = 50 mm

From Figure 19.5, this model has:

$$\text{Deflection} = \frac{WL^3}{8EI} \text{ and Max. Stress} = \frac{WL}{2Z}$$

Hence:

$$I = \frac{bd^3}{12} = \frac{0.25 \times (0.05)^3}{12} = 0.000002604\,\text{m}^4$$

$$Z = \frac{bd^2}{6} = \frac{0.250 \times (0.050)^2}{6} = 0.0001042\,\text{m}^3$$

$$W = 150 \times 10^6 \times 3.75 \times 10^{-3} = 562{,}500 \text{ Pa} = 0.563\,\text{MPa}$$

Then:

$$\text{Deflection} = \frac{WL^3}{8EI} = \frac{0.563 \times 10^6 \times (0.1)^3}{8 \times 200 \times 10^9 \times 2.604 \times 10^{-6}} = 1.35 \times 10^{-7} \text{ m}^2 = 0.000135\,\text{mm}^2$$

$$\text{Max. Stress} = \frac{WL}{2Z} = \frac{0.563 \times 10^6 \times 0.1}{2 \times 1.024 \times 10^{-4}} = 275{,}000{,}000 \text{ Pa} = 275\text{MPa}$$

Applying a FOS of 1.5 to this figure we get stress = 412.5 MPa.

For both stress and deflection these results are well within acceptable limits. If they were not, the dimension *d* would have to be increased.

19.14.3 Analysing Core Pins

Slender core pins, with a high length to diameter ratio, are particularly susceptible to undesirable amounts of deflection, often leading to high levels of rejection. This is, usually, caused by unbalanced forces due to the gate position and high injection pressures and speeds.

19.14.3.1 Unsupported Cores

The greatest amount of deflection takes place when a core pin is unsupported, as shown in Figure 19.12(a) and with a gate adjacent to the free end of it. This is a frequently encountered problem that creates many problems in production.

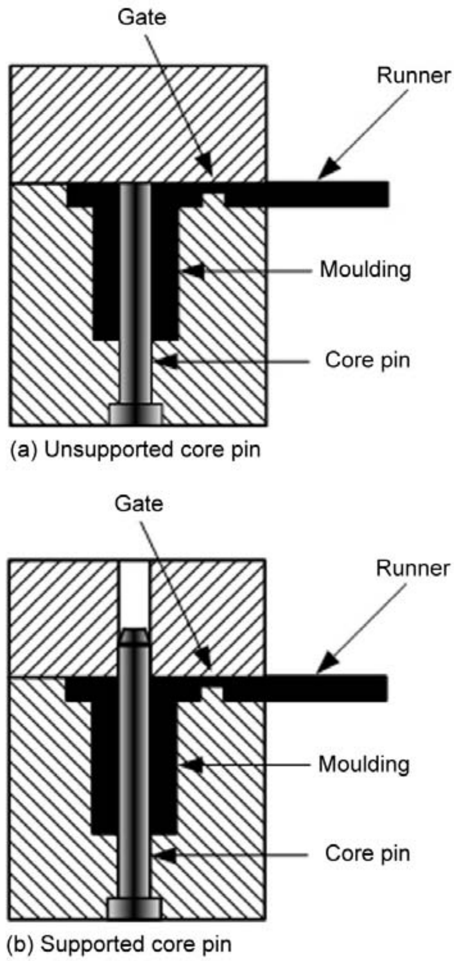


Figure 19.12 Supported and unsupported core pins

In this case, the core is supported only at one end and is modelled by a cantilever with a uniformly distributed load (UDL) along its length. The amount of deflection is given by

$$\text{Deflection} = \frac{WL^3}{8EI}$$

19.14.3.2 Supported Cores

In Figure 19.12(b) the gate position is the same but the core is supported at both ends and is modelled by a beam, fixed at both ends with the same UDL. In this case:

$$\text{Deflection} = \frac{WL^3}{384EI}$$

It can immediately be seen for the two cases that the unsupported core is subject to 48 times more deflection than the supported core. The conclusion is therefore obvious. Always support the core pins at both ends wherever possible, particularly when using long, slender cores. Calculations to determine the stress and deflection levels are carried out in exactly the same way as those previously shown.

If the core pins are circular, however, the formulae for the second moment of area should be the one for a circular beam.

Note: The current practice for determining plate sizes is to 'guestimate' the size and then look for the nearest available standard plate size to it.

One argument against plate analysis goes something like this: 'Its all very well calculating a plate size of, say, 21.75 mm thickness, but the nearest standard size available is 23 mm; you cannot obtain this awkward size, so what is the point?'

The first part of this argument is true, but there is nothing to stop a plate of 21.75 mm being ordered from the same supplier: they will provide whatever you ask for. It may be more expensive initially, but what we should be concerned about is the overall cost of the project, including the cost of production.

Why heat and cool a plate that is too large for the purpose and do it for millions of cycles? For many applications the extra cost of the 'non standard' plate can pale into insignificance compared with the savings in energy cost in reduced cycle times.

19.15 Summary

1. The mass of the mould determines how much energy is required to run it and the length. This is turn will influence the cost of production.

2. If the appropriate formulae are put on to a computer, the analyses can be carried out in a matter of a few minutes.

3. Many water leaks from mould tools are attributable to unseen deflection or stress cracking through water channels.

4. Carrying out a basic analysis can save cost and machine downtime.

5. Increasing competition necessitates a more critical analysis of the mould design.

6. Mould components that have failed in production should be analysed to establish the correct parameters.

See Chapter 20 on Fatigue, which links the combined problems of stress, deflection and stress-induced fatigue with an actual example.

20 Fatigue

20.1 Observations

Many failures in mould tools are due to metal fatigue. An injection mould tool is a highly stressed heat exchanger and has to undergo at least thousands and sometimes millions of cycles. Additionally, during production the tool is subject not only to cyclic mechanical stresses but also to cyclic thermal stresses.

On each cycle, the tool is clamped, heated by incoming material, cooled and then unclamped. These cyclical loading conditions are classically those that can lead to components failing from fatigue.

Metal fatigue is understood well by metallurgists and engineers designing cars, aircraft, trains and so on. Indeed, such people would be considered negligent if fatigue studies were not undertaken, as fatal failures due to fatigue could occur.

Unfortunately, the moulding industry does not in general, carry out any fatigue checks at all on mould tools at the design (or any other) stage. Serious accidents to personnel are unlikely to occur if fatigue-induced failures happen on a mould tool during moulding, and perhaps it is for this reason that performance of fatigue analyses on mould tools does not carry the same importance as other in industries. However, serious accidents cannot be ruled out entirely.

Nevertheless, it is a fact that, traditionally, fatigue-induced mechanical failures of the mould tool cost the injection moulding industry millions of pounds annually. For this reason there is an increasing realisation that fatigue analysis is necessary as competition forces manufacturing costs down, with potentially more breakages occurring as mould tools are increasingly run nearer the limit of their capability.

The following approach is a necessarily simplified descriptive version of fatigue analysis as this topic can be considerably involved. It is nonetheless a perfectly valid and useful approach for the analysis of mould tools.

20.2 Facts on Fatigue

Here are few basic observations on fatigue, some of which are obvious and some not so obvious:

- When subjected to repeated (or cyclical) stresses as opposed to continuous or static loading, the capacity of a metal to withstand stresses gradually decreases and in most cases the metal will not recover.
- Metals subject to changing loads will break after a finite number of load cycles even though the stress may be well below the ultimate yield stress of the metal.
- Tests have shown that if a steel component, under a particular load, has not broken after roughly two million cycles, it will not break under the same load in the future.
- For ***fatigue failure***, the time interval between applied loads is immaterial. Only the number of cycles is significant. For example; a tool running on a 15-second continuous 24 hour cycle will complete one million cycles in 173 days. If the cycle could be reduced to 5 seconds the tool would complete the same number of cycles in 58 days. The effect of fatigue in both cases is the same.
- When torque is applied to a screw, the screw is subjected to ***tensile*** and ***torsional*** stresses. As soon as the screw has been tightened, however, the torsional force ends, leaving the screw in tension only. It is for this reason that screws should be lubricated to reduce the ***torsional stress***.
- The possibility of failure from fatigue is greater if the load cycles from positive to negative: for example, from a tensile load to a compressive one. It is a fact that many of the component parts of a mould tools are subject to this condition.
- Fatigue-induced cracks on a tool are often the cause of water leaks.

A typical example of a fatigue-related fracture in a mould tool is demonstrated in Figure 20.1. This is an actual example of a mould that developed a serious persistent leak after a few weeks' production followed by a hairline fracture of core **A**.

An examination of the tool revealed a stress fracture emanating from the upper water cooling channel which had been responsible for the leaking problem. This was due to the cyclic out-of-balance load being exerted on core **A**, which was being flexed every cycle by first a load of 27 tonnes generated in the right-hand cavity during the initial injection phase followed by a force of 20 tonnes generated in the left-hand cavity as this cavity filled. This meant that almost the full force of 27 tonnes was acting on the right-hand side of core **A** until the left-hand cavity filled developing a force of 20 tonnes.

At this point the resultant force on core **A** was reduced to 7 tonnes (27 t – 20 t) from the right-hand cavity. Eventually core **A** fractured owing to this continuous variable cyclic stress imposed on it. However, with extended production the resultant force of 7 tonnes alone would have been enough to cause the same stress fracture to occur even if both cavities filled at the same time, albeit over a longer period.

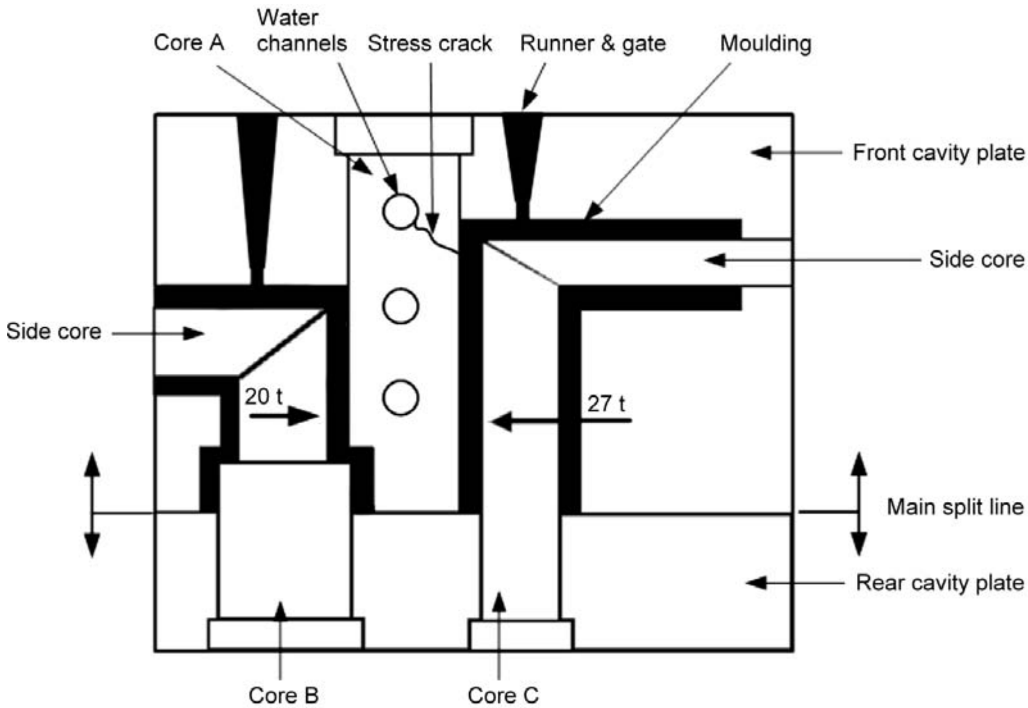


Figure 20.1 Ventilation duct mould with fatigue-related fracture

The problem was solved by:

1. Introducing a support key at the bottom of core **A** as shown in Figure 20.2.

2. Controlling the filling characteristics to balance the loads more evenly on both cavities during the injection phase.

3. Polishing the water channels to remove any potential stress raisers occurring as a result of a rough 'as drilled' hole.

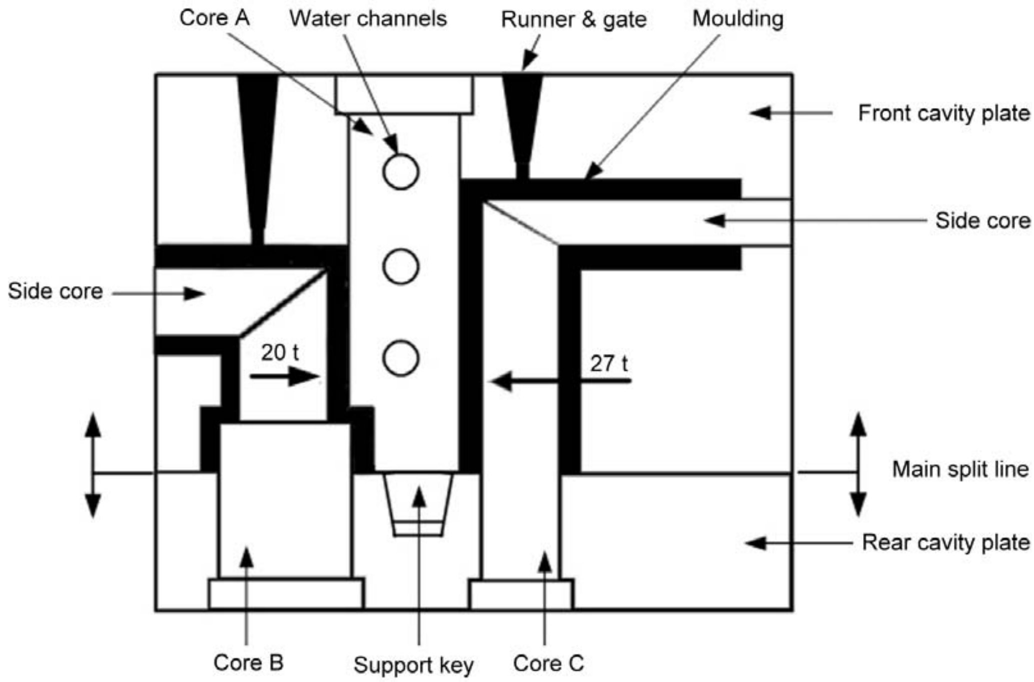


Figure 20.2 Ventilation duct mould

The effect of introducing the support key was to change the model from a cantilever to a beam fixed at both ends. This immediately increased the stiffness of the core, minimising the deflection and lowering the stress.

20.3 Calculating Shut-off Areas

Shut-off areas are necessary to ensure the clamping pressure is concentrated around the cavity inserts. The smaller this area is, the greater the clamping pressure will be. This in turn means there will be more clamping pressure available to counteract the pressure generated by the injection pressure trying to force the mould apart. However, if the clamping area is too small there is a danger that the increased clamping pressure will generate a very large stress, resulting in damage to the mould surface by exceeding the stress limit of the steel.

Unfortunately these shut-off areas on the two split faces of a tool are rarely calculated and remain a topic of mystery and guesswork to many in the injection moulding world. This is highly undesirable because the shut-off area has to meet two conflicting but important conditions, restated here:

- It must be small enough to achieve adequate clamping pressure.
- It must be large enough to avoid fatigue (displayed by fracturing of the edges and heavy bruising and chipping).

Figure 20.3 below shows a typical shut off area (shown shaded) on a mould tool having a rectangular hardened insert.

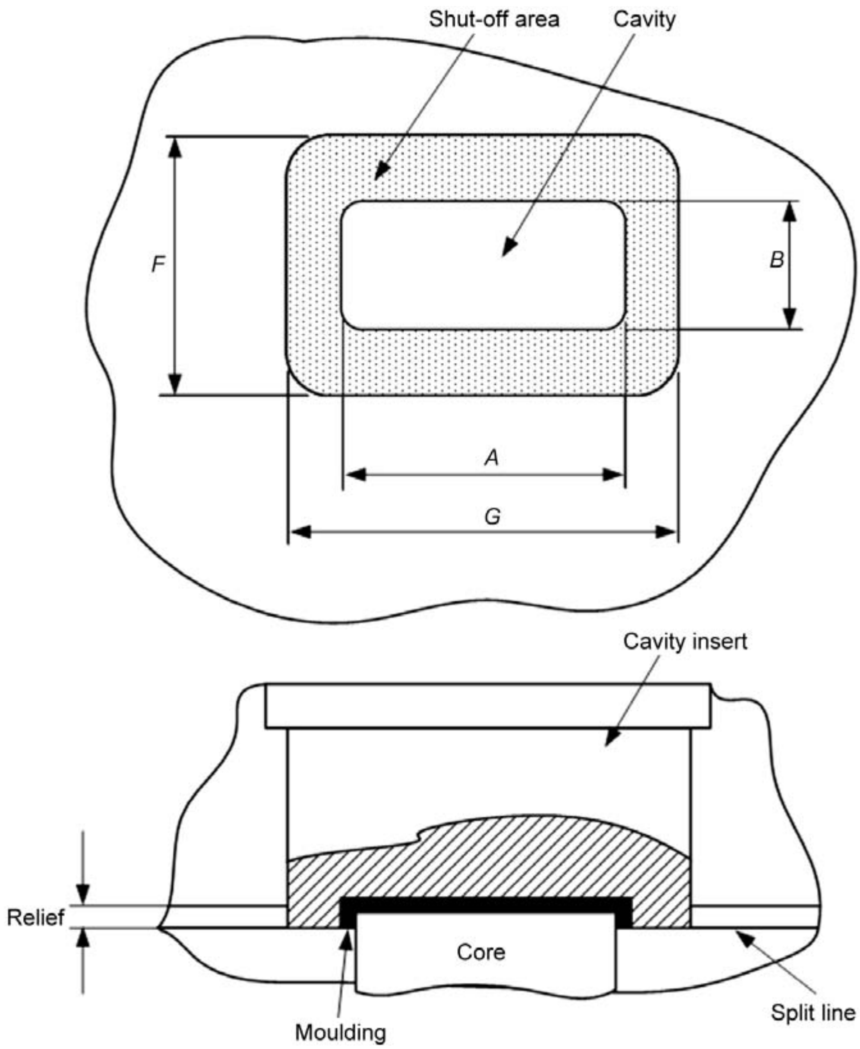


Figure 20.3 Shut-off area

The shut off area here is the area of the insert less the area of the cavity ($F\times G - A\times B$ shown shaded). It is on this area that the full clamping pressure is taken. If this area is too large, the locking force is spread over too large a surface, resulting in a low clamping pressure making the tool more prone to flash.

As the area decreases, the pressure and hence the stress (stress = load/area) increases. If the area is too small the stress on the steel can be very high. Combining this with the cyclic loading conditions it can easily lead to ***fatigue cracking*** and bruising of this area.

The critical factor here is to calculate the minimum shut off area that falls within safe fatigue limits.

To calculate shut-off areas, use the following values:

Maximum allowable fatigue stress of hardened alloy steel = 40 MPa

Maximum allowable fatigue stress of soft alloy steel = 20 MPa

20.3.1 Example

A four-impression tool is used to make circular components as follows:

OD of part	10 cm
Injection pressure	125 MN
Mould material	H13 hardened nickel–chrome alloy tool steel
Fatigue limit of steel	40 MPa
Factor of safety (*K*)	1.2

Area of cavity $= \dfrac{\pi d^2}{4} = \dfrac{3.146 \times (10^2)}{4} = 78.54\ \text{cm}^2 = 0.00785\ \text{m}^2$

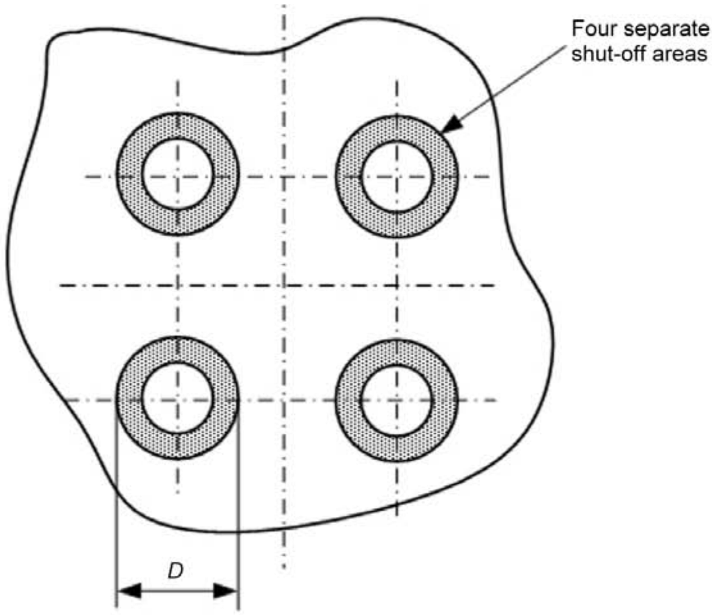
So for four cavities, the total projected area $= 4 \times 0.00785 = 0.0315\ \text{m}^2$

Locking force F_c = Projected area × Injection pressure × K.

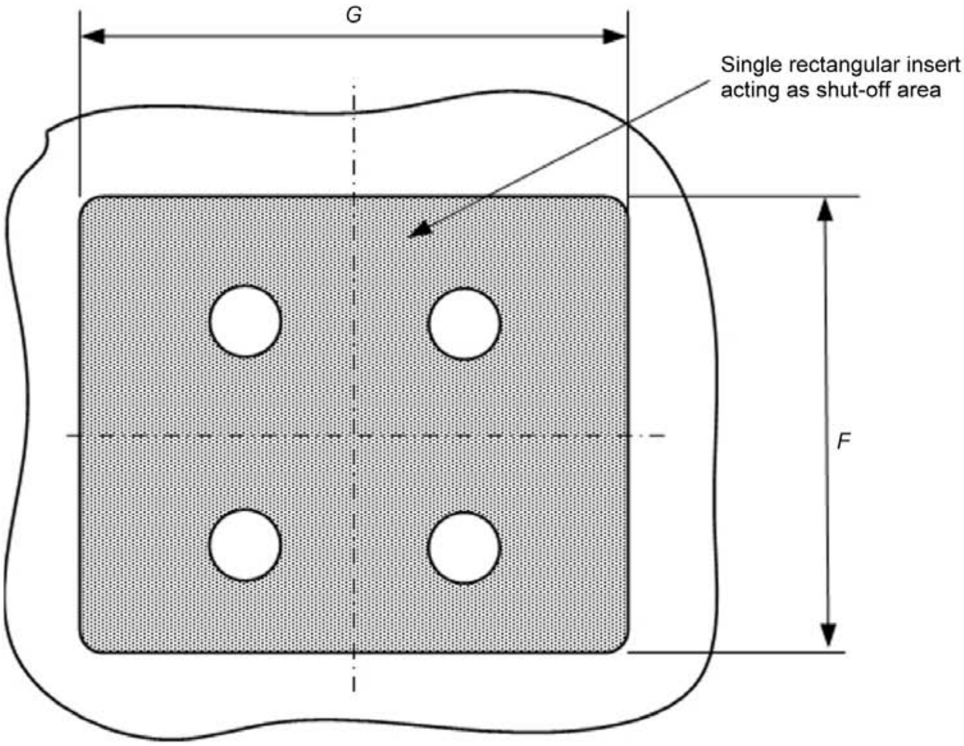
$$F_c = 0.0315 \times 125 \times 1.2 = 4.725\ \text{MN} = 472.5\ \text{Tonnes}$$

$$A_f = \frac{4.725}{40} = 0.1181\ \text{m}^2 = 1181\text{cm}^2$$

Hence a shut-off area of 1181cm^2 is required. This area can be arranged in two ways: Either using individual circular pads or a single rectangular insert containing all four cavities or cavity inserts (Figure 20.4).



(a) Separate circular shut-off areas



(b) Rectangular shut-off area

Figure 20.4 Shut-off areas

20.3.1.1 Case 1 Circular Inserts

Total shut-off area required = 378 cm^2

$$\text{Shut-off area required per insert} = \frac{1181}{4} = 295.25 \text{ cm}^2$$

Total area of insert = Area cavity + 295.25 = 78.54 + 295.25 = 373.79 cm^2

$$\text{Hence diameter } D = \sqrt{\frac{4 \times 373.79}{\pi}} = 21.82 \text{ cm}$$

20.3.1.2 Case 2 Rectangular Inserts

Here we require that:

$F \times G$ = Shut-off area + area of cavities = 1181 + (4 × 78.5) = 1181 + 314 = 1495 cm^2

The dimensions of F and G will depend on the design layout of the impressions. Here, for example, we could use a square insert so that $F = G = \sqrt{1495} = 38.67$ or, say, 39 cm to round this result up.

20.4 Factors Affecting Fatigue Life

Several factors affect the fatigue life of components in a mould tool. These include the following major items:

- Stress concentrations
- Stress raisers
- Machining marks
- Surface finish

20.4.1 Stress Concentrations

All mould tools are affected by stress concentrations and in many cases these are responsible for component failures. The designer must be aware of the conditions that can give rise to such stresses, so that these may either be avoided or at least minimised.

Stress concentrations appear in a number of ways. For example, they can be the result of faults in the steel or of bad design. If a solid component is subjected to a tensile load, the stresses within it are reasonably evenly distributed throughout it. If a hole is machined into the component, however, the stresses around the hole increase significantly and can lead to premature fracture. This explains why mould components often indicate that they have failed by the sudden appearance of a water leak from a waterway.

In mould design it is often impossible to avoid holes in stressed parts, but where the part is relatively thin and may be subject to fluctuating loads, attention should be given to the surface finish of the hole. This effect of polishing can be seen in Figure 20.5, clearly showing the advantages of a polished hole which withstands higher levels of stress before failure.

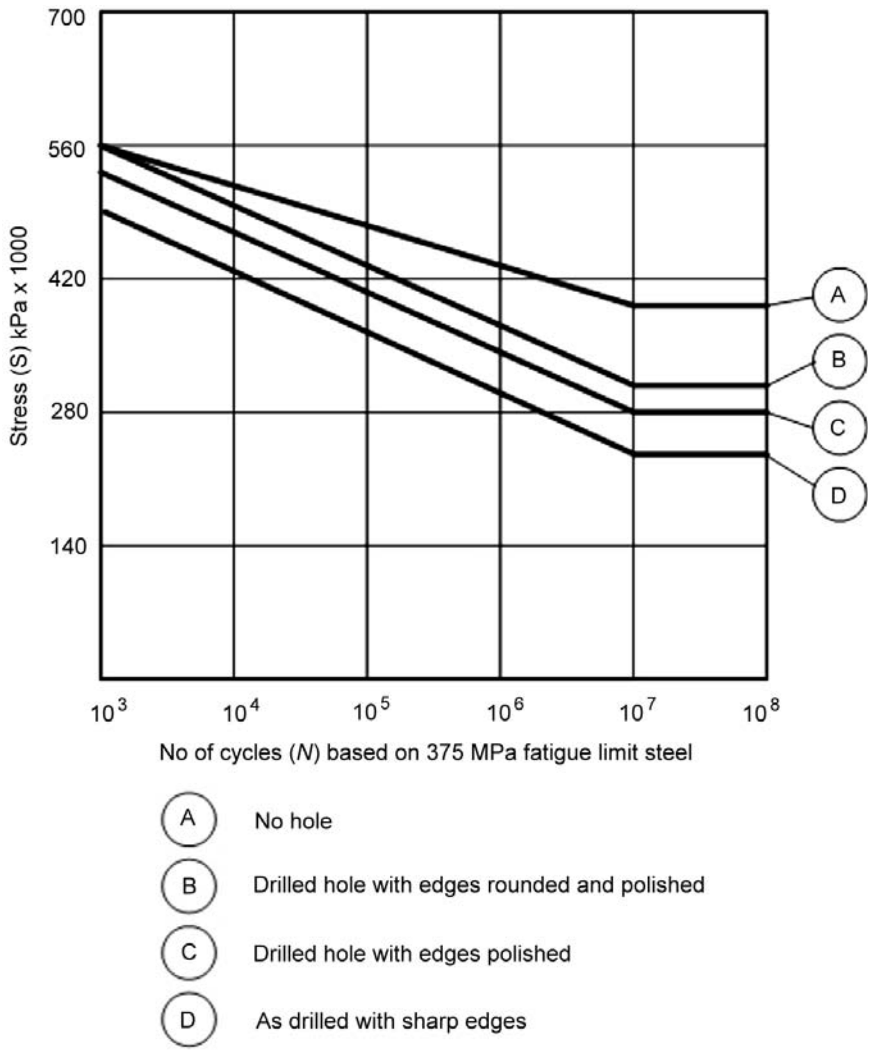


Figure 20.5 *S-N* curves: effect of holes

Figure 20.6 shows how different methods of melting steel can affect fatigue limits. It can be seen that vacuum-melted steel is superior to air-melted steel.

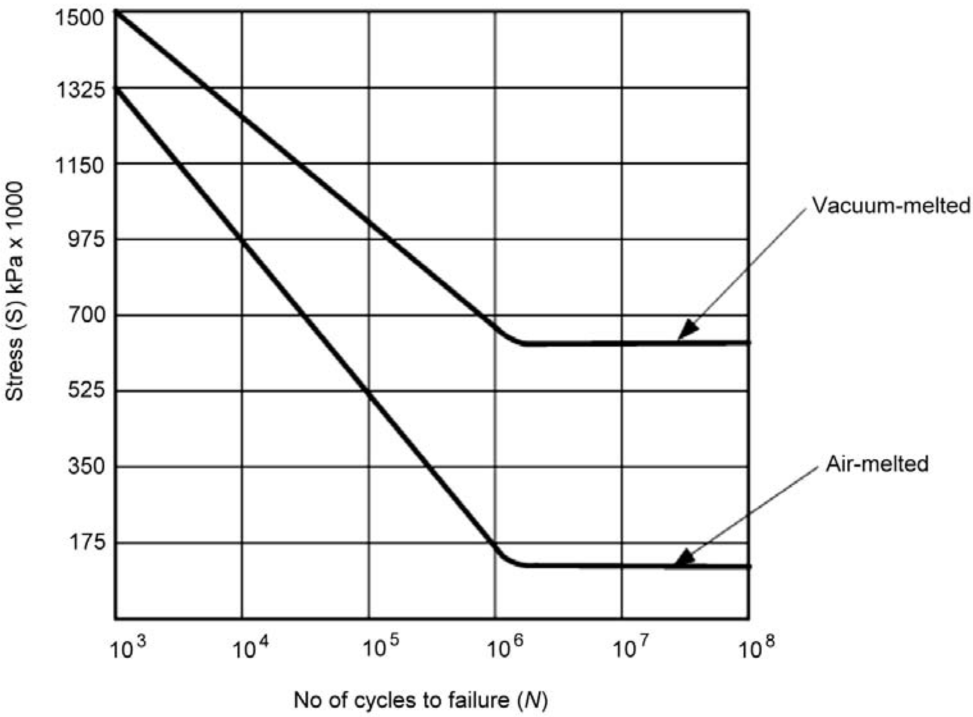


Figure 20.6 *S-N* curves for air and vacuum melted steel

20.4.2 Stress Raisers

Particular attention should be paid to fillet radii. Sharp corners are a notorious cause of failure due to fatigue and all fillet radii should be as large as possible (Figure 20.7). If larger radii are not possible, then the surface finish should be as high as possible to minimise the effect and improve the fatigue life.

Similar attention should be paid to O-ring grooves. For satisfactory performance the manufacturer's recommendations regarding radii and surface should be observed.

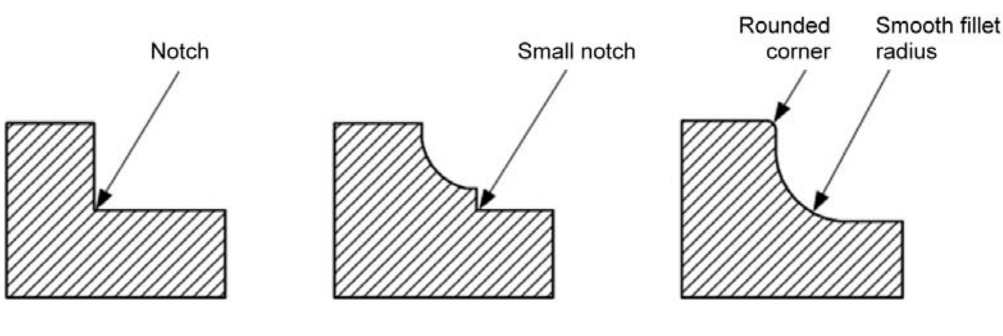


Figure 20.7 Corner rounding and fillet radii

Stress diagrams for various corner configurations are shown in Figure 20.8. This clearly shows how effective smooth fillet radii can lower the stress levels in components.

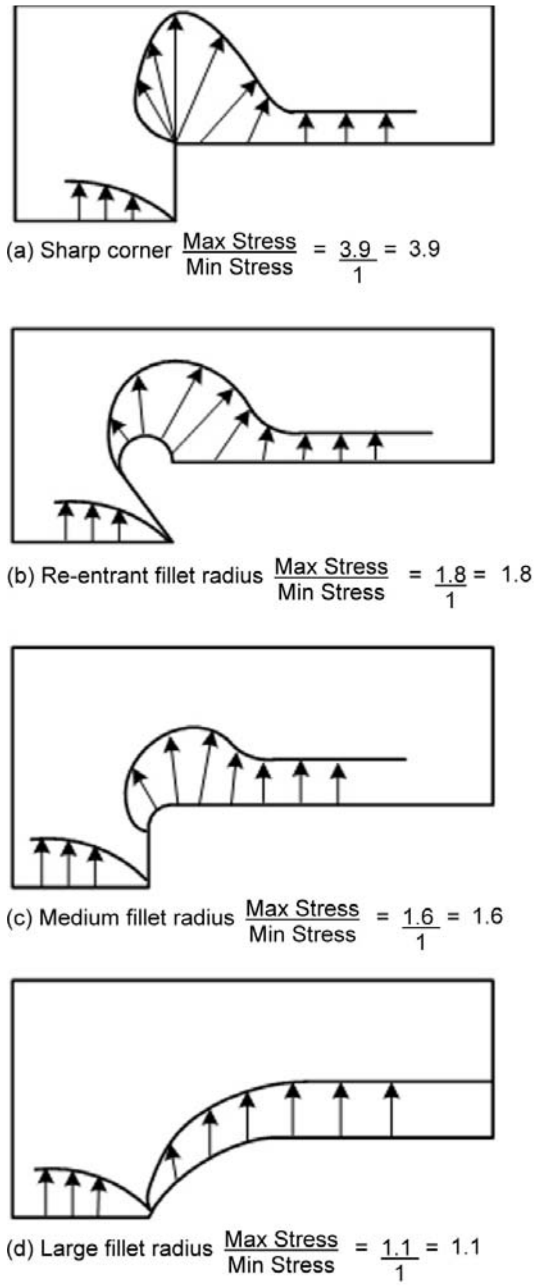


Figure 20.8 Stress diagrams for different corner stress raisers

20.4.3 Machining Marks

For maximum fatigue life, all bored and drilled holes should have a smooth finish, without any machining witness marks showing. Special drills are available that impart a smoother finish than a twist drill where this is necessary. Reaming would give a better result but this can be difficult to do, as well as being an expensive operation, and is therefore rarely used. Mechanical honing is even more expensive and almost never used.

A more practical alternative is fluid bed-honing. In this process abrasive slurry is forced, under pressure, inside melt flow channels. This has the effect not only of increasing the fatigue life but also of improving the polymer flow.

Although it may seem that these are extreme lengths to go to, these factors become very important on tools subject to millions of cycles in preventing premature failure if maximum economy of production and trouble free operation is important, for example in very competitive markets.

Water cooling holes are nearly always left with a drilled finish. While this promotes turbulent water flow, it also promotes corrosion. The corrosion starts at the tool marks and progressively eats into the steel, creating a sharp-notched effect. As the corrosion effect cannot be seen, the problem does not become apparent until water leaks start occurring.

The walls of cavities are always highly stressed on every injection cycle, by the pressure of the incoming melt. Any channels or screw holes in the cavity insert can worsen this problem, with each feature of this type creating stress raisers.

If channels are too close together, this has the cumulative effect of acting like a series of perforations and will severely decrease the fatigue life. The designer can compensate for this by 'overdesigning' in most cases. Where space is at a premium, however, this is not possible and calculations should be carried out to ensure adequate strength. Such calculations can be tedious and the application of a few rules will enable the designer to avoid potential pitfalls. The most important of these are:

- Do not make wall thicknesses too small.
- Apply adequate safety factors.
- Avoid excessive steel hardness.
- Avoid water channels and holes being too close together.
- Avoid poor finishes on holes.
- Avoid sharp corners and notches.

20.4.4 The Effect of Surface Finish

We have already discussed the effect that surface finish can have on the fatigue life of steels in conjunction with tool marks. In a more general sense, the comparison of different surface finishes is shown in Figure 20.9. This shows the results of applying reversing torsional stress to a round shaft, which is the worst possible case.

The steel has a UTS of 1.585 GPa but, as the diagram shows, a rough turned part has a fatigue limit of only about 18% and a polished, hardened steel one of only 22% of its UTS. This demonstrates that when a part will be subjected to extreme cyclic loading a safety factor of 5–6 should be applied in design calculations.

Note that, in general, the hardness is approximately proportional to the tensile strength of a steel at a ratio of 1 °Rockwell C scale to every 34.5 MPa. Hence 30 °Rc = 1.034 GPa and 50 °Rc = 1.723 GPa.

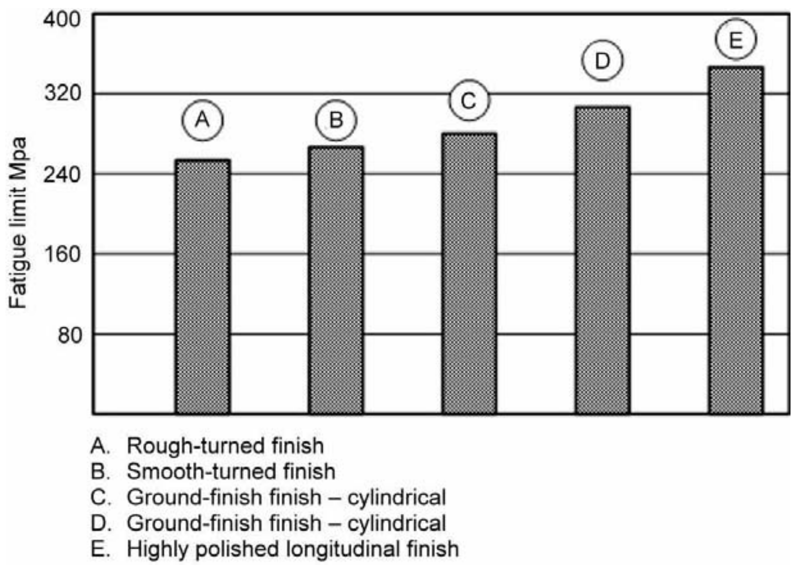


Figure 20.9 Effect of surface finish on fatigue

Figure 20.10 shows the effect of surface finish on the fatigue life of alloy tool steel specimens that have been heat-treated to different hardness levels.

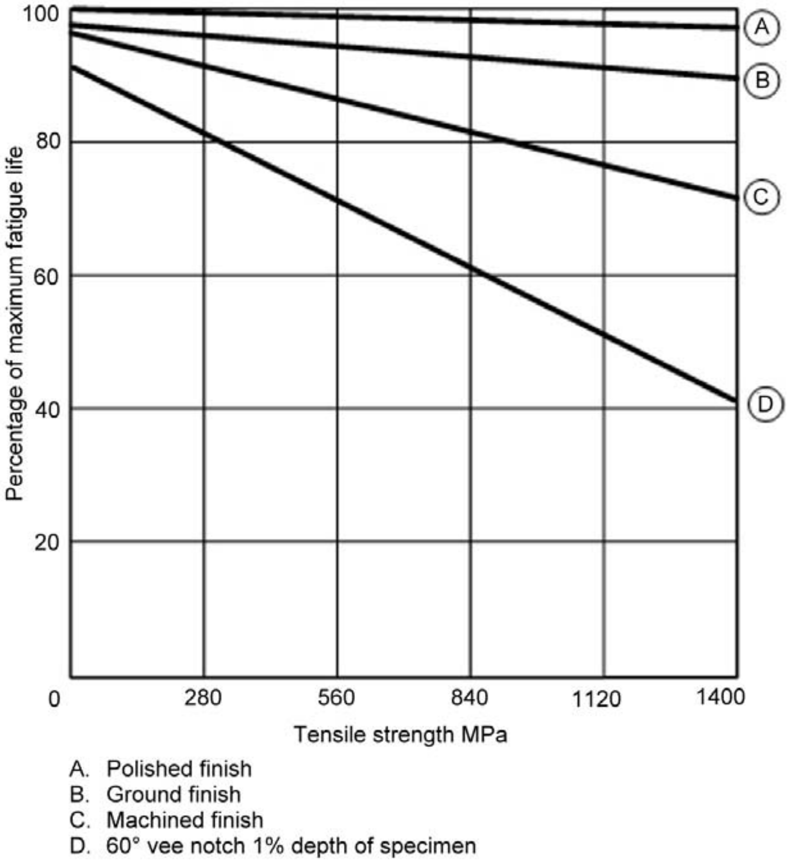


Figure 20.10 Effect of surface finish and hardness on alloy tool steel

20.4.5 Hardness Factors

It is very important to ensure the correct heat treatment processes are used when hardening alloy tool steels. Failure to temper back alloy tool steels after initial quenching will lead to premature fatigue failure and stress cracking. High-carbon–high-chrome alloy tool steels are particularly prone to this.

Premature fatigue failure can also be caused by EDM machining at high rates of material removal. This leaves a brittle surface that is also prone to stress cracking. To combat this, the work should be tempered back to reduce the hardness developed. A better technique is to use EDM on the unhardened steel to remove the majority of the material followed by hardening and tempering and then applying the finishing EDM process at a low material removal rate.

20.5 Summary

Premature fatigue failure and stress cracking can be prevented by:

- Ensuring shut-off areas are correct.
- Avoiding sharp edges and corners.
- Using smooth surface finishes where possible on all critical areas.
- Polishing all cavities, cores and other critical features or components.
- Avoiding high material removal rates when using EDM on hardened steel.

21 Limits and Fits

21.1 Interchangeability

In most engineering applications, situations arise where components are required to fit interchangeably with a variety of other parts. For example, one factory may be producing shafts that are required to be a slide fit in bushes being made by a totally different factory somewhere else, even in a different country. Each of the parts made say, by factory A must achieve the required fit in all of the parts made by factory B and *vice versa*.

The same requirements exist in the manufacture of mould tools and mould tool components. For example, standard parts suppliers like DMS, DME, Hasco, etc. market a number of components such as guide pillars, ejector pins, return pins, sprue bushes and so on. Each of these must be manufactured to sizes that ensure they will fit satisfactorily into other mating components or holes that have been machined into the mould tool by the toolmaker. Equally, the toolmaker has to ensure he makes the mould tool so that when buying these parts, they will have the required fit in the tool.

21.2 Tolerance

In order to do this successfully, both parties have to a work within a ***tolerance***. A tolerance is the difference between the smallest size and the largest size the component may be made to. The ***tolerance zone*** must satisfy two conditions:

- It must be large enough for the part to be able to be made.
- It must guarantee that the desired fit is achieved with its intended mating part.

A component may have a tolerance of, say, 0.05 mm, which means that the maximum difference between the smallest and largest size is 0.05 mm.

There are two standards for specifying tolerances that appear in engineering drawings: ***unilateral*** and ***bilateral***. If we have a shaft with a ***nominal*** diameter of 10 mm and a total tolerance of 0.04 mm, the drawing would show one of the following:

21.2.1 Unilateral

This means that all the tolerance is specified to one side of the nominal size i.e.,

$$10^{+0.004}_{-0} \quad \text{or} \quad 10^{+0}_{-0.04}$$

In the first case the smallest size permitted is 10.00 mm and the largest size 10.04 mm. In the second case the largest size permitted is 10.00 mm and the smallest 9.96 mm.

21.2.2 Bilateral

With this system some of the tolerance is allowed on either size of the nominal, as in the following examples:

$$10^{+0.03}_{-0.01} \quad \text{or} \quad 10^{+0.02}_{-0.02}$$

In the first case the smallest size allowed would be 9.99 mm and the largest size allowed is 10.03. In the second case the smallest size is 9.98 mm and the largest 10.02 mm.

21.3 Limits

The limits are the smallest and largest sizes a component is allowed to be. These limits are known as the ***lower limit*** and the ***upper limit***. Table 21.1 shows examples of this system.

Table 21.1 Tolerances, and lower and upper limits

Dimension	Tolerance	Lower limit	Upper limit
$25.00^{+0.05}_{-0.03}$	0.08	24.97	25.05
$20.00^{+0.01}_{-0.05}$	0.06	19.95	20.01
$18.40^{+0.05}_{-0.03}$	0.08	18.37	18.45
$53.00^{+0.05}_{-0.02}$	0.70	52.98	53.05
$14.75^{+0.03}_{-0.03}$	0.06	14.72	14.78
30	0.60	29.70	30.30

The last size (30) is called an ***open tolerance dimension*** as no tolerance has been given. In this case the tolerance takes the default value stated on the drawing. These default values should always be stated on every drawing. An example is shown in Figure 21.1. In this case, there are zero decimal places after the decimal point; hence, using this example, the tolerance to be used must be ± 0.3

XYZ ENGINEERING LIMITED 256 Lower Angel Road, London							
	Tolerances unless otherwise stated					Drawn	MPS
	0	0.0	0.00	0.000	Angular	Scale	1:1
	+/- 0.3	+/-0.1	+/- 0.05	+/- 0.005	+/- 0.5 Degrees	Date	25.02.07
TITLE	TWO IMP GENERAL ARANGEMENT					Part No	P10785
PART	L & RH BUSH COMPONENTS					Tool No	1764
CLIENT	STX DESIGNS					Machine	N/Bossi
DRAWING No	E1005A					Type	V 80

Figure 21.1 Title block

21.4 Fits

In order to for us to be able to describe the type of fit that is required, they are assigned names that are intended to indicate the class of fit.

21.4.1 Running Fit

This is a smooth, easy (but not loose) fit between mating components. There is a minimum clearance between the parts so that a sliding fit is obtained for linear motion or a bearing fit for rotary motion.

Guide pillars, ejector pins, return pins and side cores or splits require a running fit. Many running fits are required on mould tools, one of the most critical being on ejector pins. Low-viscosity materials like Nylon will flash down very small gaps – as low as 0.013 mm for example.

The tolerances used for achieving satisfactory fit to prevent this can be very small – a total tolerance of 0.02 mm is not unusual.

21.4.2 Push Fit

This type of fit can be assembled with light hand pressure. Mould tools, sprue bushes, cavity inserts, register rings, etc. would be a push fit.

21.4.3 Drive Fit

Drive fits are assembled with a hammer or mallet. They are used where a semipermanent fit is required such as a keyed pulley on a shaft. This is sometimes called a press fit.

Drive fits are occasionally used in mould making, perhaps where watertight fits are required on certain components – on a baffle system, for example.

21.4.4 Force Fit

Force fits require heavy pressure to assemble them. They are designed to give a permanent fit like hubs on shafts and similar applications

Mould tools almost never use force fits as, invariably, the mould tool will need to be disassembled for servicing or repair during its lifetime.

21.5 British Standard Hole and Shaft Fits

In describing a fit – a running fit for example – the tolerance used would depend upon the application. It would be unnecessarily costly to use a precision fit where it really is not needed. Similarly, for precision applications, a large-tolerance running fit might also be unsuitable.

Another difficulty arises when different people are making two (or more) components that have to fit together. Unless they all work to the same nominal and tolerance sizes, the required fit would not be achieved.

In order to overcome these problems the ***British Standard Hole and Shaft Specification*** was introduced. This system ensures that if holes and shafts are specified according to the standard, all interchangeable fits for different components will be satisfactory. The shortened version of this covers three classes of fit: ***clearance, transition and interference.*** These three fits include all the fits mentioned previously, as follows.

21.5.1 Clearance Fit

This covers all fits that do not ***interfere*** with each other. In other words it includes all fits from wide-tolerance clearance fit up to low-tolerance precision running fits. The shaft is ***always*** smaller than the hole in to which it fits.

21.5.2 Transition Fit

A transition fit covers the range Minimum Clearance to Light Drive Fits. In this category **the lower limit of the shaft is less than the upper limit of the hole and the upper limit of the shaft is greater than the lower limit of the hole.**

21.5.3 Interference Fit

This fit covers everything in the range Light Drive Fits to Force Fits. With this category **the lower limit of the shaft is always greater than the lower limit of the hole.** Thus all clearance and running fits are excluded.

21.6 British Standard Clearance Fits

Figure 21.2 shows a shortened version of BS4500 covering a range of clearance fits that cover most design and toolroom requirements. The table is very easy to use after a little explanation as follows.

On the left-hand side of the table, the nominal sizes are listed in size ranges that cover diameters from less than 3 mm up to 500 mm.

At the top of the table there is a visual descriptive indication of the type of fit. This is shown by a horizontal line above which are shown the tolerance zones for the holes and below which are shown the tolerance zones for the shafts.

The pictograms for the holes all rest on the horizontal line and those for the shafts are all below the horizontal line to varying degrees. This indicates these are ***hole based tolerances*** because only the shafts are varying away from the line. In this system, the lower limit of all holes is the nominal size of the hole.

The first pictogram shows that the shaft is always a lower size than the hole because the shaft pictogram is well below the horizontal line. As we travel to the right across the table, the upper limit of the shaft gets nearer and nearer the horizontal line. **This gives a visual indication that the clearance between the hole and shaft is getting smaller.** This means we can choose, simply by looking at the pictograms, the type of fit we require quite quickly.

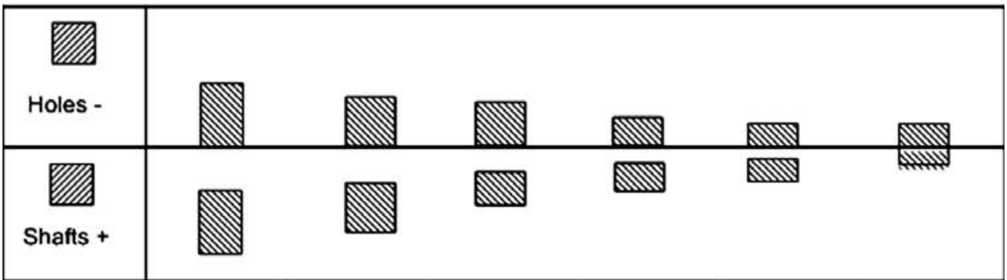
For holes and shafts a prefix letter is used. For holes it is always a capital letter followed by a number. For shafts, a lower-case letter is used followed by a number. The letter designations run from **A** to **Z** for holes and **a** to **z** for shafts.

The full set of tables is very comprehensive and covers both ***primary*** and ***secondary fits***. Figure 21.2 shows the **H** category holes only together with a range of suitable shafts. All the tolerances in the tables are given in μm.

It can also be seen from the tables that the difference between the upper limit of the shaft and the lower limit of the hole gets less and less as we move to the right across the table. At the same time, the tolerances for both hole and shaft get smaller and smaller.

Note also that as this happens the shaft designations ascend the alphabet and the numbers get smaller: e.g., c11, d10, e9, f8, g6 and h5.

21.7 British Standard Clearance Fits – Hole Basis



Nom Size		Tolerance		Tolerance		Tolerance		Tolerance		Tolerance		Tolerance	
Over	to	H11	c11	H9	d10	H9	e9	H8	f7	H7	g6	H7	h6
0	3	+60 0	-60 -120	+25 0	-20 -60	+25 0	-14 -39	+14 0	-6 -16	+10 0	-2 -8	+10 0	-6 0
3	6	+75 0	-70 -145	+30 0	-30 -78	+30 0	-20 -50	+18 0	-10 -22	+12 0	-4 -12	+12 0	-8 0
6	10	+90 0	-80 -170	+36 0-40	-40 -98	+36 0	-25 -61	+22 0	-13 -28	+15 0	-4 -12	+15 0	-9 0
10	18	+110 0	-95 -205	+43 0	-50 -120	+43 0	-32 -75	+27 0	-16 -34	+18 0	-6 -17	+18 0	-11 0
18	30	+130 0	-110 -240	+52 0	-65 -149	+52 0	-40 -92	+33 0	-20 -41	+21 0	-7 -20	+21 0	-13 0
30	40	+160 0	-120 -280	+62 0	-80 -180	+62 0	-50 -112	+39 0	-25 -50	+25 0	-9 -25	+25 0	-16 0
40	50	+160 0	-130 -290										
50	65	+190 0	-140 -320	+74 0	-100 -220	+74 0	-60 -134	+46 0	-30 -6	+30 0	-10 -29	+30 0	-19 0
65	80	+190 0	-150 -340										
80	100	+220 0	-170 -390	+87 0	-120 -260	+87 0	-72 -159	+54 0	-36 -71	+35 0	-12 -34	+35 0	-22 0
100	120	+220 0	-180 -400										
120	140	+250 0	-200 -450	+100 0	-145 -305	+100 0	-84 -185	+63 0	-43 -83	+40 0	-14 -39	+40 0	-25 0
140	160	+250 0	-210 -260										
160	180	+250 0	-230 -480										
180	200	+290 0	-240 -530	+115 0	-170 -335	+115 0	-100 -215	+72 0	-50 -96	+46 0	-15 -44	+46 0	-29 0
200	225	+290 0	-260 -550										
225	250	+290 0	-280 -570										
250	280	+320 0	-300 -620	+130 0	-190 -400	+130 0	-110 -20	+81 0	-56 -108	+52 0	-17 -49	+52 0	-32 0
280	315	+320 0	-330 -650										
315	355	+360 0	-360 -720	+140 0	-210 -440	+140 0	-125 -265	+89 0	-62 -119	+57 0	-18 -54	+57 0	-36 0
355	400	+360 0	-400 -760										
400	450	+400 0	-440 -840	+155 0	-230 -480	+155 0	-135 -290	+97 0	-68 -131	+63 0	-20 -60	+63 0	-40 0
450	500	+400 0	-480 -880										

Figure 21.2 Data sheet 4500A. Selected ISO fits – hole basis (Sheet No.1)

The table in Figure 21.2 is an extract from BS 4500:1969 and its use is best explained by an example. This table is suitable for nearly all tolerancing and classes of fit in mould design and toolmaking.

21.7.1 Example

An ejector is required to eject a moulded component on a circular boss (Figure 21.3). The nominal diameter of the ejector pin is 24 mm. In this example we will analyse the fit required for this component to be a sliding fit in a bush in the mould tool based on a H7/g6 fit.

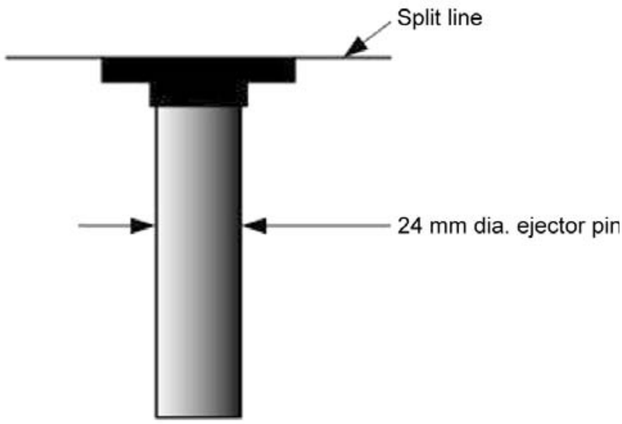


Figure 21.3 Ejector Pin sample

In the table (Figure 21.2), this diameter lies in the range 18–30 mm in the clearance fit table. The g6 shaft designation shows a tolerance range of –0.007 to –0.020 mm: a tolerance of 0.013 mm.

Hence the ejector will have an upper limit of 23.993 mm and a lower limit of 23.980 mm. The corresponding H7 hole in the bush has a tolerance range of 0 to +0.021 mm: a tolerance of 0.021 mm. Therefore, the lower limit of the hole is 24.000 mm and the upper limit 24.021 mm.

This shows that the **minimum clearance is 0.007 mm** and the **maximum clearance is 0.041 mm.** Therefore, a running fit (or slide fit) is guaranteed.

BS Hole and Shaft designations are specified on all engineering drawings and catalogues of engineering components requiring specific interchangeable fits.

The full sets of BS specifications can be obtained through most technical booksellers, but most people use the abridged versions shown here. This abridged form is included in the 'Zeus Precision Data Book' available from most engineering tool suppliers.

Note: For most normal mould designs and construction the H7/g6 combination is adequate.

21.8 Geometric Tolerancing

There are many occasions when relationships between different features of a component need to be defined where these have an important function.

Where this is the case, the relevant tolerance needs to be specified on the drawing at the design stage. There is a comprehensive list of geometrical tolerances defined by British standards, but a shortened list is shown here that covers most eventualities in mould design. These are listed below and shown (with some others) in Figure 21.4.

- Straightness
- Flatness
- Roundness
- Cylindricity
- Profile of a line
- Surface profile
- Position
- Concentricity

(a) Tolerances of form. These do not need to be referenced to a datum.

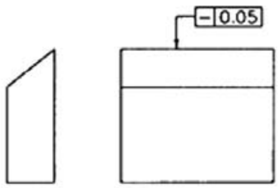
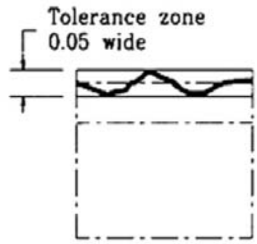
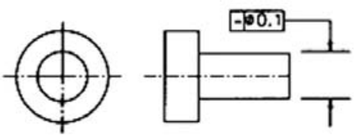
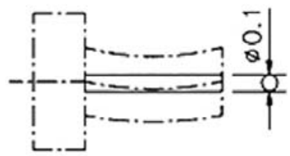
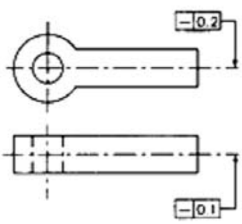
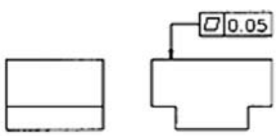
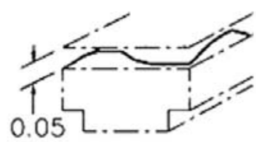
Characteristic	*Example*	*Interpretation*
Straightness Controls the straightness of a line on a surface, an edge, or the axis of a feature. The tolerance zone may be the area between two parallel straight lines or a pair of cylinders.		The edge must lie between two parallel straight lines 0.05 apart in the plane of the drawing. 
		The axis of the dimensioned cylinder must lie within a tolerance zone formed by a cylinder of diameter 0.1. 
		The axis of the whole component must lie within a parallelepiped 0.2 wide in the horizontal plane and 0.1 wide in the vertical plane.
Flatness Controls the deviation of a surface from the true plane, its tolerance zone being the space between two parallel planes. If required, notes such as NOT CONCAVE can be added.		The surface must lie between two parallel planes 0.05 apart. 

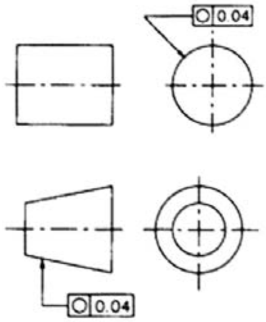
Figure 21.4a Tolerances of form

Characteristic	*Example*	*Interpretation*

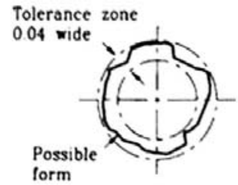
Roundness

Controls the errors in form of a circle in the plane in which it lies. It may refer to a section of a solid of revolution (sphere, cylinder etc.) the tolerance controlling the roundness of the cross-section.

Roundness is not concerned with the position of the circle.

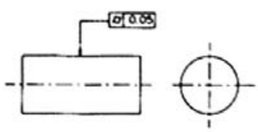


In both of these examples the toleranced feature is any cross section at right angles to the axis of the designated surface. The tolerance zone is the space between two concentric circles 0.04 apart.

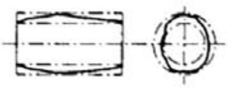


Cylindricity

Combines roundness, straightness and parallelism, and is applied to the surface of a cylinder. To avoid problems with inspection it is often preferable to tolerance roundness, straightness and parallelism separately.

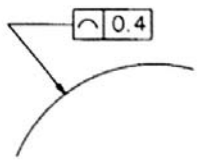


The curved surface of the cylinder must lie between the surfaces of two concentric cylinders 0.05 apart.



Profile of a line

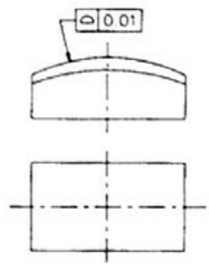
A profile tolerance controls the degree of variation from the theoretical or perfect form of a line.



The tolerance zone is normally equally disposed about the true contour and defined as the area between two lines that encompass circles (with centres on the true contours) and of diameters equal to the tolerance.

Surface profile

This controls the degree of variation from the theoretically perfect form of the surface.



The tolerance zone is defined in the same manner as for the line profile, but using spheres and surfaces rather than circles and lines.

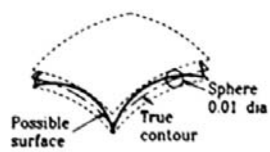


Figure 21.4b Roundness tolerances

(b) Tolerances of orientation. These need to be referenced to a datum.

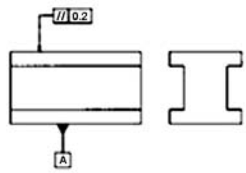
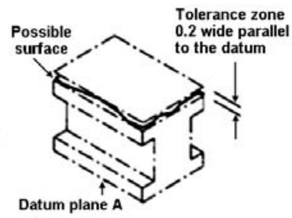
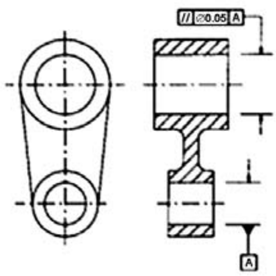
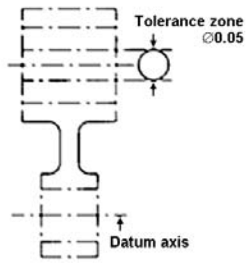
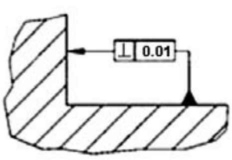
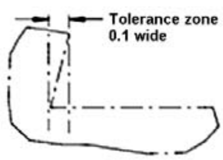
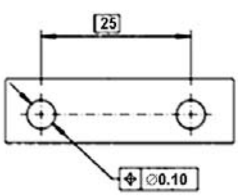
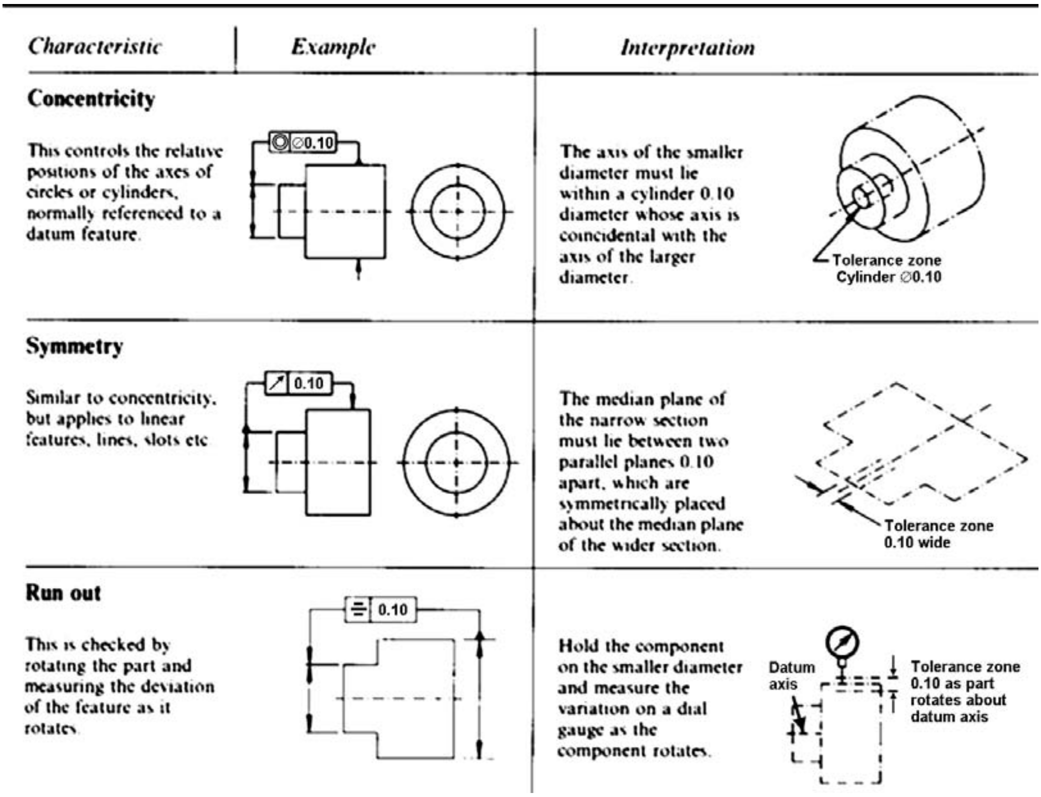
Characteristic	*Example*	*Interpretation*
Parallelism This controls the parallelism of a feature (line, surface or axis) relative to a datum which can also be a line, a surface or an axis.		The tolerance zone is the area between two parallel planes which are parallel to the datum plane and equally disposed about the true surface. The tolerance value is the distance between the two planes. 
		The upper axis must lie within a cylindrical tolerance zone 0.05 diameter, with its axis parallel to the datum axis. 
Squareness This controls the squareness of a line or a surface relative to a datum which can be a line, a plane or the axis of a hole.		The feature must lie between two parallel lines 0.1 apart, each of the planes being perfectly square to the datum. 
Position This controls the amount the actual position of a feature can deviate from its true position.		The centre of each hole must lie within a circle of diameter 0.1 centred about its true position given by the boxed dimension.

Figure 21.4c Tolerances of orientation



Characteristic	*Example*	*Interpretation*
Concentricity This controls the relative positions of the axes of circles or cylinders, normally referenced to a datum feature.		The axis of the smaller diameter must lie within a cylinder 0.10 diameter whose axis is coincidental with the axis of the larger diameter.
Symmetry Similar to concentricity, but applies to linear features, lines, slots etc		The median plane of the narrow section must lie between two parallel planes 0.10 apart, which are symmetrically placed about the median plane of the wider section.
Run out This is checked by rotating the part and measuring the deviation of the feature as it rotates.		Hold the component on the smaller diameter and measure the variation on a dial gauge as the component rotates.

Figure 21.4d Tolerances of concentricity, Symmetry and run out

22 Impression Blanking

22.1 Reasons for Impression Blanking

Very rarely do large multi-impression injection mould tools run consistently on all impressions. This can happen for a variety of reasons:

- Incorrect mould tool design
- Poor standard of toolmaking
- Unsuitable machine
- Unbalanced runner systems and incorrect gates
- Too many impressions to control and fill properly
- Damage to the cavity or cores
- Changing the material from that originally specified

Of course there may be a variety of other reasons, but it is quite common to see a mould tool not moulding on all cavities in many mould shops. This is particularly true of large multi-impression tools operating on fairly short cycle times. Unfortunately, as discussed in Chapter 6, the greater the number of impressions, the less control there is over them. With large numbers of impressions, there will be differences in conditions on each of them.

This creates a narrow ***operating window*** for moulding, which means a small range of moulding conditions over which satisfactory moulding can be achieved. Therefore, the narrower the operating window for moulding, the greater the chance of moulding rejects.

Everyone is aware that running tools under these conditions is undesirable and uneconomic, but very rarely is the loss of profit quantified. Unfortunately, the true effect often comes as a surprise when the figures become known later.

As in other industries, production is customer-driven and losing impressions on a mould tool places an extra strain on production. As the tool is now producing fewer parts per hour, it makes it almost essential to continue moulding on it to maintain a sufficient supply of parts.

To avoid losing too much money, it is desirable to have some means of quickly computing the actual cost and profit so that action may be taken if desired. To develop this procedure we will consider an example based on an 8-impression tool. This example reflects an actual case history of a job in production in a trade moulding shop and illustrates just how uneconomic it can be to lose impressions (in this case through damage) and how difficult it can be to recover the situation.

22.2 Example

22.2.1 Original Estimate

Part:	Flanged housing
Number of impressions:	8
Part weight:	15 g
Runner and sprue weight:	20 g
Material:	Polypropylene
Material cost:	£2000 per tonne
Machine lock:	80 tonnes
MHR:	£60
Cycle:	20 s

22.2.1.1 Analysis

Shot weight = (8 × 15) + 20 = 140 g

Material required to make 1000 parts = $\frac{140}{8} \times 1000$ = 17,500 g

Cost of material for 1000 parts = $\frac{17500 \times 2000}{1000000}$ = £35.00 £35.00

Time taken to produce 1000 parts = $\frac{20 \times 1000}{8}$ = 2,500 s

MHR cost to produce 1000 parts = $\frac{2500 \times 60}{3600}$ = £41.67 £41.67

Total cost = Material cost + MHR cost £76.67

Profit to be added @15% = $\frac{15 \times 76.67}{100}$ = £11.50 £11.50

Selling Price £88.17 per 1000

After three weeks' production the actual cycle time was very close to that in the original estimate. The tool, however, subsequently suffered damage on two impressions that were ***blanked off*** to keep production going on the remaining six impressions.

22.2.2 Effect of Running on Six Impressions

22.2.2.1 Analysis

New shot weight = (6 × 15) + 20 = 110 g

Material required to make 1000 parts = $\frac{110 \times 1000}{6}$ = 18,333 g

Cost of material for 1000 parts = $\frac{18333 \times 2000}{1000000}$ = £36.67 £36.67

Time taken to produce 1000 parts = $\frac{20 \times 1000}{6}$ = 3333 s

MHR cost per 1000 parts = $\frac{3333 \times 60}{3600}$ = £55.55 £55.55

Total cost = Material cost + MHR cost £92.22 per 1000

The original cost for the job on an 8-imp basis = £76.67 but the cost to run the mould on a 6-imp basis = £92.22.

The simple comparison of selling price and the cost price tells its own story: in this case £88.17 – £92.22 = **a hefty loss of £4.05 per 1000!** Although at the time the actual loss had not been quantified, it was, of course, realised that at least the job was not as profitable as it should be.

In an attempt to reduce the cost of production, progressively fine adjustments were made to the moulding parameters and mould cooling to reduce the cycle time. As a result of this a 2-second reduction in the cycle was achieved (with some difficulty).

22.2.3 Effect of Running on a 6-imp Basis with an 18-second Cycle

22.2.3.1 Analysis

As before, the cost of material per 1000 parts = £36.67 £36.67

Time taken to make 1000 parts = $\frac{18 \times 1000}{6}$ = 3000 s

MHR cost to produce 1000 parts = $\frac{3000 \times 60}{3600}$ = £50.00 £50.00

Total cost = Material cost + MHR cost £86.67

Profit = Selling price – Cost price = £88.17 – £86.67 = £1.50 per 1000

This represents a very small return indeed, but at least it avoids a loss. Nevertheless, a better return than this could be achieved by directly investing the money elsewhere instead!

Where the problem of running on a reduced number of impressions occurs, an immediate effort should be made to quantify the reduced profit level (or loss).

It is also a salutary experience to calculate the cycle that is required to achieve the original profit level. This calculation is normally sufficient to convince even the most optimistic that it not worth while spending time and effort in pursuit of this goal.

22.2.4 Cycle Required to Achieve Original Profit Level

Let

$$A = \text{Material cost/1000} = \frac{\text{Shot weight} \times \text{Material cost/tonne}}{\text{No. imps} \times 1000}$$

$$B = \text{Machine cost/1000} = \frac{\text{Cycle time (s)} \times \text{MHR} \times 1000}{3600 \times \text{No. imps}} = \frac{C \times \text{MHR}}{3.6 \times N}$$

Let P = Total original cost (MHR + Material cost), then:

$$B = P - A$$

Hence:

$$\frac{\text{C} \times \text{MHR}}{3.6 \times N} = P - A$$

Transposing this expression in terms of C, we get:

$$C = \frac{(P - A) \times (3.6 \times N)}{\text{MHR}}$$

Substituting the appropriate values from section 22.2.2.1 into this expression we get:

$$A = £36.67, N = 6$$

Hence

$$C = \frac{(76.67 - 36.67) \times (3.6 \times 6)}{60}$$

$$= \frac{40 \times 21.6}{60} = 14.4 \text{ s}$$

While it may be possible to reduce the cycle by a small amount, it should not be possible to reduce it by this extent. If it were, the original cycle would have been severely inaccurate.

It is also useful to be able to calculate quickly, and perhaps more realistically, the cycle required to break even. It may still not be possible to achieve this, but it does give a 'bench mark' to determine quickly whether the job is losing money.

22.2.5 Cycle Required to Break Even

From the above analysis we require: Selling price (SP) = $A + B$. Hence:

$$B = \text{SP} - A$$

That is:

$$\frac{C \times \text{MHR}}{3.6 \times N} = \text{SP} - A$$

Transposing this expression in terms of C:

$$C = \frac{(\text{SP} - A) \times (3.6 \times N)}{\text{MHR}}$$

Substituting the appropriate values from section 22.2.1.1:

$$C = (88.17 - 36.67) \times (3.6 \times 6)$$

$$= \frac{51.6 \times 21.6}{60}$$

$$= 18.4 \text{ s}$$

22.3 Observations

Many tools that are run on a reduced impression level have out-of-balance runner layouts, which give rise to further problems and can actually increase the cycle time and the rejection level.

Blanking off tools can also promote additional damage to the tool.

It can take a great period of time to recover the original profit position. In many cases this is never recovered.

Many companies have no idea of the ***true*** cost of running on a reduced number of impressions until it is too late to take any effective action.

22.4 Summary

Blanking off impressions by definition loses money. How much money depends on the number of impressions on the tool, the material and certain other factors. As the number of impressions on the tool decreases, the amount of money lost increases.

It is normally impossible to reduce the cycle to a level that preserves the original profit.

It is advisable to calculate the cycle to produce break even; this gives a concrete indication of whether a profit or loss is being made.

22.5 Methods of Blanking Impressions

Despite the previous analysis, there are frequently occasions when mould tool impressions will have to be temporarily blanked off. Moulders use several methods to do this as follows.

- Glueing a moulding into the offending cavities!
- Blocking the gate with a small piece of brass wire.
- Rotating the cavity so that the gate no longer lines up with the runner.
- Removing the tool and having it temporarily modified in the toolroom.
- Blanking the branch runner.

22.5.1 Glueing

Definitely not recommended! It is really a measure of desperation used by moulders that are very late on delivery to customers. It rarely works for long if at all and consequently more time is lost than gained.

Unfortunately, this practice is dangerous as well as inefficient, as when the glue fails the constant opening and closing on the resulting damaged moulding can damage the impression.

22.5.2 Gate Blocking

This method is also frequently unsatisfactory, often leading to the runner hanging up on the blanked off impressions. This in turn leads to the runner becoming trapped, with the possibility of damage occurring to the tool. However, brass wire can be quite useful for passing through sub gates.

Another problem resulting from this method of blanking is that the moulding cycle is often erratic, which further affects the cycle consistency and may give rise to quality problems.

22.5.3 Cavity Rotation

This entails rotating the cavity so that the gate no longer aligns with the runner (Figure 22.1). It is usually a good compromise but almost the full runner system is still moulded.

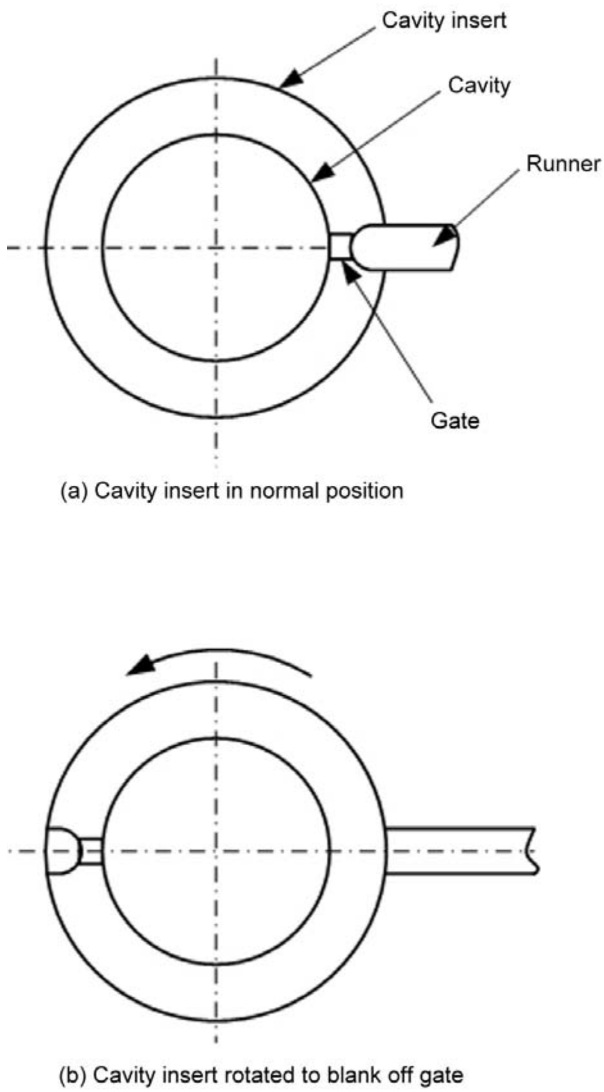


Figure 22.1 Blanking cavity inserts

This is the best overall method of getting the mould back into production and is often used. The disadvantage is that the tool usually has to be removed from the machine to do this but it is usually more cost-effective than any other method.

22.5.4 Blanking the Branch Runner

This is method is sometimes used to enable the tool to run while avoiding moulding the runner branch associated with the defective cavity. Although this notionally saves producing a redundant piece of runner, it can be fiddly to incorporate in the mould and can cause the runner to 'hang up' and not eject properly

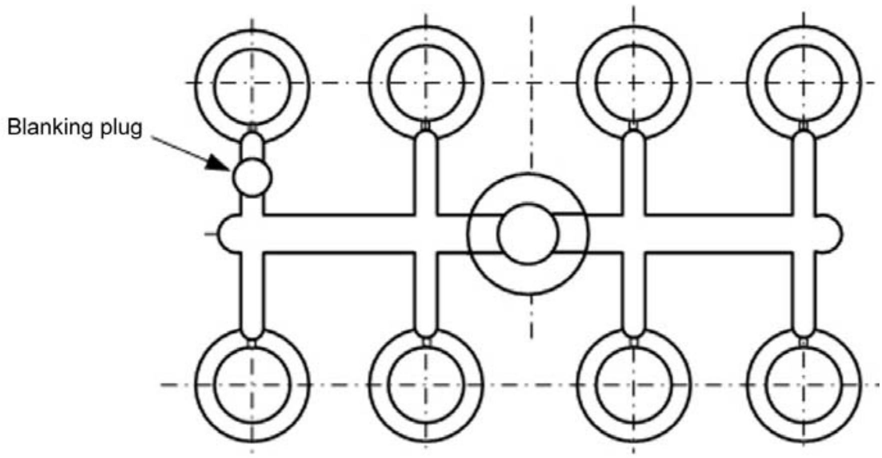


Figure 22.2 Runner blanking

22.6 Summary

Many tools that are run on a reduced impression level have out-of-balance runner layouts, which give rise to further problems and can actually increase the cycle time and the rejection level.

The runner adjacent to the blanked off cavity can be difficult to eject.

Blanking off tools can also promote additional damage to the tool.

It can take a great period of time to recover the original profit position. In many cases this is never recovered.

Many companies have no idea of the *true* cost of running on a reduced number of impressions until it is too late to take any effective action.

Blanking off impressions by definition loses money. How much money depends on the number of impressions on the tool, the material and certain other factors. As the number of impressions on the tool decreases, the amount of money lost increases.

It is normally impossible to reduce the cycle to a level that preserves the original profit.

It is advisable to calculate the cycle to produce break even, as this gives a concrete indication of whether a profit or loss is being made. This at least allows a conscious decision of the ramifications to be made before the event.

The mould often runs erratically with an unbalanced runner, which can make clean ejection difficult.

The unbalanced flow can also affect the part quality in highly technical, closely toleranced parts.

As soon as possible the mould should be repaired to enable the original profit margin to be regained and quality to be restored.

23 Summary of Mould Calculations

The purpose of this summary is to bring together in one section, all the formulae in the book for convenience.

23.1 Production Rates

$$\text{Production rate/h} = \frac{3600}{\text{Cycle (s)}} \times \text{Number of impressions}$$

When a new mould tool is being considered, however, the expression is rearranged to estimate the number of impressions necessary to achieve a desired production rate:

$$\text{Number of impressions} = \frac{\text{Production rate/h} \times \text{Cycle (s)}}{3600}$$

23.2 Cooling Channel Diameters

Q = Mass × (Enthalpy at melt temperature – Enthalpy at ejection temperature)

$= M \times (H_m - H_e)$

where:

M = the shot mass in kg

H_m = enthalpy at the material melt temperature in kJ/kg

H_e = enthalpy at the moulding ejection temperature in kJ/kg

The cooling capacity required is then this value divided by the cycle. i.e.,

$$\text{Cooling capacity } Q' = \frac{M \times (H_m - H_e)}{C}$$

where Q' = the cooling capacity in kJ/s.

For maximum cooling efficiency there should be a difference of 5°C between the cooling inlet and outlet temperatures.

The specific heat of water is 4.19. Therefore, it takes 4.19 kJ of energy to increase the temperature of 1 kg of water by 1 °C. Hence to raise it by 5 °C we would need 5 × 4.19 = 20.95 kJ.

The volumetric flow of water required to remove the heat in the mould is given by

$$V_f = \frac{Q}{20.95} \text{ kg/s}$$

$$= \frac{Q}{20.95} \text{ litres/s (since 1 litre of water weighs 1 kg)}$$

We also need a linear flow rate of 2.5 m/s to promote turbulent flow, hence the volumetric flow can also be expressed as V_f = 2.5 × cross-sectional area of channel. If the channel is circular we can write this as:

$$2.5 \times \frac{\pi d^2}{4} = \frac{Q}{20.95} \quad \text{(Note that } d \text{ is in metres here)}$$

Transposing for d gives:

$$d = \sqrt{\frac{76.37 \times Q}{\pi}} \text{ mm}$$

23.3 Runner Length Formulae

There are three equations that may be used which give a sufficiently accurate result for most moulding conditions:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi r^3}$$

$$\tau = \eta\dot{\gamma}$$

$$P = \frac{2\tau L}{r}$$

where:

$\dot{\gamma}$ = shear rate (s^{-1})

$\dot{Q}$ = flow rate (m^3/s)

r = runner radius (m)

η = viscosity of material at melt temperature (Pa-s)

P = pressure drop (MPa)

τ = shear stress (MPa)

L = runner length (m)

23.4 Gate Design

$$d = NC\sqrt[4]{A} \quad \text{(where } d = \text{gate diameter)}$$

where: A = total surface area of product (not the projected area) in mm², and N and C are empirical factors

23.5 Ejection Forces

The following formula may be used for calculating the ejection force:

$$F_p = \frac{EA\mu\alpha\Delta_t}{\frac{d}{2t} - \frac{d}{4t}m}$$

This is the way the formula is usually written in scientific texts but a slightly easier form for computational purpose is:

$$F_p = \frac{EA\mu\alpha\Delta_t}{\frac{d}{2t}\left(1 - \frac{m}{2}\right)}$$

where:

F_p = the ejection resistance force (N)

E = Young's modulus of the polymer (N/cm²)

A = total surface area of moulding in contact with cavity or core, in line of draw (cm²)

μ = coefficient of friction, polymer on steel

m = Poisson's ratio

d = the diameter of a circle whose circumference is equal to the total projected perimeter of the moulding (cm)

α = the coefficient of linear expansion of the polymer (cm/°C)

Δ_t = (polymer softening temperature) – (mould tool temperature) (°C)

t = average wall thickness of part (cm)

23.6 Stress and Strain

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

$$\text{Strain} = \frac{\text{Change in length}}{\text{Original length}}$$

$$\text{Young's modulus} = \frac{\text{Stress}}{\text{Strain}}$$

23.7 Factors of Safety

23.7.1 For Brittle Materials

$$\text{Factor of safety} = \frac{\text{Tensile strength}}{\text{Maximum working stress}}$$

23.7.2 For Ductile Materials

$$\text{Factor of safety} = \frac{\text{Yield stress}}{\text{Maximum working stress}}$$

23.8 Poisson's Ratio

$$\text{Poisson's ratio} = -\frac{\text{Transverse strain}}{\text{Longitudinal strain}}$$

23.9 Moments of Inertia

23.9.1 Rectangular Bar

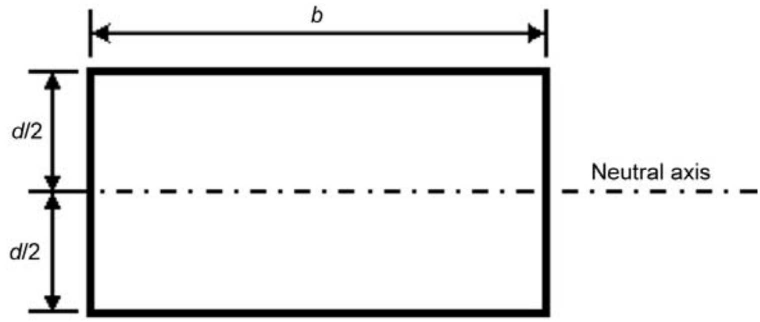


Figure 23.1 Section through rectangular bar

$$\text{Second moment of area} = \frac{bd^3}{12}$$

23.9.2 Circular Bar

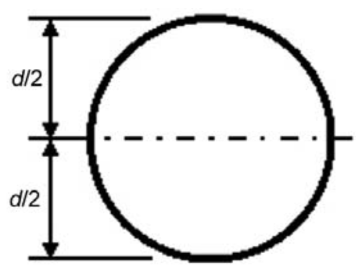


Figure 23.2 Section through circular bar

$$\text{Second moment of area} = \frac{\pi d^4}{64}$$

23.10 Temperature Stresses

Change in length = $L\alpha t$, where L = length and α = coefficient of linear expansion.

$$\text{Strain} = \frac{\text{Change in length}}{\text{Original length}}$$

$$= \frac{L\alpha t}{L} = \alpha t$$

The stress associated with temperature change = Strain × E. Hence,

$$\text{Stress} = E\alpha t$$

23.11 Bending Formulae

The general bending formula:

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

where:

M = bending moment (N-m)

I = second moment of area (m^4)

σ = bending stress (Pa)

y = distance from neutral axis at which fibres are subjected to stress σ (m)

E = modulus of elasticity (Pa)

R = radius of curvature (m)

23.11.1 Section Modulus

In a beam under load the maximum stress σ_m occurs where the distance from the neutral axis is a maximum σ_y.

From the bending formula we can then establish:

$$M = \frac{I \times \sigma_m}{y_m}$$

The quantity I/y_m is purely geometric, being dependent only on the shape of the cross-sectional area. This quantity is known as the ***section modulus Z***. The units are m^3. Hence

$$M = Z\sigma_m$$

For a rectangular bar, $Z = \frac{bd^2}{6}$

And for a circular bar, $Z = \frac{\pi d^3}{32}$

23.12 Deflection of Beams

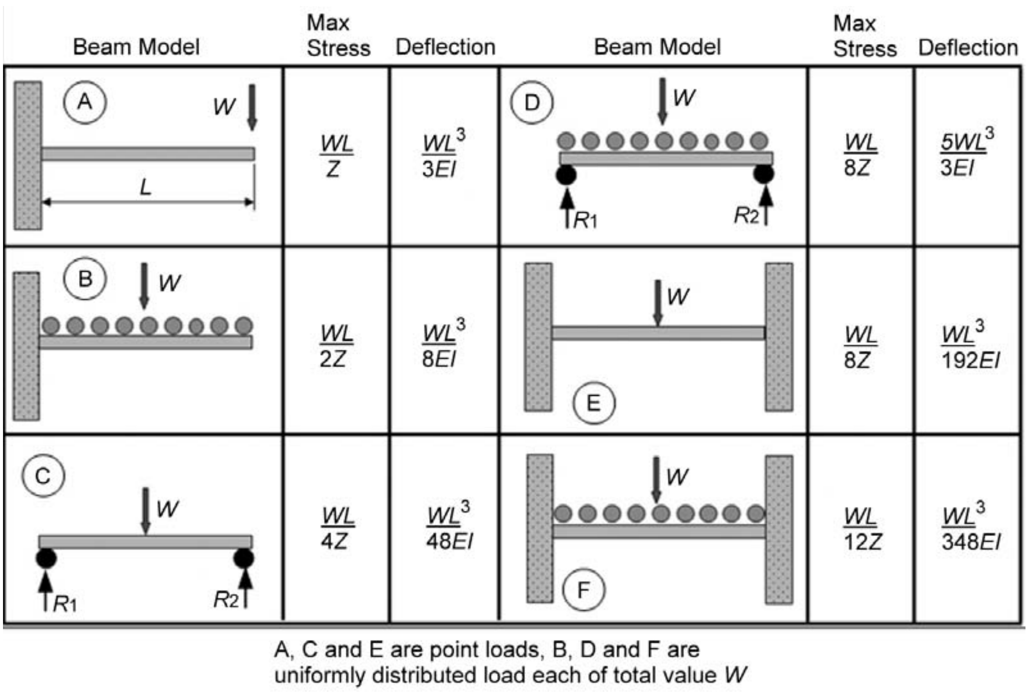


Figure 23.3 Beam models

23.13 Blanking Impressions

Cycle Required to Achieve Original Profit Level

Let:

$$A = \text{Material cost/1000} = \frac{\text{Shot weight} \times \text{Material cost/tonne}}{\text{No. imps} \times 1000}$$

$$B = \text{Machine cost/1000} = \frac{\text{Cycle time (s)} \times \text{MHR} \times 1000}{3600 \times \text{No. imps}} = \frac{C \times \text{MHR}}{3.6 \times N}$$

Let P = Total original cost (MHR + Material cost), then

$$B = P - A$$

Hence:

$$\frac{C \times \text{MHR}}{3.6 \times N} = P - A$$

Transposing this expression in terms of C, we get:

$$C = \frac{(P - A) \times (3.6 \times N)}{\text{MHR}}$$

where: C = the cycle in seconds and N = number of impressions.

24 Integrated Design Examples

The purpose of this section is to bring together many of the individual design features described in previous sections to view them as interactive, integrated whole designs.

A number of different designs are included in this section to provide a "reference base" of design ideas for future designs that should prove useful. All these designs are taken from actual working mould tools and are not simply theoretical models.

However, the designer should always check thoroughly that any design feature shown will solve the particular design requirements of any new design before incorporating them into their design.

Before using a design solution please ensure:

- That you completely understand the example design.
- That you give yourself enough time to actually understand what is going on in the design.
- That you carefully consider how an existing design can be modified and incorporated into you own design.
- That you run through the complete sequence of operation of your new design before releasing it for construction.
- That complete design features are not simply copied and incorporated in to the new designs without seeing if the new integrated design could be simplified first.

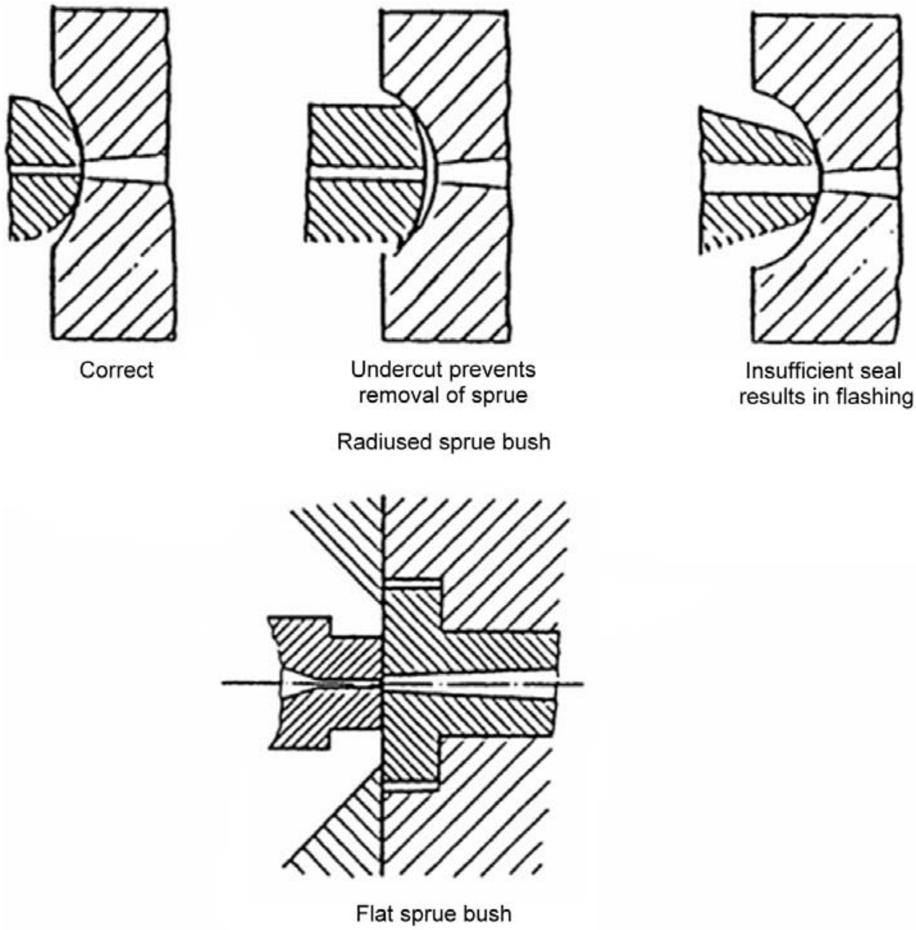


Figure 24.1 Location of machine nozzle on sprue bush

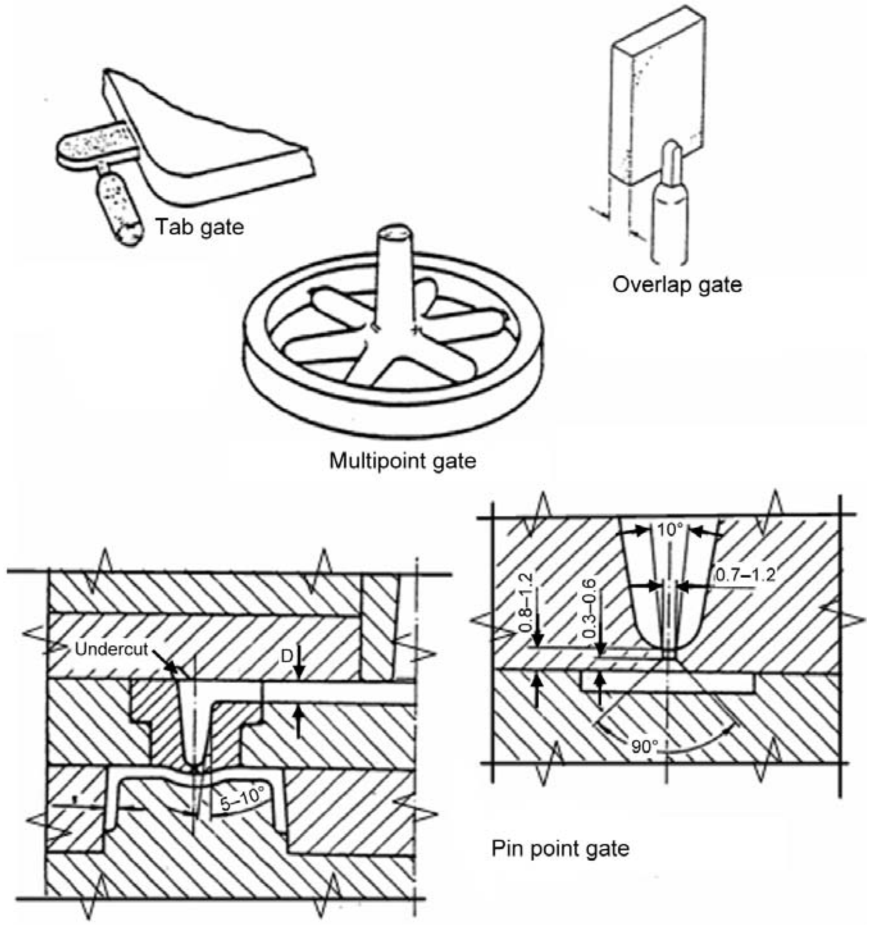


Figure 24.2 Common gate designs

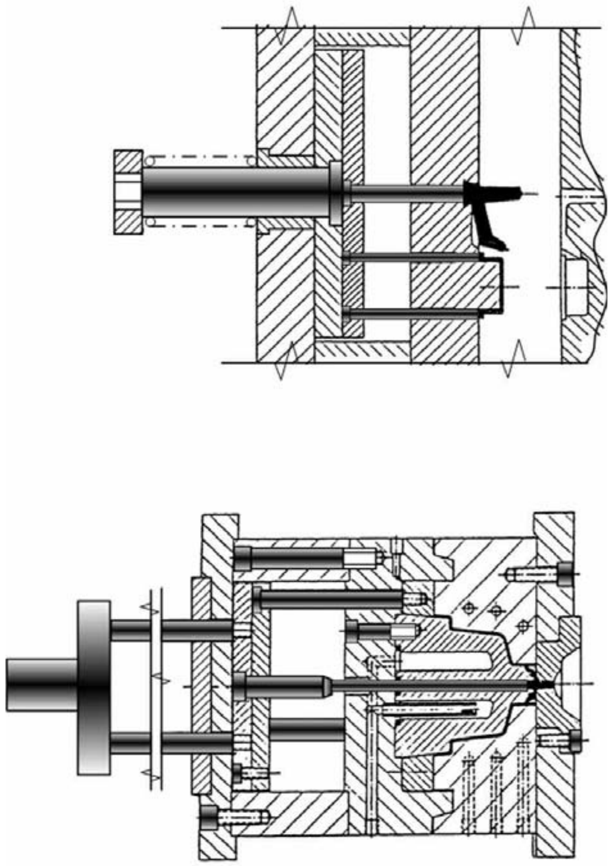


Figure 24.3 Examples of sub gates

A Anti chamber nozzle
B Nozzle heater band
C Split line A
D Date
E Cavity plate A
F End piece
G Spring loaded stop bolt
H Common cavity plate
J Cavity plate B
K Sprue bush
L Chains
M Back plate
N Chain block
O Ejector plate A
P Ejector pins A
Q Stop bolt
R Ejector plate B
S Ejector pins B
T Sprue ejector pins
U Return pins
V Spring
W Split line B
Y Mouldings
Z Runners

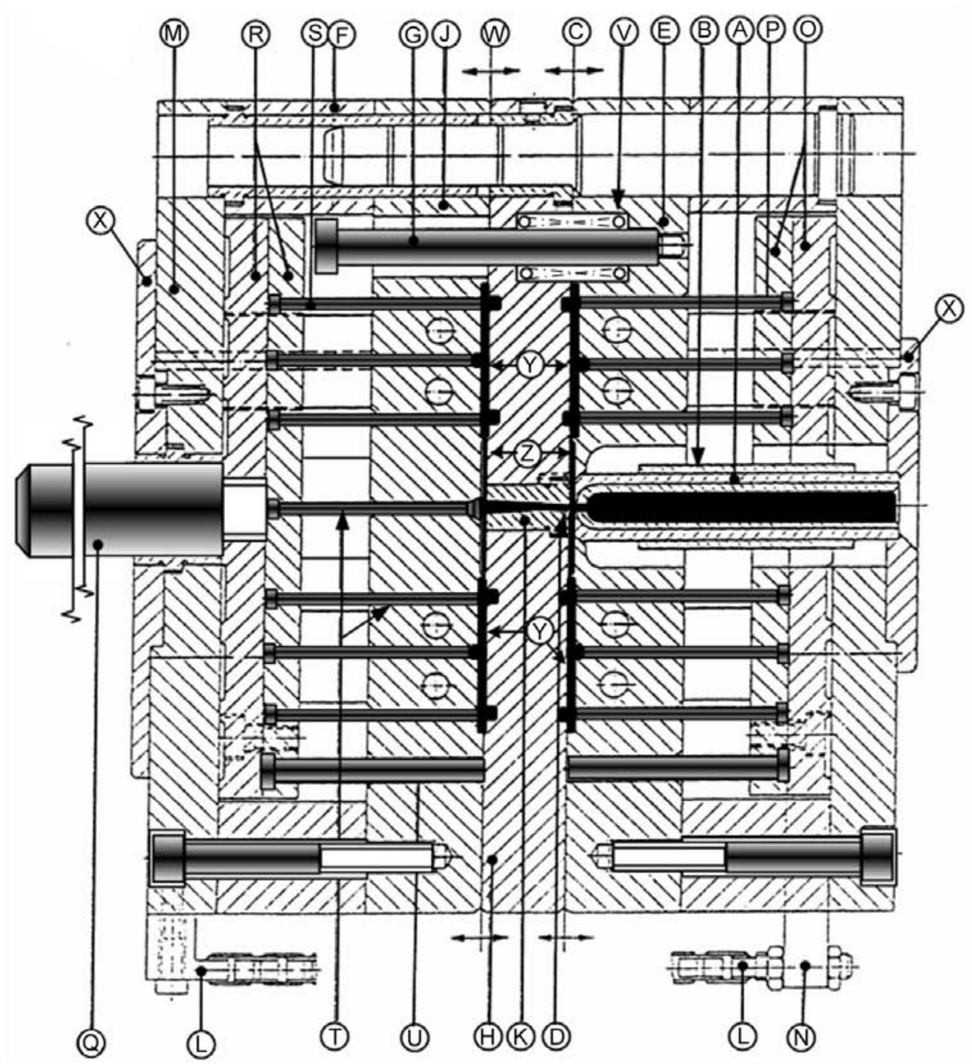


Figure 24.4 Stack tool with front-half ejection operated by chains

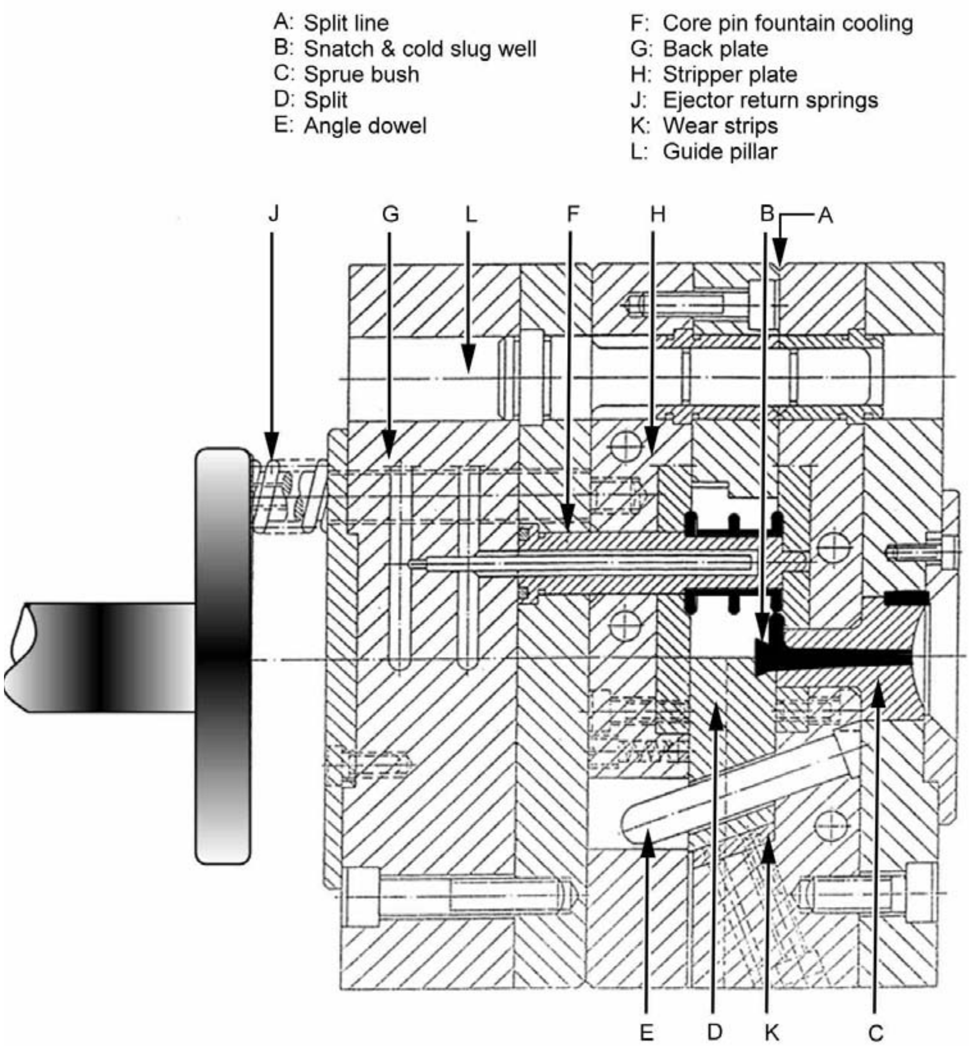


Figure 24.5 Two-impression split tool for dual coil former

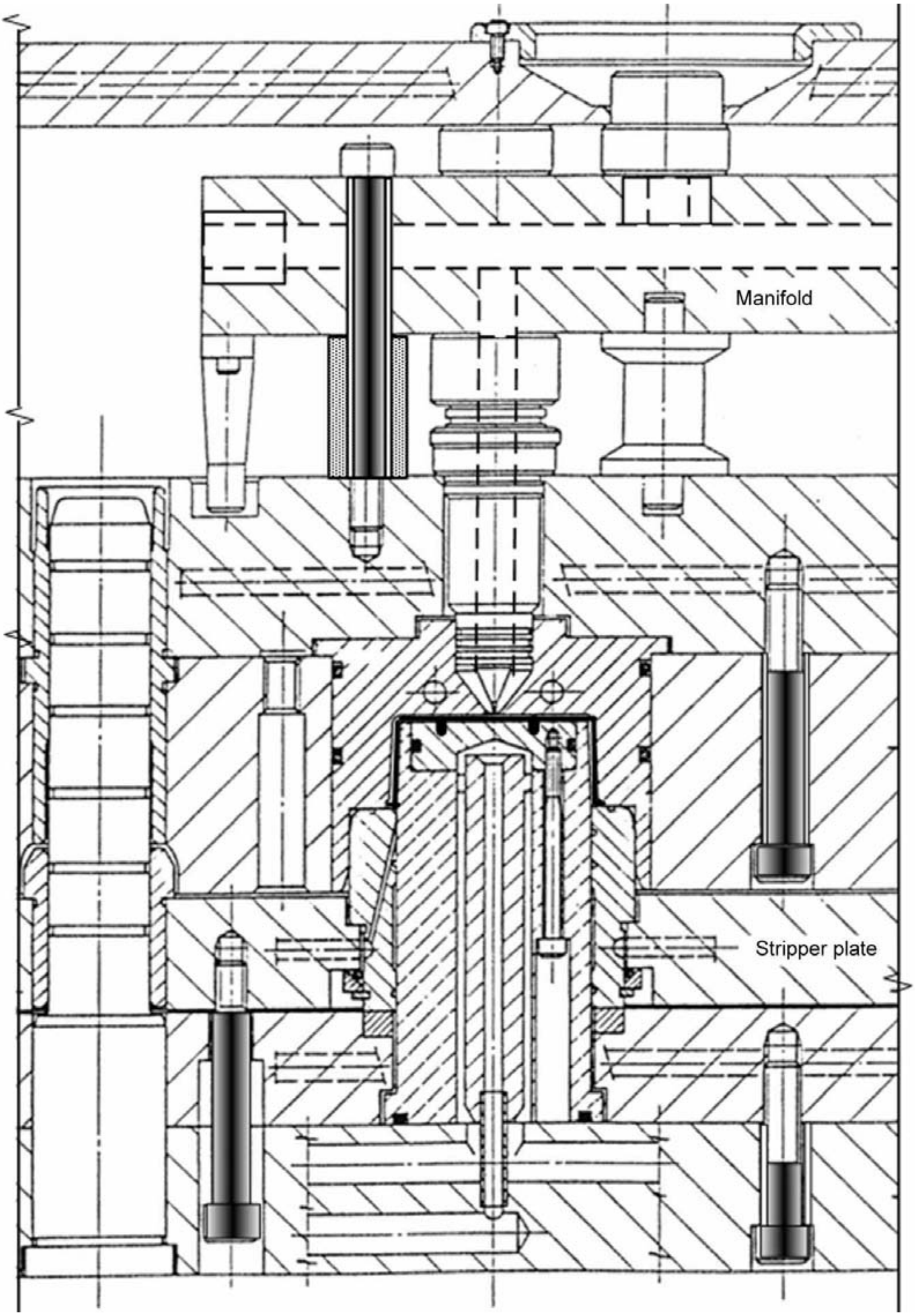


Figure 24.6 Two-impression hot runner mould

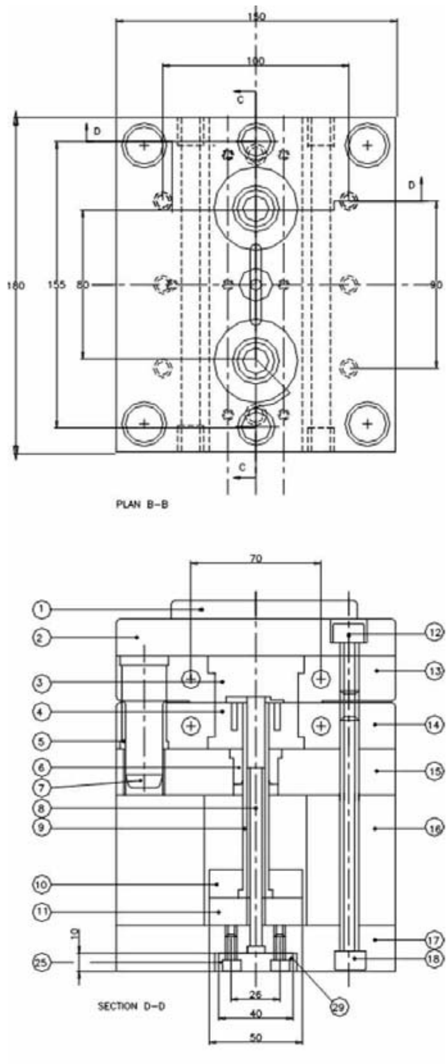
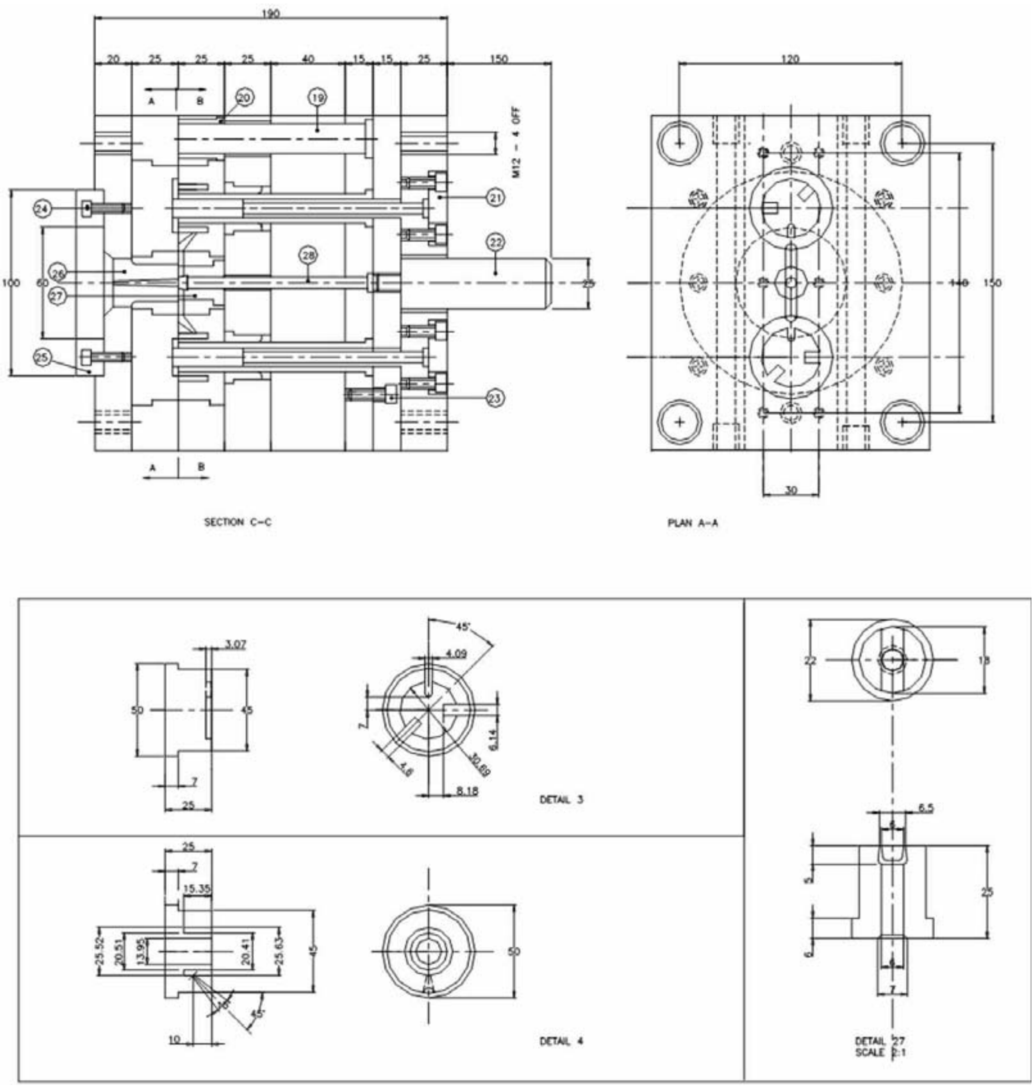


Figure 24.7 Two-impression family mould


M12 – 4 OFF
SECTION C–C
PLAN A–A
DETAIL 3
DETAIL 4
DETAIL 27
SCALE 2:1

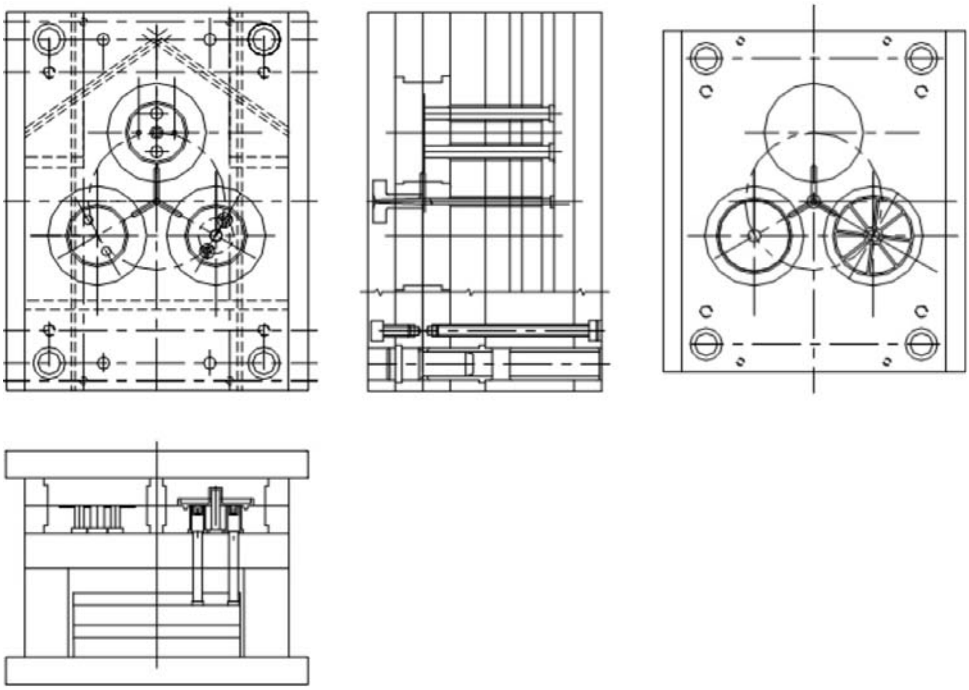


Figure 24.8 Two-impression coil platform

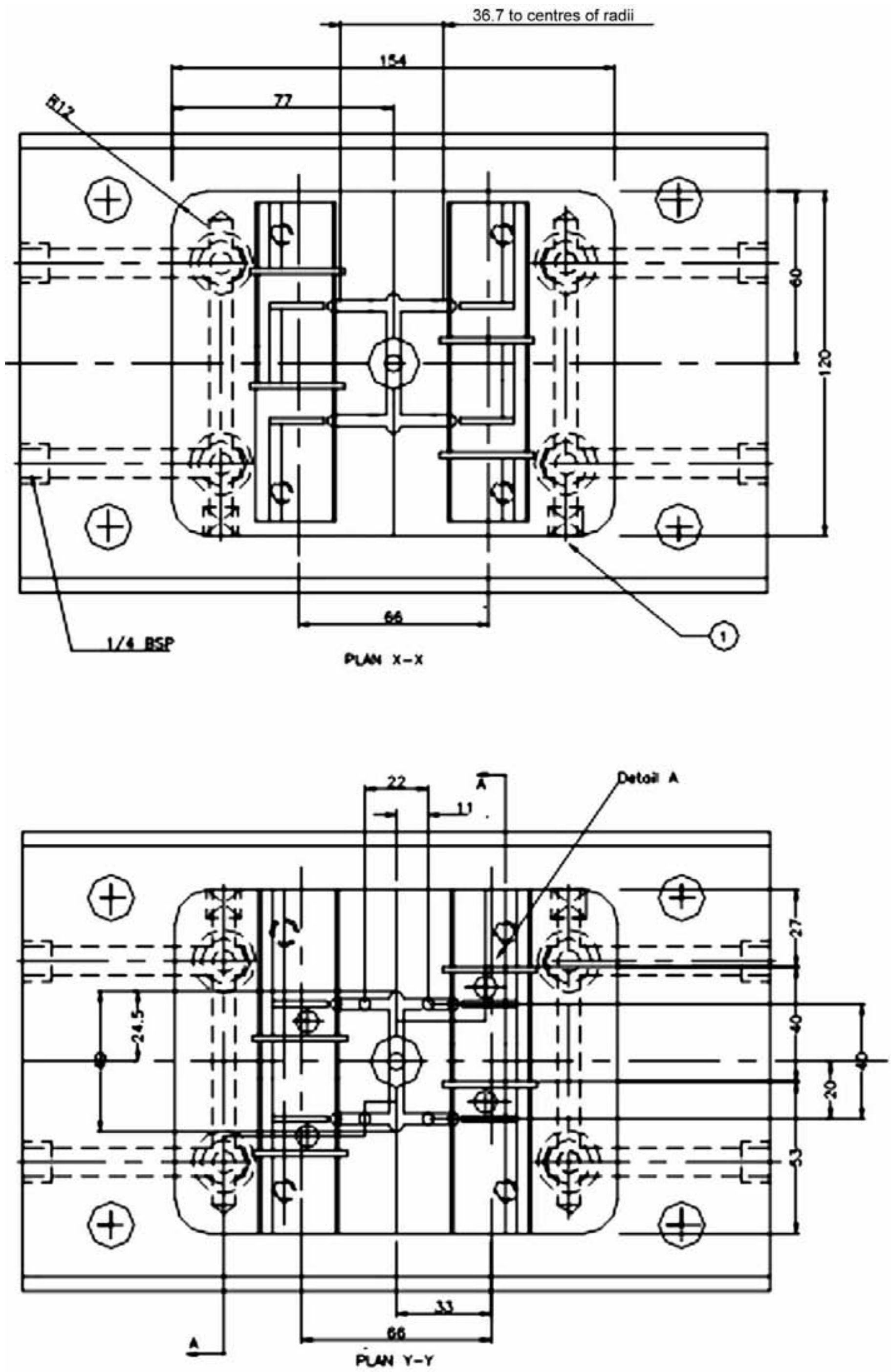
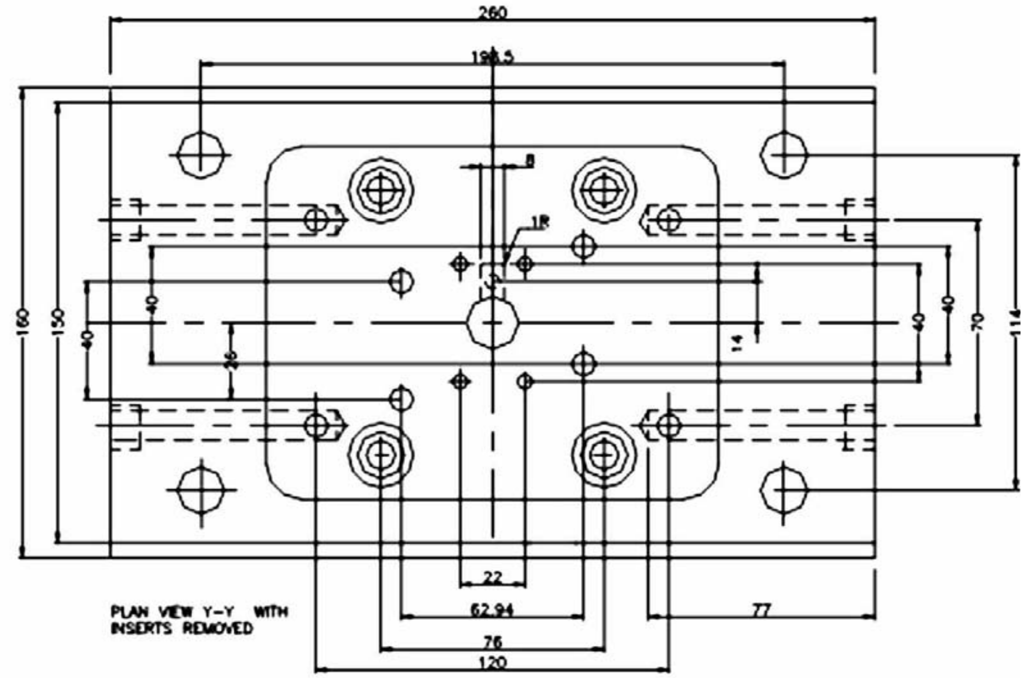
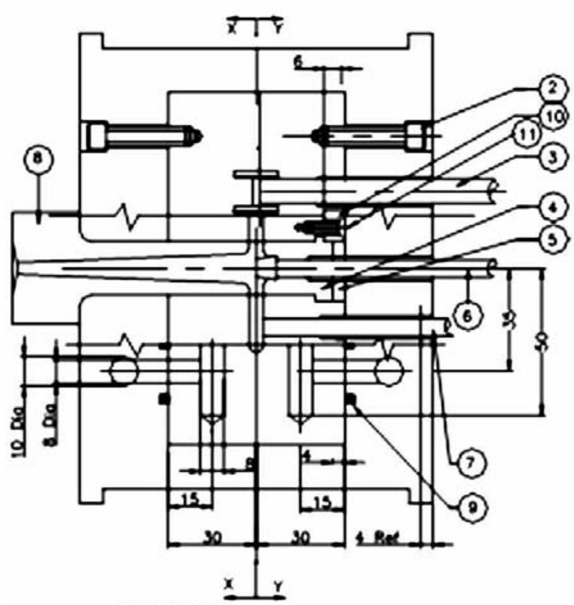


Figure 24.9 Two-impression spacer mould



PLAN VIEW Y-Y WITH INSERTS REMOVED



SECTION A-A

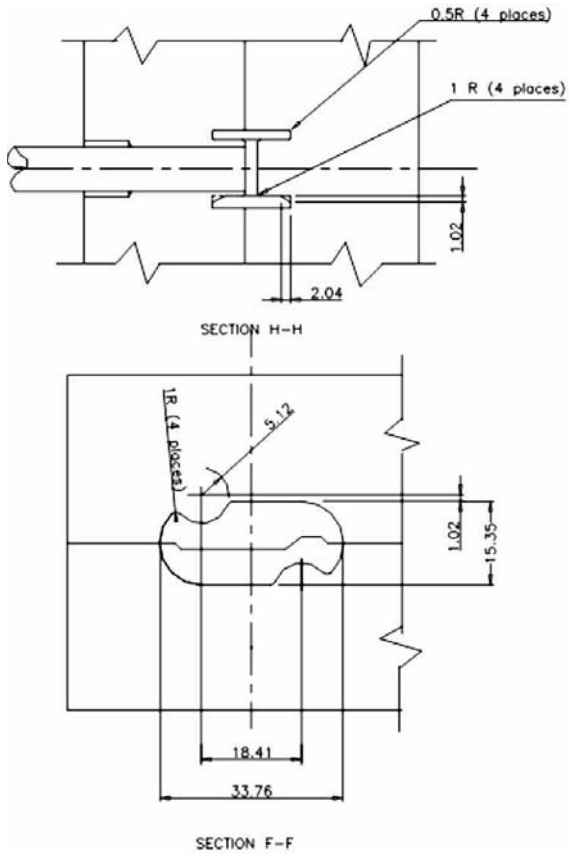
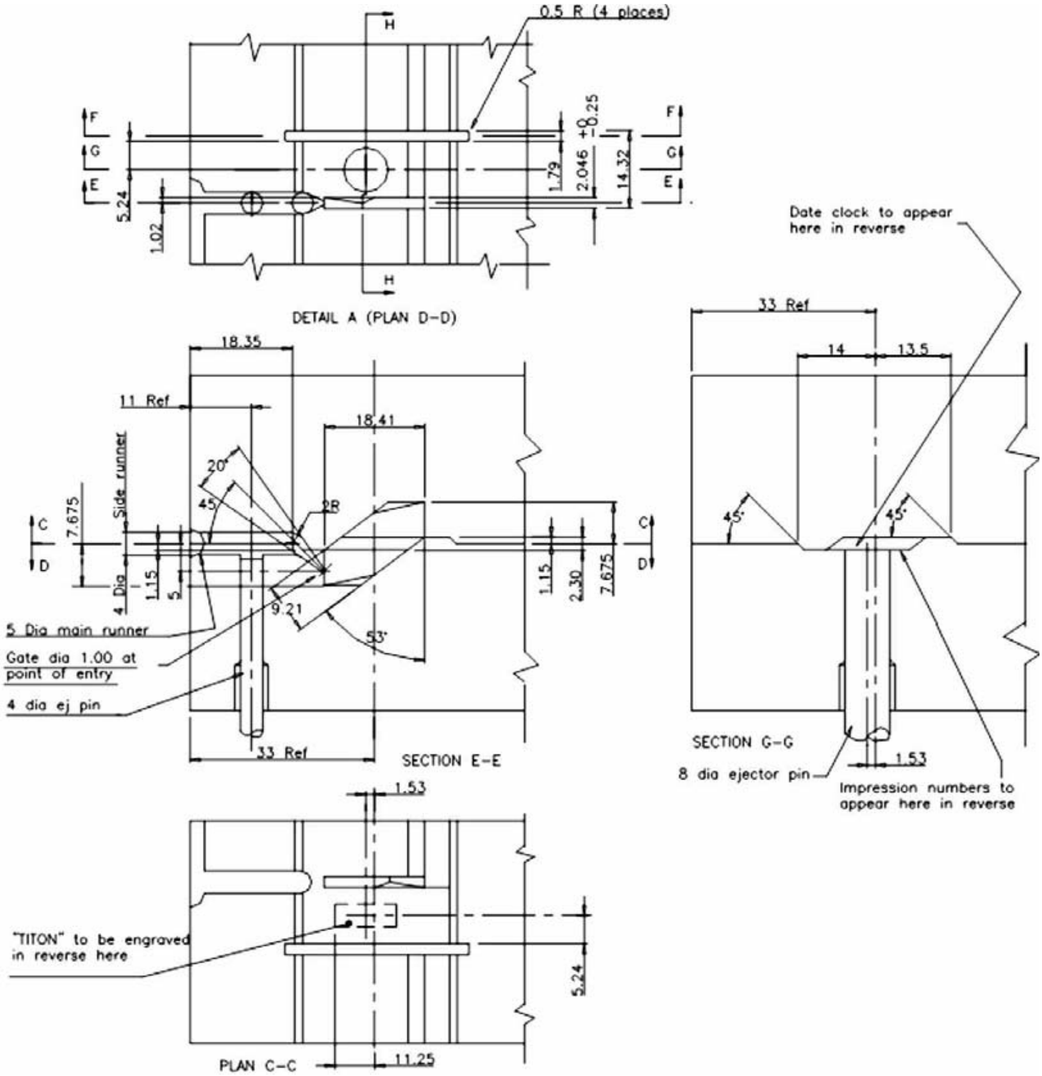


Figure 24.10 Two-impression spacer mould details



0.5 R (4 places)
H
F
G
E
1.79
2.046
14.32
5.24
1.02
DETAIL A (PLAN D-D)
18.35
11 Ref
18.41
20°
45
2R
Side runner
7.675
C
D
4 Dia
1.15
5
9.21
53°
1.15
2.30
7.675
5 Dia main runner
Gate dia 1.00 at point of entry
4 dia ej pin
33 Ref
SECTION E-E
1.53
"TITON" to be engraved in reverse here
5.24
PLAN C-C
11.25
Date clock to appear here in reverse
33 Ref
14
13.5
45°
45°
SECTION G-G
8 dia ejector pin
1.53
Impression numbers to appear here in reverse

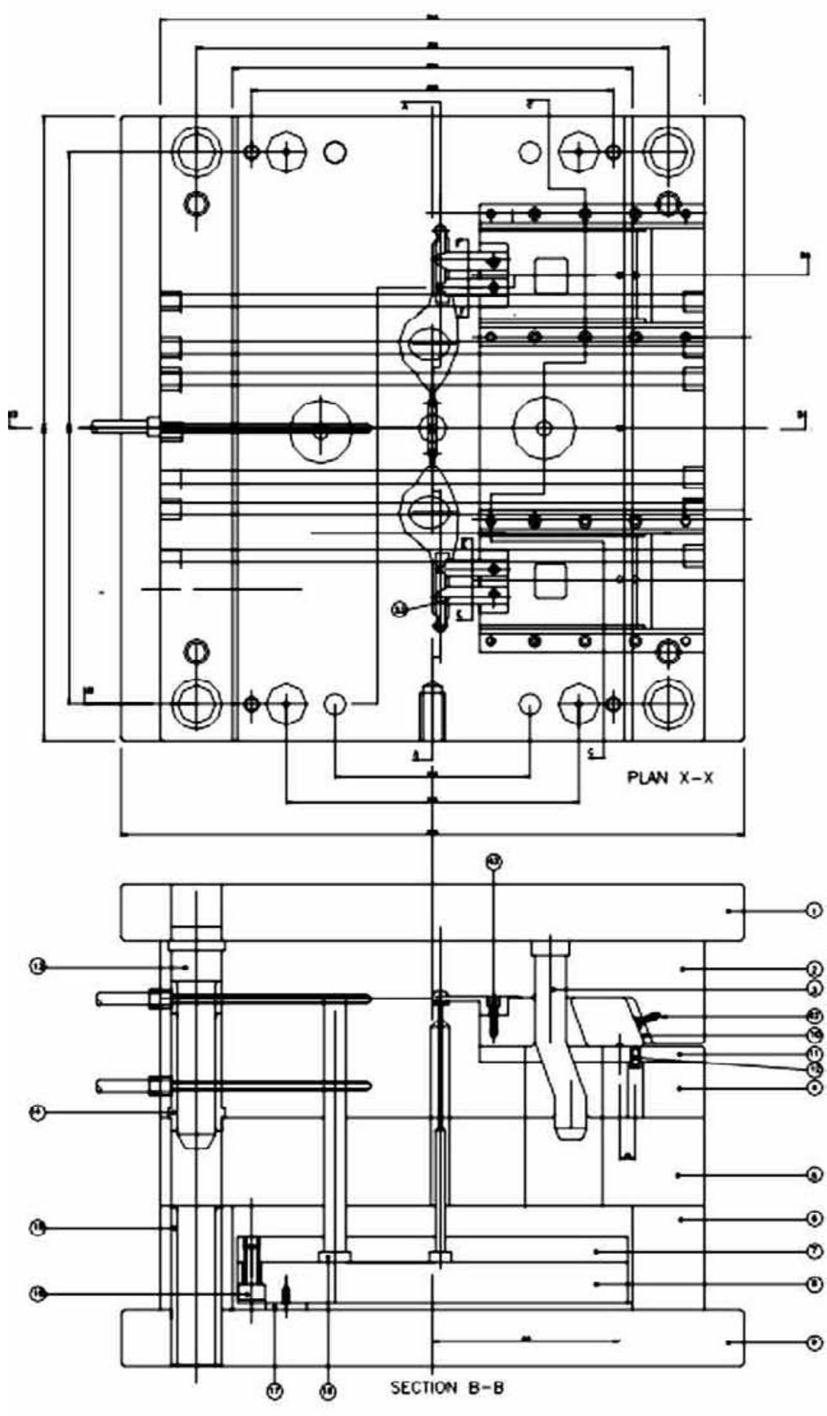
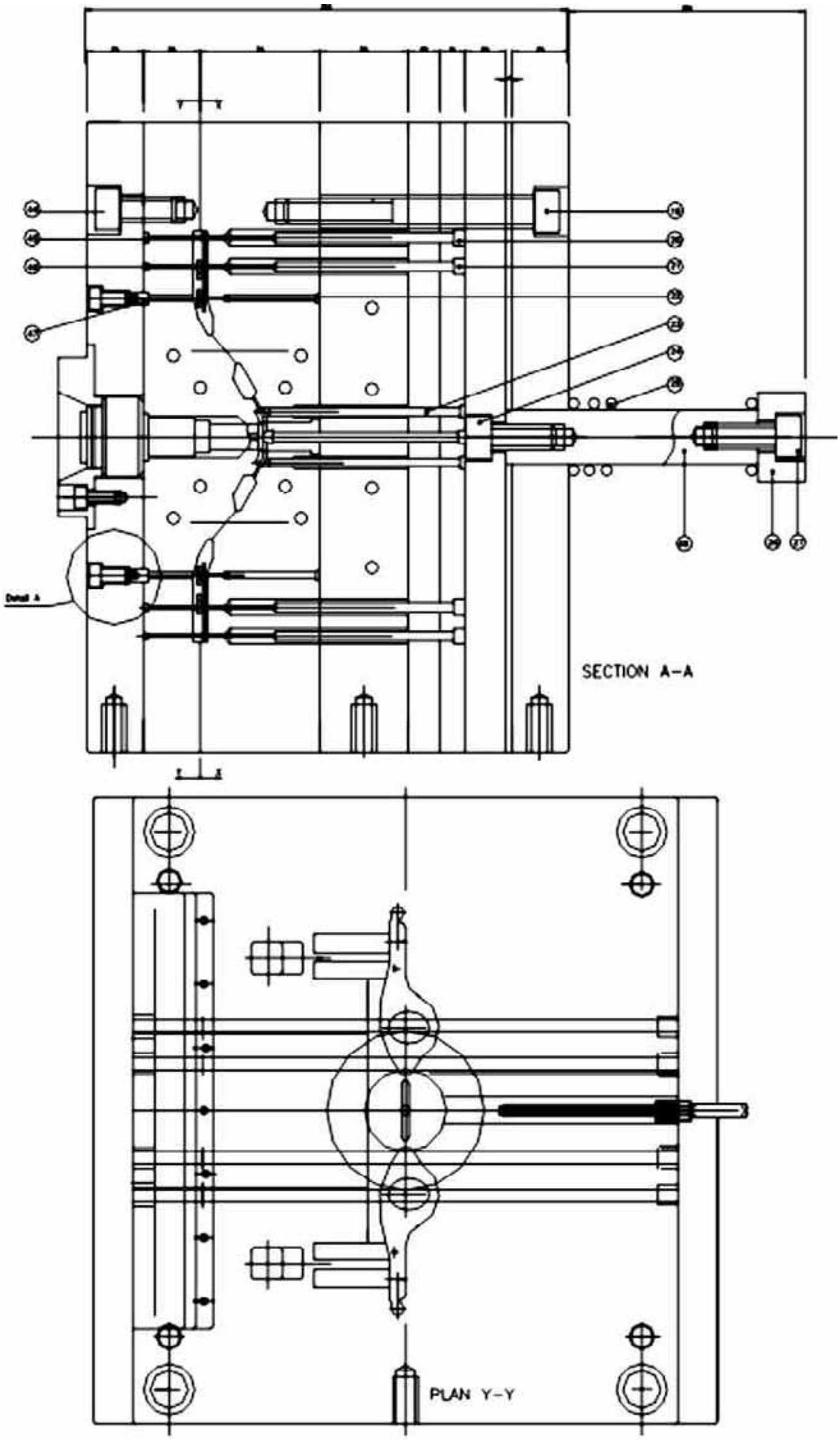


Figure 24.11 Two-impression forceps mould


Detail A
SECTION A-A
PLAN Y-Y

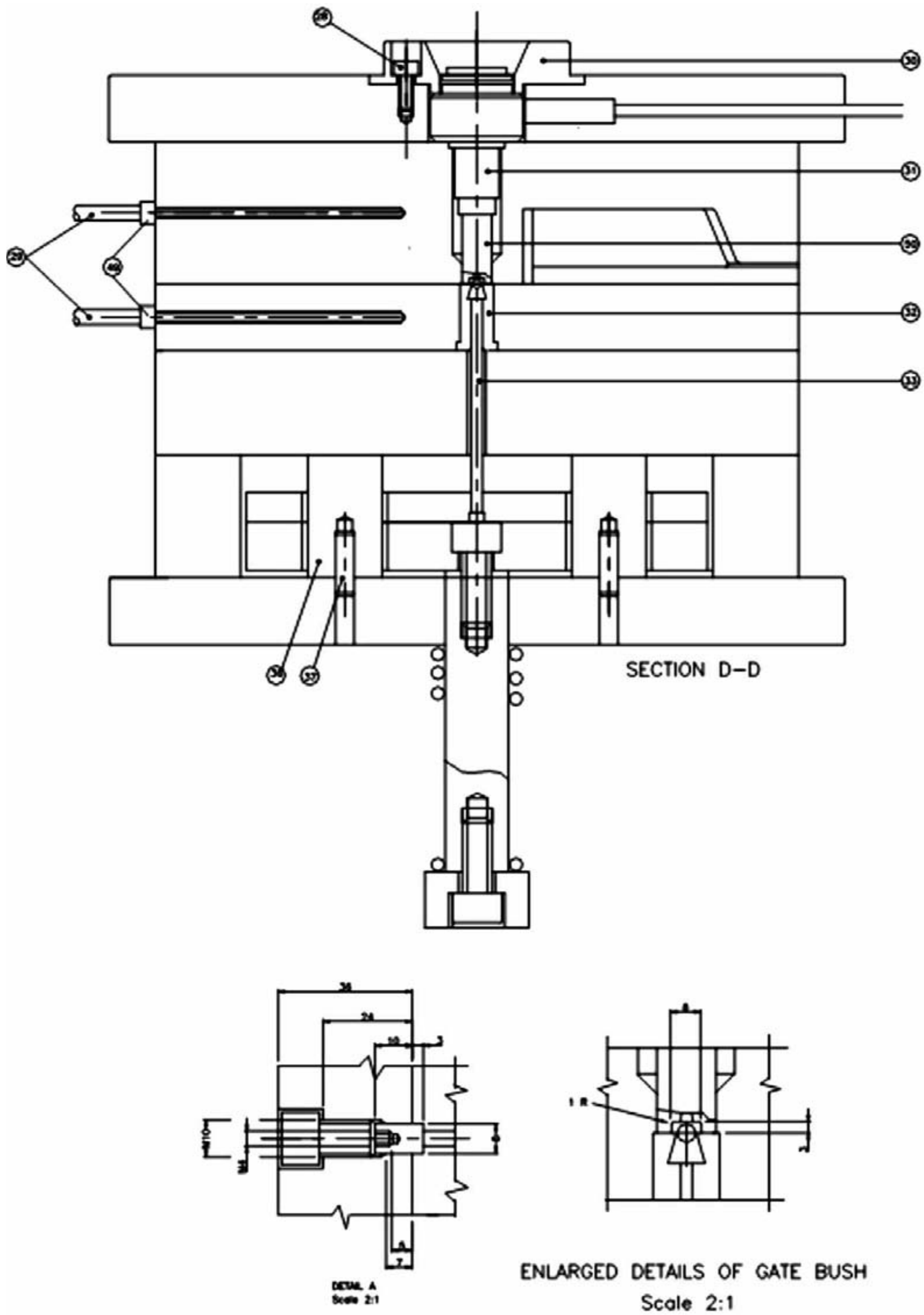
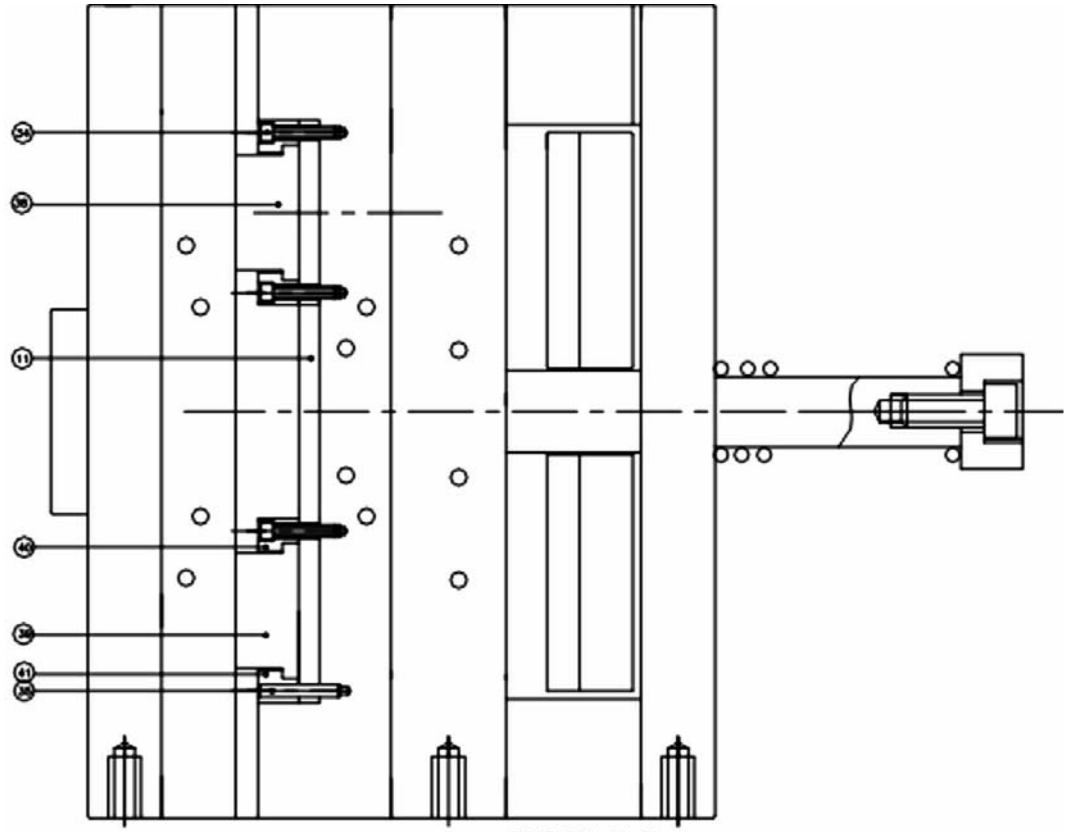
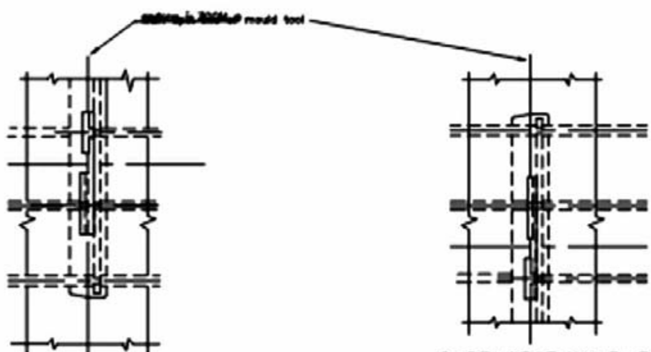


Figure 24.12 Two-impression forceps mould details

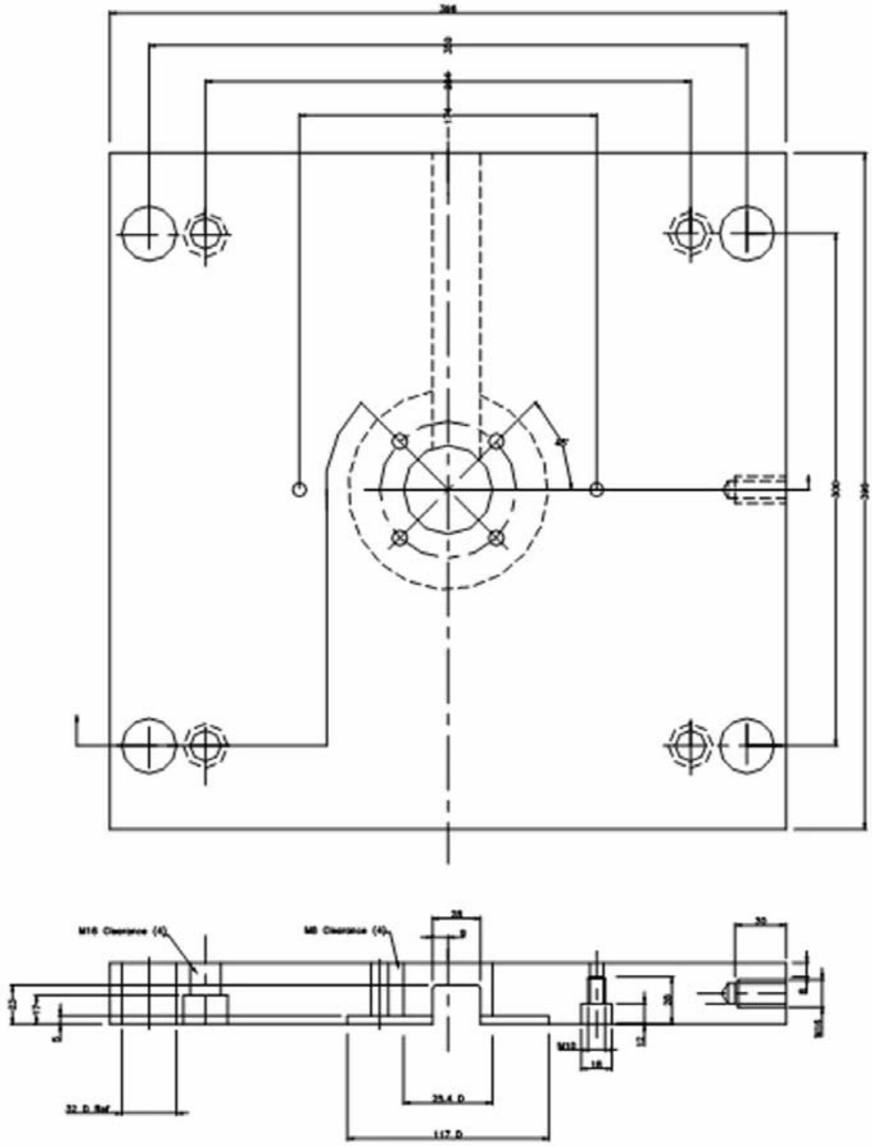


SECTION C–C



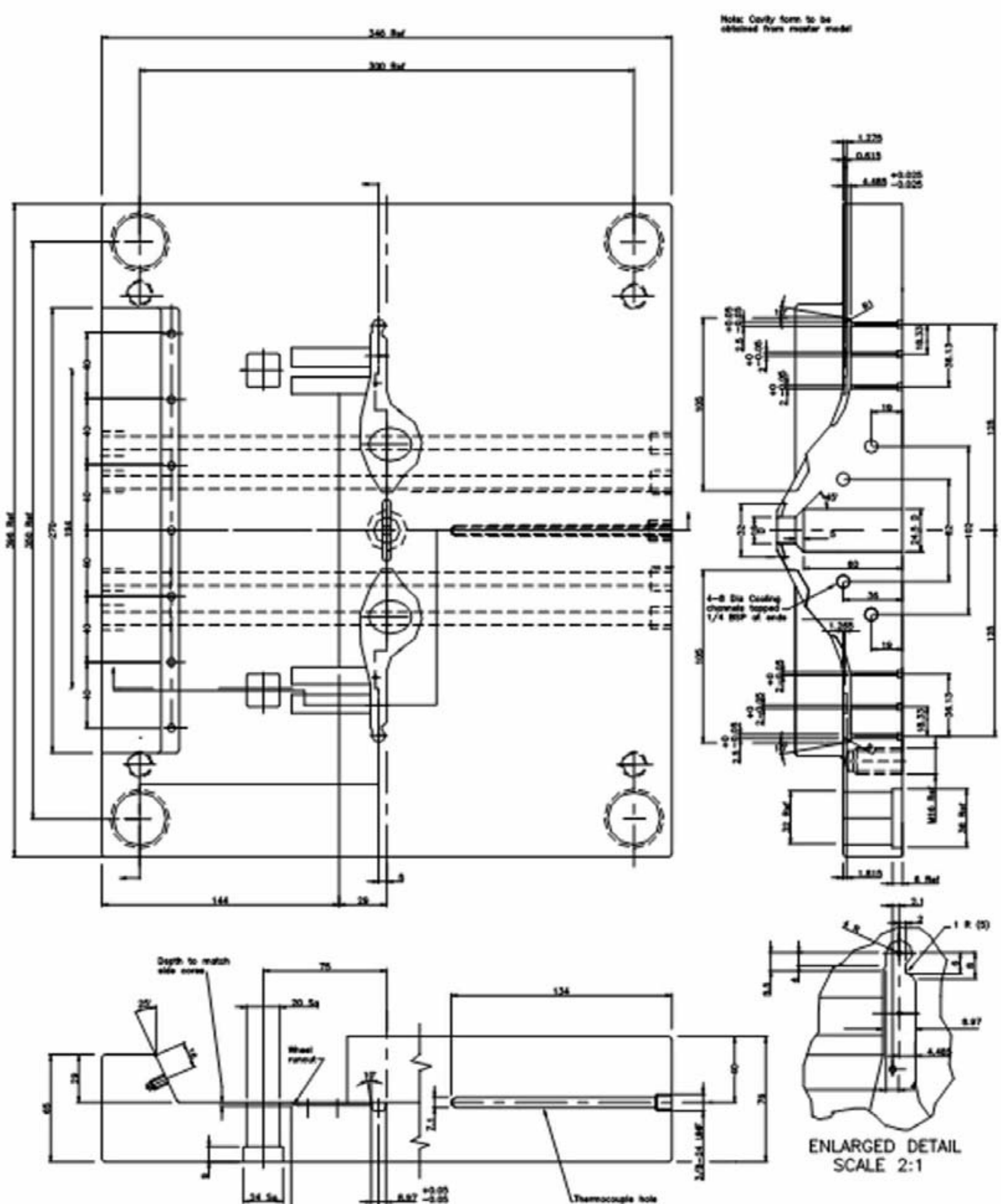
PART SECTION E–E
Scale 2:1

PART SECTION F–F
Scale 2:1

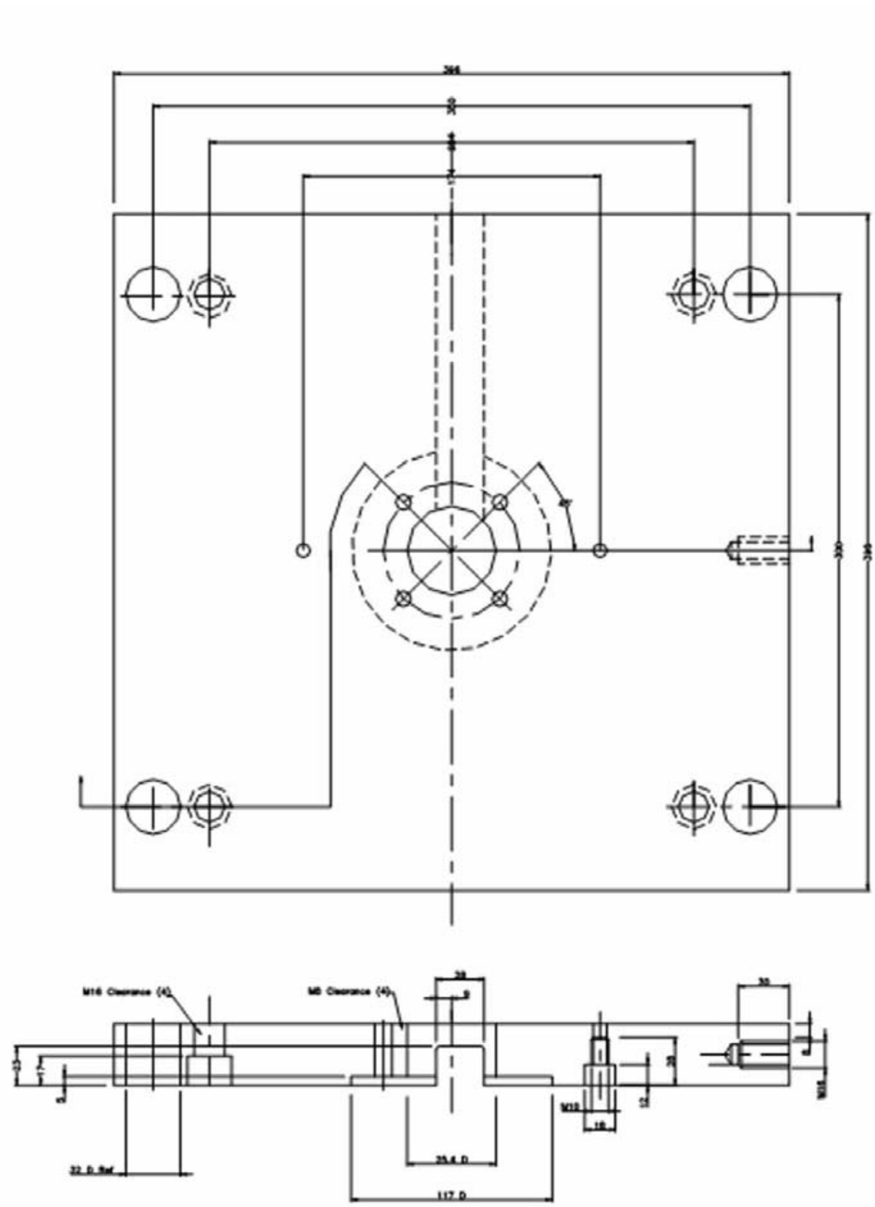


Detail of item 1

Figure 24.13 Two-impression forceps mould details

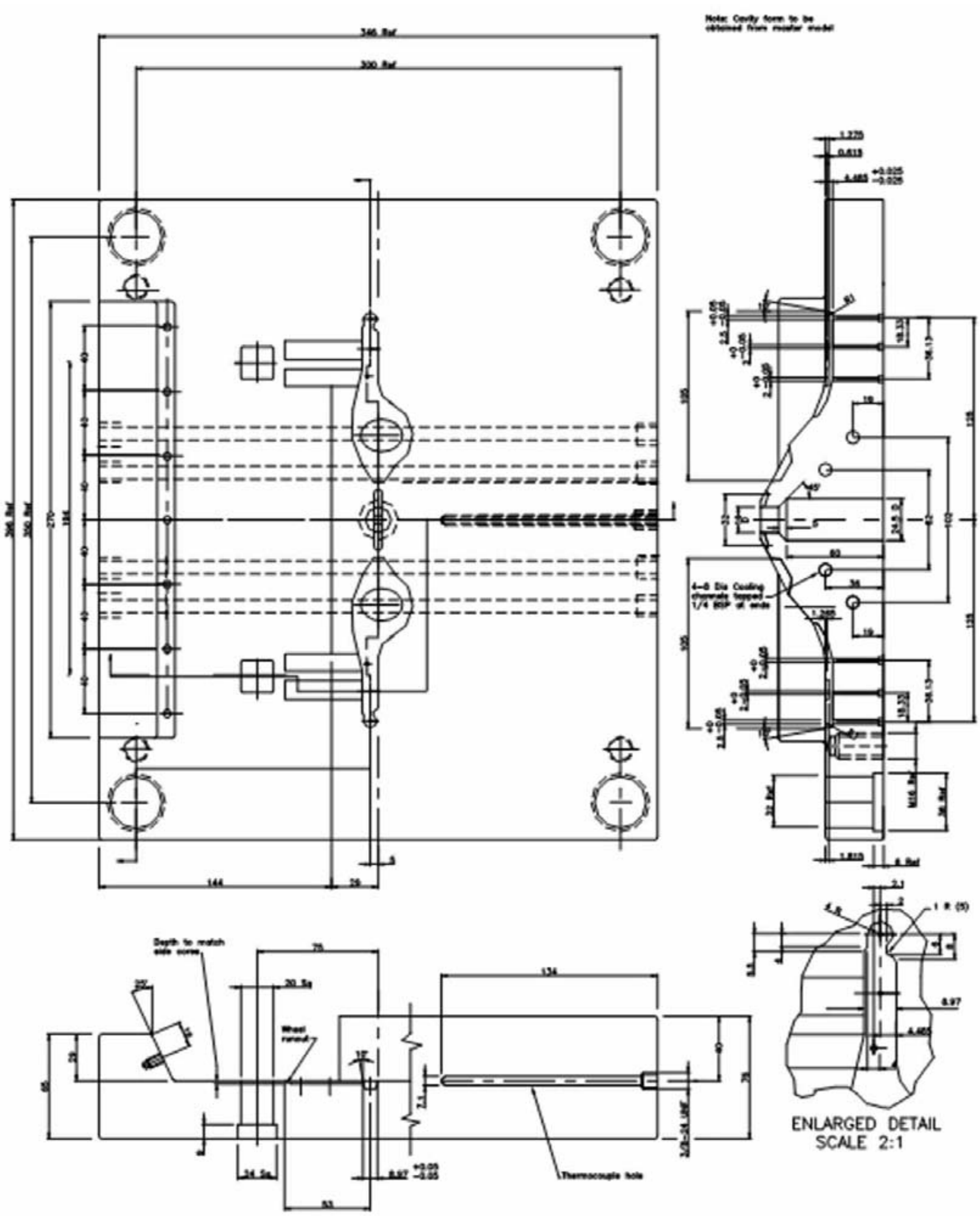


Detail of item 2



Detail of item 1

Figure 24.14 Two-impression forceps mould details



Detail of item 2

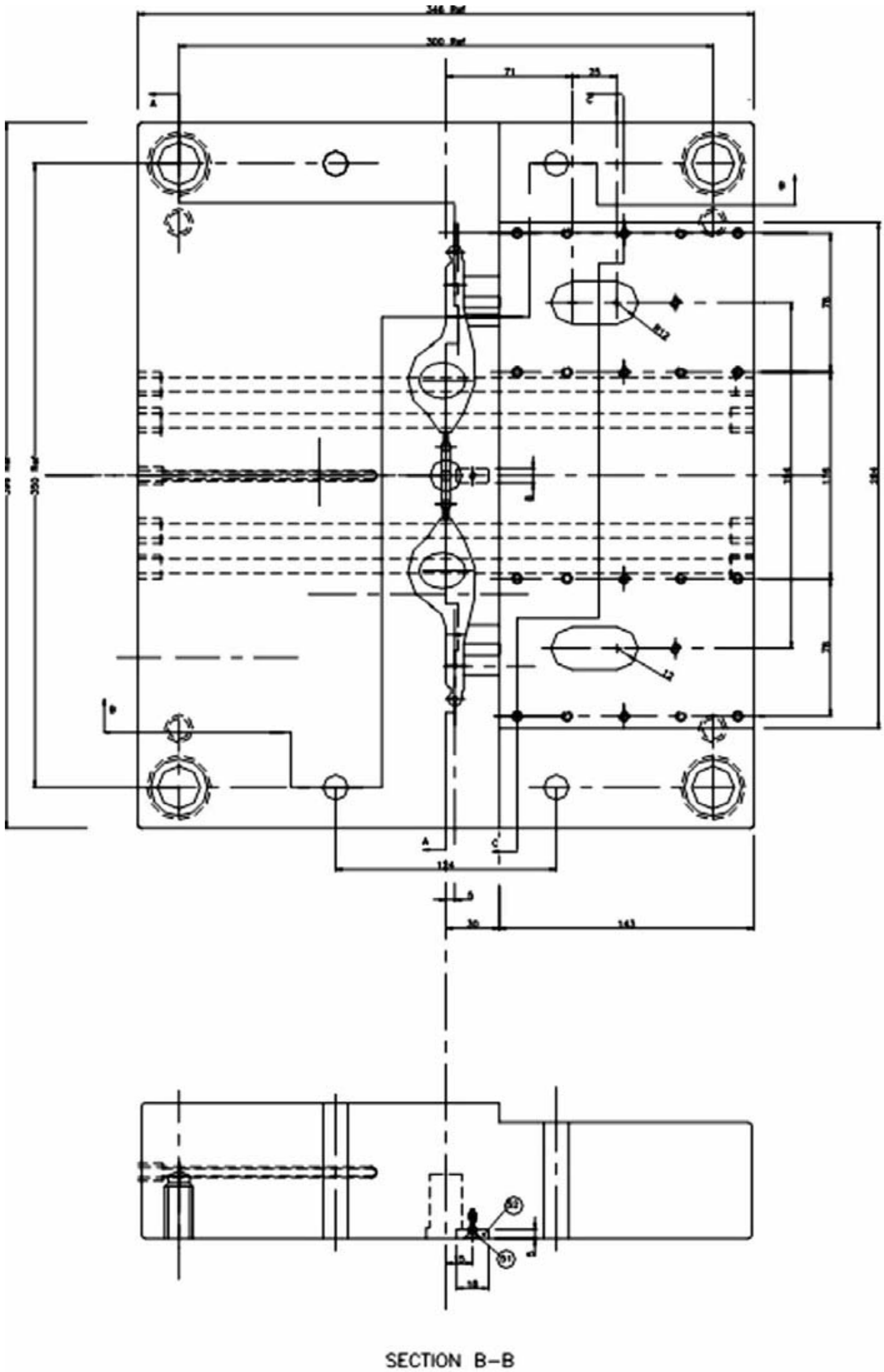
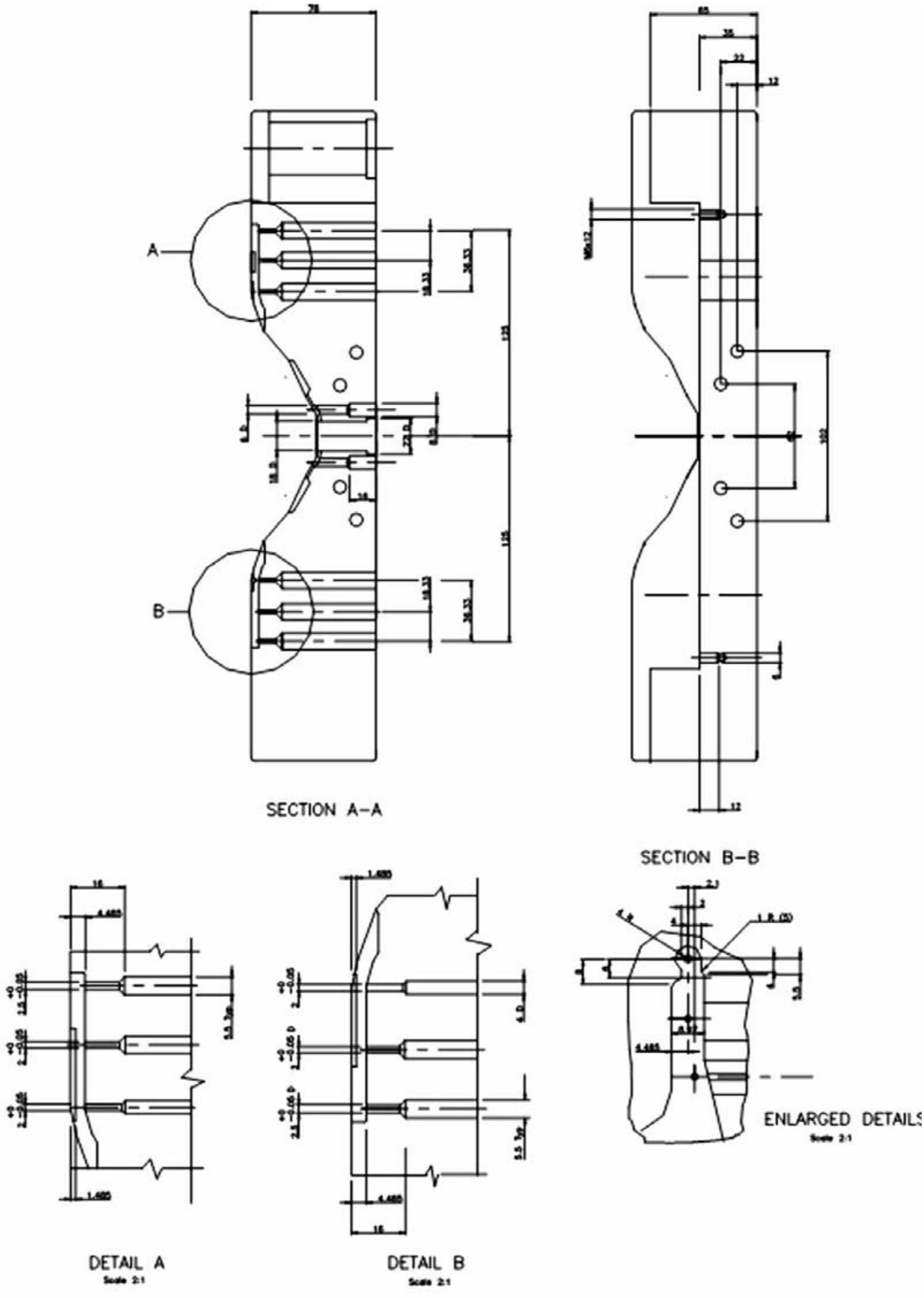
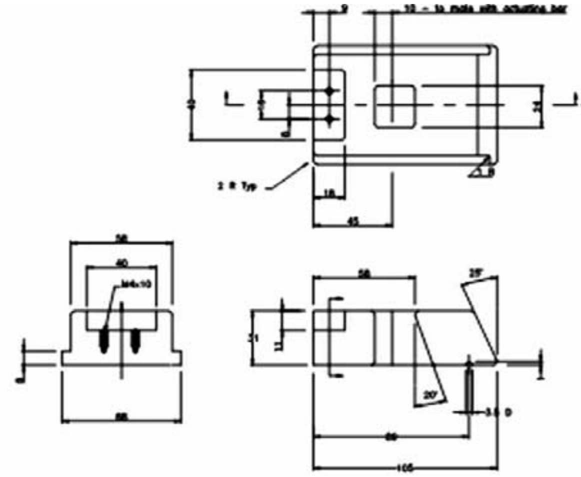


Figure 24.15 Two-impression forceps mould details


SECTION A–A
SECTION B–B
DETAIL A
Scale 2:1
DETAIL B
Scale 2:1
ENLARGED DETAILS
Scale 2:1



DETAIL – ITEM 38

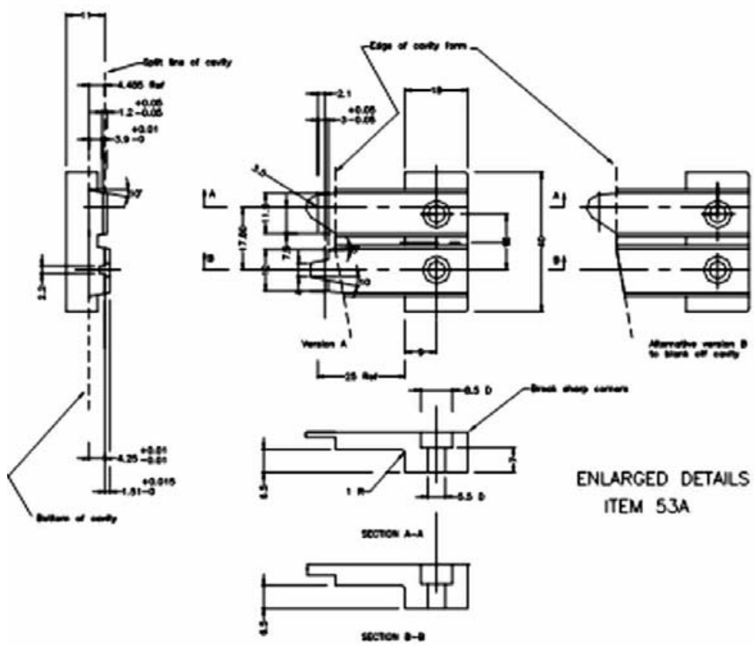
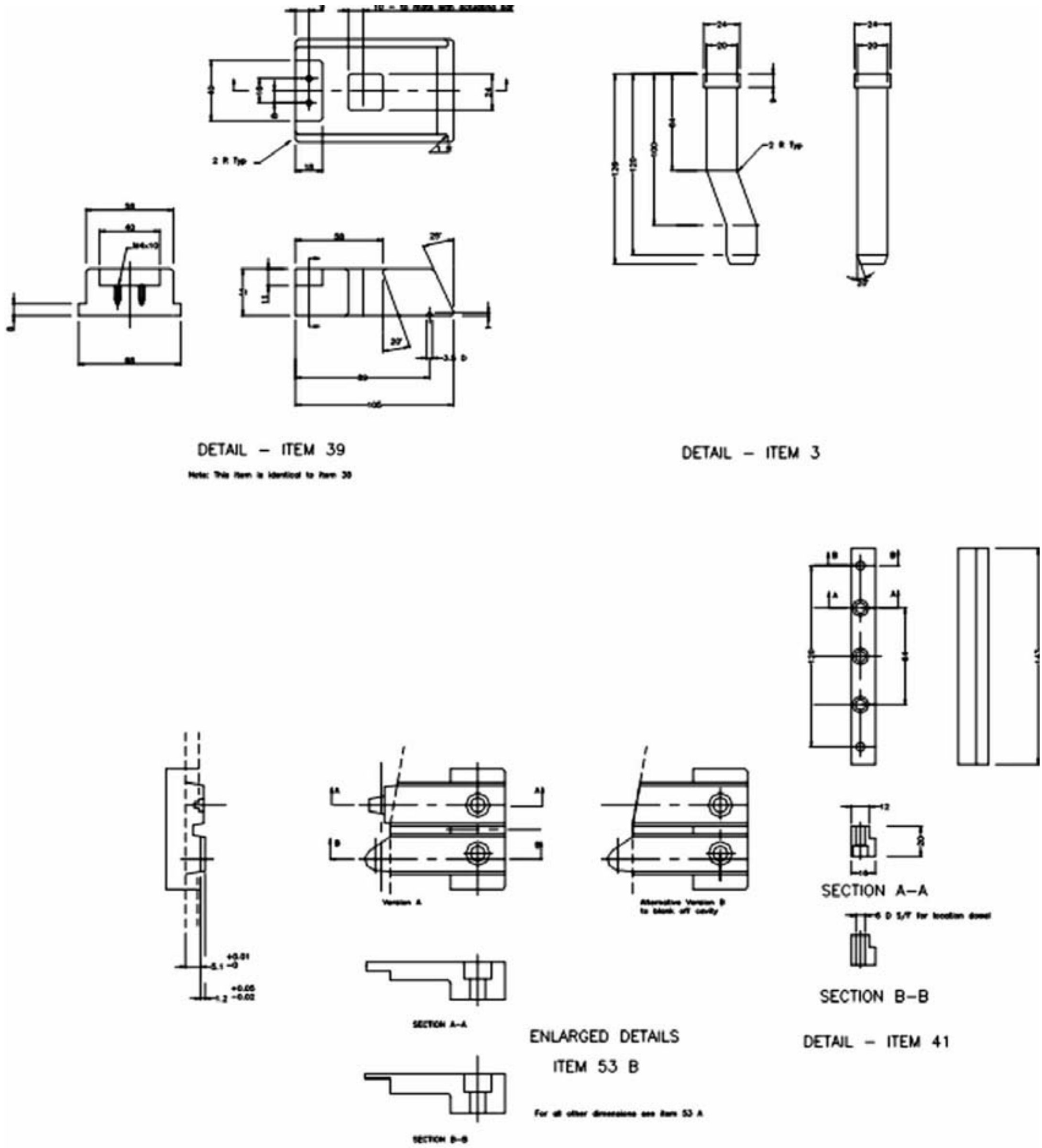
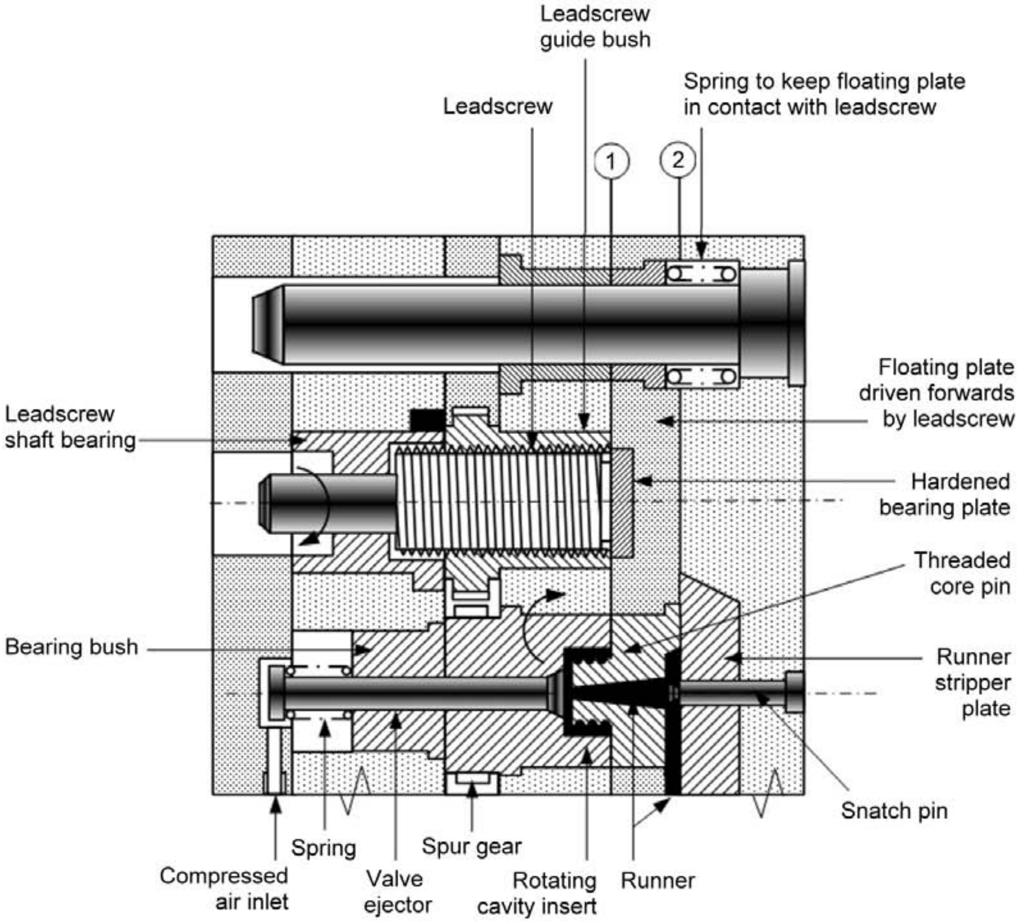


Figure 24.16 Two-impression forceps mould details



DETAIL – ITEM 39
DETAIL – ITEM 3
SECTION A–A
SECTION B–B
DETAIL – ITEM 41
Version A
Alternative Version B to blank off cavity
SECTION A–A
ENLARGED DETAILS
ITEM 53 B
For all other dimensions see item 53 A
SECTION B–B



The tool opens slowly at split line 1 first allowing the unscrewing operation to take place.

The leadscrew and the thread on the component must have the same pitch. As the cavity unscrewing takes place, the leadscrew pushes the floating plate forward at split line 1. This plate maintains contact with the leadscrew via a spring as the threaded core is progressively released during unscrewing.

Finally the tool opens at split line 2 to allow ejection and runner stripping to take place.

Note: This design is based on a component with a right hand thread. This means the cavity rotation is anti clockwise when viewed from the rear of the tool. Consequently, the leadscrew must be screwed in the opposite direction.

Figure 24.17 Rotating cavity design with axially fixed cavity

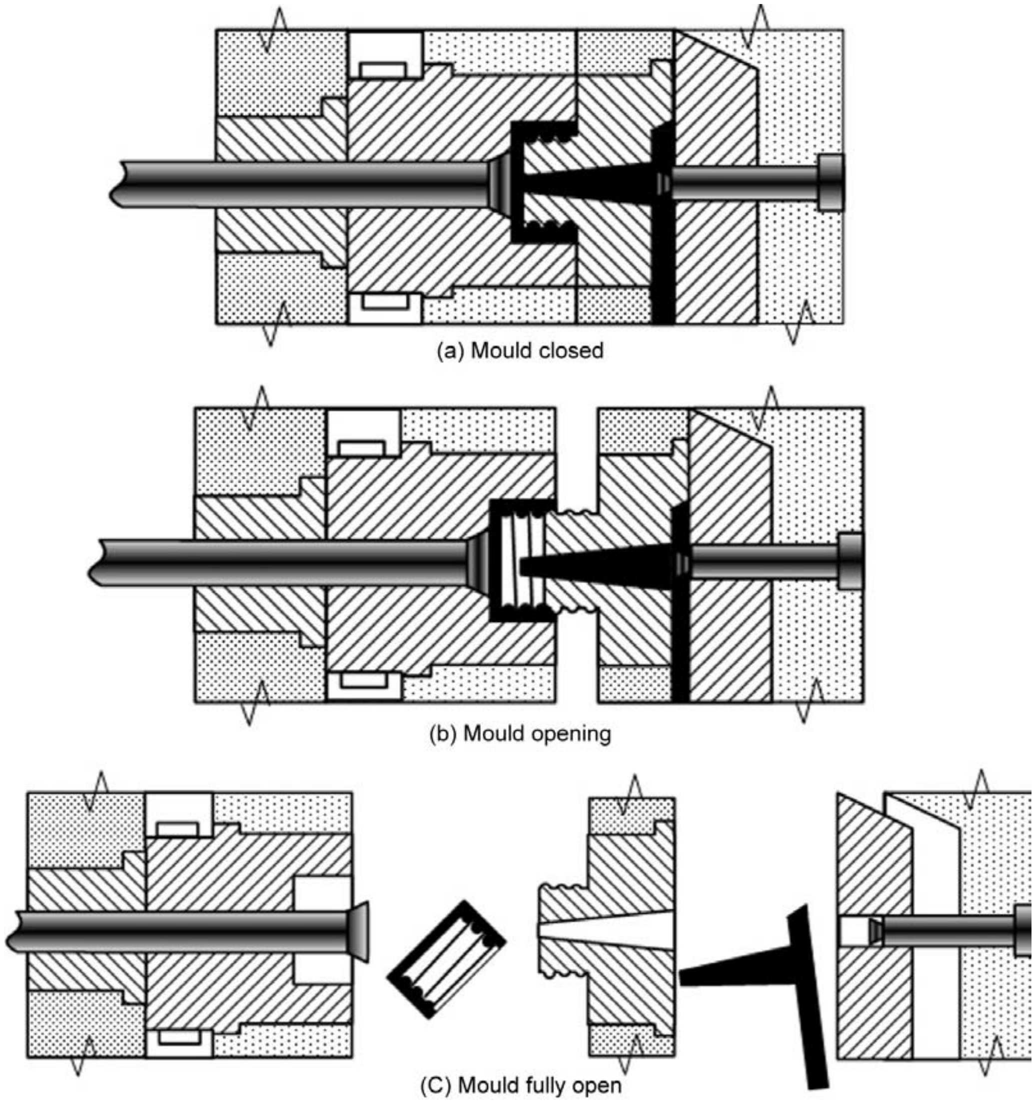


Figure 24.18 Mould opening sequence – cavity rotation

25 Mathematical and Reference Tables

25.1 Logarithms

No.	Log.	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1·0	·0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
1·1	·0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
1·2	·0792	0828	0864	0899	0934	0969	1004	1038	0172	1106	3	7	10	14	17	21	24	28	31
1·3	·1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
1·4	·1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
1·5	·1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
1·6	·2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
1·7	·2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
1·8	·2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
1·9	·2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
2·0	·3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
2·1	·3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
2·2	·3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
2·3	·3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
2·4	·3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
2·5	·3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
2·6	·4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
2·7	·4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
2·8	·4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
2·9	·4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
3·0	·4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
3·1	·4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
3·2	·5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
3·3	·5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
3·4	·5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
3·5	·5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
3·6	·5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
3·7	·5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
3·8	·5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
3·9	·5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
4·0	·6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
4·1	·6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
4·2	·6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
4·3	·6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
4·4	·6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
4·5	·6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
4·6	·6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
4·7	·6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
4·8	·6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
4·9	·6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
5·0	·6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
5·1	·7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
5·2	·7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
5·3	·7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
5·4	·7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

Continued...

Logarithms continued

No.	Log.	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
5·5	·7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
5·6	·7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
5·7	·7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
5·8	·7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
5·9	·7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
6·0	·7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
6·1	·7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
6·2	·7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
6·3	·7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
6·4	·8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
6·5	·8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
6·6	·8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
6·7	·8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
6·8	·8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
6·9	·8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
7·0	·8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
7·1	·8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
7·2	·8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
7·3	·8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
7·4	·8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
7·5	·8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
7·6	·8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
7·7	·8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
7·8	·8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
7·9	·8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
8·0	·9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
8·1	·9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
8·2	·9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
8·3	·9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
8·4	·9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
8·5	·9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
8·6	·9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
8·7	·9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
8·8	·9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
8·9	·9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
9·0	·9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
9·1	·9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
9·2	·9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
9·3	·9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
9·4	·9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
9·5	·9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
9·6	·9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
9·7	·9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	4	4	4
9·8	·9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
9·9	·9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

25.2 Anti-logarithms

Log.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

Continued...

Anti-logarithms continued

Log.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

25.3 Natural Sines

Degrees	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0·°9	Mean Differences 1	2	3	4	5
0	·00000	00175	00349	00524	00698	00873	01047	01222	01396	01571	29	58	87	117	145
1	·01745	01920	02094	02269	02443	02618	02792	02967	03141	03316	29	58	87	117	145
2	·03490	03664	03839	04013	04188	04362	04536	04711	04885	05059	29	58	87	116	145
3	·05234	05408	05582	05756	05931	06105	06279	06453	06627	06802	29	58	87	116	145
4	·06976	07150	07324	07498	07672	07846	08020	08194	08368	08542	29	58	87	116	145
5	·08716	08889	09063	09237	09411	09585	09758	09932	10106	10279	29	58	87	116	145
6	·10453	10626	10800	10973	11147	11320	11494	11667	11840	12014	29	58	87	116	145
7	·12187	12360	12533	12706	12880	13053	13226	13399	13572	13744	29	58	87	115	144
8	·13917	14090	14263	14436	14608	14781	14954	15126	15299	15471	29	58	86	115	144
9	·15643	15816	15988	16160	16333	16505	16677	16849	17021	17193	29	57	86	115	144
10	·17365	17537	17708	17880	18052	18224	18395	18567	18738	18910	29	57	86	114	143
11	·19081	19252	19423	19595	19766	19937	20108	20279	20450	20620	29	57	86	114	143
12	·20791	20962	21132	21303	21474	21644	21814	21985	22155	22325	28	57	85	114	142
13	·22495	22665	22835	23005	23175	23345	23514	23684	23853	24023	28	57	85	113	141
14	·24192	24362	24531	24700	24869	25038	25207	25376	25545	25713	28	56	85	113	141
15	·25882	26050	26219	26387	26556	26724	26892	27060	27228	27396	28	56	84	112	140
16	·27564	27731	27899	28067	28234	28402	28569	28736	28903	29070	28	56	84	112	139
17	·29237	29404	29571	29737	29904	30071	30237	30403	30570	30736	28	56	83	111	139
18	·30902	31068	31233	31399	31565	31730	31896	32061	32227	32392	28	55	83	110	138
19	·32557	32722	32887	33051	33216	33381	33545	33710	33874	34038	27	55	82	110	137
20	·34202	34366	34530	34694	34857	35021	35184	35347	35511	35674	27	55	82	109	136
21	·35837	36000	36162	36325	36488	36650	36812	36975	37137	37299	27	54	81	108	135
22	·37461	37622	37784	37946	38107	38268	38430	38591	38752	38912	27	54	81	107	134
23	·39073	39234	39394	39555	39715	39875	40035	40195	40355	40514	27	53	80	107	133
24	·40674	40833	40992	41151	41310	41469	41628	41787	41945	42104	27	53	79	106	132
25	·42262	42420	42578	42736	42894	43051	43209	43366	43523	43680	26	53	79	105	131
26	·43837	43994	44151	44307	44464	44620	44776	44932	45088	45243	26	52	78	104	130
27	·45399	45554	45710	45865	46020	46175	46330	46484	46639	46793	26	52	77	103	129
28	·46947	47101	47255	47409	47562	47716	47869	48022	48175	48328	26	51	77	102	128
29	·48481	48634	48786	48938	49090	49242	49394	49546	49697	49849	25	51	76	101	126
30	·50000	50151	50302	50453	50603	50754	50904	51054	51204	51354	25	50	75	100	125
31	·51504	51653	51803	51952	52101	52250	52399	52547	52696	52844	25	50	74	99	124
32	·52992	53140	53288	53435	53583	53730	53877	54024	54171	54317	25	49	74	98	123
33	·54464	54610	54756	54902	55048	55194	55339	55484	55630	55775	24	49	73	97	121
34	·55919	56064	56208	56353	56497	56641	56784	56928	57071	57215	24	48	72	96	120
35	·57358	57501	57643	57786	57928	58070	58212	58354	58496	58637	24	48	71	95	118
36	·58778	58920	59061	59201	59342	59482	59622	59763	59902	60042	23	47	70	94	117
37	·60181	60321	60460	60599	60738	60876	61015	61153	61291	61429	23	46	69	92	115
38	·61566	61704	61841	61978	62115	62251	62388	62524	62660	62796	23	46	68	91	114
39	·62932	63068	63203	63338	63473	63608	63742	63877	64011	64145	23	45	67	90	112
40	·64279	64412	64546	64679	64812	64945	65077	65210	65342	65474	22	44	66	88	111
41	·65606	65738	65869	66000	66131	66262	66393	66523	66653	66783	22	44	65	87	109
42	·66913	67043	67172	67301	67430	67559	67688	67816	67944	68072	22	43	64	86	107
43	·68200	68327	68455	68582	68709	68835	68962	69088	69214	69340	21	42	63	84	106
44	·69466	69591	69717	69842	69966	70091	70215	70339	70463	70587	21	41	62	83	104

Continued...

Natural Sines continued

Degrees.	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Mean Differences. 1	2	3	4	5
45	·70711	70834	70957	71080	71203	71325	71447	71569	71691	71813	20	41	61	82	102
46	·71934	72055	72176	72297	72417	72537	72657	72777	72897	73016	20	40	60	80	100
47	·73135	73254	73373	73491	73610	73728	73846	73963	74080	74198	20	39	59	79	98
48	·74314	74431	74548	74664	74780	74896	75011	75126	75241	75356	20	39	58	77	96
49	·75471	75585	75700	75813	75927	76041	76154	76267	76380	76492	19	38	57	76	94
50	·76604	76717	76828	76940	77051	77162	77273	77384	77494	77605	19	37	56	74	93
51	·77715	77824	77934	78043	78152	78261	78369	78478	78586	78694	18	36	54	72	91
52	·78801	78908	79015	79122	79229	79335	79441	79547	79653	79758	18	35	53	71	89
53	·79864	79968	80073	80178	80282	80386	80489	80593	80696	80799	17	35	52	69	87
54	·80902	81004	81106	81208	81310	81412	81513	81614	81714	81815	17	34	51	68	84
55	·81915	82015	82115	82214	82314	82413	82511	82610	82708	82806	16	33	49	66	82
56	·82904	83001	83098	83195	83292	83389	83485	83581	83676	83772	16	32	48	64	80
57	·83867	83962	84057	84151	84245	84339	84433	84526	84619	84712	16	31	47	62	78
58	·84805	84897	84989	85081	85173	85264	85355	85446	85536	85627	15	31	46	61	76
59	·85717	85806	85896	85985	86074	86163	86251	86340	86427	86515	15	30	44	59	74
60	·86603	86690	86777	86863	86949	87036	87121	87207	87292	87377	14	29	43	57	72
61	·87462	87546	87631	87715	87798	87882	87965	88048	88130	88213	14	28	42	56	69
62	·88295	88377	88458	88539	88620	88701	88782	88862	88942	89021	14	27	40	54	67
63	·89101	89180	89259	89337	89415	89493	89571	89649	89726	89803	13	26	39	52	65
64	·89879	89956	90032	90108	90183	90259	90334	90408	90483	90557	13	25	38	50	63
65	·90631	90704	90778	90851	90924	90996	91068	91140	91212	91283	12	24	36	48	60
66	·91355	91425	91496	91566	91636	91706	91775	91845	91914	91982	12	23	35	46	58
67	·92050	92119	92186	92254	92321	92388	92455	92521	92587	92653	11	22	33	45	56
68	·92718	92784	92849	92913	92978	93042	93106	93169	93232	93295	11	21	32	43	54
69	·93358	93420	93483	93544	93606	93667	93728	93789	93849	93909	10	20	31	41	51
70	·93969	94029	94088	94147	94206	94264	94322	94380	94438	94495	10	19	29	39	49
71	·94552	94609	94665	94721	94777	94832	94888	94943	94997	95052	9	18	28	37	46
72	·95106	95159	95213	95266	95319	95372	95424	95476	95528	95579	9	17	26	35	44
73	·95630	95681	95732	95782	95832	95882	95931	95981	96029	96078	8	17	25	33	41
74	·96126	96174	96222	96269	96316	96363	96410	96456	96502	96547	8	16	23	31	39
75	·96593	96638	96682	96727	96771	96815	96858	96902	96945	96987	7	16	22	29	36
76	·97030	97072	97113	97155	97196	97237	97278	97318	97358	97398	7	14	20	27	34
77	·97437	97476	97515	97553	97592	97630	97667	97705	97742	97778	6	13	19	25	32
78	·97815	97851	97887	97922	97958	97992	98027	98061	98096	98129	6	12	17	23	29
79	·98163	98196	98229	98261	98294	98325	98357	98388	98420	98450	5	11	16	21	27
80	·98481	98511	98541	98570	98600	98629	98657	98686	98714	98741	5	10	14	19	24
81	·98769	98796	98823	98849	98876	98902	98927	98953	98978	99002	4	9	13	17	22
82	·99027	99051	99075	99098	99122	99144	99167	99189	99211	99233	4	8	11	15	19
83	·99255	99276	99297	99317	99337	99357	99377	99396	99415	99434	3	7	10	13	16
84	·99452	99470	99488	99506	99523	99540	99556	99572	99588	99604	3	6	8	11	14
85	·99619	99635	99649	99664	99678	99692	99705	99719	99731	99744	2	5	7	9	11
86	·99756	99768	99780	99792	99803	99813	99824	99834	99844	99854	2	4	5	7	9
87	·99863	99872	99881	99889	99897	99905	99912	99919	99926	99933	1	3	4	5	6
88	·99939	99945	99951	99956	99961	99966	99970	99974	99978	99982	1	2	2	3	4
89	·99985	99988	99990	99993	99995	99996	99998	99999	99999	1·0000	0	1	1	1	1
90	1·000														

25.4 Natural Cosines

Degrees	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Mean Differences. 1	2	3	4	5
0	1·000	99999	99999	99999	99998	99996	99995	99993	99990	99988	0	1	1	1	1
1	·99985	99982	99978	99974	99970	99966	99961	99956	99951	99945	1	2	2	3	4
2	·99939	99933	99926	99919	99912	99905	99897	99889	99881	99872	1	3	4	5	6
3	·99863	99854	99844	99834	99824	99813	99803	99792	99780	99768	2	4	5	7	9
4	·99756	99744	99731	99719	99705	99692	99678	99664	99649	99635	2	5	7	9	11
5	·99619	99604	99588	99572	99556	99540	99523	99506	99488	99470	3	6	8	11	14
6	·99452	99434	99415	99396	99377	99357	99337	99317	99297	99276	3	7	10	13	16
7	·99255	99233	99211	99189	99167	99144	99122	99098	99075	99051	4	8	11	15	19
8	·99027	99002	98978	98953	98927	98902	98876	98849	98823	98796	4	9	13	17	22
9	·98769	98741	98714	98686	98657	98629	98600	98570	98541	98511	5	10	14	19	24
10	·98481	98450	98420	98388	98357	98325	98294	98261	98229	98196	5	11	16	21	27
11	·98163	98129	98096	98061	98027	97992	97958	97922	97887	97851	6	12	17	23	29
12	·97815	97778	97742	97705	97667	97630	97592	97553	97515	97476	6	13	19	25	32
13	·97437	97398	97358	97318	97278	97237	97196	97155	97113	97072	7	14	20	27	34
14	·97030	96987	96945	96902	96858	96815	96771	96727	96682	96638	7	16	22	29	36
15	·96593	96547	96502	96456	96410	96363	96316	96269	96222	96174	8	16	23	31	39
16	·96126	96078	96029	95981	95931	95882	95832	95782	95732	95681	8	17	25	33	41
17	·95630	95579	95528	95476	95424	95372	95319	95266	95213	95159	9	17	26	35	44
18	·95106	95052	94997	94943	94888	94832	94777	94721	94665	94609	9	18	28	37	46
19	·94552	94495	94438	94380	94322	94264	94206	94147	94088	94029	10	19	29	39	49
20	·93969	93909	93849	93789	93728	93667	93606	93544	93483	93420	10	20	31	41	51
21	·93358	93295	93232	93169	93106	93042	92978	92913	92849	92784	10	21	32	43	54
22	·92718	92653	92587	92521	92455	92388	92321	92254	92186	92119	11	22	33	45	56
23	·92050	91982	91914	91845	91775	91706	91636	91566	91496	91425	11	23	35	46	58
24	·91355	91283	91212	91140	91068	90996	90924	90851	90778	90704	12	24	36	48	60
25	·90631	90557	90483	90408	90334	90259	90183	90108	90032	89956	13	25	38	50	63
26	·89879	89803	89726	89649	89571	89493	89415	89337	89259	89180	13	26	39	52	65
27	·89101	89021	88942	88862	88782	88701	88620	88539	88458	88377	13	27	40	54	67
28	·88295	88213	88130	88048	87965	87882	87798	87715	87631	87546	14	28	42	56	69
29	·87462	87377	87292	87207	87121	87036	86949	86863	86777	86690	14	29	43	57	72
30	·86603	86515	86427	86340	86251	86163	86074	85985	85896	85806	15	30	44	59	74
31	·85717	85627	85536	85446	85355	85264	85173	85081	84989	84897	16	30	46	61	76
32	·84805	84712	84619	84526	84433	84339	84245	84151	84057	83962	16	31	47	62	78
33	·83867	83772	83676	83581	83485	83389	83292	83195	83098	83001	16	32	48	64	80
34	·82904	82806	82708	82610	82511	82413	82314	82214	82115	82015	16	33	49	66	82
35	·81915	81815	81714	81614	81513	81412	81310	81208	81106	81004	17	34	51	68	84
36	·80902	80799	80696	80593	80489	80386	80282	80178	80073	79968	17	35	52	69	87
37	·79864	79758	79653	79547	79441	79335	79229	79122	79015	78908	18	35	53	71	89
38	·78801	78693	78586	78478	78369	78261	78152	78043	77934	77824	18	36	54	72	91
39	·77715	77605	77494	77384	77273	77162	77051	76940	76828	76717	18	37	56	74	93
40	·76604	76492	76380	76267	76154	76041	75927	75813	75700	75585	19	38	57	76	94
41	·75471	75356	75241	75126	75011	74896	74780	74664	74548	74431	19	39	58	77	96
42	·74314	74198	74080	73963	73846	73728	73610	73491	73373	73254	20	39	59	79	98
43	·73135	73016	72897	72777	72657	72537	72417	72297	72176	72055	20	40	60	80	100
44	·71934	71813	71691	71569	71447	71325	71203	71080	70957	70834	20	41	61	82	102

Continued...

Natural Cosines continued

Degrees.	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Mean Differences. 1	2	3	4	5
45	·70711	70587	70463	70339	70215	70091	69966	69842	69717	69591	21	41	62	83	104
46	·69466	69340	69214	69088	68962	68835	68709	68582	68455	68327	21	42	63	84	106
47	·68200	68072	67944	67816	67688	67559	67430	67301	67172	67043	21	43	64	86	107
48	·66913	66783	66653	66523	66393	66262	66131	66000	65869	65738	22	44	65	87	109
49	·65606	65474	65342	65210	65077	64945	64812	64679	64546	64412	22	44	66	88	111
50	·64279	64145	64011	63877	63742	63608	63473	63338	63203	63068	22	45	67	90	112
51	·62932	62796	62660	62524	62388	62251	62115	61978	61841	61704	23	45	68	91	114
52	·61566	61429	61291	61153	61015	60876	60738	60599	60460	60321	23	46	69	92	115
53	·60181	60042	59902	59763	59622	59482	59342	59201	59061	58920	23	47	70	94	117
54	·58779	58637	58496	58354	58212	58070	57928	57786	57643	57501	24	47	71	95	118
55	·57358	57215	57071	56928	56784	56641	56497	56353	56208	56064	24	48	72	96	120
56	·55919	55775	55630	55484	55339	55194	55048	54902	54756	54610	24	49	73	97	121
57	·54464	54317	54171	54024	53877	53730	53583	53435	53288	53140	24	49	74	98	123
58	·52992	52844	52696	52547	52399	52250	52101	51952	51803	51653	25	50	74	99	124
59	·51504	51354	51204	51054	50904	50754	50603	50453	50302	50151	25	50	75	100	125
60	·50000	49849	49697	49546	49394	49242	49090	48938	48786	48634	25	51	76	101	126
61	·48481	48328	48175	48022	47869	47716	47562	47409	47255	47101	26	51	77	102	128
62	·46947	46793	46639	46484	46330	46175	46020	45865	45710	45554	26	52	77	103	129
63	·45399	45243	45088	44932	44776	44620	44464	44307	44151	43994	26	52	78	104	130
64	·43837	43680	43523	43366	43209	43051	42894	42736	42578	42420	26	53	79	105	131
65	·42262	42104	41945	41787	41628	41469	41310	41151	40992	40833	26	53	79	106	132
66	·40674	40514	40355	40195	40035	39875	39715	39555	39394	39234	27	53	80	107	133
67	·39073	38912	38752	38591	38430	38268	38107	37946	37784	37622	27	54	81	107	134
68	·37461	37299	37137	36975	36812	36650	36488	36325	36162	36000	27	54	81	108	135
69	·35837	35674	35511	35347	35184	35021	34857	34694	34530	34366	27	54	82	109	136
70	·34202	34038	33874	33710	33545	33381	33216	33051	32887	32722	27	55	82	110	137
71	·32557	32392	32227	32061	31896	31730	31565	31399	31233	31068	28	55	83	110	138
72	·30902	30736	30570	30403	30237	30071	29904	29737	29571	29404	28	56	83	111	139
73	·29237	29070	28903	28736	28569	28402	28234	28067	27899	27731	28	56	84	112	139
74	·27564	27396	27228	27060	26892	26724	26556	26387	26219	26050	28	56	84	112	140
75	·25882	25713	25545	25376	25207	25038	24869	24700	24531	24362	28	56	85	113	141
76	·24192	24023	23853	23684	23514	23345	23175	23005	22835	22665	28	57	85	113	141
77	·22495	22325	22155	21985	21814	21644	21474	21303	21132	20962	28	57	85	114	142
78	·20791	20620	20450	20279	20108	19937	19766	19595	19423	19252	29	57	86	114	143
79	·19081	18910	18738	18567	18395	18224	18052	17880	17708	17537	29	57	86	114	143
80	·17365	17193	17021	16849	16677	16505	16333	16160	15988	15816	29	57	86	115	144
81	·15643	15471	15299	15126	14954	14781	14608	14436	14263	14090	29	58	86	115	144
82	·13917	13744	13572	13399	13226	13053	12880	12706	12533	12360	29	58	87	115	144
83	·12187	12014	11840	11667	11494	11320	11147	10973	10800	10626	29	58	87	116	145
84	·10453	10279	10106	09932	09758	09585	09411	09237	09063	08889	29	58	87	116	145
85	·08716	08542	08368	08194	08020	07846	07672	07498	07324	07150	29	58	87	116	145
86	·06976	06802	06627	06453	06279	06105	05931	05756	05582	05408	29	58	87	116	145
87	·05234	05059	04885	04711	04536	04362	04188	04013	03839	03664	29	58	87	116	145
88	·03490	03316	03141	02967	02792	02618	02443	02269	02094	01920	29	58	87	117	145
89	·01745	01571	01396	01222	01047	00873	00698	00524	00349	00175	29	58	87	117	145
90	·0000														

25.5 Natural Tangents

Degrees	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Mean Differences. 1	2	3	4	5
0	·00000	00175	00349	00524	00698	00873	01047	01222	01396	01571	29	58	87	117	145
1	·01745	01920	02094	02269	02443	02618	02792	02967	03141	03316	29	58	87	117	145
2	·03490	03664	03839	04013	04188	04362	04536	04711	04885	05059	29	58	87	116	145
3	·05234	05408	05582	05756	05931	06105	06279	06453	06627	06802	29	58	87	116	145
4	·06976	07150	07324	07498	07672	07846	08020	08194	08368	08542	29	58	87	116	145
5	·08716	08889	09063	09237	09411	09585	09758	09932	10106	10279	29	58	87	116	145
6	·10453	10626	10800	10973	11147	11320	11494	11667	11840	12014	29	58	87	116	145
7	·12187	12360	12533	12706	12880	13053	13226	13399	13572	13744	29	58	87	115	144
8	·13917	14090	14263	14436	14608	14781	14954	15126	15299	15471	29	58	86	115	144
9	·15643	15816	15988	16160	16333	16505	16677	16849	17021	17193	29	57	86	115	144
10	·17365	17537	17708	17880	18052	18224	18395	18567	18738	18910	29	57	86	114	143
11	·19081	19252	19423	19595	19766	19937	20108	20279	20450	20620	29	57	86	114	143
12	·20791	20962	21132	21303	21474	21644	21814	21985	22155	22325	28	57	85	114	142
13	·22495	22665	22835	23005	23175	23345	23514	23684	23853	24023	28	57	85	113	141
14	·24192	24362	24531	24700	24869	25038	25207	25376	25545	25713	28	56	85	113	141
15	·25882	26050	26219	26387	26556	26724	26892	27060	27228	27396	28	56	84	112	140
16	·27564	27731	27899	28067	28234	28402	28569	28736	28903	29070	28	56	84	112	139
17	·29237	29404	29571	29737	29904	30071	30237	30403	30570	30736	28	56	83	111	139
18	·30902	31068	31233	31399	31565	31730	31896	32061	32227	32392	28	55	83	110	138
19	·32557	32722	32887	33051	33216	33381	33545	33710	33874	34038	27	55	82	110	137
20	·34202	34366	34530	34694	34857	35021	35184	35347	35511	35674	27	55	82	109	136
21	·35837	36000	36162	36325	36488	36650	36812	36975	37137	37299	27	54	81	108	135
22	·37461	37622	37784	37946	38107	38268	38430	38591	38752	38912	27	54	81	107	134
23	·39073	39234	39394	39555	39715	39875	40035	40195	40355	40514	27	53	80	107	133
24	·40674	40833	40992	41151	41310	41469	41628	41787	41945	42104	27	53	79	106	132
25	·42262	42420	42578	42736	42894	43051	43209	43366	43523	43680	26	53	79	105	131
26	·43837	43994	44151	44307	44464	44620	44776	44932	45088	45243	26	52	78	104	130
27	·45399	45554	45710	45865	46020	46175	46330	46484	46639	46793	26	52	77	103	129
28	·46947	47101	47255	47409	47562	47716	47869	48022	48175	48328	26	51	77	102	128
29	·48481	48634	48786	48938	49090	49242	49394	49546	49697	49849	25	51	76	101	126
30	·50000	50151	50302	50453	50603	50754	50904	51054	51204	51354	25	50	75	100	125
31	·51504	51653	51803	51952	52101	52250	52399	52547	52696	52844	25	50	74	99	124
32	·52992	53140	53288	53435	53583	53730	53877	54024	54171	54317	25	49	74	98	123
33	·54464	54610	54756	54902	55048	55194	55339	55484	55630	55775	24	49	73	97	121
34	·55919	56064	56208	56353	56497	56641	56784	56928	57071	57215	24	48	72	96	120
35	·57358	57501	57643	57786	57928	58070	58212	58354	58496	58637	24	48	71	95	118
36	·58778	58920	59061	59201	59342	59482	59622	59763	59902	60042	23	47	70	94	117
37	·60181	60321	60460	60599	60738	60876	61015	61153	61291	61429	23	46	69	92	115
38	·61566	61704	61841	61978	62115	62251	62388	62524	62660	62796	23	46	68	91	114
39	·62932	63068	63203	63338	63473	63608	63742	63877	64011	64145	23	45	67	90	112
40	·64279	64412	64546	64679	64812	64945	65077	65210	65342	65474	22	44	66	88	111
41	·65606	65738	65869	66000	66131	66262	66393	66523	66653	66783	22	44	65	87	109
42	·66913	67043	67172	67301	67430	67559	67688	67816	67944	68072	22	43	64	86	107
43	·68200	68327	68455	68582	68709	68835	68962	69088	69214	69340	21	42	63	84	106
44	·69466	69591	69717	69842	69966	70091	70215	70339	70463	70587	21	41	62	83	104

Continued…

Natural Tangents continued

Degrees	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Mean Differences 1	2	3	4	5
45	1·00000	00350	00701	01053	01406	01761	02117	02474	02832	03192	58	118	177	237	296
46	1·03553	03915	04279	04644	05010	05378	05747	06117	06489	06862	61	123	184	245	307
47	1·07237	07613	07990	08369	08749	09131	09514	09899	10285	10672	63	127	191	255	319
48	1·11061	11452	11844	12238	12633	13029	13428	13828	14229	14632	66	132	199	265	331
49	1·15037	15443	15851	16261	16672	17085	17500	17916	18334	18754	69	138	207	276	344
50	1·19175	19599	20024	20451	20879	21310	21742	22176	22612	23050	72	143	216	288	359
51	1·23490	23931	24375	24820	25268	25717	26169	26622	27077	27535	75	150	225	300	375
52	1·27994	28456	28919	29385	29853	30323	30795	31269	31745	32224	78	157	235	314	392
53	1·32704	33187	33673	34160	34650	35142	35637	36134	36633	37134	82	164	247	329	411
54	1·37638	38145	38653	39165	39679	40195	40714	41235	41759	42286	86	172	259	345	431
55	1·42815	43347	43881	44418	44958	45501	46046	46595	47146	47700	91	181	272	362	453
56	1·48256	48816	49378	49944	50512	51084	51658	52235	52816	53400	95	191	286	382	477
57	1·53987	54576	55170	55767	56366	56969	57575	58184	58797	59414	100	201	302	403	504
58	1·60033	60657	61283	61914	62548	63185	63826	64471	65120	65772	106	213	319	426	533
59	1·66428	67088	67752	68419	69091	69766	70446	71129	71817	72509	113	226	339	452	564
60	1·73205	73905	74610	75319	76032	76749	77471	78198	78929	79665	120	240	360	481	600
61	1·80405	81150	81900	82654	83413	84177	84946	85720	86500	87283	128	255	383	511	639
62	1·88073	88867	89667	90472	91282	92098	92920	93746	94579	95417	136	273	409	546	683
63	1·96261	97111	97967	98828	99695	2·00569	2·01449	2·02335	2·03227	2·04125	146	292	438	584	731
64	2·05030	05942	06860	07785	08716	09654	10600	11552	12511	13477	157	314	471	629	786
65	2·14451	15432	16420	17416	18419	19430	20449	21475	22510	23553	169	338	508	677	846
66	2·24604	25663	26730	27806	28891	29984	31086	32197	33317	34447	183	366	549	732	915
67	2·35585	36733	37891	39058	40235	41421	42618	43825	45043	46270	199	397	596	795	994
68	2·47509	48758	50018	51289	52571	53865	55170	56487	57815	59156					
69	2·60509	61874	63252	64642	66046	67462	68892	70335	71792	73263	Mean differences cease to be sufficiently accurate.				
70	2·74748	76247	77761	79289	80833	82391	83965	85556	87161	88783					
71	2·90421	92076	93748	95437	97144	98868	3·00611	3·02372	3·04152	3·05950					
72	3·07768	09606	11464	13341	15240	17159	19100	21063	23048	25055					
73	3·27085	29139	31216	33317	35443	37594	39771	41973	44202	46458					
74	3·48741	51053	53393	55761	58160	60588	63048	65538	68061	70616					
75	3·73205	75828	78485	81177	83906	86671	89474	92316	95196	98117					
76	4·01078	04081	07127	10216	13350	16530	19756	23030	26352	29724					
77	4·33148	36623	40152	43735	47374	51071	54826	58641	62518	66458					
78	4·70463	74534	78673	82882	87162	91516	95945	5·00451	5·05037	5·09704					
79	5·14455	19293	24218	29235	34345	39552	44857	50264	55777	61397					
80	5·67128	72974	78938	85024	91236	97576	6·04051	6·10664	6·17419	6·24321					
81	6·31375	38587	45961	53503	61220	69116	77199	85475	93952	7·02637					
82	7·11537	20661	30018	39616	49465	59575	69957	80622	91582	8·02848					
83	8·14435	26356	38625	51259	64275	77689	91520	9·05789	9·20516	9·35724					
84	9·51436	9·6768	9·8448	10·019	10·199	10·385	10·579	10·780	10·988	11·205					
85	11·430	11·664	11·909	12·163	12·429	12·706	12·996	13·300	13·617	13·951					
86	14·301	14·669	15·056	15·464	15·895	16·350	16·832	17·343	17·886	18·464					
87	19·081	19·740	20·446	21·205	22·022	22·904	23·859	24·898	26·031	27·271					
88	28·636	30·145	31·821	33·694	35·801	38·188	40·917	44·066	47·740	52·081					
89	57·290	63·657	71·615	81·847	95·489	114·60	143·24	190·98	286·48	572·96					
90	∞														

25.6 Square Roots

Degrees	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Mean Differences. 1	2	3	4	5
0	1·000	99999	99999	99999	99998	99996	99995	99993	99990	99988	0	1	1	1	1
1	·99985	99982	99978	99974	99970	99966	99961	99956	99951	99945	1	2	2	3	4
2	·99939	99933	99926	99919	99912	99905	99897	99889	99881	99872	1	3	4	5	6
3	·99863	99854	99844	99834	99824	99813	99803	99792	99780	99768	2	4	5	7	9
4	·99756	99744	99731	99719	99705	99692	99678	99664	99649	99635	2	5	7	9	11
5	·99619	99604	99588	99572	99556	99540	99523	99506	99488	99470	3	6	8	11	14
6	·99452	99434	99415	99396	99377	99357	99337	99317	99297	99276	3	7	10	13	16
7	·99255	99233	99211	99189	99167	99144	99122	99098	99075	99051	4	8	11	15	19
8	·99027	99002	98978	98953	98927	98902	98876	98849	98823	98796	4	9	13	17	22
9	·98769	98741	98714	98686	98657	98629	98600	98570	98541	98511	5	10	14	19	24
10	·98481	98450	98420	98388	98357	98325	98294	98261	98229	98196	5	11	16	21	27
11	·98163	98129	98096	98061	98027	97992	97958	97922	97887	97851	6	12	17	23	29
12	·97815	97778	97742	97705	97667	97630	97592	97553	97515	97476	6	13	19	25	32
13	·97437	97398	97358	97318	97278	97237	97196	97155	97113	97072	7	14	20	27	34
14	·97030	96987	96945	96902	96858	96815	96771	96727	96682	96638	7	16	22	29	36
15	·96593	96547	96502	96456	96410	96363	96316	96269	96222	96174	8	16	23	31	39
16	·96126	96078	96029	95981	95931	95882	95832	95782	95732	95681	8	17	25	33	41
17	·95630	95579	95528	95476	95424	95372	95319	95266	95213	95159	9	17	26	35	44
18	·95106	95052	94997	94943	94888	94832	94777	94721	94665	94609	9	18	28	37	46
19	·94552	94495	94438	94380	94322	94264	94206	94147	94088	94029	10	19	29	39	49
20	·93969	93909	93849	93789	93728	93667	93606	93544	93483	93420	10	20	31	41	51
21	·93358	93295	93232	93169	93106	93042	92978	92913	92849	92784	10	21	32	43	54
22	·92718	92653	92587	92521	92455	92388	92321	92254	92186	92119	11	22	33	45	56
23	·92050	91982	91914	91845	91775	91706	91636	91566	91496	91425	11	23	35	46	58
24	·91355	91283	91212	91140	91068	90996	90924	90851	90778	90704	12	24	36	48	60
25	·90631	90557	90483	90408	90334	90259	90183	90108	90032	89956	13	25	38	50	63
26	·89879	89803	89726	89649	89571	89493	89415	89337	89259	89180	13	26	39	52	65
27	·89101	89021	88942	88862	88782	88701	88620	88539	88458	88377	13	27	40	54	67
28	·88295	88213	88130	88048	87965	87882	87798	87715	87631	87546	14	28	42	56	69
29	·87462	87377	87292	87207	87121	87036	86949	86863	86777	86690	14	29	43	57	72
30	·86603	86515	86427	86340	86251	86163	86074	85985	85896	85806	15	30	44	59	74
31	·85717	85627	85536	85446	85355	85264	85173	85081	84989	84897	16	30	46	61	76
32	·84805	84712	84619	84526	84433	84339	84245	84151	84057	83962	16	31	47	62	78
33	·83867	83772	83676	83581	83485	83389	83292	83195	83098	83001	16	32	48	64	80
34	·82904	82806	82708	82610	82511	82413	82314	82214	82115	82015	16	33	49	66	82
35	·81915	81815	81714	81614	81513	81412	81310	81208	81106	81004	17	34	51	68	84
36	·80902	80799	80696	80593	80489	80386	80282	80178	80073	79968	17	35	52	69	87
37	·79864	79758	79653	79547	79441	79335	79229	79122	79015	78908	18	35	53	71	89
38	·78801	78693	78586	78478	78369	78261	78152	78043	77934	77824	18	36	54	72	91
39	·77715	77605	77494	77384	77273	77162	77051	76940	76828	76717	18	37	56	74	93
40	·76604	76492	76380	76267	76154	76041	75927	75813	75700	75585	19	38	57	76	94
41	·75471	75356	75241	75126	75011	74896	74780	74664	74548	74431	19	39	58	77	96
42	·74314	74198	74080	73963	73846	73728	73610	73491	73373	73254	20	39	59	79	98
43	·73135	73016	72897	72777	72657	72537	72417	72297	72176	72055	20	40	60	80	100
44	·71934	71813	71691	71569	71447	71325	71203	71080	70957	70834	20	41	61	82	102

Continued…

Square Roots continued

	0	1	2	3	4	5	6	7	8	9	Mean Differences. 1	2	3	4	5	6	7	8	9
5·5	2·3452	2·3473	2·3495	2·3516	2·3537	2·3558	2·3580	2·3601	2·3622	2·3643	2	4	6	8	11	13	15	17	19
5·6	2·3664	2·3685	2·3707	2·3728	2·3749	2·3770	2·3791	2·3812	2·3833	2·3854	2	4	6	8	11	13	15	17	19
5·7	2·3875	2·3896	2·3917	2·3937	2·3958	2·3979	2·4000	2·4021	2·4042	2·4062	2	4	6	8	10	12	15	17	19
5·8	2·4083	2·4104	2·4125	2·4145	2·4166	2·4187	2·4207	2·4228	2·4249	2·4269	2	4	6	8	10	12	14	16	19
5·9	2·4290	2·4310	2·4331	2·4352	2·4372	2·4393	2·4413	2·4434	2·4454	2·4474	2	4	6	8	10	12	14	16	18
6·0	2·4495	2·4515	2·4536	2·4556	2·4576	2·4597	2·4617	2·4637	2·4658	2·4678	2	4	6	8	10	12	14	16	18
6·1	2·4698	2·4718	2·4739	2·4759	2·4779	2·4799	2·4819	2·4839	2·4860	2·4880	2	4	6	8	10	12	14	16	18
6·2	2·4900	2·4920	2·4940	2·4960	2·4980	2·5000	2·5020	2·5040	2·5060	2·5080	2	4	6	8	10	12	14	16	18
6·3	2·5100	2·5120	2·5140	2·5159	2·5179	2·5199	2·5219	2·5239	2·5259	2·5278	2	4	6	8	10	12	14	16	18
6·4	2·5298	2·5318	2·5338	2·5357	2·5377	2·5397	2·5417	2·5436	2·5456	2·5475	2	4	6	8	10	12	14	16	18
6·5	2·5495	2·5515	2·5534	2·5554	2·5573	2·5593	2·5612	2·5632	2·5652	2·5671	2	4	6	8	10	12	14	16	18
6·6	2·5690	2·5710	2·5729	2·5749	2·5768	2·5788	2·5807	2·5826	2·5846	2·5865	2	4	6	8	10	12	14	16	17
6·7	2·5884	2·5904	2·5923	2·5942	2·5962	2·5981	2·6000	2·6019	2·6038	2·6058	2	4	6	8	10	12	14	15	17
6·8	2·6077	2·6096	2·6115	2·6134	2·6153	2·6173	2·6192	2·6211	2·6230	2·6249	2	4	6	8	10	11	13	15	17
6·9	2·6268	2·6287	2·6306	2·6325	2·6344	2·6363	2·6382	2·6401	2·6420	2·6439	2	4	6	8	10	11	13	15	17
7·0	2·6458	2·6476	2·6495	2·6514	2·6533	2·6552	2·6571	2·6589	2·6608	2·6627	2	4	6	8	9	11	13	15	17
7·1	2·6646	2·6665	2·6683	2·6702	2·6721	2·6739	2·6758	2·6777	2·6796	2·6814	2	4	6	7	9	11	13	15	17
7·2	2·6833	2·6851	2·6870	2·6889	2·6907	2·6926	2·6944	2·6963	2·6981	2·7000	2	4	6	7	9	11	13	15	17
7·3	2·7019	2·7037	2·7055	2·7074	2·7092	2·7111	2·7129	2·7148	2·7166	2·7185	2	4	6	7	9	11	13	15	17
7·4	2·7203	2·7221	2·7240	2·7258	2·7276	2·7295	2·7313	2·7331	2·7350	2·7368	2	4	5	7	9	11	13	15	16
7·5	2·7386	2·7404	2·7423	2·7441	2·7459	2·7477	2·7495	2·7514	2·7532	2·7550	2	4	5	7	9	11	13	15	16
7·6	2·7568	2·7586	2·7604	2·7622	2·7641	2·7659	2·7677	2·7695	2·7713	2·7731	2	4	5	7	9	11	13	14	16
7·7	2·7749	2·7767	2·7785	2·7803	2·7821	2·7839	2·7857	2·7875	2·7893	2·7911	2	4	5	7	9	11	13	14	16
7·8	2·7928	2·7946	2·7964	2·7982	2·8000	2·8018	2·8036	2·8054	2·8071	2·8089	2	4	5	7	9	11	13	14	16
7·9	2·8107	2·8125	2·8142	2·8160	2·8178	2·8196	2·8213	2·8231	2·8249	2·8267	2	4	5	7	9	11	12	14	16
8·0	2·8284	2·8302	2·8320	2·8337	2·8355	2·8373	2·8390	2·8408	2·8425	2·8443	2	4	5	7	9	11	12	14	16
8·1	2·8460	2·8478	2·8496	2·8513	2·8531	2·8548	2·8566	2·8583	2·8601	2·8618	2	4	5	7	9	11	12	14	16
8·2	2·8636	2·8653	2·8671	2·8688	2·8705	2·8723	2·8740	2·8758	2·8775	2·8792	2	3	5	7	9	10	12	14	16
8·3	2·8810	2·8827	2·8844	2·8862	2·8879	2·8896	2·8914	2·8931	2·8948	2·8965	2	3	5	7	9	10	12	14	16
8·4	2·8983	2·9000	2·9017	2·9034	2·9052	2·9069	2·9086	2·9103	2·9120	2·9138	2	3	5	7	9	10	12	14	15
8·5	2·9155	2·9172	2·9189	2·9206	2·9223	2·9240	2·9257	2·9275	2·9292	2·9309	2	3	5	7	9	10	12	14	15
8·6	2·9326	2·9343	2·9360	2·9377	2·9394	2·9411	2·9428	2·9445	2·9462	2·9479	2	3	5	7	9	10	12	14	15
8·7	2·9496	2·9513	2·9530	2·9547	2·9563	2·9580	2·9597	2·9614	2·9631	2·9648	2	3	5	7	9	10	12	14	15
8·8	2·9665	2·9682	2·9698	2·9715	2·9732	2·9749	2·9766	2·9783	2·9799	2·9816	2	3	5	7	8	10	12	13	15
8·9	2·9833	2·9850	2·9866	2·9883	2·9900	2·9917	2·9933	2·9950	2·9967	2·9983	2	3	5	7	8	10	12	13	15
9·0	3·0000	3·0017	3·0033	3·0050	3·0067	3·0083	3·0100	3·0116	3·0133	3·0150	2	3	5	7	8	10	12	13	15
9·1	3·0166	3·0183	3·0199	3·0216	3·0232	3·0249	3·0265	3·0282	3·0299	3·0315	2	3	5	7	8	10	12	13	15
9·2	3·0332	3·0348	3·0364	3·0381	3·0397	3·0414	3·0430	3·0447	3·0463	3·0480	2	3	5	7	8	10	11	13	15
9·3	3·0496	3·0512	3·0529	3·0545	3·0561	3·0578	3·9594	3·0610	3·0627	3·0643	2	3	5	7	8	10	11	13	15
9·4	3·0659	3·0676	3·0692	3·0708	3·0725	3·0741	3·0757	3·0773	3·0790	3·0806	2	3	5	7	8	10	11	13	15
9·5	3·0822	3·0838	3·0854	3·0871	3·0887	3·0903	3·0919	3·0935	3·0952	3·0968	2	3	5	6	8	10	11	13	15
9·6	3·0984	3·1000	3·1016	3·1032	3·1048	3·1064	3·1081	3·1097	3·1113	3·1129	2	3	5	6	8	10	11	13	14
9·7	3·1145	3·1161	3·1177	3·1193	3·1209	3·1225	3·1241	3·1257	3·1273	3·1289	2	3	5	6	8	10	11	13	14
9·8	3·1305	3·1321	3·1337	3·1353	3·1369	3·1385	3·1401	3·1417	3·1432	3·1448	2	3	5	6	8	10	11	13	14
9·9	3·1464	3·1480	3·1496	3·1512	3·1528	3·1544	3·1559	3·1575	3·1591	3·1607	2	3	5	6	8	9	11	13	14

Continued…

Square Roots continued

	0	1	2	3	4	5	6	7	8	9	Mean Differences.								
											1	2	3	4	5	6	7	8	9
10	3·1623	3·1780	3·1937	3·2094	3·2249	3·2404	3·2558	3·2711	3·2863	3·3015	15	31	46	62	77	92	108	123	139
11	3·3166	3·3317	3·3466	3·3615	3·3764	3·3912	3·4059	3·4205	3·4351	3·4496	15	30	44	59	74	89	104	118	133
12	3·4641	3·4785	3·4928	3·5071	3·5214	3·5355	3·5496	3·5637	3·5777	3·5917	14	28	43	57	71	85	99	114	128
13	3·6056	3·6194	3·6332	3·6469	3·6606	3·6742	3·6878	3·7014	3·7148	3·7283	14	27	41	54	68	82	95	109	122
14	3·7417	3·7550	3·7683	3·7815	3·7947	3·8079	3·8210	3·8341	3·8471	3·8601	13	26	39	52	66	79	92	105	118
15	3·8730	3·8859	3·8987	3·9115	3·9243	3·9370	3·9497	3·9623	3·9749	3·9875	13	25	38	51	64	76	89	102	114
16	4·0000	4·0125	4·0249	4·0373	4·0497	4·0620	4·0743	4·0866	4·0988	4·1110	12	25	37	49	62	74	86	98	111
17	4·1231	4·1352	4·1473	4·1593	4·1713	4·1833	4·1952	4·2071	4·2190	4·2308	12	24	36	48	60	72	84	96	108
18	4·2426	4·2544	4·2661	4·2778	4·2895	4·3012	4·3128	4·3243	4·3359	4·3474	12	23	35	46	58	70	81	93	104
19	4·3589	4·3704	4·3818	4·3932	4·4045	4·4159	4·4272	4·4385	4·4497	4·4609	11	23	34	45	57	68	79	90	102
20	4·4721	4·4833	4·4944	4·5056	4·5166	4·5277	4·5387	4·5497	4·5607	4·5717	11	22	33	44	56	67	78	89	100
21	4·5826	4·5935	4·6043	4·6152	4·6260	4·6368	4·6476	4·6583	4·6690	4·6797	11	22	32	43	54	65	76	86	97
22	4·6904	4·7011	4·7117	4·7223	4·7329	4·7434	4·7539	4·7645	4·7749	4·7854	11	21	32	42	53	63	74	84	95
23	4·7958	4·8062	4·8166	4·8270	4·8374	4·8477	4·8580	4·8683	4·8785	4·8888	10	21	31	41	52	62	72	82	93
24	4·8990	4·9092	4·9193	4·9295	4·9396	4·9497	4·9598	4·9699	4·9800	4·9900	10	20	30	40	51	61	71	81	91
25	5·0000	5·0100	5·0200	5·0299	5·0398	5·0498	5·0596	5·0695	5·0794	5·0892	10	20	30	40	50	59	69	79	89
26	5·0990	5·1088	5·1186	5·1284	5·1381	5·1478	5·1575	5·1672	5·1769	5·1865	10	19	29	39	49	58	68	78	87
27	5·1962	5·2058	5·2154	5·2249	5·2345	5·2440	5·2536	5·2631	5·2726	5·2820	10	19	29	38	48	57	67	76	86
28	5·2915	5·3009	5·3104	5·3198	5·3292	5·3385	5·3479	5·3572	5·3666	5·3759	9	19	28	38	47	56	66	75	85
29	5·3852	5·3944	5·4037	5·4129	5·4222	5·4314	5·4406	5·4498	5·4589	5·4681	9	18	28	37	46	55	64	74	83
30	5·4772	5·4863	5·4955	5·5045	5·5136	5·5227	5·5317	5·5408	5·5498	5·5588	9	18	27	36	46	55	64	73	82
31	5·5678	5·5767	5·5857	5·5946	5·6036	5·6125	5·6214	5·6303	5·6391	5·6480	9	18	27	36	45	53	62	71	80
32	5·6569	5·6657	5·6745	5·6833	5·6921	5·7009	5·7096	5·7184	5·7271	5·7359	9	18	26	35	44	53	62	70	79
33	5·7446	5·7533	5·7619	5·7706	5·7793	5·7879	5·7966	5·8052	5·8138	5·8224	9	17	26	34	43	52	60	69	77
34	5·8310	5·8395	5·8481	5·8566	5·8652	5·8737	5·8822	5·8907	5·8992	5·9076	9	17	26	34	43	51	60	68	77
35	5·9161	5·9245	5·9330	5·9414	5·9498	5·9582	5·9666	5·9749	5·9833	5·9917	8	17	25	34	42	50	59	67	76
36	6·0000	6·0083	6·0166	6·0249	6·0332	6·0415	6·0498	6·0581	6·0663	6·0745	8	17	25	33	42	50	58	66	75
37	6·0828	6·0910	6·0992	6·1074	6·1156	6·1237	6·1319	6·1400	6·1482	6·1563	8	16	25	33	41	49	57	66	74
38	6·1644	6·1725	6·1806	6·1887	6·1968	6·2048	6·2129	6·2209	6·2290	6·2370	8	16	24	32	41	49	57	65	73
39	6·2450	6·2530	6·2610	6·2690	6·2769	6·2849	6·2929	6·3008	6·3087	6·3166	8	16	24	32	40	48	56	64	72
40	6·3246	6·3325	6·3403	6·3482	6·3561	6·3640	6·3718	6·3797	6·3875	6·3953	8	16	24	32	40	47	55	63	71
41	6·4031	6·4109	6·4187	6·4265	6·4343	6·4420	6·4498	6·4576	6·4653	6·4730	8	16	23	31	39	47	55	62	70
42	6·4807	6·4885	6·4962	6·5038	6·5115	6·5192	6·5269	6·5345	6·5422	6·5498	8	15	23	31	39	46	54	62	69
43	6·5574	6·5651	6·5727	6·5803	6·5879	6·5955	6·6030	6·6106	6·6182	6·6257	8	15	23	30	38	46	53	61	68
44	6·6332	6·6408	6·6483	6·6558	6·6633	6·6708	6·6783	6·6858	6·6933	6·7007	8	15	23	30	38	45	53	60	68
45	6·7082	6·7157	6·7231	6·7305	6·7380	6·7454	6·7528	6·7602	6·7676	6·7750	7	15	22	30	37	44	52	59	67
46	6·7823	6·7897	6·7971	6·8044	6·8118	6·8191	6·8264	6·8337	6·8411	6·8484	7	15	22	29	37	44	51	58	66
47	6·8557	6·8629	6·8702	6·8775	6·8848	6·8920	6·8993	6·9065	6·9138	6·9210	7	15	22	29	37	44	51	58	66
48	6·9282	6·9354	6·9426	6·9498	6·9570	6·9642	6·9714	6·9785	6·9857	6·9929	7	14	22	29	36	43	50	58	65
49	7·0000	7·0071	7·0143	7·0214	7·0285	7·0356	7·0427	7·0498	7·0569	7·0640	7	14	21	28	36	43	50	57	64
50	7·0711	7·0781	7·0852	7·0922	7·0993	7·1063	7·1134	7·1204	7·1274	7·1344	7	14	21	28	35	42	49	56	63
51	7·1414	7·1484	7·1554	7·1624	7·1694	7·1764	7·1833	7·1903	7·1972	7·2042	7	14	21	28	35	42	49	56	63
52	7·2111	7·2180	7·2250	7·2319	7·2388	7·2457	7·2526	7·2595	7·2664	7·2732	7	14	21	28	35	41	48	55	62
53	7·2801	7·2870	7·2938	7·3007	7·3075	7·3144	7·3212	7·3280	7·3348	7·3417	7	14	20	27	34	41	48	54	61
54	7·3485	7·3553	7·3621	7·3689	7·3756	7·3824	7·3892	7·3959	7·4027	7·4095	7	14	20	27	34	41	48	54	61

Continued…

Square Roots continued

	0	1	2	3	4	5	6	7	8	9	Mean Differences.								
											1	2	3	4	5	6	7	8	9
55	7·4162	7·4229	7·4297	7·4364	7·4431	7·4498	7·4565	7·4632	7·4699	7·4766	7	13	20	27	34	40	47	54	60
56	7·4833	7·4900	7·4967	7·5033	7·5100	7·5166	7·5233	7·5299	7·5366	7·5432	7	13	20	27	34	40	47	54	60
57	7·5498	7·5565	7·5631	7·5697	7·5763	7·5829	7·5895	7·5961	7·6026	7·6092	7	13	20	26	33	40	46	53	59
58	7·6158	7·6223	7·6289	7·6354	7·6420	7·6485	7·6551	7·6616	7·6681	7·6746	7	13	20	26	33	39	46	52	59
59	7·6811	7·6877	7·6942	7·7006	7·7071	7·7136	7·7201	7·7266	7·7330	7·7395	7	13	20	26	33	39	46	52	59
60	7·7460	7·7524	7·7589	7·7653	7·7717	7·7782	7·7846	7·7910	7·7974	7·8038	6	13	19	26	32	38	45	51	58
61	7·8102	7·8166	7·8230	7·8294	7·8358	7·8422	7·8486	7·8549	7·8613	7·8677	6	13	19	26	32	38	45	51	58
62	7·8740	7·8804	7·8867	7·8930	7·8994	7·9057	7·9120	7·9183	7·9246	7·9310	6	13	19	25	32	38	44	50	57
63	7·9373	7·9436	7·9498	7·9561	7·9624	7·9687	7·9750	7·9812	7·9875	7·9937	6	13	19	25	32	38	44	50	57
64	8·0000	8·0062	8·0125	8·0187	8·0250	8·0312	8·0374	8·0436	8·0498	8·0561	6	12	19	25	31	37	43	50	56
65	8·0623	8·0685	8·0747	8·0808	8·0870	8·0932	8·0994	8·1056	8·1117	8·1179	6	12	19	25	31	37	43	50	56
66	8·1240	8·1302	8·1363	8·1425	8·1486	8·1548	8·1609	8·1670	8·1731	8·1792	6	12	18	24	31	37	43	49	55
67	8·1854	8·1915	8·1976	8·2037	8·2098	8·2158	8·2219	8·2280	8·2341	8·2401	6	12	18	24	31	37	43	49	55
68	8·2462	8·2523	8·2583	8·2644	8·2704	8·2765	8·2825	8·2885	8·2946	8·3006	6	12	18	24	30	36	42	48	54
69	8·3066	8·3126	8·3187	8·3247	8·3307	8·3367	8·3427	8·3487	8·3546	8·3606	6	12	18	24	30	36	42	48	54
70	8·3666	8·3726	8·3785	8·3845	8·3905	8·3964	8·4024	8·4083	8·4143	8·4202	6	12	18	24	30	36	42	48	54
71	8·4261	8·4321	8·4380	8·4439	8·4499	8·4558	8·4617	8·4676	8·4735	8·4794	6	12	18	24	30	35	41	47	53
72	8·4853	8·4912	8·4971	8·5029	8·5088	8·5147	8·5206	8·5264	8·5323	8·5381	6	12	18	24	30	35	41	47	53
73	8·5440	8·5499	8·5557	8·5615	8·5674	8·5732	8·5790	8·5849	8·5907	8·5965	6	12	17	23	29	35	41	46	52
74	8·6023	8·6081	8·6139	8·6197	8·6255	8·6313	8·6371	8·6429	8·6487	8·6545	6	12	17	23	29	35	41	46	52
75	8·6603	8·6660	8·6718	8·6776	8·6833	8·6891	8·6948	8·7006	8·7063	8·7121	6	12	17	23	29	35	41	46	52
76	8·7178	8·7235	8·7293	8·7350	8·7407	8·7464	8·7521	8·7579	8·7636	8·7693	6	11	17	23	29	34	40	46	51
77	8·7750	8·7807	8·7864	8·7920	8·7977	8·8034	8·8091	8·8148	8·8204	8·8261	6	11	17	23	29	34	40	46	51
78	8·8318	8·8374	8·8431	8·8487	8·8544	8·8600	8·8657	8·8713	8·8769	8·8826	6	11	17	22	28	34	39	45	50
79	8·8882	8·8938	8·8994	8·9051	8·9107	8·9163	8·9219	8·9275	8·9331	8·9387	6	11	17	22	28	34	39	45	50
80	8·9443	8·9499	8·9554	8·9610	8·9666	8·9722	8·9778	8·9833	8·9889	8·9944	6	11	17	22	28	34	39	45	50
81	9·0000	9·0056	9·0111	9·0167	9·0222	9·0277	9·0333	9·0388	9·0443	9·0499	6	11	17	22	28	33	39	44	50
82	9·0554	9·0609	9·0664	9·0719	9·0774	9·0830	9·0885	9·0940	9·0995	9·1049	6	11	17	22	28	33	39	44	50
83	9·1104	9·1159	9·1214	9·1269	9·1324	9·1378	9·1433	9·1488	9·1542	9·1597	6	11	17	22	28	33	39	44	50
84	9·1652	9·1706	9·1761	9·1815	9·1869	9·1924	9·1978	9·2033	9·2087	9·2141	5	11	16	22	27	32	38	43	49
85	9·2195	9·2250	9·2304	9·2358	9·2412	9·2466	9·2520	9·2574	9·2628	9·2682	5	11	16	22	27	32	38	43	49
86	9·2736	9·2790	9·2844	9·2898	9·2952	9·3005	9·3059	9·3113	9·3167	9·3220	5	11	16	22	27	32	38	43	49
87	9·3274	9·3327	9·3381	9·3434	9·3488	9·3541	9·3595	9·3648	9·3702	9·3755	5	11	16	21	27	32	37	42	48
88	9·3808	9·3862	9·3915	9·3968	9·4021	9·4074	9·4128	9·4181	9·4234	9·4287	5	11	16	21	27	32	37	42	48
89	9·4340	9·4393	9·4446	9·4499	9·4552	9·4604	9·4657	9·4710	9·4763	9·4816	5	11	16	21	27	32	37	42	48
90	9·4868	9·4921	9·4974	9·5026	9·5079	9·5131	9·5184	9·5237	9·5289	9·5341	5	11	16	21	27	32	37	42	48
91	9·5394	9·5446	9·5499	9·5551	9·5603	9·5656	9·5708	9·5760	9·5812	9·5864	5	11	16	21	26	31	36	42	47
92	9·5917	9·5969	9·6021	9·6073	9·6125	9·6177	9·6229	9·6281	9·6333	9·6385	5	11	16	21	26	31	36	42	47
93	9·6437	9·6488	9·6540	9·6592	9·6644	9·6695	9·6747	9·6799	9·6850	9·6902	5	10	16	21	26	31	36	42	47
94	9·6954	9·7005	9·7057	9·7108	9·7160	9·7211	9·7263	9·7314	9·7365	9·7417	5	10	15	20	26	31	36	41	46
95	9·7468	9·7519	9·7570	9·7622	9·7673	9·7724	9·7775	9·7826	9·7877	9·7929	5	10	15	20	26	31	36	41	46
96	9·7980	9·8031	9·8082	9·8133	9·8184	9·8234	9·8285	9·8336	9·8387	9·8438	5	10	15	20	26	31	36	41	46
97	9·8489	9·8539	9·8590	9·8641	9·8691	9·8742	9·8793	9·8843	9·8894	9·8944	5	10	15	20	26	31	36	41	46
98	9·8995	9·9045	9·9096	9·9146	9·9197	9·9247	9·9298	9·9348	9·9398	9·9448	5	10	15	20	25	30	35	40	45
99	9·9499	9·9549	9·9599	9·9649	9·9700	9·9750	9·9800	9·9850	9·9900	9·9950	5	10	15	20	25	30	35	40	45

25.7 Reciprocals

	0	1	2	3	4	5	6	7	8	9	Mean Differences.								
											1	2	3	4	5	6	7	8	9
1·0	1·0000	99010	98039	97087	96154	95238	94340	93458	92593	91743									
1·1	·90909	90090	89286	88496	87719	86957	86207	85470	84746	84034									
1·2	·83333	82645	81967	81301	80645	80000	79365	78740	78125	77519									
1·3	·76923	76336	75758	75188	74627	74074	73529	72993	72464	71942									
1·4	·71429	70922	70423	69930	69444	68966	68493	68027	67568	67114									
1·5	·66667	66225	65789	65359	64935	64516	64103	63694	63291	62893									
1·6	·62500	62112	61728	61350	60976	60606	60241	59880	59524	59172	37	74	110	147	184	221	258	294	331
1·7	·58824	58480	58140	57803	57471	57143	56818	56497	56180	55866	33	65	98	131	164	196	229	262	294
1·8	·55556	55249	54945	54645	54348	54054	53763	53476	53191	52910	29	58	88	117	146	175	204	234	263
1·9	·52632	52356	52083	51813	51546	51282	51020	50761	50505	50251	26	53	79	105	132	158	184	210	237
2·0	·50000	49751	49505	49261	49020	48780	48544	48309	48077	47847	24	48	71	95	119	143	167	190	214
2·1	·47619	47393	47170	46948	46729	46512	46296	46083	45872	45662	22	43	65	86	108	130	151	173	194
2·2	·45455	45249	45045	44843	44643	44444	44248	44053	43860	43668	20	40	59	79	99	119	139	158	178
2·3	·43478	43290	43103	42918	42735	42553	42373	42194	42017	41841	18	36	54	72	91	109	127	145	163
2·4	·41667	41494	41322	41152	40984	40816	40650	40486	40323	40161	17	33	50	67	84	100	117	134	150
2·5	·40000	39841	39683	39526	39370	39216	39063	38911	38760	38610	15	31	46	62	77	92	108	123	139
2·6	·38462	38314	38168	38023	37879	37736	37594	37453	37313	37175	14	29	43	57	72	86	100	114	129
2·7	·37037	36900	36765	36630	36496	36364	36232	36101	35971	35842	13	26	40	53	66	79	92	106	119
2·8	·35714	35587	35461	35336	35211	35088	34965	34843	34722	34602	12	25	37	49	62	74	86	98	111
2·9	·34483	34364	34247	34130	34014	33898	33784	33670	33557	33445	12	23	35	46	58	69	81	92	104
3·0	·33333	33223	33113	33003	32895	32787	32680	32573	32468	32362	11	22	32	43	54	65	76	86	97
3·1	·32258	32154	32051	31949	31847	31746	31646	31546	31447	31348	10	20	30	40	51	61	71	81	91
3·2	·31250	31153	31056	30960	30864	30769	30675	30581	30488	30395	10	19	29	38	48	57	67	76	86
3·3	·30303	30211	30120	30030	29940	29851	29762	29674	29586	29499	9	18	27	36	45	53	62	71	80
3·4	·29412	29326	29240	29155	29070	28986	28902	28818	28736	28653	8	17	25	34	42	50	59	67	76
3·5	·28571	28490	28409	28329	28249	28169	28090	28011	27933	27855	8	16	24	32	40	47	55	63	71
3·6	·27778	27701	27624	27548	27473	27397	27322	27248	27174	27100	8	15	23	30	38	45	53	60	68
3·7	·27027	26954	26882	26810	26738	26667	26596	26525	26455	26385	7	14	21	28	36	43	50	57	64
3·8	·26316	26247	26178	26110	26042	25974	25907	25840	25773	25707	7	14	20	27	34	41	48	54	61
3·9	·25641	25575	25510	25445	25381	25316	25253	25189	25126	25063	6	13	19	26	32	38	45	51	58
4·0	·25000	24938	24876	24814	24752	24691	24631	24570	24510	24450	6	12	18	24	31	37	43	49	55
4·1	·24390	24331	24272	24213	24155	24096	24038	23981	23923	23866	6	12	17	23	29	35	41	46	52
4·2	·23810	23753	23697	23641	23585	23529	23474	23419	23364	23310	6	11	17	22	28	33	39	44	50
4·3	·23256	23202	23148	23095	23041	22989	22936	22883	22831	22779	5	11	16	21	27	32	37	42	48
4·4	·22727	22676	22624	22573	22523	22472	22422	22371	22321	22272	5	10	15	20	26	31	36	41	46
4·5	·22222	22173	22124	22075	22026	21978	21930	21882	21834	21786	5	10	14	19	24	29	34	38	43
4·6	·21739	21692	21645	21598	21552	21505	21459	21413	21368	21322	5	9	14	18	23	28	32	37	41
4·7	·21277	21231	21186	21142	21097	21053	21008	20964	20921	20877	4	9	13	18	22	26	31	35	40
4·8	·20833	20790	20747	20704	20661	20619	20576	20534	20492	20450	4	9	13	17	22	26	30	34	39
4·9	·20408	20367	20325	20284	20243	20202	20161	20121	20080	20040	4	8	12	16	20	25	29	33	37
5·0	·20000	19960	19920	19881	19841	19802	19763	19724	19685	19646	4	8	12	16	20	24	27	31	35
5·1	·19608	19569	19531	19493	19455	19417	19380	19342	19305	19268	4	8	11	15	19	23	26	30	34
5·2	·19231	19194	19157	19120	19084	19048	19011	18975	18939	18904	4	7	11	15	18	22	25	29	33
5·3	·18868	18832	18797	18762	18727	18691	18657	18622	18587	18553	3	7	10	14	18	21	24	28	31
5·4	·18519	18484	18450	18416	18382	18349	18315	18282	18248	18215	3	7	10	14	17	20	24	27	30

Continued…

Reciprocals continued

	0	1	2	3	4	5	6	7	8	9	Mean Differences. 1	2	3	4	5	6	7	8	9
5·5	·18182	18149	18116	18083	18051	18018	17986	17953	17921	17889	3	7	10	13	16	20	23	26	29
5·6	·17857	17825	17794	17762	17731	17699	17668	17637	17606	17575	3	6	9	13	16	19	22	25	28
5·7	·17544	17513	17483	17452	17422	17391	17361	17331	17301	17271	3	6	9	12	15	18	21	24	27
5·8	·17241	17212	17182	17153	17123	17094	17065	17036	17007	16978	3	6	9	12	15	18	20	23	26
5·9	·16949	16920	16892	16863	16835	16807	16779	16750	16722	16694	3	6	9	11	14	17	20	23	25
6·0	·16667	16639	16611	16584	16556	16529	16502	16474	16447	16420	3	6	8	11	14	16	19	22	25
6·1	·16393	16367	16340	16313	16287	16260	16234	16207	16181	16155	3	5	8	11	13	16	19	21	24
6·2	·16129	16103	16077	16051	16026	16000	15974	15949	15924	15898	3	5	8	10	13	15	18	21	23
6·3	·15873	15848	15823	15798	15773	15748	15723	15699	15674	15649	2	5	7	10	12	15	17	20	22
6·4	·15625	15601	15576	15552	15528	15504	15480	15456	15432	15408	2	5	7	10	12	14	17	19	22
6·5	·15385	15361	15337	15314	15291	15267	15244	15221	15198	15175	2	5	7	9	12	14	16	19	21
6·6	·15152	15129	15106	15083	15060	15038	15015	14993	14970	14948	2	5	7	9	11	14	16	18	20
6·7	·14925	14903	14881	14859	14837	14815	14793	14771	14749	14728	2	4	7	9	11	13	15	18	20
6·8	·14706	14684	14663	14641	14620	14599	14577	14556	14535	14514	2	4	6	9	11	13	15	17	19
6·9	·14493	14472	14451	14430	14409	14388	14368	14347	14327	14306	2	4	6	8	10	12	14	17	19
7·0	·14286	14265	14245	14225	14205	14184	14164	14144	14124	14104	2	4	6	8	10	12	14	16	18
7·1	·14085	14065	14045	14025	14006	13986	13966	13947	13928	13908	2	4	6	8	10	12	14	16	18
7·2	·13889	13870	13850	13831	13812	13793	13774	13755	13736	13717	2	4	6	8	10	11	13	15	17
7·3	·13699	13680	13661	13643	13624	13605	13587	13569	13550	13532	2	4	6	7	9	11	13	15	17
7·4	·13514	13495	13477	13459	13441	13423	13405	13387	13369	13351	2	4	5	7	9	11	13	15	16
7·5	·13333	13316	13298	13280	13263	13245	13228	13210	13193	13175	2	4	5	7	9	11	12	14	16
7·6	·13158	13141	13123	13106	13089	13072	13055	13038	13021	13004	2	3	5	7	9	10	12	14	15
7·7	·12987	12970	12953	12937	12920	12903	12887	12870	12853	12837	2	3	5	7	8	10	12	13	15
7·8	·12821	12804	12788	12771	12755	12739	12723	12706	12690	12674	2	3	5	7	8	10	11	13	15
7·9	·12658	12642	12626	12610	12594	12579	12563	12547	12531	12516	2	3	5	6	8	9	11	13	14
8·0	·12500	12484	12469	12453	12438	12422	12407	12392	12376	12361	2	3	5	6	8	9	11	12	14
8·1	·12346	12330	12315	12300	12285	12270	12255	12240	12225	12210	2	3	5	6	8	9	11	12	14
8·2	·12195	12180	12165	12151	12136	12121	12107	12092	12077	12063	1	3	4	6	7	9	10	12	13
8·3	·12048	12034	12019	12005	11990	11976	11962	11947	11933	11919	1	3	4	6	7	9	10	11	13
8·4	·11905	11891	11876	11862	11848	11834	11820	11806	11792	11779	1	3	4	6	7	8	10	11	13
8·5	·11765	11751	11737	11723	11710	11696	11682	11669	11655	11641	1	3	4	5	7	8	10	11	12
8·6	·11628	11614	11601	11587	11574	11561	11547	11534	11521	11507	1	3	4	5	7	8	9	11	12
8·7	·11494	11481	11468	11455	11442	11429	11416	11403	11390	11377	1	3	4	5	7	8	9	10	12
8·8	·11364	11351	11338	11325	11312	11299	11287	11274	11261	11249	1	3	4	5	6	8	9	10	12
8·9	·11236	11223	11211	11198	11186	11173	11161	11148	11136	11123	1	3	4	5	6	8	9	10	11
9·0	·11111	11099	11086	11074	11062	11050	11038	11025	11013	11001	1	2	4	5	6	7	9	10	11
9·1	·10989	10977	10965	10953	10941	10929	10917	10905	10893	10881	1	2	4	5	6	7	8	10	11
9·2	·10870	10858	10846	10834	10823	10811	10799	10787	10776	10764	1	2	4	5	6	7	8	9	11
9·3	·10753	10741	10730	10718	10707	10695	10684	10672	10661	10650	1	2	4	5	6	7	8	9	10
9·4	·10638	10627	10616	10604	10593	10582	10571	10560	10549	10537	1	2	3	4	6	7	8	9	10
9·5	·10526	10515	10504	10493	10482	10471	10460	10449	10438	10428	1	2	3	4	5	7	8	9	10
9·6	·10417	10406	10395	10384	10373	10363	10352	10341	10331	10320	1	2	3	4	5	6	8	9	10
9·7	·10309	10299	10288	10277	10267	10256	10246	10235	10225	10215	1	2	3	4	5	6	7	8	10
9·8	·10204	10194	10183	10173	10163	10152	10142	10132	10121	10111	1	2	3	4	5	6	7	8	9
9·9	·10101	10091	10081	10070	10060	10050	10040	10030	10020	10010	1	2	3	4	5	6	7	8	9

25.8 Powers, Roots and Reciprocals

n	n^2	n^3	$\sqrt{n}$	$\sqrt[3]{n}$	$\sqrt{10n}$	$\sqrt[3]{10n}$	$\sqrt[3]{100n}$	$\frac{1}{n}$
1	1	1	1	1	3·1623	2·1544	4·6416	1
2	4	8	1·4142	1·2599	4·4721	2·7144	5·8480	·50000
3	9	27	1·7321	1·4422	5·4772	3·1072	6·6943	·33333
4	16	64	2·000	1·5874	6·3246	3·4200	7·3681	·25000
5	25	125	2·2361	1·7100	7·0711	3·6840	7·9370	·20000
6	36	216	2·4495	1·8171	7·7460	3·9149	8·4343	·16667
7	49	343	2·6458	1·9129	8·3666	4·1213	8·8790	·14286
8	64	512	2·8284	2·000	8·9443	4·3089	9·2832	·12500
9	81	729	3·000	2·0801	9·4868	4·4814	9·6549	·11111
10	100	1000	3·1623	2·1544	10·000	4·6416	10·0000	·10000
11	121	1331	3·3166	2·2240	10·4881	4·7914	10·3228	·090909
12	144	1728	3·4641	2·2894	10·9545	4·9324	10·6266	·083333
13	169	2197	3·6056	2·3513	11·4018	5·0658	10·9139	·076923
14	196	2744	3·7417	2·4101	11·8322	5·1925	11·1869	·071429
15	225	3375	3·8730	2·4662	12·2474	5·3133	11·4471	·066667
16	256	4096	4·000	2·5198	12·6491	5·4288	11·6961	·062500
17	289	4913	4·1231	2·5713	13·0384	5·5397	11·9348	·058824
18	324	5832	4·2426	2·6207	13·4164	5·6462	12·1644	·055556
19	361	6859	4·3589	2·6684	13·7840	5·7489	12·3856	·052632
20	400	8000	4·4721	2·7144	14·1421	5·8480	12·5992	·05000
21	441	9261	4·5826	2·7589	14·4914	5·9439	12·8058	·047619
22	484	10648	4·6904	2·8020	14·8324	6·0368	13·0059	·045455
23	529	12167	4·7958	2·8439	15·1658	6·1269	13·2001	·043478
24	576	13824	4·8990	2·8845	15·4919	6·2145	13·3887	·041667
25	625	15625	5·000	2·9240	15·8114	6·2996	13·5721	·04000
26	676	17576	5·0990	2·9625	16·1245	6·3825	13·7507	·038462
27	729	19683	5·1962	3·0000	16·4317	6·4633	13·9248	·037037
28	784	21952	5·2915	3·0366	16·7332	6·5421	14·0946	·035714
29	841	24389	5·3852	3·0723	17·0294	6·6191	14·2604	·034483
30	900	27000	5·4772	3·1072	17·3205	6·6943	14·4225	·033333
31	961	29791	5·5678	3·1414	17·6068	6·7679	14·5810	·032258
32	1024	32768	5·6569	3·1748	17·8885	6·8399	14·7361	·031250
33	1089	35937	5·7446	3·2075	18·1659	6·9104	14·8881	·030303
34	1156	39304	5·8310	3·2396	18·4391	6·9795	15·0369	·029412
35	1225	42875	5·9161	3·2711	18·7083	7·0473	15·1829	·028571
36	1296	46656	6·000	3·3019	18·9737	7·1138	15·3262	·027778
37	1369	50653	6·0828	3·3322	19·2354	7·1791	15·4668	·027027
38	1444	54872	6·1644	3·3620	19·4936	7·2432	15·6049	·026316
39	1521	59319	6·2450	3·3912	19·7484	7·3061	15·7406	·025641
40	1600	64000	6·3246	3·4200	20·000	7·3681	15·8740	·02500
41	1681	68921	6·4031	3·4482	20·2485	7·4290	16·0052	·024390
42	1764	74088	6·4807	3·4760	20·4939	7·4889	16·1343	·023810
43	1849	79507	6·5574	3·5034	20·7364	7·5478	16·2613	·023256
44	1936	85184	6·6332	3·5303	20·9762	7·6059	16·3864	·022727
45	2025	91125	6·7082	3·5569	21·2132	7·6631	16·5096	·022222
46	2116	97336	6·7823	3·5830	21·4476	7·7194	16·6310	·021739
47	2209	103823	6·8557	3·6088	21·6795	7·7750	16·7507	·021277
48	2304	110592	6·9282	3·6342	21·9089	7·8297	16·8687	·020833
49	2401	117649	7·000	3·6593	22·1359	7·8837	16·9850	·020408
50	2500	125000	7·0711	3·6840	22·3607	7·9370	17·0998	·02000

Continued…

Powers, Roots and Reciprocals continued

n	n^2	n^3	$\sqrt{n}$	$\sqrt[3]{n}$	$\sqrt{10n}$	$\sqrt[3]{10n}$	$\sqrt[3]{100n}$	$\frac{1}{n}$
51	2601	132651	7·1414	3·7084	22·5832	7·9896	17·2130	·019608
52	2704	140608	7·2111	3·7325	22·8035	8·0415	17·3248	·019231
53	2809	148877	7·2801	3·7563	23·0217	8·0927	17·4351	·018868
54	2916	157464	7·3485	3·7798	23·2379	8·1433	17·5441	·018519
55	3025	166375	7·4162	3·8030	23·4521	8·1932	17·6517	·018182
56	3136	175616	7·4833	3·8259	23·6643	8·2426	17·7581	·017857
57	3249	185193	7·5498	3·8485	23·8747	8·2913	17·8632	·017544
58	3364	195112	7·6158	3·8709	24·0832	8·3396	17·9670	·017241
59	3481	205379	7·6811	3·8930	24·2899	8·3872	18·0697	·016949
60	3600	216000	7·7460	3·9149	24·4949	8·4343	18·1712	·016667
61	3721	226981	7·8102	3·9365	24·6982	8·4809	18·2716	·016393
62	3844	238328	7·8740	3·9579	24·8998	8·5270	18·3709	·016129
63	3969	250047	7·9373	3·9791	25·0998	8·5726	18·4691	·015873
64	4096	262144	8·000	4·000	25·2982	8·6177	18·5664	·015625
65	4225	274625	8·0623	4·0207	25·4951	8·6624	18·6626	·015385
66	4356	287496	8·1240	4·0412	25·6905	8·7066	18·7578	·015152
67	4489	300763	8·1854	4·0615	25·8844	8·7503	18·8520	·014925
68	4624	314432	8·2462	4·0817	26·0768	8·7937	18·9454	·014706
69	4761	328509	8·3066	4·1016	26·2679	8·8366	19·0378	·014493
70	4900	343000	8·3666	4·1213	26·4575	8·8790	19·1293	·014286
71	5041	357911	8·4261	4·1408	26·6458	8·9211	19·2200	·014085
72	5184	373248	8·4853	4·1602	26·8328	8·9628	19·3098	·013889
73	5329	389017	8·5440	4·1793	27·0185	9·0041	19·3988	·013699
74	5476	405224	8·6023	4·1983	27·2029	9·0450	19·4870	·013514
75	5625	421875	8·6603	4·2172	27·3861	9·0856	19·5743	·013333
76	5776	438976	8·7178	4·2358	27·5681	9·1258	19·6610	·013158
77	5929	456533	8·7750	4·2543	27·7489	9·1657	19·7468	·012987
78	6084	474552	8·8318	4·2727	27·9285	9·2052	19·8319	·012821
79	6241	493039	8·8882	4·2908	28·1069	9·2443	19·9163	·012658
80	6400	512000	8·9443	4·3089	28·2843	9·2832	20·0000	·012500
81	6561	531441	9·0000	4·3267	28·4605	9·3217	20·0830	·012346
82	6724	551368	9·0554	4·3445	28·6356	9·3599	20·1653	·012195
83	6889	571787	9·1104	4·3621	28·8097	9·3978	20·2469	·012048
84	7056	592704	9·1652	4·3795	28·9828	9·4354	20·3279	·011905
85	7225	614125	9·2195	4·3968	29·1548	9·4727	20·4083	·011765
86	7396	636056	9·2736	4·4140	29·3258	9·5097	20·4880	·011628
87	7569	658503	9·3274	4·4310	29·4958	9·5464	20·5671	·011494
88	7744	681472	9·3808	4·4480	29·6648	9·5828	20·6456	·011364
89	7921	704969	9·4340	4·4647	29·8329	9·6190	20·7235	·011236
90	8100	729000	9·4868	4·4814	30·000	9·6549	20·8008	·011111
91	8281	753571	9·5394	4·4979	30·1662	9·6905	20·8776	·010989
92	8464	778688	9·5917	4·5144	30·3315	9·7259	20·9538	·010870
93	8649	804357	9·6437	4·5307	30·4959	9·7610	21·0294	·010753
94	8836	830584	9·6954	4·5468	30·6594	9·7959	21·1045	·010638
95	9025	857375	9·7468	4·5629	30·8221	9·8305	21·1791	·010526
96	9216	884736	9·7980	4·5789	30·9839	9·8648	21·2532	·010417
97	9409	912673	9·8489	4·5947	31·1448	9·8990	21·3267	·010309
98	9604	941192	9·8995	4·6104	31·3050	9·9329	21·3997	·010204
99	9801	970299	9·9499	4·6261	31·4643	9·9666	21·4723	·010101
100	10000	1000000	10·000	4·6416	31·6228	10·000	21·5443	·0100

25.9 Thermal Properties of Some Common Mould-making Materials

Material	Density g/cm³	Thermal conductivity kcal/m · h · deg. C	Specific heat kcal/kg · deg. C	Coefficient of linear expansion deg. $C^{-1} \cdot 10^6$
Steels				
C 8 WS	7.85	64	0.115	10–14
105 WMnCr6	7.80	34	0.113	10–14
X 45NiCrMo4	7.85	29	0.110	10–14
X 40 Cr 13	7.70	21.5	0.110	11–12
X 10 Cr Ni 18 8	7.80	12.5	0.120	16–19
Cast iron				
3% Ni	7.60	50	0.115	9–15
1% Ni	7.60	43	0.115	9–15
Aluminium	2.65	197	0.210	22–25
Bronze 90% Cu, 10% Sn	8.76	36	0.092	18–25
Copper	8.93	338	0.092	17
Brass 70% Cu, 30% Zn	8.40	94	0.092	19
Zinc	7.10	108	0.093	35
Cu/Co/Be-alloy	8.80	158	0.1	17
Cu/Be/Co-alloy	8.80	76	0.1	17
Epoxy resin, unfilled	1.20	1.8	0.30	50–70
Epoxy resin, filled	—	9.0	—	—

25.10 Typical Thermal and Mechanical Properties of Steels for Injection Moulds

AISI No.	Density (kg/m^3)	Thermal conductivity ($W/(m \cdot K)$)	Thermal expansion ($10^{-6}K^{-1}$)	Spec. heat capacity ($J/(Kg \cdot K)$)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
1020	7850	46.7	11–15	460	520	440	20
1030	7833	46.7	14.9		600	510	17.5
1040	7833	46.7			680	450	16
1095	7800	43.3	11–14	470	1380	960	10–15
4130	7833	46.7			560	360	28
6150	7860	60.6	10–12	460	665	410	23
8620	7833				535	385	31
S1	7960	62.3	11–13	440	2070	1900	4
S7			14.9		2170	1450	7
H13	7800	24.6	12–13	460	950	750	20
P20	7800	29.0	12.7	460	950	750	20
420	7800	23.0	11–12	460	2050	1600	8

25.11 Thermal Properties of Plastics Materials

Polymer operat.	Specific gravity	Specific heat (KJ/kg°C)	Thermal conductivity (W/m/K)	Coeff. of therm. exp. (μm/m/K)	Thermal diffusivity $(m^2/s)x10^{-7}$	Max. temperature (°C)
ABS	1.04	1.47	0.3	90	1.7	70
Acetal (Homo-pol.)	1.42	1.47	0.2	80	0.7	85
Acetal (Co-pol.)	1.41	1.47	0.2	95	0.72	90
Acrylic	1.18	1.47	0.2	70	1.09	50
Cellulose Acetate	1.28	1.50	0.15	100	1.04	60
Epoxy	1.90	-	0.23	70	-	130
Mod. PPO	1.06	-	0.22	60	-	120
PA66	1.14	1.67	0.24	90	1.01	90
PA66 +30%GF	1.38	1.26	0.52	30	1.33	100
PET	1.37	1.05	0.24	90	-	110
PET +30%GF	1.63	-	-	40	-	150
Phenolic	1.40	1.30	0.35	22	1.92	185
PC	1.15	1.26	0.2	65	1.47	125
u-Polyester	1.20	1.20	0.2	100	-	-
PP	0.905	1.93	0.24	100	0.65	100
PS	1.05	1.34	0.15	80	0.6	50
LDPE	0.92	2.30	0.33	200	1.17	50
HDPE	0.95	2.30	0.63	120	1.57	55
PTFE	2.10	1.00	0.25	140	0.7	50
u-PVC	1.40	1.00	0.16	70	1.16	50
p-PVC	1.30	1.67	0.14	140	0.7	50
SAN	1.08	1.38	0.17	70	0.81	60
PS-foam	0.032	-	0.032	-	-	-
Steel	7.854	0.434	60.00	-	14.1	800

25.12 I.S.O. Metric Fine Threads in mm

O.Dia	Core	Pitch	Depth	Flat	Effec.	Tapp'g Drill	C/ance Drill
8	6.773	1.00	0.6134	0.125	7.35	7.00	9.0
10	8.467	1.25	0.7668	0.156	9.18	8.75	11.0
12	10.467	1.25	0.7668	0.156	11.18	10.75	13.5
16	14.160	1.50	0.920	0.187	15.025	14.50	17.5
20	18.160	1.50	0.920	0.187	19.025	18.50	21.5
24	21.546	2.00	1.226	0.250	22.70	22.00	25.5
30	27.546	2.00	1.226	0.250	28.70	28.00	31.5
36	32.319	3.00	1.841	0.375	34.05	32.75	38.0
42	38.265	3.00	1.841	0.375	40.05	38.75	44.0
48	44.28	3.00	1.841	0.375	46.05	44.75	51.0
56	51.093	4.00	2.455	0.500	53.40	51.75	59.0
64	59.065	4.00	2.455	0.500	61.40	59.75	67.0

25.13 I.S.O. Metric Coarse Threads in mm

O.Dia.	Core	Pitch	Depth	Flat	Effec.	Tapp'g Drill	Cl'ance Drill
1.6	1.1706	0.35	0.2147	0.04375	1.373	1.25	1.65
1.8	1.3706	0.35	0.2147	0.04375	1.573	1.45	1.85
2.0	1.5092	0.40	0.2454	0.05000	1.740	1.60	2.05
2.2	1.6480	0.45	0.2760	0.05625	1.908	1.75	2.25
2.5	1.9480	0.45	0.2760	0.05625	2.208	2.05	2.60
3.0	2.3866	0.50	0.3067	0.06250	2.675	2.50	3.10
3.5	2.7638	0.60	0.3681	0.07500	3.110	2.90	3.60
4.0	3.1412	0.70	0.4294	0.08750	3.545	3.30	4.10
4.5	3.5798	0.75	0.4601	0.09375	4.013	3.80	4.60
5.0	4.0184	0.80	0.4908	0.10000	4.480	4.20	5.10
6.0	4.7732	1.00	0.6134	0.12500	5.350	5.00	6.10
7.0	5.7732	1.00	0.6134	0.12500	6.350	6.00	7.20
8.0	6.4664	1.25	0.7668	0.15625	7.188	6.80	8.20
10.0	8.1596	1.50	0.9202	0.18750	9.026	8.50	10.20
12.0	9.8530	1.75	1.0736	0.21875	10.863	10.20	12.20
14.0	11.5462	2.00	1.2269	0.25000	12.701	12.00	14.25
16.0	13.5462	2.00	1,2269	0.25000	14.701	14.00	16.25
18.0	14.9328	2.50	1.5336	0.31250	16.376	15.50	18.25
20.0	16.9328	2.50	1.5336	0.31250	18.376	17.50	20.25
22.0	18.9328	2.50	1.5336	0.31250	20.376	19.50	22.25
24.0	20.3194	3.00	1.8403	0.37500	22.051	21.00	24.25
27.0	23.3194	3.00	1.8403	0.37500	25.051	24.00	27.25
30.0	25.7060	3.50	2.1470	0.43750	27.727	26.50	30.50
33.0	28.7060	3.50	2,1470	0.43750	30.727	29.50	33.50
36.0	31.0924	4.00	2.4538	0.50000	33,402	32.00	36.50
39.0	34.0924	4.00	2.4538	0.50000	36.402	35.00	39.50
42.0	36.4790	4.50	2.7605	0.56250	39.077	37.50	42.50
45.0	39.4790	4.50	2.7605	0.56250	42.077	40.50	45.50
48.0	41.8646	5.00	3.0672	0.62500	44.752	43.00	48.75
52.0	45.8646	5.00	3.0672	0.62500	48.752	47.00	52.75
56.0	49.2522	5.50	3.3739	0.68750	52.428	50.50	56.75
60.0	53.2522	5.50	3.3739	0.68750	56.428	54.50	60.75
64.0	56.6388	6.00	3.6806	0.75000	60.103	58.00	64.75
68.0	60.6388	6.00	3.6806	0.75000	64.103	62.00	68.75

25.14 B.S.F. Threads (55°)

Dia.	O.Dia.	Core	Pitch	Depth	Radius	Effec.	T.P.I.
3/16	0.1875	0.1475	0.0312	0.0200	0.0046	0.1675	32
7/32	0.2188	0.1730	0.0357	0.0229	0.0049	0.1958	28
1/4	0.2500	0.2008	0.0385	0.0246	0.0053	0.2254	26
5/16	0.3125	0.2543	0.0454	0.0291	0.0062	0.2834	22
3/8	0.3750	0.3110	0.0500	0.0320	0.0069	0.3430	20
7/16	0.4375	0.3663	0.0555	0.0356	0.0076	0.4019	18
1/2	0.5000	0.4200	0.0625	0.0400	0.0086	0.4600	16
9/16	0.5625	0.4825	0.0625	0.0400	0.0086	0.5225	16
5/8	0.6250	0.5336	0.0714	0.0457	0.0098	0.5793	14
3/4	0.7500	0.6432	0.0833	0.0534	0.0114	0.6966	12
7/8	0.8750	0.7586	0.0909	0.0582	0.0125	0.8168	11
1"	1.0000	0.8720	0.1000	0.0640	0.0137	0.9360	10
1 1/8	1.1250	0.9828	0.1111	0.0711	0.0153	1.0539	9
1 1/4	1.2500	1.1078	0.1111	0.0711	0.0153	1.1789	9
1 3/8	1.3750	1.2150	0.1250	0.0800	0.0172	1.2950	8
1 1/2	1.5000	1.3400	0.1250	0.0800	0.0172	1.4200	8
1 5/8	1.6250	1.4649	0.1250	0.0800	0.0172	1.5450	8
1 3/4	1.7500	1.5670	0.1429	0.0915	0.0196	1.6585	7
2"	2.0000	1.8170	0.1429	0.0915	0.0196	1.9085	7
2 1/4	2.2500	2.0366	0.1666	0.1067	0.0229	2.1433	6
2 1/2	2.5000	2.2866	0.1666	0.1067	0.0229	2.3933	6
2 3/4	2.7500	2.5366	0.1666	0.1067	0.0229	2.6433	6
3"	3.0000	2.7439	0.2000	0.1280	0.0275	2.8719	5

25.15 Whitworth Threads (55°)

Dia.	O.Dia.	Core	Pitch	Depth	Radius	Effec.	T.P.I.
1/8	0.1250	0.0930	0.0250	0.0160	0.0034	0.1090	40
3/16	0.1875	0.1341	0.0417	0.0267	0.0057	0.1608	24
1/4	0.2500	0.1860	0.0500	0.0320	0.0069	0.2180	20
5/16	0.3125	0.2414	0.0556	0.0356	0.0076	0.2769	18
3/8	0.3750	0.2950	0.0625	0.0400	0.0086	0.3350	16
7/16	0.4375	0.3460	0.0714	0.0457	0.0098	0.3918	14
1/2	0.5000	0.3933	0.0833	0.0534	0.0114	0.4466	12
9/16	0.5625	0.4558	0.0833	0.0534	0.0114	0.5091	12
5/8	0.6250	0.5086	0.0909	0.0582	0.0125	0.5668	11
3/4	0.7500	0.6219	0.1000	0.0640	0.0137	0.6860	10
7/8	0.8750	0.7327	0.1111	0.0711	0.0153	0.8039	9
1"	1.0000	0.8399	0.1250	0.0800	0.0172	0.9200	8
1 1/8	1.1250	0.9420	0.1429	0.0915	0.0196	1.0335	7
1 1/4	1.2500	1.0670	0.1429	0.0915	0.0196	1.1585	7
1 1/2	1.5000	1.2866	0.1667	0.1067	0.0229	1.3933	6
1 3/4	1.7500	1.4939	0.2000	0.1281	0.0275	1.6219	5
2"	2.0000	1.7154	0.2222	0.1423	0.0305	1.8577	4 1/2

25.16 British Pipe Thread (B.S.P.) – Basic Sizes in Inches

Nom. Size	Threads per inch	Pitch	Depth of Thread	Major Diam.	Effect. Diam.	Minor Diam.	Gauge Length
$\frac{1}{8}$	28	0·03571	0·0229	0·3830	0·3601	0·3372	0·1563
$\frac{1}{4}$	19	0·05263	0·0337	0·5180	0·4843	0·4506	0·2367
$\frac{3}{8}$	19	0·05263	,,	0·6560	0·6223	0·5886	0·2500
$\frac{1}{2}$	14	0·07143	0·0457	0·8250	0·7793	0·7336	0·3214
*$\frac{5}{8}$	14	,,	,,	0·9020	0·8563	0·8106	0·3214
$\frac{3}{4}$	14	,,	,,	1·0410	0·9953	0·9496	0·3750
*$\frac{7}{8}$	14	,,	,,	1·1890	1·1433	1·0976	0·3750
1	11	0·09091	0·0582	1·3090	1·2508	1·1926	0·4091
$1\frac{1}{8}$	11	,,	,,	1·4920	1·4338	1·3756	0·4091
$1\frac{1}{4}$	11	,,	,,	1·6500	1·5918	1·5336	0·5000
$1\frac{3}{8}$	11	,,	,,	1·7450	1·6868	1·6286	0·5000
$1\frac{1}{2}$	11	,,	,,	1·8820	1·8238	1·7656	0·5000
*$1\frac{5}{8}$	11	,,	,,	2·0820	2·0238	1·9656	0·6250
$1\frac{3}{4}$	11	,,	,,	2·1160	2·0578	1·9996	0·6250
*$1\frac{7}{8}$	11	,,	,,	2·2440	2·1858	2·1276	0·6250

25.17 British Standard Taper Pipe (B.S.T.P.) Tolerances and Allowances, Turns of Thread

B.S.P. Size (Nominal Bore of Tube)	Gauge Length (Distance of Gauge Plane from Pipe End)		Position of Gauge Plane on Internal Screws	Length of useful Thread on Pipe End not less than: (for Basic Gauge Length)	Fitting Allowance
	Basic	Tol. Plus and Minus	Tol. Plus and Minus		
in.					
1/8	4 3/8	1	1 1/4	7 1/8	2 3/4
1/4	4 1/2	1	1 1/4	7 1/4	2 3/4
3/8	4 3/4	1	1 1/4	7 1/2	2 3/4
1/2	4 1/2	1	1 1/4	7 1/4	2 3/4
3/4	5 1/4	1	1 1/4	8	2 3/4
1	4 1/2	1	1 1/4	7 1/4	2 3/4
1 1/4	5 1/2	1	1 1/4	8 1/4	2 3/4
1 1/2	5 1/2	1	1 1/4	8 1/4	2 3/4
2	6 7/8	1	1 1/4	10 1/8	3 1/4
2 1/2	7 9/16	1 1/2	1 1/2	11 9/16	4
3	8 15/16	1 1/2	1 1/2	12 15/16	4
3 1/2	9 5/8	1 1/2	1 1/2	13 5/8	4
4	11	1 1/2	1 1/2	15 1/2	4 1/2
5	12 3/8	1 1/2	1 1/2	17 3/8	5
6	12 3/8	1 1/2	1 1/2	17 3/8	5
7	13 3/4	2	2	19 1/4	5 1/2
8	15	2	2	20 1/2	5 1/2
9	15	2	2	20 1/2	5 1/2
10	16 1/4	2	2	21 3/4	5 1/2
11	13	2	2	18 1/2	5 1/2
12	13	2	2	18 1/2	5 1/2

25.18 Hardness Comparison Table

BRINELL 10m/m Ball 3000kg load.	FIRTH or VICKERS 120kg	ROCKWELL C .Scale 120°Cone 150kg load.	ROCKWELL B.Scale 1/16"Ball 100kg load.	BRINELL 10m/m Ball 3000kg load.	FIRTH or VICKERS 120kg	ROCKWELL C.Scale 120°Cone 150kg load	ROCKWELL B.Scale 1/16"Ball 100kg load
800	-	72	-	276	278	30	105
780	1220	71	-	269	272	29	104
760	1170	70	-	261	261	28	103
745	1114	68	-	258	258	27	102
725	1060	67	-	255	255	26	102
712	1021	66	-	249	250	25	101
682	940	65	-	245	246	24	100
668	905	64	-	240	240	23	99
652	867	63	-	237	235	22	99
626	803	62	-	229	226	21	98
614	775	61	-	224	221	20	97
601	746	60	-	217	217	19	96
590	727	59	-	211	213	18	95
576	694	57	-	206	209	17	94
552	649	56	-	203	201	16	94
545	639	55	-	200	199	15	93
529	606	54	-	196	197	14	92
514	587	53	120	191	190	13	92
502	565	52	119	187	186	12	91
495	551	51	119	185	184	11	91
477	534	49	118	183	183	10	90
461	502	48	117	180	177	9	89
451	489	47	117	175	174	7	88
444	474	46	116	170	171	6	87
427	460	45	115	167	168	5	87
415	435	44	115	165	165	4	86
401	423	43	114	163	162	3	85
388	401	42	114	160	159	2	84
374	390	41	113	156	154	1	83
370	385	40	112	154	152	-	82
362	380	39	111	152	150	-	82
351	361	38	111	150	149	-	81
346	352	37	110	147	147	-	80
341	344	37	110	145	146	-	79
331	335	36	109	143	144	-	79
323	320	35	109	141	142	-	78
311	312	34	108	140	141	-	77
301	305	33	107	135	135	-	75
293	291	32	106	130	130	-	72
285	285	31	105	-	-	-	-

25.19 Conversion Factors

Multiply	by	to obtain:
Mass		
Short ton (2,000 lb.)	0.9072	t
Long ton (2,240 lb.)	1.0160	t
Metric tonne (t)	1,000.0	kg
Kilogram (kg)	2.2046	lb.
Pound (lb.)	0.4536	kg
or	16.0	oz.
Ounce (oz.)	28.3495	g
Gram (g)	0.03527	oz.
Length		
Meter (m)	39.3700	in.
or	3.2808	ft.
Millimeter (mm)	0.03937	in.
Inch (in.)	0.0254	m
or	25.4	mm
Volume		
Cubic centimeter (cm^3)	0.0610	$in.^3$
Cubic inch ($in.^3$)	16.3871	$cm.^3$
Cubic foot ($ft.^3$)	0.0283	m^3
or	28.3168	L
Ounce (Imperial, liquid)	28.4131	cm^3
Ounce (U.S., liquid)	29.5735	cm^3
Gallon (Imperial)	4.5461	L
Gallon (U.S.)	3.7854	L
Liter (L)[a]	1,000.0	cm^3
Density (mass density) [b]		
$lb./in.^3$	27.6799	g/cm^3
g/cm^3	0.03613	$lb./in.^3$
Force		
Newton (N)	0.1020	kgf
or	0.2248	lbf
Kilogram-force (kgf)	9.8066	N
Tonne-force (tf)	9.8066	kN
Pound-force (lbf)	4.4482	N
KiloNewton (kN)	101.972	kgf
Velocity		
Foot/second (ft./s)	0.3048	m/s
Acceleration/deceleration		
Gravity (g) (average)	32.1740	$ft./s^2$
or	9.8066	m/s^2
Foot/second square ($ft./s^2$)	0.3048	m/s^2
Torque (moment of force)		
Pound force (lbf)	1.3558	N.m
or	0.1383	kgf.m
Newton.meter (N.m)	0.7376	lbf.ft
or	0.1020	kgf.m
Kilogram.force.meter	7.2330	lbf.ft
or	9.8066	N.m

Continued…

Conversion Factors continued

Multiply	by	to obtain:
Pressure		
Poundforce/inch² (lbf/in.², psi)	0.006895	MPa
or	6.8948	kPa
or	0.0703	kgf/cm²
Kilogramforce/cm² (kgf/cm²)	14.2233	psi
Pascal (Pa)	1.0	N/m²
KiloPascal (kPa)	0.1450	psi
or	1.0	kN/m²
or	101.972	kgf/m²
or	0.01020	kgf/cm²
Column mercury inch	3.3741	kPa
Column water inch (at 20 °C)	0.2486	kPa
Atmospheric pressure (bar)	0.9869	kg/cm²
or	100.0	kPa
Degrees (heat)		
Temperature difference (ΔT)		
Degree Celsius (°C)	1.0	°Kelvin (°K)
or	1.8	°F
Degree Fahrenheit (°F)	0.55556	°C
Temperature		
Degrees Fahrenheit (°F)	[(°F – 32) × 5/9]	°C
Degrees Celsius (°C)	[(°C × 9/5 + 32]	°F
Degrees Kelvin (K)	add 273.15 to °C	K
Energy		
Joule (J)	1.0	N.m
British thermal unit (BTU)	1.055	J
or	0.252	Cal
or	778.0	ft.-lb.
Calory (international)	4.1868	J
Kilowatt hour (kWh)	3.6	MJ (megaJoule)
Watt second (Ws)	1.0	J
Power		
Watt (W)	1.0	J/s
BTU/hr	0.2931	W
Horsepower (hp)	746.0	W
Heat flow (conductivity)		
BTU /(ft.² × hour × °F)/inch thickness	0.1442	W/(m × °C)/cm
Viscosity		
Dynamic:		
Poise (P)	1.0	N.s/m²
or	1.0	dyn.s/cm²
Kinematic:		
Stokes (St)	0.1	cm²/s
ft.²/s	0.0929	m²/s

[a] The use of the term liter (L) is discouraged by SI standards. Volumes should be expressed in mm³, cm³, or m³.

26 Glossary of Moulding Terminology

26.1 Time Elements in a Moulding Cycle

Cooling time: This is normally considered to be the time in seconds from the moment injection time (including injection hold time) ends, until the moment the mould starts to open. In reality, however, the cooling time is usually the same time as the cycle time since the coolant flows through the mould continuously, regardless of whether the mould is moving, stopped open or closed. However the statement is true if any form of pulsed cooling is used.

Cycle time: The time in seconds from the start of one shot to the start of the next shot including the mould open time. This is usually measured with a stopwatch at the point when the mould reaches the mould closed position.

Dry cycle (time): This is the time in seconds from the moment the mould starts closing from its fully open position, to the point it arrives again in the fully open position after having closed completely. The times for injection, hold and cooling periods are not included.

The dry cycle includes the mould closing time, the time to clamp and unclamp the mould and the mould opening time.

The dry cycle is an important measure of the clamping performance of a moulding machine. The shorter the dry cycle, the less time is wasted. This is of particular importance in fast cycling applications such as when moulding packaging products.

The dry cycle time depends significantly on the distance the moving platen has to move. The shorter the stroke, the shorter the dry cycle is.

Ejection time: This is the time in seconds required to eject all the mouldings from the mould after the mould starts opening. It includes the time to clear the mould of all mouldings and runners, multi-stroke ejection times and the use of any robots.

The ejection time is part of the overall cycle time. Long ejection times can affect the cycle time seriously because they may require a slow opening speed of the clamp (the dry cycle), or it may require additional mould open time, or the lengthening of any mould open time already in the cycle to accommodate special ejection designs.

Ideally, the ejection time should take place during the mould opening time, and be completed by the time the mould starts closing again, without requiring any mould open time or pause time.

Occasionally, the ejection phase extends into the mould closing time (during the mould closing phase); providing all obstructions are cleared before the mould closes.

Injection hold time: The time in seconds from the moment the first stage (high) injection pressure ends to the end of all subsequent secondary (lower) injection pressure phases. These lower pressure phases are necessary to compensate for the volumetric shrinkage of the material as it cools in the mould cavities.

In very thin walled parts the hold time is frequently not used.

Injection time: The time in seconds during which material is injected into the mould during the first high pressure phase, but not including second stage or holding pressure phases.

Mould closed time: The time in seconds from the moment the mould is fully clamped up, to the moment when it starts opening.

Mould open time: The time in seconds from the moment the mould arrives in the fully open position to the moment when it starts closing for the next cycle. Ideally, a mould should run without any open time but it is often necessary to ensure the mould is clear of all mouldings, runners or robotic removal devices.

Passive cycle: In certain hydro-mechanical machines (using shutters) this occurs at the point the machine is ready to open. After the cooling cycle ends, the clamp force is first relaxed, which takes a fraction of a second, followed by the shutters being withdrawn, which takes another fraction of a second. The total of these time elements, before the mould actually starts opening, is called the passive cycle.

The mould will remain closed at this time and the actual set cooling time includes the time for the passive cycle. This has to be taken into account when setting the cooling period.

However, on fully hydraulic machines and on toggle machines, there is no passive cycle. As soon as the cooling time is ended, the mould starts to open.

Profiled injection: With modern machines controlled by microprocessors, injection and hold pressures can be programmed to change relative to the injection time and/or stroke. The injection pressures or speeds can be increased or decreased in steps, or at a variable rate, to "profile" the injection rate depending on the machine.

With older machines, injection and hold times are distinct times, which are individually set for each individual pressure and time.

26.2 Mould and Processing Terminology

Amorphous: Having no pattern or structure, molecular chains are oriented at random. Amorphous materials have low shrinkage values compared to crystalline materials.

Barrel: This has the same meaning as "Cylinder", see below.

Bolster: A tool usually consists of a set of impressions containing the form to produce the mouldings and a set of plates screwed together into which they are located. This set of containing plates is termed a bolster.

Burned: When the melt is injected into a tool, the advancing front of material has to displace the air from the cavities in order to fill them and for the melt to solidify into the moulding. If the air gets trapped and cannot escape, the incoming melt compresses it, causing the air temperature to rise. This temperature can reach a value that degrades or decomposes the material which gives the moulding a characteristic black sooty appearance.

Cartridge heater: A cylindrical heating element available in different diameters, lengths and wattage ratings. Most often used for heating hot runner manifolds.

Cavity: The portion of the tool containing most of the female form of the moulding. A 4 cavity mould means 4 mouldings are produced each cycle – a 6 cavity, 6 mouldings produced, and so on. The term "impression" is also used in this context, i.e., a 6 impression mould would produce 6 mouldings per cycle.

Clamp force and preload: To ensure that the mould will not open during the injection phase, it must be held closed with a force, or "preload", greater than the minimum clamping force required to just hold the mould closed. This preload is generated by the clamping mechanism of the moulding machine.

As the mould closes, the two mould halves meet at the parting line. At this moment, there is no force on either of the mould halves.

As the clamping mechanism starts to exert its full force, the mould halves start to become compressed together. As the locking force increases, the fixed platen is forced away from the clamping mechanism until the full clamp is achieved. Counteracting this force are the tie bars (see below), which connect the stationary platen to the machine clamping mechanism.

Clamping force: The force that holds the mould together from mould closing to the start of mould opening so that the injection pressure of the material inside the cavity space cannot force the mould open and cause it to flash at the split line. The required clamping force F can be determined by multiplying the total projected area of all cavities (plus any additional area due to cold runners) by the injection pressure.

The term "Locking force" has the same meaning.

Clamping force is measured in kN (kilo Newtons) or MN (Mega Newtons). See "Newton" below.

The clamping force should only be sufficient to ensure the mould will not open while the material is being injected. If excessively high clamping forces are used, the stress on the split line surfaces of the mould may be high enough to damage them. It is also undesirable to mount a small mould on a relatively large machine due to potential damage to the machine platens through the tendency of the mould to "hob" into them.

Clamping pressure: The clamping force divided by the total projected area of the tool.

Closed loop: This is a control system that monitors and adjusts melt temperatures, pressures and other moulding parameters automatically through feedback obtained via transducers in the mould.

Cold runner: A cold runner tool produces a solidified runner and sprue as well as the mouldings each cycle. The runner and sprue are usually re-processed and re-used.

Crystalline: Having a regular or ordered structure termed crystals.

Cushion: When adjusting the length of the injection stroke of a machine, the stroke should be about 10 mm more than the actual shot volume required to fill the mould. This means that when the mould is filled after the end of the injection stroke, there will be still a small amount of plastic left in the cylinder to provide a "cushion", of material at front of the machine screw.

With amorphous plastics (e.g., acrylics, PC, SAN, and PS), there is less or no need for a cushion since their shrinkage is quite small compared to crystalline materials.

The cushion provides a reservoir of material for the holding pressure, to make up for shrinkage. It also overcomes the difficulty of stopping the screw in precisely the right position every time as it retracts (screws back) during plasticising when preparing the shot for the next injection cycle.

A cushion also ensures that in the case of some plastic leaking back through the check valve at the tip of the screw during injection, there will always be sufficient material to fill the mould.

When moulding crystalline materials and/or thick walled products a cushion is essential to provide a reserve of material for adequate filling during the holding pressure phase. However, with fast cycling thin walled products there is often no cushion required.

Cylinder: The tubular container that holds the rotating screw and material. It has heater bands on the outside to help melt the plastic material.

Down time: A term used to describe the time a machine does not have a mould tool on it. This is frequently due to a mould suffering damage and having to be removed from the machine for immediate repair.

Ejected: A part has been ejected when it has been forced out of the mould by an ejector.

Ejector: A device for forcing the moulding components out of the mould tool after the mouldings have solidified and the mould opened (or during mould opening). These are available as pins and blades, or may be specially shaped.

End user: The company that markets the moulding either directly or as part of some other piece of equipment.

Feed: Another term used for “Gate”, see below.

Flash: This is surplus material (usually in the form of a thin film) which is attached to the moulding, resulting in the moulding being rejected. There may be several causes of flash occurring, as follows:

- Material being forced into the cavities at too high a pressure resulting in material penetrating areas of the cavity construction it is not supposed to, for example, down the sides of ejectors
- As the tool wears, gaps in mating sliding parts become larger (making flash more likely)
- As the result of the locking force of the machine being insufficient to keep the tool closed against the incoming injection pressure, which causes the tool to open slightly and allows the material to spread across the faces of the split line of the tool
- Using low viscosity materials that tend flash more easily than high viscosity materials

Force: See “Newton”.

Freeze, frozen: Terms used to describe the condition when the melt has solidified.

Gate: A feature machined into the cavity to connect the runner to the moulding. It is smaller than the runner so that it may be detached easily from the moulding. The gate also performs other functions to control the way in which the melt enters the cavity.

A variety of different gates are used which vary in shape, size and form depending on the size of the moulding and the material being used. A gate is sometimes called a feed.

Guard: A safety device preventing access to the mould tool or dangerous parts of the machine. Opening the guard door of a machine renders the machine (and hence the tool) inoperable and stops all functions.

Guide pillar: Circular steel shafts fixed in one side of the tool and located into a bush (guide bush) on the other half of the tool. The purpose is to make sure that both halves of the tool align together properly as the tool closes.

"Heavy wall" and "thin wall" mouldings: These are subjective descriptions but one common method uses the length to thickness (L:T) ratio, which applies mainly to containers with a more or less uniform wall thickness. Depending on the ratio, a part is deemed either thin walled or heavy/thick walled.

Hobbing: A process where one piece of steel (A) is forced into another (B), thereby leaving a female impression of it in B. This is sometimes used in cavity construction.

Holding pressure: The reduced pressure exerted by the screw after the main injection pressure phase to compensate for volumetric shrinkage. See also "Holding time".

Hopper: The container into which the raw material is poured to feed the material into the cylinder for processing.

Hot runner: A hot runner mould tool is one in which the runner remains at melt temperature. Only the mouldings are produced thus saving wastage or re-processing costs.

Impression: This is a term used to describe all the parts of the tool required for forming the moulding, usually (but not always) in separate insert sets.

Injection unit: The complete injection assembly comprising the cylinder, the screw, heater bands, hopper, metering devices, limit switches and the hydraulic cylinders and motors necessary to actuate injection.

Injection pressure: The first stage pressure exerted by the screw on the molten material to inject the material into the mould tool.

Injection stroke: The distance the screw moves forward to displace the melt into the mould tool. The longer the stroke, the more the material is forced into the mould tool.

Insert: A separate unit located in the mould tool distinct from the plates.

Lock, locking force: These have the same meaning as "Clamping force".

Manifold: Used in hot runner tools. It consists of a block of steel into which a runner system is machined. It contains cartridge heaters and thermocouples to maintain the temperature required to keep the material at melt temperature. It is insulated from the rest of the mould tool to prevent loss of heat.

Mass: The inertia of a body can be described as being its reluctance to start moving, or to stop moving once it has started. A body of large mass requires a large force to change its speed or direction by a noticeable amount, i.e., the body has a large inertia. Thus the mass of a body is a measure of its inertia.

Mass is measured in grams (g) or kilogrammes (kg).

Material: The term used to describe the raw material or "plastic". Polymer is also used in the same context.

Melt: A term used to describe a material in its molten form at its melt temperature.

Melt Flow Index (MFI): A measure of how easily a molten material will flow. The lower the MFI, the more difficult the material it is to inject.

Micron: 0.001 millimetres.

Mould: The total mechanical assembly that provides the means by which the mouldings are produced. The terms "Tool" and "Mould tool" have the same meaning.

Mould designer: The person responsible for designing the mould tool to a standard whereby satisfactory production and quality is achieved.

Moulder: A commonly used term to describe the injection moulding company or department carrying out the moulding operation.

Newton: The force required to give a mass of 1 kg an acceleration of 1 metre per second every second. Prefixes are used by international agreement (SI) to describe quantity. E.g.,

- kN (Kilo Newtons) = 1,000 Newtons
- MN (Mega Newtons) = 1,000,000 Newtons

There are many other prefixes but these (kN and MN) are most frequently used in the injection moulding industry.

Very roughly 10,000 N (or10 kN) = 1 tonne = 1000 kg force. Machine locking or clamping forces are usually expressed in kN. Hence a 400 kN machine has a locking or clamping force of 40 tonnes (force).

Force is also sometimes expressed as 10 kgf, 100 gf, etc, to distinguish it from mass.

Open loop: A method of moulding where no automatic adjustments are made to the processing conditions during moulding, as opposed to a closed loop system (see above).

Operating window: A term used to describe the range of operating settings or conditions of the moulding machine and mould, such as melt temperatures, cooling periods, pressures and other cycle times within which mouldings of satisfactory quality can be produced.

The operating window is heavily dependent on the mould design and mould quality, and in particular the gate size and location and satisfactory ejection. The larger the operating window, the easier it is for the moulder to achieve satisfactory mouldings. By contrast, narrow operating windows require frequent "fiddling" of the moulding conditions incurring higher reject and production costs.

In effect, the wider the operating window, the easier it is for the moulder to produce mouldings of the required quality with low rejections levels.

Plasticised: A material is plasticised when it reaches the melt temperature.

Platen: The part of the machine on which the mould tool is mounted. The fixed platen is at the injection end of the machine and does not move. The moving platen is moved by the machine locking system, via toggles or links, to open and close the mould.

Plates: The basic structure of a mould tool is made up of steel (sometimes aluminium) plates. They may be circular solids or rectangular solids that are available in various diameters, widths, lengths and thicknesses.

The plates have to be machined to accept the cavities or impressions and all other operating mechanisms required by the design. Plates are supplied in different grades of steel or aluminium depending on where they used in the tool construction.

Polymer: The material used for the moulding operation. The terms "Material" and "Plastic" are also used.

Projected area: The total area of the mouldings seen in the direction of the clamping force. In cold runner moulds the area of the runners must also be included. In hot runner moulds, only the projected area of the cavities need be considered.

The forces due to the projected area are the product of the projected area and the injection pressure being used. This force is resisted by the clamping force to ensure the mould is kept closed during the injection phase.

Reprocessed material: Material that is reclaimed by a process in which redundant material, like cold runners and rejects, generated during production may be reused. A granulator is used to chop up the material into small pieces which may be recycled in a controlled proportion in with the "virgin" material.

Runner: A channel machined into the mould tool to direct the flow of the melt to the gates and into the cavities.

Screw: A bar of steel machined with continuous spiral channels in the form of a helix. It is similar to an achimedian screw. The flights of the screw get progressively shallower towards the tip of the screw. The purpose of the screw is to transport the material to the front of the cylinder ready for injection and to provide frictional heat.

Seized, seizing, seized up: When two sliding components start to abrade each other, their surfaces become damaged and ultimately "weld" or "lock" themselves together.

Shear heat: Frictional heat developed in the material by the "shearing" action of the rotating screw on the material and by the material passing through the gates.

Short, shorts: A term used to describe an incomplete moulding.

Shot: The total number of items ejected from the mould tool each time it opens, i.e., all the mouldings and associated runner and sprue (if present).

Shot capacity: Used for defining the maximum amount of plastic that can be injected by the machine. This depends on the screw and cylinder diameter and the stroke of the screw. Shot capacity is usually specified as the maximum mass in grams that the machine can inject in polystyrene, having a specific gravity of 1.05. When moulding other materials, with a different specific gravity, this mass must then be divided by 1.05 to get the corresponding shot volume, and then be multiplied by the value of the specific gravity for such material to obtain its shot mass.

Shot weight: The weight of the total mass of all components moulded during one complete moulding cycle. The shot weight includes all the mouldings and the runner and sprue in cold runner moulds. To maintain adequate control the shot weight should not be less than 25% and not more than 80% of the rated shot capacity of the machine on which the mould is going to be run.

Shrinkage: All materials undergo a volumetric reduction when injected into a cavity. The final size of the moulding is less than that of the cavity in which it is formed. It is necessary to make the cavities large enough so that after shrinkage has taken place, the moulding will be the correct size. Crystalline materials have a higher shrinkage than amorphous ones.

Snatch, snatches, snatch pin: Features designed to ensure that runners are held on the correct half of the tool so that they may be successfully ejected.

Split line: All mould tools must separate into two parts (sometimes more) to allow the part to be ejected from it. The plane where these two halves meet is called the split line.

Split line moulding: Most moulding operations are carried out on a horizontal machine. That is, all the movements of the machine and the tool take place in a horizontal plane. In split line moulding, the injection takes place along the split line of the tool. The tool movements are horizontal and the machine injection carriage vertical.

Sprue: A cylindrical tapered part of the runner system leading from the sprue bush to the runner and thus to the cavities.

Sprue bush: A shaped circular piece of steel that contains the sprue. It is hardened to resist the impact from the nozzle of the cylinder.

Starve feeding: A method of adjusting the injection system so that the injected volume of material is exactly the same as the volume of the cavity space (plus any runners). This method is usually used for moulding thin wall components where there is no need for holding pressure. This is because the material enters the cavity so quickly that it almost immediately fills it, with the result that the moulding instantly freezes along with the gate.

Until the time the cavity is filled, the material exerts relatively little pressure on the mould walls. However, in this case, by the time the mould is full, no more material is being injected due to the lack of cushion and hold pressure. Hence there is only a relatively small force trying to open the mould against the clamping force.

The advantage of this method is that a thin walled moulding with a large projected area can be moulded in a smaller machine with a lower locking force. Another advantage is that moulds with long, slender cores can be filled with minimal core deflection since the pressures inside the cavity are significantly less than with general moulding techniques.

Sticking back: A term used to describe a moulding staying in the wrong side of the tool (usually the fixed half) as opposed to the ejection side of the tool. Parts that have stuck back cannot be ejected from the tool and frequently have to be removed manually.

Stripper plate: Either a full plate or insert that supports the periphery of the moulding whilst ejecting it from the mould.

Temperature controller: A piece of equipment used to control the temperature of the mould coolant at a given value. A temperature controller is also used to control the temperature of hot runner manifolds.

Thermal degradation: If material is subjected to elevated temperatures for prolonged periods of time, it can decompose. This can take the form of burned particles being produced or in more serious cases, decomposition into completely carbonised material accompanied by gases.

Thermocouple: A sensor that sends information to a temperature controller enabling the temperature to be controlled within preset limits.

Thermoplastic: A material that can be melted, allowed to solidify and then re-melted again.

Thermosetting: A material that may be melted but once solidified cannot be re-melted.

Tie bar: The high strength steel bars along which the moving platen slides. The tie bars of a machine are stretched to provide the clamping force necessary to keep the mould tool closed during the moulding process. There are usually four tie bars on a machine.

Tie bar stretch: The tie bar stretch is proportional to the clamping force. Knowing the tie bar stretch and the tie bar diameter and length, the actual clamp force can be calculated easily. The tie bar diameter determines the maximum possible clamp force of a machine. Machine manufacturers ensure that the maximum tie bar stretch is not greater than 10% of the yield stress of the tie bar material to maximise their operating fatigue life.

Tool: See "Mould".

Toolmaker: This can either mean an individual that works on the manufacture of a mould tool or a company that manufactures mould tools.

Twin barrel: A machine having two cylinders or barrels; used for increasing the nominal capacity of the shot weight of the machine. It is also used for moulding in two colours on the same moulding.

Virgin: Describes material that has not previously been used. It is in the original untouched state as supplied by the material manufacturer.

Viscosity: The degree of fluidity of the melted polymer. The lower the viscosity the easier it flows and vice-versa. Low viscosity materials are more like water while high viscosity materials are more "treacle like".

Weight: This is defined as the force acting on the mass due the local gravitational attraction of the earth, or:

$$W = mg$$

It is a consequence of Newtons Second Law of Motion (Force = Mass x Acceleration). In the UK, the value of g is usually taken as 9.81 metres per second per second. For less critical calculations a more approximate value of 10 metres per second per second is used.

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