R T Pritchard

T3 Workshop Technology for Mechanical Engineering Technicians

SI Edition

T3 Workshop Technology Pritchard

T. 3
WORKSHOP TECHNOLOGY

For Mechanical Engineering Technicians

R. T. Pritchard
C Eng, M I Prod E, Full Tech. Cert. C G L I,
Teacher's Cert. in Metalwork

Lecturer in Mechanical Engineering,
Garretts Green Technical College, Birmingham.
Examiner for the City and Guilds of London Institute,
The Union of Educational Institutions, and
The Welsh Joint Education Committee

Illustrations by Joy Armon

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Edited by
E. G. Sterland, JP, MA, BSc(Eng), FIMechE, FRAeS
Principal, Rolls-Royce Technical College, Bristol

Consulting Editor
P. D. Collins, MSc, CEng, FIMechE, FIProdE
Principal, Worcester Technical College

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Editor's Foreword

The Technical College Series covers a wide range of technician and craft courses, and includes books designed to cover subjects in National Certificate and Diploma courses and City and Guilds Technician and Craft syllabuses. This important sector of technical education has been the subject of very considerable changes over the past few years. The more recent of these have been the result of the establishment of the Training Boards, under the Industrial Training Act. Although the Boards have no direct responsibility for education, their activities in ensuring proper training in industry have had a marked influence on the complementary courses which Technical Colleges must provide. For example, the introduction of the module system of training for craftsmen by the Engineering Industry Training Board led directly to the City and Guilds 500 series of courses.

The Haslegrave Committee on Technician Courses and Examinations reported late in 1969, and made recommendations for far-reaching administrative changes, which will undoubtedly eventually result in new syllabuses and examination requirements.

It should, perhaps, be emphasised that these changes are being made not for their own sake, but to meet the needs of industry and the young men and women who are seeking to equip themselves for a career in industry. And industry and technology are changing at an unprecedented rate, so that technical education must be more concerned with fundamental principles than with techniques.

Many of the books in the Technical College Series are now standard works, having stood the test of time over a long period of years. Such books are reviewed from time to time and new editions published to keep them up to date, both in respect of new technological developments and changing examination requirements. For instance, these books have had to be rewritten in the metric system, using SI units. To keep pace with the rapid changes taking place both in courses and in technology, new works are constantly being added to the list. The Publishers are fully aware of the part that well-written up-to-date textbooks can play in supplementing teaching, and it is their intention that the Technical College Series shall continue to make a substantial contribution to the development of technical education.

E. G. STERLAND

Author's Preface

FEW people outside the engineering industry appreciate the contribution of modern technology in meeting the demands and needs of our present-day civilisation. The study of the scientific principles underlying the art of engineering manufacture is the study of Workshop Technology, an all-important subject when one considers that it is skill in engineering manufacture that makes possible a standard of living beyond the wildest expectations of the previous generation.

It is the emergence of the machine tool within the last 150 years that has made possible the ability of the civilised world to provide the essentials of existence to its own rapidly growing population, and perhaps of greater importance, to make available modern techniques and processes to the underdeveloped territories of the world.

The need for efficient and well-trained mechanical engineering technicians is great. The stated aim of the scheme of work contained in the Mechanical Engineering Technicians' Course is to meet the needs of those who aspire to supervisory duties, shop and process control, drawing office practice, plant maintenance and other forms of responsibility.

This class book is written to meet the needs of those engaged on the third year of the technicians' course. It is a continuation of the two preceding volumes, and once again I have attempted to keep the approach simple and direct, making full use of line diagrams to illustrate the text.

Finally I have been much encouraged by the favourable reception given to the preceding volumes of this series, and I am indebted to those who have written to me expressing their appreciation of my efforts. I am grateful too, to Miss Joy Armon for the diagrams, and to Brian G. Staples, MA, FLA, for his continued help and advice in reading the proofs.

Sutton Coldfield — R. T. PRITCHARD

Contents

1 Welding

1.1 The importance of welding

WELDING is essentially a metal joining process. We define it as the art of joining two metal parts in such a way that the resultant joint is equivalent in composition and characteristics to the metals used. This is shown in fig. 1.1. Ideally parts A and B, when welded, are equivalent to the metal bar shown at D; this means that the welded joint has in no way weakened, say, the u.t.s. of the welded bar shown at C. This is the true purpose of welding: the production of a homogeneous bond between the two metal parts joined together.

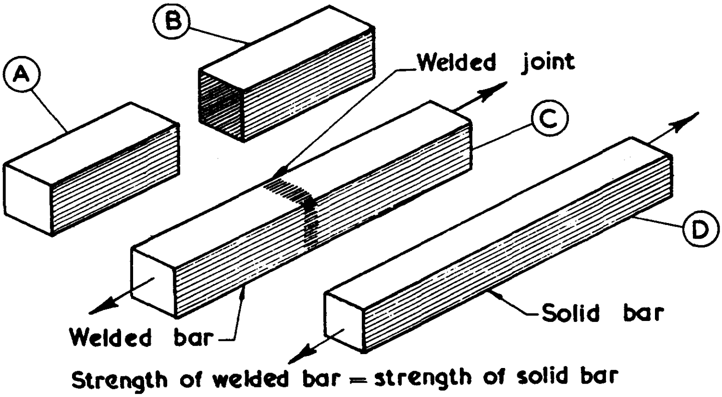


Fig. 1.1—Essentials of a Welded Joint.

The rapid and efficient joining of metal parts is an essential requirement of modern engineering manufacture. To meet the demands of mass and flow production of engineering components, enormous strides have been taken in the development of welding techniques within the last 50 years, and it is true to state that no other engineering process makes greater use of scientific principles than the welding process.

Two simple examples will serve to illustrate the importance of welding. Fig. 1.2 shows a V pulley, prefabricated from four bright mild-steel sheet pressings.

This pulley is part of the driving mechanism of a mass-produced domestic washing machine. Clearly the mild-steel pressings shown as details 1, 2, 3 and 4 in the sectional view of the pulley in fig. 1.2 can be rapidly and cheaply produced using press tools.

Note that the pressings 2 and 3 are welded to pressing 1, while pressing 4 is welded to pressing 3.

The front elevation shows the welding points; a total of 22 are required to join the parts together. The steel bush has a serrated face permitting positive drive to the welded pulley, and is a force fit on the phosphor bronze bush.

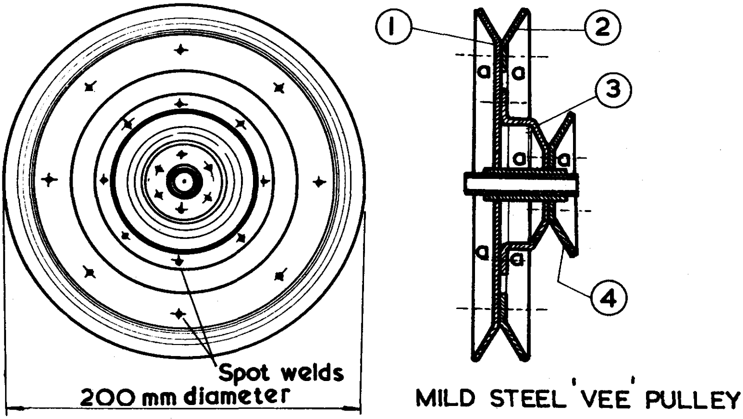


Fig. 1.2—Prefabricated V Pulley.

The alternative method of manufacture is to die cast a pulley in a non-ferrous alloy, with subsequent precision machining of the bore. Clearly the welding technique, which allows the prefabrication of this pulley, offers very great savings, not only in the amount and cost of the material required, but also in manufacturing time.

Fig. 1.3 shows another important advantage of the utilisation of a welding process. The lathe tool illustrated has a high-speed cutting portion, butt welded to a tough medium carbon or alloy steel shank. High-speed steel is an expensive metal, and the cost of this and similar tools is greatly reduced because of the butt welding technique adopted to make use of a cheaper yet

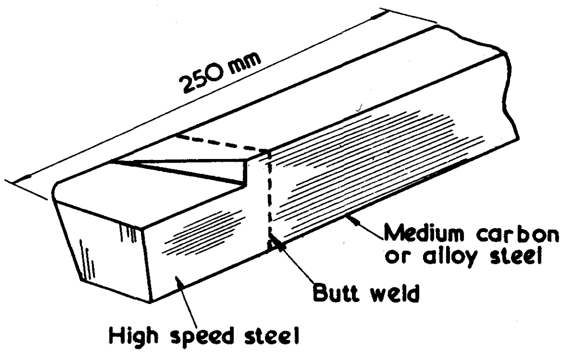


Fig. 1.3.—Butt Welded Lathe Tool.

suitable metal for the body of the tool. Most high-speed drills and reamers have butt welded shanks of alloy steels.

1.2 Welding techniques

Clearly the two previous examples of welding differ greatly in the actual technique employed to join together the metal parts.

The assembly of the pulley shown in fig. 1.2 is brought about by welding at different parts or spots, whilst the joining of a high-speed cutting portion to the body of a lathe tool involves the total joining over a fairly large contact area. In both cases **fusion** of the metals results, but the actual technique or classification of the weld used depends on the type of joint required, the metal thickness, and the area of contact. Metal fusion requires the application of heat, and the heat source is a useful indication of the type of weld obtained.

The following diagram, fig. 1.4, indicates the main welding techniques or processes. Note that **two** main sources of heat are employed: **chemical** and **electrical.** Note also that a much greater scope is offered by the electrical

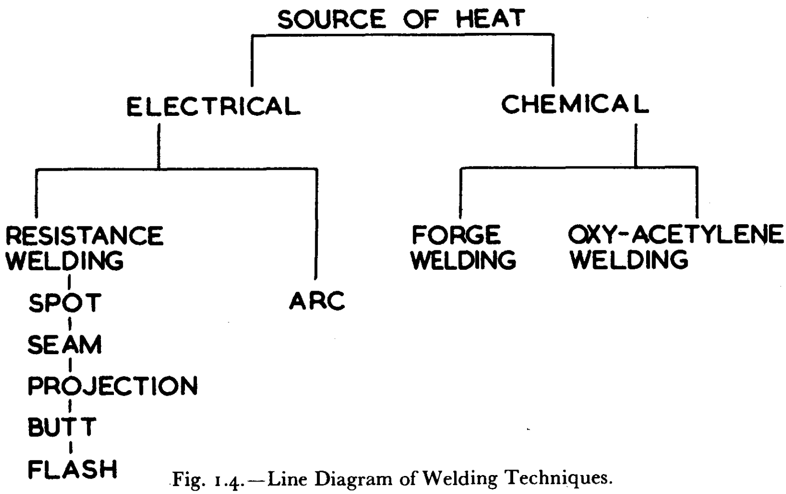


Fig. 1.4.—Line Diagram of Welding Techniques.

source of heat. If we remember, too, that electricity is readily controlled and easily applied, then we will realise that electrical methods of heat supply are certain to be much in evidence in the welding techniques or processes used in the mass-production of engineering components. Most of these electrical methods of welding have been developed within the last few decades mainly as a result of the limitations of the oxy-acetylene welding process.

1.3 Oxy-acetylene welding

The invention in 1895 of the oxy-acetylene blowpipe is credited to the French thermodynamicist Le Chatelier, and all modern oxy-acetylene welding techniques owe their existence to this important development.

It is known that the primitive engineers of prehistoric times were able to forge precious metals into simple ornaments. The principle adopted was the same as that used in forge welding at the present time: namely the insertion of the parts to be welded into a suitable forge or fire. This meant that forge welding was a static process; the metal had to be taken to the source of heat. Only towards the end of the nineteenth century did the art of welding take a great surge forward with the introduction of the principle underlying Le Chatelier's blowpipe. The heat could now be taken to the parts to be joined.

It is the oxy-acetylene flame that produces the heat required to bring about a fusion weld of two metal parts. This flame is the product of combustion of the two gases, oxygen and acetylene, supplied to the mixing chamber of the blowpipe or torch. The control of this flame is a matter of skill and experience, with manipulation of the oxygen and acetylene regulating knobs producing the following types of flame:

(i) neutral flame (equal oxygen and acetylene),
(ii) oxidising flame (surplus oxygen),
(iii) carburising flame (surplus acetylene).

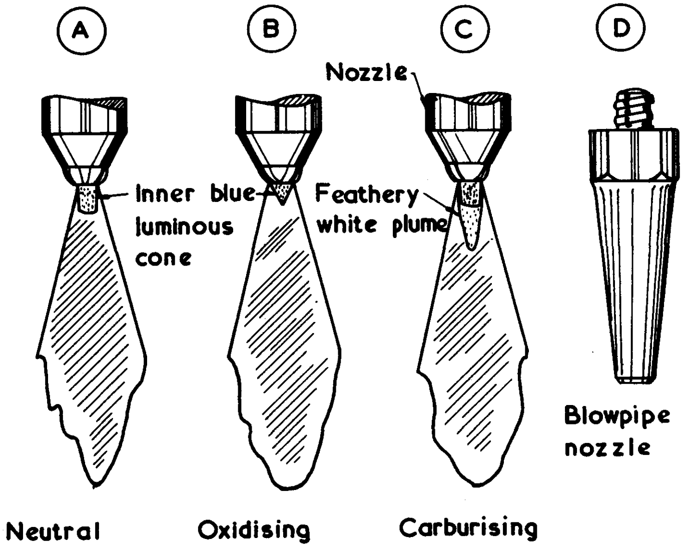


Fig. 1.5.—Welding Flames.

These flames are simply illustrated in fig. 1.5. The neutral flame is most used for welding; a maximum flame temperature of about 3000° C is possible. The size of the flame is determined by the bore of the removable nozzle at the end of the torch. A typical nozzle is shown at fig. 1.5D.

Oxygen and acetylene are stored under pressure in separate bottles. These bottles are extremely strong solid drawn steel chambers. Each bottle is equipped with a **head** which carries a pressure regulator and two pressure gauges. The high reading pressure gauge indicates the pressure within the bottle; the second pressure gauge shows the pressure of gas fed to the torch, and this pressure may be adjusted with the regulator.

Rigid safety precautions must be observed with regard to the storage and handling of both oxygen and acetylene bottles. Oxygen cylinders are usually painted black, with right-hand threads for the outlet connections. Acetylene cylinders are painted maroon, with left-hand threads on the outlet connections. Oxygen and acetylene bottles must not be exposed to flames, heat or shock conditions.

1.3.1 The fusion process, or homogeneous welding

Fig. 1.6 illustrates the application of the oxy-acetylene flame in the welding of the metal parts A and B. The weld shown is known as a vertical fillet weld.

At the right hand we see the application of the welding blowpipe in heating the parts until a pool or puddle of liquid metal results. Note the use of filler or welding rod to augment or reinforce the joint.

A section of the finished weld is shown on the left-hand side. On solidification of the liquid pool of metal, together with the additional metal supplied by the filler, a homogeneous joint results between the welded parts A and B.

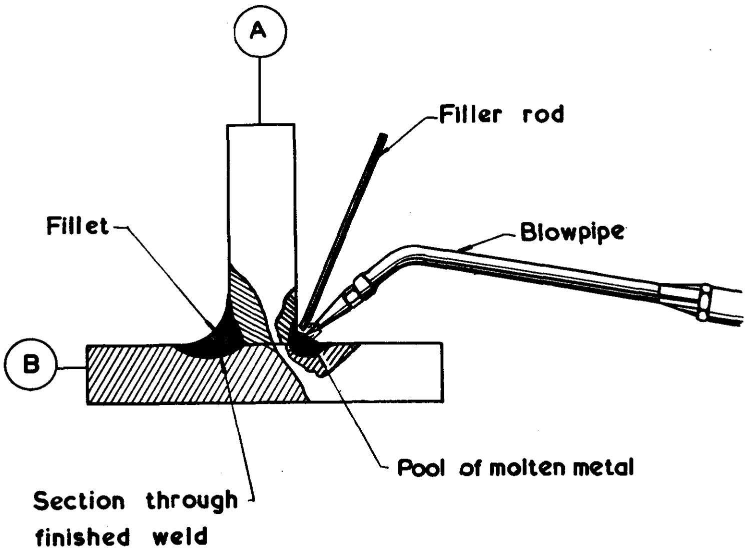


Fig. 1.6.—Oxy-Acetylene Welding.

With skill and experience the welder moves the flame and the filler rod along the joint at a predetermined rate, joining the parts with a pool of liquid metal augmented by the filler rod. Thin metal plates are **leftward** welded, that is to say the blowpipe flame points **away** from the deposited metal.

Rightward welding is adopted for plates of thicker section. This means that the blowpipe flame points **towards** the deposited metal. Fig. 1.7 gives a typical application of both techniques. The great advantage of the oxy-acetylene welding process is considerable versatility in the type of welded joint possible, together with relatively easy manipulation of the blowpipe. There is, however, a very great deal of skill required by the user of the blowpipe if efficient welds are to be produced.

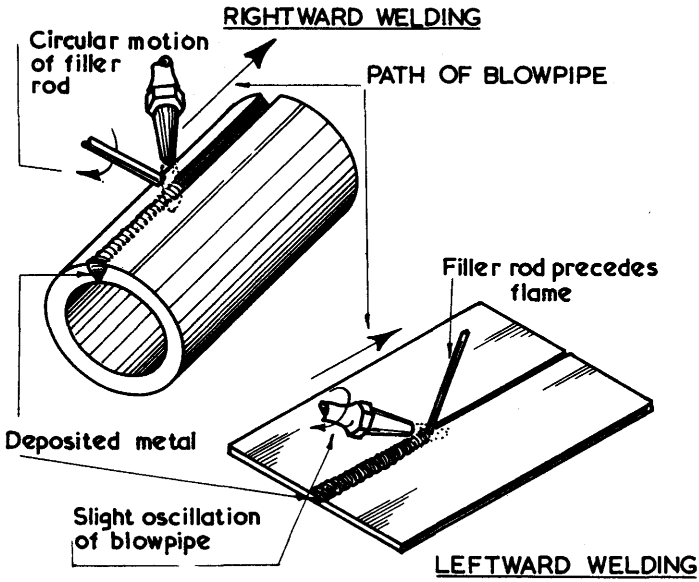


Fig. 1.7.—Rightward and Leftward Welding.

There is also the problem of holding and moving the filler rod in such a way that metal or joint augmentation is neither excessive nor insufficient.

These factors militate against the use of oxy-acetylene apparatus for the automatic welding of metal parts, and we shall see later the great advantages offered by the arc welding process for the automatic or mechanical welding of metal parts on a mass or flow production basis.

1.4 Oxy-acetylene flame cutting

The oxy-acetylene flame can, with suitable modification, be used as a cutting tool on steel plates. This means that intricate profiles may be flame cut from steel sheet. The process is readily adaptable to mechanisation, with several highly efficient flame cutting machines available.

Fig. 1.8 illustrates the profile of a component required in 50 mm thick mild-steel plate. If only one component is required, the profile is marked out on the steel plate. With a simple attachment known as a radius bar the circular portions are easily obtained, and simple devices are also used to cut the straight portions. In this way the profile of the component shown in fig. 1.8 can be produced in reasonable time.

In the event of large numbers of this component being required a **profile cutting machine** will be used.

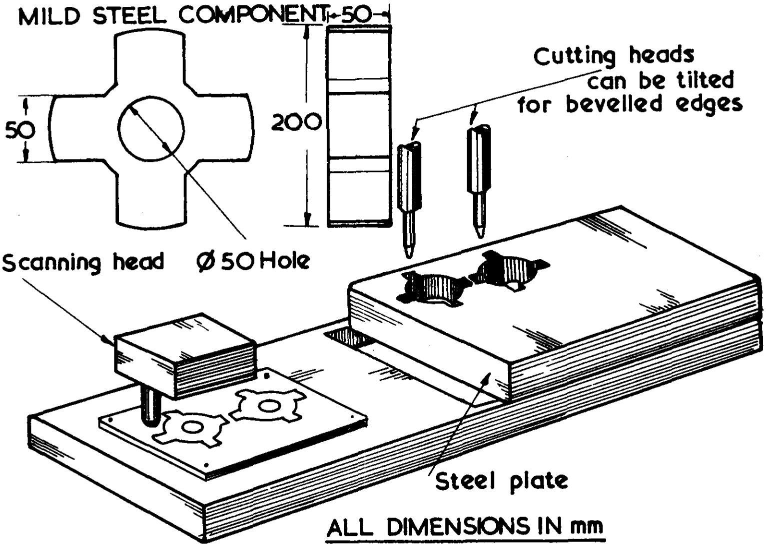


Fig. 1.8.—Principle of Profile Cutting Machine.

1.4.1 Profile cutting machines

These machines are used to produce steel components from flat stock. The cutting tool is an oxygen-enriched oxy-acetylene flame, capable of cutting through a steel plate more than 150 mm thick, leaving a remarkably good finish.

All are copying machines; it is necessary to make a template or drawing of the required profile, and many ingenious mechanisms are used to convert the outline of the component into movement of the cutting flame.

The more modern profiling machines are capable of cutting accurate profiles on 150 mm thick steel plate by the electronic scanning of an inked drawing of the required part. Accuracies in the region of $\pm$ 0.1 mm are claimed for straight lines and gentle curves, while the electronic scanning head which guides or controls the path of the cutting flame cannot deviate more than 0.075 mm from the inked line.

It is possible to have more than one cutting head on these machines, allowing very good production figures for complicated profiles in heavy steel plate.

The principle of a flame cutting machine of the type described is shown in fig. 1.9.

1.4.2 Principle of flame cutting

Fig. 1.9A shows a section through the cutting head of an oxy-acetylene blowpipe or cutting torch. Note that the outlet of the cutting head has **two** orifices: the outer orifice supplies a mixture of oxygen and acetylene, and this flame is shown at fig. 1.9B preheating the steel to be cut.

When the steel has reached the correct preheating temperature of 900° C the operator depresses a small trigger on the welding torch. This releases a jet of pure oxygen through the centre orifice, which on striking the preheated steel brings about violent oxidisation. The pressure of the oxygen jet is such that the iron oxide and molten iron particles are carried away by the pressure of the jet, and a neat cutting face results.

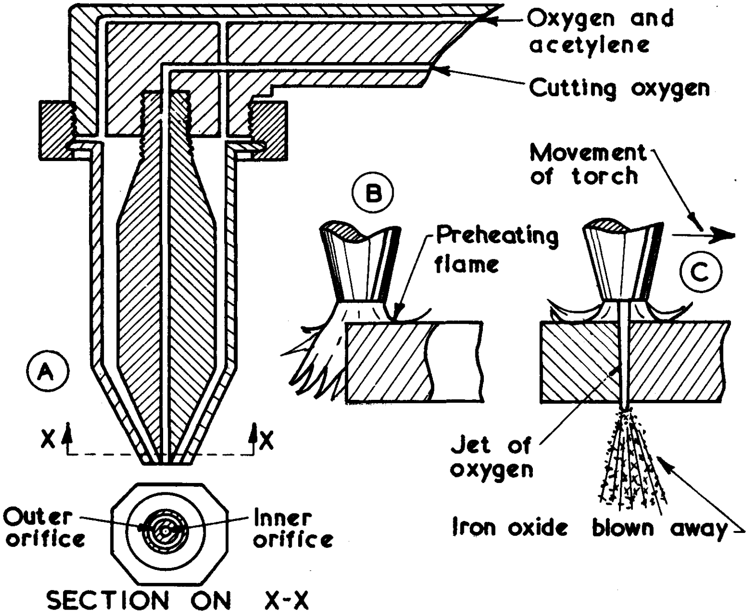


Fig. 1.9.—Technique of Flame Cutting.

The cutting action is shown in fig. 1.9C. For 50 mm steel plate the speed or rate of movement of the flame along the required profile is approximately 12 m/h, or 3 mm/s. Thus a twin head profiling machine will produce two of the components shown in fig. 1.8 in about five minutes.

A clean-cut profile cannot be obtained on non-ferrous metals, and can be achieved only with difficulty on cast iron and stainless steel. This is owing to the fact that the oxides of these metals do not melt at a lower point than the metals themselves. In the case of steel, however, the melting point of the iron oxide, Fe_3O_4, is well below that of the iron or ferrite present in the steel. Thus the iron oxide melts and is blown away, leaving a relatively smooth edge. Non-ferrous metals melt at the edges, and an irregular, inaccurate edge results.

1.5 Arc welding

We have seen in our discussion on oxy-acetylene welding that additional metal is required to augment the molten pool in the path of the oxy-acetylene flame. The manipulation of the blowpipe and of the filler rod which provides the additional metal puts a severe limitation on the efficiency, and increases the cost, of the oxy-acetylene welding process.

At the same time deep penetration of the metal requires large nozzles producing large flames with consequent risk of turbulence and scale within the weld.

The great advantage possessed by the arc welding process is that the metal electrode used to strike the arc acts as a filler rod. This means that mechanical welding on a production basis is readily achieved.

1.5.1 Principle of arc welding

The principle of arc welding is illustrated in fig. 1.10. This type of arc welding process is known as **alternating-current arc welding.** A transformer is used, requiring little or no maintenance.

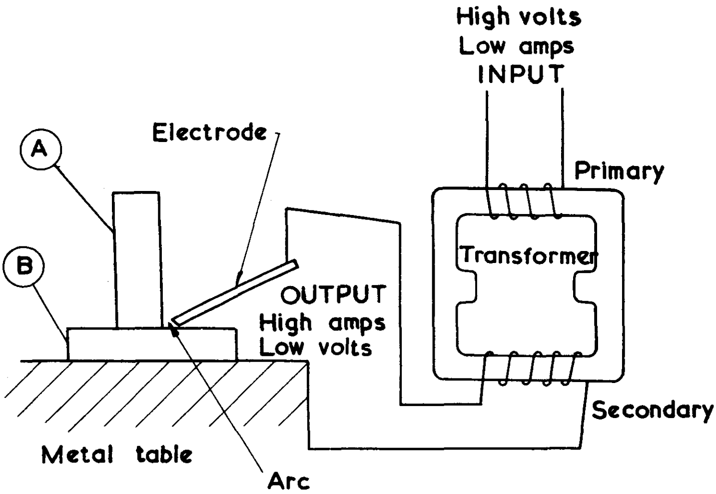


Fig. 1.10.—Principle of Arc Welding.

The purpose of the transformer is to change the high input voltage and low amperage to a low voltage and high amperage. The output from the transformer is about 80 to 100 volts, and thus there is little risk of shock to the operator. The voltage required to strike the arc exceeds the voltage required to maintain it: an average striking voltage of 80 volts would result in a working voltage of 30 to 40 volts.

1.5.2 The arc

The arc is produced between the electrode tip and the parent metal. Fig. 1.11 shows a close-up view of the arc produced from an a.c. transformer. The temperature of the arc can exceed 3000° C; this causes the formation of a liquid pool of metal and the transfer of metal from the electrode to the molten pool.

Movement of the electrode in the direction of arrow A results in the deposition of metal along the path of the electrode; in this way a **fusion** weld is produced.

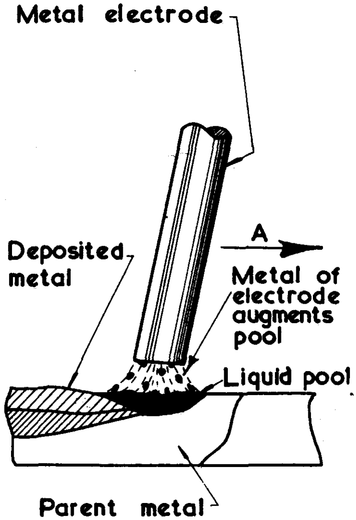


Fig. 1.11—Arc Welding.

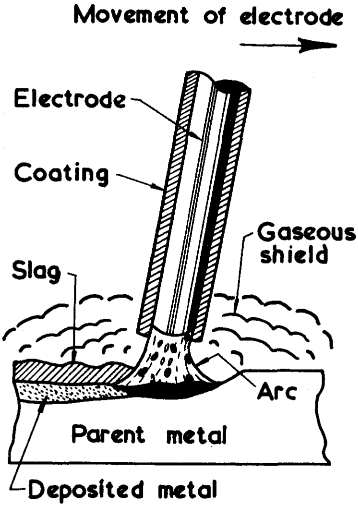


Fig. 1.12.—Shielded-arc Welding.

It is necessary to maintain a constant gap between the electrode tip and the surface of the molten pool; this gap should be about the diameter of the electrode used. Fig. 1.11 shows the application of a bare metal electrode. It is clear from the diagram that the pool of liquid metal is open to the atmosphere, as also are the globules of molten metal leaving the metal electrode.

1.6 Disadvantages of the bare metal electrode

The welds produced by the process shown in fig. 1.11 are much weakened by the absorption of oxygen and nitrogen from the atmosphere into the weld. The absorption of these gases makes the weld brittle and porous, and this undesirable state of affairs is aggravated by the rapid cooling of the deposited metal. If the arc, electrode tip and molten pool can be protected or **shielded** from the atmosphere, the resultant weld will be much stronger.

1.6.1 Shielded-arc welding

This principle is illustrated in fig. 1.12. Note that the metal electrode is covered with a shield or coating. This coating is a type of flux, extruded under high pressure on the outside surface of the metal electrode, and possessing a higher melting point than the metal electrode. It will be seen in fig. 1.12 that the coating extends beyond the electrode tip during the welding action. In this way further shielding against the atmosphere is afforded to the metal globules drawn into a liquid pool. Note not only that the melting of the coating produces a gaseous shield which acts as a barrier against the inclusion of both oxygen and nitrogen into the weld, but also that on solidification the melted coating forms an insulating layer of slag on the surface of the deposited metal. This insulating layer promotes slow cooling of the weld while protecting the solidifying weld from the atmosphere.

The use of a shielded-arc electrode also gives greater economy of welding rod, as vaporisation of the electrode is prevented by the shielding effect of the molten coating. Extensive use is made of shielded-arc electrodes in modern welding practice, and the automatic welding of steel parts is now commonplace. The development of the shielded-arc principle represents perhaps one of the greatest advances in welding technique.

The welds produced are strong, reliable and ductile. The process is now widely used as a production tool in the fabrication of a great number of engineering components.

Welding speeds are high; the a.c. transformers are trouble-free and require little maintenance. The main limitation of this process is the length of the coated electrodes, which varies from 200 to 450 mm.

Long runs require the changing of electrodes, with loss of welding time together with the risk of a discontinuous joint at the point of electrode changing. Clearly if a coil of bare wire electrode could be used, automatic welding over long distances would be easily achieved. But a bare wire electrode, as we have seen, produces welds which have been exposed to the oxygen and nitrogen in the atmosphere, with serious weakening of the weld metal.

If, now, a coil of bare wire used as an electrode produces an arc whilst **submerged** in a shielding flux, strong welds will result, equal in quality to those produced by the shielded-arc electrode. This is achieved in submerged-arc welding.

1.6.2 Submerged-arc welding

This technique is adopted for the production of long continuous welds, or the mass-production of welded joints.

The principle is illustrated in fig. 1.13.

The flux is fed as a powder in front of the path of a moving head which carries the bare wire electrode coil. This flux has both high electrical resistance and heat insulating properties. The heat generated by the arc is confined to the weld area which is surrounded by the molten flux. In this way the flow of metal from the electrode is achieved in complete isolation from the harmful gases of the atmosphere; the rate of cooling of the deposited metal is slow, and it is also protected from the atmosphere while cooling.

At the end of the run the slag is easily broken away, and a neat, clean weld results. An automatic feeding device ensures that the gap between the electrode tip and the parent metal is constant.

The welding process is entirely automatic and represents a tremendous advance in welding technique. The process is best used for the continuous welding of components having thicknesses from 12 to 50 mm. Typical applications are the welding of pressure vessels and boilers. Considerable economy in weight is achieved if a boiler is welded instead of riveted; the reduction in weight may be as much as 25 per cent, with the welded boiler capable of withstanding pressures of the order of 17 MN/m^2. A further advantage of the submerged-arc process is that there is no flash or glare visible, the powdered flux completely shielding the arc.

1.7 Argon arc welding

This process is much used for the welding of stainless steel and non-ferrous metals such as aluminium, magnesium and copper. Two principles are in use, the first requiring the use of a filler rod to augment the metal of the weld. This is known as **tungsten electrode** welding.

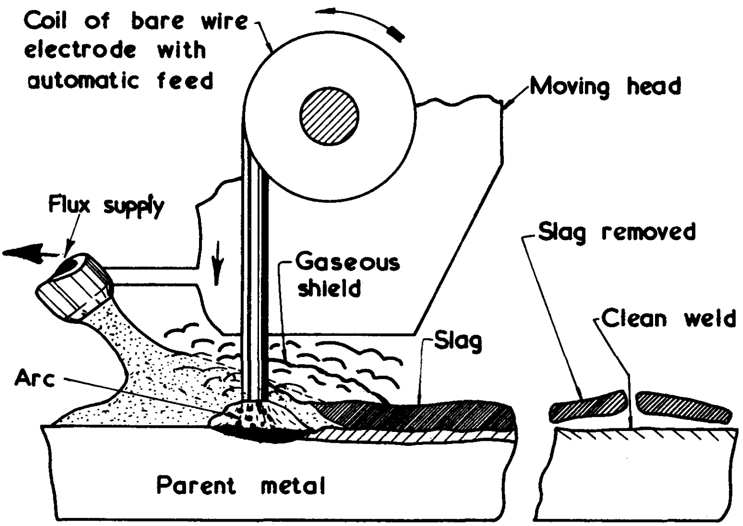


Fig. 1.13.—Submerged-arc Welding.

1.7.1 Use of the tungsten electrode

Fig. 1.14A illustrates a section through the working end of an argon arc welding torch. Note that the argon gas provides an inert shield against the atmosphere, allowing the use of bare metal filling rods. As no flux is used, no slag is formed and a clean weld results.

1.7.2 Bare wire electrode

Long continuous runs are achieved with the use of a wire electrode. This principle is shown in fig. 1.14B, and it will be seen that the technique is similar in many respects to that of submerged-arc welding. Reference to the diagram shows that the electrode, fed from a coil, augments the pool of liquid metal completely shielded by a curtain of inert argon gas. The whole unit is attached to a moving head which travels automatically along the path of the weld. The feeding of the wire is automatically controlled, with the arcing gap between the parent metal and the electrode wire tip at a constant distance.

This technique is much used for the production of clean, slag-free welds in components fabricated from stainless steel and other non-ferrous metals.

1.8 Pressure resistance welding

All the welding techniques described so far result in fusion welds. No external pressure is applied. The principle in each case revolves around the formation of a liquid pool of metal between the two parts to be joined, with further augmentation of this homogeneous liquid pool using a filler rod or metal electrode. The continuation of this along the joint, either by hand or by automatic methods, welds the two parts together.

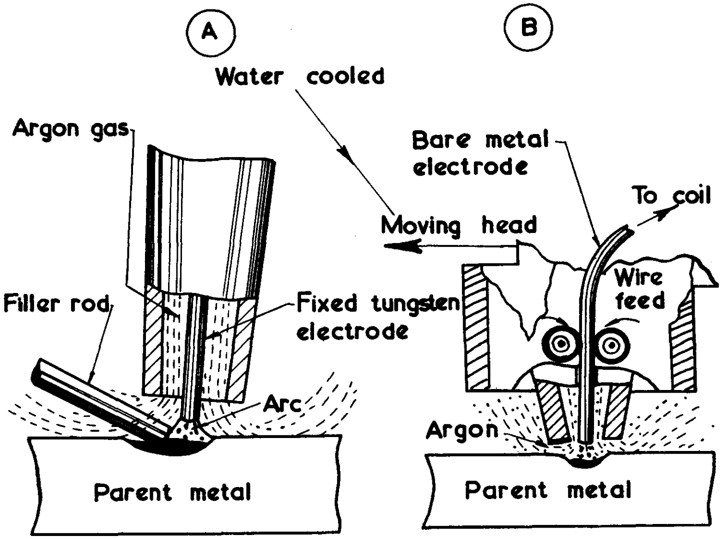


Fig. 1.14.—Argon Arc Welding.

There are, however, a great many occasions in engineering when welds are required to replace nuts and bolts or rivets in relatively thin metal. This need can be seen by referring back to fig. 1.2, where a fabricated pulley to take two V belts is shown.

The front elevation shows that twenty-two **spot** welds are used; these welds are indicated by lines *aa* on the sectional end elevation. The development of spot welding has been remarkable, and the process is now firmly established as being efficient and highly productive.

1.8.1 Principle of spot welding

The technique of spot welding is best applied to the joining of two metals of similar composition and thickness.

The principle is shown in fig. 1.15.

1.8.2 The electrodes

These must possess high thermal and electrical conductivity. The bottom electrode is fixed, whilst the top electrode moves down and applies pressure to the work in the order of 70 MN/m^2 over the electrode contact area.

When the correct welding pressure is reached, an electronic control passes a high amperage current through the electrodes. Because the electrodes are made from high quality copper with a little cadmium to increase their useful life, the high amperage current flows with little resistance through the electrodes, but meets with considerable resistance at the inner contact faces of the parts to be joined.

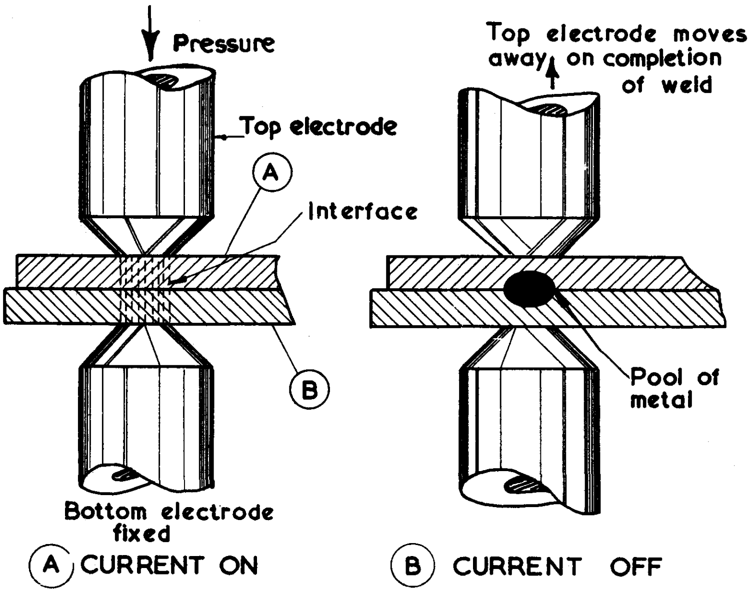


Fig. 1.15.—Principle of Spot Welding.

A rapid temperature rise takes place at the interface, resulting in the formation of a small pool of liquid metal.

At this point the current ceases to flow, while the pressure is maintained until the pool of liquid metal or weld solidifies.

Note that the weld does not extend to the outer faces of the parts being joined. This is due to the fact that the greatest resistance to the current flow is at the interface of the metal parts, and that the current is stopped as soon as the metal melts, as shown in fig. 1.15B.

1.8.3 Applications of spot welding

Clearly any welding process capable of replacing nuts and bolts or rivets finds a wide application in engineering manufacture. If, also, spot welding machines are available both as fixed and portable types, then there is practically no limit to the use of spot welds as a method of permanently joining metal parts up to 10 mm thick.

Provided the position of the weld is such that the electrodes can be applied at the points required, spot welding is a cheap, rapid and efficient technique, each spot weld taking only a few seconds or less.

To give an indication of the efficiency of the spot welding process, the underbody of a motor car made mainly from 0·7 mm and 0·9 mm mild steel has about 1000 spot welds, yet the output rates are approximately 25 underbodies per hour, or approximately one every two minutes.

This output, of course, is achieved with the aid of special jigs, in which banks of electrodes move forward at predetermined intervals, the whole sequence being incorporated in an automatic press welding circuit.

1.8.4 Seam welding

Seam welding is adopted when watertight or airtight seams are required It is achieved by making a series of spot welds in such a way that the welds tend to run into each other or overlap. The principle is shown in fig. 1.16; note the use of circular electrodes. The application of the welding current is intermittent and is controlled by synchronous timing devices. The pressures exerted by the revolving electrodes are identical with those exerted by the electrodes used in spot welding.

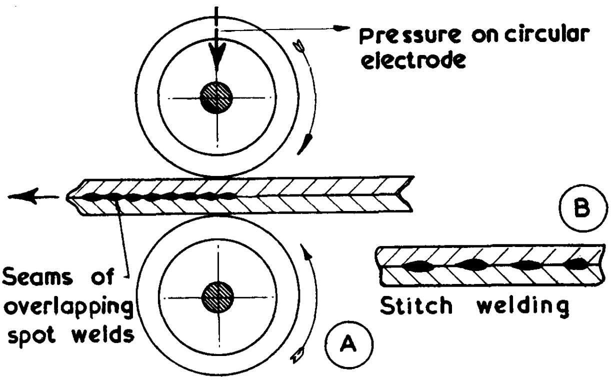


Fig. 1.16.—Principle of Seam and Stitch Welding.

With the electrodes revolving, a series of spot welds is made, each weld slightly overlapping its neighbour. The process is continuous and ideal for the joining of overlapping metal parts which make up watertight or airtight containers.

1.8.5 Stitch welding

Circular electrodes may also be used to **stitch weld** metal parts. This process consists in making a series of welds at regular or constant pitch, as shown in fig. 1.16B.

The roofs of most modern motor cars are stitch welded to the bodies, a hand operated, balanced circular electrode welding device being used. The principle underlying this technique is illustrated in fig. 1.17. The use of wheel type electrodes permits very high welding production rates, and once again we see the application of a welding technique as a production tool. Stitch welding is best considered as a form of continuous spot welding, and may also be carried out using the single electrodes shown in fig. 1.15.

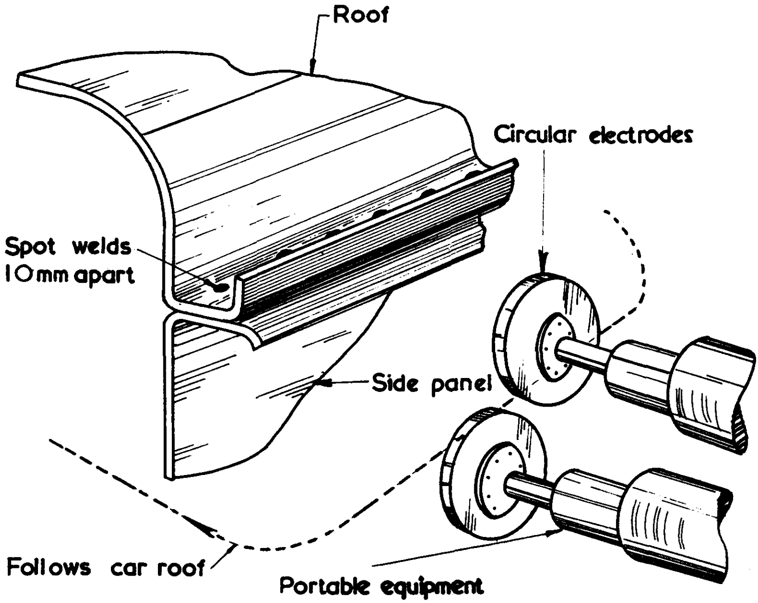


Fig. 1.17.—Stitch Welding Motor Car Roof.

1.8.6 Projection welding

This technique is mainly employed for the joining of metal parts which could be spot welded only with difficulty.

The principle is identical with that of spot welding, namely the making of small localised areas of welds at predetermined points.

Fig. 1.18 shows two mild-steel pressings that are to be projection welded, the finished assembly making up a brake shoe for a motor vehicle. Clearly the spot welding of these components presents a difficult problem; part A is assembled lengthways to part B.

The application of the projection-welding technique is achieved by providing part A with several projections, as shown in fig. 1.18. The principle underlying the projection welding technique is also shown in fig. 1.18.

Note that pressure is exerted on part A, followed by application of the welding current. This leads, as in spot welding, to local heating at the interface areas between the projections on part A and the face of part B. The pro-

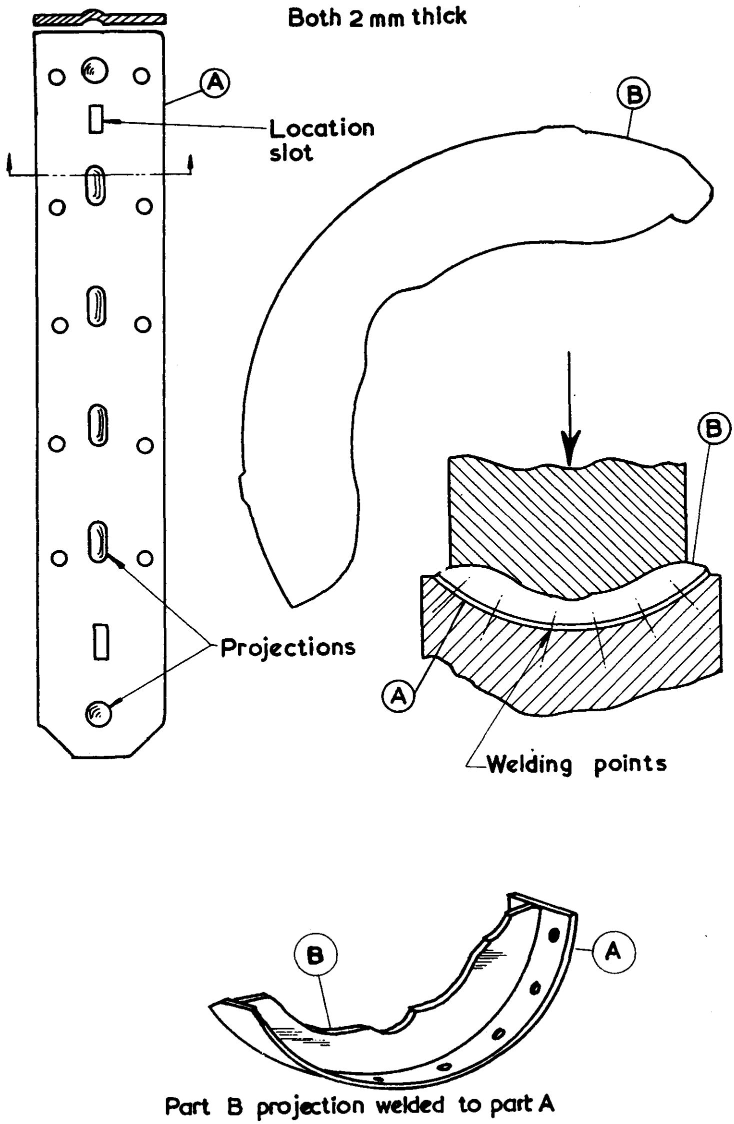


Fig. 1.18.—Mild-steel Pressings for Brake Shoe.

jections melt and fuse with part B, fusion taking place simultaneously at all the contact points.

In this way several spot welds are made in one operation, and the process is readily mechanised, with automatic feeding, welding, and removal of the welded assembly. With both parts produced by press blanking tools, the manufacture and welding of this brake shoe is entirely automatic, with the very high output figure of 20 brake shoes per minute.

The projection-welding technique may be used also to weld plugs and bushes to heavy steel plate, or to weld together two relatively solid steel parts. The techniques are shown in fig. 1.19, and it may be appreciated that considerable saving in time and material can result with the use of this technique.

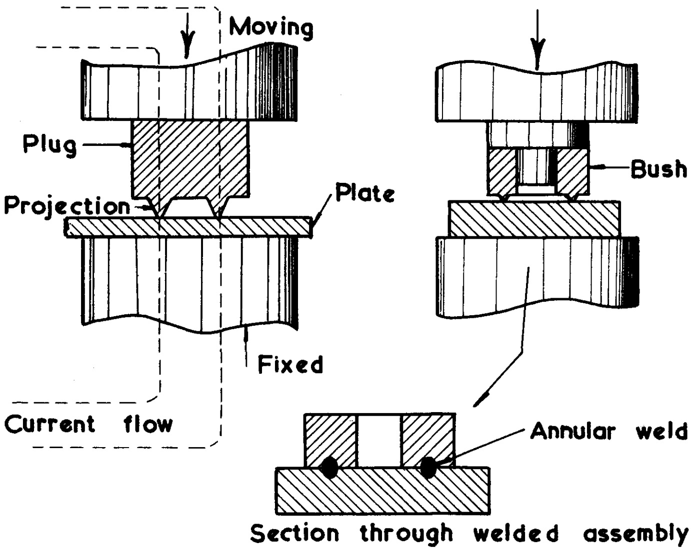


Fig. 1.19.—Projection Welding of Bushes.

1.9 Butt and flash-butt welding

1.9.1 Butt welding

Fig. 1.3, which shows a heavy duty lathe tool, provides a good example of the butt welding technique. It will be seen that the high-speed-steel cutting end of the lathe tool is butt welded to a medium-carbon-steel shank, thus providing considerable economy of the more expensive high-speed steel.

The principle is shown in fig. 1.20, and consists in bringing together the two ends to be joined, and passing the welding current through the joint. As soon as the joint reaches the required temperature, further pressure is applied while the welding current is cut off. This technique is restricted to fairly low areas of contact, not exceeding three square centimetres, and it is essential that a very good match exists between the two areas to be joined.

1.9.2 Flash-butt welding

This technique is used for the butt welding of large sections, and is the actual method employed for the joining of the two separate steels making up the lathe tool shown in fig. 1.3.

The principle of flash-butt welding is shown in fig. 1.21. The mating areas need not be a good match or surface fit. Three separate stages are involved.

Stage 1. *Preheating*

This consists in switching on the welding current and bringing the two ends to be joined in contact. Both ends immediately undergo a temperature rise. Because of the poor surface fit the temperature rise will vary across the interfaces. To prevent local overheating, the two ends are drawn slightly apart at regular intervals until the interface area is at a uniform temperature.

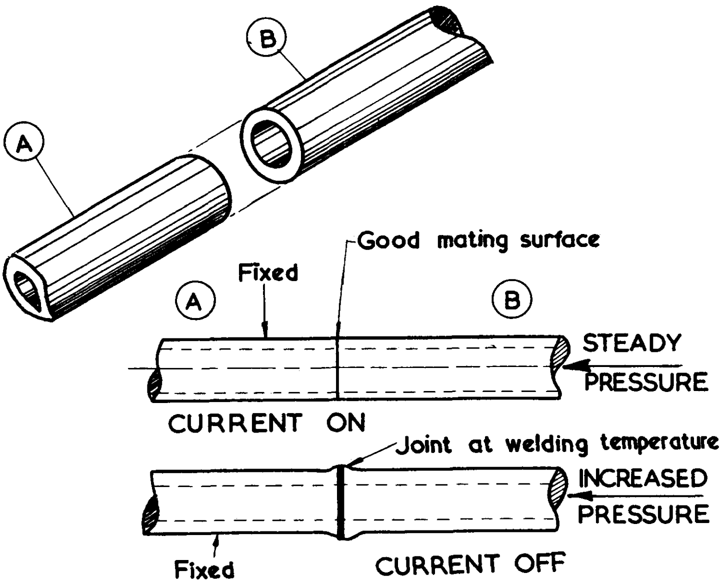


Fig. 1.20.—Butt Welding.

Stage 2. *Flashing*

This takes place when the two areas are in close contact and at the correct temperature.

Stage 3. *Upsetting*

As soon as the flash point is reached a heavy pressure is applied, resulting in the welding or fusion of the joint. Note that upsetting of the joint takes place, as shown in fig. 1.21 (3).

The welds produced by the flash-butt welding technique are of high quality, and the technique is readily applied to aluminium alloys and copper. When thinner sections, such as the rims of bicycle wheels, require to be flash-butt welded, a slightly different technique is employed. The two ends are first brought together under medium pressure, whereupon local heating takes place. At this point, owing to the uneven matching faces, the heating is not uniform and some arcing takes place. Continuation of the pressure causes the forcing out of the surplus or irregular metal at the interface, until finally the two ends are brought firmly together with the welding current switched off.

The flash-butt welding of bicycle and other vehicle rims is invariably performed with the whole operation completely mechanised, and once again high output figures are easily obtained.

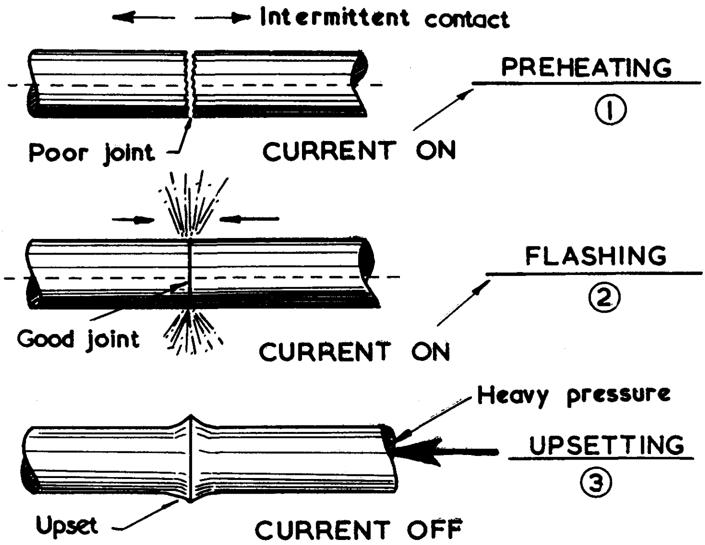


Fig. 1.21.—Stages in Flash-butt Welding.

1.10 Importance of electrical resistance welding

The resistance offered by a metal to the passage of a heavy current is the basis of all electrical resistance welding.

Unlike electric arc or oxy-acetylene welding, where the fusion of the metal is achieved by the heat of the arc or flame, resistance welding employs only an electric current as the heat source. There is a complete absence of flash and glare, allowing the use of spot welding machines as part of a production line. With the use of suitable electronic equipment, the welding current time can be varied from $\frac{1}{100}$ second for the spot welding of thin metal plate to 2 minutes for the flash-butt welding of heavy sections.

Perhaps the most important feature of resistance welding is that the process is readily automated with complete elimination of the human element.

1.11 Testing of welds

The testing of welded joints differs little in principle from the standard tests adopted to determine the mechanical properties of the parent metals from which the joints are made.

For example, the tensile strength, resistance to impact and ductility of a welded joint can be readily determined from a specimen weld, using standard testing machines.

It must be clearly understood, however, that the results obtained refer only to the test piece under test, and if a large welded structure, say a pressure vessel, has been hand welded, it is possible that faults may exist as a result of the quality of the workmanship.

Clearly it is not practicable to cut away a section of the pressure vessel in order to determine the efficiency of the welded joint, and this means that all weld testing techniques must fall into one of the following two categories:

(i) destructive tests
(ii) non-destructive tests.

1.12 Destructive tests

In addition to the standard tests for tensile strength using a tensile testing machine, or resistance to impact using an Izod impact testing machine, much useful information can be gained by carrying out a macrostructure examination of a section of the welded joint.

1.12.1 Macrostructure examination

The following remarks give a brief indication of the procedure adopted when making a macrostructure examination of a welded joint; books on materials will supply more detailed information.

The surface area of the weld section under test is brought to a smooth polished condition. An etching reagent is applied; for mild steel this is usually a solution of nitric acid and alcohol. The effect of the reagent is to etch away the grain boundaries of the welded area, thus not only showing the crystal size, but also revealing the presence of discontinuities and cracks.

1.13 Non-destructive tests

Apart from close visual examination of the weld, from which an experienced inspector is able to make a fair assessment of the weld quality, there are several non-destructive tests in use.

A popular test for the magnetic metals, such as the carbon and certain alloy steels, is the magnetic method of crack detection.

1.13.1 Magnetic crack detection

This method is used as a supplement to visual examination. It is not possible for the human eye to detect, unaided, minute or very fine hair cracks which may be present in or around the surface of the weld area. But provided the weld area under test has a reasonably smooth surface it is possible to detect even the finest hair crack when using the magnetic crack detection method.

Briefly the principle consists in passing a magnetic flux through the metal of the weld, after covering the surface with a mixture of magnetic iron oxide powder and paraffin. The presence of any break or discontinuity on the surface of the metal creates a magnetic field across the break or crack, and the magnetic iron powder is attracted in considerable quantity to this field.

The principle is illustrated in fig. 1.22. Note that the powder is attracted along the direction of the crack, thus providing clear visual evidence of the presence of a break or discontinuity of the metal.

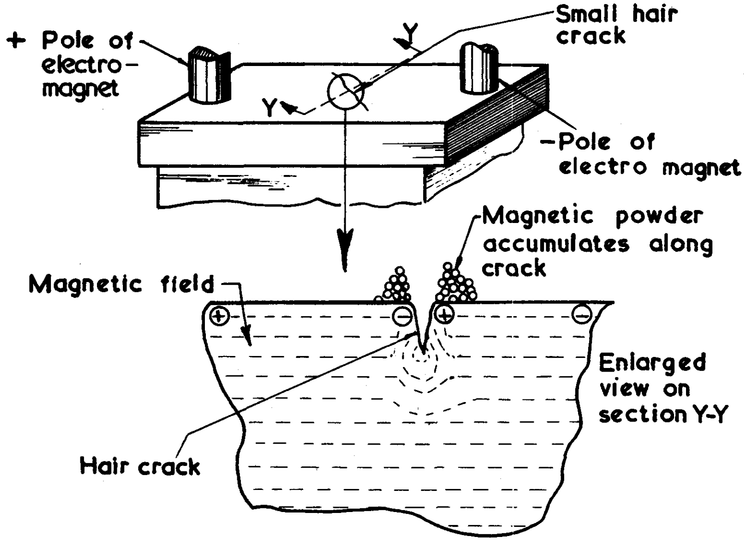


Fig. 1.22.—Principle of Magnetic Crack Detection.

1.13.2 X-ray examination

This technique is widely used for the testing of welds in pressure vessels and similar structures. It is essentially a non-destructive testing technique. Although the apparatus is relatively expensive, it permits an assessment to be made of the quality of the weld with regard to internal defects.

The joint is exposed to a beam of X-rays, and the amount of this radiation absorbed by the metal depends on the amount of metal opposing the path of the X-rays.

The presence of any internal voids, cavities or defects presents no opposition to the X-ray radiation, and a photographic plate or film can be used to reveal variations in the path of the X-ray radiation. There are also many other non-destructive testing techniques in use; much skill, patience and experience is required for their efficient use.

Summary

Workshop technology may be described as the practical application of the scientific principles underlying manufacturing techniques or processes. There is little doubt that of all the manufacturing processes used in modern engineering manufacture, the welding process demands the greatest knowledge of scientific principles.

If we consider also the fact that the greatest advances in recent years in the field of production techniques have been made in the art of welding, then it is clear that welding now represents a major activity in modern production engineering.

It is not so long ago that welding was considered primarily as a process for the repair or renewal of broken components, but we have seen in the preceding pages that welding is now an accomplished and proven production engineering technique by which metals are joined as part of a mass-production process.

Although the principle underlying the joining of two metals remains constant, namely the formation of a liquid metal pool between the interfaces of the parts to be joined, several sources of heat supply are adopted.

The use of the oxygen and acetylene flame is essentially a chemical process, requiring considerable care in the storage and pressure of these gases, together with the need for protection of the eyes of the welding torch operator. There is need, too, for the use of a filler rod as a means of augmenting the weld by the addition of extra metal. This makes the production of long continuous welds of uniform strength a difficult matter, and the exposure of the weld to the oxygen and nitrogen of the atmosphere reduces the efficiency or strength of the weld.

The shielded-arc principle produces much stronger welds, free from the weakening influences caused by the absorption of the atmosphere into the weld, while the arc produced between the work and the electrode used as a filler rod provides a clean and troublefree source of heat. Because the length of the flux-covered electrode limits the amount of welding possible as a continuous run, much use is made of a coil of bare wire electrode, with shielding from the atmosphere achieved by surrounding the weld with powdered flux (submerged-arc welding), or providing a shield of inert gas (argon arc welding).

These techniques allow not only the automatic welding of large-section ferrous welds, but also automatic welding of thin-section non-ferrous metals.

Large sections can be butt or flash-butt welded, a heavy electrical current providing the heating source. For the localised welding of relatively thin steel components, great use is made of electrical resistance pressure welding, typical techniques comprising spot, seam and stitch welding.

The types and varieties of welding machines available to the engineering industry are very large in number. Most of the welding machines using electricity as a source of heat are equipped with complicated electronic devices controlling not only the amount of the welding current, but also the time of current application.

These machines, rightly, are the province of the electrical engineering technician, but it is not a bad thing if the mechanical engineering technician appreciates some of the basic principles underlying their design and application.

EXERCISE 1

1 Show by means of a simple line diagram the techniques adopted for the production of **fusion** welds and **pressure** welds. What is the essential difference between a fusion weld and a pressure weld?

2 (a) With a neat diagram illustrate the technique of oxy-acetylene welding.
(b) What is the purpose of the filler rod?
(c) Give a typical application for oxy-acetylene welding.

3 (a) What is meant by the term "flame cutting"?
(b) Why is this process generally restricted to ferrous metals such as the carbon steels?
(c) Make a neat sketch of a component that could have its profile flame cut. Describe briefly the technique adopted if a large number of similar components is required.

4 (a) What is the essential difference between arc welding and oxy-acetylene welding?
(b) Make a neat sketch illustrating the principle of arc welding.
(c) Describe the manner by which additional metal is added to an arc weld.

5 Describe a typical application for the technique of submerged-arc welding. List **three** advantages of this process.

6 What is the purpose of a **covered** or **shielded** electrode as used in arc welding? Explain the limitations of covered electrodes that are to be used on a production long-run welding operation.

7 (a) Describe **two** techniques adopted to prevent atmospheric contamination of the weld when using bare wire electrodes.
(b) Give a typical application for each technique.

8 (a) Show by means of a neat sketch the welding principle adopted to replace rivets when joining thin mild-steel components.
(b) Sketch a typical application of the use of spot welding when joining mild steel pressings to make up an engineering assembly.

9 (a) Sketch typical applications of the following welding techniques:
(i) seam welding
(ii) stitch welding
(iii) projection welding
(iv) butt welding
(b) Describe **one** of the above welding principles in some detail.

10 Describe in some detail an application of each of the following testing techniques:
(i) non-destructive testing
(ii) destructive testing.

2 Measurement

2.1 The need for precision measurement

THE mass-production which characterises so many branches of modern engineering manufacture would be impossible if component parts could not be produced to close dimensional tolerances and thus made interchangeable. Motor vehicles, refrigerators and washing machines, to name only a few examples, could not be made available in the quantities our modern civilisation has come to take for granted.

It is seldom, however, that the components themselves are subjected to precision checks, and it is therefore essential that the accuracy required should be built into the machine tools, jigs and fixtures which produce them. Precision measurement is concerned with the precise determination of the linear, angular and non-linear functions of the machined surfaces of the tools and devices used to produce engineering components.

Fig. 2.1 illustrates two pressed-steel components used to make the brake-shoe previously described and illustrated in fig. 1.18. The parts are produced with press tools at the rate of about twenty per minute. Note that part B has

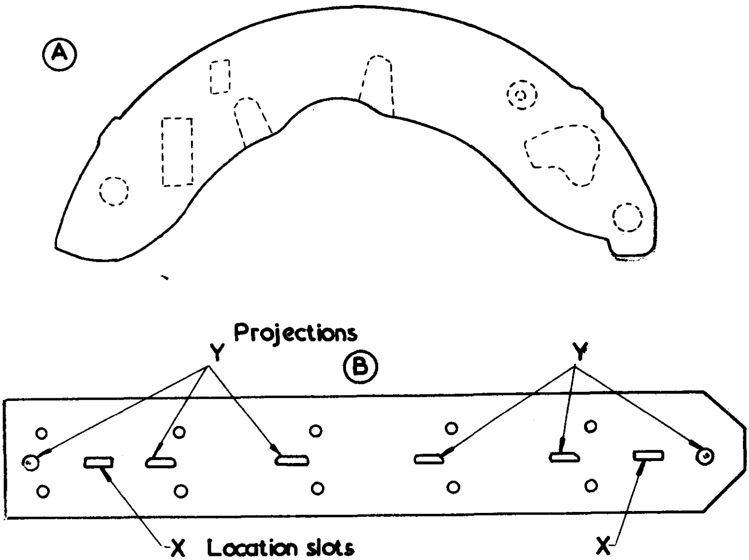


Fig. 2.1.—Mild-steel Pressings for Brake Shoe.

ten pierced holes to accommodate the rivets holding the brake lining; note also the location slots and the raised projections shown as Y.

The dotted lines on component A represent further piercing and notching operations carried out after projection welding part A to part B. If we consider the manufacturing time for this component, namely three seconds, then clearly it is an impossible task to measure the linear dimensions of the hole centres, slot and projection positions. We must rely on the part being a faithful replica of the tools used to produce it, and for this reason it is vital that the dies and punches are both made and measured as accurately as possible, and within the specified limits laid down in the drawing or blueprint.

Precision measurements must be carried out on both the dies and the punches of the press tools used, and provided the dimensions are within the limits laid down the press tool can be put into production with every confidence in the acceptability of the parts produced. We see now that precision measurements are always required in the manufacture of press tools, and much the same can be said for the manufacture of machine tools such as lathes, milling machines and drilling machines. The dimensional and geometrical accuracy of the components produced using the above machine tools is proportional to the inherent accuracy built into the machine tool, and thus the operator or craftsman is able to produce accurate work.

2.2 Limitations of line standards

Equipment for the direct measurement of linear dimensions falls into two categories: line standards and end standards. Engineers' steel rules, vernier calipers and vernier height gauges are all examples of line standards; they are described in detail in *Workshop Processes* 1, Chapter 4, and 2, Chapter 5, where it is pointed out that the accuracy of line standards is limited by the fact that the engraved lines themselves possess thickness. Greater accuracy can be achieved with the use of end standards.

2.3 End standards

2.3.1 Slip gauges

Some typical applications of those end standards which are more commonly known as slip gauges may be found in *Workshop Processes* 2, Chapter 5. It is seldom, however, that slip gauges are used to determine linear dimensions in excess of 250 mm, and this is for the following reason. To build up a measurement of 250 mm, assuming that an 83 piece slip-gauge set is available, four slips are required (100, 90, 10 and 50 mm). This means that the overall height of the slip pile will be slightly in excess of 250 mm, owing to the accumulation of the plus tolerances on each slip. More accurate determination of linear distances in excess of 250 mm is achieved with the use of end measuring bars.

2.3.2 End measuring bars

Fig. 2.2. shows a section through a large blanking die; it is required to check the distance between two die inserts. This distance, 480·25 mm, is checked using end measuring bars in conjunction with slip gauges. Manu-

factured from high grade carbon steel, hardened at each end and specially processed to give perfect stability, end measuring bars are about 20 mm in diameter, and a typical set will have the following bars:

25, 50, 75, 100, 125, 175, 200, 375, 575, and 775 mm.

This set will give combinations up to 975 mm with two bars, and combinations up to 1550 mm with three bars.

Workshop bars are provided with tapped holes at both ends, allowing the bars to be joined together without any appreciable loss of accuracy, and a

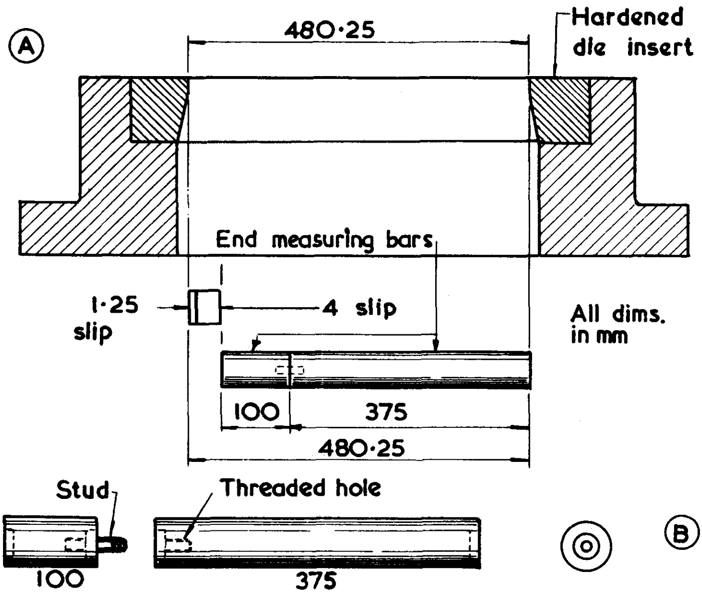


Fig. 2.2.—Measuring the Width of a Blanking Die.

useful range of accessories is available. Both bars and accessories are manufactured to very close limits of accuracy, for example the tolerance at 20° C on a 100 mm workshop bar is plus 0·0005 mm, whilst the Inspection, Calibration and Reference sets are made to even greater degrees of accuracy.

Fig. 2.2 shows the measuring technique involved in the use of end measuring bars. The overall distance of 480·25 mm is made up by joining the 375 mm bar to the 100 mm bar, as shown in fig. 2.2B, whilst workshop slip gauges of 4 mm and 1·25 mm are further wrung to one end of the measuring bars. Provided great care is used, together with a nice sense of touch or feel, the user will be able to determine the width or distance between the die inserts to within plus and minus two micrometres.

Support of end measuring bars

Fig. 2.3 shows, in exaggerated form, the conditions caused by incorrect support of end measuring bars. At A we see the bars supported at each end, giving rise to a sag or droop at the centre; whilst at B, with the bars supported at mid-point, drooping of both ends takes place.

Clearly the conditions at both A and B give rise to an out-of-parallel condition of the ends of the measuring bars, and as these are the measuring faces, errors must result. The correct supporting technique is shown in fig. 2.3C. Note that the bars are supported at what are known as the **Airy points.** As shown in the diagram, the distance between these points is equal to the length of the composite bar divided by the square root of three. End measuring bars supported in this way will have minimum deflection or bending.

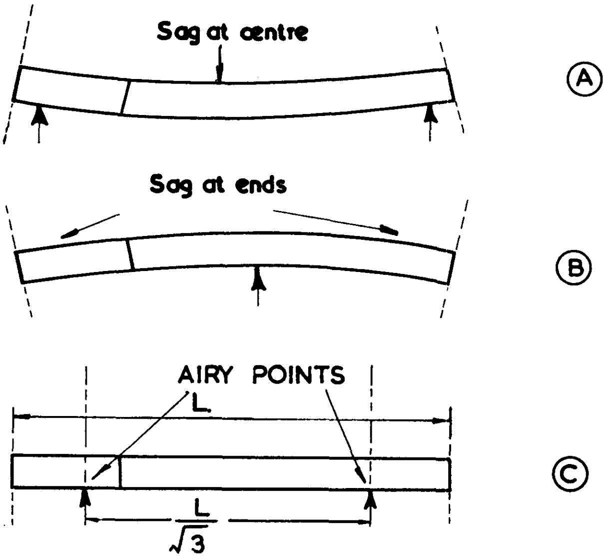


Fig. 2.3.—Airy Points.

2.3.3 Standard or precision rollers and balls

Sets of precision rollers are available ranging from 1 mm to 25 mm diameter. These rollers are made from good-quality steel, hardened and tempered, with the length of each roller equal to its diameter. Both diameter and length are within two micrometres of the stated size. Precision steel balls are also available in sets, and the use of rollers and balls in conjunction with slip gauges and end measuring bars permits a wide range of methods when determining linear dimensions to a high degree of accuracy.

The following examples will serve to illustrate the principles and techniques involved in the application of end standards to determine both linear and angular dimensions.

EXAMPLES

(i) Fig. 2.4 shows a plan view of a die for a press tool. It is required to check the radius shown as *R*. We may assume that the die has been brought to the inspection department for checking, and we are now concerned only with the determination of the linear distance or radius *R*.

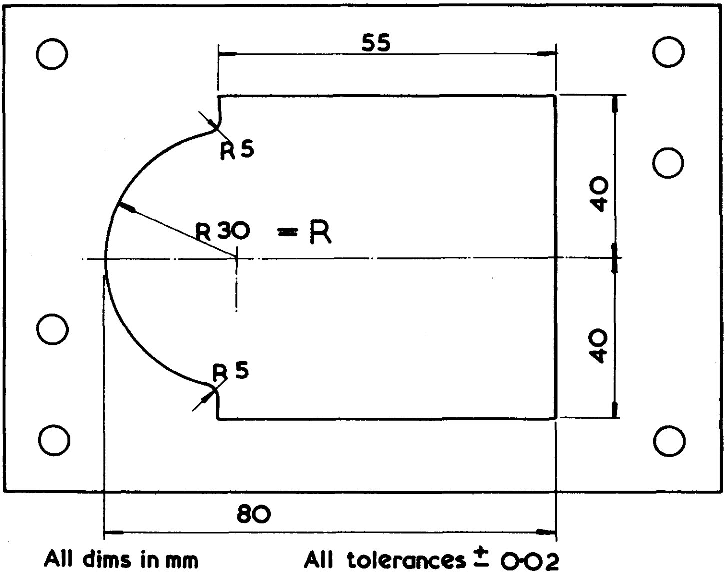


Fig. 2.4.—Die for Press Tool.

The set-up is illustrated in fig. 2.5A. Note that a 50 mm slip gauge is placed in the part circle as shown, with a 5 mm roller placed at the bottom of the part circle. The problem now is to calculate the slip-gauge height that will just enter the gap between the top surface of the roller and the bottom surface of the 50 mm slip gauge. At fig. 2.5B we see the essential geometry involved; referring to the diagram:

Let height of slip gauges = H
then $H = \mathrm{AD} - (\mathrm{AC} + d)$
or $H = R - (\mathrm{AC} + d)$

The problem now is to calculate the distance AC; this may be carried out as follows:

$$\begin{aligned} R^2 &= \mathrm{BC}^2 + \mathrm{AC}^2 \\ \therefore\ \mathrm{AC}^2 &= R^2 - \mathrm{BC}^2 \\ \therefore\ \mathrm{AC} &= \sqrt{(R^2 - \mathrm{BC}^2)} \\ &= \sqrt{30^2 - 25^2} \\ &= \sqrt{275} = 16{\cdot}58\ \mathrm{mm} \end{aligned}$$

Now distance $H = R-(16{\cdot}58+d)$
$= 30-(16{\cdot}58+5)$
$= 8{\cdot}42$ mm

This means that a slip gauge pile of 8·42 mm should just enter the gap between the roller and the 50 mm slip gauge. An experienced inspector will be able to determine the actual slip height that just enters, and thus determine the error by rearranging the formula used to obtain the theoretical height of slips.

(ii) The principle of the dovetail slide is widely used in machine-tool construction, and the measurement of both the linear and angular dimensions of these dovetail slides provides interesting examples, not only of the use of precision balls and rollers, but also of the need for a good working knowledge of geometrical and trigonometrical principles.

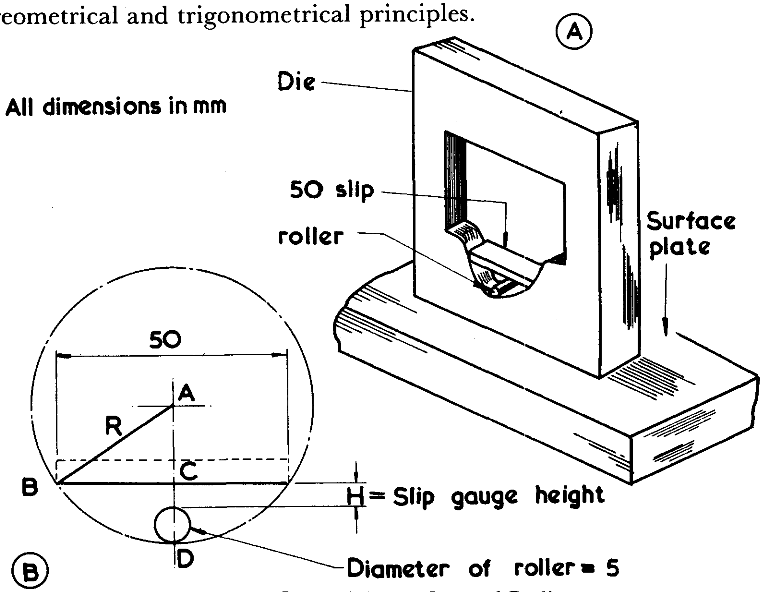


Fig. 2.5.—Determining an Internal Radius.

Fig. 2.6A shows an external dovetail; it is required to check the distance X, which is the width of opening. At fig. 2.6B we see the set-up for the job. Two rollers of equal diameter are placed in opposite corners as shown. By trial and error the distance shown as H in the diagram is obtained with the use of slip gauges. If this distance is in excess of 250 mm, then end measuring bars must be used.

Distance X may be calculated from the following formula:

$$X = h+d+\left(d \cot \frac{\alpha}{2}\right)$$

where h = slip-gauge distance,
d = diameter of rollers,
α = angle of dovetail.

Internal dovetails may also be checked in like manner with the aid of slip gauges and precision rollers. Fig. 2.6C shows the technique adopted. Note the use of a slip-gauge **nest** or **cage,** in which slip gauges are clamped, thus permitting easier manipulation of the assembled slips, and also avoiding handling of slip gauges during the measuring operation (fig. 2.6D).

An external micrometer may be used to determine the distance h, and once again the accuracy achieved will depend on the experience and skill of the user.

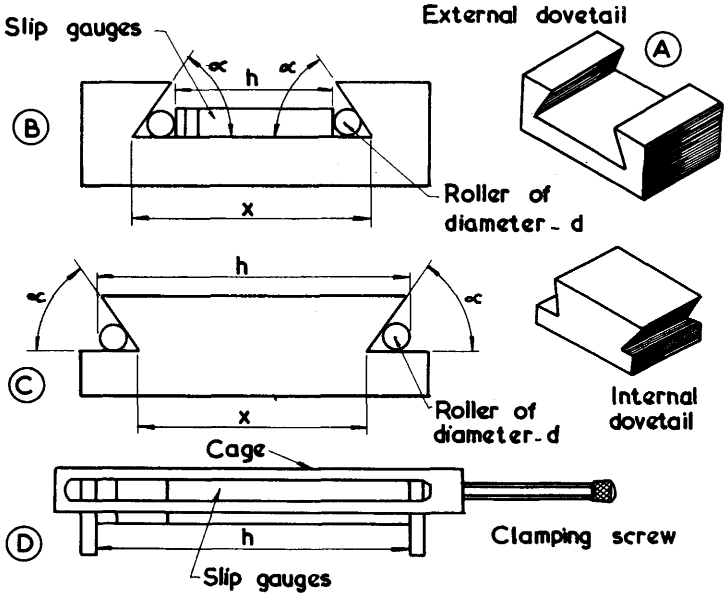


Fig. 2.6.—Measuring Internal and External Dovetail Slides.

The width of the opening shown as X in fig. 2.6C may be calculated from the following formula:

$$X = h - d - \left(d \cot \frac{\alpha}{2}\right)$$

(iii) It has been assumed in Examples (i) and (ii) that the angles of the dovetails are within the limits laid down in the drawing or blueprint. It is not difficult, however, to check these angles, and fig. 2.7 shows the technique adopted.

Two rollers of identical size are placed as shown, and the distance across their outside faces determined. The same rollers are now placed on equal-height slip gauges, as shown in fig. 2.7, and once again the distance across their outside faces is determined.

If Y = the first linear distance,
and X = the second linear distance,
then

$$\tan \alpha = \frac{h}{\frac{(Y - X)}{2}}$$

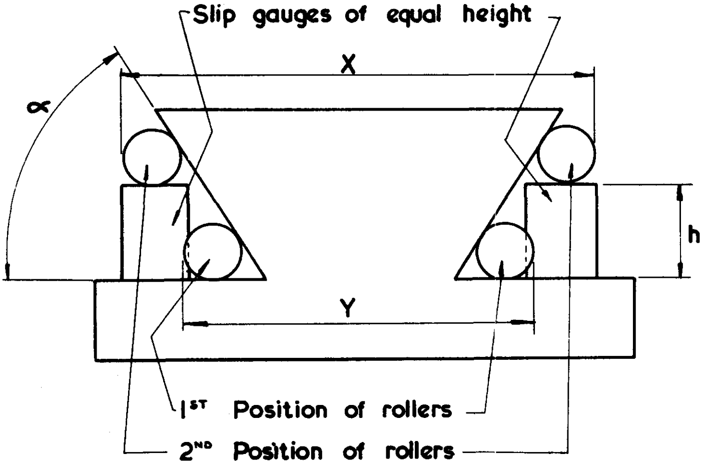


Fig. 2.7.—Angular Check of Dovetail Slide.

The determination of the angle of an internal taper provides a good example of the use of precision balls.

(iv) Fig. 2.8 shows a milling cutter adapter; it is required to check the internal taper. This is achieved by carefully inserting, in turn, two precision balls as shown in the diagram. With the smaller-diameter ball in position close to the small end of the taper, the adapter is placed on a toolmaker's flat, with two slip-gauge piles of equal height placed either side.

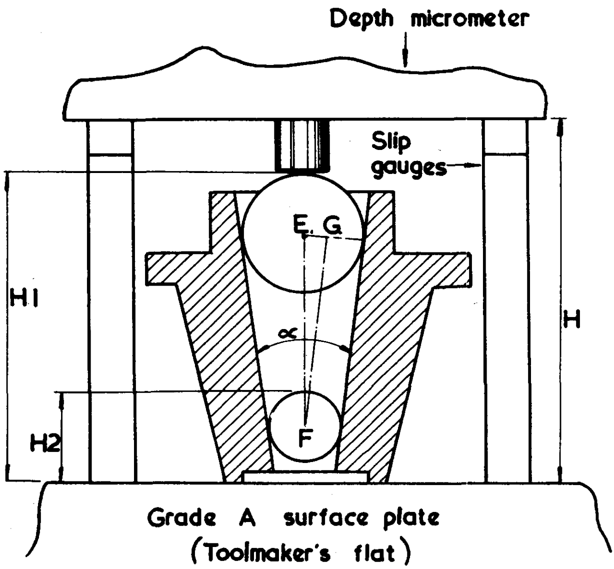


Fig. 2.8.—Determination of an Internal Taper.

A depth micrometer is now used to determine the distance from the top surface of the slips to the surface of the precision ball. The same procedure is repeated when the small ball is removed and the larger ball rolled into position. The distances shown as H_1 and H_2 on the diagram may now be calculated and the angle of the taper found from the formula

$$\sin\frac{\alpha}{2} = \frac{(R-r)}{\text{EF}}$$

where α = included angle of taper,
R = radius of large ball,
r = radius of small ball,
EF = centre distance of balls.

The examples described represent only a few of the very many applications of working standards to determine linear and angular dimensions to close limits of accuracy. It is essential that all the equipment be carefully checked before use. For example, the depth gauge used in Example (iv) should be tested using slip gauges, with a toolmakers' flat used as a reference plane or datum surface. The method is shown in fig. 2.9; note the adjusting screw, which will permit the depth micrometer to be adjusted should an error be detected.

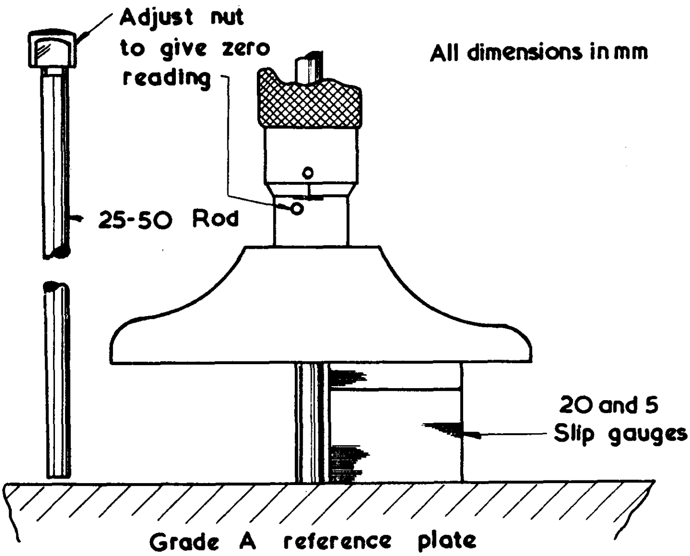


Fig. 2.9.—Checking Accuracy of Depth Micrometer for Zero Setting.

2.4 Limitations of direct measurement

Perhaps the best way of demonstrating the limitations of direct measurement using working standards is for the student to carry out for himself the measuring techniques described in the four examples given. Better still, let (say) four students each carry out the determination of the respective dimensions independently, and then compare results. It is certain that there will be discrepancies, and these will not all be caused by arithmetical errors. In all the examples given, the troublesome question of **feel** exists. With practice it is possible to find the height of slip gauges that will just enter a gap, within two micrometres from a height which will not enter or just **nip.** This means that the distance *H* shown in fig. 2.10 can be determined to within approximately one micrometre or 0·001 mm. Fig. 2.10 shows also the use of a toolmaker's straight-edge to determine the overall height of the component together with the parallelism of the top face with the base. Clearly much depends on the skill of the inspector, and to measure large numbers of

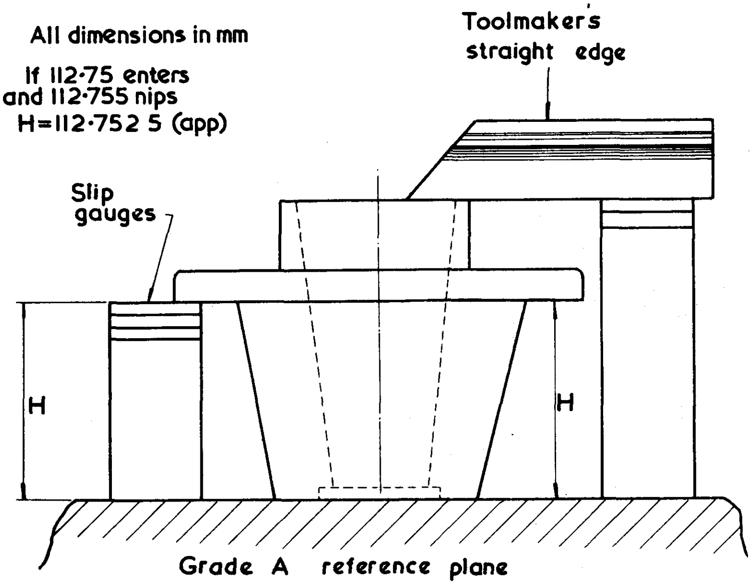


Fig. 2.10.—Use of Slip Gauges and Toolmaker's Straight-edge.

components using the equipment and techniques under discussion will present very great difficulties, owing to the variations that must result as a direct outcome of the human element. It must now be appreciated that if precision measurements are to be made with consistent accuracy, then as far as possible the problem of feel must be solved, and this can only be achieved with complete removal of the human element.

At the same time we need to **magnify** the difference between the linear dimension under test and the working standard used. If this difference can be clearly shown on a dial or any other recording device, then clearly it is possible for precision measurements to be made reasonably free from error introduced by the inspector. This is the principle of **measurement by comparison.**

2.5 The use of comparators

Measurement by comparison can be made only with the aid of a suitable **comparator.** The function of any comparator is to magnify and record any difference in height between the working standards used to set the comparator to zero and the component under test. Let us assume that we have a large number of precision rollers of 40 mm diameter, and that we wish to measure the diameter of each roller.

It is not as we have seen, a practicable proposition to employ (say) six inspectors, giving each a 25–50 mm micrometer. This must entail individual measurement of each roller, with any variation due to the human element affecting the resulting measurements. Clearly a better plan is to select an an end standard of 40 mm, and then compare the height of each roller against this known standard. We may merely select the 40 mm slip gauge from the Inspection set, knowing that this slip gauge is accurate to within two tenths of a micrometre. With this slip gauge wrung to a toolmaker's flat, which is equivalent to a high grade reference plane, all that is now needed is a precision comparator that will clearly magnify any linear displacement of the measuring plunger, as shown in fig. 2.11.

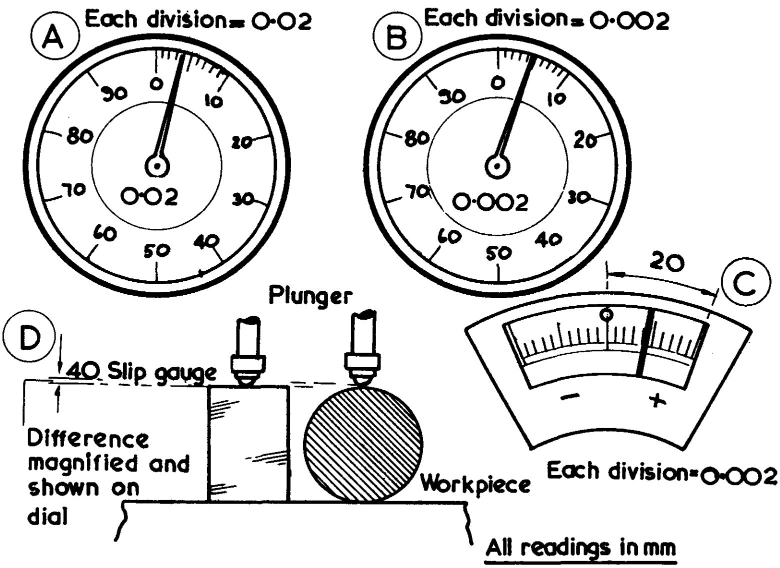


Fig. 2.11.—Principle of Measurement by Comparison.

Note the indicating dials shown as A, B and C. The magnification of the comparator used is the ratio between the distance moved by the pointer on the indicator scale and the distance moved by the plunger. At A we see the popular 0.02 mm comparator, more commonly known as a **dial test indicator.** The width of one division on the dial of this type of instrument is about 1·5 mm; thus the magnification is approximately 75:1. It is unlikely that this type of comparator would be used to check the height of the rollers, because it is necessary to calculate or estimate to within one micrometre.

At B we see the dial of a 0·002 mm dial indicator. Each division is now equivalent to a plunger movement of two micrometres, and 0.02 mm movement of the plunger results in pointer movement of approximately 10 mm. Thus the magnification of this instrument is of the order of 500:1.

At C we see the dial of a comparator most likely to be used to determine the diameters of the rollers under test. Note that the measurable range is only plus and minus two hundredths of a millimetre. This means that this comparator cannot be used to check components having tolerances in excess of plus and minus two hundredths of a millimetre. A movement of 0·02 mm of the plunger gives rise to a pointer movement of about 20 mm; thus the instrument has a magnification of 1000:1.

Clearly it is a relatively simple matter to set this instrument to read zero with the plunger resting on a 40 mm inspection slip gauge, as shown at D. Any variation in height is immediately indicated by the pointer as the rollers under test are passed beneath the plunger. Although a division on the dial is about two millimetres in width, representing a plunger movement of 0·002 mm, it is not difficult to estimate the pointer position to within one quarter of a division. In this way roller diameter errors may be detected to within half a micrometre.

This technique solves several of our measuring problems. **Firstly**, as we have seen, considerable accuracy is achieved, according to the type of comparator used. **Secondly,** not only are we able to use end standards, but also we are able to do so with the troublesome aspect of feel removed. We may define feel as the pressure exerted on the slip-gauge surface by the plunger when setting for zero. If the precise comparison is to be made, it is essential that the plunger exerts the same pressure on the roller under test. This of course is exactly what the instrument is capable of doing, irrespective of the skill and experience of the person who passes the roller under the plunger.

Thirdly, then, the rollers can be checked using relatively unskilled operators, and the **fourth** and perhaps most important point is that the measuring operation is performed in a very short space of time.

The reasons given above account for the wide and increasing use of the principle of measurement by comparison in the measurement of engineering components.

2.6 Types of comparators

Several principles are adopted in order to obtain magnification of plunger movement, and a comparator used for the measurement of engineering components may be classified under the following headings:

(i) mechanical,
(ii) electrical,
(iii) optical,
(iv) pneumatic.

Irrespective of the principle used, all comparators should satisfy the following essential requirements:

(i) The comparator should be able to stand up to normal wear and tear without loss of accuracy.

(ii) The measuring head should be capable of vertical adjustment to allow for the checking of components of differing heights.

(iii) Means should be provided to allow the instrument to be set to zero.

(iv) The reading should be **dead beat.** This means that the pointer is free from oscillations, and responds immediately and positively to the plunger movement.

(v) A hard-wearing contact should be provided at the working face of the plunger, and the force exerted by this point or contact face should not exceed 3 N. A value of about 2·5 N is acceptable. A simple lever or other similar device should be available for easy lifting of the plunger.

2.7 Mechanical comparators

As the name suggests, a mechanical comparator uses mechanical principles in order to obtain magnification of the plunger movement. The principles involved are those used by engineers when transmitting motion from one part of a mechanism to another. If a mechanical comparator has a rotary dial, as shown in fig. 2.11 A, B and C, then clearly a simple definition of the requirements is maximum rotary movement of the pointer for minimum linear movement of the plunger. The only disadvantage is that any wear, play, backlash or dimensional faults in the mechanical devices used will also be magnified.

2.7.1 Dial indicators

Essentially a dial indicator is a mechanical comparator using gear systems together with a rack and pinion. A suitable spring gives constant plunger pressure, whilst hair springs may be employed to eliminate play or backlash. If a dial indicator is to provide faithful magnifications of the plunger movement, the dimensional and functional features of the gears, racks and pinions used must possess a high degree of precision. Dial indicators, however, seldom exceed 60 mm in diameter, and this means that the moving parts are of necessity quite small. This fact increases the difficulty of machining these parts to the very high degree of precision required; thus dial indicators are limited to an accuracy of about 0·002 mm.

It will be found that dial indicators capable of reading to 0·002 mm require very great care in use and handling; very often better results are possible using a dial indicator with graduations of 0·01 mm, or even 0·02 mm.

2.7.2 Correct use of a dial indicator as a comparator

If a dial indicator is to be used as a comparator, the set-up shown in fig. 2.12 should be adopted. Note the rigid column, with provision for vertical adjustment, and the small accurate reference plane, or worktable, with provision for fine adjustment. Such a simple comparator is ideal for the checking of components to within a tolerance of, say, plus and minus 0·05 millimetres.

Note, too, the use of adjustable limit indexes; it is now a simple matter to determine whether large numbers of components are machined to within the tolerance of plus and minus 0·05 mm. With the comparator set to middle limit using slip gauges, and the limit indexes set 0·05 mm each side of the zero position, rapid and efficient measurement of the components is readily achieved by unskilled operators. Clearly, if the operator is instructed only to reject those components that cause the pointer to record outside the limit indexes, the comparator is now used as a **visual gauging device.** It is not strictly necessary for the operator to be made aware of the fact that each division on the dial of the dial indicator represents 0·02 mm movement of the plunger. The operator of the comparator is now, in effect, gauging the dimension under test; that is to say, merely ensuring that the dimension is within its high and low limit and thus acceptable.

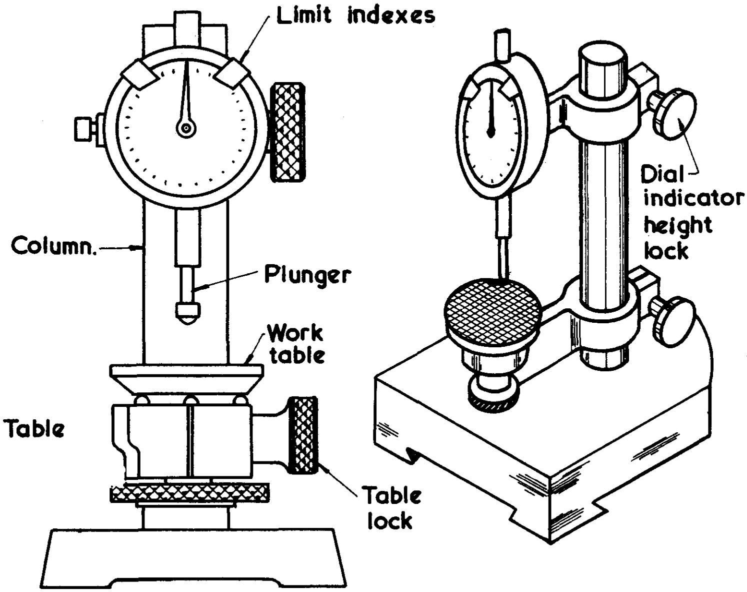


Fig. 2.12.—Dial Indicator Comparator.

2.7.3 Lever comparators

The principle of the lever when used to obtain magnification of small linear movements is appreciated by all toolroom turners, who often make use of the device shown in fig. 2.13. This simple device, usually referred to as a **wiggler,** is used to assist the turner in centring, say, a centre dot or drilled hole prior to further machining. The illustration at A shows the working point inserted in a centre dot; if a drilled hole requires centring, a small steel ball is placed over the point.

The geometry of this simple magnifying device is shown in fig. 2.13B. If the centre dot does not lie on the lathe centre line, linear displacement of the working point of the rod takes place; thus a movement of the working point shown as AC gives rise to a movement at the recording end of the rod EB. Note that the magnification is of the order of 10:1. Note also that the distance AC is a linear distance at 90° to CE, and is equal to $r \sin \theta$, whilst the magnified movement at the recording point is along the arc EB. This distance is equal to $R\theta$, with the angle θ in radians. This magnification of straight-line displacement in the form of movement along an arc sets a limitation on the use of this principle with regard to its adaptation for comparators. This is because the scale representing the magnified movements of the working point or plunger will have unequal divisions. In other words, unless the angular movement is very small, equal increments of the plunger do not produce equal increments of the angular movement of the pointer. Fig. 2.14 illustrates a simple mechanical comparator in which the lever principle is used in conjunction with a sector-and-pinion device. Note that movement of the plunger causes the sector arm to rotate slightly about the fulcrum O. Thus the point A moves along a small arc, as does the point B; equal angular movements of the sector arm produce equal angular movements of the pointer. This means that the divisions on the scale are equal.

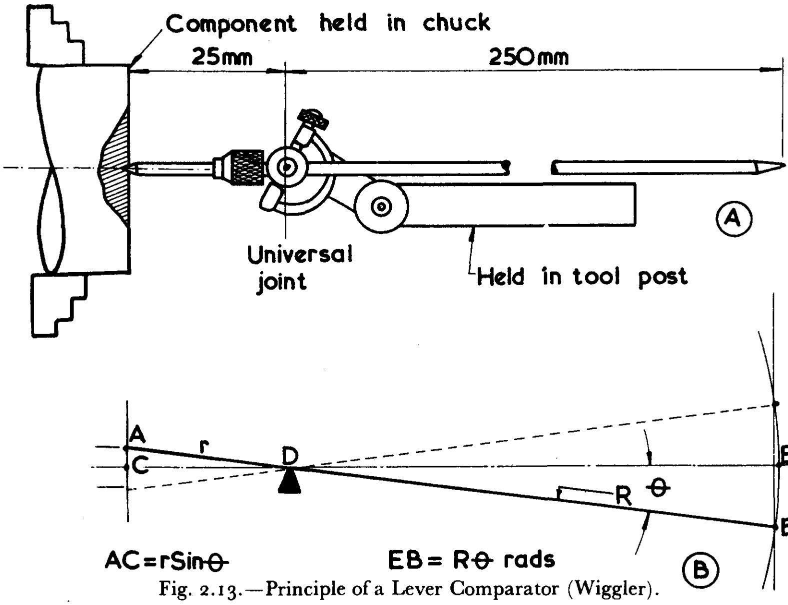


Fig. 2.13.—Principle of a Lever Comparator (Wiggler).

The scale for this instrument is also shown in fig. 2.14, and it will be seen that a range of 0·2 mm limits the plunger movement to this amount. Each division on the scale is equivalent to a plunger movement of 0·005 mm. Perhaps one objectionable feature of the principle shown in fig. 2.14 is that the pointer records a magnification of **upward** movement of the plunger. This means that if the plunger is accidently subjected to a sudden upward blow (something very easily done when setting the instrument to zero) there is a serious risk of damage to the delicate mechanism. Stops are always fitted within the instrument to guard against this, but better types of mechanical comparators are designed in such a way that the pointer is actuated only by **downward** movement of the plunger; thus accidentally knocking the plunger upwards has no ill effect on the delicate mechanism of the instrument.

2.7.4 Twisted-strip comparator

The principle underlying the design of this comparator has for many years formed the basis of a simple mechanical toy. It is hoped that all students will be able to recognise the device illustrated in fig. 2.15A. If we remember that the purpose of a comparator is to convert small linear movements of a plunger into large circular movements of a pointer, then clearly the twisted-strip principle has something to offer.

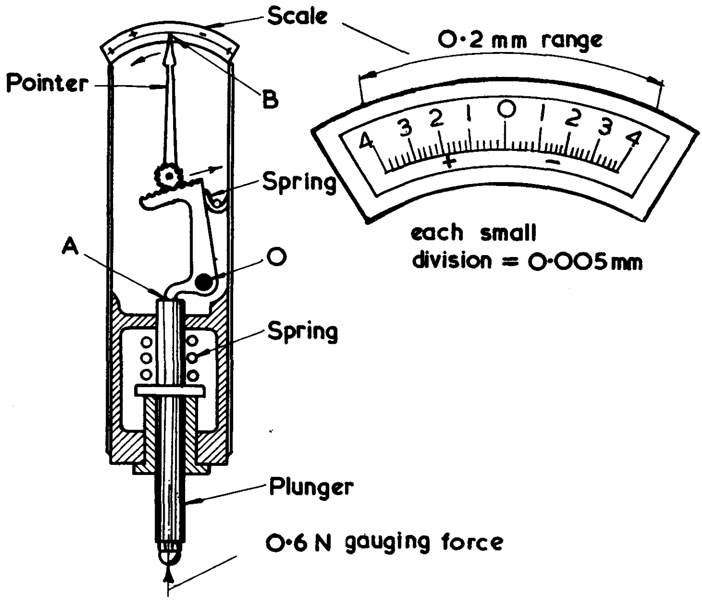


Fig. 2.14.—Upward Reading Mechanical Lever Comparator.

For very small linear movements of the twisted cord in the direction of the arrows, the disc rotates at considerable speed; a point X on this disc would move through a very great distance indeed. This is the principle of the twisted-strip comparator, and the mechanism is indicated in fig. 2.15B. Vertical movements of the plunger are transferred to the right-hand side of a thin twisted metal strip. Stretching or elongation of this strip causes rotation of the central portion, in exactly the same way as the stretching of the twisted cord sets up rotation of the cardboard disc of the mechanical toy illustrated in fig. 2.15A. A delicate pointer is attached to the central portion of the twisted metal strip; thus very small linear movements of the plunger are recorded by this pointer on a suitably calibrated scale.

A wide variety of high magnifications are possible using the simple principle outlined. We owe the introduction of this type of instrument to a Swedish engineer, H. Abramson, who was responsible for its design, and to the well-known precision engineering concern of Messrs. C. E. Johansson, who manufactured it.

2.7.5 Sigma comparator

This is a British-designed and British-manufactured comparator of considerable popularity. The type shown in fig. 2.16 is of relatively simple design with regard to the external features of the instrument, as comparators are available capable of carrying out several checks on the one component.

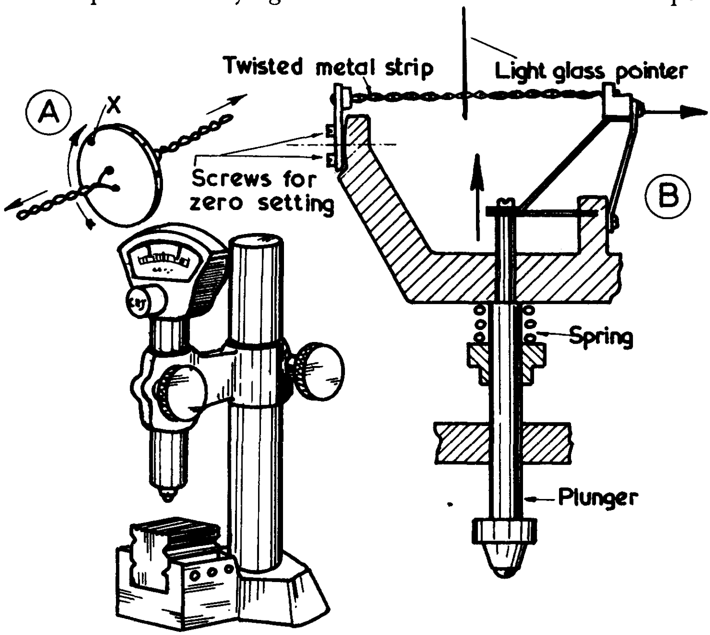


Fig. 2.15.—Twisted-strip Comparator.

The type illustrated is available with a choice of scale ranges. A typical example is a measuring range of plus and minus 0.07 mm, with scale graduations of 0·002 mm. As the width of one division on the scale is 2 mm, and equivalent to a movement of the plunger of 0·002 mm, the magnification of the instrument is 1000:1.

An important feature of this instrument is that the pointer, which is dead beat, is actuated by **downward** movement of the plunger, thus eliminating the possibility of damage to the mechanism arising from excessive upward blows on the plunger. Both the contact tip and worktable are interchangeable, according to the shape of the work to be checked, and these comparators are available with vertical capacities from 150 to 600 mm; that is to say components up to 600 mm in height can be checked. Note the provision of limit indexes, or tolerance pointers as they are more commonly called, allowing the use of relatively unskilled operators to work to close limits when checking the accuracy of machined dimensions.

There are of course, many other types of mechanical comparators in use, but the types chosen are a good indication of both the ingenuity of design and the manufacturing precision required for the production of an efficient and reliable comparator.

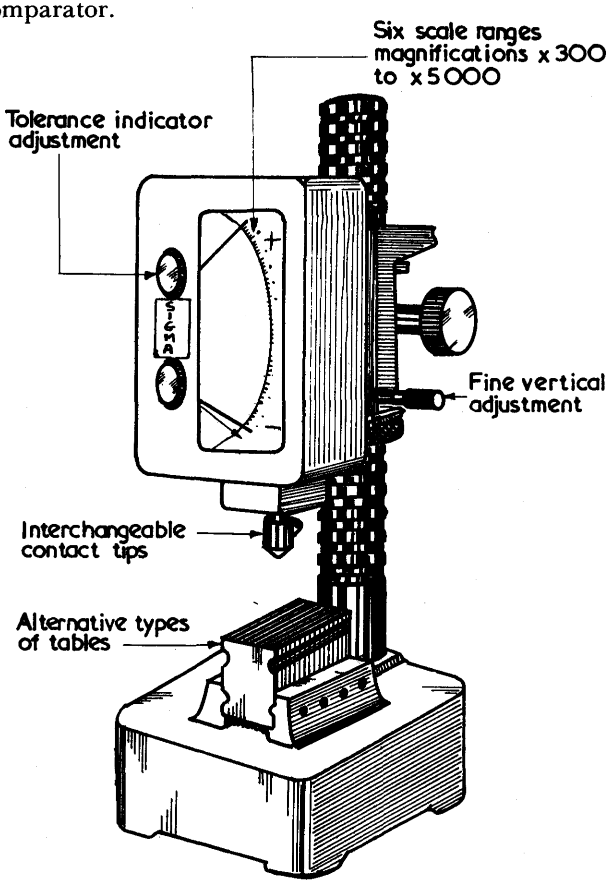


Fig. 2.16.—Sigma Mechanical Comparator.

2.8 Electrical comparators

Some very great advantages are offered by the use of electrical comparators. Mechanical devices, as we have seen, may be actuated by levers, gears, racks and pinions. All of these are subject to the effects of wear and friction, which are likely to affect the accuracy and useful life of the instrument. Electrical comparators, on the other hand, by their very nature will possess a minimum of moving parts; thus we can expect a high degree of reliability from these instruments.

In general, **two** important applications of electrical comparators are of the greatest interest:

(i) the use of electrical comparators as measuring heads,

(ii) the use of electrical gauging heads to provide visual indication as to whether a dimension is within the limits laid down.

The first application is of great value when very precise measurements are required; say the checking or comparison of workshop slip gauges against inspection slip gauges. The second application is used not as a method of determining a linear dimension to within plus and minus 0·02 micrometres, but to indicate with a green light if a dimension is within the limits. An undersize dimension is indicated with a red lamp; an oversize dimension with a yellow one. Once again it is no longer necessary for the operator to be aware of the actual tolerances on the dimension. Provided the instrument is correctly set, the placing of the component under the plunger of the gauging head is all that needs to be done. The signal lamps provide instant and positive indication of the acceptability of the dimension under test.

2.8.1 Principle of the electrolimit gauge

Fig. 2.17 illustrates in a simple manner the principle of the electrolimit gauge or measuring head. Vertical movements of the plunger are transmitted to an armature, which is suspended, as shown in the diagram, on thin metal strips. At the left-hand side of the armature it will be seen that it lies between two electromagnetic coils A and B. These coils form two arms of an a.c. bridge circuit.

Any movement of the armature between the two electromagnetic coils sets up out-of-balance effects, which are recorded by a microammeter. Provided

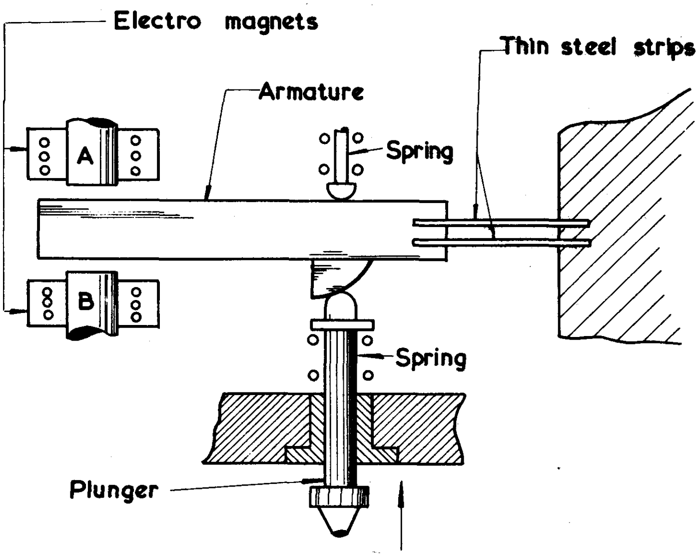


Fig. 2.17.—Principle of the Electrolimit Measuring Head.

the microammeter is calibrated in terms of the displacement of the plunger, direct reading of extremely small movements of the plunger is readily achieved. A front view of the complete instrument is shown in fig. 2.18. Note that the recording head is a separate unit, and that a supply of mains voltage is required. Fluctuations of up to 15% have no effect on the accuracy.

A great advantage possessed by this electrical comparator is the dual magnification available. A simple switching arrangement enables a second magnification to be obtained, exactly double the first. Thus, assuming the instrument is being used with a magnification of 5000, it is a simple matter to increase this to 10 000. Even with the first magnification, the measuring range will be quite small, no more than 0·02 mm, whilst in the second case the range will be only 0·01 mm.

Such is the accuracy or sensitivity of these instruments that they may be used with little trouble to check the accuracies of slip gauges and other measuring standards.

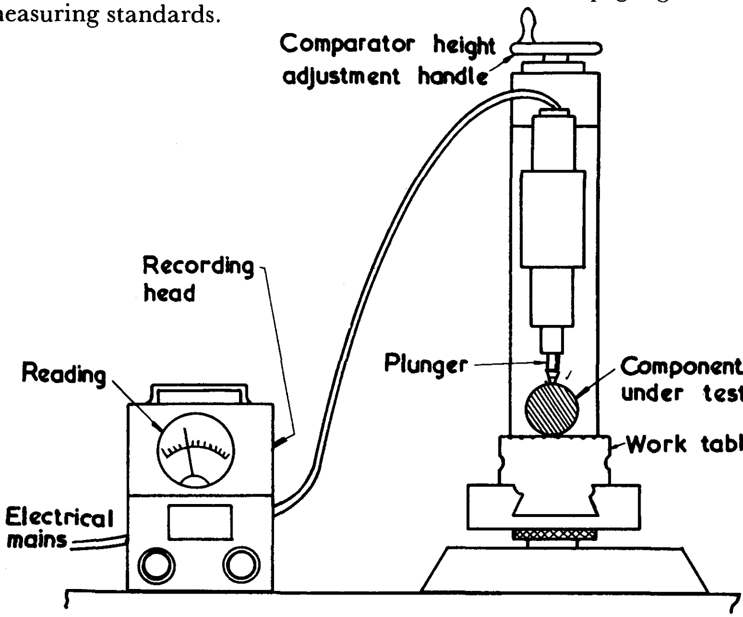


Fig. 2.18.—Electrical Comparator.

2.8.2 Visual gauging heads

The purpose of these heads is to give a visual indication, using small coloured signal lamps, of the acceptability of an engineering component with regard to the dimension under test. Clearly an electrical principle is involved, which may be simply described as follows, with reference to fig. 2.19. Vertical displacement of an interchangeable plunger causes movement of the rod C either to the left or right, as shown in the diagram. A and B are electrical contacts, capable of precise adjustment in the direction of the arrows; a micrometer device is available.

In the position shown, that is to say with the rod in mid-position between the contacts A and B, the dimension under test is within the limits. If the dimension is oversize, the rod C moves to the right and makes contact with B. Immediately the top red lamp is illuminated. Likewise if the dimension is undersize the rod moves to the left, making contact with A and illuminating the yellow lamp.

Note that the actual magnifying device is not shown on the diagram; levers and thin steel strips, together with knife-edge seatings, are employed.

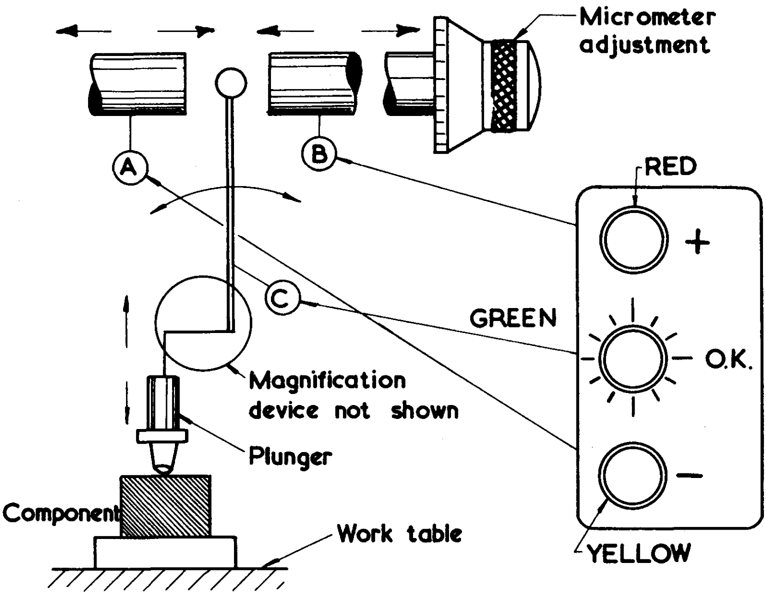


Fig. 2.19.—Principle of a Visual Gauging Head.

With various detachable plungers, there is practically no limit to the application of this instrument. Fig. 2.19 illustrates the visual gauging of a single dimension, but we may apply the principle shown to several dimensions simultaneously. This technique is shown diagrammatically in fig. 2.20.

2.8.3 Multi-gauging machines

The component in fig. 2.20 is shown having four diameters visually checked simultaneously. The component is set in a hand-operated carrier slide and pushed into the gauging station. A glance at the indicating panel will reveal whether the four diameters under test are within the limits laid down. If so the four centre green lights will signal, and the operator will remove the acceptable workpiece and replace it with another.

Perhaps it is now evident to the student that we have come a long way in this matter of precision measurement. We see now the complete removal of the human element, for it is not difficult to arrange for automatic loading of components into the gauging station. It is not difficult, too, to arrange for automatic rejection of undersize components, and retention, for subsequent salvage, of oversize components. Not only diameters, but also internal dimensions and heights, can be checked in the manner just described. Machines are available capable of the visual checking of over 30 dimensions on a fairly large-size workpiece.

The setting, maintenance and care of machines such as these are most certainly the province of both mechanical and electrical technicians, and it is certain that great strides are being taken in the development and adaptation of these machines.

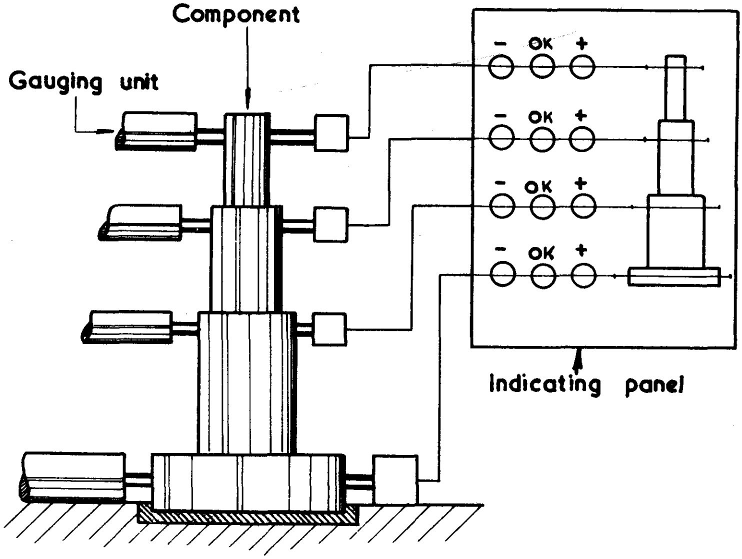


Fig. 2.20. —Application of the Multi-gauging Device.

2.9 Optical comparators

There are many types of optical comparators in use, but all of them operate on one of two main principles:

(i) the use of the optical lever,
(ii) the use of an enlarged image.

2.9.1 Optical magnification of movement

An optical comparator is a device that provides considerable magnification of small linear movements of a measuring plunger. The principle adopted is that of the **optical lever,** and although the design of optical comparators varies considerably, the principle involved remains essentially the same.

The principle of the optical lever is simply illustrated in fig. 2.21. A beam of light AC is directed onto a mirror, as shown at A, and is reflected onto the screen, appearing at O as an illuminated dot. Note that the angle θ at which the beam strikes the mirror is equal to the angle θ at which the beam is reflected from the mirror; both angles are measured from the normal, that is from a line projected at 90° to the surface of the mirror.

At B we see the effect of vertical movement of the plunger, which causes the mirror to tilt on the pivot shown. Note that the reflected ray of light has now moved through the angle shown as $2a$; this is twice the angle of tilt introduced by the plunger movement. The illuminated dot now moves to B; thus a linear movement h of the plunger produces a movement of the dot equivalent to the distance OB on the screen.

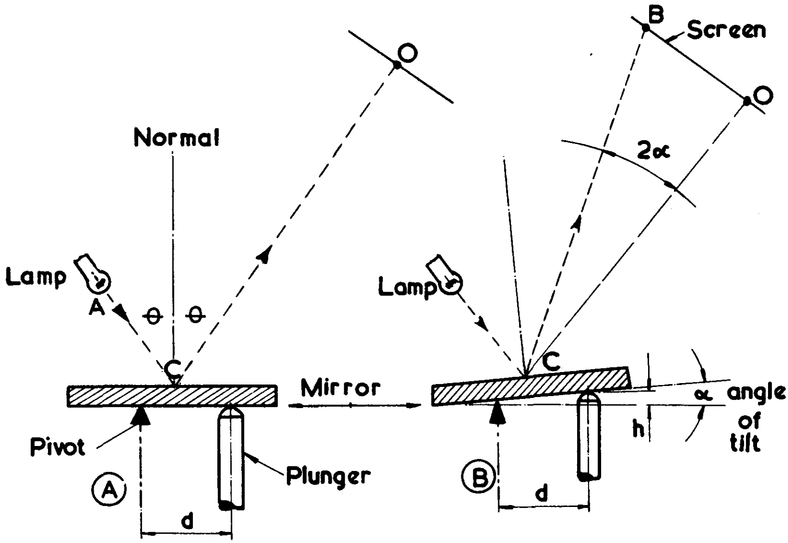


Fig. 2.21.—Principle of the Optical Lever.

The magnification of the device shown may be calculated as follows:

Because the angle of mirror tilt will be small, we may consider the angle in terms of radian measure. Let d equal the distance of the fixed pivot from the centre line of the movable plunger, and h equal the vertical displacement of this plunger.

Then from radian measure,

$$a \text{ radians} = \frac{h}{d}$$

Similarly

$$2a \text{ radians} = \frac{OB}{CO}$$

Thus

$$2a \text{ radians} = \frac{2h}{d}$$

and

$$\frac{OB}{CO} = \frac{2h}{d}$$

∴

$$\frac{OB}{h} = \frac{2CO}{d}$$

Now the magnification of a comparator, as we have seen, is the ratio between the distance moved by the indicating pointer and the displacement of the measuring plunger.

Because OB is the distance moved by the spot of light, we may consider, and indeed use, this spot of light as an indicating pointer. With h as the distance moved by the plunger, the magnification of the device must be OB/h, and this ratio is equal to $2CO/d$.

It is now clear that as CO represents the distance of the screen from the tilting mirror, the greater this distance, the greater will be the magnification of the instrument. Also the smaller the distance between the fixed pivot and the centre line of the plunger, the greater will be the magnification.

Many systems are in use to satisfy the requirements outlined above, and the following example is but one of a wide choice of optical-comparator operating principles.

2.9.2 Application of the optical lever plus a mechanical lever

Fig. 2.22 shows a typical application of the optical lever principle combined with a simple mechanical lever. The instrument which makes use of the principle shown is quite suitable for shop use; it is of rigid construction, simple to operate, reliable in use and ideally suited for the checking of linear dimensions under mass-production conditions.

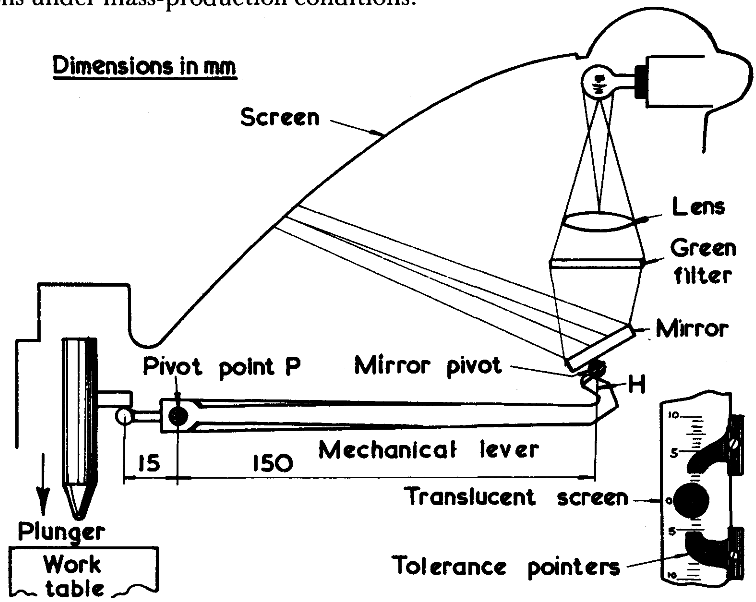


Fig. 2.22.—Principle of an Optical Comparator.

Referring to fig. 2.22, we can see that downward movement of the plunger tilts the mechanical lever about its pivot P. Note that a mechanical magnification of 10:1 is achieved with the dimensions given. The end of the lever shown as H causes a small mirror to tilt, thus deflecting a ray of light emanating from an electric bulb. From here on, the optical lever principle applies, and a green filter provides a clear visual pointer on the translucent screen.

A view of this screen is shown at fig. 2.22B. The overall length is about 150 mm, and the magnification of the instrument is 1000:1, so that the measuring range is plus and minus 0·075 mm. Note the use of tolerance pointers.

A pictorial view of this comparator is given in fig. 2.23.

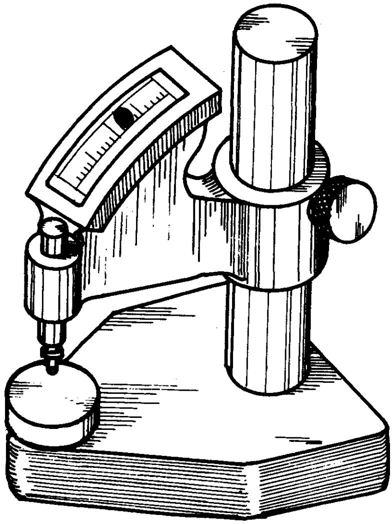


Fig. 2.23.—Optical Comparator.

2.9.3 Use of an enlarged image

Optical comparators which make use of the enlarged image principle are commonly known as **optical projectors.** The technique underlying the use of this measuring device is in accordance with our often stated rule of measurement; namely the determination of an unknown value by comparison with a known standard.

We may define the purpose of an optical projector as follows: to compare the shape or profile of a relatively small engineering component with an accurate standard or drawing much enlarged. The optical projector throws onto a screen an enlarged image of the component under test; the principle is illustrated in fig. 2.24.

Note that the rays of light from the lamp A are collected by the condenser

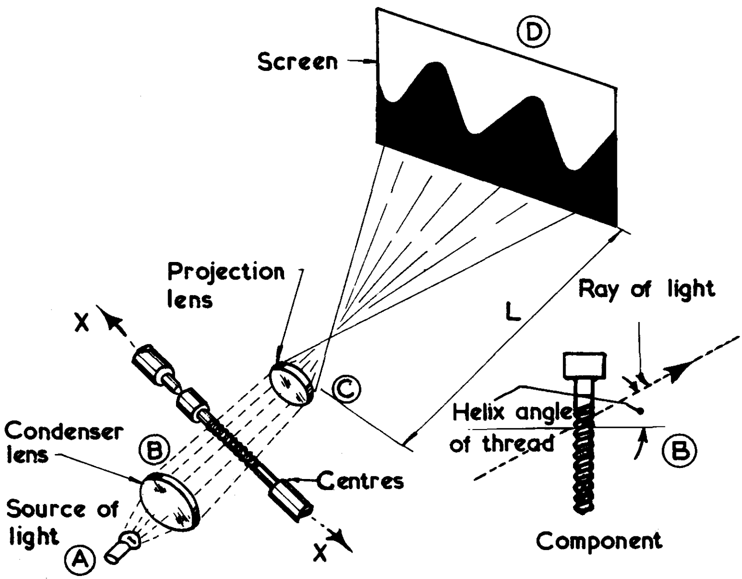


Fig. 2.24.—Principle of the Optical Projector.

lens B, from which they are transmitted as a straight beam. It will be seen in the diagram that the threaded component E has been placed between the condenser lens and a projection lens C.

In this way the beam of light is interrupted, and a magnified image appears on the screen as shown. A sharp or well-defined image is obtained by focusing, or adjustment of the distance between the component and the projection lens. Once again the magnification of the system will be equal to the size of the projected image divided by the size of the component; such magnifications are arranged in relation to the focal length of the objective lens and its distance from the screen.

The magnification may vary from 10 to 100. If we assume that a magnification of 100 is used in the arrangement shown in fig. 2.24, a drawing is made of the thread profile, with all dimensions one hundred times full size; thus the profile of the thread is magnified 100 times, allowing a comparison of the resultant image with the accurately produced master drawing.

It is not difficult, using a micrometer device or slip gauges, to control the linear movement of the worktable on which the holding centres are located. This means that variation of the magnified image from the master drawing can be determined accurately by noting the movement required along the axis shown by the arrow X in the diagram.

It is essential that the worktable be rotated through an angle equal to the helix angle of the thread, as shown in fig. 2.24B. Because the distance from the projection lens to the screen has a direct effect on the amount of magnification obtained (that is to say, the greater this distance the greater the magnification), mirrors are often used to increase this distance without making the projector unnecessarily bulky and causing it to occupy undue floor space.

2.9.4 The toolmaker's microscope

A toolmaker's microscope is essentially a microscope that has provision for the fitting of various standards, against which a magnified image of the profile under test can be compared. These standards are in the form of graticules —glass discs on which are engraved thread angles or other reference lines.

A typical graticule is simply shown in fig. 2.25A; this is one used to check rack-tooth angle form. A special device allows rapid setting of the line shown as P parallel to the direction of the worktable travel, when the circular scale is set at 0°.

The initial setting, shown at A, illustrates an image of the rack tooth with the axis of the rack parallel to the worktable movement. At this position the circular scale reads zero. At B we see the technique adopted to determine the rack-tooth angle. The view shown represents the result of rotation of the work in order to bring the surface of the tooth, shown as RT, parallel with the graticule line S. A separate microscope may be used to determine to a high degree of accuracy the angle of rotation through which the protractor unit carrying the graticule has rotated.

In this way very accurate determination of the accuracy of small rack teeth may be made. Typical examples of the need for this sort of measurement are

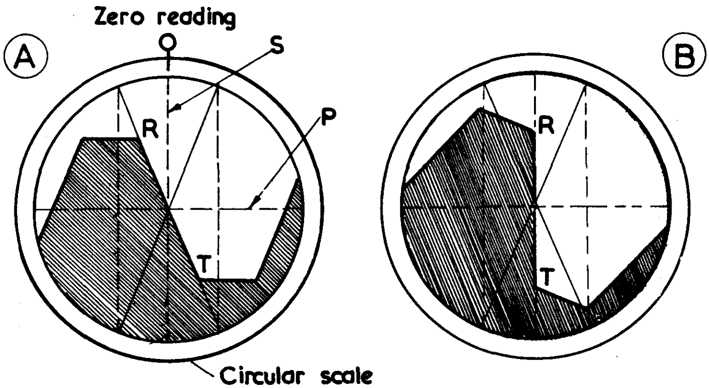


Fig. 2.25.—Graticules for Toolmaker's Microscope.

provided by the racks, pinions and levers used in the mechanical comparators previously described.

There are, of course, many other measuring operations that can be carried out with the aid of a toolmaker's microscope. Graticules having a wide range of thread profiles are available, allowing the checking of small screws, screw gauges and thread-cutting tools. Fig. 2.26 illustrates in a simple manner a typical toolmaker's microscope. Note that the worktable has micrometer adjustment.

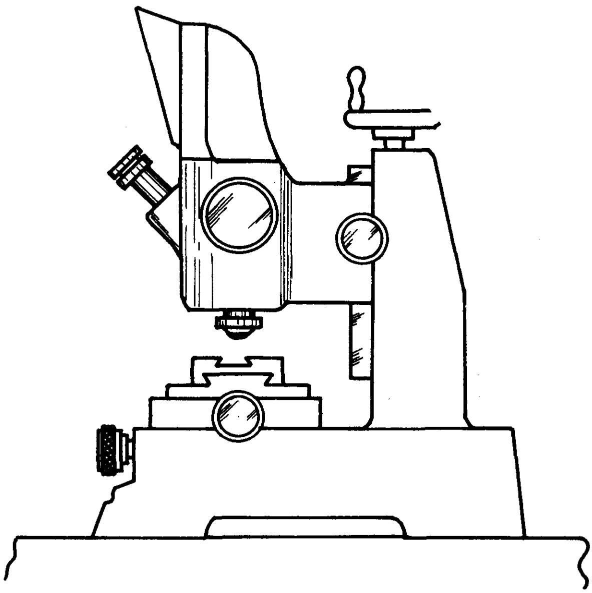


Fig. 2.26.—Toolmaker's Microscope.

Summary

Precision measurements are an essential feature of all toolrooms and inspection departments. It is a general principle of engineering manufacture that when precision components are required, machine tools, jigs, fixtures and press tools are used in order to produce them. In the same way, the accuracy of a drop forging or pressure die casting depends on the dies used; provided the dies are manufactured and checked to within the limits of tolerance laid down on the drawing or blueprint, the dimensional accuracy of the forging or casting remains constant, subject only to wear or deterioration of the dies. We have seen that precision dimensions require the use of accurate working standards such as slip gauges, precision rollers and balls.

Provided the student has a good working knowledge of geometry and trigonometry, a wide range of measuring techniques is possible, with linear accuracies of within plus and minus two micrometres. These techniques, as we have seen, involve the principle of direct measurement, and the student will no doubt discover in the course of his laboratory work that a great deal of skill, patience and time is required if accurate results are to be obtained. All these factors are dependent on what we may consider as the human element.

It is not enough that a dimension is carefully checked on a single occasion; close tolerances demand precision checks at fixed intervals, especially if the component is mass-produced using an expensive machine tool such as a centreless grinding machine.

Precision checks of this nature must be carried out quickly, yet with the achievement of consistent and precise results, preferably with the use of unskilled or semi-skilled personnel. This work is possible with the use of comparators, or the principle of measurement by comparison. The dimension required is determined by comparison against a known standard; any deviations are suitably magnified and shown on a dial or scale. The principles of magnification may be mechanical, electrical, optical, or even pneumatic. A wide range of instruments embodying one or more of the above principles is available, and it is important that the mechanical engineering technician has some knowledge of the principles involved. This is the true purpose of technology, namely the application of scientific principles to manufacturing techniques or processes.

EXERCISE 2

1 With a practical example, explain the need for the precision measurement of an engineering component.

2 What is the essential difference between direct measurement and measurement by comparison?

3 Why are end measuring bars necessary for the direct measurement of certain linear dimensions? What precautions must be taken when using these bars?

4 With the aid of a neat sketch, show a typical measuring set-up requiring the use of working standards such as slip gauges, precision rollers or balls. What degree of accuracy can be expected from the set-up shown?

5 What are the limitations when determining linear dimensions using direct measurement techniques involving working standards? A centreless grinding machine produces inlet

valves for a motor-car engine at the production rate of 720 per hour, with the diameters ground to within plus and minus two micrometres (see *Workshop Processes* 2, fig. 90). Describe a suitable measuring technique for the checking of the diameter at three different points at intervals of 10 minutes.

6 Explain the purpose of a comparator as used in engineering measurement. What are the advantages offered by the use of comparators when making precision linear checks?

7 With a neat diagram illustrate the principle of a typical mechanical comparator; show clearly the method adopted to obtain magnification of the plunger movement.

8 Describe a typical comparator used on a production line, providing visual indication by means of coloured signal lamps whether **six** separate diameters are within the limits.

9 Make a neat sketch of a component that would require an optical projector in order to determine whether it possesses the required accuracy.

10 What is meant by the principle of the optical lever? With a neat diagram show the application of this principle to a typical optical comparator of the vertical type.

3 Inspection

3.1 Introduction

THE difference between measurement and inspection was fully outlined in *Workshop Processes* 2, but perhaps some revision will assist at this stage.

We can define measurement as a specific attempt to determine a linear or angular dimension, or the non-linear functions of flatness, roundness, concentricity or alignment. While it is not possible to obtain **exact** results, the use of the equipment outlined in the previous chapter allows a high degree of accuracy. In all measuring techniques a quantitative result is achieved; in other words we get an answer to the measuring problem. For example, if we measure the diameter of a piston for a motor-car engine, we must arrive at a certain linear dimension, say 75·05 mm.

The accuracy of this dimension with respect to the precise or exact diameter of the piston depends on the type and precision of the measuring equipment used, together with the skill and experience of the person making the measurement. Inspection, on the other hand, is not concerned with the determination of dimensions, but with the **control** of these dimensions.

3.1.1 Dimensional control

This is the true purpose of engineering inspection. It is an essential process if the mass-production of engineering components is to produce components which not only are of reasonable quality, but also have the important property of a long and reliable life. Before the advent of modern manufacturing techniques, engineering assemblies such as steam engines, pumps and other mechanical devices were hand fitted. The fitting of each individual part to its mating part was a long and expensive business requiring highly skilled and highly paid craftsmen. In the event of breakage or damage at a later date, the repair proved both costly and time-consuming. The new component would require machining and fitting, perhaps demanding the services of the same craftsman who fitted the original assembly. Such an assembly was an example of the manufacturing process called custom building; each assembly, although capable of performing exactly the same task as another assembly, was a separate unit. No part or component could be interchanged.

3.1.2 Mass-production

Mass-production can only be achieved through rigid application of the principle of dimensional control. Although the first seeds of the mass-production technique germinated in Europe with the manufacture of completely interchangeable musket locks, it was the American inventor Eli Whitney who first introduced the principle of mass-production to the manufacture of engineering components. As early as 1819, muskets and pistols were mass-produced in American arsenals. The importance of having components for articles such as these completely interchangeable needs no emphasising. The mass-production technique was quickly adopted for the manufacture of clocks and other domestic appliances.

Meanwhile mass-production was also being appreciated in Great Britain. By 1857 the Royal Small Arms Factory at Enfield was producing 1000 rifles per week; this figure was later increased to 2000. Over 700 operations were required in the manufacture of a single rifle, yet each part was completely interchangeable. All this was achieved by ensuring that each dimension was within the limits laid down; in other words interchangeability is only possible with the application of dimensional control.

3.2 The need for limit systems

Consider the assembly illustrated in fig. 3.1. The needle valve shown at A is a close slide fit in the phosphor-bronze bush shown at B. This bush is a drive fit in the body of the instrument, as is the hardened and tempered steel bush shown at C. Movement of the valve in the direction of the arrow X seals the orifice at O, thus regulating the pressure of air or oil through the orifice.

Clearly if this assembly is to be mass-produced cheaply and efficiently, and the customer or user is to be provided with a spare-part service, we must decide on the sort of fits present in the assembly. Of greater importance, we must decide on the dimensions that will produce the sort of fits needed. If

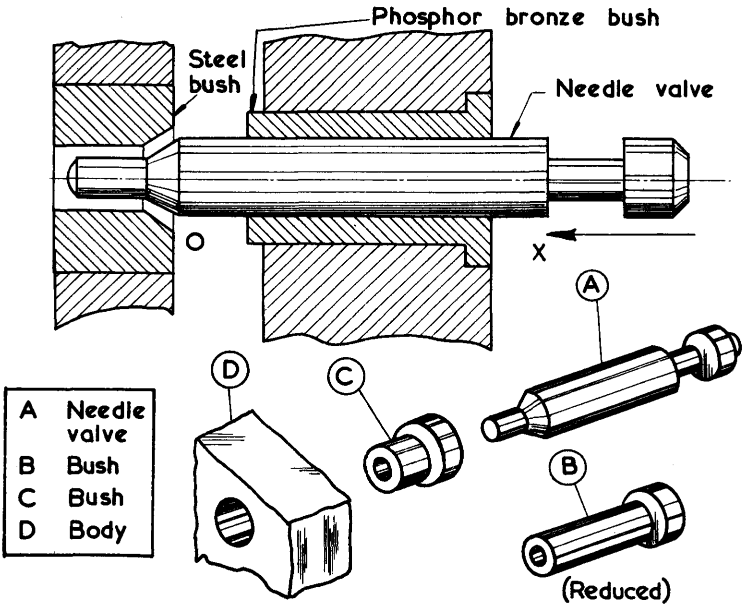


Fig. 3.1.—Needle Valve Assembly.

every engineering designer were allowed free rein in this matter of deciding the sizes of mating components to produce different kinds of fits, then complete and utter chaos would result.

It is the purpose of a limit system to establish the types of fits most likely to be needed in engineering manufacture, and to recommend the dimensions of the mating parts.

3.2.1 BS 4500:1969, "ISO limits and fits"

This British Standard Limit System supersedes BS 1916:1953, "Limits and fits for engineering". Following a complete review of the whole field of limit systems, it was decided to develop a new limit system based on the ISA system. (Formulated by the International Federation of National Standardizing Associations, more commonly known then as ISA and now as ISO, the ISA system had long been used with much success on the Continent.) Briefly the system makes use of the following important items:

(i) fundamental tolerance,
(ii) fundamental deviation.

3.3 Tolerance grades

Let us consider once more the assembly shown in fig. 3.1. If this assembly is to be mass-produced, then it is an accepted rule that the tolerances on the component parts be as large as possible. This is because small tolerances

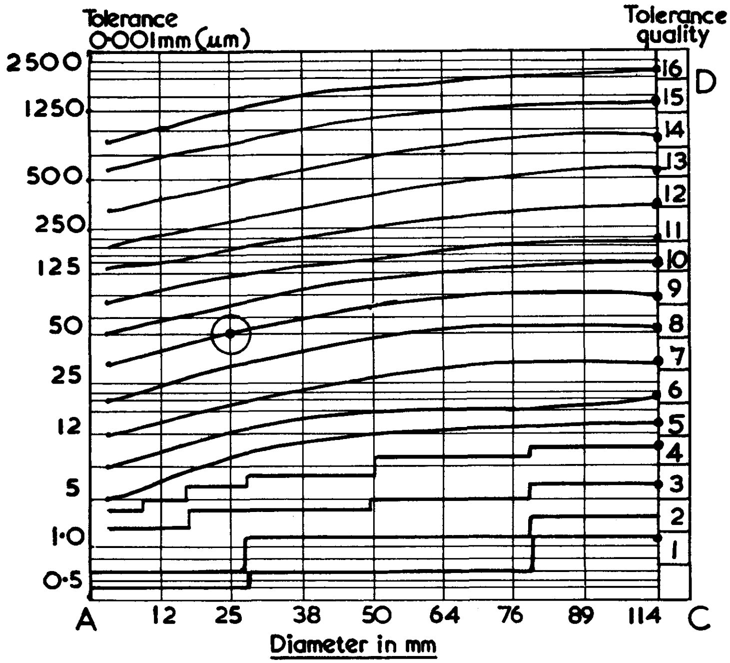


Fig. 3.2.—Degree of Accuracy expected from Machine Tools.

place a heavy burden on the manufacturing cost of the components; expensive machine tools are needed, together with delicate and costly measuring equipment. Unless the greatest care is taken scrap rates will be high, and this must add to the cost of the finished article. Ideally, dimensions should be machined to an exact size, but this is not possible, and the design engineer must decide on the largest tolerance permissible, keeping in mind the quality or useful life of the completed assembly.

3.3.1 Choice of tolerance grades

BS 4500 provides eighteen grades of tolerance, designated IT01, IT0, IT1 to IT16. The choice of a particular tolerance is governed by the earlier stated maxim of economic manufacture allied with satisfactory performance. Economic manufacture can be achieved only with the use of machine tools, and the degree of accuracy which can reasonably be expected from these machine tools determines the value of the tolerance grade.

This degree of accuracy is shown in graphical form in fig. 3.2. On the vertical line AB we see the tolerance in units of one-thousandth of a millimetre; on the opposite vertical line CD we see the ISO tolerance grades or quality. Clearly the higher the degree of accuracy of which the machine

IT	*Class of work*	*Machine tools*
16	Sand casting, flame cutting	Flame cutting machine
15	Stamping (approximately)	Drop forging hammer
14	Die casting or moulding; rubber moulding	Die casting machines
13	Press work, tube rolling	Machine presses
12	Light press work; tube drawing	Machine presses
11	Drilling, rough turning and boring, precision tube drawing	Drilling machines, lathes
10	Milling, slotting, planing, metal rolling and extrusion	Milling, slotting and planing machines
9	Worn capstan or automatic lathe, horizontal and vertical boring machines	Capstan and automatic lathes, borers
8	Centre lathe turning and boring, reaming, capstan or automatic in good condition	Lathes, capstan and automatic
7	High quality turning, broaching, honing	Lathes, honing and broaching machines
6	Grinding, fine honing	
5	Machine lapping, fine or diamond boring, fine grinding	Lapping, boring and grinding machines
4	Gauges, precision lapping	Precision lapping machines
3	Good quality gauges	—
2	High quality gauges	—
1	Workshop standards and gauges	—
0	Inspection standards and gauges	—
01	Work of the highest quality	—

Table 3.1 Tolerance grades (ISO series of tolerances)

tool is capable, the smaller is the tolerance. Note also that the horizontal line AC shows the effect on the tolerance of increasing diameter. Table 3.1 gives the fundamental tolerances, together with the machine tools used and the type of work.

Much depends, of course, on the condition of the machine tools used, and it is no exaggeration to state that the greater part of reject work is due to the inability of the machine tool or the tooling arrangement to hold the required tolerance. This is particularly so in the drilling, boring or reaming of holes, or for that matter when producing a hole by any other method. For this reason BS 4500 recommends that in the case of a shaft mated to a hole, the hole is allocated a tolerance one grade coarser than the shaft. The production of shafts to close dimensional limits is a much better proposition than the production of holes of similar quality.

It is important that Table 3.1 be used in conjunction with fig. 3.2. This will allow us to see the true value of a machine tool, that is to say its ability to produce accurate work.

Let us take as an example the quality of tolerance allocated to a worn capstan lathe. This is IT9, and if we assume that work of 25 mm diameter is turned, then reference to fig. 3.2 shows that the tolerance is approximately 0·05 mm. This point is ringed in the diagram. Thus it is unwise to attempt to work to (say) a tolerance of plus and minus 0·02 mm on a capstan lathe which is not in good condition. Much reject work will result, with much time spent by the capstan setter in his attempts to produce work within the dimensional tolerance of 0·04 mm, while the basic fault lies in the continued use of a machine tool which does not possess the accuracy needed for the class of tolerance given to the component.

3.3.2 Derivation of the standard tolerance

We have seen that the grade or quality of tolerance allocated to a dimension depends mainly on the class of work required, together with the type and quality of machine tool used. All standard tolerances are multiples of a basic tolerance unit called i.

The value for i is calculated as follows:

$$i(\text{micrometres}) = 0{\cdot}45 \times \sqrt[3]{D} + 0{\cdot}001 \times D. \quad (D \text{ in millimetres})$$

In each of the above cases D is the geometric mean of the diameter steps involved. Tolerance steps progress geometrically to allow for the increased expansion and deformation which affect both gauges and workpieces as dimensions become greater. The effect of the geometric progression is to make each successive tolerance grade about 60% greater than its predecessor.

Fig. 3.3 shows a diagrammatic representation of the clearance fit illustrated in fig. 3.1. This is a simple way of showing the definitions of the terms used. Note that the tolerance is shown as a dark band on the top of the valve guide, while in actual fact it is, of course, applicable to the whole diameter. Note also that we have given this shaft a tolerance grade of 6, in accordance with the use of Table 3.1. Before we turn to the method of determining the amount of this tolerance without reference to fig. 3.2, let us examine the second important item of BS 4500, namely the fundamental deviation.

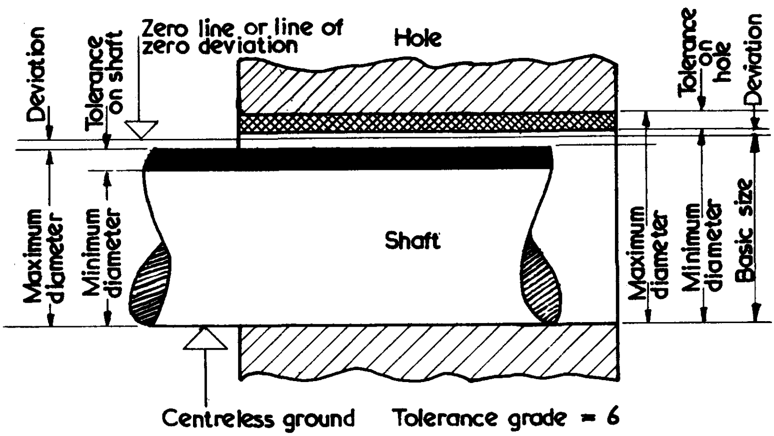


Fig. 3.3.—Clearance Fit.

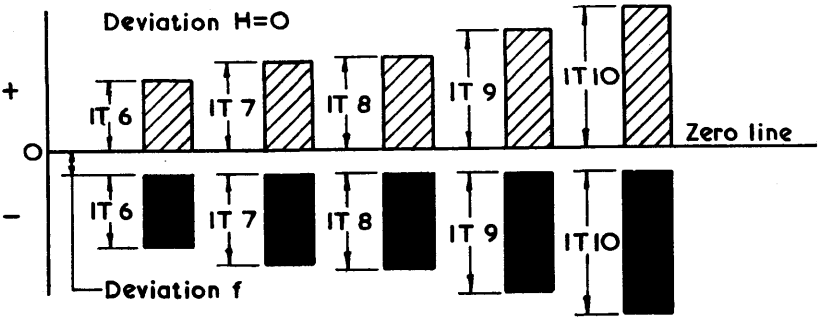


Fig. 3.4.—Fundamental Deviations.

3.4 Fundamental deviation

The fundamental deviation determines the **type of fit** obtained when mating a shaft to a hole. The quality of the fit is determined by the tolerance grade, hence the actual nature of the fit results from the magnitudes of the fundamental deviations and tolerances on the mating parts. There are 27 different deviations for both holes and shafts, and fig. 3.4 illustrates the association of fundamental deviations and tolerances. Note that the shaded areas represent the tolerances of H holes, all of which have zero deviation, that is to say the low limit of the hole lies on the zero line. On the other hand, the f shafts shown have a minus deviation with varying tolerances according to the quality of fit required. Thus the smaller the deviation on the shaft the closer is the fit, and the smaller the tolerance grade the better is the quality.

3.4.1 Designation of fundamental deviations

Fundamental deviations are designated by the letters of the alphabet, capital for holes and lower case for shafts; thus the letter "a" indicates a large negative deviation, whilst letter "z" represents a large positive deviation. All the letters of the alphabet are used, with the exception of i, o, l, q and w.

The fundamental deviations are for holes:
A B C CD D E EF F FG G H JS J K M N P R S T U V X Y Z ZA ZB ZC
for shafts:
a b c cd d e ef f fg g h js j k m n p r s t u v x y z za zb zc

The complete designation of the limits of tolerance for a shaft or hole requires the use of the correct letter indicating the fundamental deviation, followed by a suffix number indicating the appropriate tolerance grade. Thus, as all holes in engineering have a recommended zero deviation, a hole with a tolerance grade IT 7 is designated H7, and similarly a shaft of "f" deviation and tolerance grade IT 8 is designated f8.

To indicate a fit, the hole diameter must first be stated, followed by the hole limits, then the shaft limits. For example, a 50 millimetre diameter hole designated H6, mated to a shaft p5 is indicated thus:

50 H6–p5 or 50 H6/p5

Such indications should appear on design drawings only; on all working drawings the actual limits of both hole and shaft must be explicitly stated.

3.5 Selection of fits

Although BS 4500 provides a comprehensive system covering diameters from 3 mm to 3150 mm diameter, for ordinary engineering purposes only a relatively small number of fits are required. It is recommended that H holes only be used. All H holes have zero deviation, as shown in the diagram of fig. 3.5; note the curve (shown in dotted line) resulting from the geometric

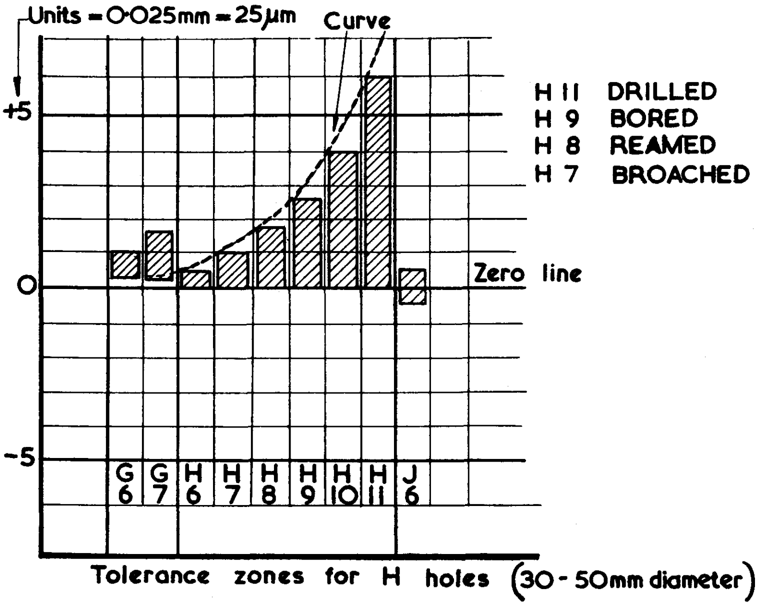


Fig. 3.5.—Recommended Holes for Ordinary Engineering Purposes.

arrangement of the tolerance zones. Note also that these holes have unilateral tolerances, that is to say plus plus.

Reference to fig. 3.5 shows that for ordinary engineering purposes only **four** grades of holes are required, as listed below:

Grade	*Produced by*
H7	high quality boring, broaching, honing
H8	centre lathe boring, reaming, good quality capstan work
H9	horizontal and vertical boring, worn capstan work
H11	standard drilling

ES = Upper deviation   Unit = 0·001 mm
EI = Lower deviation   = 1μm

Nominal sizes		*H7*		*H8*		*H9*		*H11*	
Over	*Up to and including*	*ES* +	*EI*	*ES* +	*EI*	*ES* +	*EI*	*ES* +	*EI*
mm	mm								
—	3	10	0	14	0	25	0	60	0
3	6	12	0	18	0	30	0	75	0
6	10	15	0	22	0	36	0	90	0
10	18	18	0	27	0	43	0	110	0
18	30	21	0	33	0	52	0	130	0
30	50	25	0	39	0	62	0	160	0
50	80	30	0	46	0	74	0	190	0
80	120	35	0	54	0	87	0	220	0
120	180	40	0	63	0	100	0	250	0
180	250	46	0	72	0	115	0	290	0
250	315	52	0	81	0	130	0	320	0
315	400	57	0	89	0	140	0	360	0
400	500	63	0	97	0	155	0	400	0

Table 3.2
Limits of tolerance for selected holes (BS 4500:1969)

It must be appreciated that the tolerance zones shown in fig. 3.5 are applicable only to holes within a diameter range of from 30 mm to 50 mm, as indicated on the diagram. It is suggested by BS 4500 that diameters within a range of from 3 mm to 500 mm will meet the needs of an average engineering works. Table 3.2 shows the British Standard limits for H holes within this range.

Note that the units given in the table are equal to 0·001 mm, and that the tolerance increases with the diameter. Note also that ES means upper deviation, and EI means lower deviation.

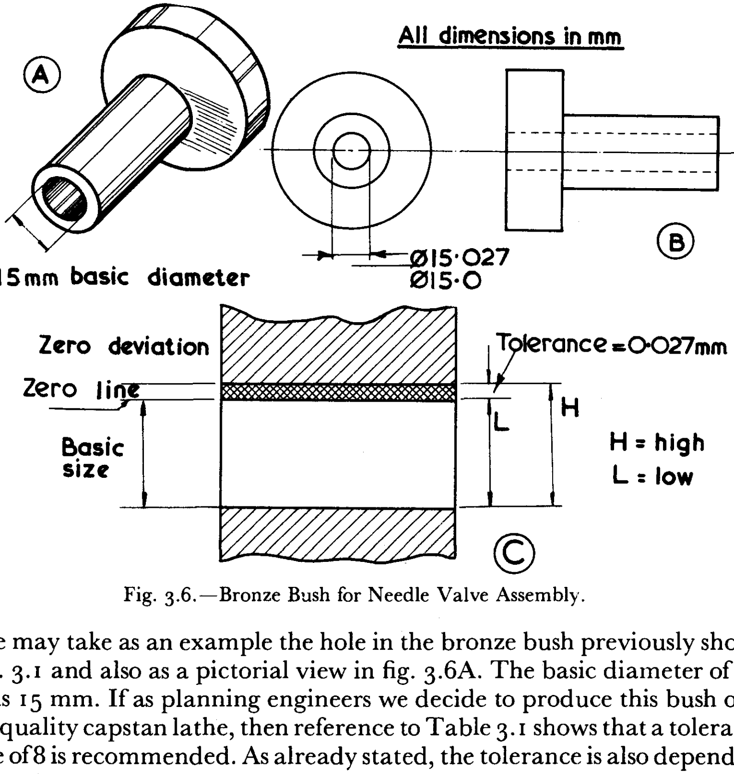


Fig. 3.6.—Bronze Bush for Needle Valve Assembly.

We may take as an example the hole in the bronze bush previously shown in fig. 3.1 and also as a pictorial view in fig. 3.6A. The basic diameter of the hole is 15 mm. If as planning engineers we decide to produce this bush on a good quality capstan lathe, then reference to Table 3.1 shows that a tolerance grade of 8 is recommended. As already stated, the tolerance is also dependent on the diameter size, and reference to Table 3.2 gives the upper deviation for a ϕ15 H8 hole as 27 units.

This means that the limits of size within which the hole must be machined are:

$$15^{+0{\cdot}027\,\text{mm}}_{+0}$$

Fig. 3.6B shows an orthographic drawing of the bush, giving the limits of size for the machined hole, while at fig. 3.6C is shown a conventional representation of the hole. Note that the tolerance zone for a hole is cross-hatched, while that for a shaft is shown in black.

All that is now required is the selection of a shaft size that will produce the required fit between the needle valve (shaft) shown also in fig. 3.1 and the H7 hole already chosen.

3.6 Types of fits

3.6.1 Clearance fits

A clearance fit is obtained when the low limit of a hole exceeds the high limit of the shaft that is to mate with the hole. This means that the shaft must possess a negative deviation, as shown in fig. 3.3.

Clearly the greater this deviation the coarser or slacker will the resultant fit be; Table 3.3 shows the clearance fits suitable for the average engineering works as recommended by BS 4500.

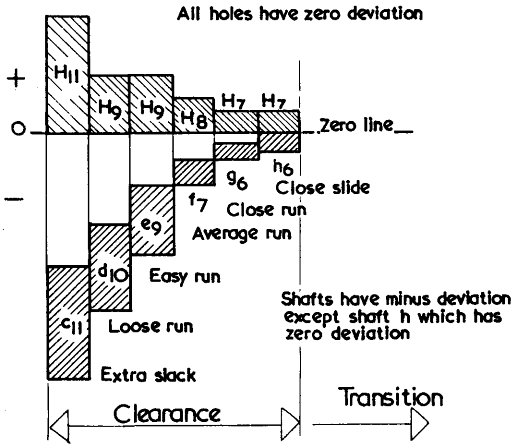


Table 3.3 Selected clearance fits

Example of a clearance fit

We see from the above table that a fairly wide choice of clearance fits is available, ranging from an extra loose running fit to a slide fit. It is the duty of the engineering designer to decide on the actual type of clearance fit, and designate it by using the recommended symbols. Fig. 3.7A illustrates a typical example of a **loose running fit,** shaft "d".

This combination of H9/d10 is suitable for most loose running fits such as loose pulleys or gland seals. The diagram shown at fig. 3.7B illustrates the essential conditions for the type of fit required. Note that the tolerance grade for the hole is given as H9; reference back to Table 3.2 shows us that the tolerance is plus zero, plus 0·062 mm, the diameter of the hole lying in the 30 mm to 50 mm range.

With a tolerance grade of 9, or 0·062 mm tolerance, the machining of this hole will present no problem. If the pulleys are to be mass-produced, it is certain that a capstan lathe will maintain this kind of accuracy under production conditions, and, as we have already pointed out, much scrap or wastage results if the machine tool used is unable to produce the work consistently to the tolerance.

In this example the shaft is one grade coarser than the hole, but for better quality fits it is better to make the hole one grade coarser than the shaft.

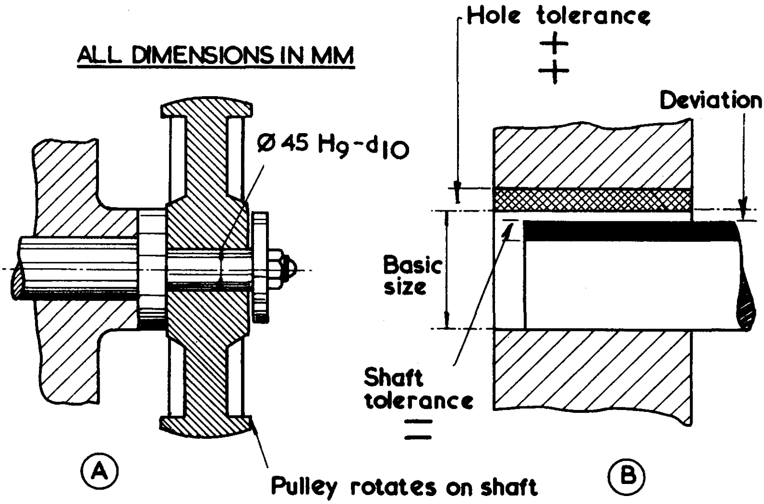


Fig. 3.7.—Practical Example of a Loose Running Fit.

3.6.2 Transition fits

Some confusion appears to exist with regard to the definition of a transition fit. Perhaps reference to fig. 3.8A will assist in clearing away some of the problems associated with a correct appreciation of this type of fit.

At A we see the conditions necessary to produce a transition fit. If, now, the hole is on its high limit and a shaft on low limit is mated to it, then clearly, as shown in fig. 3.8B, a clearance fit must result. On the other hand, if the hole is on its low limit and is assembled to a shaft on high limit, a slight interference fit results, as shown in fig. 3.8C.

Do not be misled by the exaggerated proportion of the diagrams. The tolerances associated with transition fits are very small indeed, and the interference is so slight that hand pressure is sufficient to cause entry of the shaft. The important point to remember, however, is that the type of fit obtained depends on the actual dimensions of the hole and shaft; in actual practice both hole and shaft will be somewhere around the middle limit. This means that the conditions shown in fig. 3.8A exist, and this is a good example of a true transition fit. Any variation of either hole or shaft within the tolerance range tends to produce a slight clearance or interference according to the direction of the tolerance variation. Thus the actual fit obtained will be a transition fit, liable to change from one type to another.

Example of a transition fit

Fig. 3.8D shows a good example of a transition fit. The device shown is much used on machine tools equipped with leadscrews, rotation of which

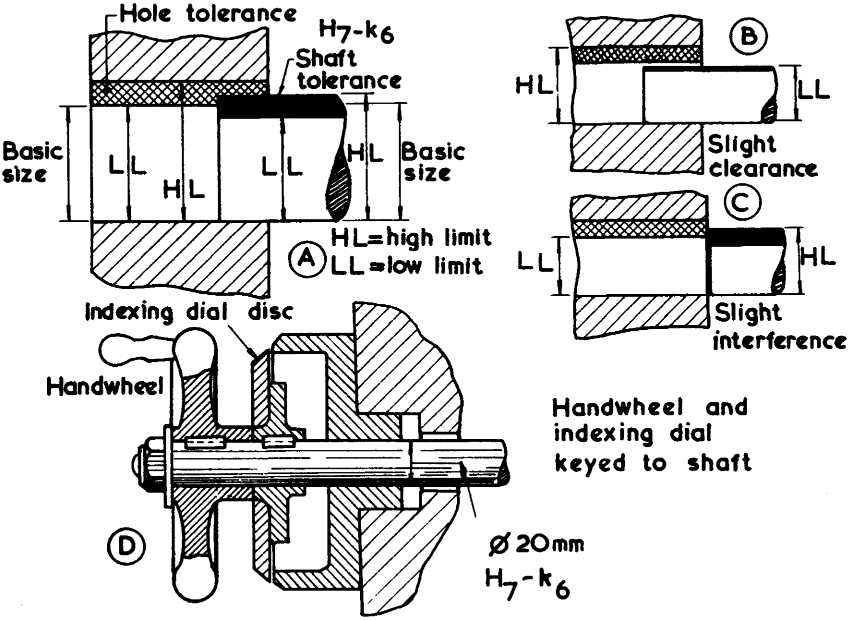


Fig. 3.8.—Practical Example of a Transition Fit.

gives rise to linear movement of a slide or worktable. Both handwheel and indexing dial disc are keyed to the leadscrew shaft, and because this assembly is used on a machine tool it is certain to be subject to considerable vibration.

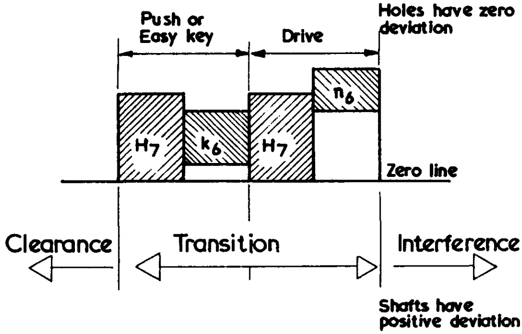


Table 3.4 Selected transition fits

A slight interference fit is recommended, and this is achieved with a combination of H7/k6, as shown on the diagram. Note that the tolerance on the hole is one grade coarser than that on the shaft; the hole limits are +0·021 mm, +0 mm, the shaft limits are +0·002 mm, +0·015 mm.

This is only one of the transition fits recommended by BS 4500; Table 3.4 sets out fuller details of the recommended types of transition fit. Once again the choice of the classification is the problem of the design engineer, but once a decision has been made on the type of transition fit required, application of BS 4500 is to be recommended.

3.6.3 Interference fits

An interference fit is obtained when a low-limit shaft exceeds the diameter of a mating hole on high limit. This means, that provided a batch of holes is machined to within the limits, all shafts taken from a batch also machined to within the limits will be interference fits with the holes. The amount of interference determines the degree of force required to assemble or mate the shaft to the hole. Some care is required when considering the type of interference fit required for a particular assembly. The quality of the surface finish of the mating parts, the size of the diameters, the metals from which they are made, all affect the quality of the fit obtained.

BS 4500 recommends two interference fits, and the appropriate information is shown in Table 3.5

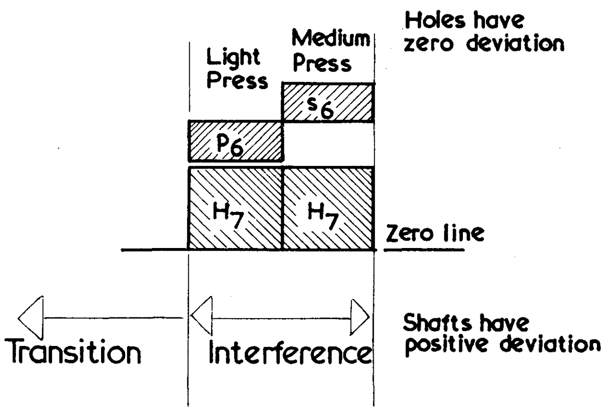


Table 3.5 Selected interference fits

Examples of an interference fit

Interference fits are used as a cheap and efficient method of joining together two components. We see from Table 3.5 that a **light press** fit may be used; this is our first interference fit. Its use in engineering manufacture is confined to the assembly of ferrous components which require removal for purposes of renewal or replacement at a later date.

If the components to be joined are not likely to require separating at a later date, a **press** fit may be used. Typical examples are bearing bushes in alloy housings or castings. When severe gripping forces are required the parts may be shrunk to one another. This involves the heating, or alternatively the refrigeration, of one component to a suitable temperature, whereupon it is assembled to the mating part. When room temperature is restored powerful forces are brought into play, resulting in a permanent joint between the two components. Fig. 3.9 illustrates three typical examples of interference fits.

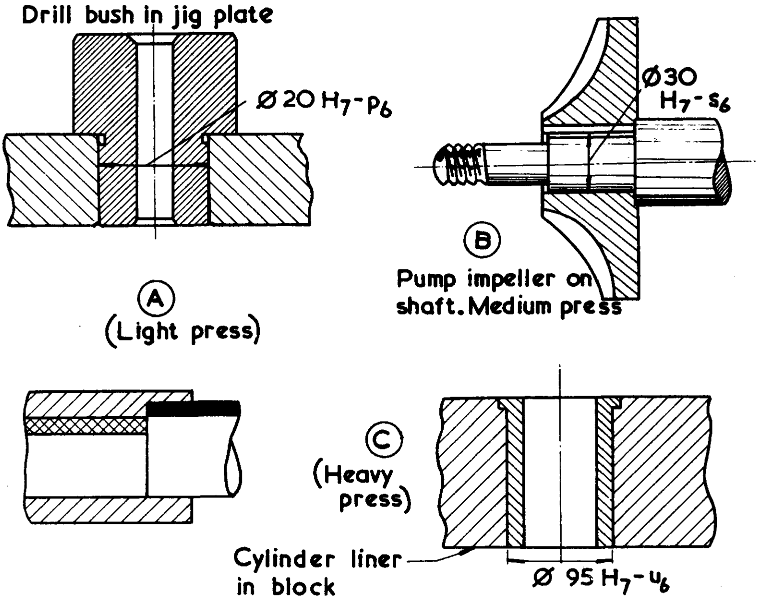


Fig. 3.9.—Examples of Interference Fits.

Fig. 3.9*A*

A drill bush in a jig plate. The combination H7/p6, although producing a relatively small amount of interference, is sufficient to give a press fit which can be dismantled and assembled when required without overstraining the parts.

Fig. 3.9*B*

A pump impeller on a shaft. A medium press fit, using the combination H7/s6; can be driven home, and is sometimes referred to as a light drive fit.

Fig. 3.9*C*

A cylinder liner in a cast-iron block. Classified as a heavy drive fit, producing a permanent or semi-permanent assembly between liner and block. Large sizes require heating and shrinking to avoid the possibility of damage which exists if we attempt to assemble cold.

3·7 Use of BS 4500:1969

All the necessary information, recommendations and relevant tables are to be found in the booklet BS 4500:1969, entitled "ISO limits and fits", issued by the British Standards Institution. Provided the mechanical engineering technician is familiar with the symbols used for both holes and shafts, it is a relatively simple matter to convert these to decimal dimensions and insert them on the working drawing.

It is certain that the engineering designer will himself make the fullest use of BS Handbook No. 18, entitled "Metric standards for engineering". The fullest information is given with regard to recommended combinations of shaft and hole for various types of fits, together with suitable alternatives or second choices. While the actual dimensions of manufactured components are governed by considerations of quality, appearance and economy of manufacture, all of which the engineering designer takes into account before arriving at a theoretical size, much advantage is to be gained if **preferred sizes** are finally adopted.

3·7·1 Preferred numbers

Let us assume that a designer has calculated that the diameter of a pulley shaft should be 26·314 mm if it is to have the necessary strength to stand up to service conditions. Now 26·314 mm is an awkward size, and it is bad practice to put a number of this sort on an engineering drawing. ISO recommendations for Metric Standards in Engineering are that the designer refers to a series of preferred numbers, and Table 3.6 shows an extract from the basic series of preferred numbers.

It is clear that the R40 scale provides the nearest value to the 26·314 mm diameter of the pulley shaft, and the preferred number 26·5 can be chosen.

The correct choice of scale must take into account the technical and economic factors involved in the manufacture of a component. The R5

1	2	3	4	5
	Basic series			
Serial number	R5	R10	R20	R40
16	25·0	25·0	25·0	25·0
17				26·5
18			28·0	28·0
19				30·0
20		31·5	31·5	31·5
21				33·5
22			35·5	35·5
23				37·5
24	40·0	40·0	40·0	40·0

Table 3.6 Extract from basic series of preferred numbers

scale has wide steps and may lead to a waste of materials, while a closely spaced scale such as the R40 may involve increased costs in tooling or gauging.

3.8 Limit gauges

We have seen that dimensional control can be achieved with the use of comparators, and that these are especially helpful if the tolerance on the dimension to be checked is a small one. Another cheap and efficient method is provided by limit gauges, which can be used to test shaft and hole diameters, slot widths and depths, and many other dimensions occurring in the manufacture of engineering components. It is the purpose of a limit gauge, as its name suggests, to ensure that no dimension is outside the acceptable limits.

3.8.1 BS 1044: Part 1: 1964, "Gauge blanks"

We shall be concerned with gauges of three basic kinds: plug gauges for holes, and gap and ring gauges for shafts. BS 1044 covers all recommendations with regard to the design of plug, ring and gap gauges. Tables give sizes for gauging members and handles according to the diameter range of the work to be tested. Recommendations are also made for the marking or stamping of the finished gauge.

3.8.2 Application of limit gauges

Let us consider the limit gauging required to ensure that the assembly shown in fig. 3.7A has been correctly machined, and discuss the different types of gauge with this purpose in mind.

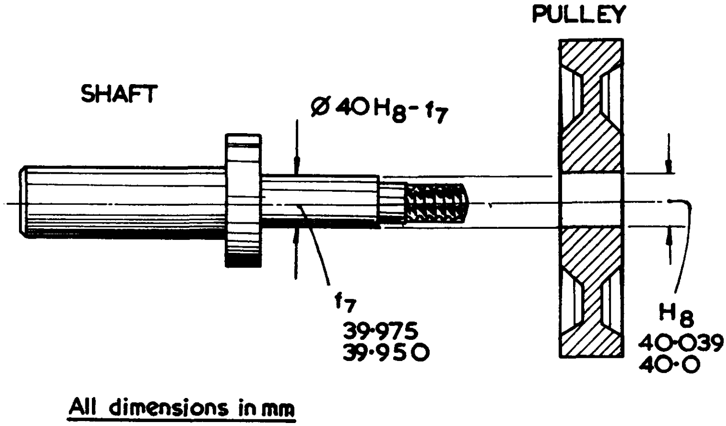


Fig. 3.10.—Assembly requiring Gauges.

Fig. 3.10 shows a drawing of both pulley and shaft. Referring to the BS tables for a 40 H8/f7 fit, we arrive at the following limits of size for the assembly:

high limit hole = 40·039 mm	high limit shaft = 39·975 mm
low limit hole = 40·000 mm	low limit shaft = 39·950 mm

3.9 Plug gauges

The gauge used for the checking of the hole is a solid-type cylindrical **plug gauge.** Three types of plug gauge are illustrated in fig. 3.11.

At A we see a **single-ended** plug gauge. If this type of gauge is used to check the H8 hole in the pulley **two** gauges are needed: a GO plug gauge at 40 mm diameter and a NO GO plug gauge at 40·039 mm diameter.

At B we see a **double-ended** plug gauge; note that the NO GO member is shorter than the GO member, thus allowing easy recognition between GO and NO GO ends.

At C we see a **progressive** plug gauge. This gauge requires the minimum of operations on the part of the gauge user, but its use is limited to through holes; it could not be used to check a blind hole.

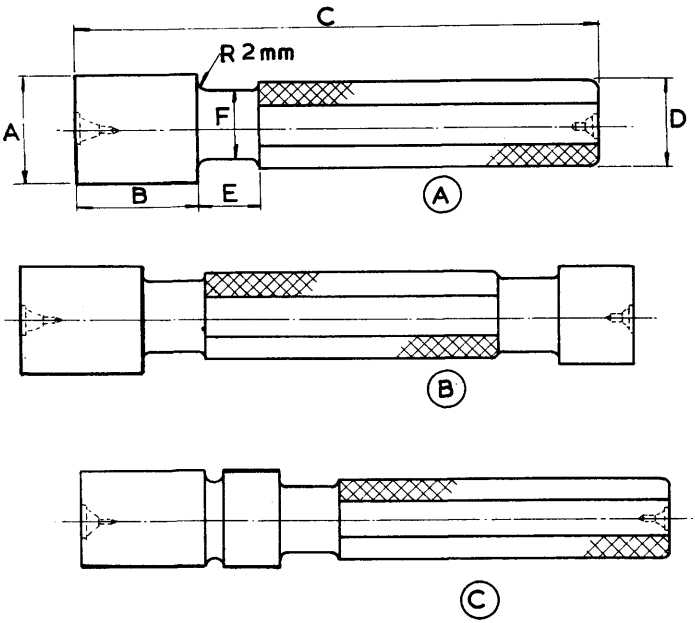


Fig. 3.11.—Solid-type Cylindrical Plug Gauges.

3.9.1 Renewable-end plug gauges

Although solid-type plug gauges may be hard-chromed and re-ground, thus avoiding scrapping the gauge on account of wear of the gauging diameters, considerable economies are possible by the use of renewable ends or handles. Two types of renewable-end plug gauges are in use:

(i) taper-lock design,
(ii) trilock design.

Taper-lock design

This type of renewable-end plug gauge is suitable for diameters up to and including 60 mm. Fig. 3.12 illustrates both the gauging member and the handle of a gauge used to check the H hole in the pulley. Note that a progressive gauging member may be used instead of the single GO member shown in fig. 3.12A. Provided the tapers in both gauging member and handle are accurately machined and assembled, the taper lock is equivalent to a solid gauge with respect to rigidity or freedom from shake.

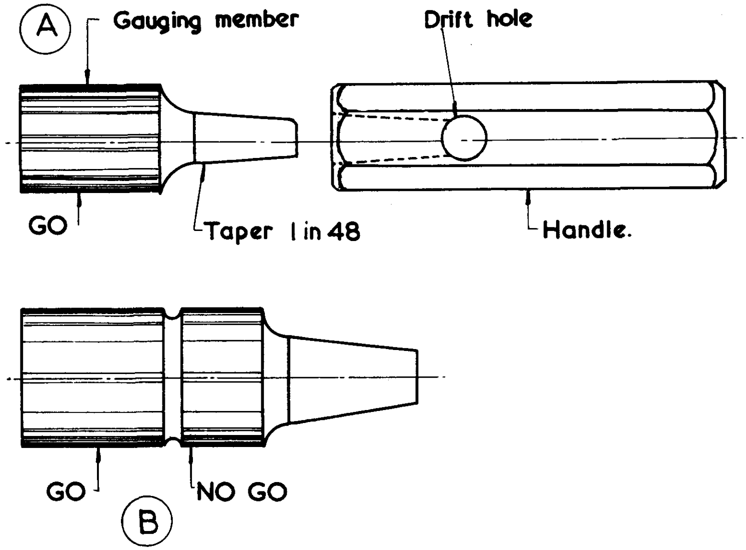


Fig. 3.12.—Renewable-end Plug Gauges with Taper Lock.

Trilock design

This design was originated by the Pratt & Whitney Co., and the Taft-Peirce Manufacturing Co., both of America. Although it is protected by patent, these companies have waived all rights and offer no objection to its use as recommended by BS 1044:Part 1:1964, "Gauge blanks". The principle is illustrated in fig. 3.13, and it is recommended for diameters in excess of 60 mm and up to 200 mm.

At A we see a part sectioned view of the complete gauge. A positive lock between gauging member and renewable handle is achieved with the V projections shown in the end of the handle at fig. 3.13B. These projections locate in V grooves machined in the gauging member, which is held in firm contact by the screw shown at D. Note that the gauging member is reversible. It is, of course, possible to have a double-ended trilock plug gauge, the hollow handle permitting the use of a rod to remove the second member. Large-diameter plug gauges need protection of the end of the gauging members, and this may be achieved by reducing the diameter at the end of the gauging member. This technique is shown at fig. 3.14, together with the use of lightening holes; these holes also serve an additional purpose by allowing the escape of air when checking the diameter of a blind hole.

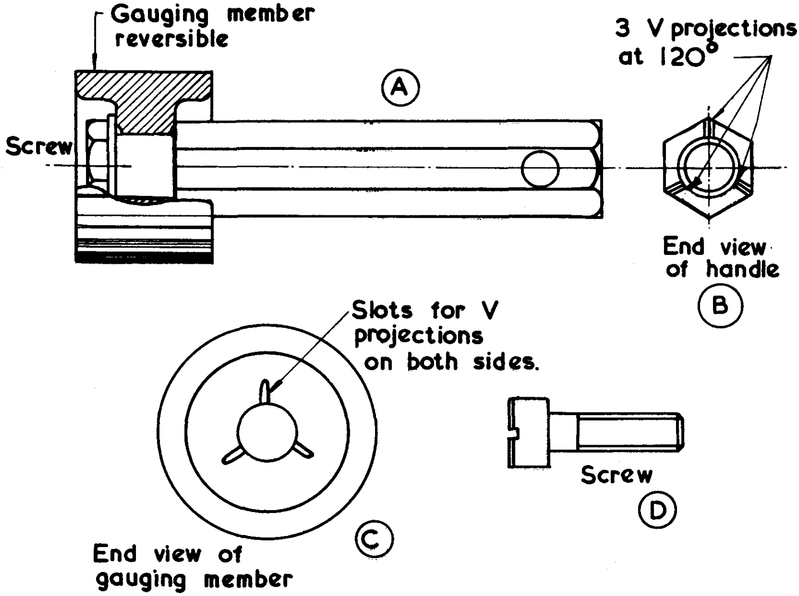


Fig. 3.13—Trilock Design Plug Gauges.

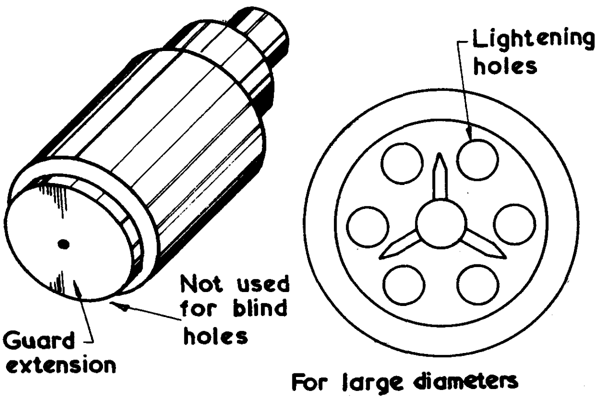


Fig. 3.14.—Details of Gauging Members for Trilock Design.

3.10 Gap gauges

We can now turn to the type of gauge required to check the f7 shaft on which our pulley with its H8 hole is to rotate freely. Always remember that this is the true purpose of limit gauges: to see that the correct type of fit is obtained by strict observance of the principle of dimensional control, in other words by ensuring that no dimension is outside the limits set by the recommended tolerances given in BS 4500:1969.

Three types of gap gauges are mentioned in BS 1044:

(i) solid gap gauges, type A: flat steel sheet,
(ii) solid gap gauges, type B: steel forgings,
(iii) adjustable-type gap gauges.

All three types are illustrated in fig. 3.15.

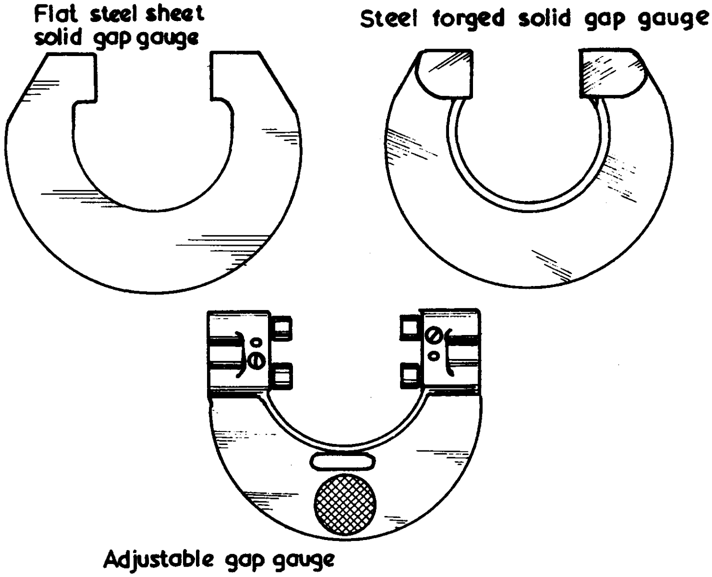


Fig. 3.15.—Gap Gauges.

There are, of course, variations of the types shown. It is often convenient to have a progressive gap gauge; this is based on the same principle as the progressive plug gauge, namely the insertion of the NO GO member immediately after the GO member.

3.11 Ring gauges

Ring gauges are always used as GO gauges; they check not only diameter, but also roundness or concentricity. A typical ring gauge is illustrated in fig. 3.16. If the diameter of the shaft to be checked is in excess of 80 mm it is common practice to modify the section as shown in fig. 3.16B, thus providing a more positive method of holding and lifting the gauge off a flat surface. Fig. 3.16C illustrates a further change in section adopted for the slimmer workshop gauges, once again enabling the gauge user to pick the gauge up from a flat surface with little risk of dropping and possibly damaging it.

3.12 Gauge tolerance

The manufacture of limit gauges calls for a high degree of skill and experience. In the same way that it is not possible for the operator of the machine tool to work to precise or exact dimension, it is also not possible for the toolmaker or gaugemaker to produce a plug gauge with an exact diameter.

Let us consider the gauge required for checking the hole in the pulley shown in fig. 3.10. A simple progressive plug gauge is shown in fig. 3.17. As we have stated, it is not possible for the tool or gaugemaker to work to the precise dimensions shown on the diagram. He must be given a tolerance, and this is known as the **gauge tolerance.**

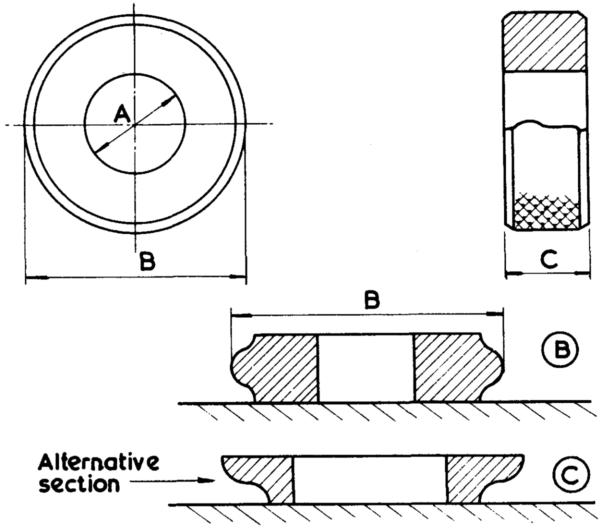


Fig. 3.16.—Ring Gauge Details.

3.12.1 BS 969:1953, "Plain limit gauges: limits and tolerances"

This standard is intended to facilitate the manufacture of limit gauges, and to ensure that the use of such gauges will not reject any component that is within the tolerance laid down. It is the gauge tolerance that leads to difficulty, for if this tolerance is put **outside** the component tolerance, the possibility will exist of accepting work which is outside the permissible limits. Let us have a look at a diagrammatic representation of the effect of the gauge tolerance.

Fig. 3.17B shows such a diagram. It will be seen that the GO gauge tolerance is placed **inside** the work or component tolerance, while the NO GO gauge tolerance is placed **outside** the component tolerance. The effect of placing the GO gauge tolerance inside the component tolerance is to reduce the amount of tolerance available to the machine-tool operator. It will be seen, however, that the gauge tolerance for the NO GO increases the amount of tolerance available.

Thus the NO GO gauge will not reject any hole which is within its high limit,

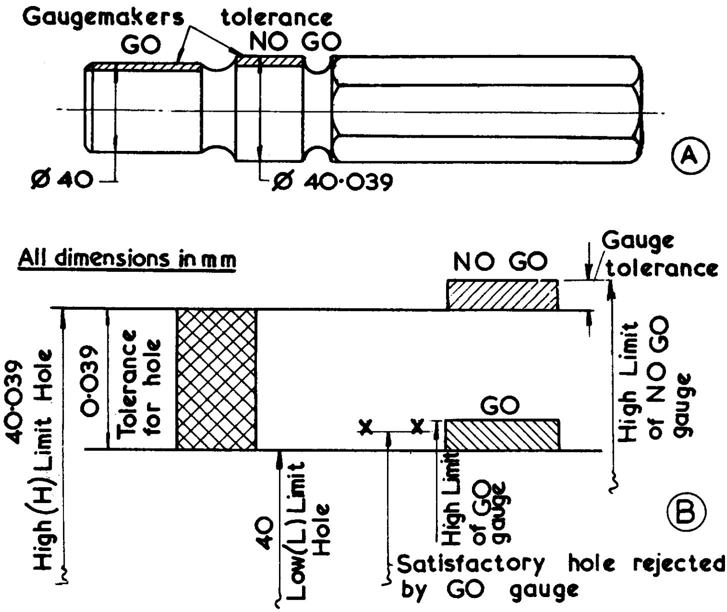


Fig. 3.17.—Progressive Plug Gauge Showing Gauge Tolerance.

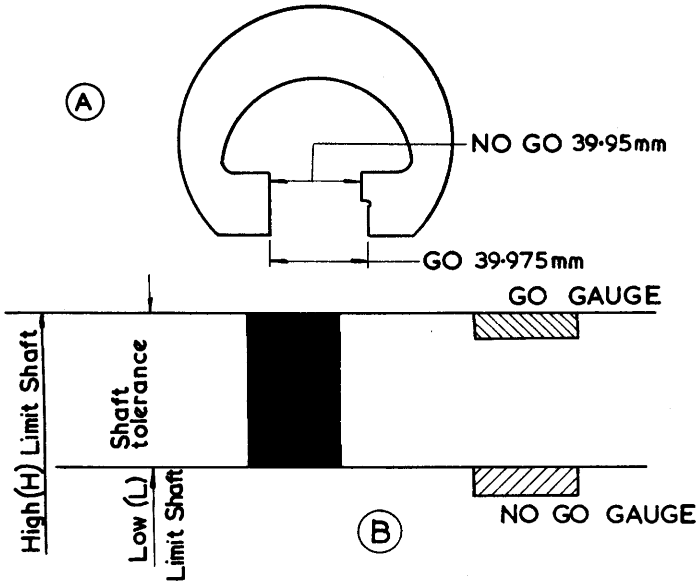


Fig. 3.18.—Progressive Gap Gauge with Gauge Tolerance.

40·039 mm, provided that the gauge has been manufactured to the specified gauge tolerance. On the other hand it is possible for the GO gauge to reject a hole which is within the component tolerance. Let us assume that the diameter of this hole is equivalent to the line XX shown just above the low limit of the hole. It will be seen from the diagram that the hole diameter, although within the limits allowed, is **less** than the diameter of the GO plug gauge when the gauge is made to the high limit of its tolerance. Thus the GO gauge will not enter the hole, and the pulley is rejected. It is considered, however, that such cases are rare events and can be easily resolved by direct measurement of the component.

Checking the diameter of the shaft on which the pulley is to be a free rotating fit can be achieved by using the progressive gap gauge shown in fig. 3.18A. Reference back to fig. 3.10 reminds us that the high limit for the shaft is 39.975 mm, while the low limit is 39.95 mm. At fig. 3.18B we see a diagrammatic representation of the gauge tolerance; once again the tolerance of the GO gauge is within the component tolerance, while the tolerance of the NO GO gauge is outside the component tolerance.

3.12.2 Obtaining the gauge tolerance

The recommended tolerances for the gauges described are easily obtained from the tables given in BS 969:1953. The amount of gauge tolerance depends on two factors:

(i) work tolerance (component tolerance),
(ii) size of work.

Table 3.7 shows an extract from the relevant tables entitled "Tolerances for ring and gap gauges". It can be seen that the gauge tolerance for the gap gauge is 0·002 mm.

1	2	3	4	5	6	7
Work tolerance Difference between high (H) limit and low (L) limit		*Gauge tolerance*	*Disposition of gauge tolerance*			
			GO		*NOT GO*	
Above	*Up to and including*		*H limit of gauge tolerance from H limit of work*	*L limit of gauge tolerance from H limit of work*	*H limit of gauge tolerance from L limit of work*	*L limit of gauge tolerance from L limit of work*
mm	mm	mm	mm	mm	mm	mm
0·0075	0·015	0·0012	0	−0·0012	0	−0·0012
0·0175	0·030	0·002	0	−0·002	0	−0·002
0·030	0·034	0·0032	0	−0·0032	0	−0·0032

Table 3.7 Tolerances for ring and gap gauges

A similar table gives the recommended tolerances for plug gauges, and reference to this table gives the tolerance on the plug gauge as 0·002 mm.

A further table recommends minimum gauge tolerances relevant to type and size of gauge. A cylindrical plug gauge between 25 mm and 50 mm diameter has a recommended minimum tolerance of 0·002 mm. This agrees with the tolerance given to our 40 mm basic-size plug gauge.

Clearly the tolerances on both the plug gauge and the gap gauge required for the checking of our pulley and shaft assembly are very small indeed. The accurate determination of the diameters of the gauging members of the plug gauge represents a good example of the need for measurement by comparison, and it is certain that much use will be made of the comparators described in Chapter 2.

At the same time, determining the widths of the gauging members of this gap gauge requires application of the principle of direct measurement; end standards or slip gauges will be employed for this purpose.

Summary

In this chapter we have seen the interconnecting links between mass-production, limit systems, high and low limits on component dimensions, limit gauges, and the high and low limits on the gauging members. All this stems from the need to assemble mass-produced components that have been produced at high production speeds using machine tools. It is not possible to machine to exact dimensions; a tolerance must be given to allow for the imperfections of the machine tool or operator. Immediately a dimension is given a tolerance it has two limits, a high limit and a low limit. Provided the actual dimension machined is within these limits it is acceptable, and it is the purpose of inspection to ensure that no component having any dimension outside the permissible limits is passed to assembly or to the customer.

The reliability of an engineering assembly is closely connected to the accuracy and quality of the different kinds of fits present. These fits may be clearance, interference or transition, and the purpose of a limit system is to ensure that complete standardisation of these fits is achieved. The limit system recommended is the British Standard system, set out in BS 4500: 1969. Based on the ISO system, BS 4500 offers a comprehensive range of fits. The H hole is recommended for engineering assemblies, such holes having zero deviation. Thus a shaft with a plus deviation provides an interference fit, while a shaft with minus deviation gives a clearance fit. In this way the disposition, together with the amount, of the deviation determines the type of fit obtained.

The amount of the tolerance is mainly determined by the class of work or the type and quality of the machine tools used. High-grade work such as precision lapping is given a small tolerance number, while relatively rough work such as sand casting is given a high tolerance number; thus the tolerance number determines the quality of the fit.

Finally, the limits received by a dimension following tolerancing permit the use of limit gauges. Limit gauges provide a rapid and cheap form of dimensional control; they are easily carried about by the inspector, removing the need for costly, delicate measuring equipment. Elements of gauge design are fully covered in BS 1044:Part 1:1964, while BS 969:1953 deals with the amount and allocation of the gauge tolerance.

EXERCISE 3

1 Explain the essential difference between the techniques of measurement and inspection, illustrating your answer with a practical example of both techniques.

2 What is the essential purpose of a limit system? Sketch, using simple engineering assemblies, **three** different types of fit.

3 Write a simple but adequate description of the main features of the British Standard limit system (BS 4500:1969).

4 Define the following features of BS 4500:
  (i) ISO tolerances,
  (ii) fundamental deviation,
  (iii) preferred numbers.

5 What factors determine the choice of the tolerance number when using BS 4500? Why are holes usually given a tolerance one grade coarser than the shaft?

6 Using the tables provided in this chapter, make a dimensioned sketch of the following:
  (i) A 200 mm pulley with a 50 mm diameter hole to be a close running fit on a 50 mm shaft (H7/g6).
  (ii) A 30 mm diameter case-hardened mild-steel pillar to be a drive fit in a mild-steel bolster (H7/s6).

7 Make a neat sketch of an engineering assembly having four different types of fits. Using BS 4500 terminology, classify each fit.

8 What is the purpose of limit gauges? With a neat diagram illustrate the allocation of the gauge tolerance, showing clearly how a GO gauge may reject a satisfactory component.

9 Sketch the following gauges:
  (i) double-ended solid plug gauge,
  (ii) progressive renewable-end-type plug gauge.

10 Sketch the gauges required to check the assembly shown in fig. 3.10 (ϕ40 H8/f7). Insert in full the dimensions of the gauging members, making reference to the tables given in BS 969:1953.

4 Cutting Tools

4.1 Introduction

We have seen in the previous chapter that if engineering components are to be machined for subsequent assembly, the tolerances on the functional dimensions may have a very small value. Fig. 4.1 illustrates a phosphor-bronze wormwheel casting produced on a capstan lathe.

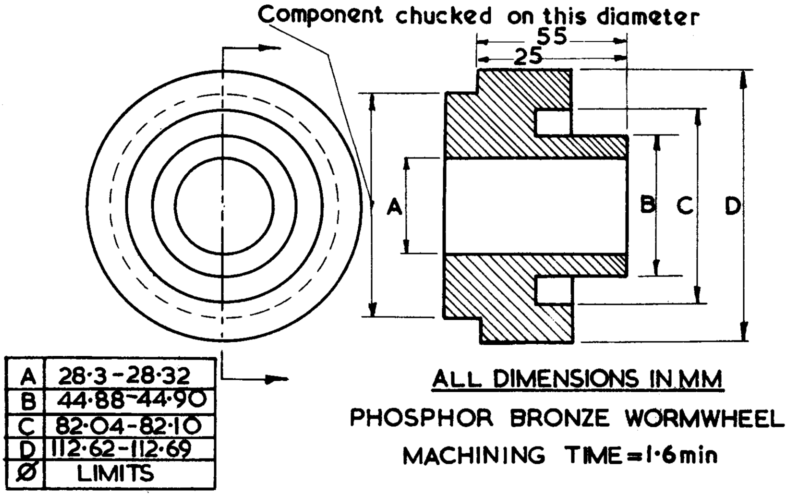


Fig. 4.1.—Component Machined on Capstan Lathe.

This casting is held in a three-jaw air chuck and machined with tungsten-carbide cutting tools, an overall floor-to-floor time of 1·6 minutes each being achieved. Note the limits for the bore, namely 28·32 mm high limit and 28·30 mm low limit, giving the operator a tolerance of 0·02 mm. The tolerances on the other diameters are also quite small; 0·02 mm on the boss, 0·05 mm on the recess and 0·07 mm on the outside diameter. Yet this component is machined in the remarkable time of 1·6 minutes, and this includes the time required to load and unload the casting.

In this way a capstan operator is able to machine, say, 230 of these castings in a working day, and we can be sure that limit gauges will be used to ensure that the diameters are within the limits shown in fig. 4.1. It is worthwhile at this point to remember that while gauges will detect any dimension outside its limits, preventing the casting being progressed on to the assembly line, the fact remains that the casting is still reject, and action must be taken to remedy the fault. Although the use of gauges provides a means of dimensional control, the accuracy of the machined dimensions is actually determined by the efficiency of the **cutting tools** used. Not only must the cutting tools possess the necessary hardness to resist the abrasion inherent in the removal of metal but they must also be tough enough to withstand the heavy pressures involved when metal is removed at high speed.

Clearly the cutting tools used to produce the phosphor-bronze component shown in fig. 4.1 require not only that the cutting angles are of the correct value, but also that the cutting edges are able to maintain their shape and size even when the production rate is about 40 components per hour. Remember that any wear of the cutting tool used for a specific machining operation must result in variation in the size of the machined dimension, together with deterioration of the surface finish. Remember, too, that the efficiency of a machine tool such as a capstan lathe is measured in terms of the volume of metal removal per minute. If we add to this the fact that the machined dimensions must be within the prescribed limits, it is clear that the cutting tool plays a vital part in engineering manufacture.

4.2 Cutting-tool materials

The most important factor in cutting-tool efficiency is the material from which the cutting tool is made. Correct design and accurate rake and clearance angles amount to nothing if the tool material is unable to stand up to the cutting conditions. All cutting-tool materials must possess the following two properties:

(i) hardness,
(ii) toughness.

Fig. 4.2 illustrates in simple diagrammatic form the properties of hardness and toughness with respect to the more commonly used cutting-tool materials. Note that the vertical scale represents hardness while the horizontal scale shows toughness; it is important, too, to appreciate that the diagram gives an indication of these properties at a temperature of 500° C. This is the approximate temperature of a metal chip sheared by a cutting tool under conditions of efficient machining, although the use of coolants and lubricants may reduce this temperature.

If we now refer to the diagram, taking the various cutting-tool materials in turn, we shall see the advantages and limitations of the materials under discussion, and we can then turn to the problems involved in the best design and application of cutting tools, using the cutting-tool material best suited to the particular job in hand.

4.2.1 High-carbon steel

Reference to fig. 4.2 shows that high-carbon steel has a relatively low hardness figure at 500° C. This is owing to the fact that this steel rapidly loses hardness when it is taken to temperatures in excess of 220° C; indeed at 350° C the steel has almost reverted to its normal hardness value. This sets a

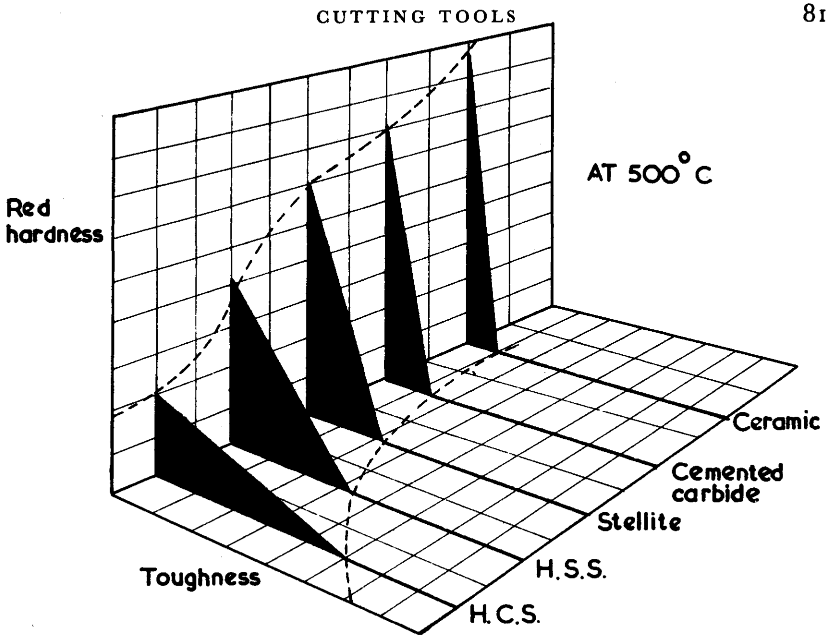


Fig. 4.2.—Comparison of Cutting Tool Materials.

serious limitation on the use of high-carbon steel as a cutting-tool material. It cannot be used if high machining speeds are required, such as those used in the machining of the wormwheel illustrated in fig. 4.1. It is, however, eminently suitable for cutting tools not likely to be subjected to undue friction leading to a rise in temperature, such as cold chisels, punches, files and scribers.

Fig. 4.3 shows the effect of temperature rise on the hardness of hardened high-carbon steel. It will be seen that a rapid fall in hardness value takes place at about 220° C, and at 350° C the steel has lost most of the hardness gained at the initial hardening treatment.

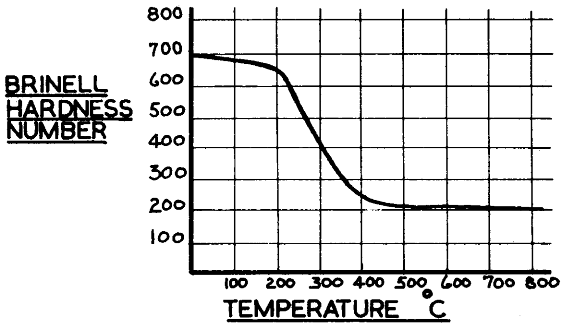


Fig. 4.3.—Effect of Rise in Temperature on Hardened High-carbon Steel.

4.2.2 High-speed steel

Fig. 4.4 shows the effect of heat on hardened high-speed steel. It will be seen that the hardness increases between 400° C and 550° C. This is quite

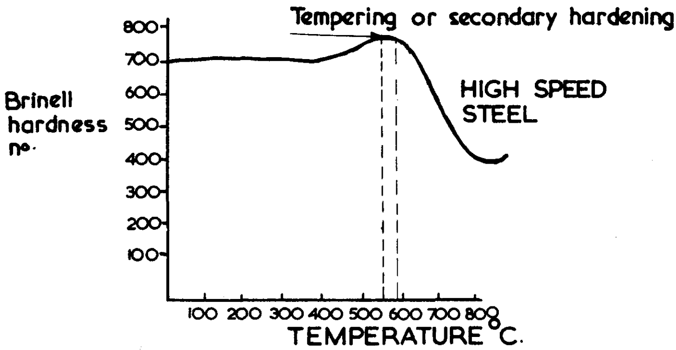


Fig. 4.4.—Effect of Rise in Temperature on Hardened High-speed Steel.

unlike the behaviour of high-carbon steel, and it is clear that the friction involved when machining at high speeds will not affect the hardness value of hardened high-speed steel. The high-speed steel is said to possess the quality of **red hardness;** that is to say it has the ability to retain its hardness value even when the swarf is leaving the parent metal at red heat.

High-speed steel is a relatively expensive metal, easily ten times the cost of high-carbon steel. Most drills, reamers and milling cutters are made from

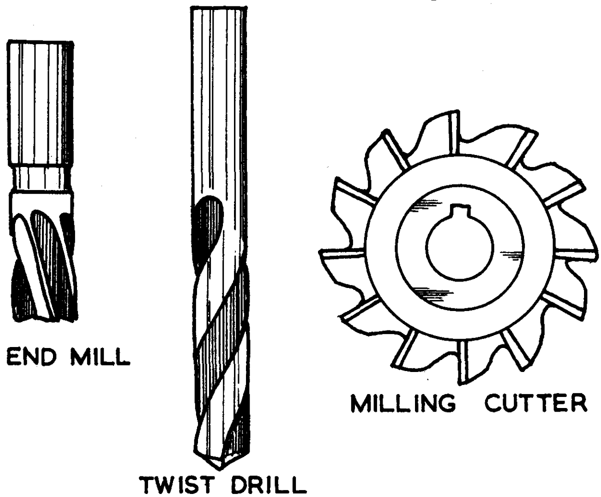


Fig. 4.5.—High-speed Steel Cutting Tools.

high-speed steel. Wherever possible welding to a cheaper and tougher material will be adopted, providing not only a cheaper tool but also one that is more likely to stand up to cutting conditions. Fig. 4.5 shows some typical applications of high-speed steel as a cutting-tool material.

4.2.3 Stellite

Stellite is the trade name of a special material. It is a non-ferrous alloy containing high proportions of cobalt, chromium and tungsten. Reference back to fig. 4.2 shows that Stellite is harder than high-speed steel at a temperature of 500° C. When poured in the liquid state from an electric furnace Stellite is self-hardening; thus a Stellite casting allowed to cool in air has a Rockwell hardness value of about 62 on the C scale.

This inherent hardening property allows the use of Stellite as a hardfacing metal, available for electrodes to be used in the arc-welding technique described in Chapter 1. Fig. 4.6 illustrates the application of a Stellite electrode to recondition or reface a knife-edge bearing surface. It will be seen that a layer of Stellite has been welded onto the damaged surface. On cooling the Stellite deposit is extremely hard and cannot be machined with normal cutting tools, but must be ground to the required shape as shown in fig. 4.6C.

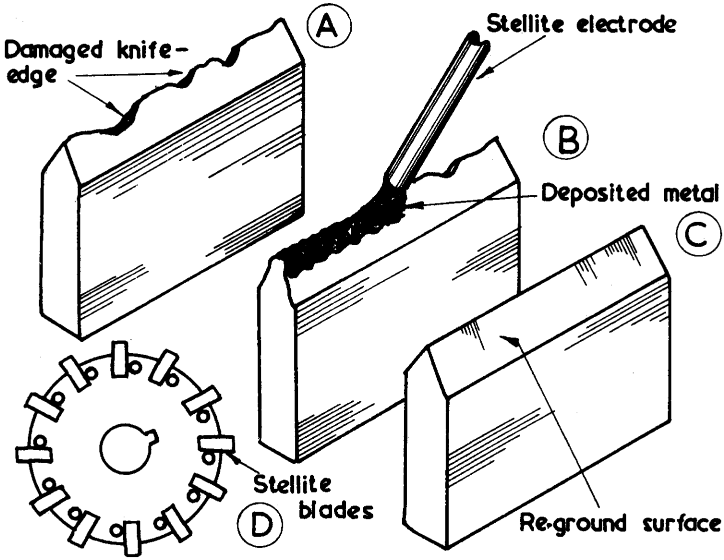


Fig. 4.6.—Applications of Stellite.

Fig. 4.6D shows the use of Stellite inserts for a large-diameter milling cutter; this is a much better proposition than making a large-diameter milling cutter from high-speed steel. Apart from the high cost of a solid high-speed milling cutter, there is the considerable risk of cracking or distortion during the heat-treatment process, not to mention the possibility of tooth breakage when in use, leading to the scrapping of the cutter. The inserted-tooth-type milling cutter using Stellite teeth is an efficient and reliable multi-point cutting tool, the high tensile strength of Stellite allowing the inserted blades to stand up to the considerable stress involved when taking heavy cuts.

4.2.4 Cemented or tungsten carbides

The exceptional hardness of tungsten carbide was appreciated as far back as 1886, but the brittleness of this alloy prevented its use as a cutting-tool material. It was the German firm Krupps of Essen who first produced an alloy of tungsten carbide and cobalt and successfully used it as a cutting-tool material. Called Widia from the German *wie Diamant* ("like a diamond"), it was used as a tip, securely supported and brazed to a carbon-steel shank and employed as a lathe tool. It was found that fairly rapid wear of the tungsten-carbide tip occurred when the tipped tool was used on the softer steels, and this led to the introduction of the elements tantalum and titanium. The addition of these elements produces a tungsten-carbide tip with excellent steel-cutting properties and a long tool life.

4.2.5 Ceramics

Ceramics represent the latest development in cutting-tool materials. It will be seen from fig. 4.2 that ceramics possess a higher hardness value than tungsten carbide at a temperature of 500° C, but are more brittle. Chemically inert, with a low coefficient of friction and low heat conductivity, a ceramic-tipped tool has very high metal-removal capacity, together with the ability to produce a good finish. Of greater importance is the fact that the life of a ceramic-tipped tool is high even when working at maximum speeds, and this means that a machine tool such as an automatic lathe equipped with ceramic tooling is capable of producing machined surfaces at high production speeds to very close dimensional tolerances.

4.2.6 Application of carbide and ceramic tips

The inherent brittleness of both carbide and ceramic materials necessitates their use as tips for cutting tools. We see on referring back to fig. 4.5 that the milling cutters may be made wholly from high-speed steel. This is not possible with either carbide or ceramic. These materials are much too brittle, and a milling cutter made from either tungsten carbide or ceramic would have as much practical value as a delicate china or porcelain ornament. Not only is it necessary to use the material as tips; it is also essential to ensure that the tips are given adequate support and are rigidly held in position.

4.2.7 Tungsten-carbide-tipped tools

The technique used to join the tungsten-carbide tip to the tool body or shank is that of brazing. A typical tipped lathe tool is shown in fig. 4.7, with the machined component shown at B. This tipped tool is used to machine the groove to take a V belt. Although several brazing techniques may be employed, such as the use of a gas-air blowpipe, electric furnace, gas furnace or high-frequency heating coils, essentially the principle remains the same; namely the secure joining of the carbide tip while in solid contact with the face shown as F on the diagram. It is of the greatest importance that the resultant force exerted on the tip during the cutting operation is taken or resisted, not by the brazed joint, but by the solid abutment provided by the face F as shown in fig. 4.7A. Best results are obtained when using high-frequency coils, and this technique is known as **induction brazing.** Fig. 4.8 illustrates both blowpipe and induction brazing. In the case of induction brazing, the source of heat is obtained from interference of an intense magnetic field within

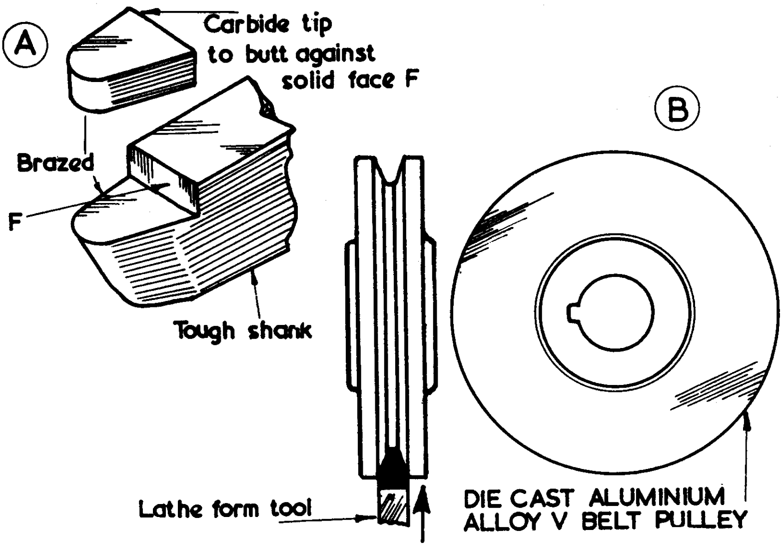


Fig. 4.7.—Application of Tungsten-carbide Tips.

the water-cooled copper coil caused by the presence of the tool and tip when inserted within the coil. This coil carries a high-frequency current of up to 500 000 hertz. With the tool in position, the operation of brazing is reduced to the pressing of a button; the current is automatically switched on and applied for the correct length of time to allow melting of the thin strip of copper foil between the tool and the tip.

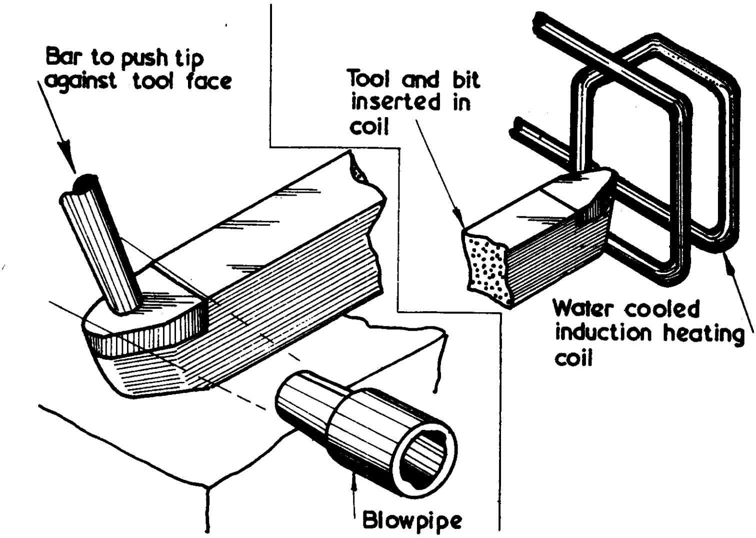


Fig. 4.8.—Brazing Techniques for Tipped Tools.

Although the tool shank heats at a faster rate than the carbide tip, just before the actual brazing temperature the temperature of the tip exceeds that of the shank, and this is a desirable feature.

Although fig. 4.8 shows only a tungsten-carbide-tipped lathe tool, tungsten carbide is used to tip drills, reamers and other cutting tools.

4.2.8 Ceramic-tipped tools

Although a ceramic tip may be brazed to a carbon-steel lathe-tool shank, this technique is seldom adopted when making use of ceramic tips. This is owing to the considerable difficulty encountered when attempting to re-sharpen a ceramic-tipped lathe tool. It is a better and cheaper proposition to discard or throw away the ceramic tip rather than embark on the costly and sometimes lengthy project of grinding ceramic tips.

The adoption of this principle of discarding worn tips has led to the introduction of the now-popular throw-away tip technique. Fig. 4.9 illustrates a typical practical application of this technique. At A we see the principle adopted when a square ceramic bit is used to machine a low-strength metal such as copper, aluminium alloy or soft steels. These metals require a positive rake, and it will be seen from the diagram that this is obtained from the design of the tool holder. This means that four cutting edges are available, and may be easily and quickly indexed or presented to the work with minimum loss of time.

Harder metals require the ceramic tip to have a negative rake, and once again the tool holder is used to provide this angle, as shown in fig. 4.9B.

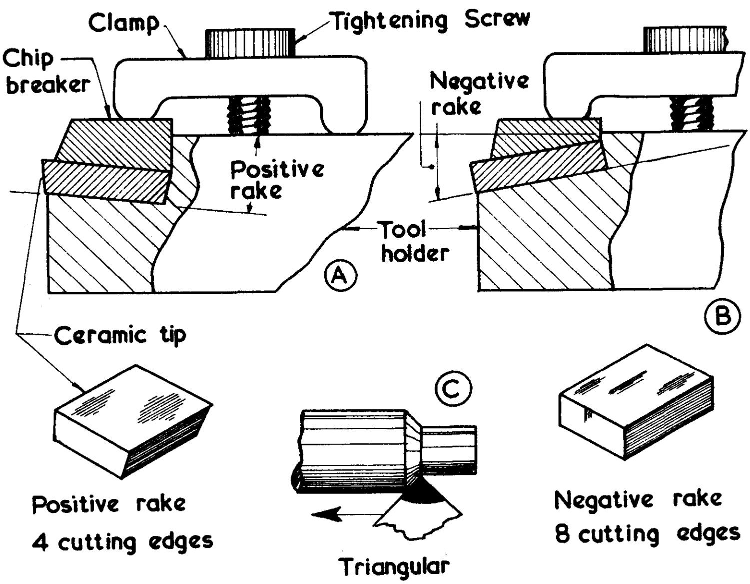


Fig. 4.9.—Applications of the Throwaway-tip Technique.

The square tip now has eight cutting edges which may be presented to the work in turn.

Ceramic inserts are also available as triangular or circular bits, and fig. 4.9C shows the application of a triangular bit. It is customary to use a chip-breaker behind the ceramic tip. This chipbreaker may be adjustable, as shown in the diagram, allowing control of the chip.

This principle of throw-away tips is now applied to face-milling cutters. Three sizes are available, 100 mm, 150 mm and 200 mm diameter; the tips used are cemented carbide, locked in place with a simple lever action, with provision for roughing and finishing in one pass of the face mill by having two opposed finishing tips set lower than the tips used for roughing.

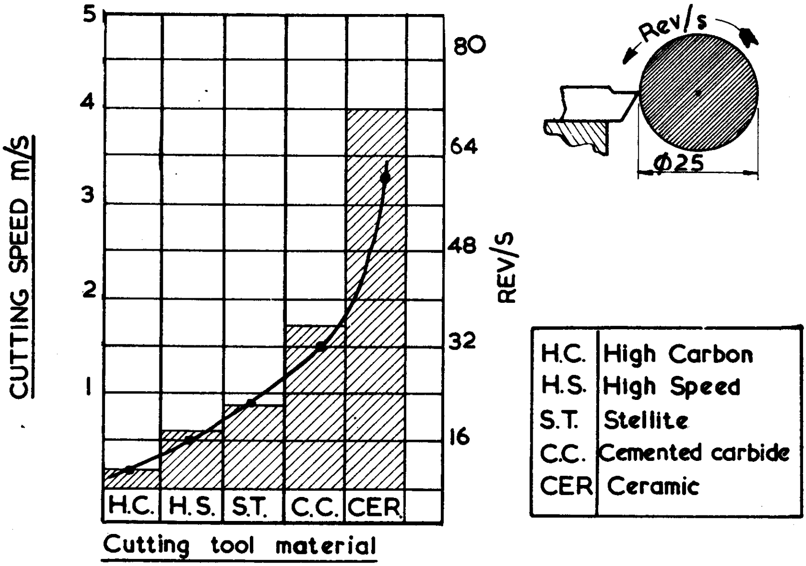


Fig. 4.10.—Cutting Tool Materials and Cutting Speeds.

4·3 Cutting speeds

The introduction of the newer cutting materials such as Stellite and cemented or tungsten carbides has led to a great increase in the rate of metal removal. This is achieved by increase of the cutting speed, that is to say the speed of the work relative to the tool when turning on a centre lathe. Fig. 4.10 gives some idea of the increase in cutting speed when turning mild steel on a centre lathe, and using different tool materials. The shaded areas represent the approximate cutting speed in m/s for the cutting tool materials shown, while the curved line gives the approximate rev/s when turning a mild-steel bar of 25 mm diameter.

We see at once that a speed of about 5 rev/s is required when using a high-carbon-steel cutting tool, while at the other end of the scale it will be seen that a speed of about 60 rev/s is required when a ceramic-tipped tool is used.

The figures given apply only to a mild-steel bar of 25 mm diameter, as shown in the diagram; smaller diameters or softer metals will require higher speeds. It is evident that at the speeds required for carbide or ceramic-tipped tools considerable friction must result from the high velocity of the sheared chip moving across the tool face or tip face. The velocity of this chip and the pressure it exerts on the tool face are the main factors leading to deterioration of the tool face and subsequent failure.

4·4 Tool failure

Tool failure can be considered as the inability of the cutting tool to maintain the required accuracy either of dimensions or surface finish. The period of time during which the cutting tool performs satisfactorily is known as the **life** of the tool. A cutting tool that possesses a long life offers very great advantages to the production engineer.

The time required to set, say, a capstan lathe is unproductive time. The engineering value of a capstan lathe, as of any other machine tool, lies in its ability to produce accurate, well-finished work in the minimum time. Not only is the machine idle while the tools are changed; the cutting tools also are expensive, and both time and money are required to restore the cutting edges or regrind the cutting tool. The causes underlying tool wear are of some importance, for if tool wear could be prevented, in theory a cutting tool would last indefinitely, permitting high production figures of well-finished components having all dimensions within the limits laid down.

Fig. 4.11 shows a pictorial view of **orthogonal** cutting, the condition that exists when the tool breast is at 90° to the path of the tool. Note the wedge

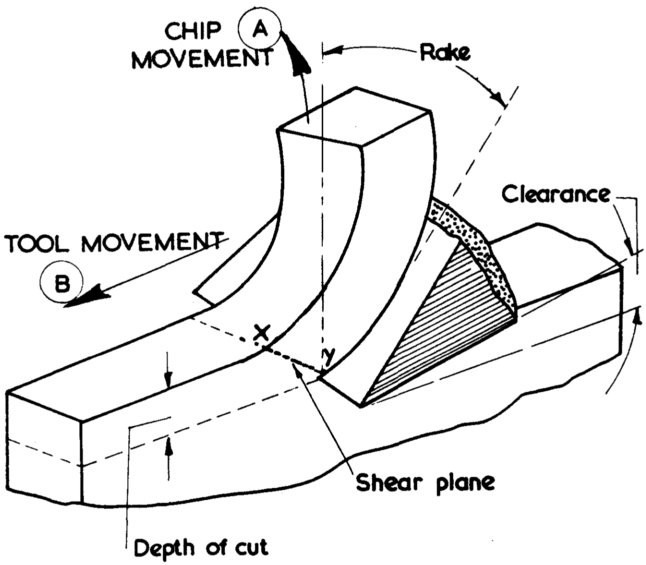
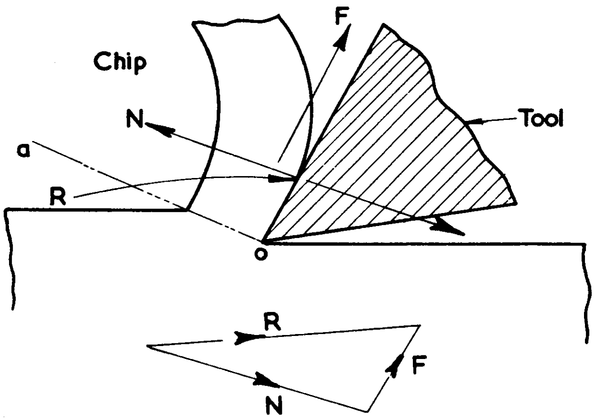


Fig. 4.11.—Orthogonal Cutting.

shape of the cutting tool. The diagram is representative of shaping, planing, milling and turning, or for that matter of all metal cutting using the wedge principle.

Two movements can be seen; the movement or speed of the tool in the direction of the arrow shown as B, and the movement or speed of the sheared chip in the direction indicated by the arrow A. Thus the tool exerts a force on the metal, resulting in partial shear of the metal along the shear plane shown as XY. The chip shown is characteristic of mild steel, a fairly ductile metal allowing considerable elongation of the chip under the force exerted by the cutting tool.



N = Force normal to tool face
F = Frictional force of chip
R = Resultant of N and F

Fig. 4.12.—Simplified Diagram Illustrating Forces acting at Tool Point.

Fig. 4.12 shows a side view of the cutting action; the force exerted by the tool is at 90° or normal to the tool face, and is shown as *N* in the diagram. The force exerted by the moving chip is parallel to the tool face, and is shown as *F*. If we now resolve these two forces as shown, then *R* is the resultant. It is this resultant force that leads to tool wear and failure, because of the high frictional effect of the fast-moving chip on the tool face.

4.5 The built-up edge and cratering

Fig. 4.13 shows the formation of a built-up edge on the tool face. As the chip leaves the parent metal the underside of the chip has no time to oxidise, and as a result possesses a very clean or pure surface. Forced against the tool face by the resultant force *R*, surface particles of the fast-moving chip weld themselves onto the tool face. In this way a build-up of chip metal particles takes place, and the moving chip now rides on this built-up edge as it leaves the parent metal. The built-up edge is now subjected to the severe frictional force of the moving chip, resulting in severe work hardening and subsequent breaking away of metal particles. This formation and disintegration of the built-up edge takes place at a very rapid rate, assisted by the high temperatures and pressures at the tool point.

As the built-up edge breaks away, minute particles of the tool face, pressure welded to the chip, are taken away, and the continuation of this process results in the formation of a hollow or crater on the tool face, as shown in fig. 4.14. The extension of this crater to the point of the tool is the main cause of tool failure.

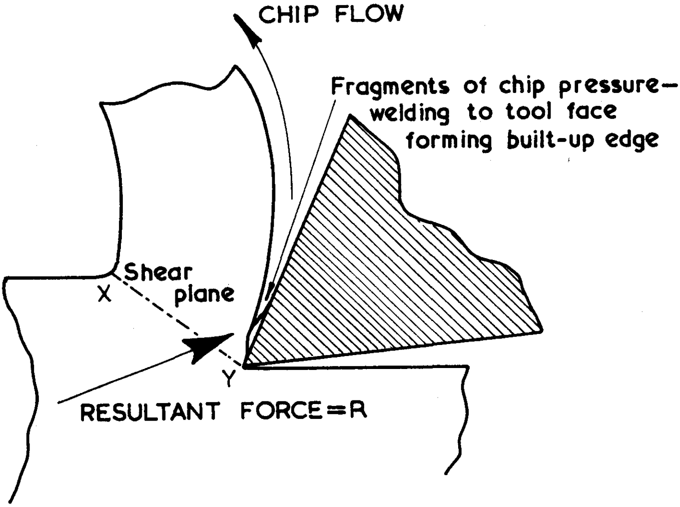


Fig. 4.13.—Formation of the Built-up Edge.

4.5.1 Avoidance of the built-up edge

Not only does the formation of a built-up edge bring about eventual failure of the cutting tool, but also when components are produced by turning on centre, capstan or automatic lathes, small severely work-hardened particles of the built-up edge weld or adhere to the surface of the machined components. The presence of these hard particles of metal substantially reduces the life of an assembly in which the two mating parts are to be a running or rotating fit.

The following factors tend to delay the formation of a built-up edge:

(i) high cutting speed,
(ii) fine feed,
(iii) large rake angle,
(iv) sharp cutting edge,
(v) smooth surface on breast of tool,
(vi) efficient cutting fluid,
(vii) low coefficient of friction between tool and chip.

Which of these factors can be introduced and exploited is determined by the actual cutting tool material and the material being machined. For example, if a high-speed steel lathe tool is to be used, then it is important that the rake angle be as large as possible without undue weakening of the tool point. The smoother the tool face or breast, the more efficient will the tool be, while the application of an adequate supply of a suitable cutting fluid will effect even further improvement.

If, too, a roughing tool is used to obtain maximum metal removal with less regard for surface finish and dimensional accuracy, then a finishing tool can be used with a high cutting speed and fine feed. Carbide and ceramic-tipped tools often require no cutting fluids or coolant, and may have a negative rake angle because of their relative brittleness.

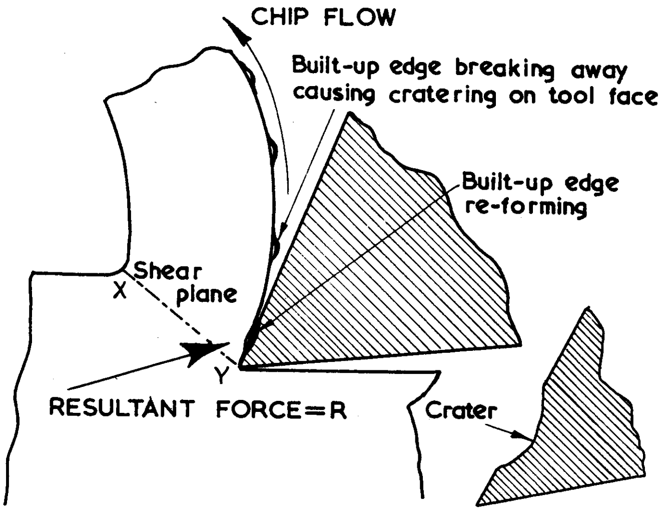


Fig. 4.14.—Cratering on Tool Face.

4.6 Forces acting at cutting-tool points

The calculation of the forces acting at the point of a lathe tool provides an interesting experiment that can be carried out in the workshop or machine-tool laboratory. In order to determine the magnitude of the forces acting on a lathe tool a **dynamometer** must be used. A dynamometer is essentially an instrument designed to measure energy; thus a lathe dynamometer measures the forces acting on the tool point.

These three forces are shown in fig. 4.15A, and are the forces exerted by the tool on the work. At B we see the equal and opposing forces exerted by the work on the tool. These are:

T = the vertical or tangential force,
F = the feed force,
H = the horizontal force.

The greatest of these three forces is the vertical force T, which can be considered as approximately equivalent to the force present in the turning moment of the work.

$$\text{Torque} = \text{force} \times \text{radius}$$

To calculate the power required to machine work on the centre lathe:

$$\text{torque (newton metres)} = \text{force (newtons)} \times \text{radius (metres)}$$
$$\text{power} = 2\pi NT \text{ watts}$$
$$\text{where } N = \text{rev/s}$$
$$T = \text{torque in newton metres}$$

It is now possible to calculate the following items using the lathe dynamometer illustrated in fig. 4.16.

(i) resultant force on tool point and its direction,
(ii) effect of varying side rakes on power consumed,
(iii) effect of varying approach angles,
(iv) machinability of different materials,
(v) pressure in N/mm^2 on tool point.

The following notes will give some idea of the use of the dynamometer; the basic principle is shown in diagrammatic form in fig. 4.16.

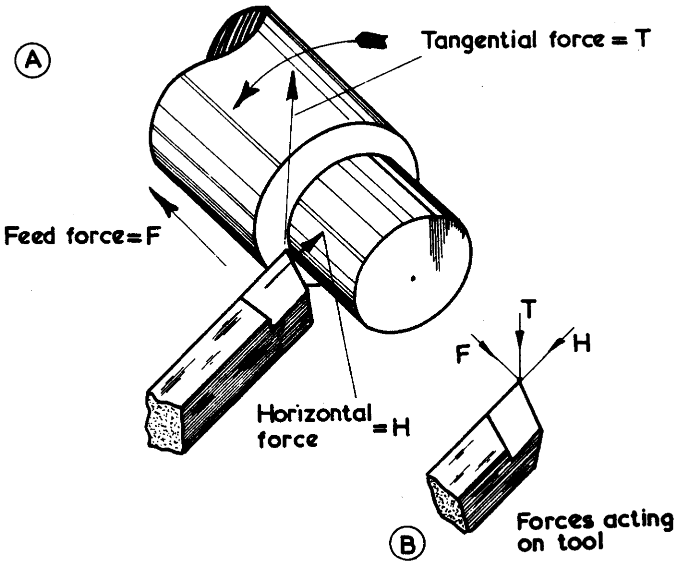


Fig. 4.15.—Forces Acting on a Lathe Tool.

4.6.1 To find the magnitude and direction of the resultant force on a lathe tool

With the lathe tool securely clamped to the dynamometer with the correct length of tool protruding, fix the dynamometer in the tool post. Set all dial indicators to zero. Choose suitable rev/s, depth of cut and feed, and note readings on all three dial indicators. Convert readings to newtons using calibration charts supplied with dynamometer; this will give the values of forces T, F and H in newtons.

Draw T and F to a suitable scale and at right angles. As shown in the diagram (fig. 4.16A) the resultant of these two forces (RFT) is at an angle of $\alpha°$ to the vertical plane; this angle may be carefully measured. We must now consider the effect of the horizontal H, and construct another vector diagram with the object of resolving the two force components RFT and H. This is also shown in fig. 4.16, and the resultant of these two components is indicated as R. Note that it makes an angle of $\theta°$ to the horizontal.

The angles can if required be calculated mathematically, and the value of this experiment lies in the fact that it is possible to calculate the resultant thrust on a carbide or ceramic tip, and design the tool holder so that this thrust is opposed by a machined face.

4.6.2 To find the effect of varying top rakes

Four knife-edge lathe tools are required with the following side rakes: 0°, 10°, 20° and 30°.

Set each tool in turn in the dynamometer and note the dial indicator readings for the vertical force T. Convert readings to newtons and hence to watts; then plot power against side rake angle, as shown in fig. 4.16B. This experiment is most useful in proving that increase in rake angle decreases the shear plane and thus the energy requirements.

4.6.3 To determine the machinability of different materials

Several bars of identical diameter but of different materials are required for this experiment. Suggested materials are mild steel, brass, copper, grey cast iron, duralumin, perspex and nylon.

A suitable (though approximate) technique is to keep the tool angles, rev/s, feed and depth of cut constant for each machining test; thus the only variable is the metal or material under test. The magnitude of the vertical force T may be taken as an indication of the machinability of the material. As mild steel is perhaps the most widely machined metal it can be given an index of 1, and relative machinability figures can be obtained in proportion to the vertical force T obtained in each case. Fig. 4.16C shows a typical chart giving an indication of the machinability of the more common engineering materials.

4.6.4 To find the pressure acting on a lathe tool

This experiment is best carried out using a mild-steel test piece. With a reasonable depth of cut, feed, and rev/s, note the reading on the dial indicator for the vertical force; convert into newtons using the calibrated chart.

This force acts on an area equal to the feed multiplied by the depth of cut, as shown in the diagram (fig. 4.16D). Let us take some approximate figures.

Let depth of cut = 2mm
feed = 0·2 mm
force T = 650 N

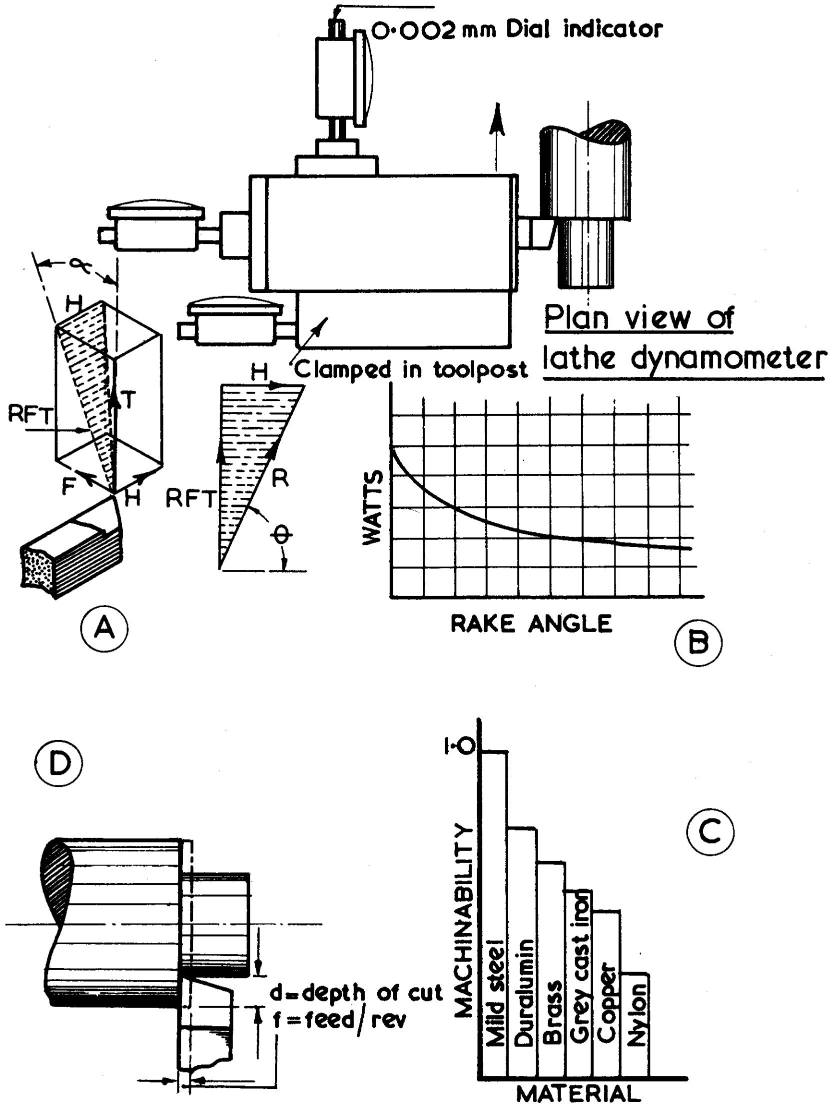


Fig. 4.16.—Practical Applications of the Lathe Dynamometer.

Area of chip $= 2 \times 0{\cdot}2 = 0{\cdot}4\ \text{mm}^2$

On an area of $\frac{4}{10}\ \text{mm}^2$ acts 650 N

On an area of 1 mm^2 acts

$$\frac{650 \times 10}{4}\ \text{N} = 1625\ \text{N}$$

Now a force of 1625 N/mm^2 is equivalent to 1625 MN/m^2, and as the shear stress of mild steel is about 400 MN/m^2 it is clear that this value greatly exceeds the shear strength of mild steel, and accounts for the apparent ease with which the chip leaves the parent metal.

4.7 Radial cutting

Fig. 4.15 illustrates a typical example of **radial cutting**, that is to say cutting with the tool in line with the radius of the turned work. In view of the relatively severe pressure acting on the cutting tool, usually in the range of 900 to 1600 N/mm^2 for mild steel, this is not the best way of presenting the tool to the work.

Fig. 4.17 illustrates the principle involved. The vertical force F acting downwards induces bending and vibration of the cutting tool with subsequent deterioration of the dimensional accuracy and finish of the turned work. This effect is often known as **chatter,** and if the work/tool area of contact is large, the machine tool is likely to vibrate in harmony with the cutting tool, setting up a noisy clangour.

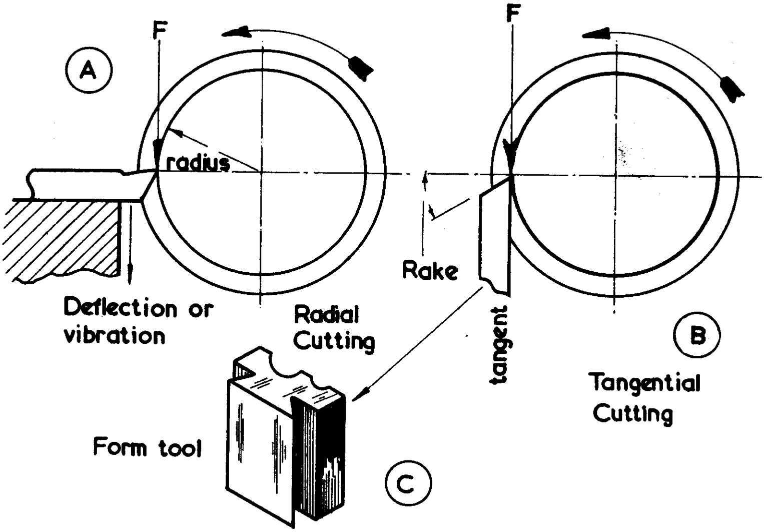


Fig. 4.17.—Radial and Tangential Cutting.

4.8 Tangential cutting

The principle of tangential cutting is shown in fig. 4.17B. It will be seen that the tool now lies along a plane tangential to the surface of the turned work. In this position the tool is better able to absorb the force exerted on it, and the possibility of deflection or vibration is reduced to a minimum. A popular application of tangential turning is the use of form tools. Inevitably a form tool must have a relatively large work/tool contact area, and much greater rigidity is obtained if the principle of tangential cutting is adopted. Thus the form tool illustrated at fig. 4.17C is applied to the work as shown at B, and locates in a dovetail slide.

Another popular application of the tangential cutting principle is the chipstream roller box used for reduction of diameters on the capstan lathe.

4.9 Negative-rake cutting

Negative-rake cutting, as the name suggests, involves the use of cutting tools having a negative rake. This technique is applied only when relatively brittle cutting materials are used. The reason for this is that the grinding of a positive rake on a cutting tool, although reducing the area of metal to be sheared, reduces also the volume of metal at the point of the cutting tool itself, and this is precisely where the maximum amount of metal is needed.

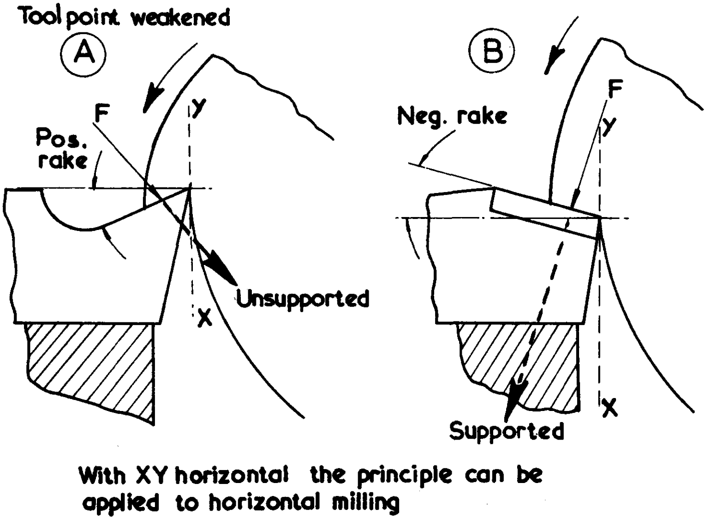


Fig. 4.18.—Positive and Negative Rake Cutting.

This is shown in fig. 4.18A, where it can be seen that the rake angle has considerably reduced the ability of the tool point to withstand not only the considerable pressure exerted by the cutting or shearing action, but also any sudden blow or shock encountered when the tool first makes contact with the work. If we consider the application of cemented-carbide and ceramic tips, with their excellent hardness but inherent brittleness, then it is clear that if these tipped tools are provided with positive rake their life is likely to be very short. The smallest amount of chipping or damage on the breast of these tipped tools has a marked effect on the ability of the tip to remove metal efficiently, and it is essential that the tip be provided with the maximum strength in order to promote a long life. This is achieved by providing the tipped tool with negative rake.

Fig. 4.18B shows the side elevation of a negative-rake tipped tool. It can be seen that the vertical cutting force is taken on a supported section of the tool, and not on the unsupported section of the tool point, as shown at A. The increased strength of the tool point obtained by adopting the negative-rake principle allows the use of very high cutting speeds, as we have seen in fig. 4.10. For example, when cutting mild steel at a cutting speed of approximately 4 m/s, a 25 mm diameter bar will require a spindle speed of about 50 rev/s, if it is being machined on a lathe.

A considerable amount of heat is generated at the shear plane, raising the temperature of the metal to such a degree that the chip becomes semi-plastic and less force is required to shear it from the parent metal. In this way the increased shear plane caused by the negative rake is counteracted by the greater ease with which the plastic chip is sheared from the parent metal. It must now be appreciated that the correct application of both cemented-carbide- and ceramic-tipped tools demands the use of machine tools specially built for carbide or ceramic tooling.

We may list the essential requirements for negative-rake cutting as follows:

(i) maximum rigidity of machine tool, work and cutting tool,
(ii) provision for ample range of high cutting speeds,
(iii) adequate power supply,
(iv) avoidance of any rubbing of tool,
(v) mirror finish on breast of cutting tool.

4.10 Cutter grinding

The renovation of the cutting edge of a cutting tool is still an essential requirement. Although the use of throw-away ceramic tips removes the necessity for cutter or tip grinding, we must remember that the use of such tips is confined to machine tools especially designed for this type of tooling, and this means that a very great percentage of metal removal is still achieved with the use of high-speed-steel cutting tools.

Apart from correct maintenance of the rake and clearance angles, it is an essential part of cutter grinding that the best possible finish be obtained on the tool breast. With carbide or ceramic tips a final lapping operation is needed, using diamond-impregnated lapping discs or Bakelite-bonded lapping wheels impregnated with diamond dust.

The mirror finish possible when lapping the tipped cutting tool materially reduces the friction between the sliding chip and the tool breast or face. In this way the formation of the built-up edge is prevented, and there is little doubt that the operation of lapping a mirror finish to the tip breast is worthwhile, resulting in considerable increase in cutting-tool life.

Summary

Cutting tools are still a vital and essential part of modern engineering manufacture. We have seen that the advance in cutting efficiency has resulted as a direct outcome of the introduction of new cutting-tool materials. The main property required of a cutting-tool material is that it prevents the formation of a built-up edge and consequent cratering. Both cemented carbide and ceramic materials are used as tipping media for cutting tools, while the latter are also finding increasing application for throw-away tips. At the same time there is still an important use for both high-carbon and high-speed steel cutting tools. Provided a tool is not likely to be subject to an appreciable rise in temperature when in use, high-carbon steel is ideal, and most hand tools are still made from this material.

High-speed steel is still in widespread use for milling cutters, drills, reamers, and many other cutting tools used on fairly modern machine tools. In all these applications the correct rake angle is of the greatest importance, reducing the energy requirements and promoting a good finish. The use of the negative-rake technique is restricted to carbide or ceramic-tipped tools, the tool points gaining considerable additional strength.

Finally it must be remembered that carbide and ceramic tooling demands the use of machine tools built for this type of machining. Ample horsepower, great rigidity and a high range of cutting speeds are essential requirements if the best use is to be obtained from the new cutting materials now available.

EXERCISE 4

1 Explain why high-carbon steel is seldom used as a material for making milling cutters. Sketch three cutting tools which would be quite serviceable when made from high-carbon steel.

2 Define the term "red hardness". Sketch a cutting tool that can be used for high speed turning at a centre lathe, stating the material from which the tool is made.

3 What advantages are offered by the use of Stellite as a cutting-tool material? Give a particular use for this material.

4 Why are the cemented carbides always used as a material for tipping tools? Make a neat sketch of a carbide-tipped lathe tool.

5 Sketch a typical throw-away-tip ceramic lathe tool.

6 What is meant by the term "built-up" edge? Outline the factors that promote the formation of a built-up edge.

7 Why is it essential to reduce or prevent the formation of a built-up edge?

8 Describe a typical experiment that could be carried out to determine the effect of rake angle on high-speed steel lathe tools on:

(i) power consumed,

(ii) pressure on tool point.

9 With the aid of a neat sketch show the essential difference between tangential and radial cutting with respect to lathe tools.

10 Explain why cemented-carbide and ceramic-tipped tools are usually given negative rake. What are the essential factors underlying the correct use of negative-rake tipped tools?

5 The Centre Lathe

5.1 Introduction

We are concerned in this chapter with further work on the centre lathe. It must be appreciated at the outset that the use of a centre lathe demands a highly skilled and experienced craftsman, but most of the techniques he employs are also basic to the use of capstan, turret and automatic lathes. As with all metal-removing machine tools, the centre lathe has as its primary purpose the production of geometrical surfaces. There are few geometrical surfaces that cannot be produced at the centre lathe, and for this reason it is an essential machine tool, always found in toolrooms, maintenance shops, development and prototype departments, and in most other places where the business of engineering manufacture is carried on.

5.2 Limitations of the centre lathe

Although capable of producing a wide range of surfaces, including cylindrical, plane, conical, spherical and helical, the centre lathe suffers from the disadvantage that the tool-holding and work-holding devices used require

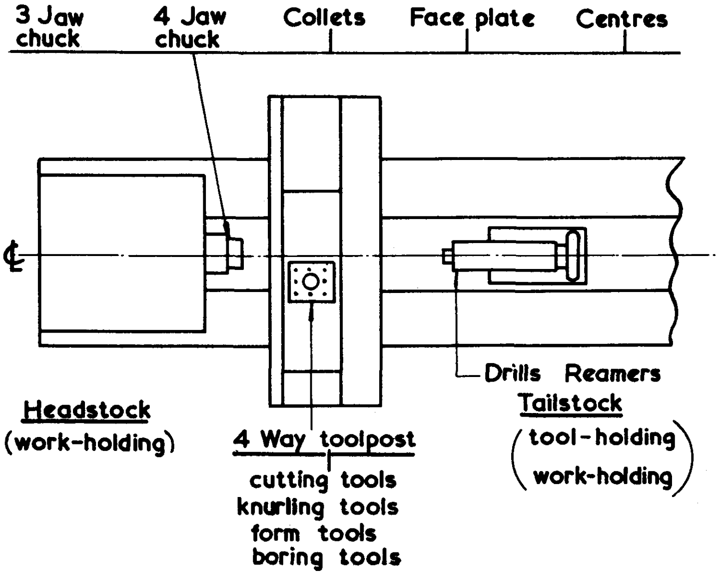


Fig. 5.1.—Work Holding and Tool Holding on a Centre Lathe.

considerable setting and changing. Fig. 5.1 shows the plan view of a centre lathe, and indicates the tooling positions and work-holding stations. It will be seen that the work-holding devices include chucks, collets and faceplate, all of which must be attached to the lathe spindle.

5.3 Tool holding

The tool-holding device on a centre lathe is the four-way tool post, which can be indexed to the workpiece, while further tools can be held in the tailstock. Thus a centre lathe equipped with a four-way tool post and a tailstock can be said to have five tooling stations and one work-holding station. This means that if the centre-lathe turner wishes to use an alternative method of work holding it will be necessary to remove the work-holding device already in the lathe and replace it with the alternative device. Each time a different drill or reamer is used in the tailstock it means that work stops while the tools are changed.

It is perhaps not realised that the skilled turner spends a great deal of his time, not in actual machining, but in tool changing and setting. It may be said, too, that this tool changing and setting represents the more skilled side of his work; the actual removal of the metal and the geometrical accuracy of the machined surfaces is the province of the machine tool, although linear and angular accuracy are under the control of the centre-lathe turner. We will see in the next chapter the great advantages offered by capstan and turret lathes with regard to this matter of tool changing and setting; there the skill of the craftsman is applied to the tooling of the lathe, thus permitting the use of semi-skilled personnel for the actual machining or operating of the machine tool.

5.4 Work holding

Let us now take a closer look at the use of the work-holding devices available on a centre lathe, keeping in mind the fact that the same principles will be used when we deal with capstan and turret lathes.

5.4.1 Chucks

A lathe chuck may be considered as the equivalent of a bench vice, except that while the vice is permanently attached to the work bench, the lathe chuck must be capable of accurate and temporary location to the lathe spindle. Like a vice, a chuck possesses gripping jaws, and lathe chucks are described according to the number and type of jaws. Both three- and four-jaw chucks should be familiar at this stage of our studies, including the draw-in-collet type of chuck. All these chucks are used for the holding of circular work, although the standard three-jaw chuck is equally capable of holding hexagonal work. Although seldom used, two-jaw chucks are available, having soft mild-steel jaws which can be machined to accommodate a casting or forging of irregular shape. Fig. 5.2 shows the basic uses of the more common types of chucks, and their respective applications are outlined below.

Fig. 5.2*A*

Three-jaw universal chuck, self centring; all jaws move together, with the work held on either inside or outside faces of jaws. Two sets of jaws available; the reversible jaws considerably increase the effective work-holding diameter. Much used for the production of small parts in one setting, e.g. drill bushes from cold rolled or bright drawn sections.

Fig. 5.2*B*

Four-jaw independent chuck; all jaws have independent movement. Superior gripping power to three-jaw chuck. Used for holding square, octagonal or irregular work. Often used for second settings in conjunction with dial indicator to obtain concentricity with previous setting. Unlike the three-jaw chuck, in which the chuck centre line is that of the lathe, a four-jaw chuck has a variable centre line, determined by the positions of the four jaws. This difference between the lathe and chuck centre line allows the turning of diameters which are eccentric, or not concentric with each other.

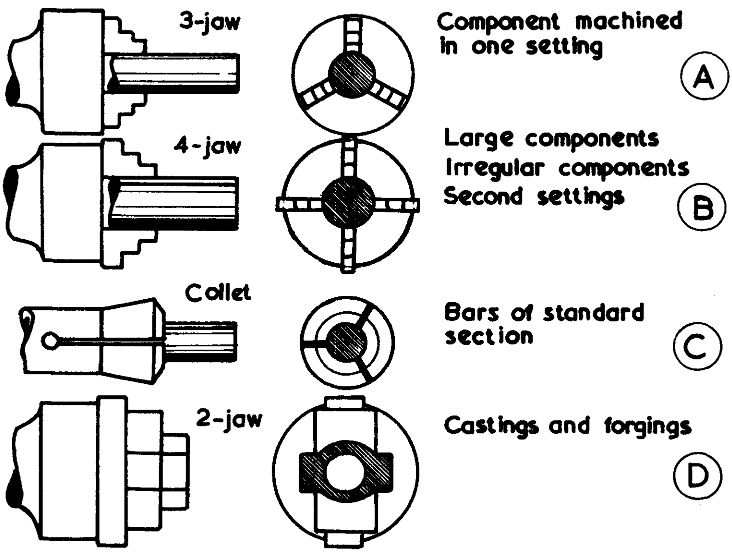


Fig. 5.2.—Work-holding Devices.

Fig. 5.2*C*

Draw-in-collet chuck, more commonly referred to simply as a collet. Although it is not immediately apparent, collet chucks have three jaws which close and grip the work when the collet is pulled or drawn into its seating. Most accurate of all the chuck family, collets are mainly used for the holding of standard diameters, although collets for square or hexagonal sections are available. It must be appreciated that a collet is usually only suitable for one specific diameter or size, and this means that a range of collets is required.

Fig. 5.2*D*

Two-jaw chuck; more commonly used on capstan or turret lathes, but most useful when dealing with prototype castings to be machined on centre lathes. The jaws are of soft mild steel, capable of being case-hardened. The profile of the casting is machined in the two soft jaws, allowing the gripping or holding of a casting that could not be held in any other manner. Forgings may also be held in suitably machined two-jaw chucks.

5.4.2 Faceplate

The purpose of a lathe faceplate is to provide a datum face or reference plane at 90° to the lathe centre line. Initially this datum face permits the location and clamping of castings or other components having relatively large surface areas, but it is possible also to clamp additional equipment such as angle plates and V blocks to a lathe faceplate.

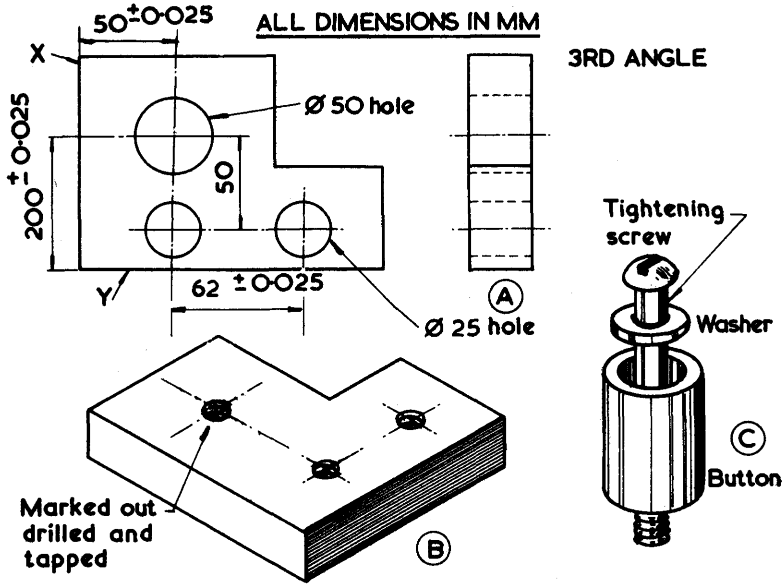


Fig. 5.3.—Application of Toolmaker's Buttons.

Fig. 5.3 illustrates a typical component requiring the use of a faceplate; it is required to bore the 50 mm diameter hole shown to within a tolerance of plus and minus 0·025 millimetres from the faces shown as X and Y in the diagram. Note also the two 25 mm diameter holes at a centre distance of 62 mm. We will see that it is the setting up that requires the skill, while the machining is a relatively simple affair.

Toolmaker's buttons

The use of toolmaker's buttons in conjunction with the faceplate of a centre lathe is an interesting example of the use of end standards and reference planes allied with turning techniques. Three buttons are required for the job shown in fig. 5.3, and the purpose of these buttons is to ensure that the linear dimensions are within the limits shown on the diagram, namely plus and minus 0·025 millimetres. Fig. 5.3B shows the preliminary operation of marking off the dimensions, drilling and tapping the three hole centres for the button-holding studs. The dimensional accuracy of the hole centres from the datum faces is not, at this stage, of great importance.

A typical button is shown at fig. 5.3C; note that considerable clearance exists between the diameter of the stud and the internal diameter of the button. Reference to fig. 5.4 will make clear the necessity for this clearance. Here we see the method of ensuring that the linear dimensions of the hole centres with respect to both centre distances and distances from the datum faces are held to very close limits. The 50 mm diameter hole is first dealt with.

The toolmaker's button is first positioned by lightly screwing down the nut; alternatively a long screw may be used. Toolmaker's buttons are hardened cylindrical steel bushes, available in sets of three or more, and of different lengths, but with outside diameters identical and to a specified size, say 20 mm.

Thus the distance from the face X to the centre of the toolmaker's button must be 50 mm minus one-half the button diameter:

$$50-\frac{20}{2} = 40 \text{ mm}$$

In the same way the distance of the button centre from the datum face Y will be:

$$200-10 = 190 \text{ mm}$$

The clearance of the stud or screw now permits adjustment of the button with the slip-gauge pile (190 mm) in the position shown in fig. 5.4A. When the

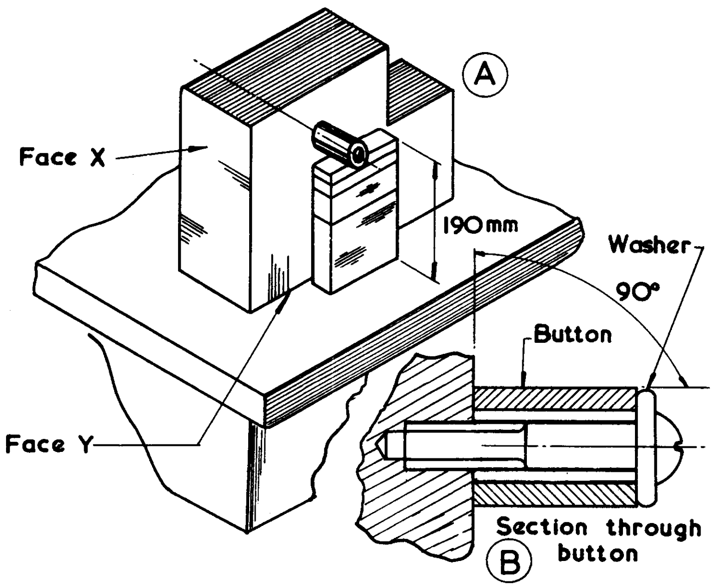


Fig. 5.4 —Method of Setting First Button.

feel of the slip pile between the button and the surface plate is to the satisfaction of the turner, the button is securely tightened in place and then carefully rechecked to ensure that no subsequent movement has occurred.

At fig. 5.4B is shown a sectional view of the button; it will be seen that an essential condition of accuracy is that the button faces be truly at 90° to the outside surface.

With the ultimate position for the 50 mm diameter hole assured by the precise location of the button, the two remaining holes may now be dealt with in a similar manner, as shown in fig. 5.5.

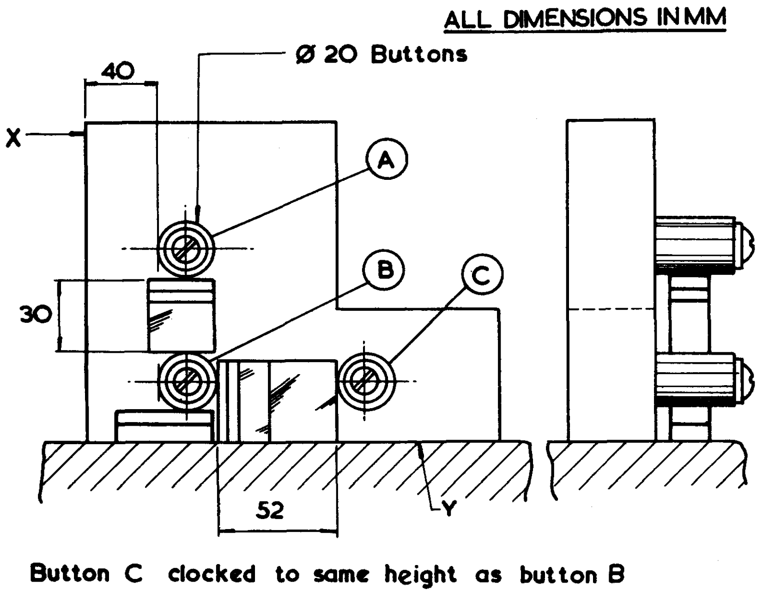


Fig. 5.5.—Toolmaker's Buttons in Position.

Boring the holes

The workpiece, with the three toolmaker's buttons securely attached, must now be clamped to the faceplate, and if the large-diameter hole is the first to be bored the centre of the button must lie on the centre line of the lathe. In other words the external surface of the button becomes a datum face and can be used to bring the centre of the button on the lathe centre line. This is done by using a dial indicator or **clocking** the button; the technique is shown in fig. 5.6. In this way the axis of the button coincides with the axis of rotation, provided the dial indicator pointer reads zero through one complete revolution of the work.

The button is now removed, the threaded hole opened out to within about 0·5 mm of finished size, a boring bar mounted in the tool post, and the hole bored to the finished size. The same procedure is repeated for each hole in turn, and provided the necessary care has been taken with respect to final checking of the buttons and clocking prior to drilling and boring, no trouble

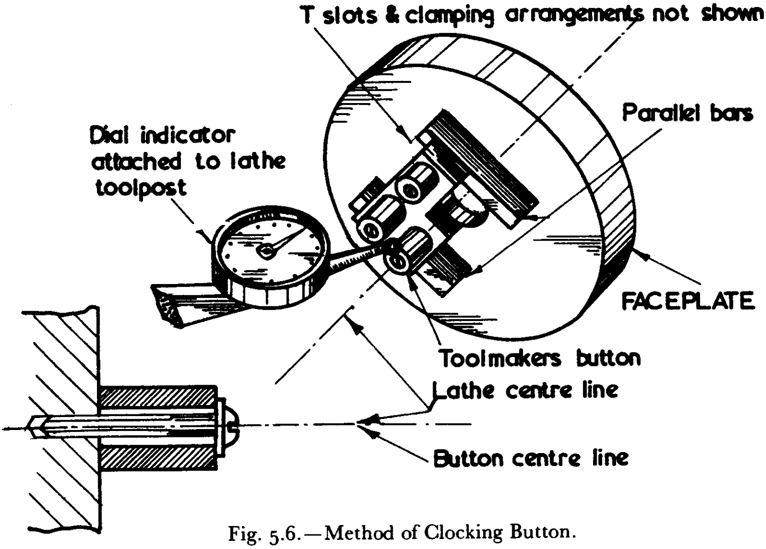


Fig. 5.6.—Method of Clocking Button.

will be experienced in keeping the linear dimensions to within plus and minus 0·025 millimetres.

Perhaps this example of the use of a lathe faceplate, together with the application of end standards or slip gauges, will serve to demonstrate not only the considerable skill required by the centre-lathe turner, but also the large amount of time occupied by setting up for the machining operation. If a large

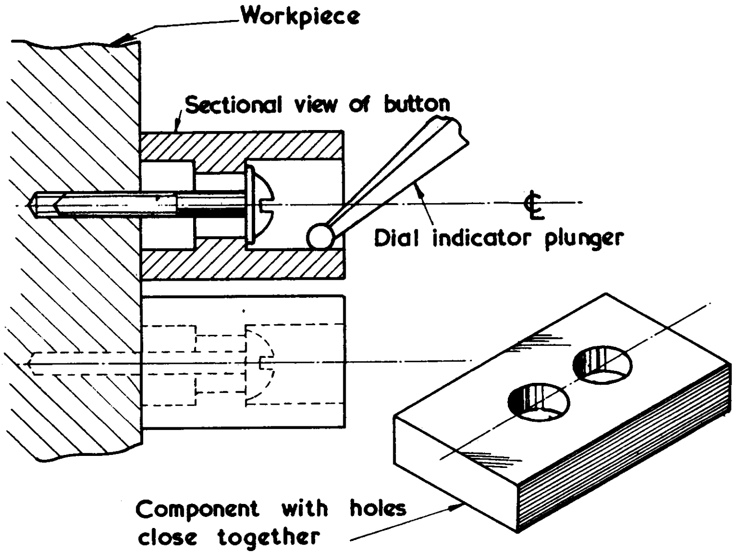


Fig. 5.7.—Technique for Close Proximity Holes.

number of holes were required to close limits of accuracy, then the time required to set up the work using toolmaker's buttons would be quite out of proportion to the machining time. To meet the need for accurate hole drilling in the minimum of time, machine tools called **jig borers** have been introduced.

Before leaving the subject of button boring it must be mentioned that when holes are close together considerable difficulty may be experienced when attempting to clock the buttons. To overcome this the buttons are available in different lengths, or alternatively they may have the section shown in fig. 5.7; note the close proximity of the two holes. The clocking of the buttons is now achieved by locating the plunger of the dial indicator on the internal cylindrical surface of the button, which is of course concentric with the outside diameter.

Faceplate balancing

Reference back to the set-up illustrated in fig. 5.6 shows that the faceplate carries a considerable mass of equipment; in addition to the component and parallel bars shown, it is also necessary to make use of suitable clamps and clamping bolts. Fig. 5.8 shows a plan view of the faceplate with the set-up for button boring. Note that the faceplate is out of balance owing to the fact that the mass of the parts used in the set-up is not distributed evenly about the lathe centre line.

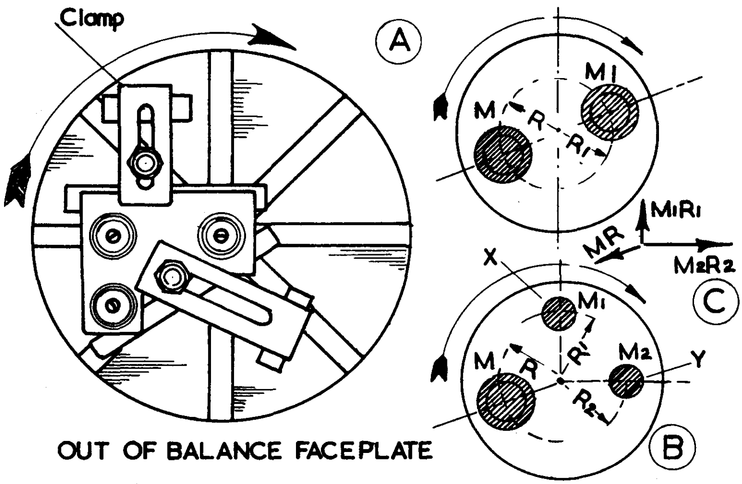


Fig. 5.8.—Principle underlying Faceplate Balancing.

Rotation of the faceplate under these conditions of unequal balancing is not only damaging to the spindle bearings but also dangerous to the operator. Added to these most undesirable features we have the vibration caused, which will be transmitted to the surface of the bored holes, resulting in a poor finish. The use of balancing masses eliminates all the unwanted characteristics of an unbalanced faceplate; the technique is shown in fig. 5.8. With the spindle set in the neutral position so that it rotates freely, masses are either added to or taken from the positions shown at X and Y until the faceplate has the tendency to stop in different positions after being given a swing by hand.

If the faceplate comes to rest in the same position after repeated swings it is a sure indication that a condition of unbalance still exists. It is possible, though very seldom done in practice, to calculate the amount and position of the balancing masses required to balance a set-up or a casting of which the mass and centre of gravity are both known.

Thus fig. 5.8A shows the out-of-balance effect as being equal to $M \times r$. Provided the value M is known in kilograms it is a relatively simple matter to calculate either of two things:

(i) the distance from the centre at which to put a balancing mass of known value,

(ii) the amount of the balancing mass to be put at a given centre distance.

With the balancing mass placed directly opposite to the out-of-balance force as shown in the diagram, the following formula may be used:

$$M \times r = M_1 \times r_1$$

With M, r, and M_1 known it is a simple matter to calculate the distance from the centre at which to put the known balancing mass. Alternatively the method shown at fig. 5.8B may be adopted if two balance masses are to be used. Let M represent the out-of-balance force acting at a distance R from the faceplate centre. It is required to balance this force by clamping two masses as shown in the diagram; the angle between the two masses is 90°, as can be seen. The following information is known:

Mass of set-up acting at its centre of gravity	M	= 30 kg
Distance of M from faceplate centre		= 280 mm
Mass of balance mass M_1		= 30 kg
Mass of balance mass M_2		= 35 kg

It is required to calculate the distances at which to clamp the balance masses M_1 and M_2, for with these distances known the time required to balance the faceplate is very much reduced.

Use of a vector diagram

Vector diagrams are an application of scientific principles. Their practical value may be appreciated if we consider the problems encountered when attempting to balance a lathe faceplate.

The out-of-balance force caused by a rotating set-up similar to that shown in fig. 5.8 is proportional to the mass and its distance from the lathe centre line, the out-of-balance force acting outwards from the centre. A simple force diagram is shown in fig. 5.8C; note that the three forces are in equilibrium and that they are represented by product of the mass and its distance from the centre.

A vector diagram may now be constructed by drawing to a suitable scale three lines representing the direction and magnitude of each product of mass and distance. This diagram is illustrated in fig. 5.9. The vector *ab* is drawn at 30° to the horizontal and to a scale of (say) 1 : 100. This vector represents the out-of-balance force of the casting, which is equivalent to *Mr* or 30 × 280 = 8400 kg mm.

Referring back to fig. 5.8B the reader will see that a balancing mass is shown in the vertical position, or at an angle of 120° to the centre of gravity of the casting. The out-of-balance effect produced by this 30 kg mass (M_1) is represented vectorially by drawing a vertical line through b, as shown in the diagram.

A similar procedure is adopted for the second balancing mass of 35 kg (M_2). As can be seen, this weight is at 90° to M_1, and can be represented vectorially by drawing a horizontal line through b in the vector diagram, meeting the previously drawn vector at c. This completes the construction of our vector diagram.

It is now possible, with the aid of this diagram, to calculate the distances at which to place the balancing masses M_1 and M_2. Careful measurement of both vectors and conversion to actual units gives the out-of-balance effect in each case. Thus for the mass M_1 the out-of-balance effect is $42 \times 100 = 4200$

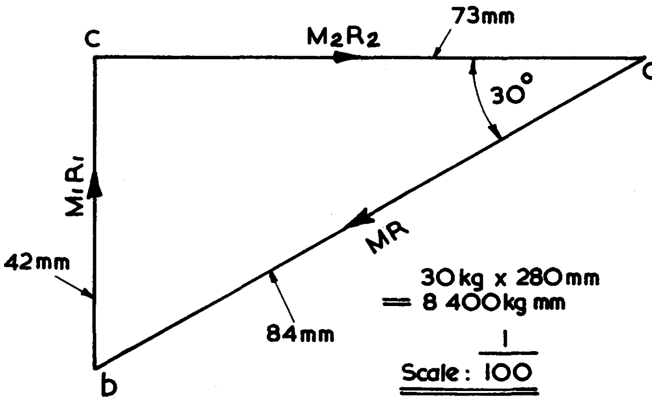


Fig. 5.9.—Vector Diagram.

kg mm, because on measurement bc is found to be 42 mm. Similarly, for M_2 it is $73 \times 100 = 7300$ kg mm, since ca measures 73 mm.

Now we know that

$$M_1 \times R_1 = 4200$$

so that

$$R_1 = \frac{4200}{30} = 140 \text{ mm}$$

and

$$M_2 \times R_2 = 7300$$

so that

$$R_2 = \frac{7300}{35} = 208{\cdot}3 \text{ mm}$$

The balancing masses are now clamped as follows:

the 30 kg mass at a radius of 140 mm,

the 35 kg mass at a radius of 208·3 mm.

Reference back to fig. 5.8B will show the positions for these two masses. Remember that the mass of the casting to be balanced acts at the centre of gravity of the casting.

5.4.3 Centres

We have seen that the use of a faceplate as a work-holding device involves the centre-lathe turner in considerable setting of the work to be turned. This is true also for the use of a four-jaw chuck, and if the turned work is to be passed on for further machining (such as milling or grinding) it is certain that centres will be used as a work-holding device. Not only do the centres offer a means of holding the work, but they also provide datum or location points, permitting the rapid setting up of work to be turned. A typical component requiring the use of centres is shown in fig. 5.10A. This is a splined gear shaft with turned diameters, milled splines and milled gear teeth. For each of the machining operations given above, the centres will provide the location and work-holding points; in this way concentricity of the turned diameters, the splines and the gear teeth is assured.

Because the centres are the datum points or faces it is essential that they be carefully machined, and fig. 5.10B shows a simple sectional view of one end of the splined shaft. Note the small recessed diameter; this helps to prevent damage to the bearing surfaces of the centre. A good finish is required on the bearing surface shown as *aa* in fig. 5.10C. When the centre is being machined an excellent finish will result if the centre drill is allowed to dwell after the drill is taken to depth, with an adequate supply of cutting fluid supplied to the drill point. Should the component be case-hardened it is a good plan to lap the centres carefully, using a short length of copper rod. One end of this rod may be turned to 60°, as shown in fig. 5.11A; a small drilling machine is quite suitable for the lapping operation, and a smooth-grade lapping compound is needed. The technique is illustrated in fig. 5.11B, and is to be carried out after the case-hardening of the turned blank.

If the part cannot be easily supported on the drilling-machine table it is a

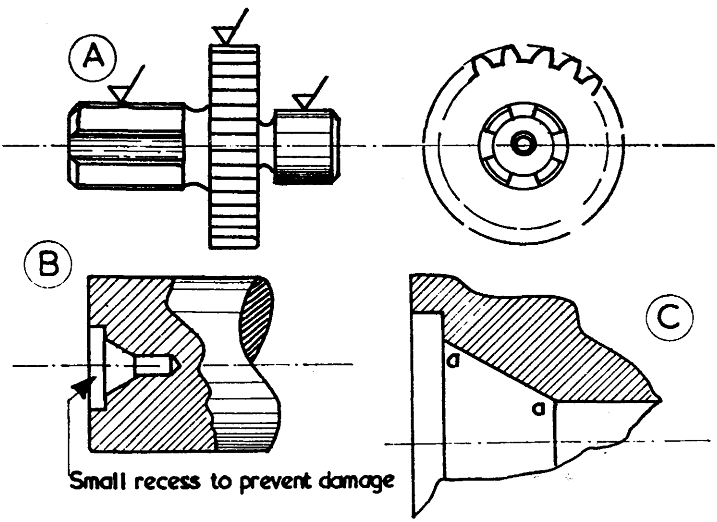


Fig. 5.10.—Application and Details of Centres.

simple matter to hold the copper lap in a suitable collet inserted in the spindle of a centre lathe. With the other end of the component located in the tailstock centre, the part may be held in the hand and gently brought up to the revolving lap, the movement being brought about by rotation of the tailstock hand wheel. This technique is illustrated in fig. 5.11C.

It will be clear from the example given that the use of centres is limited to components of solid section, although special devices are available for the support of components having drilled or bored holes. When the hole or bore is large enough, the principle of turning between centres is extended by the use of a suitable **mandrel.**

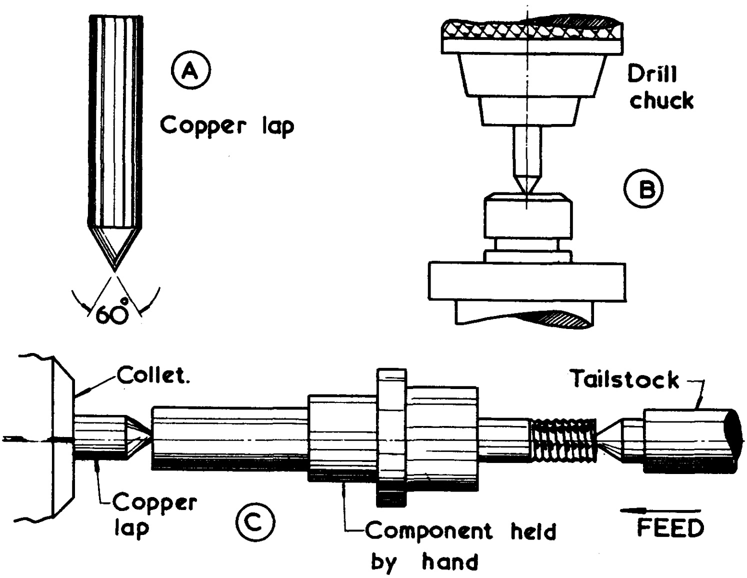


Fig. 5.11.—Methods of Lapping Centres.

5.4.4 Mandrels

Mandrels are work-holding devices having the additional advantage of precise location; this is provided by accurate centres at both ends. Their main use is to allow the machining of outside diameters or the cutting of threads concentric with a previously bored hole. All mandrels should be made from tool steel suitably hardened and tempered, although there is no objection to the use of a case-hardening mild steel. Several types of mandrels are available, depending on the method adopted to hold or grip the workpiece. Some simple types are illustrated in fig. 5.12, together with typical applications. Remember that a mandrel is a precision work-holding device and must be treated as such. The bearing surface must be free from damage or burrs, while the centres must be kept clean and in good condition. The use of a friction mandrel demands considerable care. If the fit is too tight and undue force is used to assemble the component, scoring and misalignment of the bore are likely

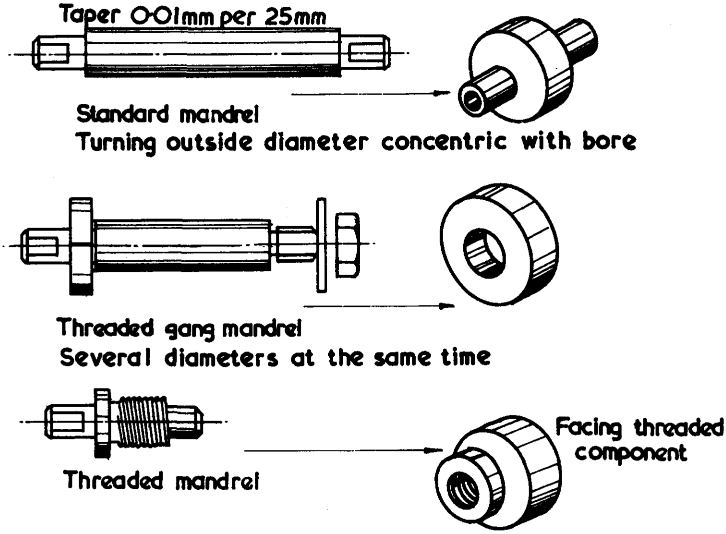


Fig. 5.12.—Applications of Mandrels.

to result, with the attendant possibility of rejection of the finished component. The application of a little oil to the surface of the mandrel is always a wise precaution.

5·5 Screw cutting

The cutting of screw threads is an accepted part of the work of a centre-lathe turner. All modern lathes are fitted with gearboxes, allowing a wide and

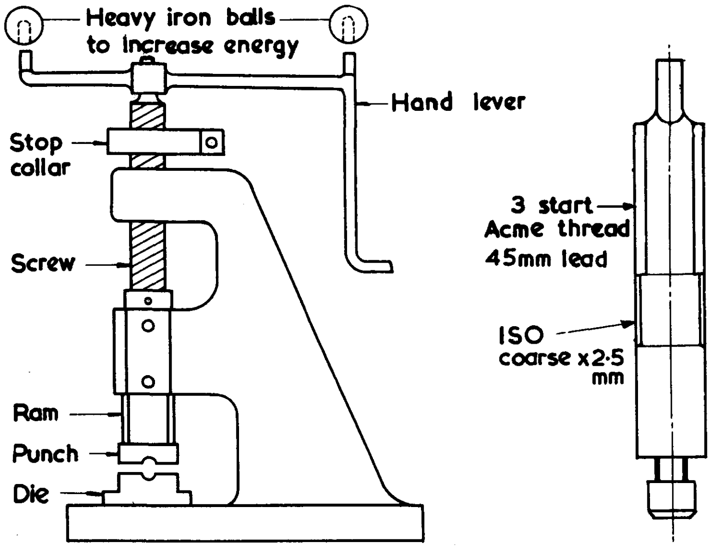


Fig. 5.13.—Fly Press and Fly Press Leadscrew.

instant choice of both English and metric pitches to be selected merely by the movement of gear handles. It may be, however, that an awkward pitch or multi-start thread may require cutting, and the following example will serve to illustrate the considerable knowledge and skill involved.

Fig. 5.13 shows the screw of a small fly press; the principle of the fly press or hand press is also shown in fig. 5.13, and it will be seen that rotation of the hand lever by the operator provides vertical movement of the ram. This type of press is much used for small-capacity work, and it is important that a considerable vertical movement of the ram results from each revolution of the hand lever if the operator is to be relieved from undue effort. This means that a large or coarse-pitch thread is required, and as the thread is required to transmit motion, a square or Acme form is essential. Note that a single-start thread of ISO coarse form and having a pitch of 25 mm is also required; the purpose of this thread is to allow secure clamping of the stop collar, thus controlling the setting of the punch for depth.

5.5.1 The need for a multi-start thread

We have seen that a coarse thread pitch is essential if the time and energy to be expended by the operator are to be kept to a minimum. It is important to appreciate that the depth of thread is proportionate to the pitch; the coarser

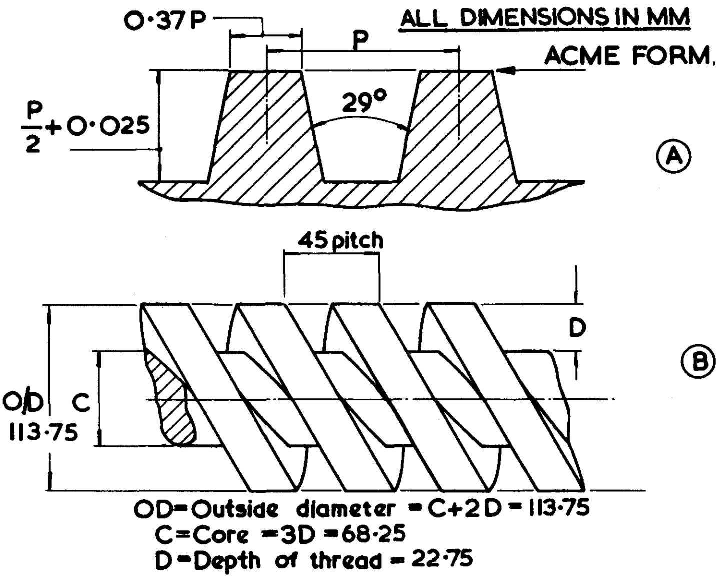


Fig. 5.14.—Single-start Thread.

the pitch, the deeper will be the thread depth. With a single-start thread this would tend to produce severe weakening of the screw, which can be avoided only by increase in diameter. Fig. 5.14 shows the effect of cutting a single-start thread of 45 mm pitch, which is the pitch required for the screw of the fly press. It will be seen that the thread proportions for an Acme thread are such that the depth of thread is equal to one-half the pitch plus 0·25 mm.

At. fig. 5.14B we have made the core diameter equivalent to three times the depth of thread in order to produce a screw of reasonable strength. Reference to the calculations given makes it clear that the outside diameter of the screw will be 113·75 mm. Clearly this diameter is out of all proportion to the application of this screw to a simple fly press; yet if a single-start thread is specified, reduction of this outside diameter will result in serious weakening of the screw. In cases such as this a multi-start thread allows the requirement of a coarse pitch to be reconciled with that of a reasonable outside diameter.

5.5.2 Lead and pitch

The **lead** of a thread is the distance moved for each complete revolution of the screwed member; the **pitch** is the distance between equivalent points on a thread form. For a single-start thread the lead is therefore equal to the pitch. Fig. 5.15A illustrates the set-up for cutting the first start; note that the movement of the tool for one revolution of the work is 45 mm, and this is the lead of the thread.

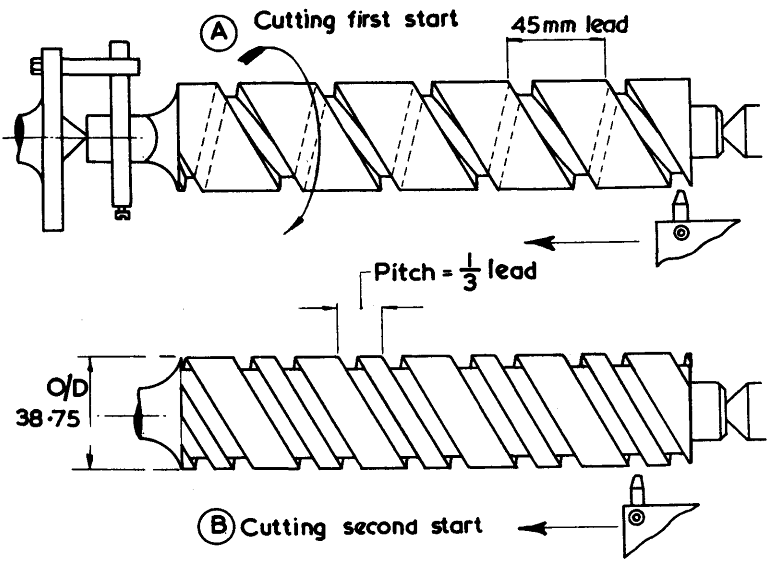


Fig. 5.15.—Cutting First and Second Starts.

5.5.3 Calculating the change gears

The calculation of the change gears is a simple matter provided the correct formula is used:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{\text{lead to be cut}}{\text{pitch of leadscrew}}$$

Assuming that the lathe leadscrew has a pitch of 5 mm, then

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{45}{5} = \frac{9}{1}$$
$$= \frac{3}{1} \times \frac{3}{1}$$
$$= \frac{60}{20} \times \frac{90}{30}$$

A compound train of gears can be made up, having 60- and 90- tooth drivers with 20- and 30- tooth driven gears.

5.5.4 Calculating the depth of thread

Reference back to fig. 5.15B shows the fly-press leadscrew with the second start cut. Note that the pitch is equivalent to one-third of the lead, for

$$\text{Pitch} = \frac{\text{lead of thread}}{\text{number of starts}}$$

The pitch in this instance is therefore one-third of 45 mm, which is 15 mm. The depth of thread of the three-start fly-press leadscrew can now be calculated from the formula:

$$\text{Depth of thread} = \frac{\text{pitch}}{2} + 0{\cdot}25 \text{ mm}$$
$$= \frac{15}{2} + 0{\cdot}25 \text{ mm}$$
$$= 7{\cdot}5 + 0{\cdot}25 \text{ mm}$$
$$= 7{\cdot}75 \text{ mm}$$

If we maintain the same proportions as we gave earlier when considering the making of a single-start 45 mm pitch leadscrew, namely having the core diameter equal to three times the depth of thread, the following will be the calculations for the outside diameter.

Let depth of thread $= d$

Then core diameter $= 3d$

and outside diameter $= \text{core diameter} + 2d$

$$= 3d + 2d$$
$$= 5d$$
$$= 5 \times 7{\cdot}75 \text{ mm}$$
$$= 38{\cdot}75 \text{ mm}$$

The advantage of multiple or multi-start threads will now be clear. If we had made our fly-press leadscrew by cutting a single-start thread of 45 mm pitch we should have had to use a 120 mm diameter bar, whereas if we cut a three-start thread we can use a 40 mm diameter bar.

5.5.5 Locating the starts

It is essential that the centre-lathe turner starts each cut in its correct position; that is to say, the pitch of the thread must be precisely 15 mm. This means that, having cut the first start, we must now move the tool a distance of 15 mm towards the headstock of the lathe.

There are several ways of achieving this accurate linear movement, and perhaps the simplest method is to index the compound slide forward a distance of 15 mm. This is easily achieved with the aid of the indexing dial, and it is a simple matter to check this movement using a dial indicator secured to the toolpost or lathe bed. Care must be taken to ensure that all backlash is removed prior to cutting the first start.

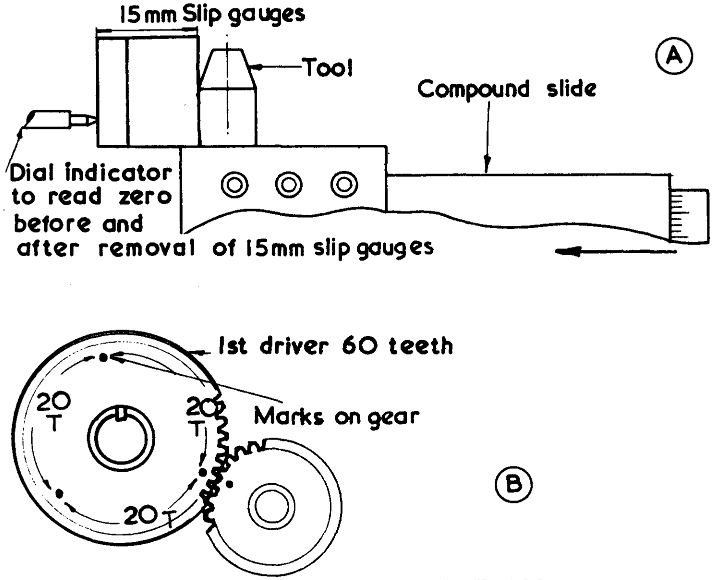


Fig. 5.16.—Methods of obtaining Precise Tool Movement.

Another method is to mark one of the teeth of the first driving gear against its mating position with the first driven gear. An indelible pencil or chalk mark will suffice. At the completion of the first start, the first driver is removed and the lathe spindle carefully rotated until the driving gear can be replaced exactly one-third of a revolution from the first position. Clearly it is necessary that the number of teeth in the driving gear be a multiple of three; for example, if the compound train earlier calculated is used, then the first driver will have 60 teeth, allowing the gear to be marked at intervals of twenty teeth. The two techniques described are simply illustrated in fig. 5.16.

5.5.6 Grinding and setting of the cutting tool

Considerable care is also required from the turner when grinding and setting the cutting tool that is to produce the Acme thread. Fig. 5.17 illustrates the correct relationship between the tool section and the lathe centre line when viewed in the vertical plane. It will be seen that the helix angle, shown as θ in the diagram, needs to be calculated if the cutting tool is to be ground with the correct clearance angles; note also that the top face of the tool requires grinding so that it is at 90° to the helix angle of the thread. Once again a knowledge of trigonometry is required; the relevant calculations are given below.

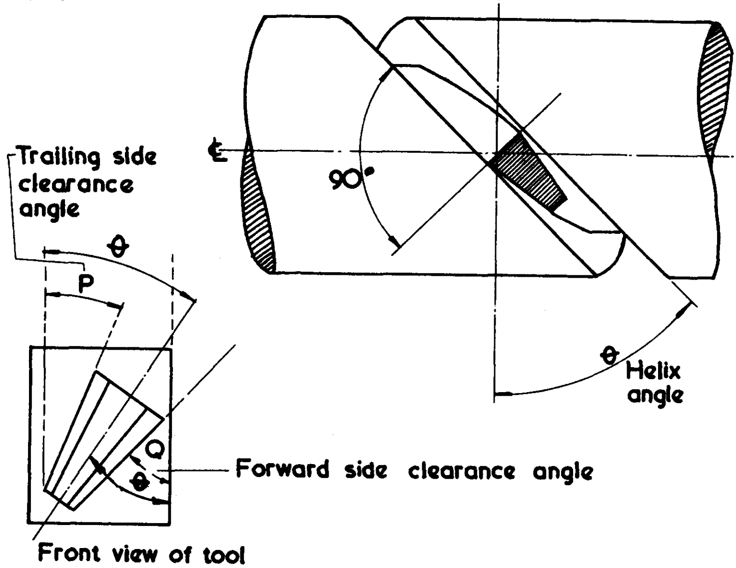


Fig. 5.17.—Effect of Helix Angle on Tool Shape.

5.5.7 Calculating the helix angle

Fig. 5.18A shows a cylinder which represents the lead of the thread at the core diameter. At B we see a development of this cylinder, from which it may be deduced that if the helix angle is equal to θ, then

$$\tan \theta = \frac{\text{lead}}{\pi d}$$

where d = core diameter of thread.

If a clearance angle of 8° is required for both the forward and trailing sides of the thread cutting tool, then the following formulae may be used.

$$\text{Forward clearance angle} = \left(\tan^{-1} \frac{\text{lead}}{\pi d}\right) + 8^\circ$$

$$\text{Trailing clearance angle} = \left(\tan^{-1} \frac{\text{lead}}{\pi d}\right) - 8^\circ$$

(Note: $\tan^{-1}$ is an expression or symbol for "the angle whose tangent is".)

The clearance angles are indicated in fig. 5.17B, where the forward clearance angle is shown as Q, while the trailing clearance angle is shown as P. Remember that the view shown is a front elevation of the cutting tool; when it is set in the lathe the operator or lathe turner has a reverse view of the tool.

Although the example of a multiple or multi-start thread given in the preceding text may be considered as fairly extreme, producing a relatively fast or coarse-pitch thread, it should be clear that the cutting on a centre lathe of square or Acme threads, whether single- or multi-start, requires considerable care with respect to the calculation and subsequent grinding of the cutting-tool angles.

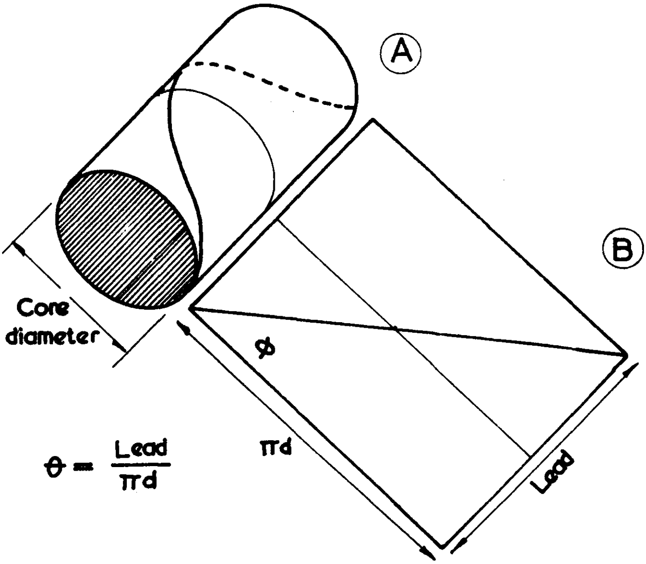


Fig. 5.18.—Calculation of Helix Angle.

5.6 Vertical boring machines

Although the centre lathe may be considered as the most versatile of all the machine tools, it suffers from the disadvantage that large or heavy work requiring the use of the faceplate as a work-holding device poses a difficult problem to the centre-lathe turner, when one considers the difficulty of lift-int a heavy casting and clamping it to a vertical reference plane. Added to this there is the undesirable feature of deflection caused to the lathe spindle owing to the unsupported weight of the casting. These factors have led to the

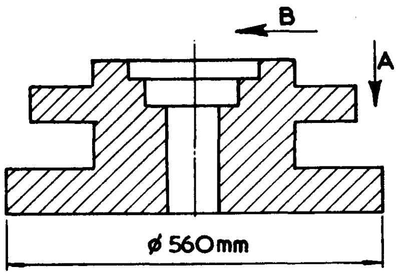


Fig. 5.19.—Typical Component suitable for Vertical Boring.

introduction of vertical boring machines, or vertical boring mills as they are more commonly called.

In principle a vertical boring mill may be considered as a vertical centre lathe, with a large faceplate mounted in a horizontal position. With the faceplate in this position the loading and clamping of heavy work is greatly simplified, leading to safer working conditions for the operator, together with

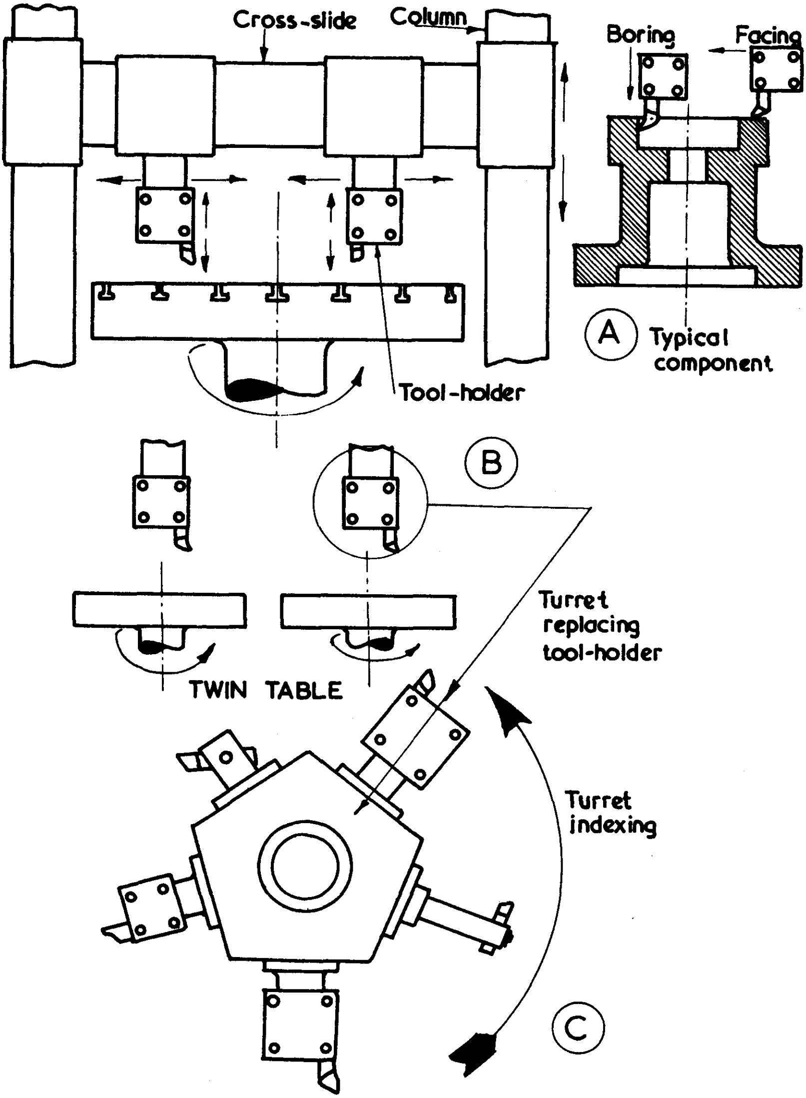


Fig. 5.20.—Vertical Boring Techniques.

much reduction in the time required to set up the work. The weight of the work to be machined is now taken directly by the bearing surfaces of the faceplate or worktable, with no forces causing spindle deflection. Thus a vertical boring mill is well suited for the machining of both internal and external cylindrical surfaces on large components.

Such a component is illustrated in fig. 5.19; it will be seen that a tool movement vertically in the direction of arrow A is required for the machining of the external cylindrical surfaces, together with the internal cylindrical surfaces or bores. The plane surfaces will require movement of the cutting tool in a horizontal plane, as shown by arrow B.

5.6.1 Types of boring mill

The standard vertical boring mill is illustrated in simple form in fig. 5.20A. This type of machine is much used for medium to large work; it has two tooling stations, allowing the machining of bores and external turning to take place simultaneously. Each tool post is carried on a rigid ram capable of vertical traverse under either manual or automatic feed. Both rams have independent movement along the cross-slide, with a range of automatic feeds. Slides are provided on the vertical columns, allowing the raising or lowering of the cross-slide to accommodate work of different sizes. The capacities of these machines vary; the larger sizes represent some of the biggest machine tools in use, having worktables up to 8 metres diameter, and a working height of about 5 metres.

5.6.2 Duplex boring mill

A serious limitation of the boring mill just described is that the rotation of the worktable cannot be at the optimum revolutions per minute to suit two differing machining operations. If we refer to fig. 5.20A, it is evident that a considerable variation exists between the diameter of the work undergoing boring and that undergoing facing. If the cutting speed is correct (say) for boring, then this same speed will be much too slow for facing, and the efficiency of machining will be reduced.

The duplex boring mill avoids this defect by employing two worktables, together with two tooling stations. It is important to appreciate that each ram is provided with separate driving and feeding arrangements, allowing the correct feed to be applied to suit the actual machining condition. The principle underlying the duplex boring mill is shown in fig. 5.20B.

5.6.3 Vertical turret lathe

Although called a vertical turret lathe, this machine tool is essentially a close relative of the boring mill. The advantages possessed by these machines consist in the provision of a multi-tooling device, more commonly known as a **turret.** This principle of multi-tooling is a necessary condition if efficient machining is to be achieved. The time taken to remove and replace a cutting tool can be considered as lost or unproductive, and perhaps the reader may have observed that all the machine tools so far described have been equipped with simple tool posts. While a 4-way tool post permits the presentation of four tools to the workpiece, it is very seldom that the tools are set in position in these tool posts.

The great advantage possessed by a turret tooling device is that the tools can be set in position and then indexed to the work in sequence. This allows the rapid and efficient machining of medium-sized components that require several machining operations, and we shall see, in the next chapter on turret and capstan lathes, the very considerable advantages offered by the correct application of turret tooling.

Fig. 5.20C shows a typical turret as fitted to the duplex boring and turning mill illustrated in fig. 5.20B. Note that more than one tool may be accommodated in the tool-box; although the turret has five tooling stations, more than five tools can be presented to the work. Each tool is presented to the workpiece by rotation of the turret, which indexes in a precise manner. This principle is ideal for the batch production of small to medium-sized components that require several operations on both external and internal faces.

Summary

If a small number of cylindrical formed workpieces are to be machined to close limits, the centre lathe cannot be equalled for this type of work. The advent of the axial flow jet engine has tended to re-assert the importance of the lathe as a machine tool, for engines of this type are required in relatively small numbers, necessitating the manufacture of the component parts in small batches. Although it is true that the lathes used for this purpose are of the turret or capstan type, the general principle of operation remains the same; namely the presentation of a cutting tool to the rotating work.

The great disadvantage of the centre lathe lies in the small number of tooling stations, and much of the time of the centre-lathe turner is taken up in removal, replacement and tool setting. We must also remember that linear control of the cutting tool is the responsibility of the turner; only with skilled and careful use of the indexing dials can diameters be held to within, say, plus and minus 0·02 millimetres. Yet we have seen that provided the turner is skilled and competent, he is able, with the aid of toolmakers' buttons and slip gauges, to bore holes to accuracies almost comparable with those obtained when using a jig-boring machine.

He can also screw-cut single or multiple threads, and may choose either chucks, collets or centres as methods of work holding. It cannot be emphasised too strongly that the efficient use of a centre lathe demands a craftsman of the highest order. It is unfortunate that about 40 to 60% of his time is spent in unproductive work—in tool changing and setting, and in the skimming of diameters to establish datums. This has led to the use of capstan and turret lathes, and we shall deal with these in the next chapter. Finally the machining of large cylindrical work requires the use of vertical boring mills. The weight of the work acts axially along the spindle, and there is no tendency for spindle deflection. At the same time the loading and clamping of the work are greatly simplified. Several types of boring mills are in use, and we have seen for the first time the introduction of the turret as a device enabling the adoption of the multi-tooling principle.

EXERCISE 5

1 With a typical example, illustrate an application of each of the following workholding devices with respect to centre-lathe work:

(i) faceplate,
(ii) collet-type chuck,
(iii) two-jaw chuck.

2 Describe in some detail a sequence of operations for the machining of the component shown in fig. 5.21 at a centre lathe.

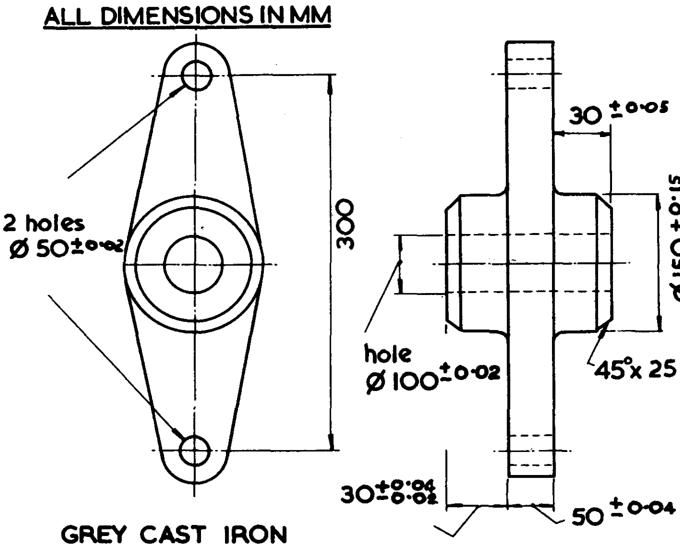


Fig. 5.21.

3 Using a component of your own choice, illustrate the technique known as button boring. State the degree of accuracy expected, and explain why this method of machining holes to accurate dimensions is seldom adopted.

4 Why is it essential to ensure that a lathe faceplate set-up for button boring is accurately balanced? Using a vector diagram, calculate the distance from the lathe centre at which two 40 kg masses at an angle of 120° must be placed, so that a set-up of 120 kg acting at 250 mm from the lathe centre is accurately balanced.

5 With components of your own choice, illustrate the application of three different types of lathe mandrels. What precautions must be taken when using a friction mandrel?

6 A square thread having two starts of 12 mm pitch and an outside diameter of 50 mm is to be machined on a centre lathe with a leadscrew of 5 mm pitch.

Calculate the following:

(i) depth of thread,
(ii) lead of thread,
(iii) core diameter,
(iv) helix angle.

7 Make a neat front elevation of the cutting tool required to cut the square thread described in question 6, and insert, after suitable calculation, the clearance angle for both leading and trailing sides of the tool. (Note: angle to be calculated from top face of tool.)

8 Explain why centre lathes are seldom used for the machining of relatively heavy castings.

9 With a simple diagram, illustrate the principle of a vertical boring and turning mill. Sketch, giving approximate dimensions, a typical component that would be suitable for machining on a vertical boring mill.

10 What are the disadvantages of a two-head, single-table vertical boring mill, equipped with standard-type tool posts? Explain how the principle of multiple or multi-tooling is achieved on a duplex vertical boring mill, and state also the advantages to be gained when machining fairly large numbers of medium-sized cylindrical formed components.

6 Turret and Capstan Lathes

6.1 Introduction

We have seen, in our short discussion on the centre lathe in the previous chapter, that considerable skill and knowledge are required by the centre-lathe turner if he is to obtain the best results from his machine tool. Yet the actual time taken in the application of this skill and knowledge, namely the setting up of the workpiece and the cutting tools, constitutes unproductive time. We must not forget that a machine tool is a power-driven apparatus designed to produce geometrical surfaces, with metal being removed in most cases. If it is to operate under ideal conditions, then as much as possible of its time must be spent in removal of metal.

It is clear that this fact was appreciated as far back as 1855, at least in the United States of America, where fully developed turret lathes were used for the manufacture of guns. It is worthwhile to recall at this stage the remarks made in an earlier chapter with regard to the manufacture of muskets having completely interchangeable parts. Before attempting to establish and maintain a system of dimensional control using measuring instruments or limit gauges, it is first necessary to have machine tools capable of producing the component parts to the required accuracy. This accuracy concerns not only the geometrical surfaces of components but also their linear and angular dimensions. Of equal importance is the fact that the machine tools must produce the parts economically; that is to say at high production rates and using unskilled or semi-skilled operators. Experience suggests that on the average about 50% of the time spent in producing a component at a centre lathe is unproductive; this is owing to the necessity for continual tool changing and setting. It is clear that if very large numbers of cylindrical shaped components are required, such as are to be found in the moving parts of pistols and guns, the centre lathe must be replaced as a production machine tool.

6.2 Turret and capstan lathes

The purpose of turret and capstan lathes is to produce, with the aid of relatively unskilled labour, large numbers of repetitive parts of cylindrical shape to within the dimensional limits required. This is achieved by equipping both turret and capstan lathes with additional tooling stations, thus permitting the setting up of enough tools to complete the whole of the machining operation. These additional tooling stations are provided by a device known as a **turret.** The mobility of this turret determines whether the lathe is described as a turret or a capstan lathe. Perhaps a quick look at the sort of components likely to be produced will assist in differentiating between these two machine tools.

6.2.1 The turret lathe

Fig. 6.1 shows a component to be used in the undercarriage of an aircraft. The first batch is of 200 components; all dimensions are to within fairly close limits, and the surfaces are required to have a fine tool finish. Note the overall length of this component. The turret lathe is designed especially for relatively large work, and this is achieved by allowing a hexagonal turret to be indexed

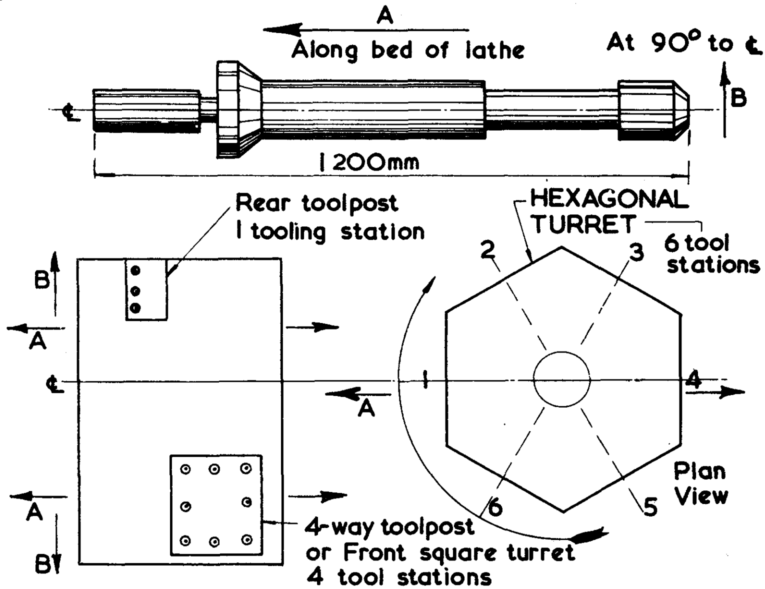


Fig. 6.1.—Tooling Stations on a Turret Lathe.

to the revolving workpiece. This turret is mounted on a carriage which is able to traverse the **whole** length of the lathe bed; this movement is indicated on fig. 6.1 by the arrow A. A turret lathe is also equipped with a front tool post, or square turret as it is sometimes called, together with a rear tool post. Both front and rear tool posts are mounted on a cross slide, and have movement at 90° to the lathe centre line. If the slide carrying the front tool post is equipped with automatic feed the machine is known as a **combination** turret lathe. Note that the turret lathe has **eleven** tooling stations. There are six positions on the hexagonal turret, four positions on the front tool post, and one position on the rear tool post.

It is possible for a skilled turret-lathe turner not only to set the cutting tools in position accurately, but also to set and adjust **stops** so that control can be maintained over linear dimensions when several identical components are required.

A simple outline drawing of a turret lathe is shown in fig. 6.2; note the great similarity to a centre lathe. As already stated, the main difference consists in the replacement of the loose headstock or tailstock by a hexagonal turret. Mounted, as can be seen, on its own carriage or saddle, this turret is capable of movement along the bed of the lathe under either manual or automatic feed. At the end of one machining operation the turret can be rotated or indexed in a positive manner, and a fresh tooling device presented to the work.

Provided the movements of the cutting tool have been controlled with the accurate setting of adjustable stops or indicating dials, the greater part of the working time is now spent on the removal of metal.

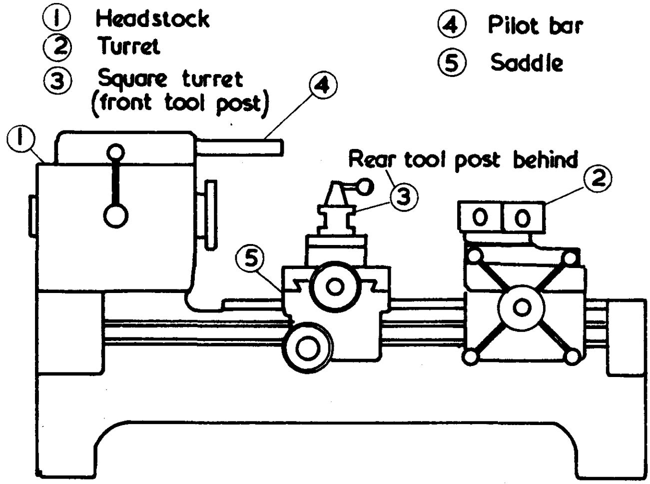
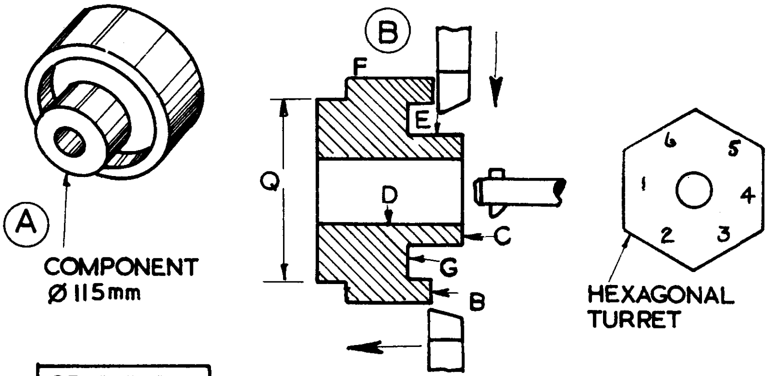


Fig. 6.2.—Elements of the Turret Lathe.

6.2.2 The capstan lathe

We have seen that the best use of a turret lathe is for the machining of fairly large components. There are many instances, however, when very large numbers of small to medium-size components are to be machined from standard bar or rod. This work is best done by a **capstan** lathe. Reference to the component shown in fig. 6.3A will indicate clearly the different technique adopted in the design and utilisation of the capstan lathe.

The component shown is a phosphor-bronze wormwheel casting, previously illustrated in fig. 4.1 when the use of high-efficiency cutting tools was being discussed. The floor-to-floor time for this component when machined on a capstan lathe is approximately 1·6 minutes, with tolerances of plus and minus 0·01 millimetres maintained on the bore. It can be seen that relatively short movements of the cutting tool are required for this component; the overall length of the casting does not exceed 45 mm. This is further shown in outline in fig. 6.3B, which also includes a brief description of the operations required and the tool positions. Note that the front tool post or square turret is not used. The facing of the faces C and B is achieved with the use of the reverse tool post, while all the other turning and boring is carried out from the hexagonal turret.



OPERATION	
Chuck on diameter Q	
Rough faces B & C	Rear toolpost
Rough turn D E G F	Hex. Turret 1
Finish turn D E G F	Hex. Turret 2
Bore D	Hex. Turret 3
Remove	

FLOOR
TO FLOOR
TIME
1·6 MINUTES

Fig. 6.3.—Machining Technique on a Capstan Lathe.

For small lengths of traverse such as are present on the phosphor-bronze casting, only relatively short movements are required from the tools situated in the hexagonal turret.

Fig. 6.4 shows the arrangement for the location of the turret on a capstan lathe. Note that the turret is mounted on a slide which is clamped to the bed of the capstan lathe. This restricts the movement of the turret along its slide

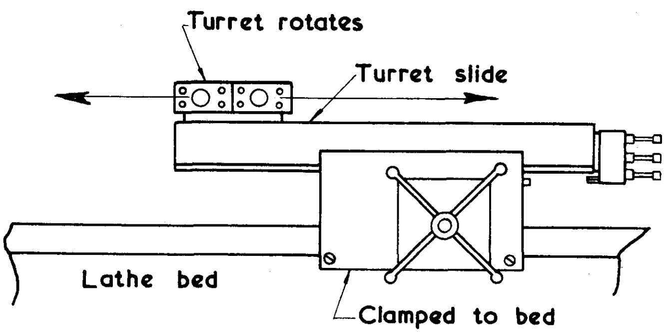


Fig. 6.4.—Details of the Capstan Lathe Turret.

to several centimetres as long as the slide is clamped in position. While the turret lathe has a capacity limited only by the length of the bed, all capstan lathes have a fixed capacity with regard to the maximum and minimum movements possible from the tooling arrangements in the hexagonal turret. It must be remembered that capstan lathes, like centre lathes, are available in a range of sizes or capacities.

6.3 Control of dimensions

All turret and capstan lathes are fitted with devices that permit fairly close control over the linear dimensions of length or diameter, and the type of device fitted varies a great deal from machine to machine. In general, however, it may be said that the following principles form the foundation on which most of the dimensional control devices are based.

6.3.1 The use of stops

Stops are widely used to obtain repetitive dimensions on similar components produced on capstan lathes by relatively unskilled operators. A popular type of adjustable stop is illustrated in fig. 6.5. The movement of the hexagonal turret along its slide is controlled by adjustment of the threaded screw, which is locked in position by the locking nut. For each turret position

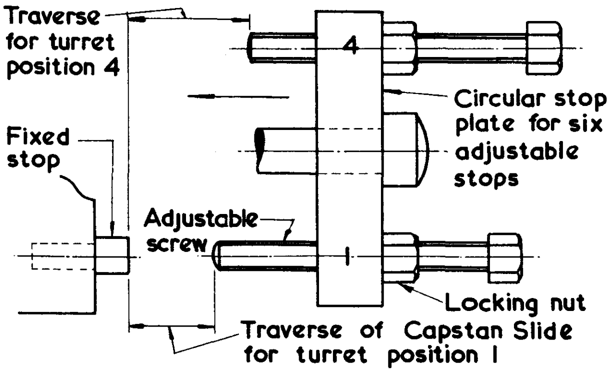


Fig. 6.5.—Turret Stops.

there is a stop available; each stop is presented in the correct position relative to the fixed stop by rotation of a circular plate, actuated by the rotation or indexing of the hexagonal turret.

It is the capstan setter who adjusts these stops when first setting-up the machine; when this setting is completed a capstan operator takes over. Thus

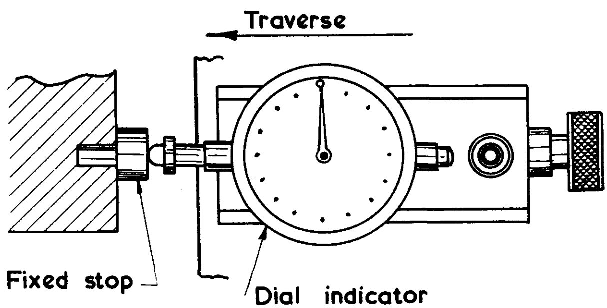


Fig. 6.6.—Micrometer Stop.

this operator is continually engaged at the machine; no time is spent in setting, tool changing and measuring of diameters for index setting.

It is customary to provide the capstan operator with limit gauges of the type described in Chapter 3; this technique affords a relatively cheap and simple method of ensuring that dimensional control is being maintained. Dial-indicator-type stops may be used when high precision work is required on high-quality turret lathes; the principle is illustrated in fig. 6.6. Instead of the operator relying on the abutment of the adjustable stop against the fixed stop to determine the final position of the transverse movement of the turret, a visual indication is obtained by traversing the turret until the pointer of the dial indicator reads zero. In this way variation of pressure against the fixed stop is avoided, with the result that more precise and consistent dimensional accuracy is obtained.

6.4 Work holding

The work-holding devices used on a capstan or turret lathe differ little from those used at a centre lathe. In order, however, to reduce the time required and the effort to be expended by the capstan operator, most work-holding devices used on capstan and turret lathes are automatically opened and closed. Pneumatic power, namely compressed air at a pressure of about 500 to 700 kN/m^2, is used for this purpose, and the chuck or collet is opened and closed through the movement of a small lever.

Fig. 6.7 illustrates the principles involved in the holding of work for capstan and turret lathes.

6.4.1 Collets

Always used for the holding of cold-rolled section or extruded section; that is to say section of fairly close accuracy. Several types of collet are available, capable of accurate and rapid holding of work especially if the collet is power-operated. Some typical spring collets are shown in fig. 6.7A.

6.4.2 Chucks

Used for the gripping of larger-sized work, or more particularly for the holding of previously turned work. Both three- and four-jaw chucks are used on capstan and turret lathes. The three-jaw power-operated self-centring chuck is widely used on capstan lathes for the production of medium-sized components from bar stock. If the chuck is to grip a forging or casting for a first operation the jaws are hard and possibly serrated. Soft-jaw chucks are used to hold components which have already received a machining operation; this prevents damage to the surface of the work. The soft jaws are easily machined if a relatively awkward-shaped casting or forging requires to be gripped. Fig. 6.7B illustrates the use of chucks for capstan work.

6.4.3 Fixtures

A fixture is a device designed to locate and grip a workpiece. If it is found that the shape of a workpiece is such that difficulty is likely when attempting to hold it in a spring collet or chuck, it may be more expedient to hold the

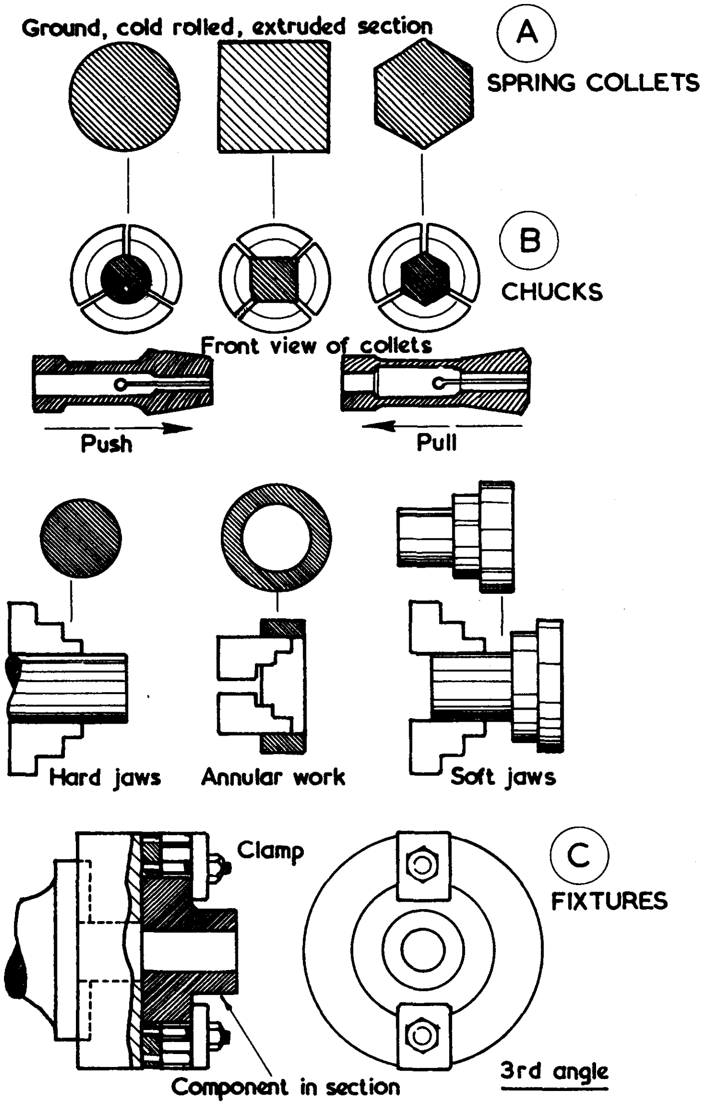


Fig. 6.7.—Work Holding on the Capstan Lathe.

component in a fixture especially designed for the purpose. Fig. 6.7C shows a typical fixture for use on a capstan lathe.

6.5 Spindle speeds

We have seen that both capstan and turret lathes are essentially improved versions of the centre lathe, the improvements consisting in the provision of increased tooling capacity together with control of tool movement by means of the adjustable stops. In this way a considerable amount of machining is possible, and may be carried out practically non-stop as soon as the workpiece is suitably chucked. However, as we have seen from earlier work, there is an ideal cutting speed at which metal should be removed, with the revolutions of the work proportional to the diameter turned. It is certain that cylindrical components which are to be produced on a capstan lathe not only will possess diameters of different sizes but also may require a range of machining operations, including turning, facing, drilling and reaming.

Because the turret lathe is designed to accommodate mainly large-sized work, a wide range of spindle speeds is essential. A small-capacity capstan need not have as many spindle speeds. The diameter of work intended for the capstan lathe may not exceed 50 mm, while the diameters to be turned on a turret lathe may range from 50 to 800 mm. It is nevertheless a great advantage if the spindle speed on a capstan lathe can be changed or reversed quickly and easily without stopping the machine and wasting production time.

6.5.1 Speed-changing techniques

Several types of speed-changing technique are in use. A popular method used in the medium-sized capstan lathe is the two-speed motor, driving a gearing arrangement providing six speed changes. Thus by altering the motor speed a total of twelve spindle speeds are made available; a typical range is from 1 to 30 rev/s. Table 6.1 shows how these speeds are arranged. Note that the twelve speeds are divided into three groups of four. Any particular group can be selected by the rotation of a lever at the front of the headstock, while movement of the two-speed motor switch together with the clutch lever gives the speed required within the group chosen.

	Motor	*Clutch lever*	*Spindle speeds (rev/s)*		
			First group	*Second group*	*Third group*
Bottom speed	slow	slow	1	1·6	3
Second speed	fast	slow	1·4	2·5	4·4
Third speed	slow	fast	6	10·5	18·5
Top speed	fast	fast	9	16	28

Table 6.1 Arrangement of spindle speeds on a capstan lathe

Selection of one of the groups shown provides adequate cutting speeds for turning, boring and reaming without the necessity of engaging speeds in either of the other groups.

High-quality turret lathes are available with eleven spindle speeds, within a range of from 0·4 to 40 rev/s, which can be selected by the movement of a single lever.

Further advances consist in providing the machine-tool operator with a preselective device. This means that the required speed can be selected by rotation of a dial carrying the spindle speeds available. Clutch engagement and plunger movement together bring about the change of speed required, and there is no shock or slip at engagement. This speed changing may be carried out while a cut is taking place, and no discernible changeover point can be detected on the machined surface.

It is important to remember that the prime purpose of modern speed-changing devices is to enable the maximum efficiency to be obtained from the machine tool. The provision of a spindle brake allows immediate stopping of the spindle; speed changes are selected with rapidity and engaged with no stoppage of the machining processes; it is a simple matter to throw the spindle speed into reverse, say for the removal of a tap during a tapping operation. All these innovations are calculated to increase the metal-removal ability of capstan and turret lathes, and under these conditions it is important that the tooling used be of the highest possible quality if full advantage is to be taken of the reduction of unproductive time.

6.6 Standard tooling devices

While standard-type single-point cutting tools may be used in the four-way tool post, or square turret as it is sometimes called, the cutting tools used in the hexagonal turret require special holding devices. Such equipment is considered as standard, and in addition to tool holders includes bar-stop and centre-drill holders, drill chucks, tap holders and extension arms. These and other equipment can be kept in stock ready to be drawn out and set up as and when required by the capstan setter.

This principle of standardising the equipment to be used on a capstan lathe helps to reduce the overall cost of tooling, always an expensive item in the machining of repetitive products. In many cases the equipment is such that two or more tools may be applied to the workpiece at the same time; this principle is known as **combination** tooling. Before considering the types of tooling applied from the hexagonal turret, it may be advisable to separate capstan work into two main categories:

(i) chuck work,
(ii) bar work.

6.7 Tooling for chuck work

We have seen that both hard and soft jaws may be used, while the work held can be bar stock, previously turned work, or even castings and forgings. For this type or range of workpiece the knee turning toolholder is an essential piece of equipment.

6.7.1 Knee turning toolholder

Illustrated in fig. 6.8, the knee turning toolholder provides rigid support for a standard single-point cutting-tool bit. Additional support is given by the overhead pilot which locates in the bush shown in the diagram. Note the screw adjustment to the turning arm, permitting a fairly wide range of diameters to be machined. If required a boring bar may be set in the central bore, permitting a combination of turning and boring to be carried out simultaneously. As already stated, this type of toolholder is suitable for most types of chuck work, and the rigidity is such that tungsten-carbide tools can be used to the fullest extent.

The principle of tool-work application is similar to that of the centre lathe; the tool is applied radially to the work. It is evident that if a heavy cut is taken on bar stock there will be a strong tendency for the bar to deflect or bend away from the tool. We will see, when we come to the toolholding for bar work, the technique adopted to prevent bar deflection under the influence of the cutting forces.

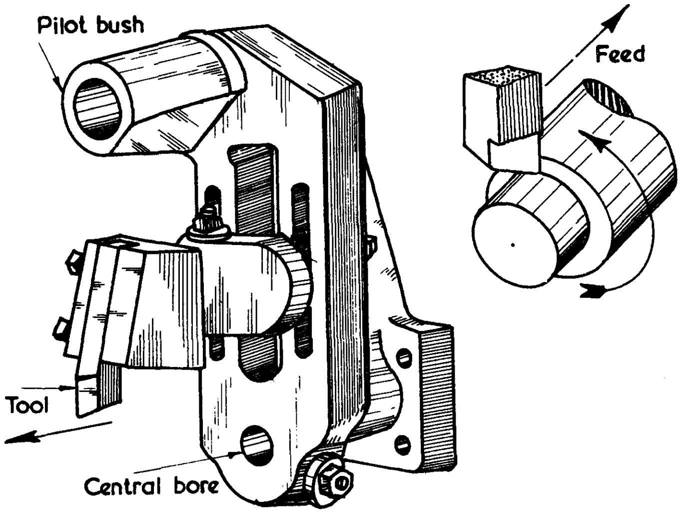


Fig. 6.8.—Knee Turning Toolholder.

6.7.2 Boring bars

A typical boring bar, suitable for clamping in the knee turning toolholder previously described, is shown in fig. 6.9. Very fine boring is possible on the smaller-diameter holes, using a boring bar with a tungsten-carbide-tipped microbore unit capable of accurate adjustment. Normal boring for larger-diameter holes is achieved using boring bars similar in design to those adopted for centre-lathe work.

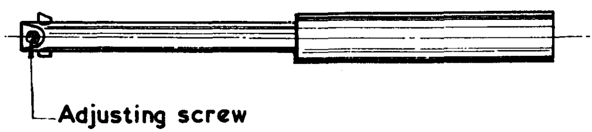


Fig. 6.9.—Boring Bar.

6.7.3 Extension arms

Bolted to the hexagonal turret and accurately located by means of a register or spigot, extension arms are widely used for holding boring bars, centres and other shank-type tools or toolholders. An extension arm is illustrated in fig. 6.10.

6.7.4 Starting drill and holder

All hole drilling at the capstan lathe should be preceded by a true start, and the device shown in fig. 6.11 is used for this purpose. Note the spade-type or flat cutter; this is usually ground at an angle of 120°

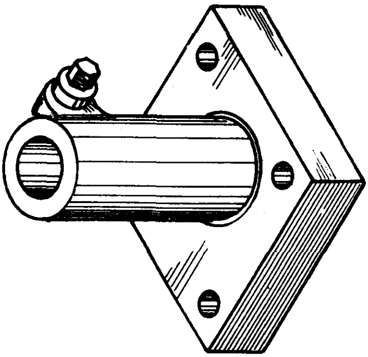


Fig. 6.10.—Extension Arm.

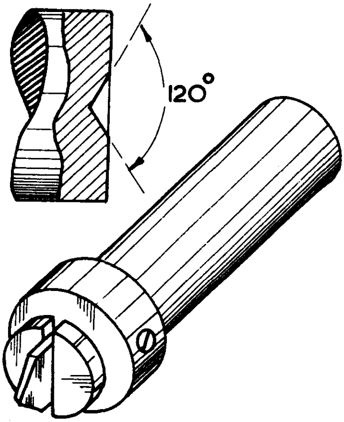


Fig. 6.11.—Starting Drill and Holder.

6.7.5 Additional equipment

In addition to the few examples of tooling devices given above, all the usual centre-lathe tooling is used. This includes standard drills and reamers, taper sleeves or sockets, taps and dies. When a high rate of production is required both self-opening die heads and collapsible taps may be used.

6.8 Tooling for bar work

The use of standard-sized bars, cold rolled or extruded, is an essential feature of the work carried out on capstan lathes. In general the diameters are relatively small, and this means that spindle speeds will be fairly high. At the same time, if the bar diameter is on the small side it is certain to be deflected if heavy cuts are taken. Yet unless substantial cuts are taken, much of the efficiency of our elaborately tooled capstan lathe is lost. The use of a roller-steady turning tool-holder allows heavy cuts to be taken without deflection of the bar.

6.8.1 Roller-steady turning toolholder

The principle of the roller-steady turning toolholder is shown in fig. 6.12. Note that the tangential turning force, shown as *F* in the diagram, is opposed by the forces exerted by the two rollers, indicated as A and B. Clearly the rollers and tool must be an integral assembly, or contained within a box-like structure. Both rollers are independently mounted on slides, adjustable

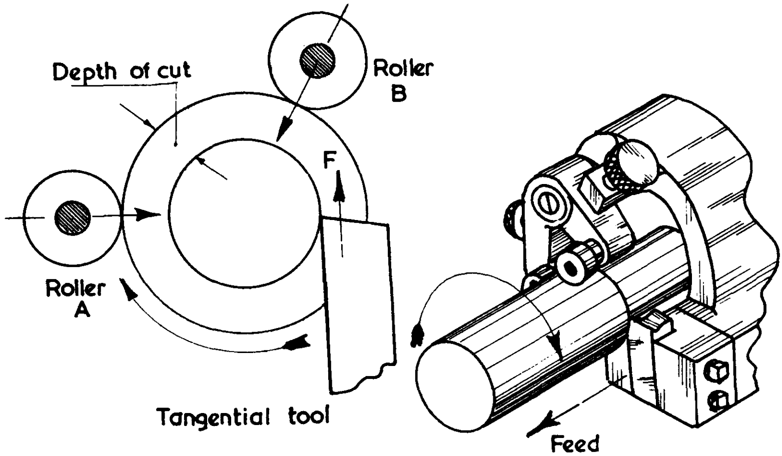


Fig. 6.12.—Roller-steady Turning Toolholder.

over a fairly wide range of diameters. If the toolholder is required to machine concentric to a previously machined diameter, the rollers are set to lead the cutting tool and bear on the machined diameter. This is shown in fig. 6.13A.

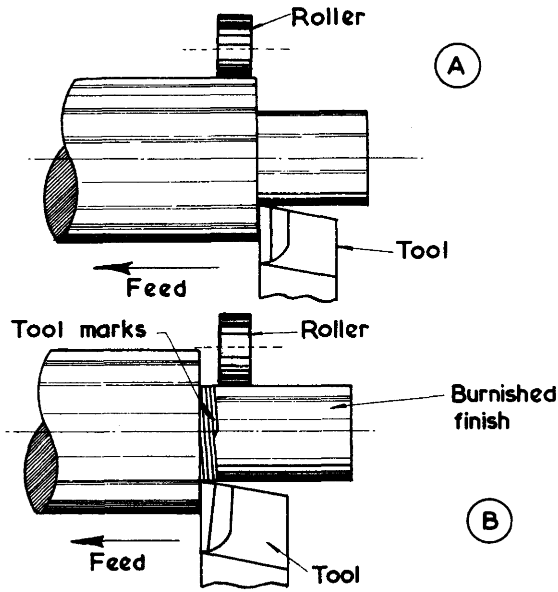


Fig. 6.13.—Rollers Leading and Following Tool.

When heavy cuts are to be taken on bars held in a power-operated collet chuck, it is necessary that the cutting tool now leads the rollers as shown in fig. 6.13B. With the highly polished rollers following the cutting tool as shown in the diagram, there is a tendency for them to burnish the machined surface, resulting in considerable improvement in the finish of the workpiece. This burnishing action is brought about by the pressure exerted on the surface of the work by the rotating rollers.

We see now two advantages of the roller-steady turning toolholder when the rollers follow the cutting tool:

(i) no deflection of the workpiece leading to inaccurate work,
(ii) improved surface finish on workpiece.

6.8.2 Roller-steady ending toolholder

We have seen that an improved finish results when the rollers follow the cutting tool. Unfortunately, however, when starting a heavy cut, the cutting tool makes contact with the work before the rollers are able to provide the required support. This means that the bar will deflect away from the cutting tool, only to be forced back as the rollers make contact. This sets up a condition which is known as **ribbing** since it results in a series of ribs on the diameter of the machined bar; this effect tends to diminish as the cutting tool continues its traverse. The use of a roller-steady ending toolholder to break down the bar end will prevent the unwanted condition described above, and fig. 6.14 shows a typical device of this kind. Note also the methods of breaking down the bar ends prior to the application of a roller-steady turning toolholder. In each case the breakdown is achieved at high speed with the roller-steady ending toolholder; the length of traverse, which is quite short, is controlled by the adjustable stop.

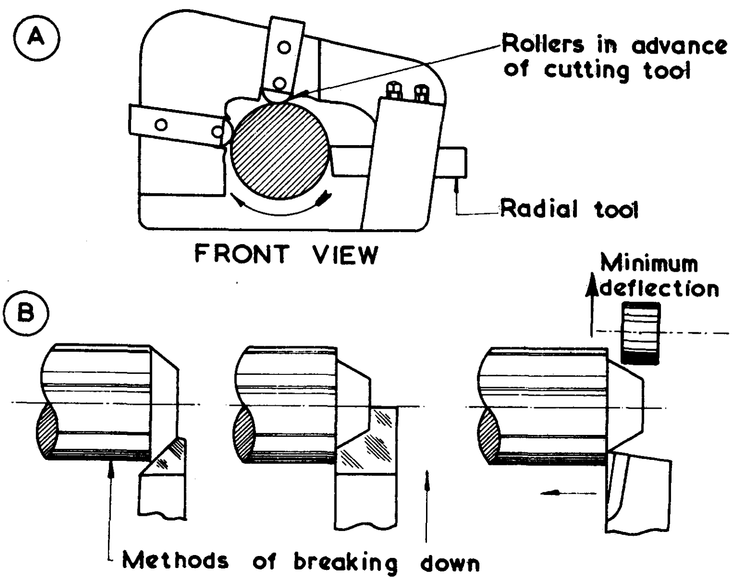


Fig. 6.14.—Roller-steady Ending Toolholder and Breaking-down Techniques.

The purpose of this breaking-down operation is to reduce the depth of cut taken by the cutting tool in the roller-steady turning toolholder, as shown in fig. 6.14B. It will be seen that only a small amount of metal is encountered by the cutting tool before the rollers make contact, and there is little or no tendency for deflection of the bar.

Before leaving the subject of toolholders, perhaps it should be noted that the cutting tool, as shown in the roller-steady turning toolholder (fig. 6.12), is presented tangentially to the work. This promotes greater rigidity, as the cutting force acts through the strongest section of the tool with no tendency to cause bending or deflection of the tool. Although a somewhat special technique is required in the sharpening of the tungsten-carbide-tipped tool, excellent results are obtained; but it is necessary to have special provision for rapid withdrawal of the cutting tool during the return stroke, to avoid chipping of the cutting tool and marking of the workpiece. The cutting tool used in the roller-steady ending toolholder shown in fig. 6.14 is presented radially to the workpiece following centre-lathe practice.

6.9 Self-opening diehead

The cutting of a screw thread at the centre lathe is a somewhat lengthy and complicated process, demanding considerable skill and confidence from the centre-lathe turner. If an external screw thread is to be cut during the machining of a component at a capstan lathe, it is certain that a self-opening diehead will be used. There is little doubt that these dieheads provide the ideal method of cutting external screw threads both accurately and quickly. Simple to use, easy to set, with removable dies that can be quickly set up in a grinding fixture and precision ground to the required angle, self-opening dieheads are to be found wherever components are produced on capstan lathes.

The advantages offered by the use of self-opening dieheads include accurate threads produced by adjustment of the cutting dies, together with considerable reduction in the machining time; reversal of the lathe spindle is not required; the dies open and may be withdrawn from the work by traversing the hexagonal turret back along its slide.

6.9.1 Principle of self-opening dieheads

The principle underlying the design of self-opening dieheads consists in the presentation of four chasers or cutting dies to the revolving work. These cutting dies may be presented radially or tangentially, as shown in fig. 6.15. Rotation of an adjusting screw permits movement of the dies either towards or away from the centre, and an indicating line normally reads at zero on a graduated scale when the dies are set at the correct diameter for the thread to be cut.

In operation the diehead, mounted in a suitable holder on the hexagonal turret, is taken to the work, with the spindle speed reduced according to the diameter of thread required. Force must not be used; gentle pressure will allow the leading edge of the dies to bite, and as the cut takes place only sufficient pressure to counteract the drag of the turret slide should be applied.

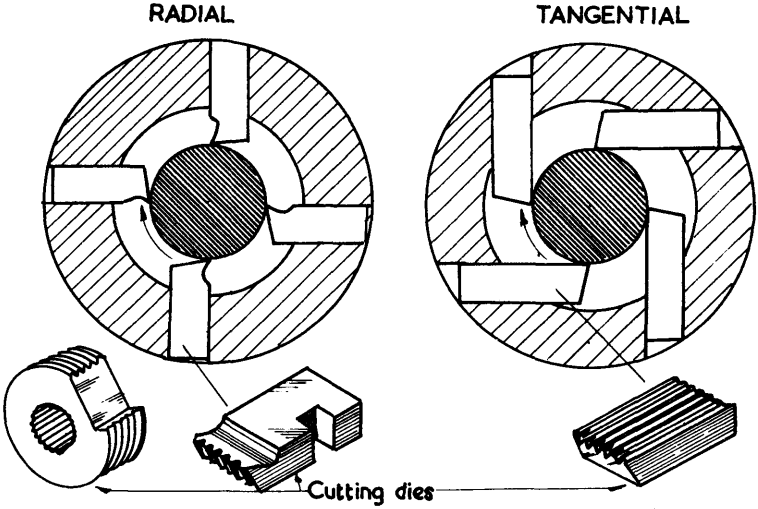


Fig. 6.15.—Radial and Tangential Cutting Dieheads.

When the traverse of the turret is arrested by its previously set stop, a section of the diehead continues to screw on, and in moving forward clears a holding device. At this point powerful springs immediately force the dies outwards, allowing the capstan operator to take the turret back. The dies must be closed before the diehead is used for the next threadcutting, and this closure may be effected with a small handle at the side of the diehead; alternatively an automatic tripping device may be used.

A typical die as used in the radial diehead is shown in fig. 6.16. It will be seen that the cutting face (shown as the line CD in the front elevation) is inclined to the centre line of the work to be threaded (indicated on the diagram as the line AB and A_1B_1). This inclination of the cutting face ensures that

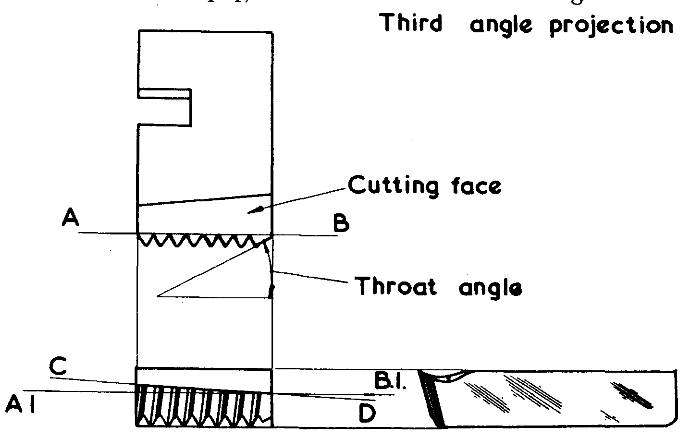


Fig. 6.16.—Die for Diehead.

the actual cutting or removal of metal is done by the edge of the throat and the first full tooth. The remaining teeth are above centre and serve to act as a nut, engaging in the thread cut by the preceding full tooth; in this way pitch accuracy is ensured.

The dies must be kept sharp, but in no circumstances must they be sharpened by hand. Simple fixtures are available which ensure that the correct angles are ground on the dies, and the greatest of care must be taken to ensure that the angles are correct and appropriate for the metal to be threaded.

6.9.2 Roughing and finishing

In accordance with the well-established principle of roughing and finishing in order to obtain both maximum metal removal and an accurate, well-finished machined surface, provision is made for two cuts to be taken: a roughing and a finishing cut. Fig. 6.17 shows a view of the popular Coventry diehead. It will be seen that in addition to the closing handle shown on the

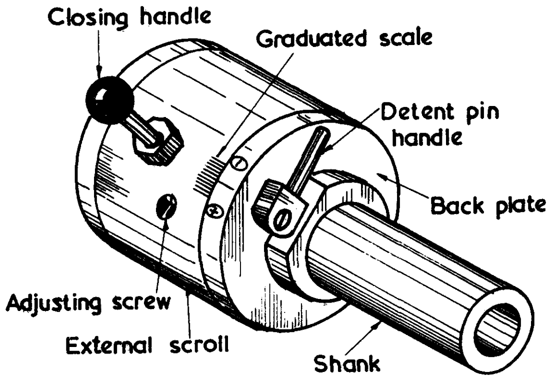


Fig. 6.17.—Self-opening Diehead.

external scroll, there is a detent pin handle attached to the back plate. This detent pin handle is used for the purpose of taking two cuts without disturbing the adjusting screw.

The first cut is taken with the detent pin handle in the roughing position; the second (finishing) cut is taken with the detent pin handle moved over to the finishing position. It is recommended that the diehead be in the open position when the changeover is made. It is also important that the diehead be used only when the detent pin holder is in either the roughing or finishing position, unless the diehead is equipped with a three-position system for the detent pin handle.

6.10 Cutting internal threads

The standard solid tap may be used when cutting internal threads at the capstan lathe. A low spindle speed is required, which must be reversed in order to secure removal of the tap. If a small-diameter thread is needed there is much risk of broken taps due to the inherent brittleness of small taps; and for light tapping operations the tap holder shown in fig. 6.18A may be used. The sleeve, as shown, is provided with a knurled finish allowing the operator to take a firm grasp when feeding the tap to the work. If it is felt that the torque is excessive, with the attendant risk of tap breakage, it is a simple matter to release the grip on the knurled sleeve. The sleeve now rotates freely, and reversal of the spindle allows withdrawal of the tap.

6.10.1 Tapping blind holes

The device illustrated in fig. 6.18B is very suitable for the tapping of blind holes. It is essentially a slipping-clutch-type tap holder, and can be set to slip at differing torques according to the size of the thread or the material being cut. Reference to the diagram shows that a strong spring presses against the slipping-clutch members. The pressure exerted by this spring can be varied by tightening or slackening the compression nut. Thus, once set by trial and error, the device can be used for the repetitive tapping of identical threads. In the event of the torque becoming excessive, the clutch member A rides over the clutch member B; reversal of the spindle together with reverse movement of the turret allows the tap to screw itself out.

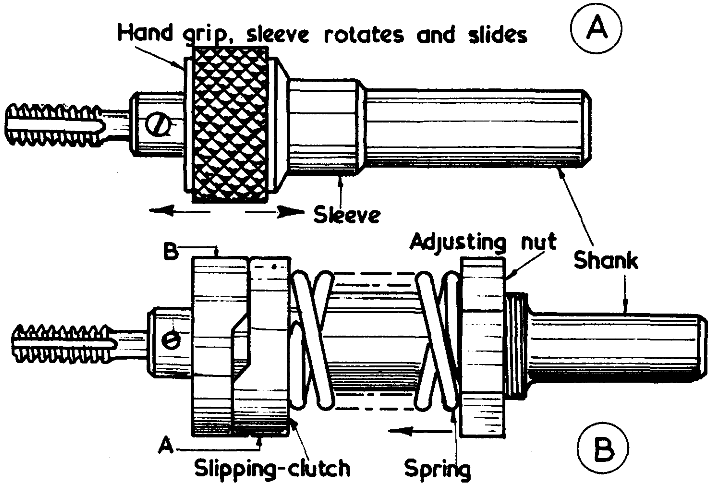


Fig. 6.18.—Slipping-clutch Type Tap Holder.

6.10.2 Collapsible taps

Provided the diameter of a threaded hole is in excess of about 25 mm, a collapsible tap may be used. The principle may be considered as the reverse process to that of the self-opening diehead; namely the closing or collapsing of threaded dies actuated by the stopping of the turret or external pressure on the collapsible-tap device. A handle is used to move the dies outwards, where they lock at the pre-set diameter.

6.11 Examples of bar work on capstan lathes

Perhaps the widest use for the medium-sized capstan lathe lies in the production of cylindrical components from bar stock. As we have seen, collet, three-jaw, four-jaw, and soft-jaw chucks may be used to locate and grip the bar from which the components are to be machined. Before deciding on the actual tooling devices to be adopted, it is important to ensure that the capacity of the capstan lathe is such that all the tooling devices have freedom of movement and do not foul any part of the machine. Capacity charts are readily available from the makers of capstan lathes, giving full details of dimensions of the machine tool, together with maximum and minimum movements of turret, front tool post and rear tool post.

Example 1

Manufacture of the 3% nickel case-hardening steel bush blank illustrated in fig. 6.19. Large numbers of these bushes are required, and will be finish ground after case-hardening. It must be appreciated that the tooling arrangements shown in the table are chosen to show the versatility of the capstan lathe as a machine tool capable of efficient and economical machining. The method shown is neither the best nor the quickest way of producing the steel bush, but will serve to give an introduction to the simple techniques underlying capstan tooling and production.

Hexagonal turret station 1

Adjustable stop, set to length of component plus width of parting-off tool plus about 0·2 mm for facing. The exact amount is a matter of setting skill, and this is where the experience and initiative of the capstan setter avoid considerable wastage of metal.

Hexagonal turret station 2

Combined centre and facing tool. Traverse of turret controlled by adjustment and setting of the stop for turret 2.

Hexagonal turret station 3

Knee turning toolholder with drill in central bore. Diameter A machined together with rough drilling of hole. Stop set so that drill just clears overall length of bush.

Hexagonal turret station 4

Knee turning toolholder with drill in central bore. Diameter B machined; drill opens out previously drilled hole. Stop set for linear dimension C.

Hexagonal turret station 5

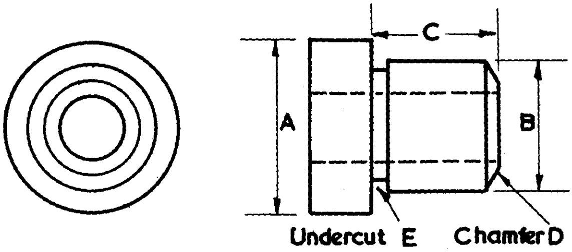
Reamer to machine bore to size.

Square turret 1 *(front)*

Single-point tool set to machine chamfer D. Correct angle provided by the tool; length of chamfer obtained by adjustment of stop.

Square turret 2 *(front)*

Single-point tool to machine undercut E. Width controlled by tool, depth and position by stops.



HEXAGONAL TURRET		SQUARE	REAR
1	Stop	Chamfer	Part-off
2	Centre face	Turn undercut	
3	Turn dia A., drill hole (rough)		
4	Turn dia B, drill hole (finish)		
5	Ream hole		
6			

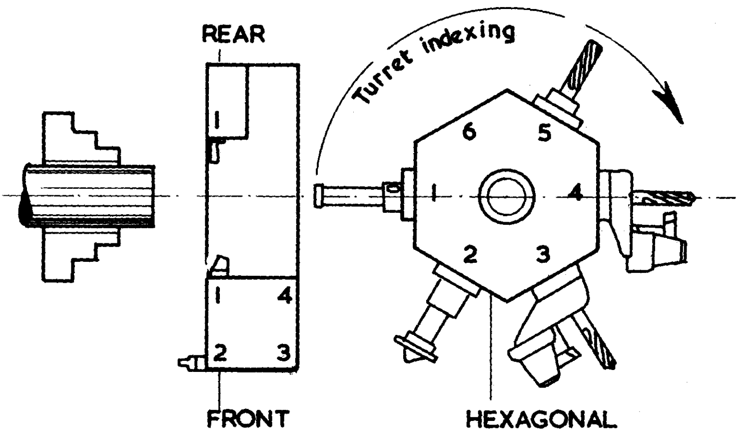


Fig. 6.19.—Set-up for Machining Bush on a Capstan Lathe.

Rear turret

Parting-off tool to complete machining of component.

It must be stressed at this point that the preceding example shows only the application of some of the standard tooling devices illustrated in the preceding pages. Many more tooling devices are available, including hollow mills, multi-toolholders, recessing tools and knurling tools. The list is much too great to consider at this stage in our studies, but excellent catalogues and descriptive material are readily available from the manufacturers of capstan and turret lathes.

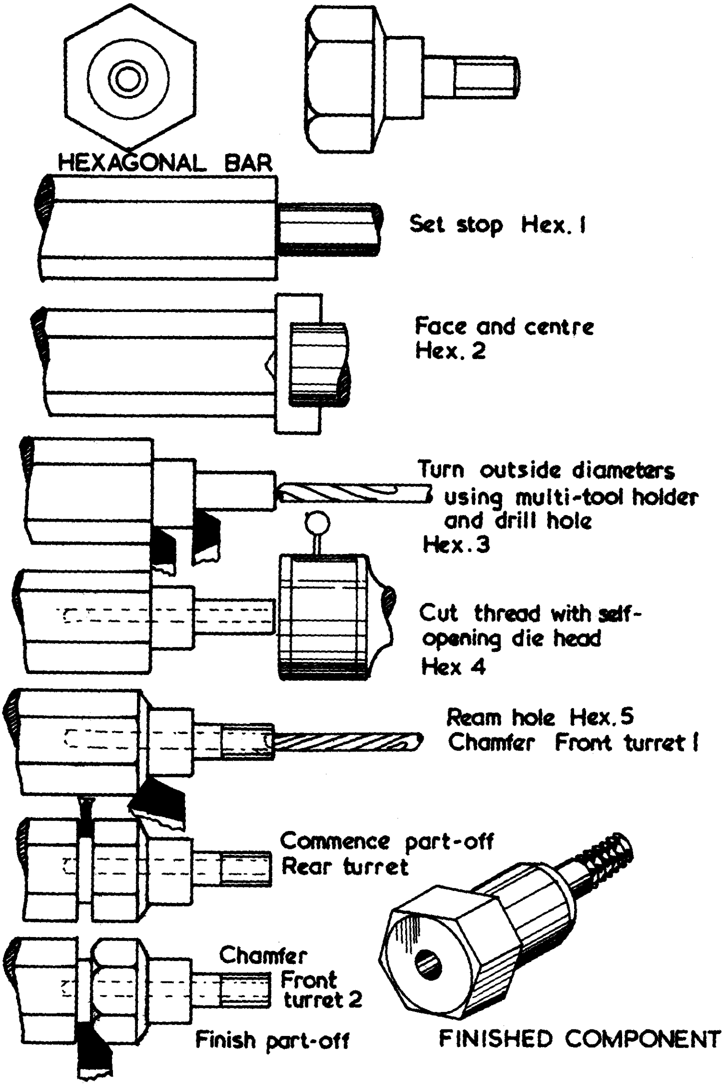


Fig. 6.20.—Sequence of Operations on a Capstan Lathe.

Example 2

A brass union is illustrated in fig. 6.20. This component is machined from hexagonal extruded brass rod 40 mm across the flats. A hexagonal spring-collet chuck will be used to grip and locate the brass bar; the sequence of operations is shown in fig. 6.20. Note also the stages in the machining of this component at the capstan lathe.

6.12 Machining times

The time required to machine components on capstan lathes is usually described as the **floor-to-floor** time; in other words it is the total time occupied in taking the forging or casting from the floor, machining it, and replacing the completed job back on the floor. (Suitable boxes or containers may, or course, be used instead of actually stacking finished jobs on the shop floor.)

It is not difficult to calculate the floor-to-floor time for the machining of components on capstan and turret lathes, but it is one thing to arrive at a theoretical time and another thing to machine the job to within the limits laid down in the drawing. Considerable practical experience is the best teacher of the technique underlying the assessment of machining times that compare favourably with the actual times required to machine the components.

The following notes will provide a simple guide to the usual technique adopted.

6.12.1 Operating or non-machining time

Non-machining time can be considered as the time required to present the tools to the work, and to chuck and unload the component. The following table gives an approximate idea of the time required to carry out some of the essential functions when operating a capstan lathe.

Operation	*Time*
Bring bar up to stop	10 seconds
Index hexagonal turret	5 seconds
Index square turret	5 seconds
Change speed	4 seconds
Change feed	4 seconds

The above times vary according to the size both of the components to be machined and of the capstan or turret lathe, and it is only practical experience that provides accurate and reliable figures. Provided the sequence of operations has been decided, however, it is a relatively simple matter to add all the non-machining times and thus arrive at a total non-machining time.

6.12.2 Actual machining time

This is the actual time that the tools are removing metal. The principle involved in the calculation of machining times is more commonly referred to as **feeds and speeds.** Let fig. 6.21 represent a reduction of diameter on a component machined in a capstan lathe. The work revolves at 8 rev/s, while the tool has a feed of 0·2 mm/rev. The distance shown as L in the diagram is the traverse of the tool. It is required to calculate the time taken by this cut.

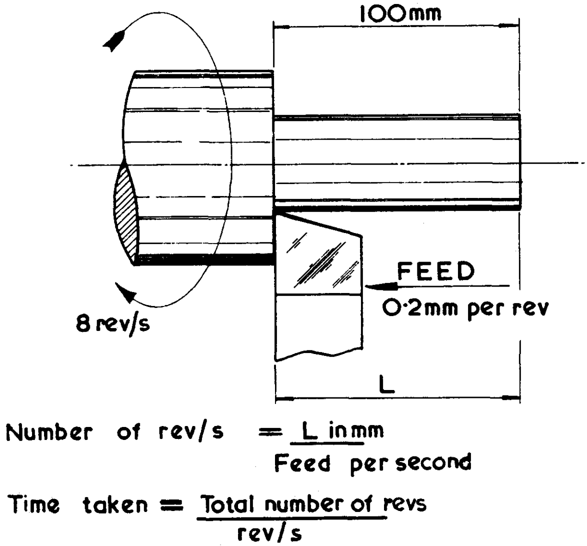


Fig. 6.21.—Calculating Machining Times.

For each revolution of the work the tool advances a distance of 0·2 mm. Thus the number of revolutions of the work in a tool movement of L mm is equivalent to the distance L divided by the feed of 0·2 mm, giving the formula:

$$\text{Number of revolutions} = \frac{L}{\text{feed per rev}}$$

$$= \frac{100}{0{\cdot}2}$$

$$= 500$$

We see from the diagram that the work revolves at 8 rev/s. Thus the time taken for the tool to traverse the distance of 100 mm will be slightly in excess of one minute; using the formula,

$$\text{Time taken (min)} = \frac{\text{total number of revolutions}}{\text{spindle rev/s}}$$

$$= \frac{500}{8}$$

$$= 62{\cdot}5 \text{ seconds}$$

Adding together all the non-machining times and all the calculated machining times gives the total production or floor-to-floor time for the component. It must, however, be remembered that the hexagonal turret is equipped with automatic traverse, as is the cross feed for the front square turret. This means that the capstan operator can machine with the front turret while the hexagonal turret cuts under automatic feed.

Summary

Turret and capstan lathes represent the basic machine tools designed for the efficient and economical machining of engineering components possessing mainly cylindrical shapes. The turret lathe has a hexagonal turret which is capable not only of being indexed in six machining positions, but also of complete movement along the whole length of the bed of the lathe.

In general the capacity of turret lathes is large. They are eminently suitable for the repetitive machining of fairly large precision components, typical examples being provided by the component parts of aircraft, turbines, and elements of machine tools. In all the examples just given, the number of components required is not likely to exceed (say) several hundred, and it is very likely that the production of the parts will be divided into small batches, say 40 per batch. This technique will permit the improvement or modification of the component in the light of experience during manufacture and in service.

The use of capstan lathes differs from the use of turret lathes mainly with respect to the size of the component to be machined. The traverse of the hexagonal turret is relatively restricted, although the slide on which the turret moves may be clamped at any convenient place on the lathe bed.

The great advantage possessed by both turret and capstan lathes is the number of tooling stations available. In the case of a capstan lathe, instead of the operator spending unproductive time in tool setting and tool changing, this work is done by an experienced and skilled setter. When the lathe is completely tooled, with the stops set to give the required linear distances, the capstan operator takes over the machining of the component. There is thus little non-machining time, and the greater part of the time is spent in the removal of metal. A wide range of tooling devices can be presented to the work in sequence. Threads are easily cut, holes may be drilled, reamed or bored, and chamfers machined both internally and externally. The machining of a complicated profile is readily achieved with the use of a form tool, held in either the front or rear tool post or the square turret.

It is important to appreciate that the capstan lathe requires a skilled setter, who is responsible for the setting of the tools and stops, while a capstan operator carries out the machining of the components. The procedure when producing components from the larger-type turret lathes is somewhat different. Here the turret-lathe operator is a highly skilled man. He both sets and operates the turret lathe; the tooling devices and stops are used to reduce the time and cost involved in the machining of several fairly large identical components required to close dimensional accuracy.

Finally, it is possible to estimate, with some degree of accuracy, the time required to produce a component on a capstan lathe. A list of the machining operations is drawn up and the total time calculated. This allows a measure of cost estimating to be carried out, and in this way a firm is able to judge whether it is an economic proposition to accept a sub-contract for a large number of components at a stated price.

EXERCISE 6

1 What is the essential difference between a turret lathe and a capstan lathe? Illustrate with diagrams.

2 Explain the advantage possessed by a capstan lathe with respect to tool holding.

3 Make a neat sketch of a component that would be suitable for production on:
(i) a capstan lathe,
(ii) a turret lathe.

4 Explain how dimensional control is maintained when producing components on both capstan and turret lathes.

5 Show, by means of sketches, typical applications of the following work-holding devices:
(i) spring-collet chuck,
(ii) three-jaw soft-jaw chuck,
(iii) three-jaw hard-jaw chuck,
(iv) turning fixture.

6 Make a neat sketch of the following tool-holding devices, showing a typical application:
(i) knee turning toolholder,
(ii) roller-steady turning toolholder.

7 Show, by means of a neat layout, the tooling arrangements suitable for the production of the component shown in fig. 6.22 from hexagonal bright mild steel.

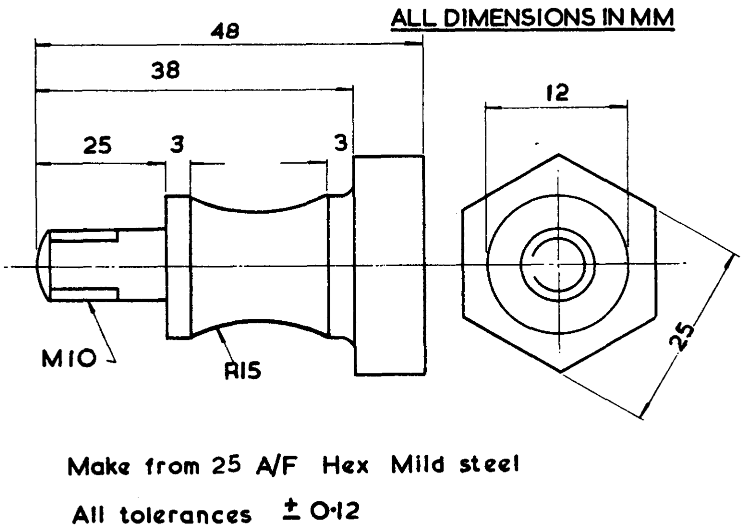


Fig. 6.22.

8 Describe the conditions best suited for the application of a roller-steady turning toolholder using a tangentially inclined tool. What precautions are necessary before:
(i) taking a cut,
(ii) returning the turret to the starting position?

9 Make a neat sketch of a component to be produced on a capstan lathe that would require the use of a self-opening diehead and a collapsible tap.

10 Why is it necessary to be able to calculate the floor-to-floor times or components produced on capstan and turret lathes? Outline the use of the study of feeds and speeds with respect to the calculation of machining times.

7 Hole Production

7.1 Types of drilling machine

FIG. 7.1 shows three typical engineering components possessing holes. The production of holes in engineering components such as these constitutes a most important aspect of engineering manufacture, and several techniques are adopted. We have already dealt with the use of sensitive, pillar, and radial drilling machines in *Workshop Processes* 1 and 2, and perhaps it will be remembered that of the three drilling machines described, only the radial drilling machine adopts the principle of taking the tool to the work.

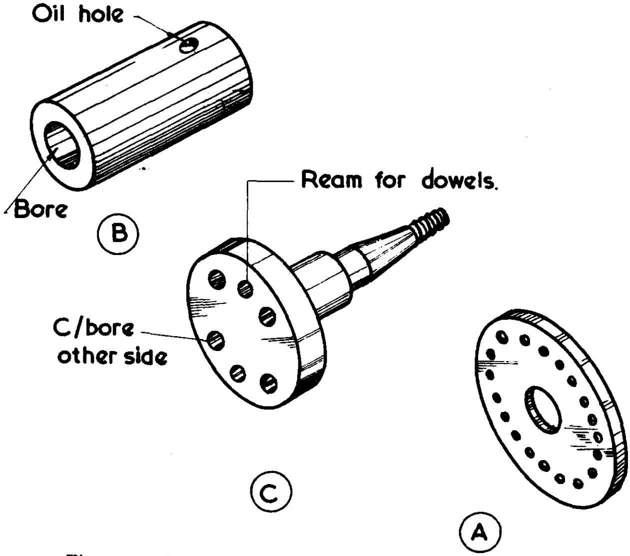


Fig. 7.1.—Engineering Components Requiring Holes.

A brief survey of standard drilling machines at this stage will serve to remind the student of their principal uses.

7.1.1 Sensitive drilling machine

Both bench and pillar types available. Three to four spindle speeds with relatively high revolutions; speed changes effected by belt changing on coned pulleys. Suitable for the drilling of small-diameter holes; vertical feed obtained by hand pressure. Not suitable for reaming, counterboring or the drilling of large-diameter holes.

7.1.2 Pillar drilling machine

Available only as a pillar type. These drilling machines are much used for the average type of work, including drilling, reaming, counterboring, counter-sinking and the tapping of holes. Automatic feeding of the spindle is available together with a choice of feeds. Speed changes effected through gearing arrangements, but the spindle may still be fed by hand (though with loss of sensitivity). Unless the table is of the compound type, that is to say unless provision exists for movement at 90°, the drilling of holes to close linear dimensions is a difficult matter.

7.1.3 Radial drilling machine

Operating on the principle of taking the spindle to the work, the radial driller is much used for the drilling of holes in large castings. A wide range of spindle speeds, together with automatic feed of the spindle, enables the radial driller to deal with most of the drilling required in large castings or forgings, but once again the drilling of holes having their centres within close limits is a difficult task. We will see later on in this chapter the principle underlying the use of a jig borer for the production of holes not only with precise diameters but also having precise linear distances between centres.

7.2 Piercing holes

This technique is the quickest method of producing holes in relatively thin material. Reference back to fig. 7.1A shows a typical component having several pierced holes. The part shown is an outer ring for the hub of a bicycle wheel. If we count the large-diameter hole at the centre, there are 17 holes in

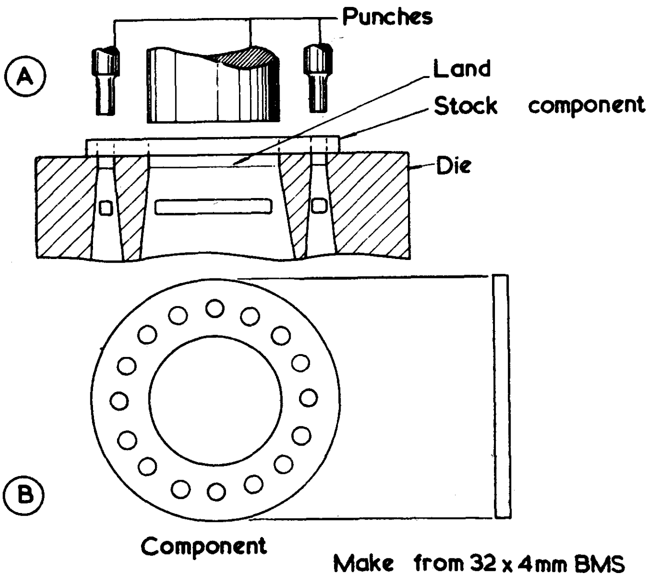


Fig. 7.2.—Technique of Piercing Holes.

this component; yet the production time for these holes is not likely to exceed more than a few seconds—the time required for the stroke of a press.

The principle of the piercing operation is shown in fig. 7.2A. The holes are produced with the combination of a punch and die; for the wheel component shown, 17 punches are required with 17 holes in the die. Both punches and dies are part of an accurate press tool, the punches being integral with the top tool while the die is integral with the bottom tool.

The top tool is mounted in the ram of a press and is accurately aligned by means of pillars so that the punches enter their respective holes in the dies with no errors of alignment. On the closing of the tool or the downward stroke of the ram, the metal stock from which the component is produced is subject to severe stress, resulting in failure of the metal across the shear plane. The area of this shear plane is equal to the perimeter or circumference of the hole multiplied by the thickness of the metal. Thus if the small holes are 4 mm diameter and the large hole is 25 mm diameter, the total shear plane or area is equal to:

$$\pi D \times 4 + 16\pi d \times 4$$
$$4\pi(D + 16d)$$

Substituting actual diameters:

$$\begin{aligned}\text{Shear area} &= 4\pi(25 + 16 \times 4)\\ &= \frac{88}{7} \times 89\\ &= 1118 \text{ mm}^2 \text{ (approx.)}\end{aligned}$$

With the total shear area known it is a relatively simple matter to calculate the theoretical force required to stamp out or pierce the 17 holes.

$$\text{Shear stress} = \frac{\text{force}}{\text{area}}$$
$$\therefore \text{force} = \text{shear stress} \times \text{area}$$

Given that the mild steel from which our component is made has a shear stress of 400 N/mm^2,

$$\begin{aligned}\text{Force to pierce holes} &= \text{shear stress} \times \text{area of shear}\\ &= 400 \times 1118 \text{ newtons}\\ &= 447 \text{ kN}\end{aligned}$$

Note the small amount of land, followed by a gradual taper or enlargement of the holes in the dies. When the hole is pierced, the unwanted metal, or **slug** as it is sometimes called, is forced into the die. It is in a state of compressive stress, and thus presses tightly on the face of the hole in the die. If this hole in the die is parallel throughout its length it is certain that a build-up of slugs will take place within it, leading to blockage and subsequent cracking of the die.

The small land, usually about $1\frac{1}{2}$ *T*, where *T* is the thickness of the metal to be sheared, ensures that the size of the hole will remain constant even after repeated grindings of the top face of the die (a necessary process if the die is to be kept in a sharp condition). The top tool is set so that the punch, at the end of the stroke, pushes the slug just clear of the land. At this position the slug begins to clear the hole owing to the angle of taper machined on the hole, and the slug is free to fall into a suitable receptacle placed beneath the press.

This technique of producing holes is widely adopted in the manufacture of engineering components. Production rates are extremely high, and the process can be completely automatic. The dimensional accuracy of the hole sizes and positions remains constant even after many thousands of components have been produced, an important factor in the mass-production of components. The need for measurement of the component is eliminated, while inspection need only be carried out at intervals. The only limitations are the thickness of the metal from which the part is to be made, and the suitability of the design of the component for press-tool manufacture.

7.3 Use of drill jigs

Fig. 7.1B shows a part produced at a capstan lathe, and it will be seen that a further oil hole is required. Perhaps it has not been appreciated that the manufacture of components at a capstan lathe is made possible because the datum of the work is the centre line, which is common to all the turning operations. The geometric accuracy of all the external diameters, and that of bored or drilled holes, is controlled by their relationship to the centre line of the work. If, however, a hole is required with an axis that does not coincide with the centre line of the work, then a totally different situation exists. It is unlikely that such a component can be finish machined at the capstan lathe.

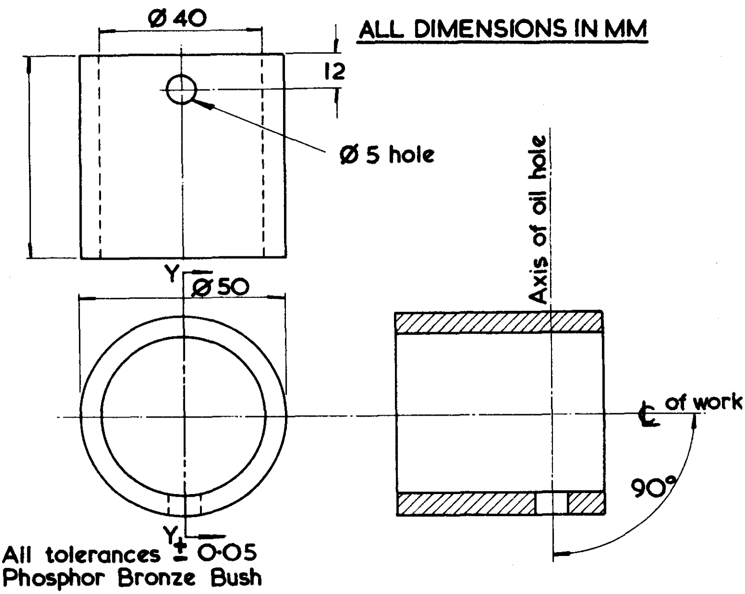


Fig. 7.3.—Component Requiring Drill Jig.

A further drilling operation is necessary. Fig. 7.3 shows the phosphor-bronze bush already illustrated in fig. 7.1B. While the 40 mm diameter bore can be bored from the hexagonal turret concentric with the external diameter of 50 mm, it will be seen that the 5 mm diameter hole has its axis at 90° to the centre line of the bush.

This fact, that each and every hole has its own geometric conditions or accuracy, makes the production or machining of holes a difficult task, and one that has concerned engineers for a good many years. Because the datum of a hole is its centre, it is a very difficult matter to produce holes having their centres to within close linear dimensions with regard to other hole centres or datum faces. Immediately the hole is machined the centre becomes non-existent or imaginary, and it is necessary to finish machine the hole before determining the accuracy.

This is unlike the technique of turning, milling or grinding, where cuts can be taken, the resultant size checked with a measuring device, and the required dimension obtained by suitable movement of cutting tool or work-table achieved by careful indexing.

In the drilling or machining of holes it is essential that the machining of the hole be commenced in the exact position. Thus the drilling of the 5 mm diameter oil hole in the phosphor-bronze bush illustrated in fig. 7.3 involves the positioning of the drill not only on the centre line of the bush or diametrally, but also at a distance of 12 mm plus and minus 0·05 mm. When large numbers are required, an efficient, accurate and economical method of producing holes is to make use of a drill jig.

7·3·1 Principle of drill jigs

The purpose of a drill jig is to provide location and support for a component while one or more drills are guided in predetermined positions. This means that the drilling of holes to accurate dimensions is now achieved by employing a device which has been constructed to a very high degree of accuracy, the actual operation of drilling being reduced to a simple matter of feeding the drill through the metal. The accuracy is obtained by ensuring that the component is correctly and positively located, and also securely held or clamped while the drilling takes place.

Fig. 7.4 shows a simple drill jig suitable for the drilling of the hole in the phosphor-bronze bush. Note that the hardened and tempered drill bush is a press fit in the top plate, with the centre of the drill bush at a distance of 12 mm from the face of the locating pad.

The centre line of the drill bush is also at 90° to the axis of the spigot on which the phosphor-bronze bush locates, as shown in fig. 7.4A. Looking then at view B we see that the centre line of the drill bush passes through the centre of the spigot and is at 90° to the base of the drill jig. As already stated, the whole purpose of the drill jig is to transfer these accurate alignments to the component being drilled, and provided the component is brought up to the location pad and held there in close contact by the tightening nut, consistent accuracy is achieved.

Note that the bore of the phosphor-bronze bush exceeds the diameter of the tightening nut, and that a C washer is used to hold the component hard against the location pad. At the finish of the drilling operation the tightening nut is unscrewed about one turn or less, the C washer lifted off and the component removed from the spigot, passing over the tightening nut. In this way the drilling of the hole becomes a matter of routine, and provided the face of the locating pad and the ends of the component are both kept free from swarf, a high rate of production is possible, with the added advantage that work produced by relatively unskilled personnel will be consistently within the limits.

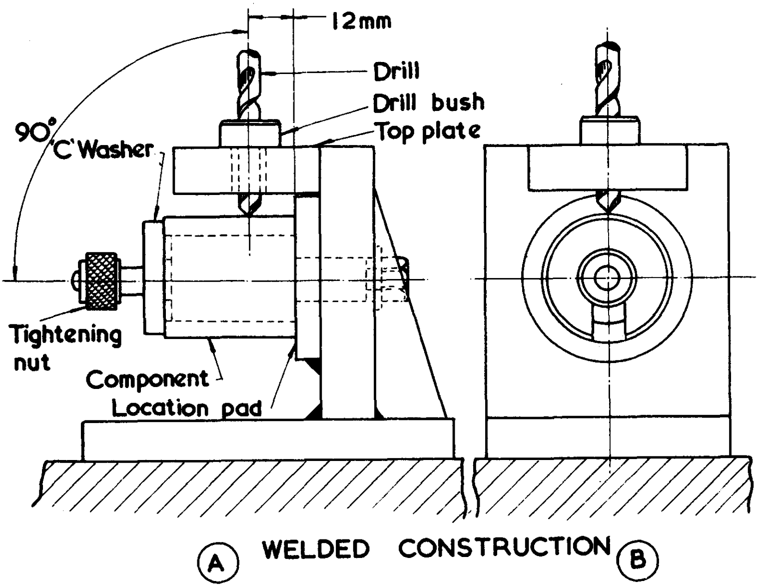


Fig. 7.4.—Typical Drill Jig.

Although a wide variety of drilling jigs are in use, basically the principle remains the same: the transfer of accurate geometric conditions to the components within the jig. Provided the holes required are the same diameter, there is practically no limit to the number of drill bushes that may be incorporated in a drilling jig, and if the jig is capable of being fairly easily handled by the operator a single-spindle drilling machine may be used. If, however, several holes of different diameter are required in a component, or differing operations are required on the holes, then a single-spindle drilling machine will be of no value. This rules out the use of sensitive, pillar and radial drillers; we need now a **multiple-spindle** drilling machine.

7.4 Multiple-spindle drilling techniques

As the name suggests, these drilling machines are equipped with more than one spindle. Two main types of multi-spindle drilling machines are in use:

(i) in-line or gang drilling machines,
(ii) multiple-head drilling machines.

Both types are essentially production machines; that is to say their use is confined to the drilling of holes on a mass-production basis.

7.4.1 The gang drilling technique

Gang drilling involves the use of two or more drilling spindles which are in line and part of the same drilling machine. Thus, having drilled one hole, the operator slides the work to the next spindle and proceeds to drill or machine a further operation on the previously machined hole. The component illustrated in fig. 7.1C is a good example of the need of a gang drilling technique. This component, a mild-steel forging, has been machined on a

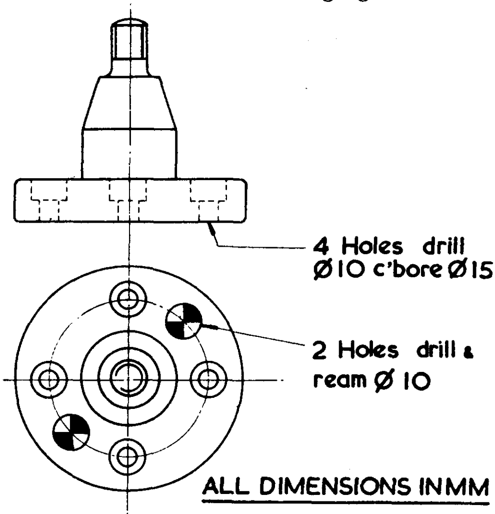


Fig. 7.5.—Component Requiring Drilled, Reamed and Counterbored Holes.

capstan lathe, and it will be seen that four further holes require to be machined. Note that these holes require counterboring; note also the two dowel holes, which will require reaming.

Four separate operations are required on this component:

(i) drill four 10 mm diameter holes,
(ii) counterbore four holes of 15 mm diameter,
(iii) drill two holes, 9·2 mm in diameter,
(iv) ream two holes of 10 mm diameter.

A drilling jig is required, and must be designed to locate and clamp the machined forging further illustrated in fig. 7.5.

We are not at this stage concerned with the design and manufacture of the drilling jig required, although this kind of work would prove a useful exercise in the application of some of the principles and techniques covered in this and previous volumes.

We see from fig. 7.5 that six holes require to be machined, as follows:

(i) four holes drilled 10 mm diameter and counterbored 15 mm diameter;
(ii) two holes drilled 9·2 mm, and reamed 10 mm diameter.

All the above operations are carried out using the same drilling jig and in one clamping of the component. The essential stages are shown in fig. 7.6, where it can be seen that four spindles are used. The procedure is as follows:

(i) drill four 10 mm diameter holes;
(ii) drill two holes 9·2 mm in diameter,
(iii) remove drilling bush for 10 mm diameter holes, replace with 15 mm counterboring bush and counterbore four holes,
(iv) remove 9·2 mm drill bush and replace with 10 mm diameter reaming bush; ream two holes.

Note the use of slip and liner bushes, as shown in fig. 7.6B. The liner bush is a drive fit in the top plate of the drilling jig; a good example of the need for precision machining to produce a desired fit. The slip bush is a push fit into the liner bush, and once again we see the need for precision work in the manufacture of engineering components.

The gang drilling machine may be equipped with guide strips to help locate the drilling jig and prevent its rotation. Each spindle has independent drive, and the rev/s are set to suit the particular operation in hand.

Once again the holes required in the forging shown in fig. 7.5 may be drilled, counterbored and reamed, not only to a consistent degree of accuracy, but also at a high rate and using relatively unskilled personnel. If, however, as is common practice, one operator carries out the drilling described, then a certain disadvantage results. Although the drilling machine used

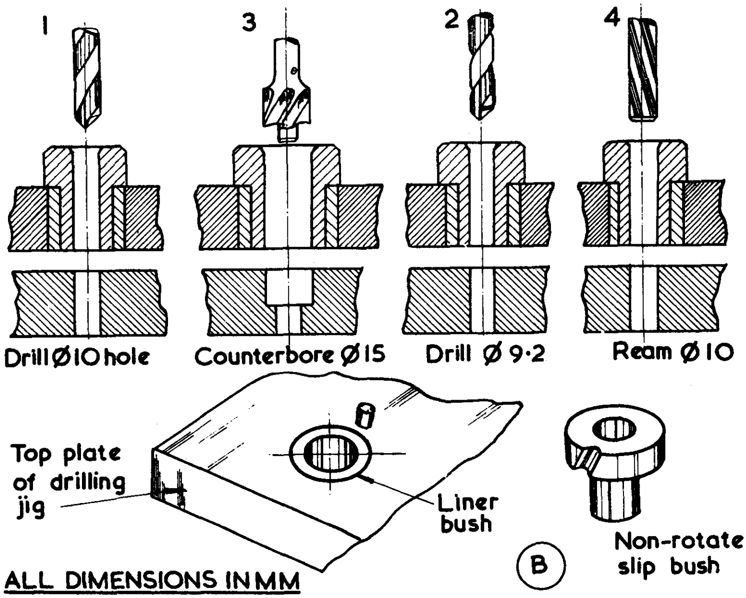


Fig. 7.6.—Use of Slip and Liner Bushes.

has four spindles, only one spindle is in use at a given time. This means that three spindles are rotating but not actually employed in the removal of metal, so that the operation of the drilling machine is not as efficient as it might be. This defect has led to the introduction of **multi-head** drilling machines.

7.4.2 Multiple-head drilling machines

These drilling machines represent perhaps the most efficient method of hole drilling. Several drills are presented to the workpiece simultaneously; there is no idle spindle time except during the loading and unloading of the component.

In both the previous examples of drilling techniques, consistent accuracy is achieved with the principle of drill-guiding or the use of hardened and tempered drill bushes. Multi- or multiple-head drilling machines need no drill jigs or drill bushes. Holes of different diameters, counterbores and tapped holes are readily machined in the one setting. For very high production figures upwards of 100 holes may be drilled simultaneously using special-purpose machines.

7.5 Broaching holes

The technique of broaching represents a marked departure from the more orthodox method of finishing a hole by rotation of a cutting tool such as a drill or reamer. It is important to appreciate that broaching holes is essentially a finishing process—the hole must already be machined to close on finished size. The normal method of giving a drilled hole a good finish is to pass a suitable reamer through it at slow rev/s and a fairly slow feed. This is a slow

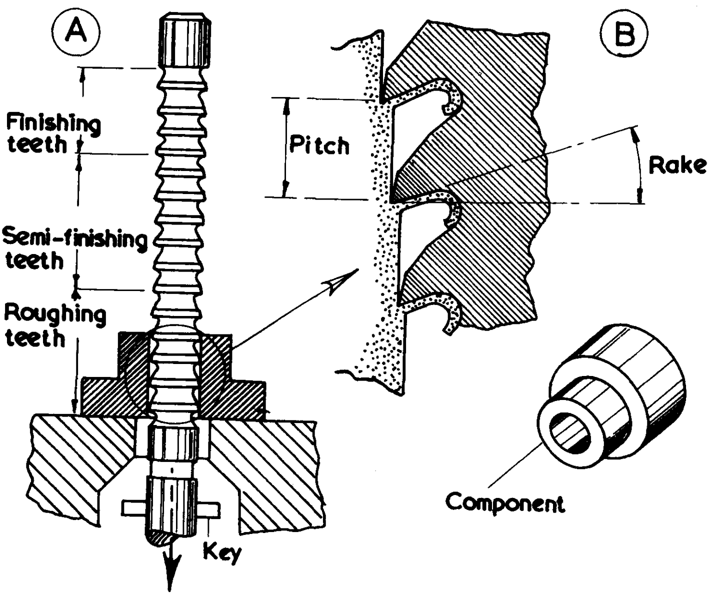


Fig. 7.7.—Technique of Broaching Holes.

process, and any wear on the reamer must result in the production of under-size holes. Although machine reamers are provided with a taper, allowing the leading edge of the reamer to do most of the roughing, with less work for the latter part of the reamer, rapid wear takes place if the reamers are used for mass-production purposes. Thus the machining of holes to close dimensional limits and possessing a good surface finish is no easy matter if reamers are used as a method of finishing previously drilled holes.

Broaching has largely replaced reaming when large numbers of holes are required, because a well-made broach has a long and accurate life; the broach is equipped with both roughing and finishing teeth. A typical broach is illustrated in fig. 7.7. This broach is a simple pull-type, that is to say the broach end is fed through the hole, joined to the pulling device by a key and pulled through the hole.

Note that the operation shown in fig. 7.7 consists in broaching a round hole, and the broach is circular. At B we see a closer view of the broach teeth; note that succeeding teeth are of larger diameter, with each tooth performing a given amount of work or removing a fixed quantity of metal. The first third of the broach is made of roughing teeth, which remove more metal than the semi-finishing teeth which follow them. Lastly the finishing teeth complete the work, and these teeth remove a relatively small amount of metal, with the last three or four teeth on finished size.

In this way the finishing teeth, which control the size of the hole and thus the life of the broach, have very little metal to remove; the greater part of the metal removal is achieved with the roughing teeth, and this means that the broach has a long, accurate life, and is capable of producing a very large number of well-finished and close-dimensioned holes in the minimum of time. It must be remembered, however, that the manufacture of broaches represents a very high standard of precision engineering, with the result that broaches are costly pieces of equipment and must be handled and treated with the greatest of care. Broaches are also eminently suitable for the production of the internal splined form shown in fig. 7.8, the broach having a similar cross-section to the internal profile of the component.

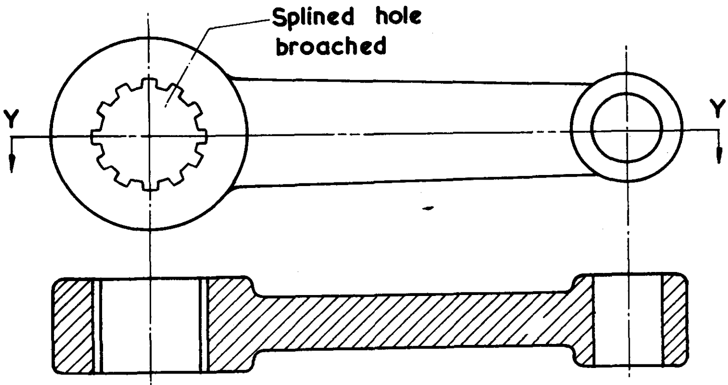


Fig. 7.8.—Component requiring a Splined Hole.

7.6 Jig boring

All the drilling examples given above refer to the production of holes on a production basis. The aim at all times is to produce well-finished holes within the limits laid down. We have seen that this is achieved with the aid of drilling jigs or multiple-head drilling machines, in which the accuracy required is built into the jig or machine used.

Clearly the manufacture of these devices requires the drilling of holes to very close dimensional limits, work which is quite outside the scope of sensitive, pillar and even radial drilling machines. When holes are required to very close dimensional tolerances with respect to both diameters and hole centres, the technique used is more usually that known as **jig boring.**

7.6.1 Principle of jig boring

Although several types of jig borer are available, there is a common principle underlying their design and operation; namely precise linear control of the worktable together with vertical control of the spindle. The difference between the types of jig borer is determined by the methods adopted to obtain precise control over the linear movement of the worktable; these movements are shown in simple form in fig. 7.9. It is clear that a jig borer is somewhat similar to a compound-table drilling machine, except that it is of much more rigid construction, with more positive methods of controlling the worktable movement.

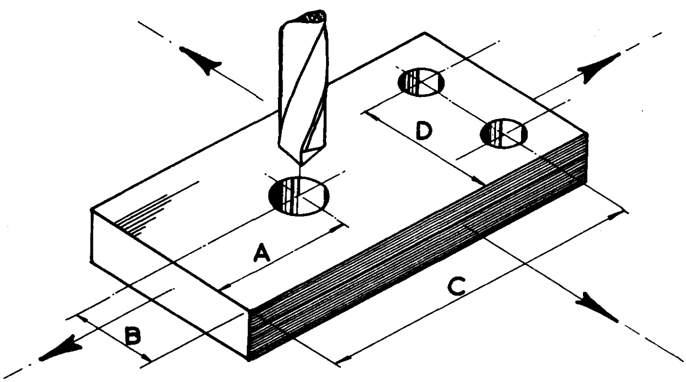


Fig. 7.9.—Co-ordinate Movements when Jig Boring.

The location of the first hole is determined by the linear dimensions *A* and *B*, both taken from the ends of the component, which may be considered as datum faces. Note that the positions of the other two holes are controlled by the linear dimensions *C* and *D*. The location of these three holes is a good example of the principle of rectangular co-ordinates introduced in *Workshop Processes* 2, Chapter 5, page 84. The purpose of a jig borer is to make possible the positive adjustment of the worktable in the directions of the arrows in fig. 7.9, to an accuracy of plus and minus two micrometres.

In general two systems are in use by which accurate linear control of the table can be maintained:

(i) the use of end standards,
(ii) the use of scale and microscope.

7.6.2 End standards method

Fig. 7.10 illustrates in a simple manner the principle underlying the use of end standards as a means of controlling the linear movement of the worktable in a jig boring machine. At A we see the set-up for the drilling of the first hole. Note the dial indicator securely clamped to the fixed member of the worktable, and the adjustable stop attached to the moving worktable. If the centre distance between the two holes is to be 127·595, then a slip build-up of this amount is placed in position, and the worktable is brought up until the dial indicator reads zero.

The first hole is now drilled to the required diameter, or a boring head may be used. The problem involved in moving the worktable a linear distance of 127·595 is now easily solved; it is only necessary to remove the slip build-up

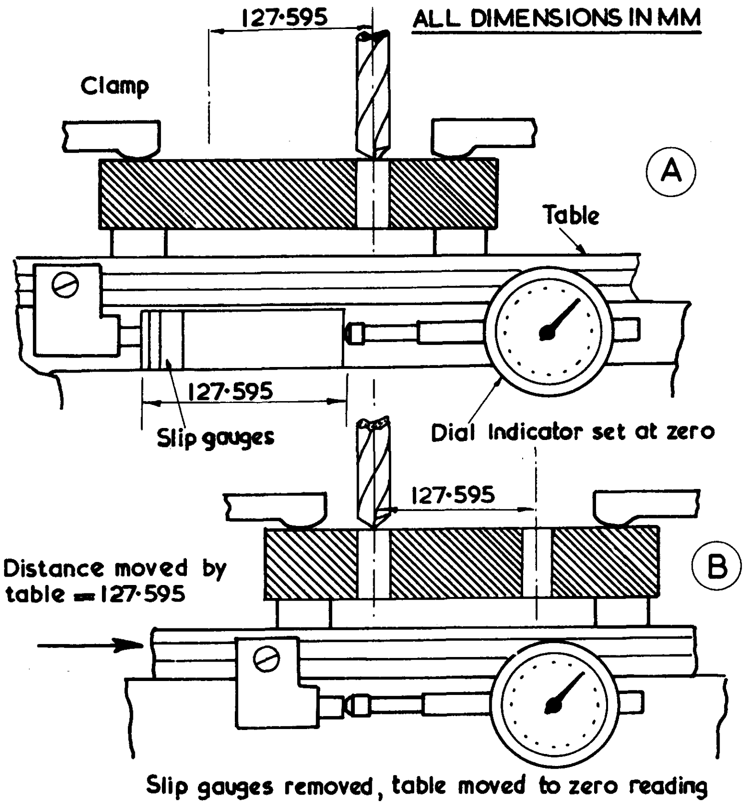


Fig. 7.10.—Control of Linear Table Movement when Jig Boring using Slip Gauges and Dial Indicator.

and bring up the worktable until the dial indicator reads zero on contact with the adjustable stop. The second hole may now be machined with complete assurance that the table has been moved the amount required.

A similar method is adopted to ensure that the movement of the worktable is also controlled at 90° to the first movement, and if the centre distances of the holes are in excess of 250 mm, end measuring bars are employed; their use has already been discussed in Chapter 2. Note that the dial indicator in the set-up shown in fig. 7.10 is used as a zero indicator and not as a measuring device. Its purpose is to eliminate the variation in pressure that is likely to take place when the operator brings the table up against the fixed stop; the dial indicator now acts as a tell-tale.

Another method of controlling the worktable movement of a jig borer involves the use of precision hardened rollers of 25 mm diameter. These rollers are accurate to within 0·5 μm, and are chromium-plated to increase their working life.

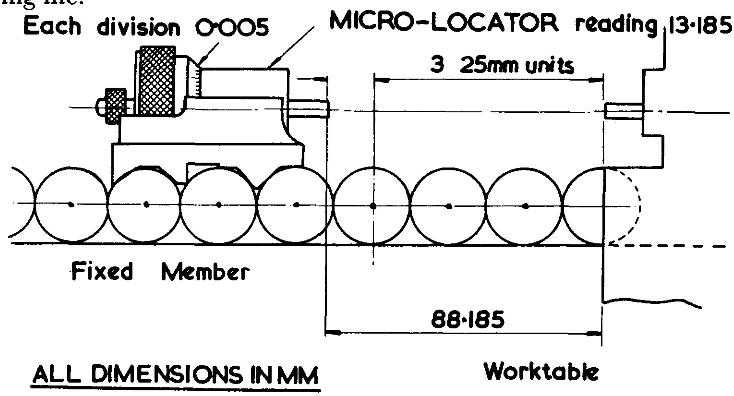


Fig. 7.11.—Application of Precision Rollers and Micrometer Head for Precise Table Movement.

Fig. 7.11 shows the basic principle involved. Each roller provides an inch measuring unit, and location of the table to within less than 25 mm is obtained by means of the micro-locator shown in the diagram. This is a micrometer device with a large-diameter thimble which provides accurate readings to two micrometres. Once again dial indicators are used as zero positioning devices. With a micro-locator placed each side of the worktable, movement of this table is achieved by moving the micro-locator across the rollers giving 25 mm steps, and then using the micrometer to obtain the remainder of the distance required. The diagram shows the set-up for a table movement of 88·185 mm; note that the dial-indicator device is not shown. This technique is a simple but effective method of controlling the movement of the worktable, and the drilling and boring of holes having their centres to within a tolerance of plus and minus two and a half micrometres presents little difficulty.

7.6.3 Scale and microscope method

As the name suggests, this method makes use of a fixed scale or line standard with an optical device to obtain precise setting of the worktable. There are no moving parts and no possibility of damage to the measuring devices.

7.6.4 Modern techniques

It is now possible to drill and bore holes having their centres to within plus and minus two and a half micrometres using a numerical control system. Instead of the operator of the jig borer setting the movements of the worktable, information is issued in the form of punched holes in cards. This information is recorded on tape and fed into a special device which actuates and controls the movement of the worktable. The rectangular co-ordinate principle is still employed, giving precise movement of the table in the direction of the large arrows shown in fig. 7.9. It is possible to operate a battery of jig borers, all performing an identical operation, using one master tape. No operators are needed, and the human element is completely eliminated.

7.6.5 Boring

Boring a hole is not quite the same thing as drilling a hole. The boring of a hole is essentially an opening-out operation, and can only be performed on an existing hole. We have seen during our discussion on the centre lathe that holes may be bored from the tool post, using a boring bar. In this case the

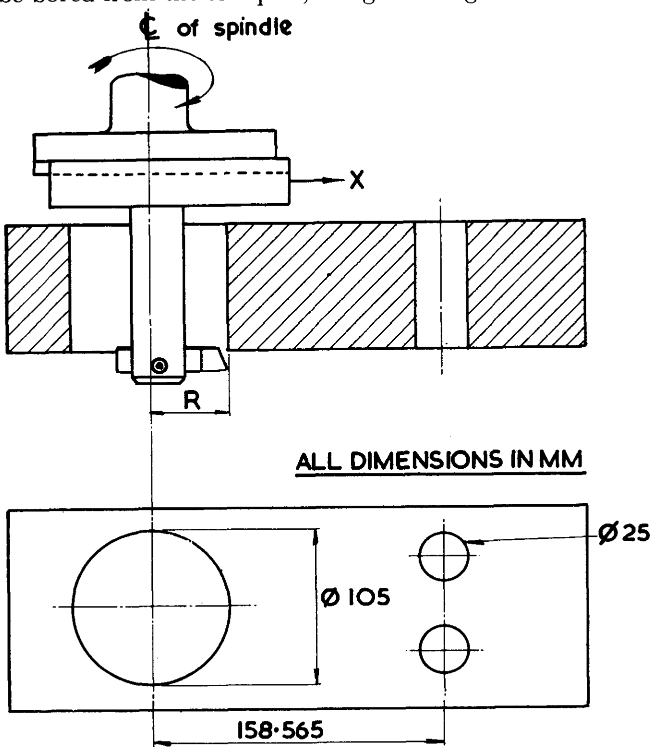


Fig. 7.12.—Principle of the Boring Head.

internal cylindrical surface is generated by a combination of work rotation and tool feed.

Much the same technique is used when boring holes at the jig borer, except that the boring bar or cutter rotates under feed while the workpiece remains stationary. Both techniques, however, have the same aim in view, namely the bringing of the hole to a specified diameter and to certain limits of alignment.

The principle of vertical boring is shown in fig. 7.12. It will be seen that if control is to be maintained over the diameter, then precise movement of the cutting tool in the direction of arrow X is required. It must be understood that the first essential is to ensure that the work centre has been brought truly to the spindle centre, for increase of the effective cutting radius shown as *R* affects only the diameter produced; the centre distance is unaffected.

In the example shown in fig. 7.12 the centre distance between the large hole and the two small holes is 158·565 mm. The need for boring is clear, for the large hole has a diameter of 105 mm. As the diagram shows, the use of a boring head permits increase of the radius *R* but, as pointed out, the worktable must be moved a distance of 158·565 mm before machining of the large diameter is commenced. The example shown is precisely the sort of work that jig borers are capable of performing, and it is also possible to carry out a limited amount of milling.

7·7 Horizontal boring

Horizontal boring may be compared with the technique of the vertical boring and turning of large-diameter work dealt with in Chapter 6. Horizontal borers, as they are commonly called, are always used for large forgings or castings which may require several large bores to be accurately machined in line. A typical component is illustrated in fig. 7.13. This is a

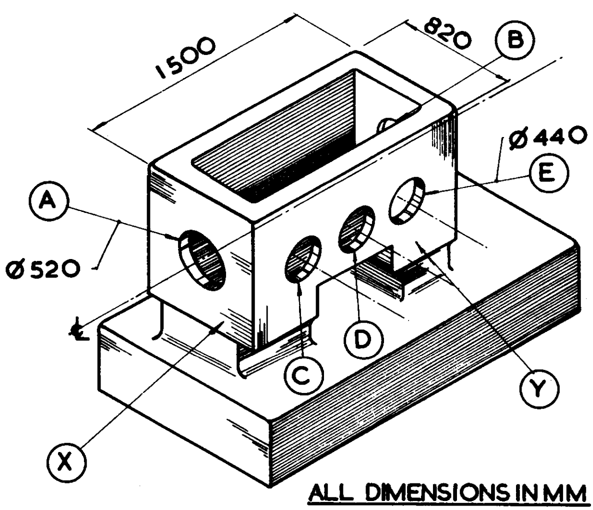


Fig. 7.13.—Typical Component for Horizontal Boring Machine.

large grey cast iron casting and is to be used as the body of a special-purpose gearbox unit. Note the large bores at both the front, rear and one side of the casting. The centre line of the 520 mm diameter bores must be at 90° to the face X, and also at 90° to the centre lines of the holes C, D and E. Both face X and face Y must be truly vertical to the base of the casting.

If accuracy with respect to the above geometric conditions is to be obtained during the machining of this component, it is desirable that as much machining as possible be carried out in one setting of the casting. Clearly the operations required are boring of the cored holes and machining of the faces X and Y. If at the same time it is possible to index the work 90°, then apart from the hole diameters, the geometric accuracy of the machining will be equivalent to the geometric accuracy inherent in the machine tool used.

Perhaps fig. 7.14 will serve to illustrate the geometrical requirements of the casting shown fully machined in fig. 7.13. The pictorial view shows that the axes of the holes are at 90° to each other and perpendicular to the faces X and Y. At the same time the axes of the holes must be parallel with the base of the casting, with distance *H* a constant value. Added to these somewhat exacting geometric requirements, the axes of the three holes must be parallel with each other.

7.7.1 Tooling and feeding on a horizontal borer

A hole is produced on a horizontal borer using a boring bar. This is shown in fig. 7.14. Note that the hole is generated by the feed of the work, as shown

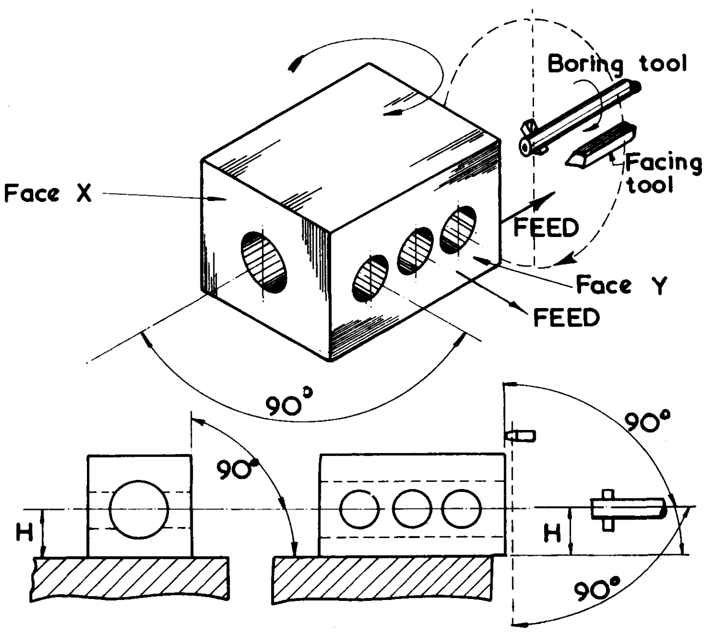


Fig. 7.14.—Essential Movements of the Horizontal Boring Machine.

in the pictorial view. If, now, provision is made for feeding the work at 90° to the direction of boring, with a single-point cutting tool caused to rotate, it is a simple matter to machine or face at precisely 90° to the axis of the bored hole. No setting is required from the operator of the machine, merely the engagement of the automatic feed actuating the movement of the work-table on which the casting is securely clamped.

Extension of this important principle of making the fullest use of the geometric movements built into a machine tool leads to the use of an auxiliary table top. This table top may be rotated and indexed in 90° positions, and may also be adjusted and set at any other angle.

Provided an auxiliary table top is used, the casting shown in fig. 7.13 may be completely machined in one setting, although it is necessary that the base of the casting be first machined and used as a datum face.

7.7.2 Essential features of the horizontal borer

Fig. 7.15 illustrates in a simple manner the essential features of a typical horizontal borer. The main parts are named and their respective movements indicated, and details of the facing head are also shown. With the boring-bar holder removed and the facing tool in position, automatic feed of the cross slide allows facing of a casting clamped on the auxiliary table. Indexing of the auxiliary table top at 90° brings another face ready for machining at precisely 90° to the first face.

Holes may be drilled and bored from the spindle, and for long bored holes a long boring bar may be supported by locating in the bearing provided in the end column support. In this event the hole is generated by feeding the table towards the headstock. Holes of smaller length may be bored by feeding an unsupported boring bar held in a suitable holder attached to the facing head, generation being achieved by horizontal feed of the spindle.

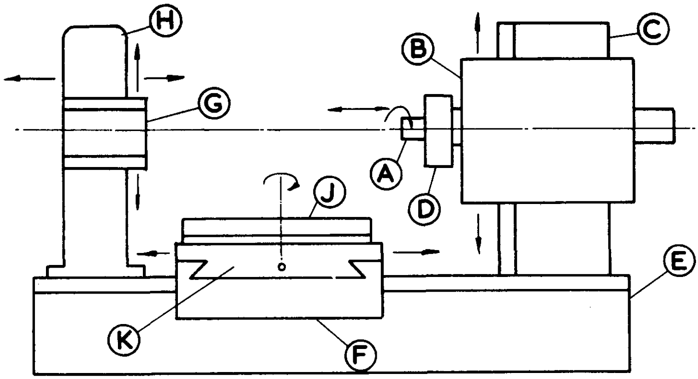
It should be clear at this stage that the production of accurate work on a horizontal boring machine calls for a very high degree of skill from the crafts-man in charge of this expensive and formidable machine tool, designed exclusively for the machining of large and heavy castings.

Snout boring, face milling and surfacing are typical operations possible, together with the boring of holes from 15 mm diameter to 500 mm diameter to close tolerances.

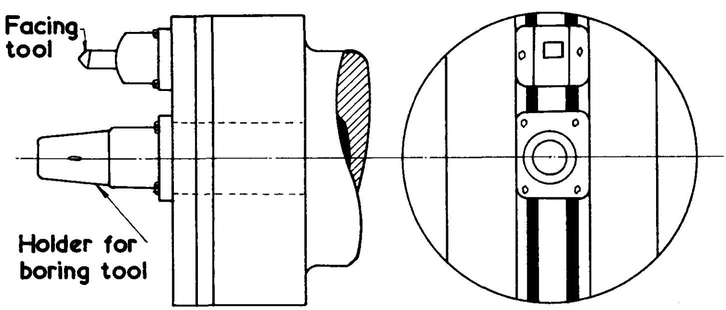
Summary

It is generally accepted that the production of an internal cylindrical surface to close dimension tolerance is one of the most difficult of all machining operations. It may be remembered that in Chapter 3 mention was made of the recommendation in BS 4500 that holes be given a tolerance one grade coarser than that given to the shaft which is to mate with them. It is because of the difficulty of producing holes to close limits that this recom-mendation is made, and this difficulty also accounts for the fact that the most expensive general-purpose machine tool is the jig borer.

We have seen that hole drilling for single or small batch production is carried out on either sensitive, pillar or radial drillers, depending on the size



	DESCRIPTION	MOVEMENTS
A	SPINDLE	Rotate and feed
B	HEADSTOCK	Vertical, up and down
C	COLUMN	
D	FACING HEAD	Rotates
E	BED	
F	SADDLE	Feed along bed
G	SUPPORT	Vertical (with headstock)
H	END COLUMN	Along bed
J	AUXILIARY TABLE TOP	Rotate and index at 90°
K	CROSS SLIDE	Feed at 90° to bed.



FACING HEAD

Fig. 7.15.—Elements of the Horizontal Boring Machine.

of the workpiece to be drilled and the diameters of the holes required. On all these machines dimensional accuracy with regard to hole centres or the linear dimensions of these centres from datum faces is not easy to achieve, and when very close or precise dimensional accuracy is required a jig boring machine is used.

The principle of rectangular co-ordinates is widely adopted for the location of hole centres and subsequent drilling or boring, and a sound practical working knowledge of trigonometry is a must for the efficient craftsman who aims at getting the best out of his machine.

Modern developments make use of punched cards and tape, whereby automatic positioning of the worktable is achieved, eliminating the necessity for any setting by the operator of the machine.

When holes are required in components that are to be produced in large numbers, three techniques are adopted, depending on the nature and size of the component.

If the part is produced from press tools in relatively thin metal, it is certain that the holes will be pierced as part of the pressing operation. When the thickness of the metal prevents this technique, the principle of drill-guiding may be adopted, in which case the dimensional accuracy of the drilled holes is obtained by the use of concentric drill bushes accurately located in drill jigs.

The use of drill jigs may require the application of multiple-spindle drilling machines arranged in line (sometimes called gang drillers), but if these machines are to be worked by a single-operator, then only one spindle at a time will be usefully employed in the removal of metal. Thus the most efficient method of producing large numbers of holes in a single component consists in the use of a multiple-head drilling machine, with upwards of 100 drilling spindles engaged in the simultaneous drilling of holes.

Finally, the production of large-diameter holes demands the use of a horizontal boring machine, and as the alignment of these bored holes is in respect to the machined surfaces from which the holes are located and drilled, the design and operation of the horizontal borer provides an interesting example in the importance of the best use of the geometric movements built into the machine tool.

Although the principle of broaching was touched upon in a simple manner, it must be appreciated that broaching is akin to reaming. It is a hole-finishing operation; a broach, like a reamer, cannot start its own hole, yet for the finishing of accurate holes on a mass-production basis it has no equal. Although perhaps representing the ultimate in the precision engineering of a hardened component, resulting in a highly expensive cutting tool, the internal broach has opened the way to the precision machining of external surfaces to tolerances within plus and minus twenty micrometres, the parts being machined on a mass-production basis.

EXERCISE 7

1 For the following drilling machines, outline a typical drilling operation, mentioning the type of cutting tool used and the appropriate spindle speed:

(i) sensitive drilling machine,
(ii) pillar drilling machine,
(iii) radial drilling machine.

2 State the advantages of piercing ten 4 mm diameter holes in a component made from stainless-steel strip. Make a neat sketch showing the principle involved, and state the limitations of the piercing process.

3 Make a neat sketch of a component requiring the use of a drill jig in order to ensure that the part may be mass-produced. Describe two factors that may result in the drilling of reject work.

4 Describe the essential difference between a multi-spindle and a multiple-head drilling machine. Which machine performs the drilling operation in the most economical manner?

5 Describe with the aid of simple sketches the technique of internal broaching as applied to the finishing of holes on a mass-production basis.

6 Make a neat sketch of a component that would require a number of holes to be jig bored. With the aid of simple sketches, show how precise linear control of the worktable is obtained.

7 Explain, with a typical example, the necessity for the boring rather than the drilling of a hole in an engineering component. Show by means of a neat sketch the geometric movements necessary to bore a hole to a precise dimension and to close dimensional tolerances from a datum face.

8 By means of a neat diagram, outline the main features and movements of a horizontal boring machine.

9 Sketch a typical component that would require the use of a horizontal borer for the production of large-diameter holes in close alignment to machined surfaces.

10 Show, by means of neat sketches, the device that makes possible the machining of the four sides of a large casting at 90°. Show also how a single-point cutting tool may be used to machine the surfaces as set up on a horizontal boring machine.

8 Milling Machines

8.1 Introduction

In *Workshop Processes* 2, Chapter 10, we saw that two main types of milling machines are in general use:

(i) horizontal milling machines,
(ii) vertical milling machines.

The terms horizontal and vertical refer to the axis of the spindle, for the technique underlying the generating or forming of geometric surfaces using a milling machine consists of rotation of the cutting tool in conjunction with a feed movement of the worktable. Although the vertical milling machine is capable of a more versatile range of work, the horizontal machine is preferred for heavy cuts. This is because of the greater support and rigidity afforded to the milling cutter by the arbor and its support.

Since the milling cutters used are multi-point (that is to say they have more than one cutting point), the rate of metal removal can be very high, and milling machines are often to be found on production lines. The range of work possible using a horizontal miller is shown in fig. 8.1.

8.2 Milling operations on the horizontal miller

8.2.1 Plain milling

Fig. 8.1A illustrates the technique known as **plain** or **slab** milling. With the work securely held in a rigid fixture, this is a quick and efficient way of producing a plane surface parallel to the axis of the cutter. It is suitable as a method of machining a first operation to provide a datum face from which further machining may be undertaken.

Slab mills seldom exceed 120 mm in length, while the diameter is restricted to about 100 mm. Thus the size of the cutter places a limitation on the area that can be milled. When fairly large areas require milling the technique of face milling is adopted.

8.2.2 Face milling

A face-milling cutter generates a surface at 90° to its centre line. The technique is illustrated in fig. 8.1B; note that the machined face is at 90° to the axis of the cutter. The diameter of face cutters is seldom less than 120 mm; the smaller sizes are often referred to as **shell end** mills, as described in *Workshop Processes* 2, Chapter 10. Larger-diameter cutters are of the inserted-blade type, with much use of cemented carbide (mentioned in Chapter 4 of this volume) as the blade material. Note that raising of the worktable enables a second cut to be taken, and that because no arbor is used relatively

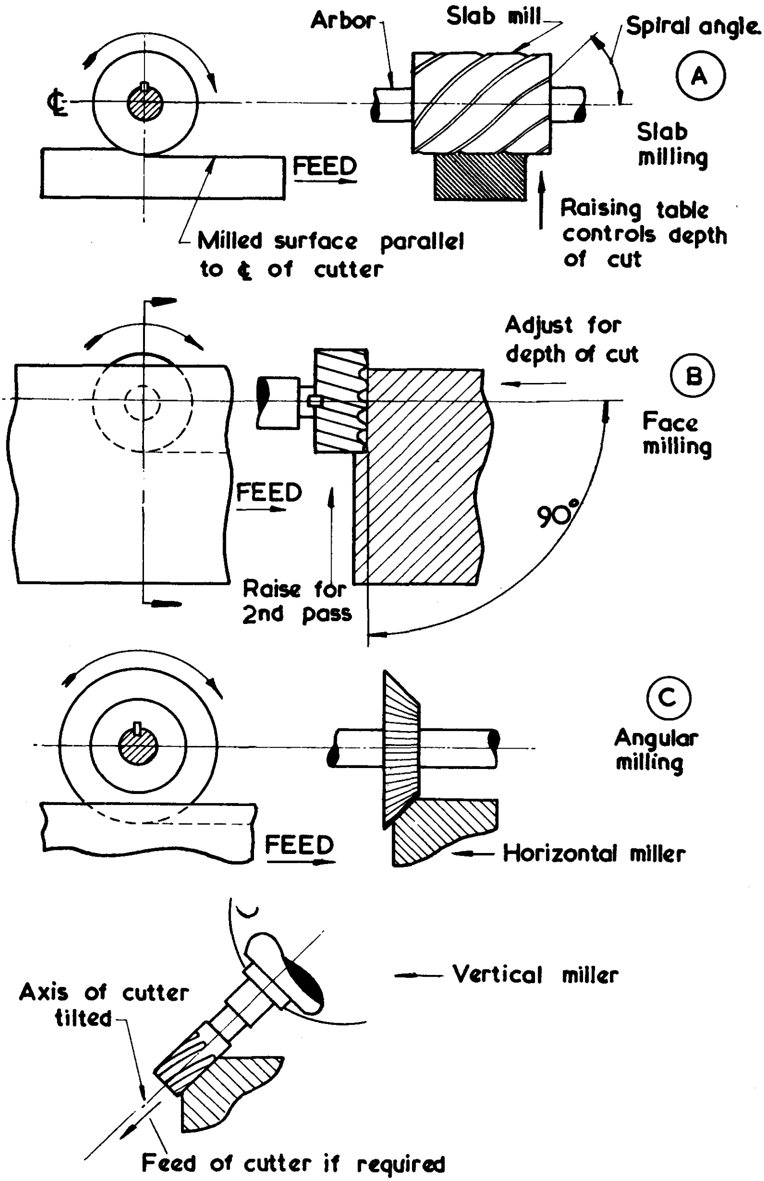


Fig. 8.1.—Horizontal and Vertical Milling Techniques.

large areas can be machined. The close proximity of the facing cutter to the headstock of the milling machine promotes good rigidity, an essential requirement for the efficient removal of a large volume of metal. Remember that while the application of slab milling is restricted to horizontal milling machines, face milling may be carried out on both horizontal and vertical types.

8.2.3 Angular milling

Angular milling, as the name suggests, consists in the production of a milled face at an angle to the centre line on the cutter axis. The technique differs slightly, as reference to fig. 8.1C shows, according to whether the operation is carried out on a vertical or a horizontal milling machine. Angular milling at the horizontal miller can only be achieved with the use of angular or form milling cutters. The principle is illustrated in fig. 8.1C. It must be remembered that the arbor of a horizontal miller is permanently set at 90° to the worktable feed; there is no provision for any movement of the cutter other than rotation. The vertical miller, on the other hand, may have the cutter axis tilted as shown in fig. 8.1C, and it is also possible to feed the cutter in a direction parallel with its axis.

It is important to appreciate that, with the exception of contoured or profiled surfaces and the milling of spirals, all milling operations consist of one or more of the techniques outlined above. When these surfaces are required on a production basis special-purpose milling machines are used, the object being to speed up the milling operation, and in general the following techniques are adopted:

(i) Reduction of non-machining times by provision of rapid traverse of the worktable up to the cutting point, with automatic application of the correct feed, automatic stop and rapid traverse back to starting point.
(ii) Removal of greater volume of metal by providing greater rigidity of set-up and machine tool.
(iii) Utilisation of two or more cutters.
(iv) Use of rotary tables.

8.3 Fixed-bed millers

Fixed-bed millers are similar in principle to horizontal millers, but are larger, heavier and of more rigid construction. The very fact that the bed is fixed contributes to this, and it means, of course, that whereas on the horizontal miller the table can move vertically, on the fixed-bed miller any variation in the distance between the cutter centre and the top of the worktable must be achieved by adjustment of the cutter slide. This limits the capacity of the machine, but even so the machine is eminently suitable for the mass-production milling of the medium-sized component.

Fig. 8.2 illustrates in outline the elements of the fixed-bed-type milling machine. Note that only two movements are available apart from the rotation of the cutter, namely feed of the table and vertical adjustment of the cutter spindle. Many of the fixed-bed millers of the type illustrated are provided with automatic machining cycles, permitting a predetermined sequence of operations to be carried out.

Thus the operator of the machine merely loads it by placing and clamping the workpiece in the milling fixture which is clamped to the table, and then presses a button. Immediately the workpiece is fast traversed to the rotating cutters, followed by metal removal at a predetermined feed, with automatic stopping of the cutters as the work is fast traversed back to the starting point.

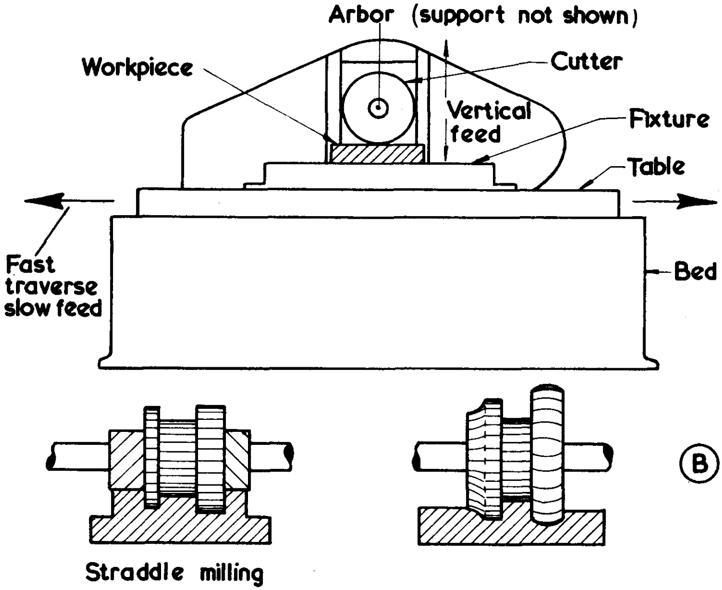


Fig. 8.2.—Fixed-bed Milling Techniques.

It is possible that the operator may be looking after two or more machines, in which case loading or unloading will be taking place at one machine while cutting takes place at the other. In this way the milling action may be considered as continuous, although two or more machines are in use.

8.4 Duplex milling machines

Duplex milling machines make use of the technique of employing two

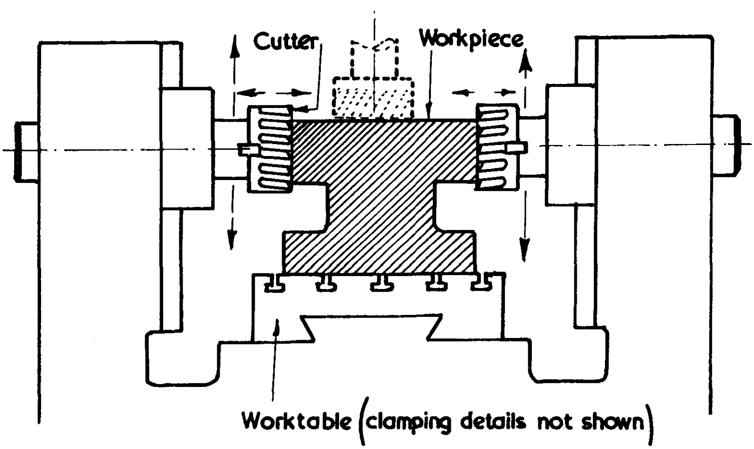


Fig. 8.3.—Principle of the Duplex Milling Machine.

cutters in order to increase the efficiency of the milling operations carried out. An end view of a duplex milling machine is shown at fig. 8.3. It may be appreciated that the type illustrated has a fixed bed. Note the vertical movements available for the cutter axis, as well as the horizontal adjustment.

We may consider this machine as a multi-purpose facing machine, very suitable for the machining of parallel faces on relatively large castings such as machine-tool slides. In special cases a cutter may be in the position shown in the diagram by dotted lines; such a machine would be known as a **triplex** milling machine.

8.5 Rotary-table production milling

The technique of rotary-table milling represents perhaps the ultimate in production milling. We have seen that the principle of one operator operating two or more fixed-bed milling machines tends to produce continuous

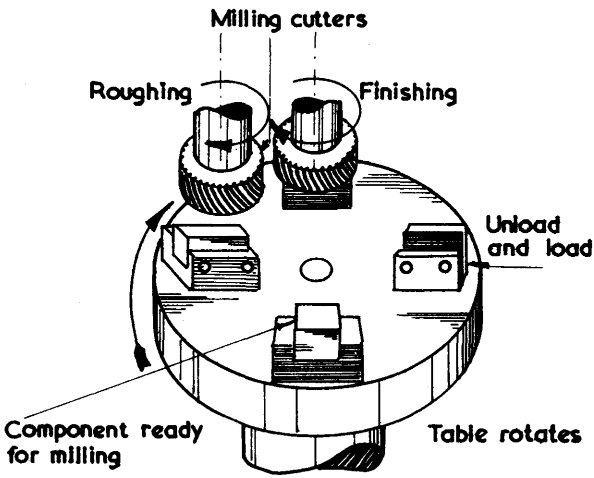


Fig. 8.4.—Principle of Rotary-table Production Milling.

milling. This is precisely the aim in making use of a rotary table when milling components on a production basis. Fig. 8.4 illustrates the principle involved. Note that the rotary table is equipped with identical milling fixtures in which the components to be milled are located and clamped. Rotation of the table brings each component in turn under the milling cutter, and while removal of metal takes place, the operator loads and unloads other components away from the rotating cutter. Most rotary-table milling makes use of special-purpose machine tools employing two or more milling cutters, the machine tools being of very heavy design and construction, giving ample rigidity.

8.6 Up-cut and down-cut milling

It is clear from the simple descriptions given that a wide range of milling machines is employed for the purpose of milling accurate surfaces on engineering components; yet unless the correct type of cutter is used the full advantage of the efficiency of the milling machine will not be obtained. Although the more common types of milling cutters were covered in *Workshop Processes* 2, Chapter 10, no mention was made there of the alternative technique known as down-cut milling.

Up-cut milling is the conventional method of milling, and this technique is shown in fig. 8.5A. It will be seen on reference to the diagram that the rotation of the cutter is in opposition to the feed of the worktable. Thus the tangential force *F* not only shears the metal but also overcomes the feed force of the worktable. At B we see the technique called **down-cut** or **climb** milling. Note that the rotation of the cutter is with the feed motion of the worktable; there is no tendency for the cutter to oppose this feed motion, and thus more power is available for shearing the metal. There are, however, other advantages gained by the adoption of the climb-milling technique. Reference to fig. 8.5A shows that the shear force *F* acts upwards; hence there

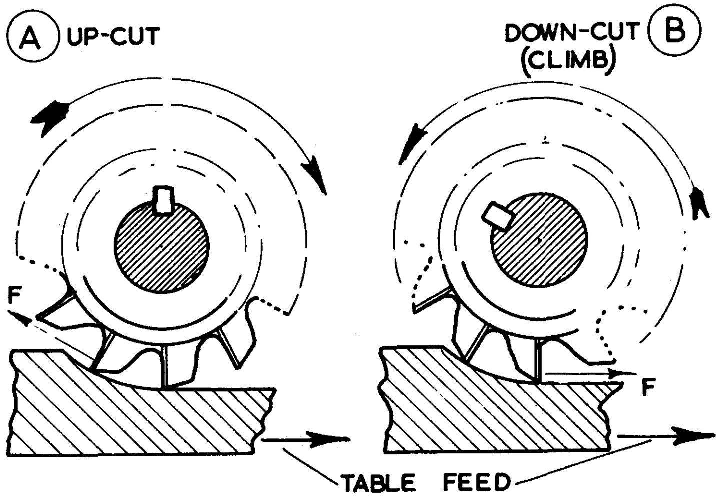


Fig. 8.5.—Up-cut and Down-cut Milling Technique.

is a tendency to lift the workpiece off the table. In fig. 8.5B we see that the shear force acts downwards, and this is a much more suitable situation when heavy cuts are taken. The cutting force is now taken by the worktable with no possibility of vibration or movement; this represents optimum cutting conditions.

Fig. 8.6 shows an enlarged view of a single tooth of a milling cutter about to take a cut during conventional or up-cut milling. The distance BC represents the movement of the table while the tooth of the cutter has rotated through the angle α. This distance is much exaggerated in the diagram; in actual practice it amounts only to a few hundredths of a millimetre. Nevertheless it can be seen that the chip is of zero thickness at the beginning of the cut and maximum thickness at the end. It is difficult for the tooth to take a bite into the metal, and this results in a considerable area of friction at point A in the diagram. Any dulling of the cutting edge of the tooth leads to a marked increase in the amount of friction created at the commencement of the cut, with consequent decrease in the efficiency of the milling operation. Additional power is needed, and the finish of the milled surface deteriorates.

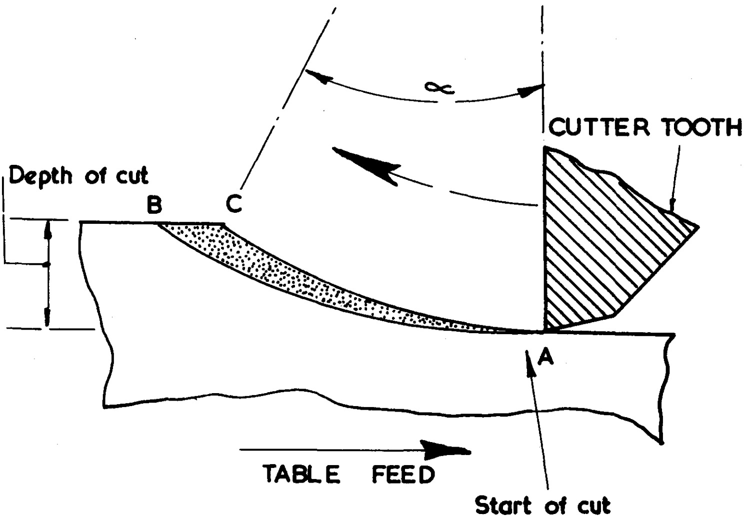


Fig. 8.6.—Tooth Action when Up-cut Milling.

Fig. 8.7 shows an enlarged view of a milling-cutter tooth taking a down-cut action. Point A indicates the commencement of the cut, and it will be seen that the thickness of the chip removed by the tooth of the milling cutter is at

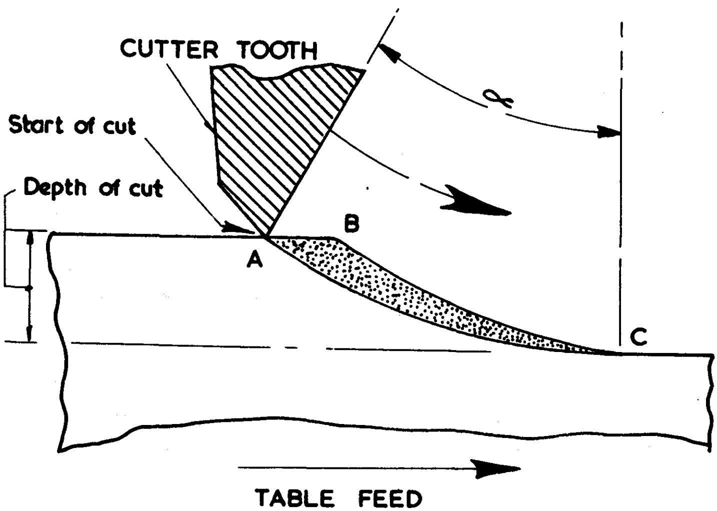


Fig. 8.7.—Tooth Action when Down-cut Milling.

a maximum. Once again the distance AB represents the feed of the table while the tooth revolves through the angle α. The cut finishes at the point C with zero removal of metal, providing a superior finish to that obtained by conventional milling.

Modern milling machines engaged on production milling make much use of the climb-milling technique. We have seen that several different types of milling machines are available, all calculated to provide maximum machining efficiency, in other words maximum metal removal in the minimum of time. If, however, the climb-milling technique is used, it is essential that there be no backlash present in the leadscrew of the milling machine. A special device is fitted to the hardened leadscrew which automatically takes up the wear between the driving nuts and the leadscrew. This device is disengaged if fast traverse is used to bring the work to the cutter, and automatically re-engaged as soon as the climb-milling cut commences.

8.7 Negative-rake milling

We have seen in Chapter 4 that the technique of negative-rake cutting is adopted when machining the harder metals at high speeds; the throw-away type of lathe-tool tip used for this purpose was illustrated in fig. 4.9. Apart from their great superiority over high-speed steels for cutting the harder metals, carbide tips are now available for the cutting of the softer steels, with tantalum and titanium as the main alloying elements. The relative brittleness of these cemented carbides, however, makes the technique of positive-rake cutting unsuitable. The main reasons are shown in fig. 8.8; the reader is also advised to refer back to fig. 4.18, where the advantages of negative-rake lathe cutting tools are shown. In both diagrams it will be seen that the main

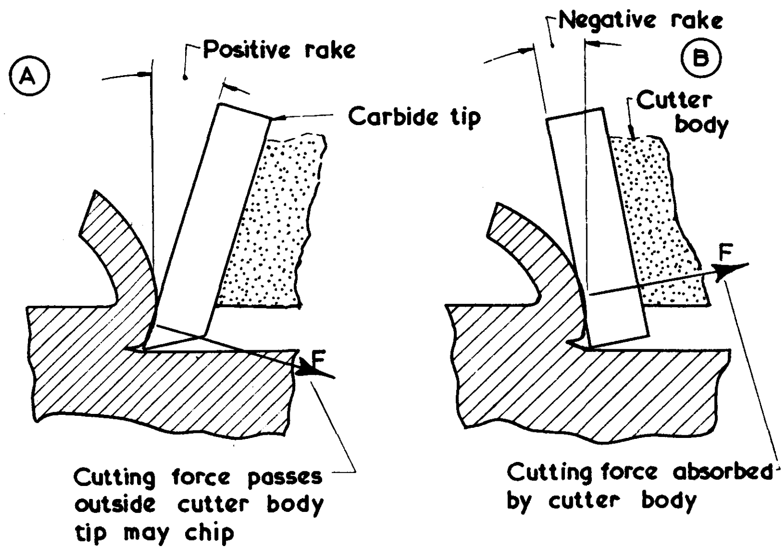


Fig. 8.8.—Positive and Negative-rake Milling.

cutting force is absorbed by the body of the tool when the technique of negative-rake cutting is adopted. A further advantage is that this cutting force acts well up the breast of the tool during negative-rake milling, thus not only reducing the risk of chipping of the cutting edge but also materially increasing the life of the cutting tool.

Note that at fig. 8.8A the main cutting force is not supported by the body of the cutter, resulting in a severe shear plane across the brittle carbide tip. At B we see that the effect of the negative rake deflects the cutting force upwards, enabling the cutter body to provide ample support to the carbide tip.

8.7.1 Negative-rake facing mills

Best results are obtained when the negative-rake milling cutter is provided with a heavy body in which the tungsten-tantalum tips are inserted. The heavy mass of the cutter body rotating at high speed tends to have a

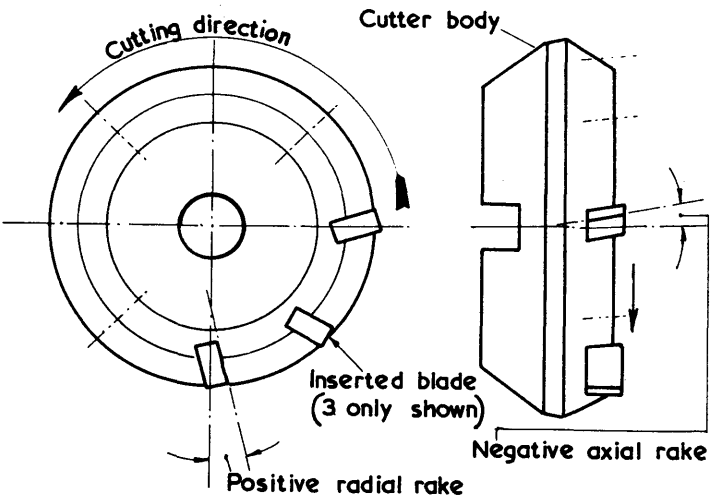


Fig. 8.9.—Inserted-blade Negative-rake Milling Cutter.

flywheel effect, smoothing out any vibration set up by the intermittent cutting action of the blades. The elimination of torsional vibrations promotes a good finish to the milled surface, with complete absence of the wavy effect more commonly known as chatter.

Fig. 8.9 shows, in diagrammatic form, a simple inserted-blade negative-rake milling cutter. Note that the cutter shown possesses both axial and radial rake. It is customary to keep the diameter of the milling cutter greater than the width of the workpiece, as shown in fig. 8.10A. The diagram shows a plan view of the milling operation, with one blade or inserted tooth about to take a cut. Note that the blade makes an angle of 45° as it contacts the workpiece. At B we see a front view of the inserted blade; the shaded area represents the portion of the cutter subject to the severe frictional forces of the fast-moving chip.

8.7.2 Further advantages of negative-rake milling

Reference back to fig. 8.8 shows that the chip is relatively scraped or struck away from the workpiece owing to the negative rake on the cutting blade. All negative-rake milling is carried out using very high spindle speeds, and this means that considerable friction is created at the area of contact. This friction leads to a sudden rise in temperature, lowering the shear stress of the metal so that less power is required to shear the chip. The high speeds employed result in rapid removal of the chip; thus the heat generated is carried away with little or no heating of the workpiece. A very good surface finish results from negative-rake milling, provided a rigid milling machine is used and ample power is available. It is also advised that the feed per tooth exceeds 0·1 mm; up to 0·3 mm per tooth gives excellent results because rubbing of the teeth is prevented.

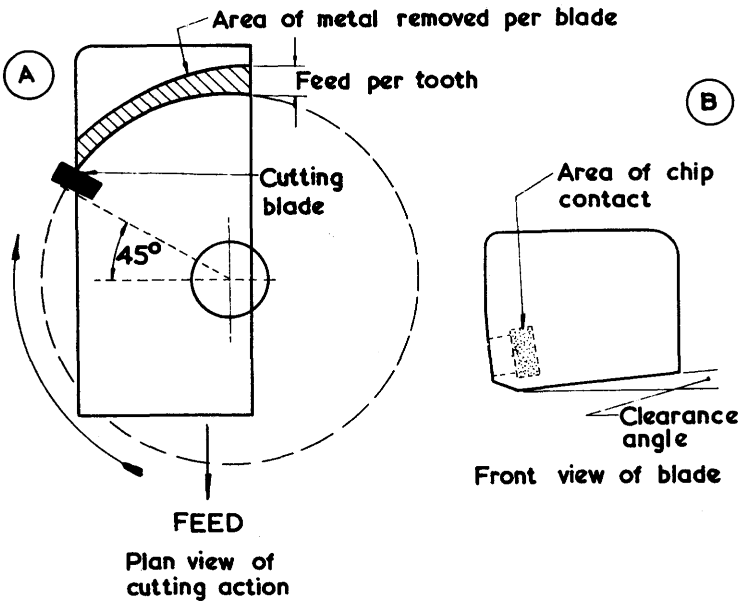


Fig. 8.10.—Cutting Action of Negative-rake Milling Cutter.

8.8 Form milling

Form-milling cutters are used to produce profiled surfaces. A good example of the need for form milling is provided when the top surfaces of the components shown in fig. 8.11 are to be produced using milling machines. It will be seen that the profile of the surface shown at A is a combination of plane and internal and external cylindrical surfaces, and that these surfaces are produced by reproduction of the surfaces of the milling cutters used.

At B we see a rack with which the spur gear shown at C is to mesh. Although the teeth of the rack possess straight sides or flanks, those of the spur gear have the popular involute form. A special milling cutter is needed for the milling of the involute teeth, and it is an essential condition of this cutter that it continues to reproduce an accurate form after repeated sharpenings. The accuracy of the involute form is important if the spur gear is to mesh efficiently with the rack; to obtain this accuracy the cutter is form-relieved.

8.8.1 Form-relieved milling cutters

A form-relieved milling cutter is so machined that, provided the cutter is sharpened by grinding the front faces of the teeth, no change of the tooth contour takes place. Fig. 8.12 illustrates the principle involved; the diagram shows a sectional front elevation of the involute gear cutter used to mill the teeth of the spur gear shown in fig. 8.11C.

The teeth have their front faces lying on a radial plane, as shown in the diagram by the lines *oa, ob, oc* and *od.* In the enlarged view of a tooth it will

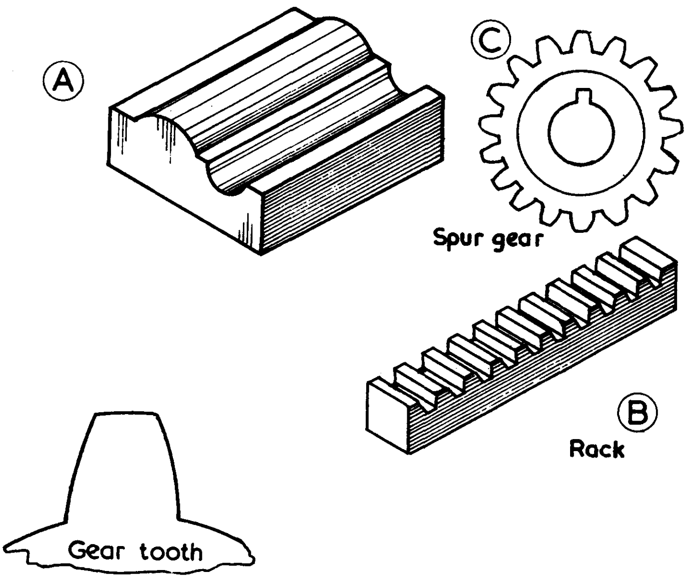


Fig. 8.11.—Applications of Form-relieved Milling Cutters.

be seen that, provided a radial plane is taken, the contour of the tooth remains unchanged. Special form-relieving devices are required for machining the relief on the cutting teeth, and particular care is required when regrinding the cutter to ensure that each tooth is accurately reground on a true radial plane. Form cutters similar to the cutter described above give best results when the cutting faces are brought to a high degree of finish.

8.9 Universal milling machine

The universal milling machine may be considered as a combination of both horizontal and vertical types, with provision for adjustment of the line of action or feeding direction of the worktable. The increased tool and table movements make possible a wide range of milling operations not practicable

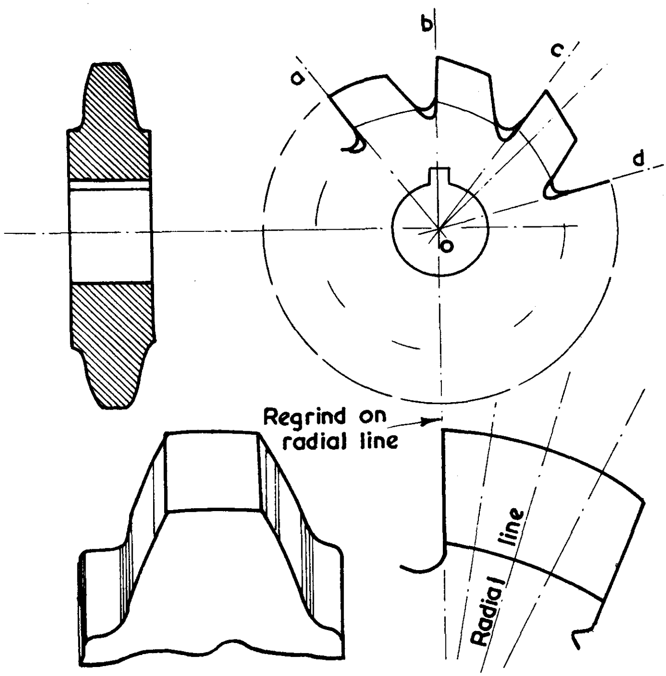


Fig. 8.12.—Principle of the Form-relieved Milling Cutter.

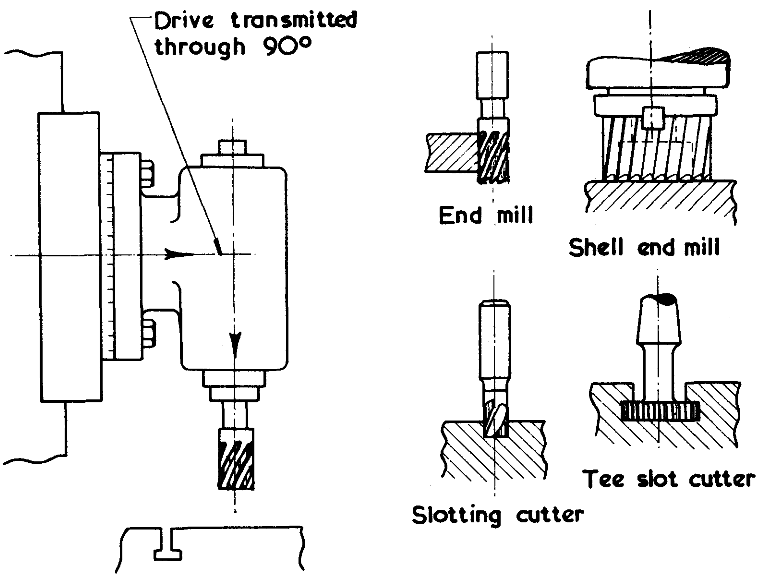


Fig. 8.13.—Vertical-milling Attachment.

with a straight vertical- or horizontal-type machine. Basically the machine is a horizontal miller, but the following attachments are available:

8.9.1 Vertical-milling attachment

This is shown in fig. 8.13, together with the milling cutters and typical operations possible with these cutters. The attachment may be considered as a 90° gearbox device with a ratio of 1:1. When small-diameter milling

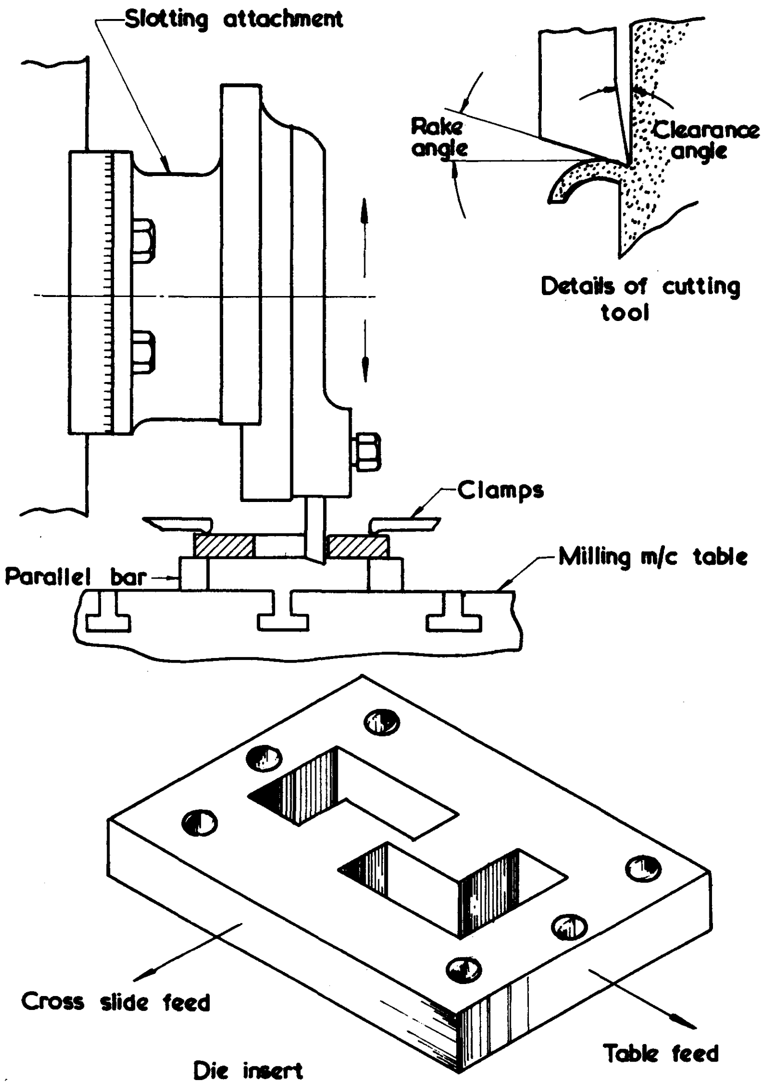


Fig. 8.14.—Slotting Attachment.

cutters are to be used, a high-speed milling attachment may be fitted to the machine instead of the standard-type vertical milling attachment. The high-speed attachment has a speed increase of about 3:1, permitting a wide range of spindle speeds.

8.9.2 Slotting attachment

The purpose of the slotting attachment for a vertical milling machine is to convert the rotary motion of the spindle into reciprocating motion; in this way it is possible to machine slots and keyways. The slotting head is capable of swivelling to any desired angle, and the length of stroke is about 100 mm. Fig. 8.14 shows a slotting attachment together with an example of its use. Note the rake and clearance angles on the slotting tool as shown in the diagram, and the use of the table and cross-slide feed to machine the sides of the die openings at 90°. Because the slotting tool must clear the work at the end of the cutting stroke it is necessary to clamp the work on two parallel bars, as shown in the diagram.

8.9.3 The dividing head

The dividing head is a most important attachment of the universal milling machine. As its name suggests, its main purpose is the location and holding of work in order that machining may take place by suitable division of the work-piece. The gear shown in fig. 8.11C is a good example of a component that requires the use of a dividing head, for if 48 teeth are required the work must be indexed 48 times. Before dealing with the different methods of indexing it is as well to remember that the dividing head is a most versatile work-holding device, capable of holding cylindrical work with the axis horizontal, vertical, or at any angle between the horizontal and the vertical; the work

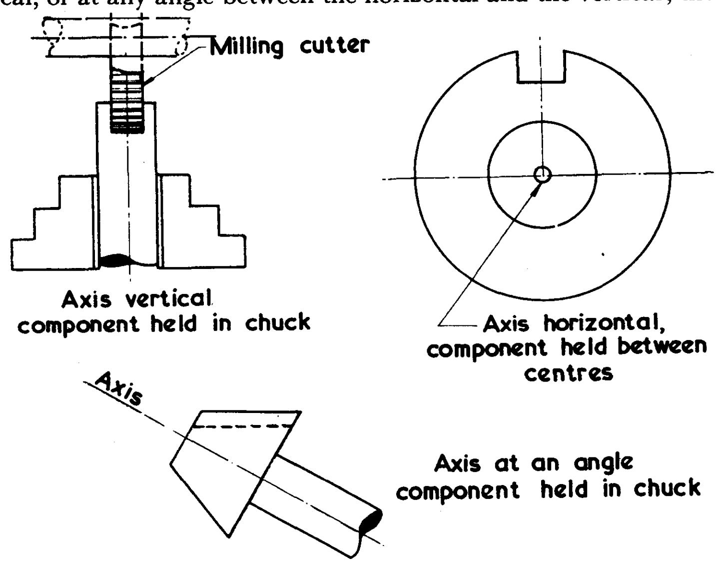


Fig. 8.15.—Axis Positions Possible with Dividing Head.

can be chucked or held between centres. Three simple examples are shown in fig. 8.15.

8.10 Methods of indexing

Four methods of indexing are in use:
- (i) direct indexing,
- (ii) simple indexing,
- (iii) compound indexing,
- (iv) differential indexing.

8.10.1 Direct indexing

An example of direct indexing is given in *Workshop Processes* 2, Chapter 10, where the technique is shown in figs. 174 and 175. It will be seen that the principle of direct indexing makes use of a gear or disc having the required divisions or slots into which a locating device engages. The indexing is directly obtained; there are no gearing arrangements.

8.10.2 Simple indexing

Simple indexing is always carried out using a standard 40:1 dividing

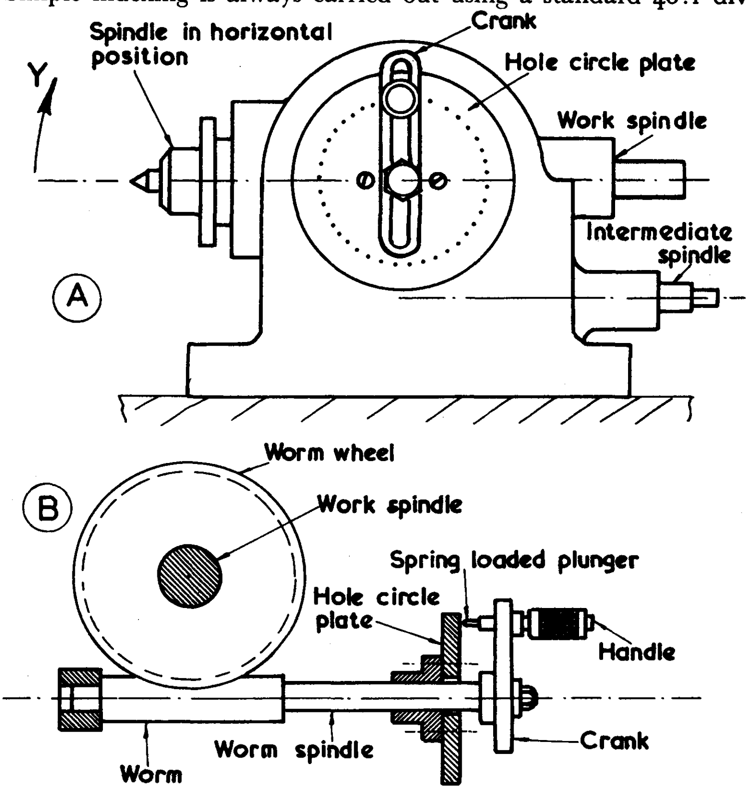


Fig. 8.16.—Principle of Simple Indexing.

head. An external view of a dividing head is given in fig. 8.16A. Note that the work-holding spindle is in the horizontal position, but can be tilted in the direction of arrow Y to the vertical position. The means by which rotation of the work spindle is achieved is shown in fig. 8.16B. Rotation of the crank turns the worm spindle which carries a worm meshing with the wormwheel. In order to rotate the work spindle one complete revolution the worm spindle requires rotating 40 times; that is to say 40 turns of the crank are required. One turn of the crank rotates the work spindle one-fortieth of a revolution; thus if a 40-tooth gear requires to be milled the simple indexing for this gear consists of one turn of the crank.

The following formula may be used to determine the indexing necessary when milling slots or teeth:

$$\text{Number of turns on crank} = \frac{40}{N}$$

where N = number of division required.

Clearly, provided the number of divisions to be milled is a factor of 40, for example 2, 4, 5, 8, 10 and 20, the indexing is easily achieved using the formula given above, the solution representing complete turns of the crank.

Thus if 5 equi-spaced slots are to be milled on a steel blank, the indexing required is simply calculated as follows:

$$\begin{aligned}\text{Number of turns on crank} &= \frac{40}{N}\\ &= \frac{40}{5}\\ &= 8 \text{ turns of the crank.}\end{aligned}$$

8.10.3 Use of hole-circle plates

Hole-circle plates are needed when the number of turns of the crank has a fractional value. Let us use the formula to calculate the indexing to mill the 48-tooth gear shown in fig. 8.11C.

$$\begin{aligned}\text{Number of turns on crank} &= \frac{40}{N}\\ &= \frac{40}{48}\\ &= \frac{5}{6} \text{ turn of the crank.}\end{aligned}$$

This is a fractional indexing, and a device is needed that will permit not only five-sixths of a turn of the crank, but also a very wide range of other possible fractional indexings.

Fig. 8.17 shows the device known as a hole-circle plate. The one illustrated is a standard plate used on the Cincinnati dividing head. This plate is reversible, having on one side the following hole circles:

24, 25, 28, 30, 34, 37, 38, 39, 41, 42, 43 holes

and on the reverse the following:

46, 47, 49, 51, 53, 54, 57, 58, 59, 62, 66 holes

Reference to fig. 8.17 shows that the plunger which is attached to the crank has been adjusted to locate in the 24-hole circle, and the indexing is now 20 holes on the 24-hole circle, because $\frac{5}{6}$ is equal to $\frac{20}{24}$.

With eleven hole circles on either side of the plate it is a simple matter to adjust the spring-loaded plunger so that it will locate in any required hole circle, and all divisions up to 60 can be obtained by using this reversible plate. Gears may be cut with teeth of all even numbers and multiples of 5 from 10 to 120. Perhaps two examples will show the great versatility of the Cincinnati reversible hole-circle plate.

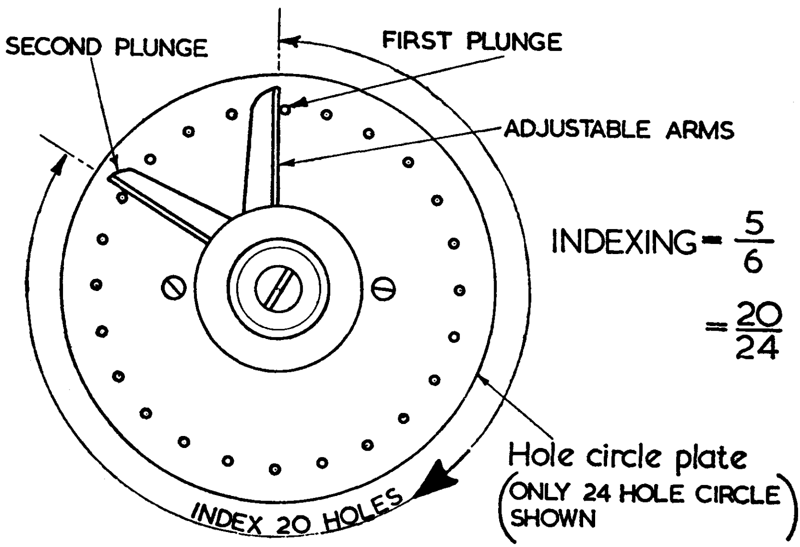


Fig. 8.17.—Application of Hole-circle Plate.

EXAMPLES

(i) Calculate the indexing required to mill a 59-tooth involute gear using a Cincinnati universal milling machine.

$$\text{Number of turns on crank} = \frac{40}{N}$$
$$= \frac{40}{59}$$

Indexing required is 40 holes on a 59-hole circle. As a precaution it is a wise policy to make full use of the quadrant shown in fig. 8.17. Both arms of this quadrant are freely adjustable, and when set to the required indexing remove the necessity for counting out the holes after each milling cut, and perhaps more important, reduce the possibility of scrapping the work through miscounting the number of holes.

(ii) Calculate the indexing required to mill eleven equi-spaced slots on a turned blank.

$$\text{Number of turns on crank} = \frac{40}{N} = \frac{40}{11} = 3\tfrac{7}{11}$$

The indexing is 3 whole turns and $\frac{7}{11}$ of a turn. We do not have an 11-hole circle, but

$$\frac{7}{11} = \frac{42}{66}$$

therefore the indexing is 3 whole turns plus 42 holes on a 66-hole circle.

8.10.4 Angular indexing

The need for angular indexing may be appreciated by reference to fig. 8.18. The component shown is a mild-steel turned blank, and it will be seen that three slots require to be machined. The first slot is to be machined with its centre coinciding with the centre line of the component, while the second is to be milled with its centre at an angle of 90° to the first slot. The third slot is to have its centre at 119° 30′ to the second slot.

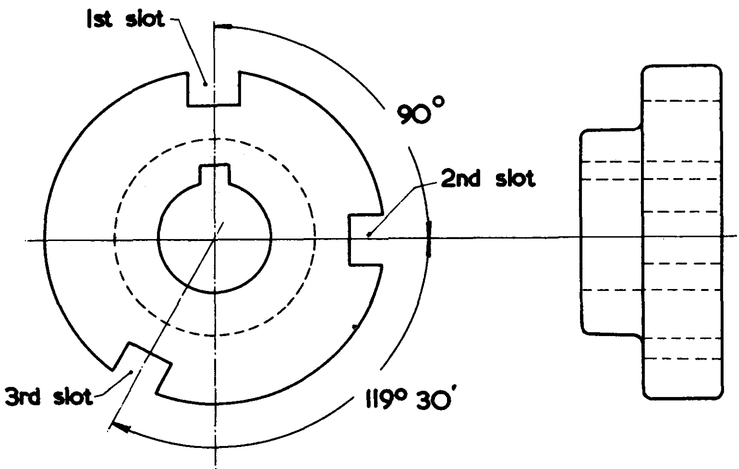


Fig. 8.18.—Component Requiring Milled Slots.

We have seen that one complete turn of the crank results in $\frac{1}{40}$ of a turn of the work spindle, to which the component is attached using either a chuck or centres. Expressed in terms of angular notation, $\frac{1}{40}$ of a turn is equal to 9°, and the following formula may be used in order to calculate the indexing required when machining slots to angular dimensions:

$$\text{Number of turns on crank} = \frac{A}{9}$$

where A = angle required in degrees.

Thus indexing for the second slot may be calculated as follows:

$$\text{Number of turns on crank} = \frac{A}{9} = \frac{90}{9} = 10$$

To calculate the indexing for the third slot:

$$\text{Number of turns on crank} = \frac{A}{9} = \frac{119\frac{1}{2}}{9} = \frac{239}{18} = 13\frac{5}{18} = 13\frac{15}{54}$$

The indexing for the component is now given below:

(i) Set component on centre, adjust plunger to 54-hole circle, remove backlash and engage in zero hole; mill first slot.

(ii) Index 10 complete turns of crank and engage plunger in zero hole; mill slot.

(iii) Index 13 complete turns plus 15 holes on 54-hole circle, engage plunger; mill slot.

8.10.5 Compound indexing

This technique is used when the dividing head is fitted with two plungers, as shown in the diagram in fig. 8.19, and the divisions required cannot be obtained by simple indexing. Reference to the diagram shows that two plungers are available, one on the turning crank and the other on a fixed pivot. The crank is rotated in the usual way, followed by rotation of the hole circle or index plate. During rotation or indexing of the crank the fixed plunger is engaged in a hole in the plate, thus holding the plate firmly in position. With the first indexing completed, the plate and the indexed crank are further rotated either in the same direction as the crank indexing or in the opposite direction.

Let the crank indexing be a holes on an A-hole circle, and the plate indexing b holes on a B-hole circle in the same direction.

Then the total indexing is $\frac{a}{A}+\frac{b}{B}$.

If, on the other hand, the plate is rotated in the opposite direction to the crank, then the total indexing is $\frac{a}{A}-\frac{b}{B}$.

Thus the object of compound indexing is to calculate **two** fractional values whose sum or difference is equal to the actual indexing fraction required.

Let us assume that a 91-tooth involute gear requires milling of the teeth. Using the formula

$$\text{Turns of crank} = \frac{40}{N}$$

the required fraction is $\frac{40}{91}$.

Checking the hole circles available on the index plate we find that a 91-hole circle is not among them. This is therefore an indexing operation that cannot be carried out using the simple indexing technique.

We will use the Brown and Sharpe dividing head for the compound indexing of the 91-tooth gear, choosing suitable hole-circle plates from one of the three available having the hole circles given below:

Plate 1: 15, 16, 17, 18, 19, 20 holes
Plate 2: 21, 23, 27, 29, 31, 33 holes
Plate 3: 37, 39, 41, 43, 47, 49 holes

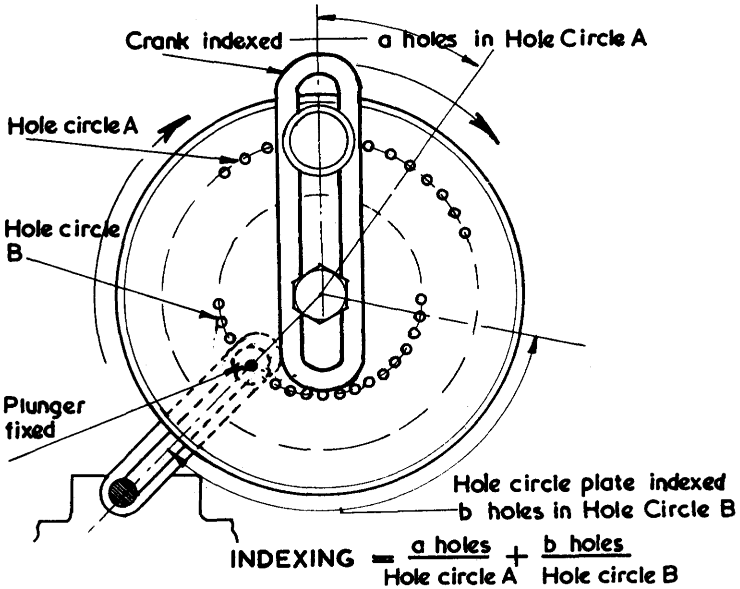


Fig. 8.19.—Principle of Compound Indexing.

Method of calculating compound indexing

First reverse the fractional indexing required and write it down thus:

$$\frac{91}{40}$$

Now factorise both numbers.

$$\frac{91 = 7 \times 13}{40 = 5 \times 2 \times 2 \times 2}$$

The next step is to choose two hole circles from the same plate; write down the relevant numbers and their factors below the line, and their difference with its factors above the line. If all the factors above the line cancel out the two hole circles chosen are suitable. Clearly the factors 13 and 7 are needed below the line; Plate 3 is an obvious choice, as it has the hole circles of 39 (13 × 3) and 49 (7 × 7).

Inserting these numbers below the line and their differences above the line,

$$\begin{aligned} 10 &= \cancel{2} \times \cancel{5} \\ \underline{91} &\underline{= \cancel{7} \times \cancel{13}} \\ 40 &= \cancel{5} \times \cancel{2} \times 2 \times 2 \\ 39 &= 3 \times \cancel{13} \\ 49 &= \cancel{7} \times 7 \end{aligned}$$

Note that all the numbers above the line cancel out; this means that the hole circles of 39 and 49 may be used, as shown in fig. 8.19. The problem now is to determine the number of holes to be indexed on each hole circle.

Writing down the two fractional indexings, we have:

$$\frac{a \text{ holes}}{39\text{- hole circle}} \pm \frac{b \text{ holes}}{49\text{-hole circle}} = \frac{40}{91}$$

Note that plus means in the same direction as the crank indexing, minus in the opposite direction (see fig. 8.19).

From
$$\frac{a}{39} \pm \frac{b}{49} = \frac{40}{91}$$

$$\frac{a}{(13\times 3)} \pm \frac{b}{(7\times 7)} = \frac{40}{(13\times 7)}$$

$$\frac{49a \pm 39b}{13\times 7\times 7\times 3} = \frac{40\times 21}{13\times 7\times 7\times 3}$$

$$49a \pm 39b = 840$$

It is now necessary to find values for both a and b that will satisfy the equation above, and the method of trial and error must be adopted.

When $a = 6$ and $b = 14$,

$$49\times 6+39\times 14 = 294+546 = 840$$

The compound indexing for the milling of the 91-tooth gear comprises the two following indexings:

(i) 6 holes on a 39-hole circle with the crank,

(ii) 14 holes on a 49-hole circle, moving or indexing the plate in the same direction as the crank.

It may be appreciated that the calculations involved in compound indexing have not made this technique a popular system, and it must be further understood that the method is only possible when the dividing head is equipped with two plungers. A more popular method is the technique known as differential indexing.

8.10.6 Differential indexing

We have seen that the principle underlying compound indexing consists in making use of the addition or subtraction of two fractions, the nett result being equivalent to the actual fraction required. One fractional indexing is made by the crank, while the other rotates the index or hole-circle plate. Much the same principle is used in differential indexing, except that rotation or indexing of the index plate is achieved through a suitable gearing arrangement.

Fig. 8.20 illustrates the essential movements of a dividing head set up for differential indexing. Rotation of the spindle crank causes rotation of the work spindle through the worm and wormwheel in the ratio of 40:1. Reference to the plan view shows that the simple gear train comprising the spur gears A, B and C transmits rotary motion from the work spindle through two equal bevel gears and two equal spur gears to the index plate. Thus rotation of the crank causes rotation of the index plate, the direction of rotation being determined by the insertion or removal of an idler gear in the gear train. In this way two fractional movements may be obtained; one by indexing the crank by hand in the usual way, and the other by the choice and insertion of suitable gears to give the required movement of the index plate.

Method of differential indexing

In dealing with the method of calculating a suitable gear train for differential indexing, we will assume that the Brown and Sharpe dividing head is to be used. This means that we must know the number and tooth range of the gears. These are given below:

20 (2), 24, 28, 32, 40, 44, 48, 56, 64, 72, 86, 100 teeth.

Let us assume that we wish to mill a gear of 97 teeth using an involute form cutter.

$$\text{Number of turns on crank} = \frac{40}{N} = \frac{40}{97}$$

Thus if a 97-hole circle were available this fractional indexing would be carried out 97 times, at the end of which the work spindle would have made one complete revolution and all the teeth of the gear would have been machined.

Then $$\frac{40}{97} \times 97 = 40 \text{ turns of the crank.}$$

In order to calculate the gears required it is first necessary to make a close approximation to the ratio $\frac{40}{97}$, and clearly if this approximate ratio is indexed 97 times an error results. The work will not make a complete revolution; if the approximation is less than $\frac{40}{97}$ a full turn is not made, and if it is more than $\frac{40}{97}$ the work revolves in excess of a full turn. The purpose of the gearing is to counteract the effect of the approximation.

Choosing an approximation of $\frac{40}{100}$

$$\frac{40}{97} = \frac{40}{100} \text{ (approximately)}$$
$$= \frac{8}{20}$$

We may attach the no. 1 plate to the dividing head and index 8 holes on a 20-hole circle. After milling 97 teeth the total indexing is

$$\frac{8}{20} \times 97 = \frac{776}{20} = 38\tfrac{8}{10} \text{ turns of the crank.}$$

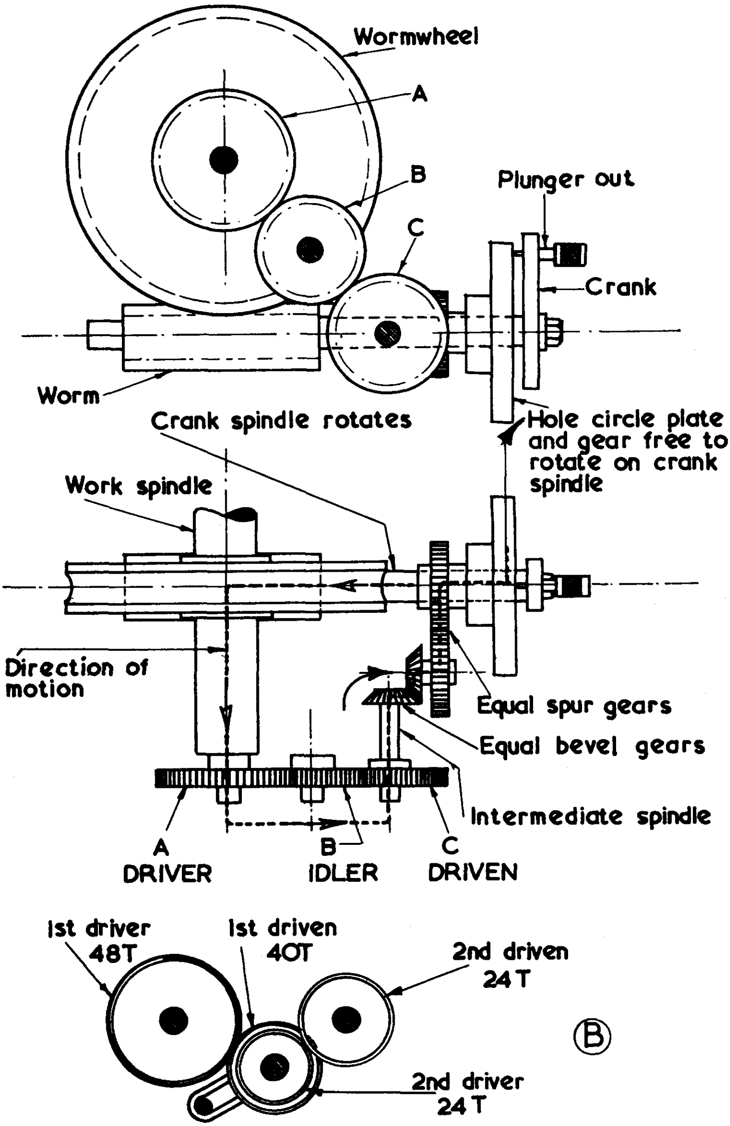


Fig. 8.20.—Gearing Arrangement for Differential Indexing.

Clearly this is $1\frac{2}{10}$ turns short, and gears must now be chosen in the following ratio:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{12}{10} = \frac{6}{5}$$
$$= \frac{2}{1} \times \frac{3}{5}$$
$$= \frac{48}{24} \times \frac{24}{40}$$

Thus the driving gears must have 48 and 24, and the driven gears 24 and 40 teeth respectively. The train needed for this gearing arrangement is shown in fig. 8.20B; the index plate is to turn in the same direction as the crank.

With this gearing arrangement set up, the crank is indexed 8 holes on a 20-hole circle, an imperceptible movement of the index plate taking place in the same direction as the crank.

8.11 Spiral milling

Spiral milling provides yet another example of the versatility of the universal milling machine when equipped with a standard 40:1 dividing head In simple, compound and differential indexing rotation of the crank is carried out by hand; there is no automatic feed or drive through the leadscrew of the milling machine. For spiral milling it is essential that the worm spindle (see fig. 8.16A) be geared to the leadscrew of the milling machine.

A typical set-up for spiral milling is shown in fig. 8.21, where it will be seen that the worm spindle is geared to the leadscrew of the milling machine. With the traverse of the table feed engaged the rotating leadscrew drives the worm spindle, which in turn drives the wormwheel and hence the workpiece. The index plate (together with the crank) rotates also, and as in differential indexing the index plate must be unlocked.

8.11.1 Lead of the machine

Before any spiral milling is carried out the lead of the machine must be known. This is the lead produced when equal gears are used between the milling machine leadscrew and the worm spindle, as shown in fig. 8.21. If the workpiece is to make one complete revolution, 40 turns of the worm spindle are required and 40 turns of the milling machine leadscrew. Most milling machines have leadscrews of 5 mm pitch; thus 40 turns of the leadscrew produce a linear movement of the table equal to $4 \times 40 = 200$ mm.

Special milling machines have different leadscrews, and it is also possible to obtain dividing heads with a ratio of 80:1. The formula for calculating the lead of any machine is:

$$\text{Lead of machine} \quad R \times P$$

where R = ratio of dividing head
P = pitch of leadscrew

EXAMPLE

Calculate the lead of a milling machine having a 5 mm pitch leadscrew and using an 80:1-ratio dividing head.

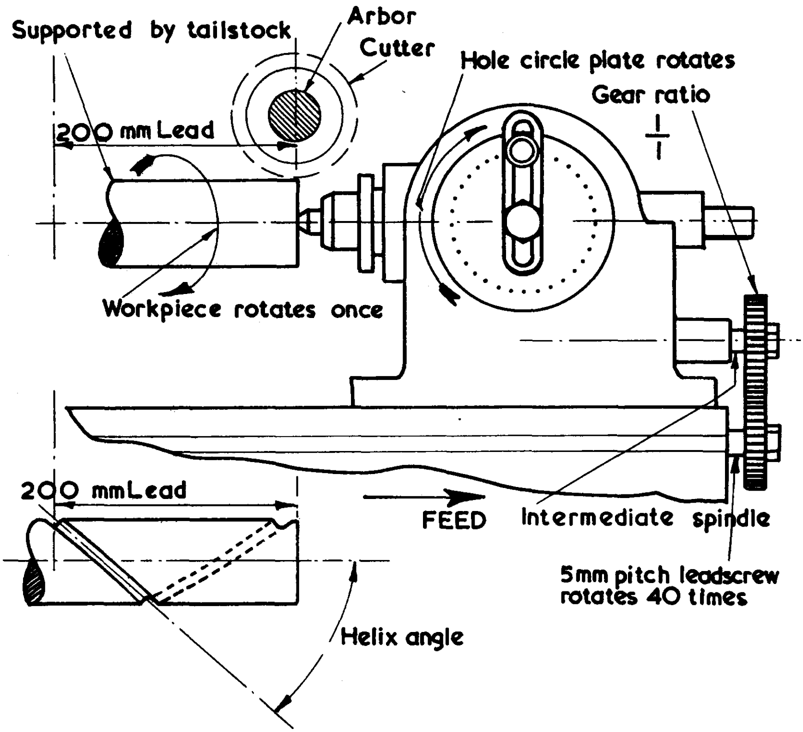


Fig. 8.21.—Set-up for Spiral Milling.

$$\begin{aligned}\text{Lead of machine} &= R \times P\\ &= 80 \times 5\\ &= 400 \text{ mm}\end{aligned}$$

Using the conversion factor of 1 in = 25·4 mm,

$$\begin{aligned}400 \text{ mm} &= \frac{400 \text{ in}}{25{\cdot}4}\\ &= 15{\cdot}748 \text{ in (to the nearest } \tfrac{1}{1000} \text{ in)}\end{aligned}$$

8.11.2 Calculating the spiral angle

The spiral angle is the angle made by the machined flute or form with respect to the centre line of the workpiece. A more correct name for this angle is the helix angle, and it will be seen from fig. 8.22 that if the spiral milling is to be performed on a horizontal milling machine the table must be swivelled in order to bring the cutter in line with the machined form. All universal milling machines have this ability to swivel the worktable through a small arc, usually about 30°.

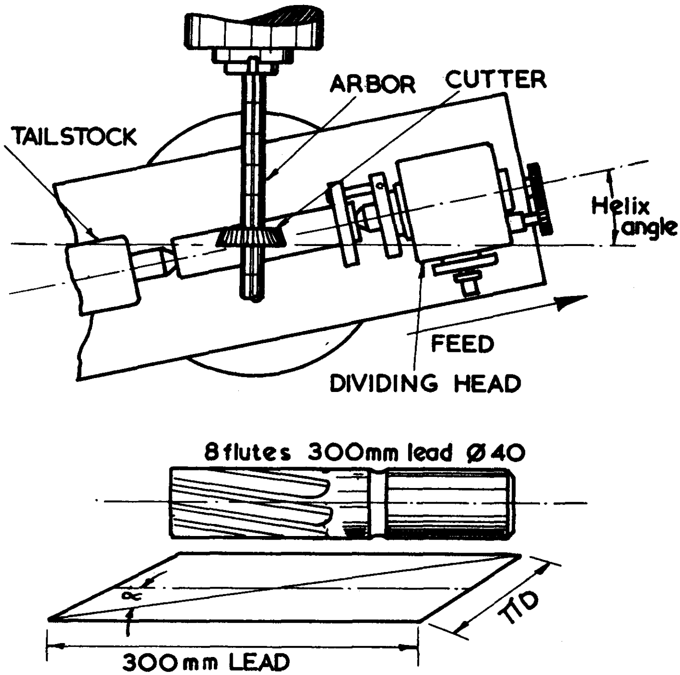


Fig. 8.22.—Need for Angular Setting of Table when Spiral Milling.

When a spiral is to be milled the following information must be available:

(i) lead required,
(ii) lead of machine,
(iii) spiral angle,
(iv) mean diameter of work.

The formula given below may be used to calculate the spiral angle:

$$\tan \alpha = \frac{\text{mean circumference of cylinder}}{\text{lead of helix}}$$

where α = spiral angle

EXAMPLE

A milling cutter of 40 mm diameter and 300 mm lead, with 8 flutes of 6·5 mm depth, is to be gashed (milled) using a universal milling machine. Calculate the angular setting for the table.

This cutter is illustrated in fig. 8.22, together with a development showing the derivation of the above formula.

$$\text{With} \qquad \tan\alpha = \frac{\text{mean circumference of cylinder}}{\text{lead of helix}}$$

$$= \frac{\pi D}{300}$$

$$= \frac{22}{7} \times \frac{33{\cdot}5}{300}$$

(Note: mean diameter = outside dia. − depth of flute)

$$= \frac{737}{2100}$$

$$= 0{\cdot}3509$$

Hence spiral angle $\alpha = 19^\circ\ 20'$.

With the two locking nuts slackened off, the milling-machine table is swivelled until the angle of 19° 20′ is indexed at the zero mark; unless the circular scale is fitted with a vernier device the 20 minutes of arc or $\frac{1}{3}^\circ$ must be estimated.

8.11.3 Calculating the gear train

Let us assume that the milling cutter illustrated in fig. 8.22 is to be gashed using a standard 40:1 dividing head on a metric machine with a leadscrew of 5 mm pitch.

The formula required to calculate the correct gears between the milling-machine leadscrew and the worm spindle of the dividing head is as follows:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{\text{lead of machine}}{\text{lead to be cut}}$$

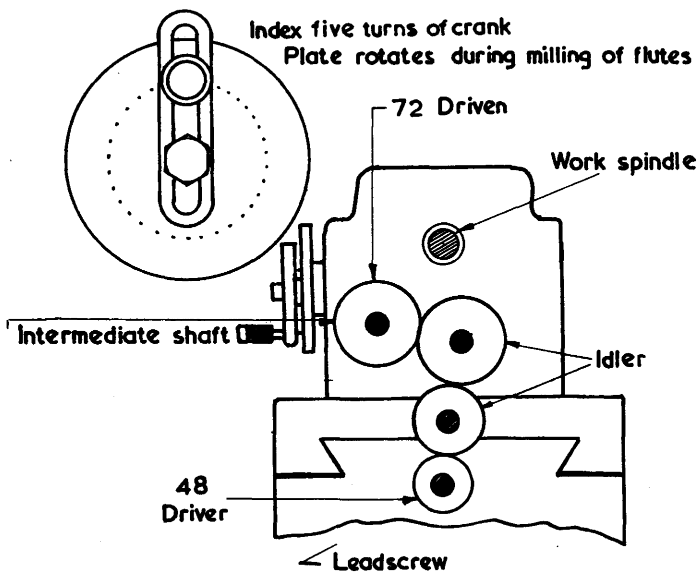


Fig. 8.23.—Gearing Arrangements when Spiral Milling.

Using this formula in order to calculate the gears for the gashing of our 300 mm lead milling cutter:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{200}{300} = \frac{2}{3} = \frac{48}{72}$$

The gears available are those given for differential indexing, dealt with earlier (8.10.6).

The indexing for the eight flutes of the cutter proceeds in the same manner as simple indexing. For the first cut, the plunger on the crank is engaged in the zero hole of the 24-hole circle. With the table traverse engaged the index plate and the crank rotate; a table stop disengages the traverse, allowing the table to be brought back by hand to the starting position. The crank is now indexed five whole turns, the plunger firmly engaged and the milling operation repeated.

Note the insertion of two idler gears between the milling-machine lead-screw and the worm spindle; the set-up is shown in fig. 8.23.

8.12 Cam milling

The milling of the contour of a constant-rise cam is a relatively simple affair, provided a universal miller, a 40:1 dividing head and the appropriate formula are available. Before dealing with the actual machining of the cam it may be as well to have a quick look at the construction and use of constant-rise cams. Fig. 8.24 shows a simple cam; note that from A to D the profile of the cam rises. In other words, if a roller rests at A, then rotation of the cam through 180° produces a linear movement of the roller from A to B. This principle of converting rotary motion into linear motion is much used when machining with automatic lathes; the movement of the cutting tool is determined by the action of a cam on a roller. In turn, the number of revolutions of the work determines the amount of revolution of the cam.

8.12.1 Lead of a cam

This is the linear rise or fall if the contour of the cam is taken through 360°; the calculation required to determine the lead of any cam is a matter of simple proportion.

In the diagram in fig. 8.24 the rise of the cam is given as 50 mm.
Thus

$$\text{Rise in } 180^\circ = 50 \text{ mm}$$

$$\text{Rise in } 360^\circ = 50 \times \frac{360}{180} \text{ mm} = 100 \text{ mm}$$

8.12.2 Set-up for cam milling

As already stated, cam milling is only possible provided a vertical milling head is available and this head is capable of rotary adjustment. We have seen that the axis of the work spindle of a dividing head may be set at any angle, and fig. 8.24B shows an extreme case, with both the cutter spindle and work spindle in a vertical position. If, now, the worm spindle of the dividing head is geared to the leadscrew of the milling machine, and automatic traverse of the table engaged, the rotation of the cam blank in conjunction with the table feed results in the machining of a constant-rise contour.

Another extreme case is shown in fig. 8.24C; here both the cutter and work

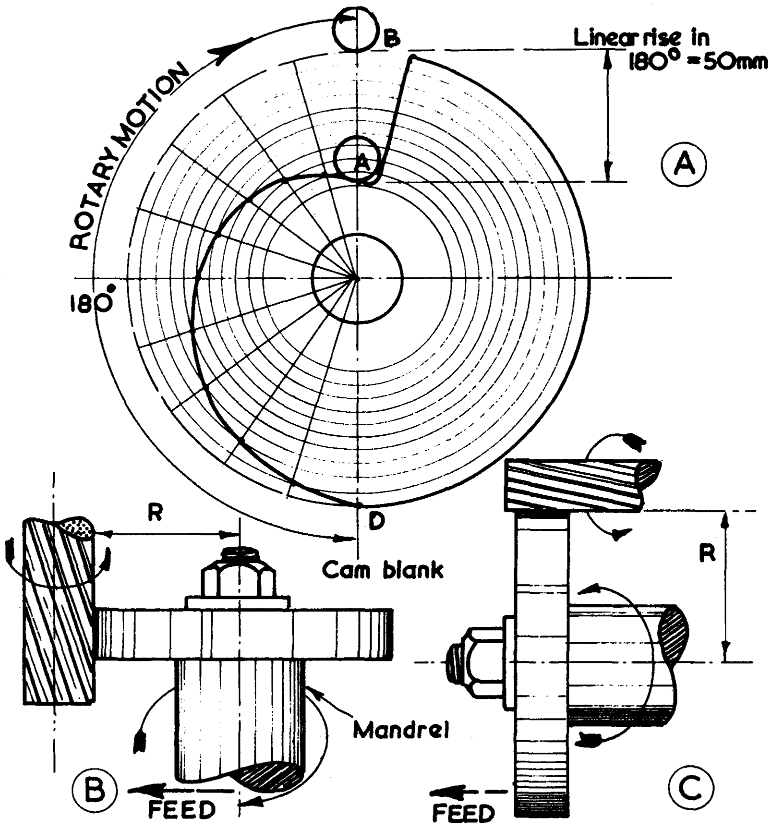


Fig. 8.24.—Principle of Cam Milling.

axis are in the horizontal position. With the dividing head still geared to the milling-machine leadscrew and the traverse engaged, a cylindrical surface is machined. The distance shown as *R* remains constant.

It may now be appreciated that tilting of the cutter and work axis and control of the rate of table feed allow the milling of constant-rise cams as shown in the set-up in fig. 8.25. The angle of tilt of both the work and spindle axis is shown as α in the diagram; note the use of compound gearing between the milling-machine leadscrew and the worm spindle.

8.12.3 Calculations for cam milling

The following symbols are used in calculations for cam milling, and the reader should become familiar with them:

α = angle of inclination,
R = gear ratio,
L = lead of cam,
p = pitch of leadscrew.

Provided a metric milling machine with a leadscrew of 5 mm pitch is used, we may employ the formula

$$R = \frac{200 \sin \alpha}{L}$$

which may be expressed in full as

$$\text{Gear ratio} = \frac{200 \sin \text{angle of inclination}}{\text{lead of cam}}$$

In the event of a British milling machine being used, the formula will be

$$R = \frac{40 \sin \alpha \times p}{L}$$

A 40:1 dividing head is used, and the metric pitch and the lead to be milled are converted to inches.

EXAMPLE

The following example will give an indication of the use of the formula given above when cam milling on the universal milling machine.

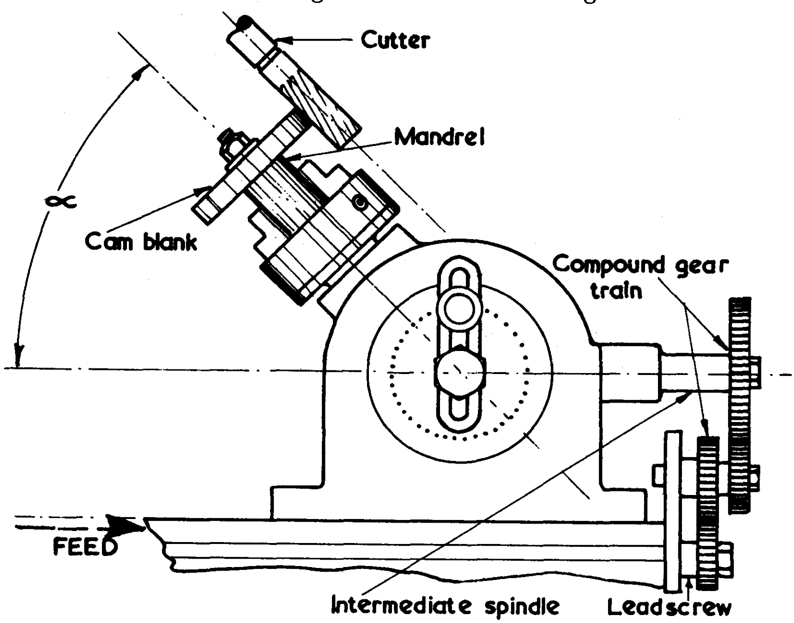


Fig. 8.25.—Set-up for Cam Milling.

Calculate the gearing and angular inclination for milling a cam having a constant rise of 40 mm in 150° of its angle, using a standard 40:1 dividing head and a milling machine with a leadscrew of 5 mm pitch.

From the formula

$$R = \frac{200 \sin \alpha}{L}$$

it will be seen that there are three unknown values, R, α and L.

To find L

$$\text{Profile rise in } 150^\circ = 40 \text{ mm}$$

$$\text{Profile rise in } 1^\circ = \frac{40}{150}$$

$$\text{Profile rise in } 360^\circ = \frac{40 \times 360}{150}$$

$$= 96 \text{ mm} = \text{lead of cam} = L.$$

With L known, two unknown values remain, and it is now necessary to assume one and calculate the other. This means that the gear ratio R may be assumed to be, say, 3:2, and this may be inserted in the formula and α calculated.

Thus

$$R = \frac{200 \sin \alpha}{L}$$

$$\frac{3}{2} = \frac{200 \sin \alpha}{96}$$

$$\therefore \sin \alpha = \frac{96 \times 3}{2 \times 200}$$

$$= 0{\cdot}72$$

The angular inclination is therefore equal to the angle whose sine is 0·72, and from tables we find this to be 46° 4′. Many dividing heads are provided with setting pins at 100 mm centres, allowing the use of a sine bar for precise angular setting of the work-spindle axis.

Reference back to fig. 8.25 shows that as the cut proceeds the work moves up the cutter, and this means that a reasonably long cutter is needed. At the same time, if the contour is to be milled from a circular blank the depth of cut increases as the table traverses. This is a most unsatisfactory arrangement, and the correct procedure is to rough out the profile first with a bandsaw, and then set up for milling. In this way the amount of metal removed will be reasonably constant, and if roughing and finishing cuts are taken a well-finished, accurate cam will result.

The accuracy may be readily checked by mounting the cam between centres on a suitable mandrel, and checking the linear rise using end standards in conjunction with a dial indicator.

Summary

The production of plane and contoured surfaces by the milling process is an established production technique, although there is, as we shall see in a later volume, a tendency for the surface broaching technique to replace face milling as a method of producing relatively large plane or contoured surfaces. We have seen in this chapter that milling may be generally divided into two main classes:

(i) production milling,
(ii) small batch or specialised milling.

When production milling the accent is on maximum metal removal together with close dimensional accuracy and good surface finish. For this kind of work the milling machines must be of rigid construction with ample power available; this allows the technique of negative-rake milling to be adopted.

When maximum output is required the method used is that of rotary milling, in which case the removal of metal is virtually continuous. Profiled surfaces are readily produced using form cutters, which require sharpening on the front faces of the teeth. Finally the universal milling machine, with the attachments available, provides an extremely versatile range of machining set-ups. These include simple, compound and differential indexing and spiral and cam milling. To produce accurate, well-finished results from all of these operations the mechanical engineering technician must know and be able to manipulate not only the milling machine but also the necessary mathematical formulae.

EXERCISE 8

1 With a neat diagram, illustrate the principle of the milling operation and explain the importance of this technique in precision engineering manufacture.

2 Illustrate with typical examples the following milling techniques:
(i) face milling,
(ii) angular milling,
(iii) vertical milling,
(iv) horizontal milling.

3 Outline the differences in construction between a standard horizontal milling machine and a miller designed for high-production horizontal milling.

4 Explain what is meant by the technique of rotary-table milling. Sketch a component for which this milling technique would be suitable.

5 What is the difference between up-cut and down-cut milling? Define the requirements if a plane surface is to be produced by the down-cut milling technique.

6 Explain the difference in cutter design when considering the manufacture of milling cutters for both positive- and negative-rake milling.

7 Sketch a component that would require the application of a form-relieved milling cutter. What precautions must be taken when regrinding a form cutter? Why must the cutter be kept always in a sharp condition?

8 A gear is to have 127 teeth of involute form for the cutting of metric threads at a centre lathe. If a Brown and Sharpe 40:1 dividing head is available, calculate a suitable set-up for the differential indexing of this gear when gashing the teeth using a universal milling machine.

9 Make the necessary calculations for milling 10 flutes of 5 mm depth, having a rake angle of 18° and a lead of 250 mm. The spiral angle of the flutes is 12°. Also make a neat sketch of the set-up.

10 Calculate and illustrate a suitable setting for the milling of a constant-rise cam whose profile rises 15 mm in 120° of its angle. A standard 40:1 dividing head is available of Brown and Sharpe design, together with a universal milling machine of 5 mm pitch leadscrew.

Index

Numbers in **bold** type refer to illustrations

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