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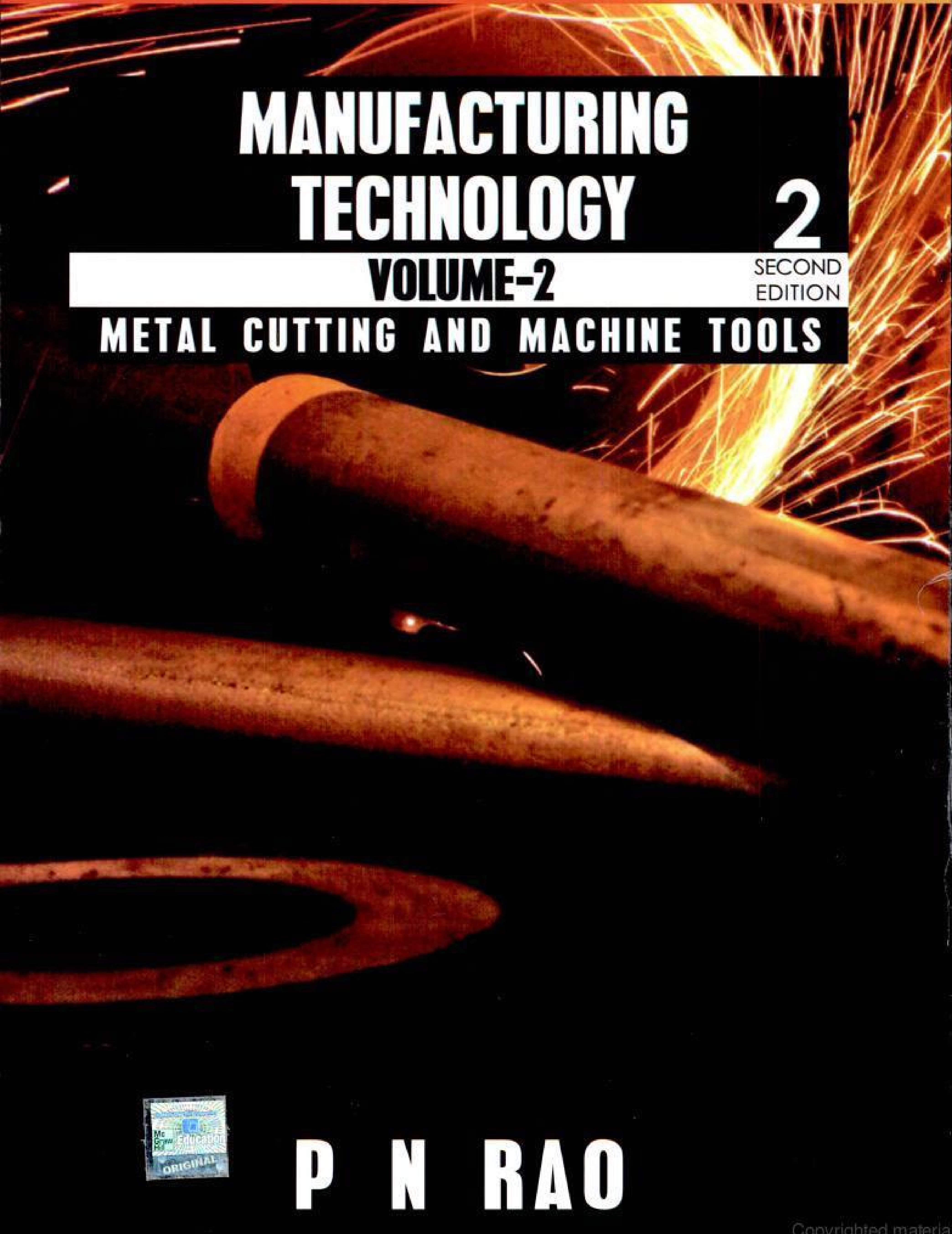

MANUFACTURING TECHNOLOGY

2 SECOND EDITION

VOLUME-2

METAL CUTTING AND MACHINE TOOLS

Mc Graw Hill Education ORIGINAL

P N RAO

Tata McGraw-Hill

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Contents

Preface

The first edition of the book has received an excellent reception from the teachers and students of engineering colleges and has become a regular textbook in many universities in India and abroad. It was my philosophy to teach workshop technology, more oriented towards a combination of theory and practice, to make the subject more exciting for the student to understand and, therefore, not be bogged down by the details. It appears that this belief has been accepted by a number of manufacturing educators by adopting it as their textbook of choice.

Almost seven years have passed since the publication of the book. In the intervening period, I had the good fortune of receiving a number of suggestions from the users of the book in the form of new topics to be included and improvements in a number of ways to expand the scope of the book further. Tata McGraw-Hill also made a thorough research of the various university syllabi to look for the topics, which are not currently covered in the book. I tried to incorporate as many of them as possible, but some had to be deliberately omitted to conserve the flow of the material as well as to keep the book of reasonable size.

Chapter 1 introduces the different material-removal processes and machine tools. Chapter 2 discusses the different aspects of metal cutting, laying emphasis on chips, BUE, cutting-tool materials, tool life and surface finish. Chapter 3 is on machine tools, their classification and elements. Chapter 4 describes centre lathe in detail, and Chapter 5 is on special-purpose lathes.

Chapters 6 and 7 discuss reciprocating machine tools and milling respectively. Chapter 8 is on hole-making operations. Chapter 9 explains the different types of abrasive processes, while Chapter 10 describes some other machine tools like sawing and broaching machines. Chapter 11 deals with some unconventional machining processes and Chapter 12 is on machine-tool testing. Chapter 13 points out some general guidelines for designing machines. Chapter 14 describes jigs and fixtures, while Chapter 15 on Metrology describes the different kinds of measurement used in machining processes. Finally, Chapter 16 deals with the numerical control of machine tools.

The book has been thoroughly revised to keep the material as up-to-date as possible. Some of the notable additions that have been done are the addition of a new Chapter 14 on jigs and fixtures, which appears to have become part of many university syllabi, and Chapter 2 with the details on coated carbides. Chapter 3 has been enhanced by the addition of topics on transmission systems including the actuators used in the machine tools. Chapter 11 on unconventional machining is rewritten to include the major developments in these processes while adding some of the new topics such as water jet machining. Chapter 15 on metrology has also been updated by the addition of a topic on common measuring equipments. In addition, many of the chapters have been enhanced by the inclusion of some more details to make them more complete. Many illustrations were redrawn to make them clearer.

The website of this book can be accessed at http://www.mhhe.com/rao/mtmcmt2e and contains the Solution Manual and PowerPoint Lecture Slides for Instructors, and Interactive MCQs, chapterwise additional questions and Model Question Papers for students.

I wish to express my sincere thanks to my current employer, University of Northern Iowa, Cedar Falls, Iowa, USA, for providing an excellent environment and facilities which I could make use of in carrying out this stupendous task. I would also like to thank the following reviewers who took time out to review the book.

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It is a pleasure to work with the editorial staff at McGraw Hill Education India who made sure that the production comes with the highest quality in the shortest time to ensure the timely availability of the text.

I would welcome further suggestions regarding the coverage in the book, and would be happy to incorporate the suggested improvements in future editions to make the book more suitable to the changing curriculum needs of the teaching of manufacturing technology.

P N RAO

Visual Walkthrough

HISTORICAL PERSPECTIVE

Provides a brief perspective of historical developments related to the processes discussed.

1

Introduction

1.1 INTRODUCTION TO MATERIAL REMOVAL PROCESSES

The study of metal cutting and machine tools is one of the most fascinating experiences. Machining of materials is adopted to get higher surface finish, close tolerances, and complex geometric shapes, which are otherwise difficult to obtain.

Of all the manufacturing processes available, metal removable is perhaps the most expensive one. This is because from the raw material, quite a substantial amount of material is removed in the form of chips in order to achieve the required shape. Also, a lot of energy is expended in the process of material removal. So, the choice of material removal as an option for manufacturing should be considered when no other manufacturing process suits the purpose. However, invariably all components undergo a material removal operation at one point or the other.

A machine tool is defined as one which, while holding the cutting tools would be able to remove metal from a workpiece, in order to generate the requisite job of given size, configuration, and finish. A machine tool is different from a machine, which is essentially a means of converting the source of power from one form to the other. The machine tools are the mother machines, since without them no components can be produced in their finished form. They are very old and the industrial revolution owes its success to them.

Existence of some form of crude machine tools is recorded as early as 700 B.C. However, the most prominent beginning of the machine tool is the *John Wilkinson's Horizontal Boring Machine* towards 1775. This invention made the *James Watt's Steam Engine* a reality. *Henry Maudsley* followed this with an *Engine Lathe* in 1794. A later machine tool to be invented is the *Planer* by *Roberts* in 1817. *Maudslay* combined a lead screw, a cross-slide, and change gears in a form, which is almost similar to the current day centre lathe. At the same time, another major machine tool to be invented is the *Milling Machine* by *Eli Whitney* in 1818.

2

Metal Cutting

Objectives

Material removal is the principal operation carried out by a majority of the manufacturing industries. This chapter provides a summary of the major factors that need to be considered in metal cutting. After completing the chapter, the reader will be able to

- understand the basic parameters in the metal cutting operation
- appreciate different types of chips formed in metal cutting, and their relevance in manufacturing
- calculate analytically the forces and other parameters associated with orthogonal cutting
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- select the cutting tool material for a given application
- understand the temperatures developed in metal cutting, and the variables that control it
- understand tool wear and tool life and the variables that control them
- determine how the surface finish varies with the process parameters
- know the various cutting fluids and their application methods
- empirically determine the cutting forces
- optimise the machining process to satisfy the required conditions

CHAPTER OBJECTIVES

Provide a quick look into the concepts that will be learned by the user.

WELL-LABELLED ILLUSTRATIONS

Provide a complete description of the object in question, labelling the various parts describing the function.

A typical system is schematically shown in Fig. 11.38.

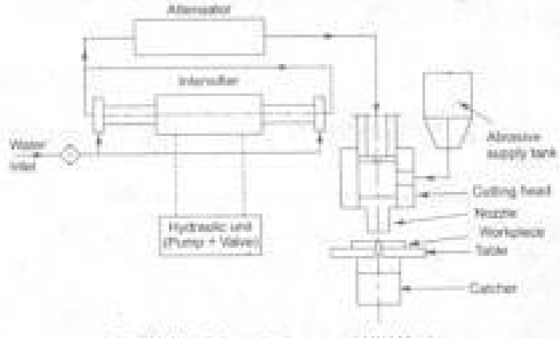

Fig. 11.38 *Schematic diagram of AWJ Machine*

Example 4.6 *Calculate the power required for roughing and finishing passes in Example 4.4.*

Roughing

Given feed rate, $f = 0.24$ mm/rev

Depth of cut, $d = 2$ mm

Cutting speed, $V = \dfrac{\pi \times 176 \times 46}{1000} = 25.43$ m/min

The value of K from Table 4.7 $= 1600$ N/mm^2

Power $= \dfrac{1600 \times 25.43 \times 0.24 \times 2}{60} = 325.5\ \text{W} = 0.326\ \text{kW}$

Finishing

Given feed rate, $f = 0.10$ mm/rev

Depth of cut, $d = 0.75$ mm

Cutting speed, $V = \dfrac{\pi \times 440 \times 43.5}{1000} = 60.13$ m/min

Power $= \dfrac{1600 \times 60.13 \times 0.10 \times 0.75}{60} = 120.26\ \text{W} = 0.120\ \text{kW}$

SOLVED PROBLEMS

Solved problems help readers review their understanding of the concepts discussed in the chapter.

SUMMARY

Provides the essence of the subject matter covered in the chapter.

Summary

Machine tools are mainly used to provide higher accuracy that is essential in the manufacturing industry. A machine tool is able to hold a cutting tool, and removes material from the stock to get the required part geometry.

- Machine tools are classified into different types based on the application, such as general purpose, production and special purpose machine tools.
- Part geometry can either be generated or formed.
- Depending on the surface, a large number of different motions are used based on the type of tools in operation.
- There is a large variation possible in accuracy and surface finish between the different operations.
- All the machine tools have work holding, tool holding, support, and work and tool motion mechanisms built in them.
- There is a variety of support structures used in machine tools depending on the type of motions required.
- Lead screws are used in machine tools to convert rotary motion to linear motion, which is used to move the table or cutting tool depending on the type of machine tool.
- Re-circulating ball screws are used for more efficient load transmission.
- Anti-friction guideways are used in a majority of the modern machine tools. The conventional guideways are also used.

Questions

1. Explain the characteristics that distinguish a milling process from other machining processes.
2. Describe the differences between a lathe and milling machine in terms of the types of surfaces generated, the types of tools used, and applicability for general and production applications.
3. Give a brief classification of various milling machines used in the industry, giving a brief note on the application.
4. How is a milling machine specified?
5. What are the various types of milling cutters that are used in milling?
6. Describe the application and relative merits of various types of milling cutters that are used in milling.
7. List the motions which the arbour mounted milling cutter has with respect to the workpiece.
8. What are the various work holding devices used in milling? Explain their relative applications and disadvantages.
9. What are the various types of end mills used in milling? Explain their applications.
10. Differentiate between up milling and down milling. Explain their applications mentioning the most commonly used method.
11. Explain the difference between straight and helical slab mills bringing out the advantages to be gained by the use of helical teeth.
12. Explain the applications and differences with neat sketches, of the following with reference to milling:
    (*a*) Straddle milling (*b*) Gang milling
13. Sketch typical setups for :
    (*a*) Reciprocal milling (*b*) String milling

REVISION QUESTIONS

Help readers test their knowledge gained by reading the chapter.

PRACTICE PROBLEMS

Provides hands-on practice in solving problems related to real-life situations.

Problems

1. Calculate the rpm of the bull gear of a mechanical shaper if the cutting speed is 35 m/min with the stroke length adjusted to 250 mm. Assume the ratio of cutting stroke to idle stroke as 1.5.
2. Calculate the machining time required for shaping a flat surface with a 250-mm length and 200-mm width on a hydraulic shaper using a cutting speed of 40 m/min and feed of 0.5 mm per stroke. The depth of cut is 4 mm. Calculate the material removal rate and the power required.
3. A hydraulic shaper is used for shaping a plane surface of 30 × 250 mm with a cutting speed of 60 m/min and feed of 0.6 mm per stroke. Calculate the machining time and material removal rate if the depth of cut is 3 mm. Also calculate the power consumed in the process.
4. The two faces of a 90° V-block each with a 50-mm length and 150-mm width is to be cut on a mechanical shaper. Calculate the actual machining time required. Make judicious assumptions if required and justify them.
5. A 60° male dovetail with a dimension of 100 mm and width 50 mm is to be cut on a mechanical shaper. Calculate the machining time required. Make judicious assumptions if required.
6. A single-point cutting tool of HSS is employed for the shaping operation on grey cast iron. Sketch the different views describing the tool, given that the inclination of the cutting edge is 10°, the tool normal rake is 12° and tool normal clearance is 8°. The major cutting edge angle is 60°.
7. A shaper is operated at 2 cutting strokes per second and is used to machine a workpiece with 150-mm length at a cutting speed of 0.5 m/s using a feed of 0.4 mm per stroke and a depth of cut of 6 mm. Calculate
   (*a*) the total machining time to produce 800 components, each with 100-mm width.
   (*b*) the percentage of the time when the tool is not contacting the workpiece, if the forward stroke is over 230°. State any assumptions made.

1

Introduction

1.1 INTRODUCTION TO MATERIAL REMOVAL PROCESSES

The study of metal cutting and machine tools is one of the most fascinating experiences. Machining of materials is adopted to get higher surface finish, close tolerances, and complex geometric shapes, which are otherwise difficult to obtain.

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The *Drill Press* is the next machine tool to be developed around 1840 by *John Nasmyth. Stephen Fitch* designed the first *Turret Lathes* in 1845. It carried eight tools on a horizontally mounted turret for producing screws. A completely automatic *Turret Lathe* was invented by *Christopher Spencer* in 1869. This is the first form of the automatic lathe utilising cams for feeding the tool in and out of the workpiece, thereby automating most of the machining tasks. He is also credited with the development of a *Multiple-spindle Lathe*. Finally, the *surface Grinder* was developed around 1880. This probably completes the development of almost all basic machine tools.

Over the intervening period, the basic machine tools have been refined by adding various attachments, as well as automating the movements. Also, the invention of various precision measurement techniques helped in improving the accuracy and productivity of the machine tools.

Manufacturing technology is going through major technological changes because of the revolutionary changes being brought in by the developments in microelectronics. The availability of computers and microprocessors has completely changed the machine tool scenario by bringing in the flexibility which was not possible through the conventional mechanisms. The development of Numerical Control in 1952 has, for the first time, brought flexibility to the metal cutting operation. At present, a majority of the manufacturing processes are making use of these principles in some form or the other. This allows for the Just-In-Time (JIT) manufacture leading to zero inventories, zero setup times, and single component batches without losing any advantages of mass manufacturing.

1.2 VARIETY OF MACHINE TOOLS

Casting processes and the metal working processes are the primary manufacturing processes, where, the metal is first shaped, into an intermediate shape, which is normally brought to its final form with the metal cutting process. Assembling of a part into workable equipment often requires the mating surfaces to be complementary to each other in terms of form, dimensions, and surface finish. The only way this can be achieved is through the use of material removal processes. The broad classification of the material removal processes is shown in Fig. 1.1. They can be classified into the traditional processes, which *rely on the difference in the hardness of the cutting tool to that of the workpiece to remove the material.* These are the first processes that have been in use for a long time. These are further divided, based on the type of workpiece geometry and the method employed for generating that geometry.

The non-traditional processes have been mostly invented in the 20th century to take care of the space age materials that are too hard and difficult to be machined by the conventional processes. These processes rely on other methods for removal, rather than the hardness difference between the workpiece and the cutting tool material.

The various material-removal processing machines that are available are

- Turning machines (lathes)
- Boring machines
- Grinding machines
- Gear cutting machines
- Unconventional machining machines
- Drilling machines
- Milling machines
- Shaping and planing machines
- Sawing machines

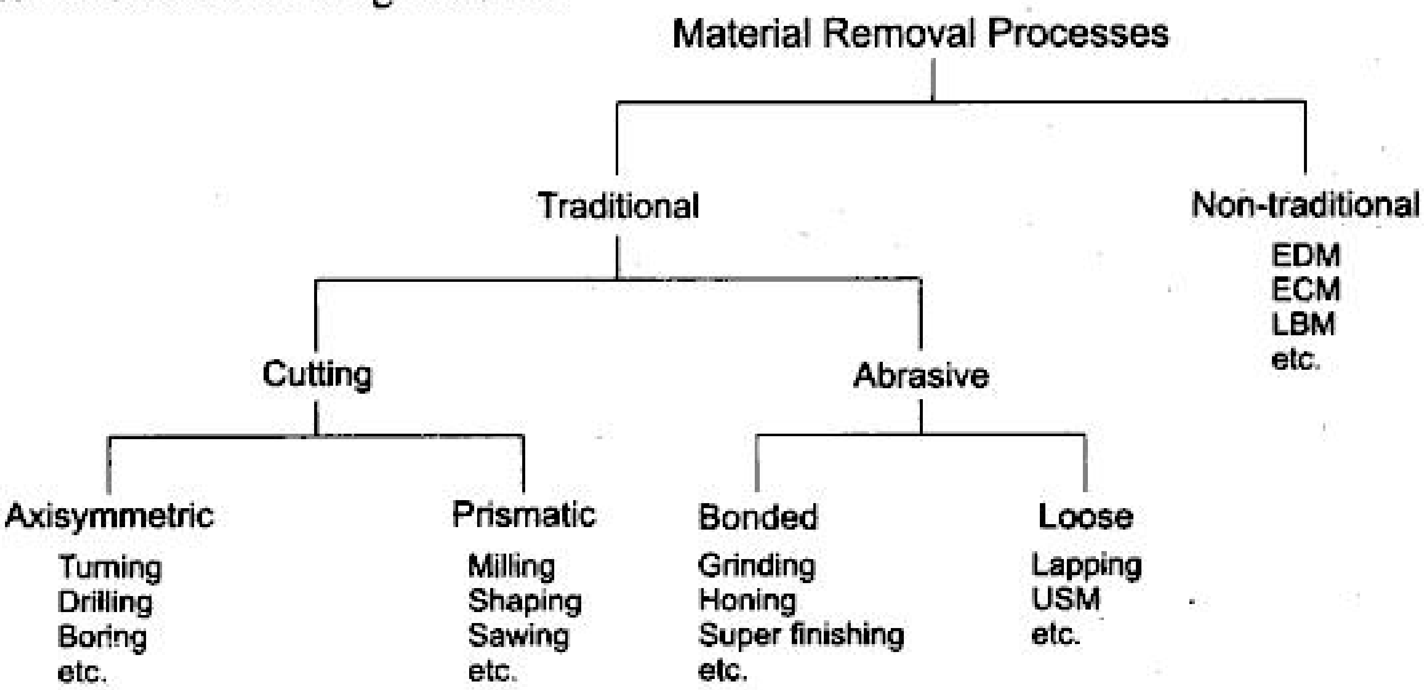

Fig. 1.1 *Classification of the material removal processes.*

Besides these main varieties of machine tools, we have a number of specialised variations depending upon the requirement. They are:

- Automats
- Form relieving lathes
- Copy milling machines
- Centre less grinding machines
- Copy turning machines
- Reaming
- Plano milling machines
- Broaching machines

Table 1.1 lists the status of the machine tool industry in India, which is considered as one yardstick towards industrialisation.

Table 1.1 *Status of Machine Tool Industry in India**

	Production	*Import*	*Export*	*Consumption*	*Share of production (less exp.) to total consumption*
		(in Rs Millions)			*(in per cent)*
1987	2,454	1,118	592	2,980	62.5
1988	2,752	1,300	301	3,752	65.3
1989	3,393	1,518	493	4,418	65.6
1990	4,132	3,404	809	6,727	49.4
1991	5,043	3,126	449	7,720	59.5
1992	4,998	3,729	236	8,491	56.1
1993	4,116	3,619	158	7,577	52.2
1994	5,990	5,537	408	11,119	50.2
1995	7,198	5,976	445	12,729	53.1
1996	8,080	11,003	249	18,834	41.6
1997	7,963	7,221	321	14,863	51.4
1998	6,712	8,405	606	14,511	42.1
1999	5,970	4,727	382	10,315	54.2
2000	6,307	4,258	330	10,232	58.4
2001	5,282	3,103	373	8,012	61.3
2002	5,175	4,332	508	8,999	51.9
2003	6,782	6768	463	13,087	49.8
2004	10,122	16,001	491	25,632	37.6

**Source:* Indian Machine Tool Manufacturers Association, http://www.imtma.in/brief_history1.htm, retrieved on April 30, 2006.

From Table 1.1 for the year 2004, out of the total consumption of Rs. 25,632 million for the machine tools, the metal cutting machine tools constitute a total of Rs. 21,398 million, which is about 84 per cent of the total machine tool consumption.

As mentioned earlier, material removal processes are very expensive and hence should be resorted to only when absolutely needed. Table 1.2 gives a relative comparison of the material removal processes with the other manufacturing processes as a qualitative comparison.

Table 1.2 *Typical comparison of the different manufacturing processes*

Manufacturing process	*Typical application*	*Size range, kg*	*Tolerance Surface Finish*	*Typical production volume*	*Relative tooling cost*	*Disadvantage to use*
Sand casting	All metals	Unlimited	± 0.030 mm/mm 3.2 μm	Unlimited	Low	Casting must be machined
Diecasting	Zinc and Aluminium alloys	Up to 7 kg	± 0.0015 mm/mm 1.6 μm	Very high	High	Porosity
Drop forging	All materials	Unlimited		Very high	Medium	Slow cycle time
Hot Extrusion	All metals	Unlimited		Very high	Low	Low production speed
Gas Metal Arc Welding	All metals	12 mm thick		High	High	Equipment cost and portability
Sheet metal blanking	All materials		± 0.08 mm	Very high	Low	Leaves burr on the part
Turning	All materials	Unlimited	± 0.050 mm 2.0 μm	Very high	Medium	Relatively slow Material wastage
Milling	All materials	Unlimited	± 0.050 mm 2.0 μm	High	Medium	Relatively slow Material wastage
Grinding	All materials	Unlimited	± 0.025 mm 0.4 μm	High	Medium	Expensive finishing operation
Electric discharge machining	Electrically conductive materials		± 0.003 mm 0.1 μm	Low	Low	Di-electric fluid must be filtered

2

Metal Cutting

Objectives

Material removal is the principal operation carried out by a majority of the manufacturing industries. This chapter provides a summary of the major factors that need to be considered in metal cutting. After completing the chapter, the reader will be able to

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2.1 INTRODUCTION

The importance of machining processes can be emphasized by the fact that every product we use in day-to-day life has used this process either directly or indirectly.

(a) In the US, more than \$100 billions were spent annually on the machining and related operations.
(b) Typically, a large majority more than 80 per cent, of all the machine tools used in the manufacturing industry are metal cutting in nature.
(c) An estimate in 1957 showed that about 10 to 15 per cent of all the metal produced in USA is converted into chips.

These facts show the importance of metal cutting in general manufacturing. It is therefore important to understand the metal cutting process in order to make the best use of it. Before the end of 19th century, some amount of work was done by people like *Tresca*, *Thime*, *Mallock*, etc. But it was mostly a scattered work. The monumental work done by *F.W. Taylor* in the last stages of the 19th century and the beginning of the 20th century has been, in fact, the starting point for rational thinking on the metal cutting process. He is mostly interested in empirical research, and the results of his 30 years of experimental work was published in Transactions of ASME in 1907 running to about 300 pages.

Later, a number of investigations have been carried out in understanding the metal cutting process, and using this knowledge to help improve the manufacturing operations involving metal cutting. In this chapter, we will study, in brief, the various understandings available from the metal cutting research work.

A typical cutting tool in a simplified form is shown in Fig. 2.1. The important features to be observed are

Rake angle It is the angle between the face of the tool, called the rake face, and the normal to the machining direction. This angle specifies the ease with which a metal is cut. Higher the rake angle, better is the cutting and less are the cutting forces. Increasing the rake angle reduces the metal backup available at the tool rake face. This reduces the strength of the tool tip as well as the heat dissipation through the tool. Thus, there is a maximum limit to the rake angle, and is generally of the order of 15 degrees for high speed steel tools cutting mild steel. It is possible to have rake angle as zero or negative, as shown in Fig. 2.2. These are generally used in the case of highly brittle tool materials, such as carbides or diamond, for giving extra strength to the tool tip.

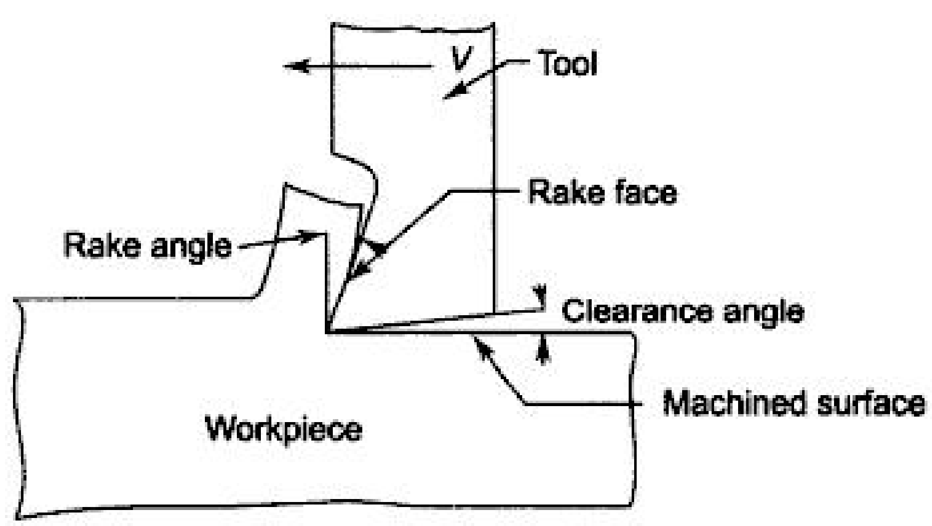


Fig. 2.1 *The general characteristics of a metal cutting tool.*

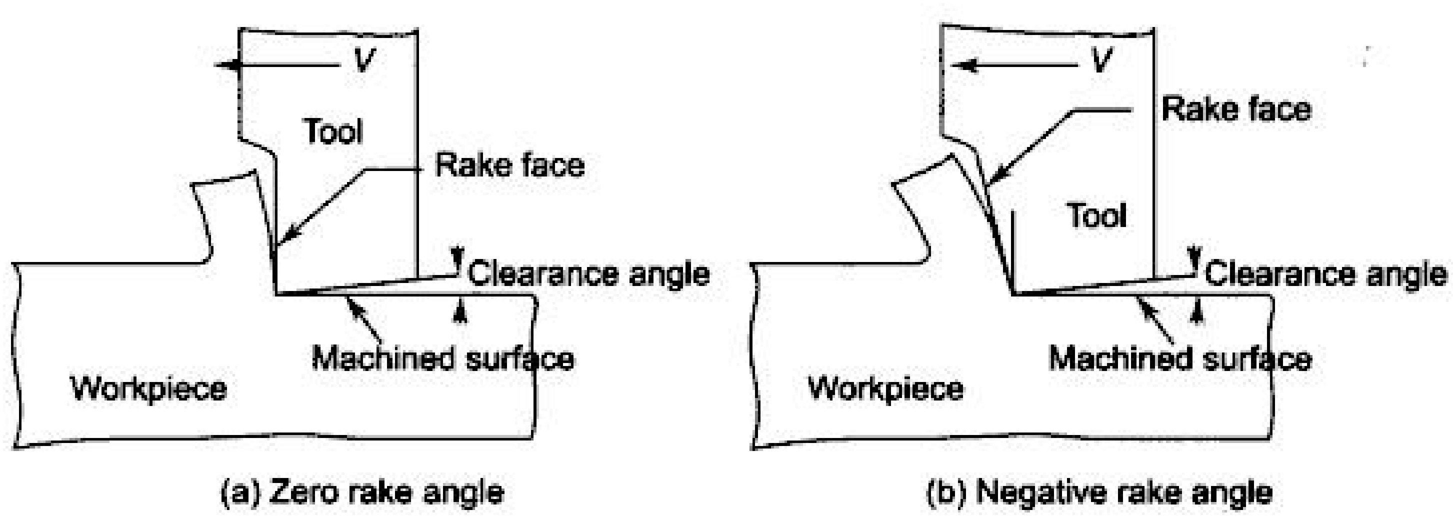


Fig. 2.2 *Tool cutting at different rake angles.*

Clearance angle This is the angle between the machined surface and the underside of the tool, called the flank face. The clearance angle is provided such that the tool will not rub the machined surface, thus spoiling the machined surface and, at the same time increasing the cutting forces. A very large clearance angle reduces the strength of the tool tip, and hence normally an angle of the order of 5 to 6 degrees is generally used.

The conditions that have a predominant influence on metal cutting are work material, cutting tool material, cutting tool geometry, cutting speed, feed rate, depth of cut, and cutting fluid used,

The cutting speed, V, is the speed with which the cutting tool moves through the work material. This is generally expressed in metres per second (ms^{-1}).

Feed rate, f, may be defined as the small relative movement per cycle (per revolution or per stroke) of the cutting tool in a direction usually normal to the cutting speed direction.

Depth of cut, d, is the normal distance between the unmachined surface and the machined surface.

2.2 CHIP FORMATION

Metal cutting process is one of the most complex processes. Fig. 2.3 shows the basic material removal operation. The metal in front of the tool rake face gets immediately compressed, first elastically and then plastically. This zone is traditionally called shear zone, in view of the fact, that the material in the final form is removed by shear from the parent metal. The actual separation of the metal starts as a yielding or fracture, depending on the cutting conditions, starting from the cutting tool tip. Then, the deformed metal, called chip, flows over the tool (rake) face. If the friction between the tool rake face and the underside of the chip (deformed material) is considerable, then the chip gets further deformed, which is termed as secondary deformation. The chip after sliding over the tool rake face is lifted away from the tool, and the resultant curvature of the chip is termed as chip curl.

Plastic deformation can be caused by yielding, in which strained layers of material get displaced over other layers along the slip-planes, which coincide with the direction of maximum shear stress.

Piispanen presented an interesting mechanism to account for the deformation process taking place at the cutting edge. He considers the undeformed metal as a stack of cards, which will slide over one another as the wedge shaped tools move under these cards, as shown in Fig. 2.4. Though this idea is an oversimplified one, it, generally accounts for a number of features that are to be found in practice. A practical example is when paraffin is cut, block-wise slip is clearly evident.

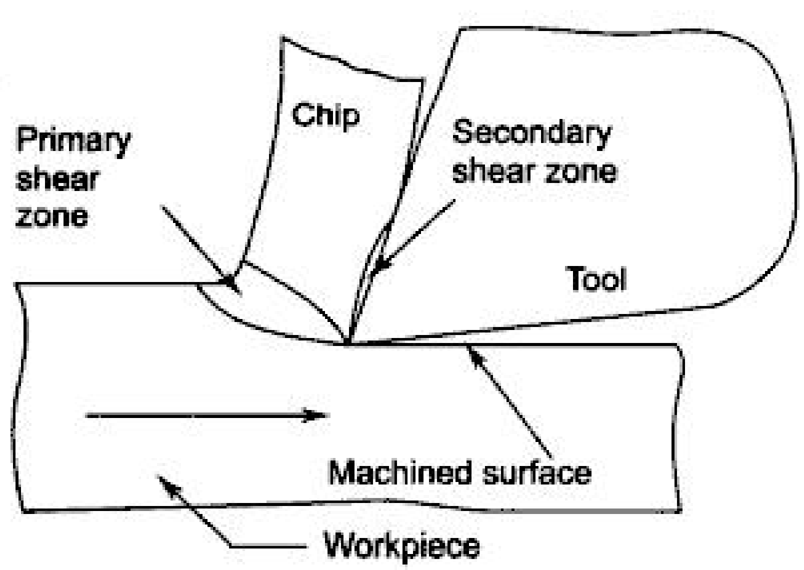


Fig. 2.3 *The possible deformations in metal cutting.*

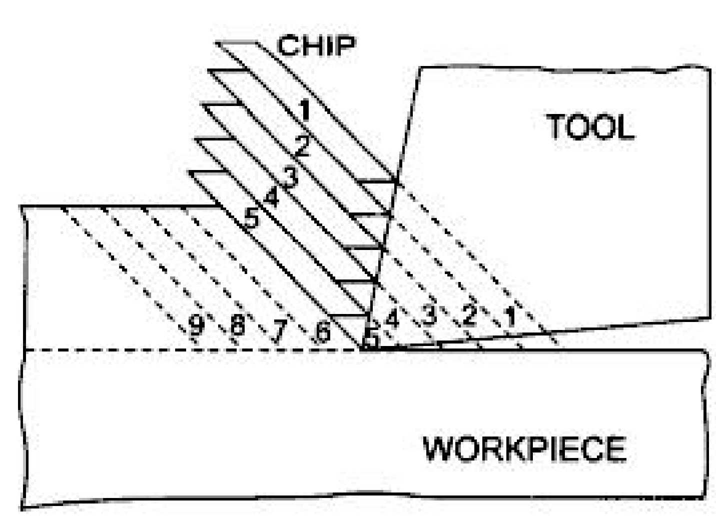


Fig. 2.4 *Piispanen's model of metal cutting.*

The chip in actual manufacturing practice is variable, both in size and shape. Study of chip is one of the most important things in metal cutting. As would be seen later, the mechanics of metal cutting are greatly dependent on the shape and size of the chips produced.

The chip formation in metal cutting can be broadly categorised into three types:

(i) Discontinuous chip
(ii) Continuous chip, and
(iii) Continuous chip with BUE

2.2.1 Discontinuous Chip

When brittle materials like cast iron are cut, the deformed material gets fractured very easily, and thus the chip produced is in the form of discontinuous segments, as shown in Fig. 2.5. In this type, the deformed material, instead of flowing continuously, gets ruptured periodically. Discontinuous chips are easier from the chip-disposal viewpoint. However, the cutting force becomes unstable with the variation coinciding with the fracturing cycle, as shown in Fig. 2.6. Also, they generally provide better surface finish. However, in case of ductile materials, they cause poor surface finish and low tool life. Higher depths of cut (large chip thickness), low cutting speeds, and small rake angles are likely to produce discontinuous chips.

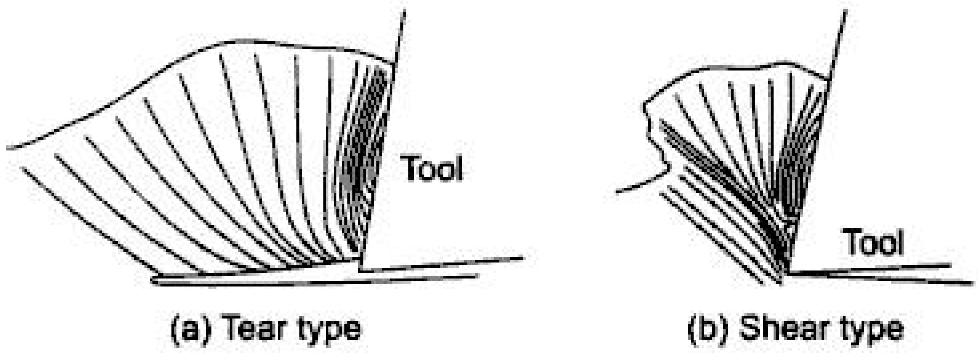


Fig. 2.5 *Possible discontinuous chip formations.*

2.2.2 Continuous Chip

Continuous chips are normally produced when machining steel or ductile metals at high cutting speeds. The continuous chip, which is like a ribbon flows (Fig. 2.7) along the rake face. Continuous chip is possible because of the ductility of metal (steel at high temperature generated due to cutting) that flows along the shear plane instead of rupture. Thus, on a continuous chip, you do not see any notches. It can be assumed that each layer of metal flows along the slip plane till it is stopped by work hardening. Each of these layers get

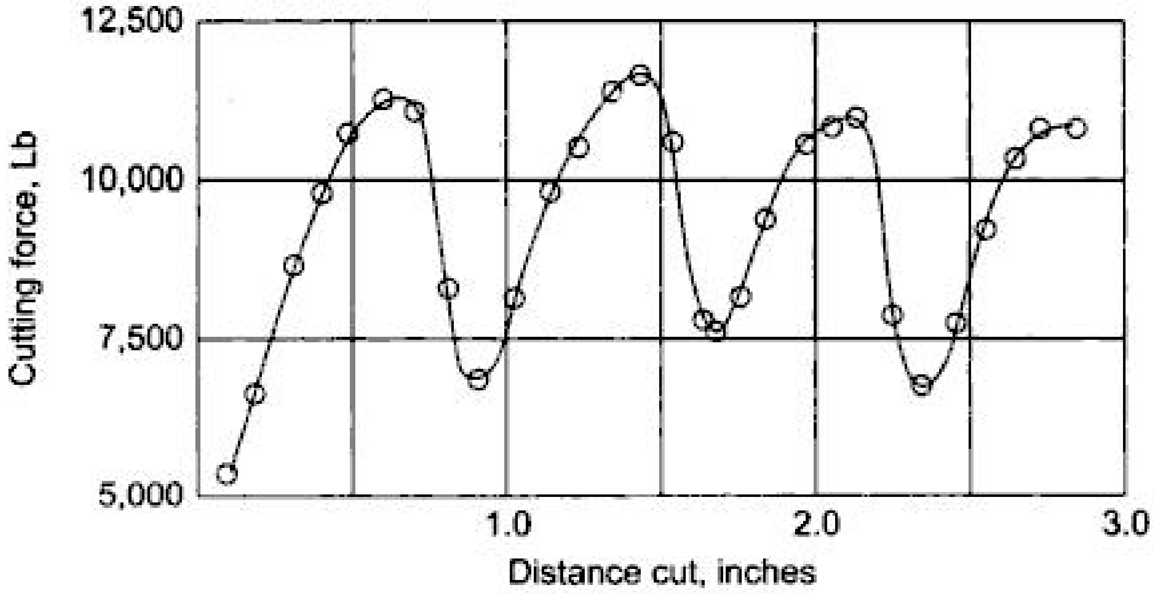


Fig. 2.6 *The variation of cutting force in discontinuous chip formation. (medium carbon steel, rake angle = 30°, cutting speed = 1.65 ft/min, depth of cut = 0.41 in, feed rate = 0.125 in/rev)*

welded to the previous ones because of the high temperature, thus forming a continuous chip. Some ideal conditions that promote continuous chips in metal cutting are sharp cutting edge, small chip thickness (fine feed), large rake angle, high cutting speed, ductile work materials, and less friction between chip tool interface through efficient lubrication.

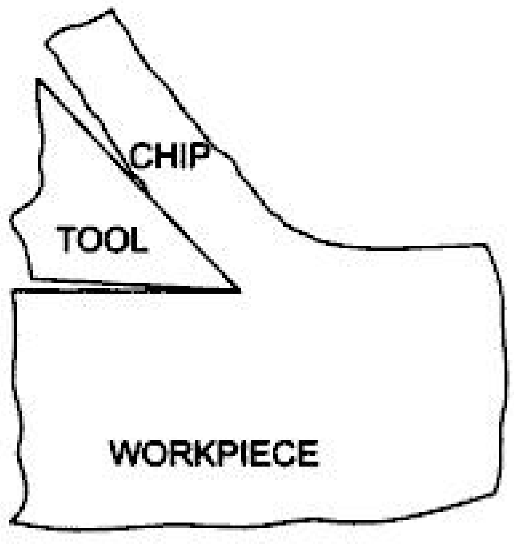


Fig. 2.7 *Continuous chip formation.*

This is the most desirable form of chip, since the surface finish obtained is good and cutting is smooth. It also helps in having higher tool life and lower power consumption. However, because of the large coils of chips, the chip disposal is a problem. To help in this direction, various forms of chip breakers have been developed, which are in the form of a step or groove in the tool rake face. The chip breakers allow the chips to be broken into small pieces so that they can be easily disposed of.

2.2.3 Continuous Chip with BUE

When the friction between tool and chip is high while machining ductile materials, some particles of chip adhere to the tool rake face near the tool tip. When such sizeable material piles up on the rake face, it acts as a cutting edge in place of the actual cutting edge, as shown in Fig 2.8. This is termed as built-up edge (BUE). By virtue of work hardening, BUE is harder than the parent work material. As the size of BUE grows larger, it becomes unstable and parts of it get removed while cutting. The removed portions of BUE partly adhere to the chip underside, and partly to the machined surface, as shown in Fig. 2.9. This causes finished surface to be rough. However, since the cutting is being carried by the BUE and not the actual tool tip, the life of the cutting tool increases while cutting with BUE. In this way, BUE is not harmful while rough machining.

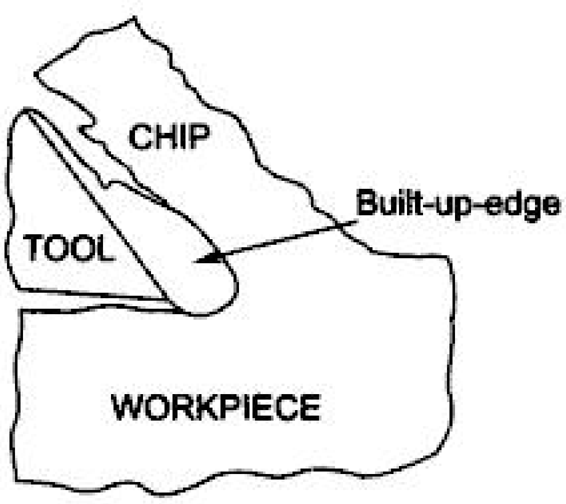


Fig. 2.8 *Closeup view of BUE.*

The conditions that normally induce the formation of BUE are low cutting speed, high feed, and low rake angle. One of the prerequisites for the formation of BUE is the work hardenability of the workpiece material. Higher the work hardenability, rougher is the machined surface produced.

Though the above is a theoretical classification of chips, in actual practice many other types, which would be appearing in the border areas of these three types would also be present.

2.2.4 BUE

The formation of a BUE on the tool is brought about by the high normal loads on the tool rake face leading to adhesion between the chip and the tool. This adhesion may be so severe that instead of the chip sliding over the tool face, considerable plastic flow and eventually rupture occur within the chip. Further layers build up until a large nose of material projects from the cutting edge.

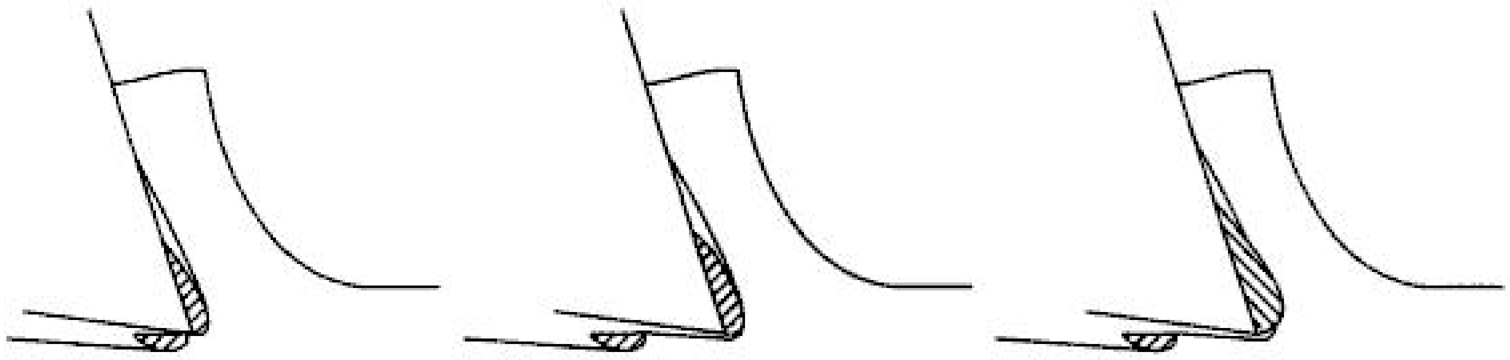


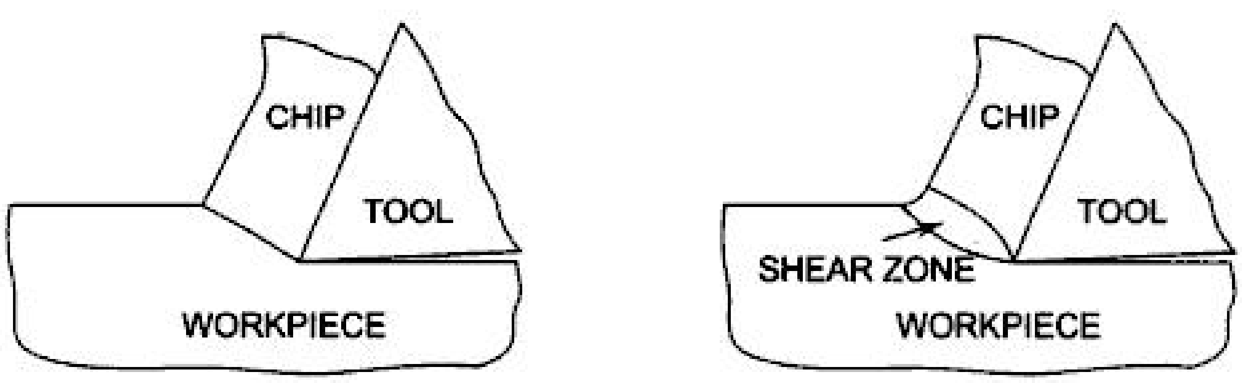
Fig. 2.9 *BUE cycle.*

The adhesion at the chip tool interface is very strong and different from the conventional adhesion characteristics of the material pair concerned. The conditions of machining are most extreme than in most other deformation processes.

(i) It is a plastic flow process with exceptionally large strains. There is a high compressive stress acting on the plastic zone which prevents rupture from occurring until the strain is well above the rupture value, such as in a tensile test.
(ii) The deformation is localised to an extremely small plastic zone. The strain rate is unusually high.
(iii) The chip material rubbing over the tool face is freshly formed from the body of the work material, and is in a chemically clean condition. This makes it more chemically active than the usual oxidised surfaces encountered in most sliding situations, a feature which increases the tendency for adhesion, and so gives a higher friction force.

2.3 SHEAR ZONE

There are basically two schools of thought to analyze the metal removal process. One school of thought is that the deformation zone is very thin and planar, as shown in Fig. 2.10a. The other school thinks that the actual deformation zone is thick with a fan shape, as shown in Fig. 2.10b.



(a) Thin shear plane model (b) Shear plane model

Fig. 2.10 *(a) Thin shear plane model, (b) Thick shear zone model.*

Though the first model (Fig. 2.10a) is convenient from the stand point of analysis, physically it is impossible to exist. This is because the transition from undeformed material to deformed material to take place along a thin plane, the acceleration across the plane has to be infinity for the velocity to change instantaneously from cutting speed V_i to V_c. Similarly, the stress gradient across the shear plane has to be very large to be practical.

In the second model (Fig. 2.10b), by making the shear zone over a region, the transitions in velocities and the shear stresses can be realistically accounted for.

The angle made by the shear plane with the cutting speed vector, ϕ is a very important parameter in metal cutting. Higher the shear angle, better is the cutting performance. From Fig. 2.10a, it can be observed that higher rake angles give rise to higher shear angles.

2.4 ORTHOGONAL CUTTING

Investigators in the metal cutting field have attempted to develop an analysis of the cutting process, which gives a clear understanding of the mechanisms involved and enables the prediction of the important cutting parameters, without the need for testing. But none of these models developed so far can be fully substantiated and definitely stated to be the correct solution. It is worth examining them because they will be explaining the phenomenon qualitatively.

A general purpose metal cutting operation, such as turning or milling, is 3-dimensional and is normally termed as oblique cutting. The obliquity comes from the angle between the cutting speed vector and the cutting edge of the tool, as shown in Fig. 2.11b. Though this is most practical, it is very difficult to analyse because of its 3 dimensions.

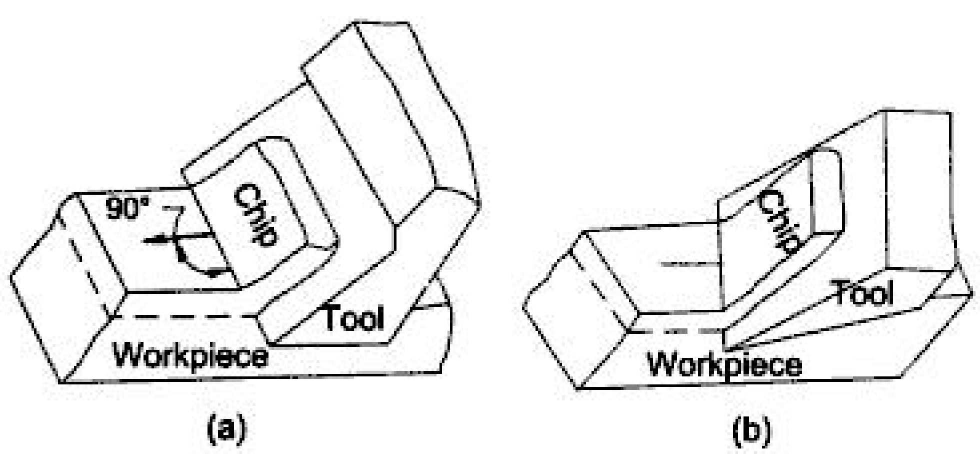


Fig. 2.11 *(a) Orthogonal cutting, (b) Oblique cutting.*

To simplify the matters, researchers often resort to orthogonal cutting, wherein the cutting edge is perpendicular to the cutting velocity, as shown in Fig. 2.11a. Though normal turning is oblique, a special case of turning a pipe from the side, as shown in Fig. 2.12, is orthogonal. Similarly, parting operation in turning is orthogonal. Since this type of cutting reduces the complexity, most of our discussion in this chapter will be based on orthogonal cutting only.

2.4.1 Mechanics of Orthogonal Metal Cutting

As mentioned previously, there are two schools of thought regarding the plastic deformation that takes place at the cutting zone. It seems that the thin zone model is likely to be the most useful because it is simple for analysis purpose.

The current analysis is based on Merchant's thin shear plane model, considering the minimum energy principle. This model is applicable at very high cutting speeds, which are generally practised in production.

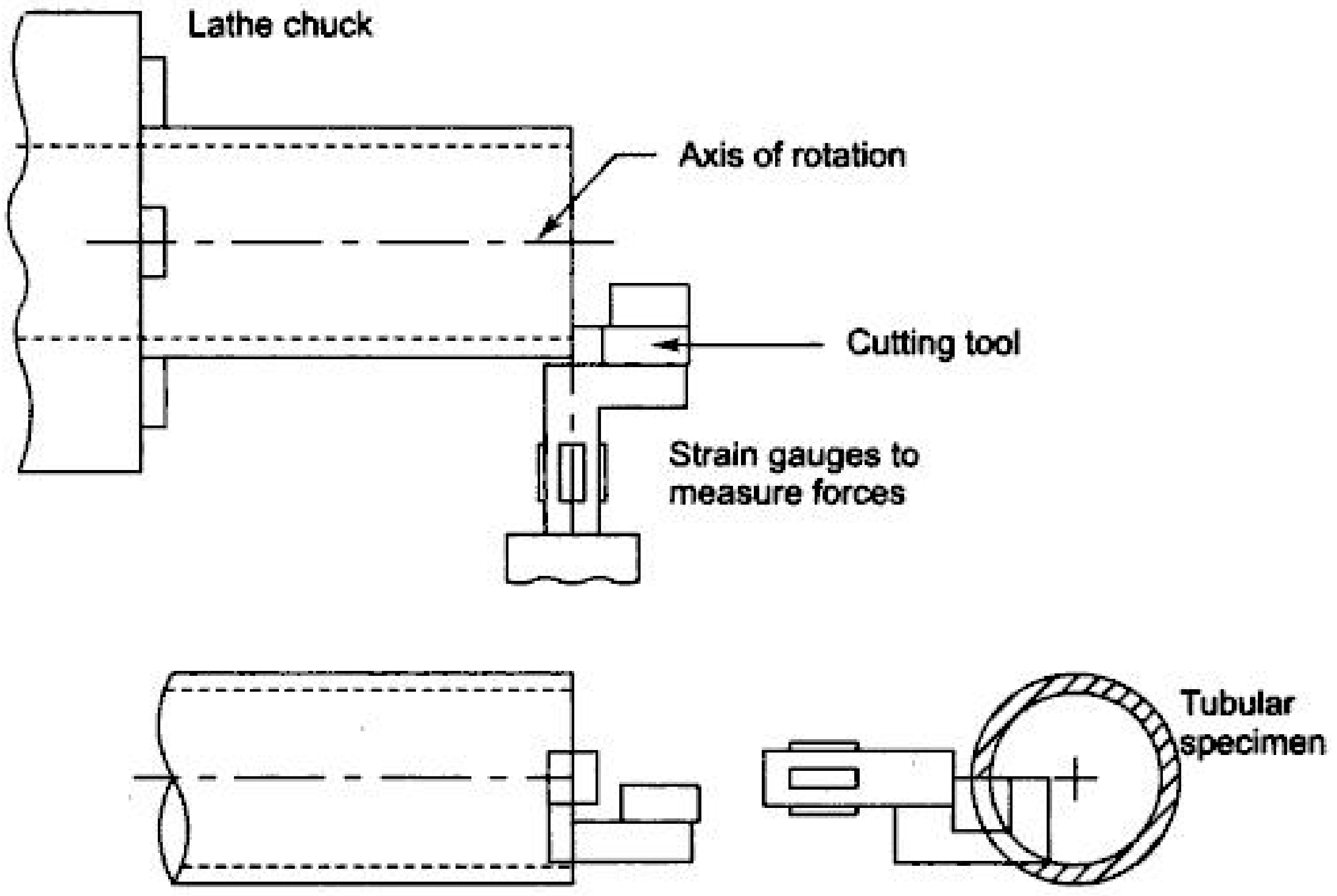


Fig. 2.12 *Realisation of orthogonal cutting in practice, while turning a tube from the end.*

Assumptions

(i) The tool is perfectly sharp and has no contact along the clearance face.
(ii) The surface, where shear is occurring is a plane.
(iii) The cutting edge is a straight line extending perpendicular to the direction of motion, and generates a plane surface as the work moves past it.
(iv) The chip does not flow to either side or no side spread.
(v) Uncut chip thickness is constant.
(vi) Width of the tool is greater than the width of the work.
(vii) A continuous chip is produced without any BUE.
(viii) Work moves with a uniform velocity.
(ix) The stresses on the shear plane are uniformly distributed.

The resultant forces can be conveniently resolved in the direction of the shear plane, along the primary tool motion and along the rake face. In order to achieve the requisite deformation, the tool would be exerting a cutting force, F_H, along the primary cutting motion direction, as shown in Fig. 2.13. Similarly, other force components are

F_V — Force perpendicular to the primary tool motion (thrust force)
F_s — Force along the shear plane
N_s — Force normal to the shear plane
F — Frictional force along the rake face
N — Normal force perpendicular to the rake face

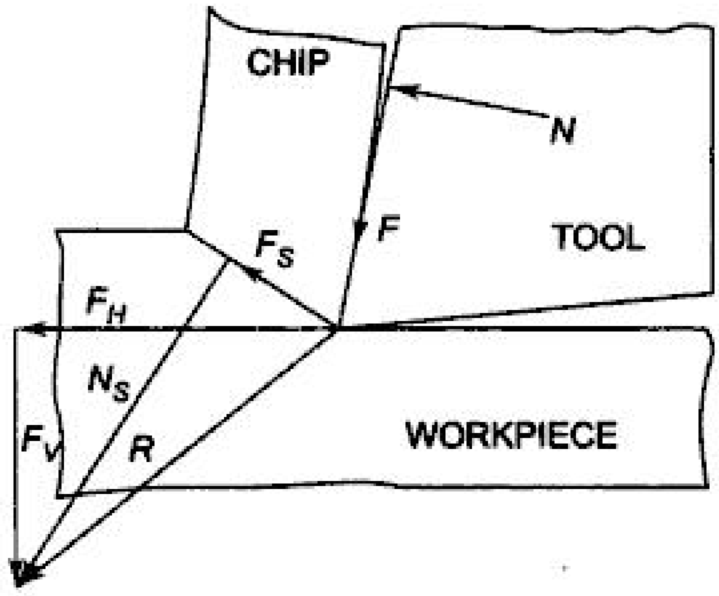


Fig. 2.13 *Various forces acting in orthogonal cutting.*

When the chip is isolated as a free body, as shown in Fig. 2.14, we need to consider only two forces, the force between the tool face and the chip (R), and the force between the workpiece and the chip along the shear plane (R'). For equilibrium,

$$R = R'$$

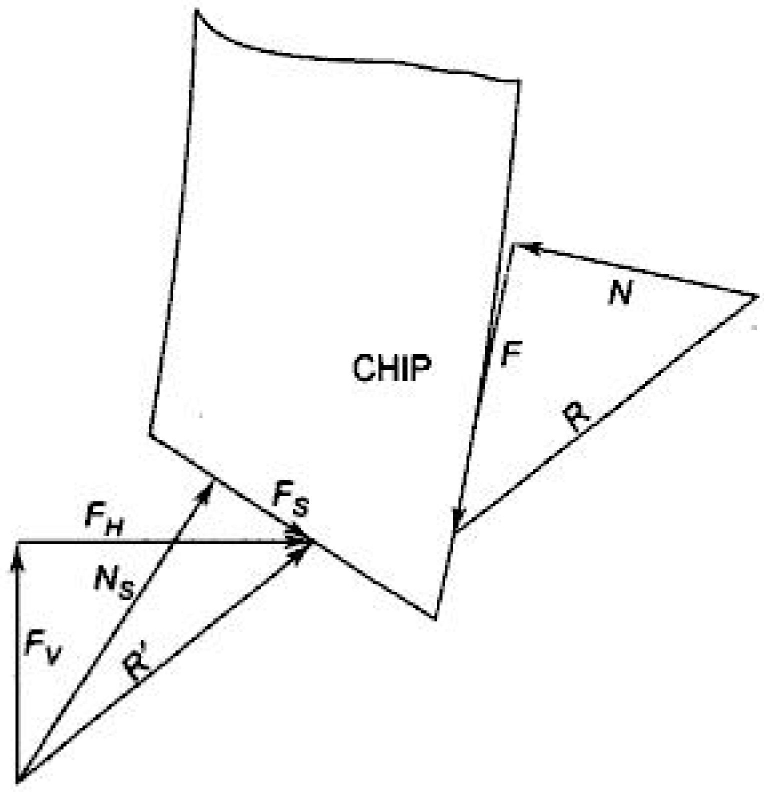


Fig. 2.14 *Forces acting on an isolated chip in metal cutting.*

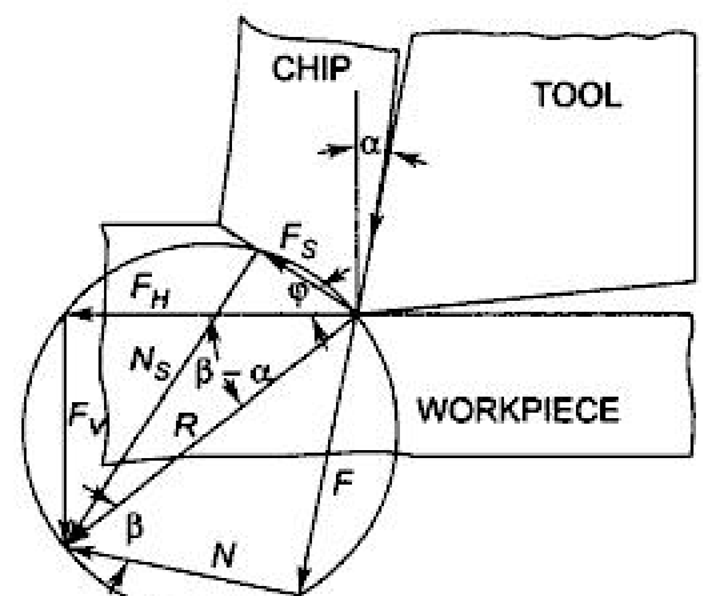


Fig. 2.15 *Merchant's cutting-force circle in orthogonal cutting.*

It is possible to represent all these forces be acting at the tool point in place of their actual point of action. By doing so, it is possible to construct a cutting-force circle, as shown in Fig. 2.15, which is often called Merchant's circle. It is a simple exercise to derive the various relationships among the forces.

We will make some construction into Fig. 2.15, to get the relationships between the various forces as in Fig. 2.16 and 2.17.

From Fig. 2.15 and 2.16, we can write

$$F_s = F_H \cos\varphi - F_V \sin\varphi \tag{2.1}$$

$$N_s = F_V \cos\alpha + F_H \sin\varphi \tag{2.2}$$

$$= F_s \tan(\varphi + \beta - \alpha) \tag{2.3}$$

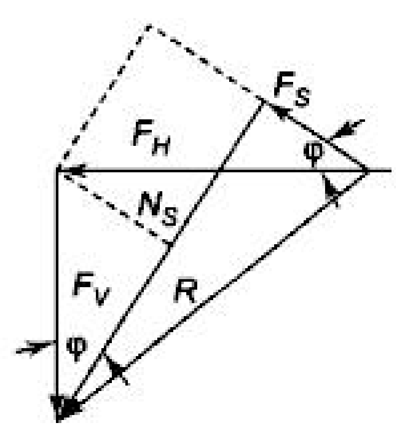


Fig. 2.16 *Part of Merchant's cutting force diagram.*

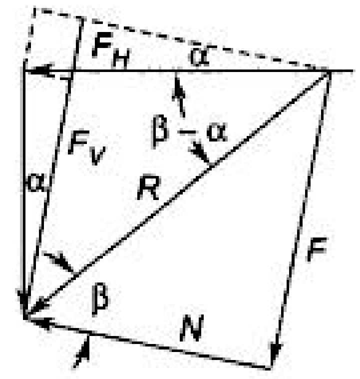


Fig. 2.17 *Part of Merchant's cutting force diagram.*

From Fig. 2.15 and 2.17, we can write

$$F = F_H \sin\alpha + F_V \cos\alpha \tag{2.4}$$

$$N = F_H \cos\alpha - F_V \sin\alpha \tag{2.5}$$

If μ is the coefficient of friction along the rake face, then

$$\mu = \tan\beta = \frac{F}{N} = \frac{F_V + F_H \tan\alpha}{F_H - F_V \tan\alpha} \tag{2.6}$$

where, β is the friction angle, and

ϕ is the shear angle

This friction is not similar to the usual sliding case, since F and N are not uniformly distributed over the sliding area. This aspect is discussed later.

Now, the area of shear plane, A_s, is given by

$$A_s = \frac{bt}{\sin\phi} \tag{2.7}$$

The shear force is given by

$$F_s = \tau A_s = \frac{\tau bt}{\sin\varphi} \tag{2.8}$$

where, τ is the mean shear stress in the shear plane.

b is the width of cut and t is the uncut chip thickness

$$\sigma = \frac{N_s}{A_s} \quad \text{or} \quad N_s = \frac{\sigma bt}{\sin\varphi} \tag{2.9}$$

where, σ is the mean normal stress in the shear plane.

We can show that by resolving

$$F_H = F_s \cos\varphi + N_s \sin\varphi \tag{2.10}$$

$$F_V = N_s \cos\varphi - F_s \sin\varphi \tag{2.11}$$

Substituting Eq. (2.3) in (2.10), we get

$$F_H = F_s\,[\cos\varphi + \sin\varphi \tan(\varphi + \beta - \alpha)] \tag{2.12}$$

Similarly,

$$F_V = F_s\,[\cos\varphi \tan(\varphi + \beta - \alpha) - \sin\varphi] \tag{2.13}$$

Rearranging, we get

$$F_H = F_s\left[\frac{\cos(\alpha - \beta)}{\cos(\varphi + \beta - \alpha)}\right] \tag{2.14}$$

$$F_H = \frac{\tau bt \cos(\beta - \alpha)}{\sin(\varphi i)\cos(\varphi + \beta - \alpha)} \tag{2.15}$$

$$F_V = \frac{\tau bt \sin(\beta - \alpha)}{\sin(\varphi i)\cos(\varphi + \beta - \alpha)} \tag{2.16}$$

Merchant considered that τ would have the value of the yield shear stress for the work material, and that μ would have the usual value for any dry sliding friction. To determine ϕ, he assumed that the minimum energy principle is applied in metal cutting so that the deformation process adjusts itself to a minimum energy condition, or

$$\frac{dF_H}{d\varphi} = \frac{\tau bt \cos(\beta - \alpha)\cos(2\varphi + \beta - \alpha)}{\sin^2\varphi\cos^2(\varphi + \beta - \alpha)} \tag{2.17}$$

or
$$\cos(2\varphi + \beta - \alpha) = 0 \tag{2.18}$$

or
$$2\varphi + \beta - \alpha = \frac{\pi}{2} \tag{2.19}$$

$$\varphi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) \tag{2.20}$$

Substituting back, we can show that

$$F_H = 2\,\tau bt \cot\varphi \tag{2.21}$$

$$F_v = \tau bt(\cot^2\varphi - 1) \tag{2.22}$$

The above deductions, which we have obtained assuming two things, are not supported by experimental evidence. Firstly, the minimum energy principle, though appealing is not supported by evidence. Next, it assumes that β and α are constant with respect to ϕ. But later studies on metal cutting have shown that at least β is dependent on ϕ. Of course, this is concerning only steady state operation. But under dynamic conditions, α also varies considerably. Experiments were conducted and it was found that this equation is not valid. We will see more about this shear angle relationship later.

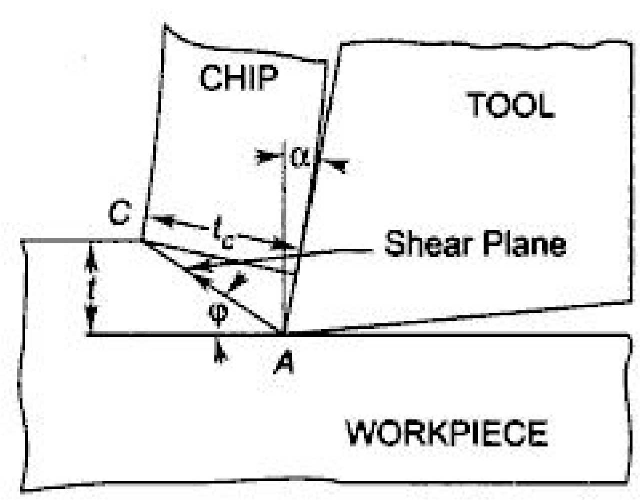


Fig. 2.18 *Orthogonal cutting with thin shear plane.*

To determine the shear angle experimentally, we have to stop the cutting process and study the zone with the help of a microscope or a photograph. Alternatively, we can also derive a relationship from the geometry of chip formation, as shown in Fig. 2.18.

From Fig. 2.18,

$$t = AB\sin\phi \tag{2.23}$$

$$t_c = AB\cos(\phi - \alpha) \tag{2.24}$$

The chip thickness ratio, r, which is also termed as cutting ratio, would be

$$r = \frac{t}{t_c} = \frac{\sin\varphi}{\cos(\varphi-\alpha)} = \frac{1}{\cot\varphi\cos\alpha + \sin\alpha} \tag{2.25}$$

$$\cot\varphi\cos\alpha = \frac{1-\sin\alpha}{r} \tag{2.26}$$

$$\tan\varphi = \frac{r\cos\alpha}{1-r\sin\alpha} \tag{2.27}$$

Experimentally, the chip thickness ratio, r, could be determined by measuring the average thickness of the chips produced under given conditions of feed and speed. From this, it is possible to evaluate the shear angle using the above equation. However, direct measurement of chip thickness is difficult, because of the roughness on the outside of the chip. For this purpose, an indirect measurement is followed, wherein the length of a chip, l_c, equivalent to a known length of uncut chip is measured. Then, considering the fact that the depth is same, the average chip thickness, t_c, would be given by

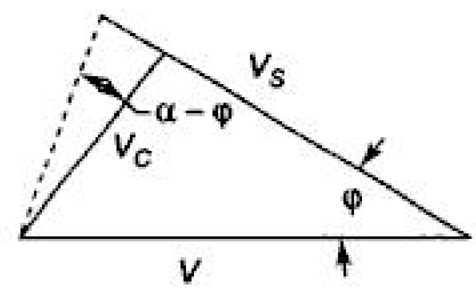


Fig. 2.19 *Velocity relationships in orthogonal cutting.*

$$t_c = \frac{tl}{l_c} \tag{2.28}$$

where, l = length of uncut chip

To get an exact size of uncut chip length, l, we may introduce a small saw cut parallel to the axis on the workpiece, so that uncut chip size is

$$l = \pi D \tag{2.29}$$

where D is the diameter of the workpiece.

The chip velocity, V_c, is the velocity of the chip relative to the tool and directed along the tool face. The shear velocity, V_s, is the velocity of the chip relative to the workpiece and directed along the shear plane. These two velocities along with the cutting velocity, V, would form a closed triangle, as shown in Fig. 2.19. From this we can get

$$\frac{V}{\sin\{90^\circ-(\varphi-\alpha)\}} = \frac{V_s}{\sin(90^\circ-\alpha)} = \frac{V_c}{\sin\varphi} \tag{2.30}$$

$$V_c = \frac{V\sin\varphi}{\cos(\varphi-\alpha)} \tag{2.31}$$

$$V_s = \frac{V\cos\alpha}{\cos(\varphi-\alpha)} \tag{2.32}$$

To evaluate the shear strains, we take the help of Piispanen's model, as shown in Fig. 2.20.
Shear strain γ is given by

$$\gamma = \frac{\Delta S}{\Delta Y} = \frac{AB}{CD} = \frac{AD}{CD} + \frac{DB}{CD} = \tan\varphi + \cot(\varphi-\alpha) \tag{2.33}$$

or $$\gamma = \frac{\cos\alpha}{\sin\varphi\cos(\varphi-\alpha)} = \frac{V_s}{V\sin\varphi} \quad (2.34)$$

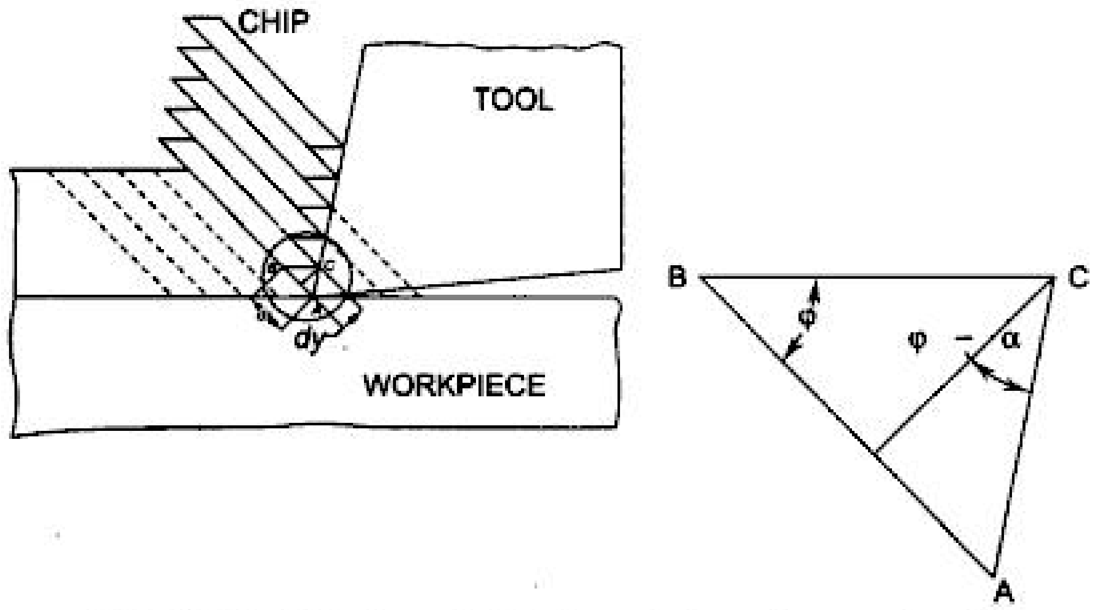


Fig. 2.20 *Strain and strain rate in orthogonal cutting.*

The strain rate is given by

$$\dot{\gamma} = \frac{\Delta S}{\Delta Y\,\Delta t} = \frac{V_s}{\Delta Y} = \frac{\cos\alpha}{\cos(\varphi-\alpha)}\frac{V}{\Delta Y} \quad (2.35)$$

where, ΔY is the thickness of the deformation zone and t is the time to achieve the final value of strain. ΔY can be considered as the mean value of the spacing of successive slip planes, which is of the order of 2.5 microns.

Most of the energy consumed in metal cutting is utilised in plastic deformation. The total work done, W, is given by

$$W = F_H V \quad (2.36)$$

The work done in shear W_s is

$$W_s = F_s V_s \quad (2.37)$$

Similarly, the work done in friction W_f is

$$W_f = F V_c \quad (2.38)$$

Thus, $$W = F_H V = F_s V_s + F V_s \quad (2.39)$$

To get a better picture of the efficiency of the metal cutting operation, it is necessary to have a new parameter, which does not depend on the cutting process parameters. The specific cutting energy, u_s, is such a parameter, which can be obtained by dividing the total work done with the material removal rate. The material removal rate is

$$MRR = Vbt \quad (2.40)$$

$$u_s = \frac{F_H V}{MRR} = \frac{\tau\cos(\beta-\alpha)}{\sin(\varphi i)\cos(\varphi+\beta-\alpha)} \quad (2.41)$$

To understand the significance of the various equations derived, a number of numerical examples are solved below.

Example 2.1. *A bar of 75 mm diameter is reduced to 73 mm by a cutting tool, while cutting orthogonally. If the mean length of the cut chip is 73.5 mm, find the cutting ratio. If the rake angle is 15°, what is the shear angle?*

Length of uncut chip, $l = \dfrac{\pi(75+73)}{2} = 232.4779$ mm

Cutting ratio, $r = \dfrac{t_c}{t} = \dfrac{73.9}{232.4779} = 0.3179$

Shear angle $\varphi = \tan^{-1}\left[\dfrac{r\cos\alpha}{1-r\sin\alpha}\right] = \tan^{-1}\left[\dfrac{0.3179\cos 15}{1-0.3179\sin 15}\right]$

Shear angle, $\varphi = \tan^{-1}(0.3346) = 19°$

Example 2.2. *In an orthogonal cutting test with a tool of rake angle 10°, the following observations were made:*

Chip thickness ratio = 0.3

Horizontal component of the cutting force = 1290 N

Vertical component of the cutting force = 1650 N

From Merchant's theory, calculate the various components of the cutting forces, and the coefficient of friction at the chip tool interface.

Given $r = 0.3$ and $\alpha = 10°$

The shear plane angle, ϕ, is

$$\tan\phi = \frac{r\cos\alpha}{1-r\sin\alpha} = \frac{0.3\cos 10°}{1-0.3\sin 10°} = 0.311679$$

$$\text{shear angle, } \phi = \tan^{-1}(0.311679) = 17.31°$$

Given $F_V = 1650, F_H = 1290$

The friction force along rake face is

$$F = F_H\sin\alpha + F_V\cos\alpha = 1290\sin 10° + 1650\cos 10° = 1848.94 \text{ N}$$

The normal force on the rake face is

$$N = F_H\cos\alpha - F_V\sin\alpha = 1290\cos 10° - 1650\sin 10° = 983.88 \text{ N}$$

The coefficient of friction, μ, at the chip tool interface is given by

$$\mu = \frac{F}{N} = \frac{1848.94}{983.88} = 1.8792$$

The friction angle, β, is given by

$$\beta = \tan^{-1}\mu = \tan^{-1}(1.8792) = 62°$$

The resultant cutting force, R, is given by

$$R = \sqrt{1650^2 + 1290^2} = 2094.42 \text{ N}$$

The shear force along the shear plane is

$$F_s = F_H \cos\varphi - F_V \sin\varphi = 1290\cos 17.31° - 1650\sin 17.31° = 740.63 \text{ N}$$

The normal force on the shear plane is

$$N_s = F_V \cos\varphi + F_H \sin\varphi = 1650\cos 17.31° + 1290\sin 17.31° = 1959.10 \text{ N}$$

The area of the shear plane is given by

$$A_s = \frac{bt}{\sin\varphi} = \frac{6\times 0.10}{\sin 17.31°} = 2.0165 \text{ mm}^2$$

To verify the shear angle from the relation suggested by *Merchant*:

$$\varphi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) = \frac{\pi}{4} - \frac{(62-10)}{2} = 19°$$

It can be seen that the actual value of the shear angle is 17.31, whereas the value calculated from the shear angle relation of *Merchant's* is 19. The error is 9.76 per cent.

Example 2.3. *The orthogonal cutting of steel with 10° rake tool, with a depth of cut of 2 mm, and feed rate of 0.20 mm/rev. The cutting speed is 200 m/min. The chip thickness ratio is 0.31. The vertical cutting force is 1200 N and the horizontal cutting force is 650 N. Calculate from Merchant's theory, the work done in metal cutting and shear stress.*

Given $r = 0.31, \alpha = 10°$

Shear plane angle, ϕ is

$$\tan\phi = \tan = \frac{0.31\cos 10°}{1 - 0.31\sin 10°} = 0.32266$$

$$\text{shear angle, } \phi = \tan^{-1}(0.32266) = 17.88°$$

Given $F_V = 1200, F_H = 650$

The shear force along the shear plane is

$$F_s = 650\cos 17.88° - 1200\sin 17.88° = 250.18 \text{ N}$$

The normal force on the shear plane is

$$N_s = 1200\cos 17.88° + 650\sin 17.88° = 1341.61 \text{ N}$$

The area of the shear plane is given by

$$A_s = \frac{bt}{\sin\phi} = \frac{2\times 0.20}{\sin 17.88°} = 1.3028 \text{ mm}^2$$

Friction force along rake face is

$$F = 650\sin 10° + 1200\cos 10° = 1294.64 \text{ N}$$

Normal force on the rake face is

$$N = 650 \cos 10 - 1200 \sin 10° = 431.75 \text{ N}$$

The coefficient of friction, μ, at the chip tool interface is given by

$$\mu = \frac{F}{N} = \frac{1294.64}{431.75} = 2.9986$$

The friction angle, β, is given by

$$\beta = \tan^{-1} \mu = \tan^{-1} (2.9986) = 71.56°$$

To verify the validity of the shear angle relationship suggested by *Merchant*:

$$\varphi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) = \frac{\pi}{4} - \frac{(71.56 - 10)}{2} = 14.22°$$

It can be seen that the actual value of the shear angle obtained from measured values is 17.88, whereas the value calculated from the shear angle relation of *Merchant's* is 14.22, the resulting error is 20.5 per cent.

The shear velocity, V_s, is given by

$$V_s = \frac{V \cos \alpha}{\cos (\varphi - \alpha)} = \frac{200 \cos 10°}{\cos (17.88 - 10)} = 198.84 \text{ m/min}$$

The chip velocity, V_c, is given by

$$V_c = \frac{V \sin \varphi}{\cos (\varphi - \alpha)} = \frac{200 \sin 17.88}{\cos (17.88 - 10)} = 61.99 \text{ m/min}$$

Shear strain, γ, is given by

$$\gamma = \frac{V_s}{V \sin \varphi} = \frac{198.84}{200 \sin 17.88°} = 3.2382$$

The strain rate is given by

$$\dot{\gamma} = \frac{V_s}{\Delta Y} \frac{\cos \alpha}{\cos (\varphi - \alpha)} = \frac{V}{\Delta Y} = \frac{\cos 10° \times 200000}{\cos (17.88 - 10)° \times 0.0025} = 79.5357$$

taking $\Delta Y = 2.5$ microns,

The shear work done, W_s is

$$W_s = F_s\, V_s = 250.1767 \times 198.84 = 49745.14 \text{ N m/min}$$

The work done in friction, W_f is

$$W_f = F \times V_c = 1294.64 \times 61.99 = 80254.77 \text{ N m/min}$$

The total work done is

$$W = F_H \times V = 200 \times 650 = 130000 \text{ N m/min}$$

The shear work proportion out of the total work done is

$$\frac{49745.14}{130000} = 38.27\%$$

Friction work proportion in total work done is

$$\frac{80254.77}{130000} = 61.73\%$$

Friction It is found that μ determined in this way is exceptionally high in value, and that it varies with tool geometry and other cutting conditions. But this is contrary to the sliding friction studies.

Under a microscope, the actual contact of two sliding surfaces through the high spots (asperities). In the case of normal contacting surfaces, as shown in Fig. 2.21, the real area of contact is different from the apparent area of contact. Real area changes by first, the elastic deformation, and when load increases, by plastic deformation. Thus,

$$A_r = \frac{N}{p} \tag{2.42}$$

where, p = mean yield stress of the asperities, and

N = applied load.

Under the influence of normal and tangential load, it has been shown that very high temperatures are developed at the contacting asperities, and that metallic bonding of the contacting high spots can occur. Thus, sliding of one surface relative to the other must be accompanied by shearing of the welded asperities.

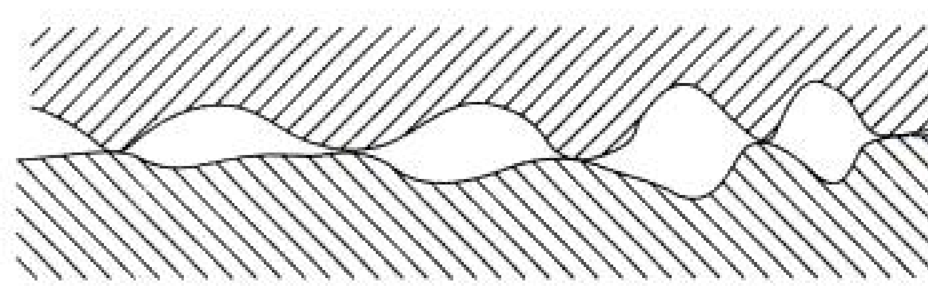


Fig. 2.21 *Micro view of asperities in contact.*

When plastic deformation takes place at the contacting surfaces, the friction mechanism is different because of the fact that real area of contact approaches that of apparent area of contact. Under these conditions, the friction force is independent of normal force.

Another similarity noted with the experimental data of metal cutting is that the friction coefficient increases with an increase in the rake angle, as shown in Table 2.1.

It is normally expected that with an increase in the rake angle, the metal cutting forces decrease, and should normally be associated with a decrease in the friction. However, in actual practice, the friction coefficient increases, as shown in Table 2.1.

Table 2.1 *Variation of coefficient of friction with rake angle in orthogonal cutting*

Rake angle, $\alpha°$	*Coefficient of friction, μ*
–20	0.58
–5	0.725
0	0.78
5	0.90
20	1.19

This happens because the influence of the rake angle is not the same on the different components of the cutting force. The normal force on the rake face decreases greatly compared to the friction face, as shown in Table 2.2. Thus, though there is an overall decrease in the forces, the coefficient of friction is increasing. That is how *Kronenberg* calls this friction coefficient as apparent coefficient of friction.

Table 2.2

Rake angle, α°	*Friction force F*	*Normal force N*	*Coefficient of friction, μ*	*Percentage decrease*	
	N	N		*F*	*N*
16	3025	4518	0.67		
30	2524	2938	0.86	16.87	35
45	2470	2034	1.21	18.62	55

In metal cutting, we have a sliding situation under conditions of high normal load and with a metal surface, which is chemically clean, having been recently exposed from the body of the parent metal. The cleanliness of the metal surfaces can explain the high value of μ, and high normal load can explain the departure from the usual laws of friction.

Thus, the friction along the rake face of a cutting tool can be considered as partially sticking and partially sliding, as shown in Fig. 2.22. In the sticking zone, the shear stress is constantly approaching the work materials yield stress, while in the sliding zone, *Coulomb's* laws of friction hold good.

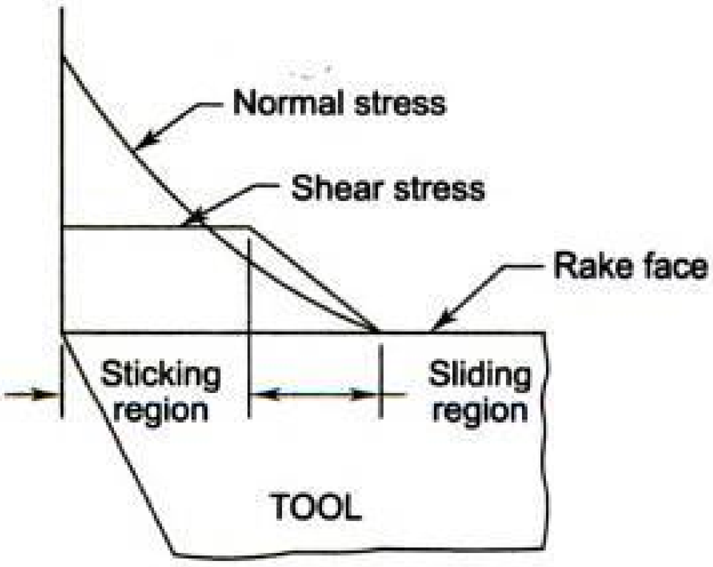


Fig. 2.22 *Stress distribution expected along the rake face.*

Another aspect to be noted is the inclusion of the rubbing force component at the clearance face in the measured forces. This component can be obtained by plotting the measured cutting force against the depth of cut and extrapolating back to zero depth. Even after the deduction of this, which is not contributing to the shear, we get a higher value of μ, which can only be explained by the distribution of stresses on the rake face, as shown in Fig. 2.22.

2.5 SHEAR ANGLE AND ITS RELEVANCE

The importance of shear angle has already been discussed previously. There were a number of attempts to derive a simple relationship for shear angle which can be predicted from the cutting process parameters, without going in for extensive experimentation.

Scientists have been interested in the shear angle, ϕ, as far back as 1877, when *Thime* published his investigations in metal cutting. Before 1896, only approaches have been made to see how the shear angle varies under differing conditions, but no specific proposal has been made as to any certain mathematical relationship. *Zvorkyn*, in 1897, first derived a relationship as follows:

$$\varphi = \frac{\pi}{4} + \frac{(\alpha - \beta - C_1)}{2} \tag{2.43}$$

where, C_1 is a constant, depending on the shape of the outer boundary of the chip.

Herman, in 1907, developed the following relationship between the shear angle, ϕ, the true rake angle, α, and the friction angle at the rake face, β.

$$\varphi = \frac{\pi}{8} + \frac{(\alpha - \beta)}{2} \tag{2.44}$$

Krystoff, in 1939, gave the following relation:

$$\varphi = \frac{\pi}{4} + (\alpha - \beta) \tag{2.45}$$

This equation would give zero shear angle for friction angle of 45° and rake angle of 0°, which is most unlikely, and hence this formula is not universally valid.

As shown above, *Merchant*, in 1941, derived the following formula:

$$\varphi = \frac{\pi}{4} + \frac{1}{2}(\alpha - \beta) \tag{2.46}$$

However, the experimental observations made (Fig. 2.23) were in variance with this formula over its entire range of operations. *Merchant* assumed, further, that shear stress, τ_s, on the normal plane would be affected by the normal compressive stress, τ_n, in a linear fashion as follows:

$$\tau_s = \tau_o + K \times \tau_n \tag{2.47}$$

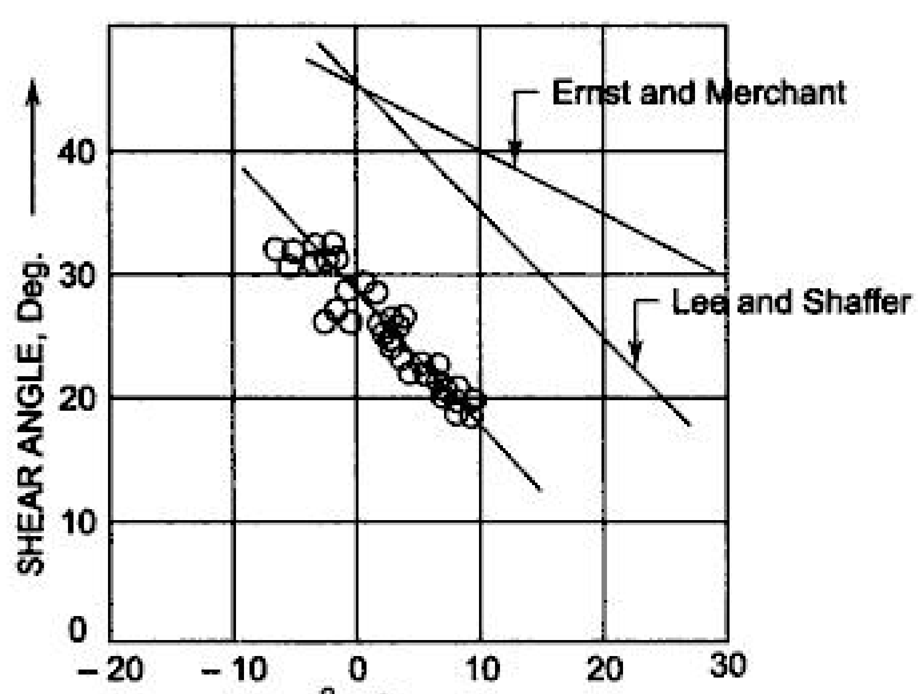


Fig. 2.23 *Comparison of experimental results with the shear angle relationships.*

The modified equation, therefore, is

$$\varphi = \frac{C}{2} + \frac{1}{2}(\alpha - \beta) \tag{2.48}$$

Where C, represents the factor dependent on the plastic properties of the material, and is given by

$$C = \cot^{-1} K \tag{2.49}$$

Merchant called this factor as machinability constant, but it is not a constant. An average value of C for steels is 75°.

Hucks established a relationship as follows:

$$\varphi = \frac{\pi}{4} - \frac{\tan^{-1} 2\mu}{2} + \alpha \tag{2.50}$$

Lee and *Shaffer* have used the mathematical theory of plasticity based on the behaviour of a rigid plastic material, to produce a solution of the orthogonal machining problem. The solution involved in the construction of a slip-line field pattern using a shear plane model (Fig. 2.24). They considered that there must be a stress field within the chip to transmit the cutting forces from the shear plane to the tool face. They represented this by a slip-line field in which no deformation occurs although it was stressed up to the yield point. This shows *Mohr's* circle for the stresses at the boundaries of the stressed zone, which results in the equation:

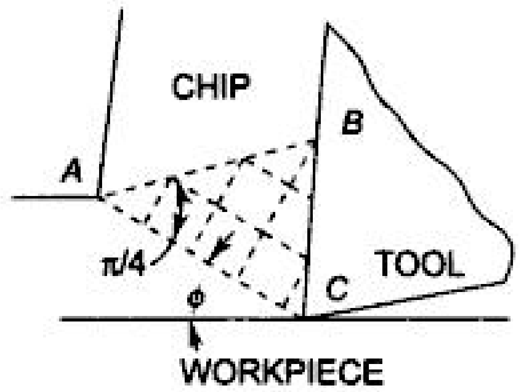


Fig. 2.24 *Shear plane model of Lee and Shaffer.*

$$\varphi = \frac{\pi}{4} + (\alpha - \beta) \tag{2.51}$$

This relationship is same as *Krystoff's* formula and is not of much use.

Shaw, Cook, and Finnie have slightly modified the above analysis by assuming that the shear plane is not a plane of maximum shear stress. Hence, shear plane will not be a slip line, and the ultimate result is the equation,

$$\varphi = \frac{\pi}{4} + \eta' + (\alpha - \beta) \tag{2.52}$$

The angle, η', is not established by the analysis. It is suggested that η' is not constant but can vary with the cutting conditions. This η' is present because of the very fact that there are differences in shearing and friction in metal cutting, in comparison with pure compression.

Some other empirical relationships given are as follows:

By *T. Sata*

$$\varphi = \frac{\pi}{4} \pm \frac{\alpha - 15}{2} \tag{2.53}$$

where, the + sign is taken when $\alpha > 15$ degrees and – sign is taken when $\alpha < 15$ degrees.

By *Stabler*

$$\phi = \frac{\pi}{4} + \frac{\alpha}{2} - \beta \tag{2.54}$$

Bastein and Weiss have given the following equation for BCC metals

$$\phi = 55° + \alpha - \beta \tag{2.55}$$

By *Oxley*

$$\varphi = \alpha - \beta + \tan^{-1}\left[\left(\frac{1}{2} + \frac{\pi}{4} - \varphi\right) + \left\{\frac{\cos 2(\varphi - \alpha)}{\tan \beta} - \sin 2(\varphi - \alpha)\right\}\right] \tag{2.56}$$

According to *Kronenberg*, there is a braking action by the tool rake face on the movement of chip, which is decelerated. Hence, he thinks that in addition to the static forces, the kinetic forces are also acting on the chip, viz. friction force and the centrifugal force. From this consideration, he gets an equation of the form

$$\tan \phi = \frac{\cos \alpha}{e^{\mu\left(\frac{\pi}{2} - \alpha\right)} - \sin \alpha} \tag{2.57}$$

which can be approximated to

$$\phi = \frac{\pi}{4} + \frac{\alpha}{2} - \beta\,(0.75 + 0.0045\,\alpha) \tag{2.58}$$

Zorev, taking a thick shear zone approach, derived the following equation:

$$\varphi = \frac{\pi}{4} + \frac{\alpha - \beta}{2} - \frac{\Psi_{sp}}{2} \tag{2.59}$$

where, ψ_{sp} is the angle between the tangent to the upper boundary of the plastic zone at the point of its intersection, with the specific shear plane and the cutting plane.

Hill suggested that the large number of unknown factors in metal cutting, such as anisotropy, work hardening, variation in the coefficient of friction, and thermal effects mean that a unique value of the shear angle may not exist. Thus, *Hill* suggests that any analysis should not be directed at establishing a single relationship, but instead should locate the possible bounds within which the shear angle must lie. Though this is a reasonable approach, it suffers from the fact that the bounds established by *Hill* are far apart for the shear angle values to be of much practical use.

Vidal uses the *Lee* and *Shaffer* solution, but introduces an efficiency factor, ε, which he terms as the efficiency of plastic deformation and arrives at the following equation:

$$\varphi = \frac{\sin^{-1}\left[\varepsilon \cos(\beta - \alpha) + (1 - \varepsilon)\sin(\beta - \alpha)\right]}{2} + \frac{(\alpha - \beta)}{2} \tag{2.60}$$

ε is an empirical constant, and from *Vidal's* test the following values are derived:

Steel = 0.97

Copper = 0.70

Tellurium lead = 0.75

When ε = 1, the expression reduces to *Lee* and *Shaffer's* solution.

Roth modified *Hill's* solution by taking the variation of hydrostatic stress on the shear plane, and the variable friction angle along the rake face. Though this analysis is more realistic, it widens the shear angle range, thus permitting all experimental values to fall in, but this analysis will be of no use as far as the practical utility is concerned.

So far, an impressive list of equations have been suggested, some of which are based purely on theory while some on theory with some empirical constants with differing assumptions. But when these are compared with the experiments, none of them has given the correct picture. A careful examination of the equations reveals that none of them incorporates the work properties or the cutting conditions. In practice, it is noted that they do play a significant role in affecting the shear angle.

In addition to this, the various assumptions made are not strictly valid, which may be the cause for the deviation. The assumption that the cutting tool is perfectly sharp, so that the tool nose force is negligible, can be a rough approximation to the actual condition, particularly at small values of undeformed chip thickness. Further, the representation of the primary deformation zone by a shear plane may be unrealistic.

Rowe and *Spick* used the minimum energy principle without reference to the coefficient of friction. It is proposed that the shear plane will be oriented at an angle, such that the total work done in plastic shearing of the material in the shear plane and at the rake face has an extremum value. They obtained the following equation:

$$\cos\alpha\cos(2\varphi-\alpha)-\xi\lambda\sin^2\varphi=0 \tag{2.61}$$

where, ξ is the ratio of shear stress at rake face to the yield stress of chip, $0\le\xi\le 1.0$,

and, λ is a multiple of t (undeformed chip thickness), defining the length of contact on rake face.

Now, when the classical methods fail, or are unable to give a satisfactory relationship, then one has to drift towards the empirical approach. One of the classical example is the dimensional analysis, which is extensively used in fluid mechanics and has been successfully applied to some problems in metal cutting by *Kronenberg*. The same approach can be tried to get a suitable relationship for the shear angle, assuming a thin shear plane as the shear zone.

Based on dimensional analysis, the following two equations have been derived:

$$\frac{\varphi}{\beta}=k\left(\frac{\alpha}{\beta}\right)^a\left(\frac{f}{d}\right)^b \tag{2.62}$$

$$\frac{\varphi}{\beta}=k_1(\cos\alpha)^{a_1}\left(\frac{f}{d}\right)^{b_1} \tag{2.63}$$

where, k, a, b, k_1, a_1, and b_1 are empirical constants to be established from the experimental data.

Fit these equations based on some experimental data and give the constants as well as the plots of equation.

2.6 CUTTING TOOL MATERIALS

Various cutting tool materials have been used in the industry for different applications. A number of developments have occurred in the 20th century thanks to aerospace and nuclear programmes. A large variety of cutting tool materials have been developed to cater to the variety of materials used in these programmes. The important characteristics of a cutting tool material are:

(i) *Higher hardness* than that of the workpiece material being machined, so that it can penetrate into the work material.

(ii) *Hot hardness*, which is the ability of the material to retain its hardness at elevated temperatures in view of the high temperatures existing in the cutting zone. This requirement becomes more and more stringent with the increasing emphasis on higher cutting speeds to bolster productivity.

(iii) *Wear resistance*—The chip-tool and chip-work interfaces are exposed to such severe conditions, that adhesive and abrasion wear is very common. The cutting tool material should, therefore, have high abrasion resistance to improve the effective life of the tool.

(iv) *Toughness*—The tool, even though is hard, should have enough toughness to withstand the impact loads that come in the beginning of cut, or to force fluctuations due to imperfections in the work material. This requirement is going to be more useful for interrupted cutting, for example milling.

(v) *Low friction*—The coefficient of friction between chip and tool should be low, which would allow lower wear rates and better chip flow.

(vi) *Better thermal characteristics*—Since a lot of heat is generated at the cutting zone, it is necessary that the tool material should have higher thermal conductivity to dissipate this heat in the shortest time. Otherwise, the tool temperature will become too high thus reducing its life.

All these properties may not be found in a single tool material. A comparison of the various properties of the cutting tool materials is presented in Table 2.3. Improvements in tool materials have been taking place over the past century to give us better cutting performance.

Table 2.3 *Comparative properties of cutting tool materials*

Cutting tool material	*Hardness, R_A*			*Transverse rupture strength $\times 10^3$ MPa*
	Room temperature	*540°C*	*760°C*	
High speed steel	85 to 87	77 to 82	Very low	3.8 to 4.5
Cast cobalt	82 to 85	75 to 82	70 to 75	1.4 to 2.8
Carbides	89 to 94	80 to 87	70 to 82	to 2.4
Ceramics	94	90	87	0.5 to 0.4
Diamond	7000 Knoop	7000 Knoop	7000 Knoop	—

2.6.1 Carbon Tool Steels

These are the earliest tool materials used. These are essentially plain carbon steels with carbon percentages between 0.6 and 1.5 per cent and some very small alloy additions, such as Manganese, Silicon, Tungsten, Molybdenum, Chromium, and Vanadium. The major disadvantage with this range of cutting tool materials is their inability to withstand high temperatures. Beyond 200°C they lose their hardness and cease to cut. Thus, these are useful only for very low cutting speeds, about 0.15 m/s, and to be used with low temperature generating operations, such as machining wood, magnesium, brass, and aluminium. They are easy to prepare and grind. As a result, they are used for form tool making to be used for low quantity production.

2.6.2 High Speed Steel

Taylor and *White* developed this new generation tool material at the turn of the twentieth century. They were able to significantly improve the cutting speeds 3 to 5 times (about 0.5 m/s) that were prevalent at that time using carbon tool steels. Because of this high cutting speed capability, they were termed as high speed steels or more popularly called HSS.

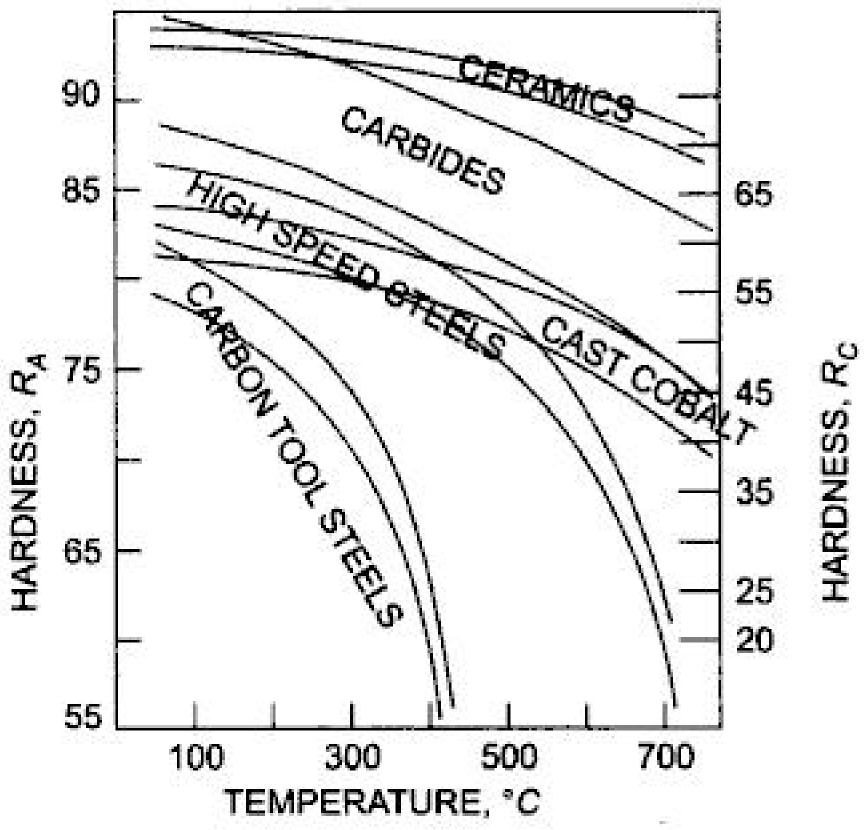


Fig. 2.25 *Variation of hardness with temperature for various cutting tool materials.*

This class of tool materials have significant quantities of tungsten, molybdenum, chromium, and vanadium. The complex carbides of tungsten, molybdenum, and chromium distributed throughout the metal matrix, provide very good hot hardness and abrasion resistance. The major alloying elements, which contribute to the hardness are tungsten and molybdenum. Tungsten is expensive, while molybdenum is cheap but has higher toughness. For the same hardness, less amount of molybdenum needs to be added, however, more care needs to be exercised in hardening as decarburizing takes place in molybdenum steels. Also, they have narrow temperature range for heat treatment. Molybdenum tool steels are more popular.

The main advantages of high speed steels is in their high hardness, hot hardness, good wear resistance, high toughness, and reasonable cost. Toughness of high speed steels is highest among all the cutting tool materials. Thus, they are quite extensively used in interrupted cutting, such as in milling. The hardness of HSS falls rapidly beyond 650°C, as shown in Fig. 2.25, and thus they are limited to lower cutting speeds of the order of 0.5 to 0.75 m/s.

Tool steels have been classified by AISI as T-type and M-type, depending on whether tungsten or molybdenum is the major alloying element present in the steel. Some typical compositions have been given in Table 2.4.

Recently, the HSS tool steels are also being produced through the powder metallurgy route. In this method fine powder of alloy tool steel is compressed under hot isostatic pressure. With suitable hardening and tempering, this method provides for more uniform dispersion of carbides in the matrix. These have been found to grind more easily, exhibit more uniform properties and perform more consistently in cutting.

Structural changes in HSS tools When the temperature is raised beyond 600°C, some structural changes occur in HSS. This temperature is reached when machining higher melting point metals and alloys at relatively high cutting speeds. Above 600°C, HSS is rapidly over-tempered. The hardness decreases after heating and the structure passes through a series of changes, which can be followed by micro examination after polishing and etching. To determine temperatures, the particular grade of HSS used must be calibrated by a series of tests, in which the fully hardened steel is reheated at known temperatures and times, followed by structural investigations and hardness measurements on the related pieces.

Another recent development is the physical coating process called Physical Vapour Deposition or PVD, at lower temperatures, which allows the HSS tools to be coated with hard nitrides of titanium and aluminium. With much favourable cutting geometries and the hard coatings, the cutting performance and tool life of HSS tools has improved substantially. The PVD coatings are generally done at low temperatures. As a result, the adherence of coating is a problem, which is solved by improved cleaning and etching techniques. There are efforts to further improve the cutting performance by improving the coating characteristics by combining various nitrides.

Table 2.4 *Typical compositions of high-speed steel materials*

AISI steel	*% Chemical composition*						
type	*C*	*Cr*	*V*	*W*	*Mo*	*Co*	*Weq*
T1	0.70	4.0	1.0	18.0			18.0
T6	0.80	4.25	1.5	2.0	0.90	12.0	21.8
M1	0.80	4.0	1.0	1.5	8.0		17.5
M6	0.80	4.0	1.50	4.0	5.0	12.0	14.0
M30	0.85	4.0	1.25	2.0	8.0	5.0	18.0
M42	1.10	3.75	1.15	1.50	9.50	8.25	20.5

2.6.3 Cast Cobalt Alloys

Cast cobalt alloys, also called stellites, are normally produced by the powder metallurgy method, though casting is also used by some manufacturers. Fine powders of a number of non-ferrous metal compositions, as shown in Table 2.5, are thoroughly mixed and compacted to the final shape under hot isostatic pressure. They are then ground to the final geometry. They retain their hardness even at elevated temperatures better than HSS, and consequently these are used at 25 per cent higher cutting speeds than HSS. Because of their formability, these are used for making form tools. They have higher toughness and higher stiffness. Currently, these are being phased out since carbides are available over much larger range of properties.

Table 2.5 *Typical compositions and uses of cast non-ferrous alloys*

Nominal % composition								*Grade*
Cr	*W*	*Mo*	*C*	*Mn*	*Si*	*Ni*	*Co*	
30	4.5	1.5	1.1	1.0	1.5	3.0	rest	Roughing
31	10.5	—	1.7	1.0	1.0	3.0	rest	General purpose
32	17.0	—	2.5	1.0	1.0	2.5	rest	Finishing

2.6.4 Cemented Carbides

The best thing to have happened for metal cutting is the invention of cemented carbides around 1926 in Germany. By far, this is the largest percentage of cutting tools used in metal cutting production. Cemented carbides are produced by the cold-compaction of tungsten carbide powder in a binder, such as cobalt, followed by liquid-phase sintering. These have a very large number of advantages compared to the other cutting tool materials, such as

(i) *High hot hardness.* These can retain their hardness to much higher temperatures and as a result, the cutting speeds used are 3 to 6 times (about 5 to 6 m/s) that of HSS.

(ii) *Higher Young's modulus.* This results in stiffer cutting tools with less tendency towards chatter. However, carbides are more brittle and expensive.

It is possible to vary the composition of carbides to get a range of properties. The variations achieved are based on the amount of Co binder, different types of carbides, and the grain size of carbide. Increasing the cobalt binder decreases the hot hardness and wear resistance, while increasing the strength. The usual composition of the straight grade carbides is 6 wt. per cent Co and 94 wt. per cent WC, witn the cobalt composition ranging from 5 to 12 wt. per cent. For heavy interrupted and roughing operations, high cobalt (Co) content is required, while medium coarse grain tungsten carbide is used to withstand the shock. For finishing applications, lower cobalt content is required as hardness becomes the important requirement. Addition of titanium carbide (TiC) increases the hot hardness, wear resistance, and resistance to thermal deformation, but decreases the strength. The usual composition is about 5–25 wt. per cent. Similarly, the presence of tantalum carbide (TaC) increases the hot hardness and resistance to thermal deformation, while decreasing the wear resistance and strength.

The ISO classification of carbide grades and their possible application is given in Table 2.6. The lower designation numbers, such as P10, M10, and K10 are for higher speed finishing cut applications, while the higher numbers such as P40, are for lower speed roughing applications.

The following guidelines would be useful for selecting a carbide grade:

(a) Choose a grade with the lowest cobalt content and the finest grain size consistent with adequate strength, to eliminate chipping.
(b) Use straight WC grades if cratering, seizure, or galling are not experienced in case of work materials other than steels.
(c) To reduce cratering and abrasive wear when machining steel, use grades containing TiC.
(d) For heavy cuts in steel, where high temperature and high pressure deform the cutting edge plastically, use a multi-carbide grade containing W-Ti-Ta and/or lower binder content.

As the cobalt content increases, toughness and strength of cemented carbide increases while hardness, Young's modulus, and thermal conductivity decreases. Fine grain carbides are harder compared to coarse grain carbides. Multi-carbide grades increase chemical stability, hardness, and hot hardness.

Since tungsten and cobalt are expensive, some special cemented carbides having predominantly tantalum carbides with Ni and Mo as binder, have been developed for auto industry application for finish machining of steels and malleable cast irons. These are sometimes called cermets. These are relatively brittle and easy to chip. These are relatively cheap and should find widespread use in future.

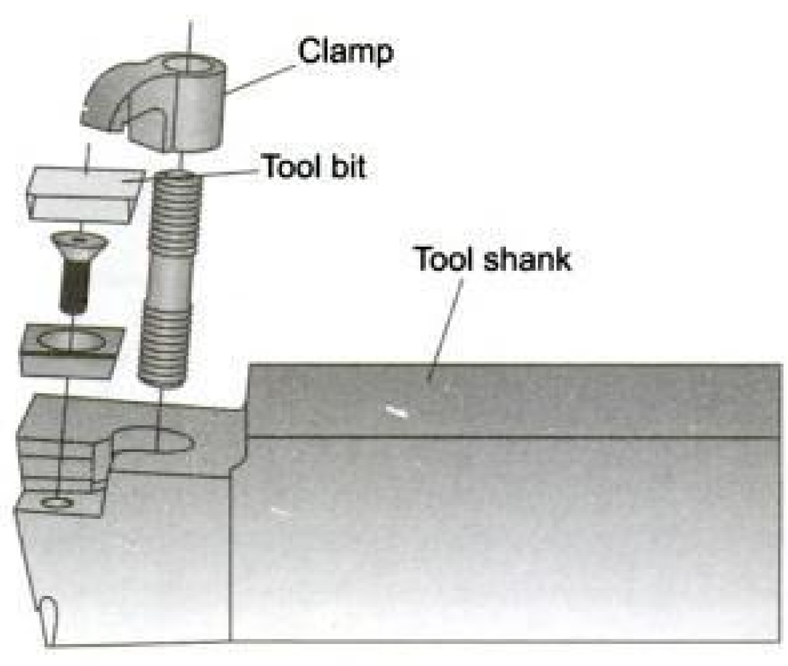


Fig. 2.26 *Construction of a Tungsten carbide turning tool (courtesy Seco Tools).*

Cemented carbides being expensive, are available in insert form in different shapes, such as triangle, square, diamond, and round. Each of the edge acts as a cutting edge. The typical construction of a cemented carbide tool is shown in Fig. 2.26. As seen from Fig. 2.26, the tool bit is made of tungsten carbide, while the tool holder

Table 2.6 *ISO Classification of cemented carbide tools*

Main groups of chip removal			*Group of application*			*Direction of increase*	
Symbol	Broad categories of materials to be machined	Colour	Designation	Material to be machined	Use and working condition	of cut	of carbide
			P01	Steel, steel castings	Finish turning and boring, high cutting speeds, small chip section, accuracy of dimensions and finish, vibration free operation		
	Ferrous	B	P10	Steel, steel castings	Turning, copying, threading and milling, high cutting speeds, small or medium chip sections		
P	metals with long chips	L	P20	Steel, steel castings, malleable cast iron with long chips	Turning, copying, milling, medium cutting speeds and chip sections, planing with small chip sections		
		U	P30	Steel, steel castings, malleable cast iron with long chips	Turning, milling, planing, medium or low cutting speeds, medium or large chip sections, and machining in unfavourable conditions		
		E	P40	Steel, steel castings with sand inclusion and cavities	Turning, planing, slotting, low cutting speeds, large chip sections with possibilities of large cutting angles for machining in unfavourable conditions, and work on automatic machines		
			P50	Steel, steel castings of medium or low strength with sand inclusion and cavities	For operations demanding very tough carbides, turning, planing, slotting, low cutting speeds, large chip sections, with possibilities of large cutting angles for machining in unfavourable conditions, and work on automatic machines		
M	Ferrous metals with long or short chips	YE	M10	Steel, steel castings, manganese steel, grey cast iron, and alloy cast iron	Turning medium or high cutting speeds, small or medium chip sections		
	and non ferrous metals	LLO	M20	Steel, steel castings, austenitic or manganese steel, and grey cast iron	Turning, milling, medium or cutting speeds and chip sections		

The coatings need to be metallurgically bonded to the substrate. These coatings, such as titanium carbide, titanium nitride, aluminium oxide, hafnium nitride, and hafnium carbide, or multiple coatings of the above, are deposited generally on the carbide tool bits by the Chemical Vapour Deposition (CVD) process. The chemical reaction necessary to deposit the required coating takes place close to the substrate. The coating is deposited atom by atom onto the surface, thereby providing a very strong adhesion between the coating and the substrate.

Typical coating materials used include TiC, TiN, Al_2O_3, TiCN, TiAlN, TiZrN, TiB_2, and diamond. Typical physical properties of the coating materials are given in Table 2.7. Figure 2.28 shows the plot of Vickers microhardness as a function of temperature from 25°C to 1000°C, for some of the coatings. The TiCN coating has the highest room temperature hardness, but above 750°C, the TiAlN coating is harder than TiCN or TiN coatings. At 1000°C, TiAlN is considerably harder than TiCN and TiN. Titanium nitride is one of the first coatings and the most widely used one. It provides low friction, high hardness, higher refractoriness, and good adhesion to the substrate. It also has greater resistance to flank wear. Titanium carbide has higher resistance to flank wear. Ceramic, such as Al_2O_3 coatings have higher refractoriness and resist crater wear as well as flank wear. However, these do not bond well with the substrate. Typical improvement in the tool life with different types of coatings in actual experiments is shown in Fig. 2.29:

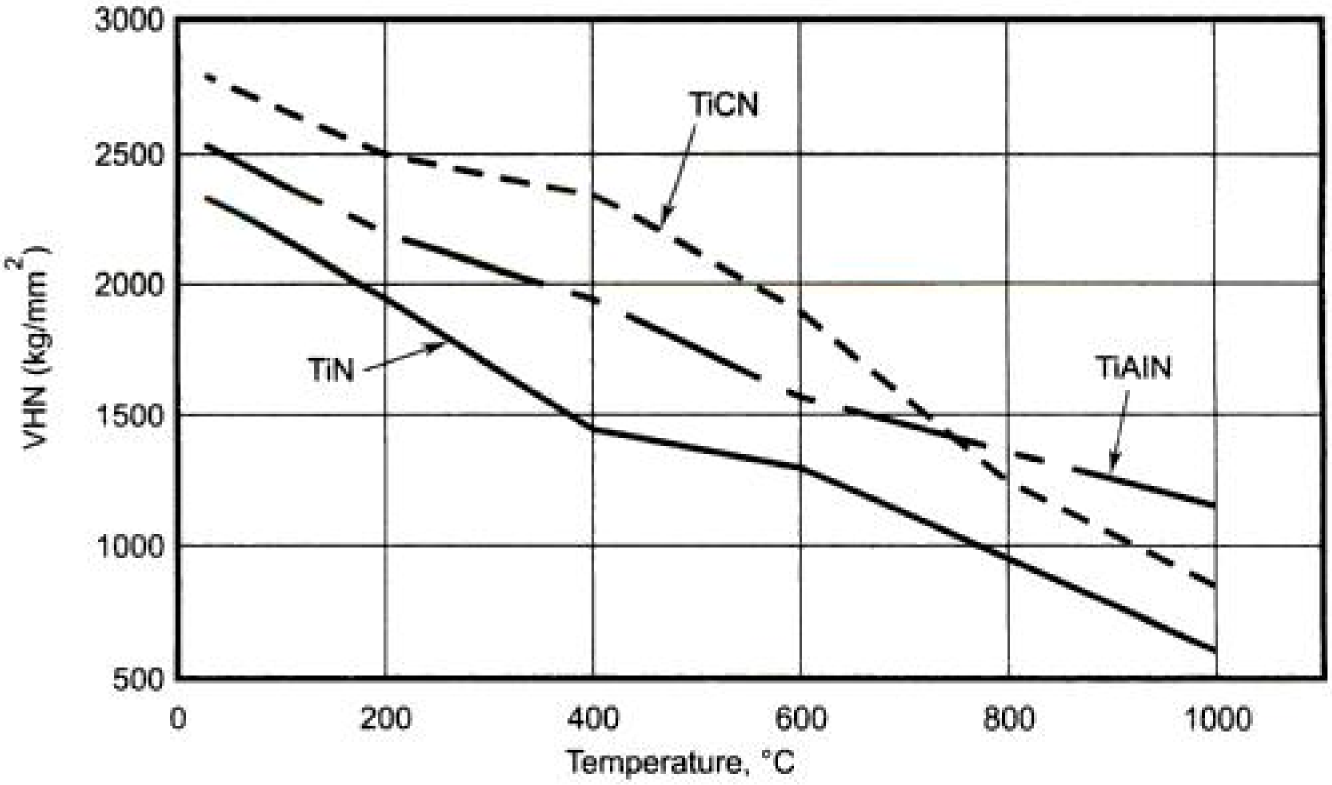


Fig. 2.28 *Variation of Vickers microhardness of the coatings, with temperature (Jindal, Santhanam, Schleinkofer, and Shuster).*

Table 2.7 *Properties of some coating materials*

Coating	*Room temperature hardness, (HV)*	*Oxidation resistance, °C*	*Coefficient of friction*
TiN	1930–2200	600	0.4–0.5
TiCN	2730–3000	400	0.3
TiAlN	3000–3500	800	0.7
TiN/AlN	4000	950	—
TiAlCN	3200	600	—

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Thus, there are a large variety of cutting tool materials available, which should be selected carefully for a given application, taking all the intervening factors into account. The recommendations and characteristics

Table 2.10 *Summary of applications for various cutting tool materials (Komanduri).*

Tool material	*Work materials*	*Remarks*
Carbon steels	Low strength, softer materials, non-ferrous alloys, and plastics	Low cutting speeds, low strength materials
Low/medium alloy steels	Low strength, softer materials, non-ferrous alloys, and plastics	Low cutting speeds, low strength materials
HSS	All materials of low and medium strength and hardness	Low to medium cutting speeds, low to medium strength materials
Cemented carbides	All materials up to medium strength and hardness	Not suitable for low speed application
Coated carbides	Cast iron, alloy steels, stainless steels, and super alloys	Not for Titanium alloys and nonferrous alloys, as the coated grades do not offer additional benefits over uncoated grades
Ceramics	Cast iron, Ni-base super alloys, non-ferrous alloys, and plastics	Not for low speed operation or interrupted cutting, not for machining Al, Ti alloys
CBN	Hardened alloy steels, HSS, Ni-base super alloys, hardened chill cast iron, and commercially pure nickel	High strength, hard materials
Diamond	Pure copper, pure aluminium, Al-Si alloys, cold pressed cemented carbides, rock, cement, plastics, glass-epoxy composites, non-ferrous alloys, hardened high-carbon alloy steels (for burnishing only), and fibrous composites	Not for machining low carbon steels, Co, Ni, Ti, and Zr

have been summarised in Table 2.10. These can act as guidelines, however, many of the cutting tool manufacturers, such as *Sandvik* and *Widia* provide detailed literature to help in the choice of cutting tools. These along with the Metal Cutting Handbook should be used for finalising the tool material selection.

2.7 THERMAL ASPECTS

Benjamin Thomson (1798) conducted first experiments on machine tools when he measured the thermal energy involved during the boring of brass cannon. He observed that all the mechanical energy is converted into thermal energy. He used the calorimetric method.

Temperature of cutting is a very important parameter, which is of great consequence with reference to the life of a tool. The surface of the tool, if proper precautions are not taken, may be overheated at isolated points and localized phase transformations can occur. This may result in softening of the surface of the tool and frequently very small cracks will be formed as a result of the intense residual stress system that accompanies surface transformation.

Because of the very large amount of plastic strain involved in metal cutting, it is unlikely that more than 1 per cent of the work done is stored as elastic energy, which can be neglected, the remaining 99 per cent goes

Crater wear The crater is on the rake face and is more or less circular. The crater does not always extend to the tool-tip, but may end at a distance from the tool-tip. It increases the cutting forces, modifies the tool geometry, and softens the tool-tip.

Flank wear Flank wear or wear land is on the clearance surface of the tool. The wear land can be characterised by the length of wear land, *w*. It modifies the tool geometry and changes the cutting parameters, such as depth of cut.

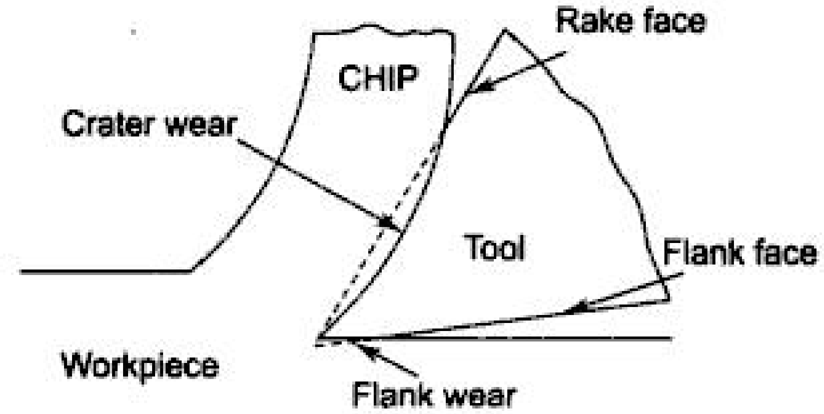

Fig. 2.36 *Typical wear patterns present in cutting tools.*

The typical wear patterns used as tool life criteria, as standardised by ISO, are shown in Fig. 2.37. These are to be used as tool life criteria as discussed later.

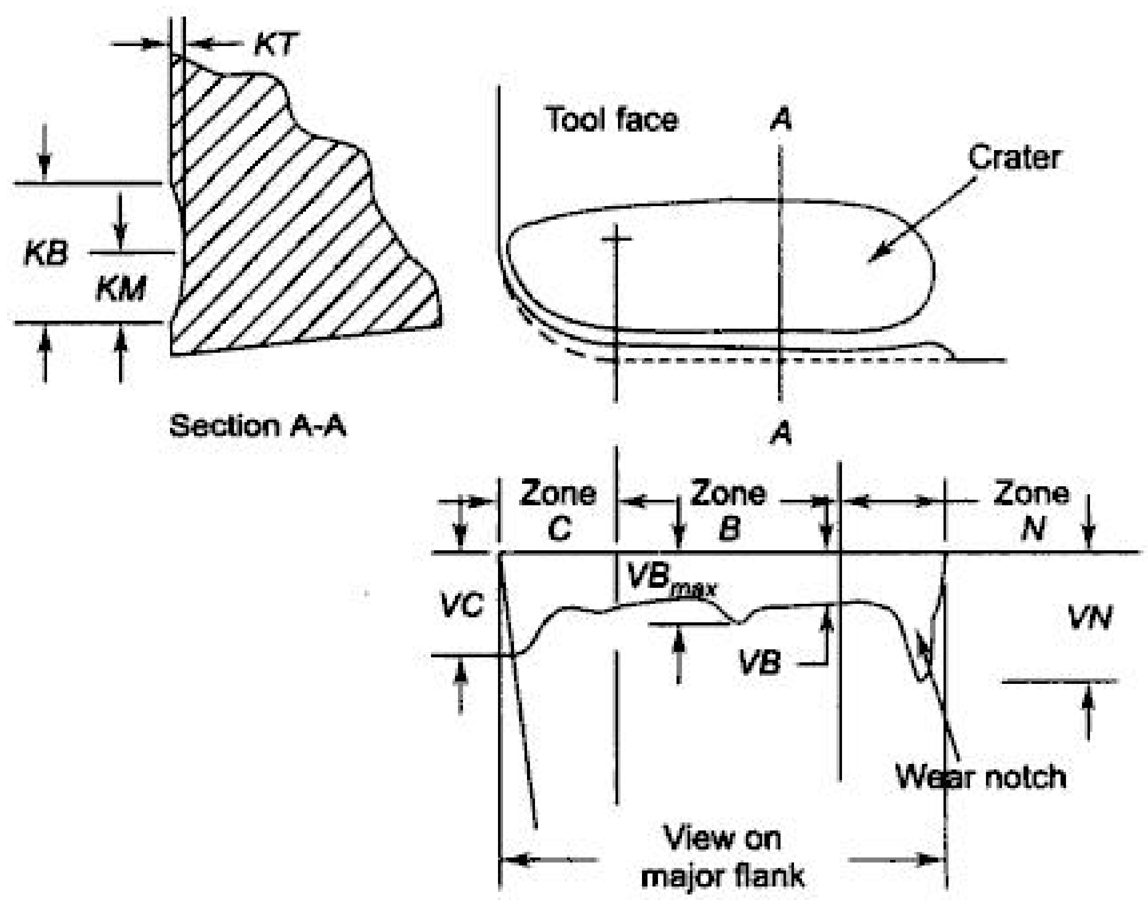

Fig. 2.37 *The wear parameters and their characterisation, as suggested by ISO.*

Cutting tools are subjected to extremely severe cutting conditions, such as the following:

- Metal-to-metal contact with work and chip
- Very high stress
- Very high temperature
- Virgin metal
- Very high stress gradients
- Very high stress gradients

Because of all the above-mentioned factors, the tool-chip and tool-work interfaces exhibit the type of wears found. As tool wear progresses, cutting forces increase and vibrations increase. Tool-tip softens and flows plastically and gets a blunt edge, which will result in further progressing of plastic deformation from tool-tip to the interior. After that, almost a tip of the tool gets separated.

The presence of crater wear in very small sizes is not of much consequence as far as the machining performance is concerned. Initially, they may increase the rake angle and thus decrease the cutting forces.

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problems, for example, in carbides, it may spoil the nearby edges, and damage to work is also present. Therefore, a large wear land size can be equivalent to total destruction.

Alternatively, the indirect methods, as mentioned above, such as the fixed increase in the value of cutting force, or increase in the power consumed or measured vibrations, etc. can be used as an indication of the end of tool life. These are more generally used in CNC machine tools, where automatic tool life monitoring facilities are present.

2.8.2 Tool Life Equation

Taylor thought that there is an optimum cutting speed for best productivity. This, he reasoned from the fact that at low cutting speeds, the tools have higher life but productivity is low, and at higher speeds the reverse is true. This inspired him to check up the relationship of tool life and cutting speed. Based on his experimental work, he proposed the following formula for tool life:

$$V T^{n} = C \tag{2.64}$$

where, T is the tool life in minutes,
V is the cutting speed in m/min, and
C and n are constants.

Though this is a fairly good formula, it does not take all the effecting parameters into account. As a result, the applicability of the above formula is restricted to very narrow regions of cutting process parameters. This formula was extended by a number of researchers to reduce this deficiency, as given below.

$$T \theta^{B} = C \tag{2.65}$$

$$T^{\frac{0.5-2x}{1-2x}} = \left[\frac{T_C\, H^{0.5}}{C'\, u_s\, A^{x}}\right]^{\frac{1}{1-2x}} \tag{2.66}$$

where, H = specific heat × thermal conductivity
θ = tool temperature
A = area of cut
u_s = specific cutting energy/unit cutting force
C and x are constants

$$\theta = \frac{c_0 u_s\, V^{0.44}\, A^{0.22}}{k^{0.44}\, \tau^{0.56}} \tag{2.67}$$

where, k = thermal conductivity of work
τ = specific heat of work

$$V T^{n} f^{n1} d^{n2} = C \tag{2.68}$$

This is the most commonly employed tool life equation by a number of researchers. The constants for the above equation for some common work materials are given in Table 2.12 (*Widia*). Since the tool life depends, besides the cutting process parameters, on the work material as well as tool material. The constants, therefore, are given for each combination of work and tool material.

The major influence on surface finish is exerted by the feed rate and cutting speed. As the feed decreases, from the above equations, we can see that the roughness index decreases. Similarly, as the cutting speed increases, we have better surface finish. Thus, while making a choice of cutting process parameters for finish, it is desirable to have high cutting speed and small feed rate.

2.10 CUTTING FLUIDS

The functions of cutting fluids, which are often erroneously called coolants are to

(i) cool the tool and workpiece,
(ii) reduce the friction,
(iii) protect the work against rusting,
(iv) improve the surface finish,
(v) to prevent the formation of built-up edge, and
(vi) to wash away the chips from the cutting zone.

However, the prime function of a cutting fluid in a metal cutting operation is to control the total heat. This can be done by dissipating the heat generated, as well as reduce the heat generated. The mechanisms by which a cutting fluid performs these functions may be listed as follows:

- Cooling action
- Lubricating action

Cooling action Originally, it was assumed that cutting fluid improves the cutting performance by its cooling properties alone. That is why, the name coolant was given to it. Since most of the tool wear mechanisms are thermally activated, cooling the chip tool interface helps in retaining the original properties of the tool, and hence prolongs its life. However, a reduction in temperature of the workpiece may, under certain conditions, increase the shear flow stress of the workpiece, thereby decreasing tool life. It has been shown through a number of investigations that cooling is one of the major factors in improving the cutting performance.

Lubricating action The best improvement in cutting performance can be achieved by the lubricating action since this reduces the heat generated, thus reducing the energy input to the metal cutting operation. However, if the cutting fluid is to be effective, it must reach the chip tool interface. However, it is not easy to visualize how it is accomplished in the case of a continuous turning with a single point turning tool, specially when the chip tool contact pressure is as high as 70 MPa. *Merchant* suggested that minute asperities exist at the chip tool interface, and the fluid is drawn into the interface by the capillary action of the interlocking network of these surface asperities.

There are three possible directions through which cutting fluid can be applied as shown in Fig. 2.44.

(i) On the back of the chip.
(ii) Along the rake crevice between the chip and rake face of the tool.
(iii) Along the clearance crevice between the finished work surface and clearance face of the tool.

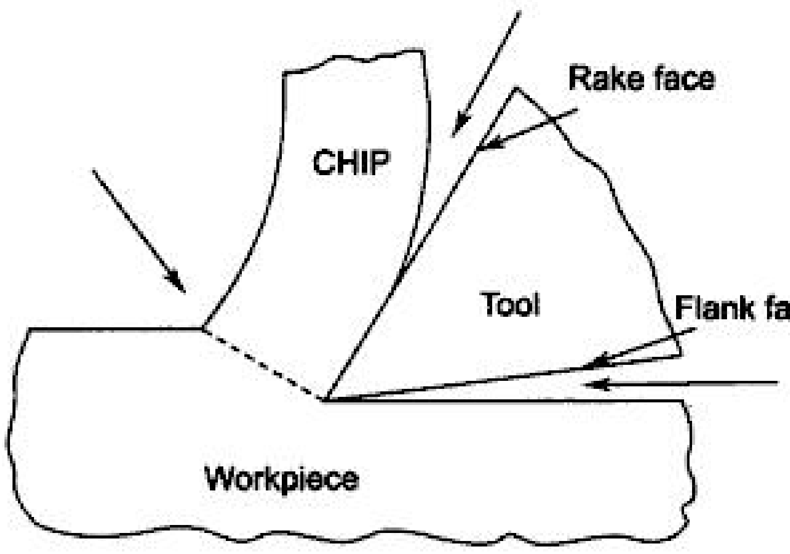

Fig. 2.44 *The directions along which cutting fluid can be applied in metal cutting.*

Cutting force is one of the major concerns in metal cutting. Thus, considerable interest and a large number of relationships have been derived from empirical and semi-empirical approaches in the past, the general oblique-cutting case, three components of the cutting force are present. They are main thrust force, F_z, radial cutting force, F_r, and axial cutting force, F_a.

A major presentation of empirical aspects has been mentioned by *Kronenberg* [2.11]. He assumes that the cutting forces are varied in direct proportion to the chip cross-sectional area, and thus arrives at equations and gives the constants for some of the more generally used materials.

Another approach is the semi-analytical approach of *Nakayama* and *Arai*, which is based on the assumption that the conventional cutting can be approximated to the orthogonal cutting when the ratio of (feed/depth of cut) and (corner radius/depth of cut) are small. They give the following equations:

$$F_t = \tau f d \left(\cot\varphi + \tan\beta\right) \tag{2.75}$$

$$F_r = \tau f d \,(\cot\varphi \tan\beta - 1) \sin(C_s + \nu) \tag{2.76}$$

$$F_a = \tau f d \,(\cot\varphi \tan\beta - 1) \cos(C_s + \nu) \tag{2.77}$$

where, ν is the chip flow angle. The various parameters of the cutting process are related with the help of empirical equations based on wide ranging experimental data, as follows

$$\xi = \xi_o - k_1 \alpha \tag{2.78}$$

$$\varphi = \varphi_o + k_2 \alpha - \frac{A}{\sqrt{V f \cos C_s}} \tag{2.79}$$

$$\nu = \tan^{-1} \frac{r + \frac{f}{2}}{d} \tag{2.80}$$

The constants used in the above equations are given in Table 2.16.

Table 2.16

	C45 steel	*C25 steel*	*Low alloy steel*	*Cast iron*
k_1	0.25	0.25	0.25	0.25
k_2	0.20	0.30	0.33	0.30
ϕ_o	34.0	28.5	35.0	28.5
ξ_o	52.0	52.0	52.0	52.0
τ, N/mm^2	706.0	588.0	715.0	392.0
A*	0.20	0.20	0.20	0.10

* for using f in m, and V in m/s

2.12 ECONOMICS

The ultimate objective of the manufacturing engineer is to produce the objects at the most economical cost. To do this, he should be able to analyze the machining process for all the possible costs, so that he is able to optimise the process to get the minimum possible costs, satisfying all the requirements.

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For a single pass turning job, it can be shown that

$$\text{Time} = t_l + t_{ul} + t_a + \frac{t_o}{p} + \frac{\pi D l}{1000\, V f} + \frac{t_c\, \pi D l}{1000\, f\, C^{\frac{1}{n}}\, V^{1-\frac{1}{n}}} \tag{2.106}$$

For getting the maximum production rate, the above expression for manufacturing time be differentiated with respect to cutting speed, V and equated to zero.

$$\frac{\partial \text{Time}}{\partial V} = -\frac{\pi D l V^{-2}}{1000\, f} + \frac{t_c\, \pi D l}{1000\, f\, C^{\frac{1}{n}}}\left[\frac{1-n}{n}\right] V^{\frac{1-2n}{n}} = 0 \tag{2.107}$$

Simplifying, we get

$$\frac{t_c}{C^{\frac{1}{n}}}\left(\frac{1-n}{n}\right) V^{\frac{1}{n}} = 1 \tag{2.108}$$

Simplifying, we get

$$V = C\left[\frac{n}{t_c\,(1-n)}\right]^n \tag{2.109}$$

$$T = \frac{t_c\,(1-n)}{n} \tag{2.110}$$

Example 2.4 *A 600-mm long job of 150-mm diameter of AISI 4140 steel is to be turned with a depth of cut of 1.5 mm, and feed rate 0.25 mm/rev. The following data is applicable for the problem:*

Labour cost per hour = Rs 12.00

Machine overhead per hour = Rs 40.00

Grinding cost per hour = Rs 15.00

Grinding machine overhead per hour = Rs 50.00

Idle time = 5 minutes

Taylor's tool life equation is given by

$$V\, T^{0.22} = 475$$

The operation can be carried out using tungsten carbide tools either as brazed tools or throw-away tools.

For brazed tools:

Initial cost = Rs 60

Grinding time = 5 minutes/edge

Tool change time = 2 minutes

9 grinds per tool before salvage

For throw-away tools:

the optimisation carried out using various constraints on the variables. For example, the following are some of the possible constraints:

(*i*) The maximum cutting power available at the machine tool spindle.
(*ii*) The maximum cutting force permissible.
(*iii*) The surface finish and the diametral tolerance to be achieved on the machined surface.
(*iv*) The limits on speed, feed, and depth of cut imposed by the machine tool and the cutting tool.
(*v*) Maximum permissible cutting temperature.
(*vi*) Maximum permissible chatter.
(*vii*) Maximum permissible workpiece static and dynamic instability.
(*viii*) Tool life and tool fracture.

Some of the possible constraints, as mentioned above, have been explained further in terms of the possible formulation in case of turning.

Power constraint The power constraint assumes significance only in case of rough machining, and hence can be ignored in the case of finish machining. The power consumed, P, during a turning operation can be expressed as,

$$P = \frac{V^{a_p} f^{b_p} d^{c_p} k_c}{60 \times 1000 \times \eta}$$

This value of cutting power should not exceed the maximum power, $P_{\max}$, available on the machine tool. In the above expression, the value of specific cutting force is constant for a particular work material. Hence, the expression for this constraint can be written as

$$C_p V^{a_p} f^{b_p} d^{c_p} \le P_{\max}, \qquad C_p = \frac{k_c}{60 \times 1000 \times \eta}$$

Surface finish constraint This constraint limits the maximum feed that can be used to attain the required surface finish on the machined feature. This constraint becomes active during finish turning. The expression for CLA value of the geometric surface finish obtained during turning operation, with a tool of nose radius r, is given as

$$SF = 1000 \times \frac{f^2}{18\sqrt{3}\, r}$$

Based on the surface finish, $SF_{\max}$, specified on the turned surface, the constraint on feed can be expressed as

$$C_s f^2 \le SF_{\max}, \qquad C_s = \frac{1000}{18\sqrt{3}\, r}$$

Maximum and minimum speed constraints Usually, these constraints are imposed by the machine tool. However, in the case of carbide and ceramic tools, certain minimum cutting speeds need to be maintained, to avoid the failure of these cutting tools due to BUE formation or micro-chipping. Hence, the minimum speed constraint is determined as the larger of the values of minimum cutting speed from machine tool, and minimum cutting speed due to cutting tool ($V_{\min}$). Thus, the speed constraint can be expressed as

$$\max\left\{\frac{\pi D N_{\min}}{1000}, V_{\min}\right\} \le V \le \frac{\pi D N_{\max}}{1000}$$

37. Explain the basis for the selection of a specific cutting fluid for a given application. Take the example of turning, milling, and grinding, and suggest the type of cutting fluid used.
38. What is the mechanism suggested for the cutting fluid to reach the chip-tool interface in spite of the adverse conditions of high pressure existing? Explain with a neat sketch.
39. What is meant by machinability? Explain the method of representing the machinability.
40. What are the factors that control surface finish in turning? How do you select the cutting process parameters for finish turning?
41. Derive the relationship for the minimum cost, cutting speed in single point turning of a cylindrical workpiece. State the assumptions made.
42. Derive the relationship for the maximum production rate cutting speed in single point turning of a cylindrical workpiece. State the assumptions made.
43. Derive the relationship for the minimum cost tool life from first principles in single point turning of a cylindrical workpiece. State the assumptions made.
44. Derive the relationship for the maximum production rate tool life in single point turning of a cylindrical workpiece. State the assumptions made.
45. Discuss the forms of tool life equations generally used with their applicability.
46. Suggest the grade of carbide you would use for (i) rough milling of medium carbon steel, (ii) finish turning of white cast iron rolls. Justify your recommendation.
47. Find the tool life for the minimum cost per piece in single pass turning given:

    a = machine rate including labour and overhead
    b = tool cost per cutting edge
    t = tool change time
    n = exponent in *Taylor's* tool life equation
    C = constant in *Taylor's* tool life equation

    Make any valid assumptions with justification.
48. Give a comparative evaluation of the various cutting tool materials.
49. What are the desirable properties of a cutting tool material?
50. What are the locations where heat is produced in an orthogonal cutting tool? Show their approximate percentages.
51. Explain how effective is tungsten carbide as a cutting tool material in comparison to the other cutting tool materials. What are the improvements caused by the coated carbides.

Problems

1. A 100 mm bar is turned by means of a tool with a rake angle of 15 degrees orthogonally. Depth of cut is 5 mm and feed rate is 0.25 mm/rev. If the mean length of a cut chip representing one rotation of the workpiece is 90.5 mm, find the shear plane angle.
2. During a metal cutting test under orthogonal conditions, in a lathe with a tool of rake angle 20 degrees, with a depth of cut of 3 mm, and feed rate of 0.38 mm/rev, the following data is recorded:

    Average chip thickness = 0.89 mm
    Horizontal component of the cutting force = 1600 N
    Vertical component of the cutting force = 2340 N

    Calculate the following:

    (*a*) coefficient of friction at the chip tool interface

22. An orthogonal cutting process is being carried out with the following process parameters:

Uncut chip thickness = 0.15 mm Cutting speed = 120 m/min
Rake angle = 10° Width of cut = 6 mm

The observed values of the other parameters are as follows:

Chip thickness = 0.225 mm Horizontal force = 550 N
Vertical force = 1230 N

Calculate the percentage of the total energy that goes into overcoming the friction at the chip-tool interface.

23. If *Taylor's* tool life constants for a given operation are specified as $n = 0.5$ and $C = 400$, what is the percentage increase in tool life when the cutting speed is reduced by half?

24. In an orthogonal cutting operation, given the rake angle is 10°, what is the percentage change in the chip thickness when the friction angle changes from 30° to 50°? Do not use the shear angle relationship derived by *Merchant's* minimum energy principle.

25. Using *Merchant's* cutting mechanics analysis, derive a relationship between shear energy and frictional energy in terms of rake angle, shear angle, and friction angle.

26. The tool life of a high speed steel (HSS) tool and carbide tool have the same tool life of 60 minutes at a cutting speed of 75 m/min. The exponent of tool life in *Taylor's* equation (n) is 0.15 for HSS, while it is 0.2 for carbide. Compare the life of the two tools at a speed of 90 m/min.

27. An automatic lathe is to be used to machine a brass component, 75 mm long and 50 mm in diameter, with a depth of cut of 1.25 mm and feed rate of 0.2 mm/rev. The lathe has 3 kW motor with drive efficiency of 70%. Select the cutting speed to give the minimum machining cost under the following conditions:

Operating cost of the lathe = Rs 75 per hour
Regrinding cost of cutting edge = Rs 15 per edge
Time to load and unload a component = 15 seconds
Tool change time = 5 minutes
Tool life constants $n = 0.2$; $C = 400$

28. In a normal turning operation, the tool life varies with cutting speed, as shown in the following table:

Cutting speed, V, m/min	*Tool Life, T, min*
25	30
70	2

Estimate the tool life for this operation at a speed of 60 m/min.

29. A carbide cutting tool has tool life exponent $n = 0.27$. It gives a tool life of 60 minutes while machining a mild steel workpiece at a cutting speed of 120 m/min. Compute the tool life if it is to be cut at a 20% higher cutting speed. Also, what is the cutting speed if the tool life is to be doubled?

30. Free cutting steel workpieces of length 200 mm and 100 mm in diameter are to be turned on a lathe using a feed of 0.15 mm/rev and a depth of cut of 2 mm. It is possible to use brazed and throw-away type cemented carbide tools for the operation. The overhead cost is Rs 80 per hour, while the tool life constants are $n = 0.25$ and $C = 200$. Compare the minimum cost and maximum productivity times and costs of these with the following data:

	Brazed tools	Throw-away tools
Tool cost	Rs 90	Rs 30
No of regrinds	10	No. of edges = 4
Regrinding cost	Rs 15	
Tool change time	3 min	1 min

The application of the above four types can be shown graphically in Fig. 3.1.

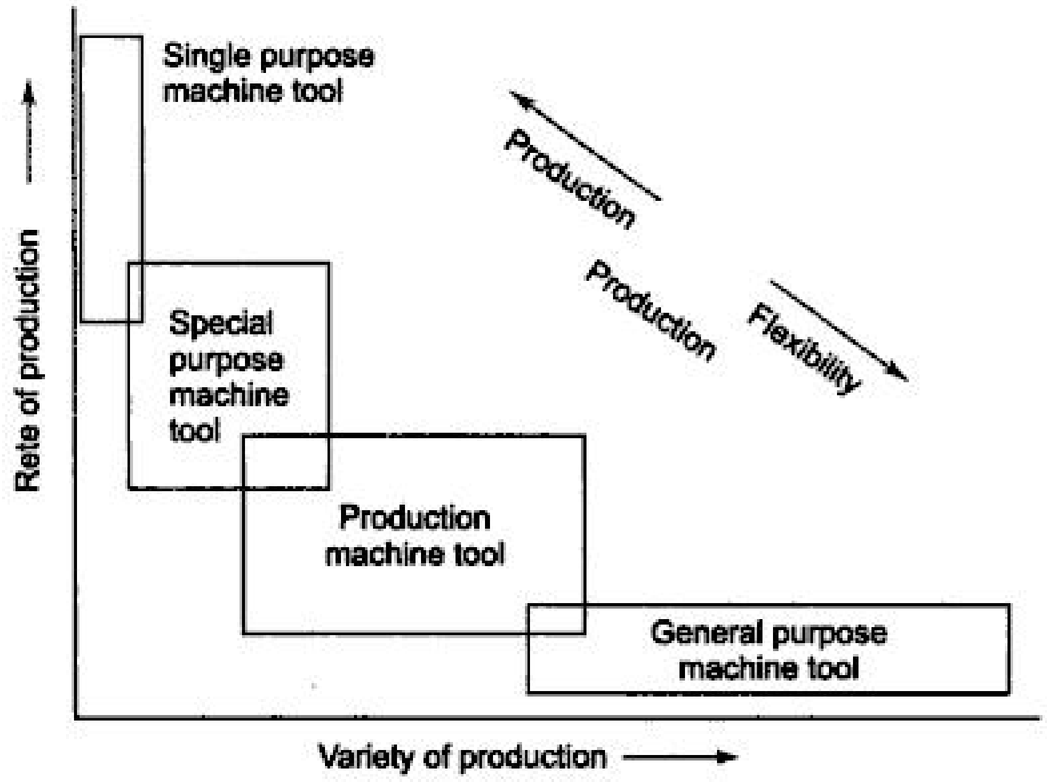

Fig. 3.1 *Application of machine tools based on the capability.*

3.3 GENERATING AND FORMING

Generally, the component shape is produced in machine tools by two different techniques, generating and forming.

Generating is the technique in which the required profile is obtained by manipulating the relative motions of the workpiece and the cutting tool edge. Thus, the obtained contour would not be identical to the shape of the cutting tool edge. This is generally used for a majority of the general profiles required. The type of surface generated depends on the primary motion of the workpiece as well as the secondary or feed motion of the cutting tool.

For example, when the workpiece is rotated and a single point tool is moved along a straight line parallel to the axis of rotation of the workpiece, a helical surface is generated, as shown in Fig. 3.2 (*a*). If the pitch of the helix or feed rate is extremely small, or the surface generated may be approximated to a cylinder. This is carried out in lathes and is called turning or cylindrical turning.

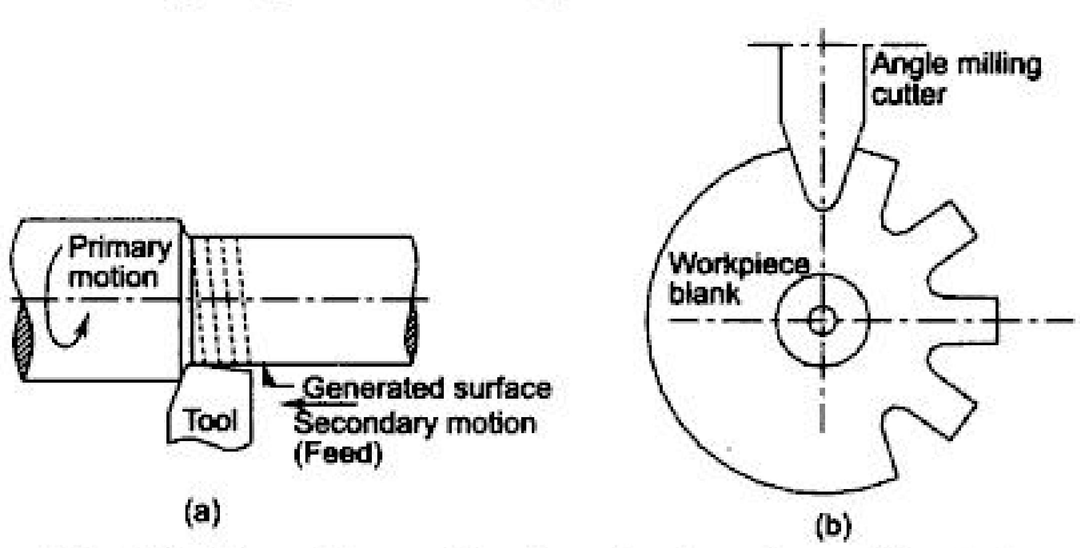

Fig. 3.2 *Generating and forming of surfaces by machine tools.*

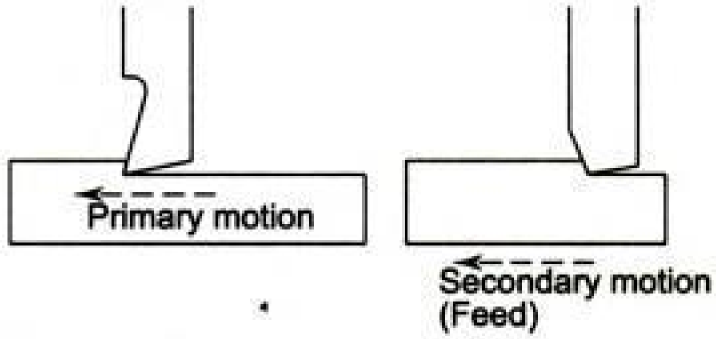

Fig. 3.11 *Generating a flat surface with linear motion of a single-point cutting tool.*

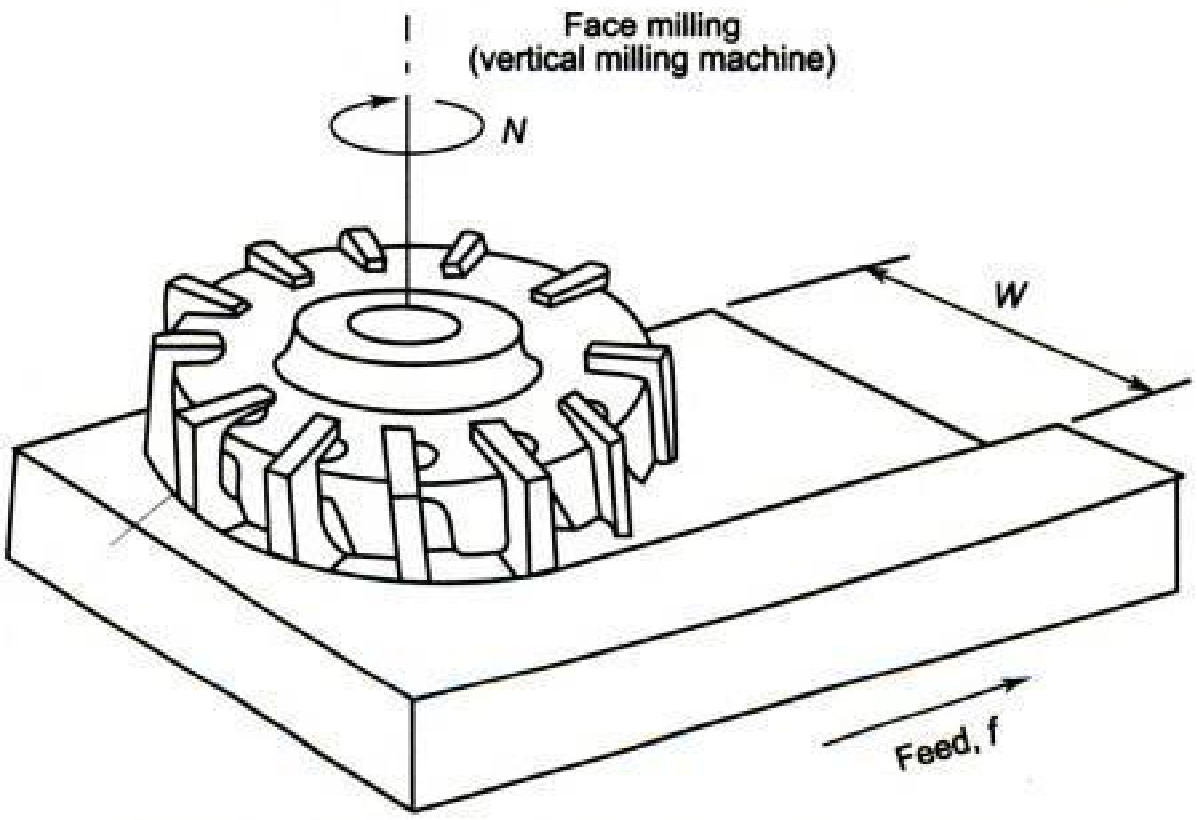

Fig. 3.12 *Multi-point cutting tool generating a plane surface.*

3.5 ACCURACY AND FINISH ACHIEVABLE

It is necessary to select a given machine tool or machining operation for a job such that it is the lowest cost option. There are various operations possible for a given type of surface and each one has its own characteristics in terms of possible accuracy, surface finish, and cost. This selection is made at the time of process planning. The obtainable accuracy for various types of machine tools is shown in Table 3.1. The surface finish expected from the various processes is shown in Fig. 3.13. The values presented in Table 3.1 and Fig. 3.13 are only a rough guide. The actual values greatly vary depending on the condition of the machine tool, the cutting tool used, and the various cutting process parameters.

Table 3.1 *Accuracies achievable in machining operations*

Machining operation	*Accuracy*
Turning	+ 25 μm
Shaping, slotting	+ 25 μm/side
Planing	+ 65 μm/side
Milling	+ 12 to 25 μm

(*Contd.*)

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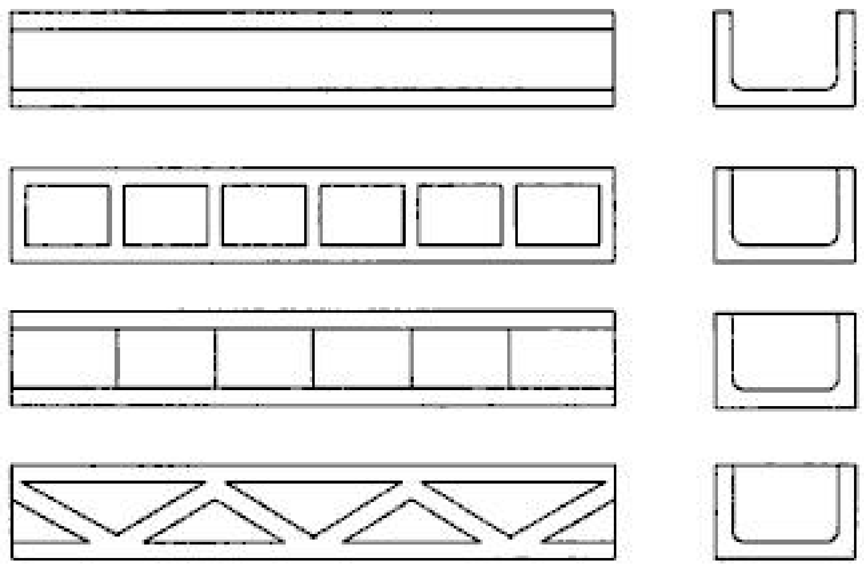
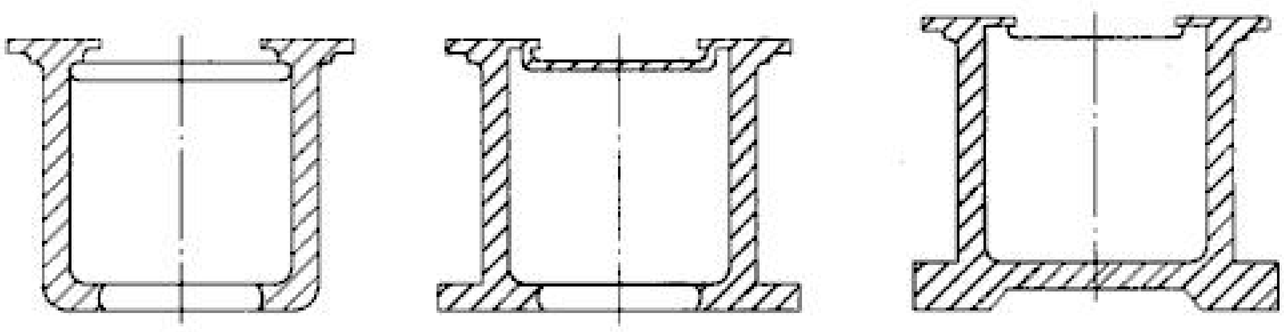


Fig. 3.15 *Different types of ribs used for strengthening machine tool beds.*



(a) (b) (c)

Fig. 3.16 *Different styles of beds used in machine tools.*

Slant bed construction With the advent of numerical control machines, slant bed construction for lathes has become more common. The slant bed, as shown in Fig. 3.17, would allow for better chip and coolant disposal besides better torsional rigidity, compared to the conventional flat bed construction. It provides a better view of the machining area for the operator.

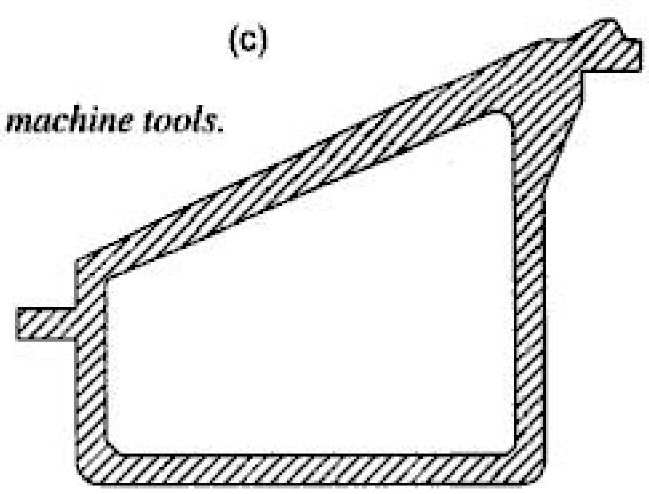


Fig. 3.17 *Typical slant bed construction used in lathes for easy disposal of chips.*

3.8 POWER TRANSMISSION

The main power is provided by the spindle motor in most of the machine tools. From this source with a standard speed, the power needs to be transmitted to run the spindle at different speeds, and provide feeds for different machining situations. As seen earlier, speeds and feeds used during machining operations have a great effect on the tool lives and machining performance. The machine tool needs to provide a large variety of speeds and feeds to cater to the diverse range of materials that are being cut.

Spindle speeds The choice of the range of speeds that need to be provided will depend on the range of cutting speeds to be obtained along with the range of diameters of workpieces that need to be cut. The final speed at the spindle can be obtained in two ways:

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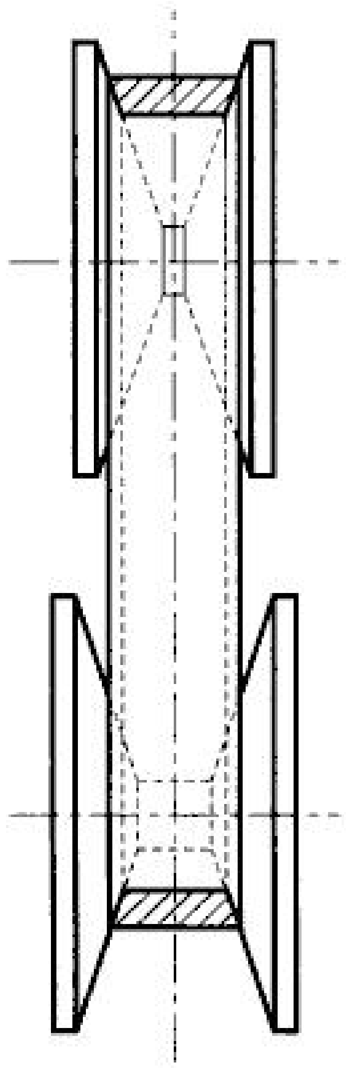

Fig. 3.19 *Stepless drive utilizing V-belt.*

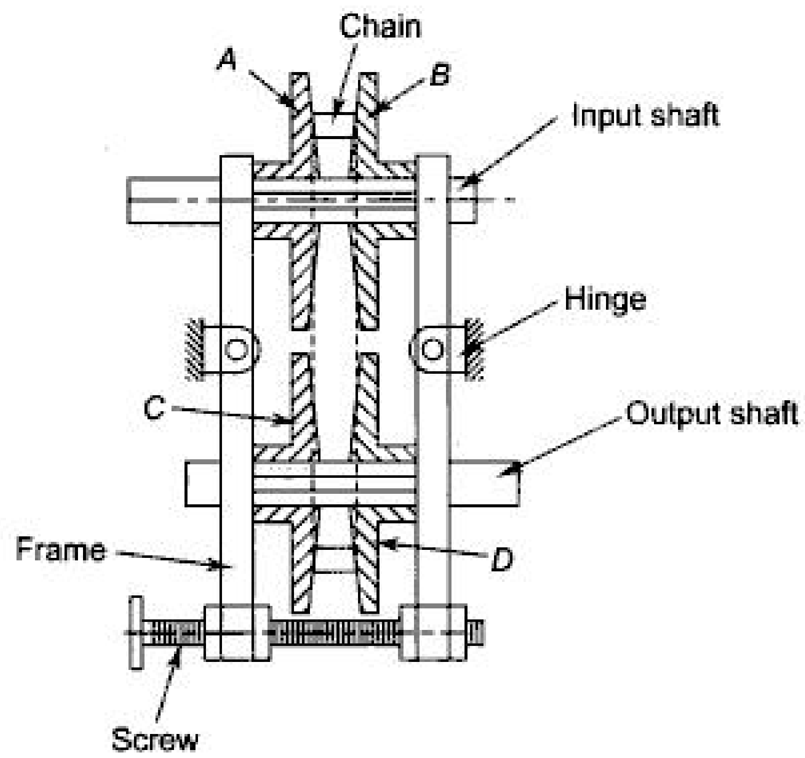

Fig. 3.20 *PIV drive.*

Another stepless drive used is a positively-infinitely-variable or PIV drive, as shown in Fig. 3.20. In this system, a chain is used in place of the V-belt, as shown earlier. Because of the use of a chain, the transmission will be appositive torque transmission. This system consists of two pairs of conical wheels *A*, *B*, *C* and *D*, which are movable on their axis, as shown in Fig. 3.20. These conical wheels are connected by means of a special chain. The conical wheel faces are radially serrated. The laterally movable slats of the chain engage the tooth spaces of the conical wheel face and transmit the torque positively. When the conical wheels move axially, the effective diameter of engagement varies, thereby changing the speed ratio. The chains are normally provided with an automatic chain-tensioning device, for positive power transmission.

3.9 ACTUATION SYSTEMS

Lead screws The rotary motion from the drive motor needs to be converted to linear motion to move the various axes of the machine tool. In conventional machine tools, the square (Acme) thread is normally used for this purpose. However, in view of the metal-to-metal and sliding contact between the nut and the screw, the friction is very high. This results in greater power being utilised for the movement of the axes. Typical friction coefficients for these systems are shown in Table 3.3. Further, in view of the clearance provided between the nut and the screw, in the case of Acme thread, as shown in Fig. 3.21, to reduce friction, there is the problem of backlash whenever there is a reversal of motion. If any attempt is made to reduce the backlash, the friction increases. Hence, most of the higher-end machine tools use a lead screw with a re-circulating ball nut.

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perfectly vertical, since the load would be equally distributed among the faces of *V*. However, in metal cutting, tangential force is more compared to radial force. Thus, in asymmetrical *V*, the longer face is normally made perpendicular to the direction of the resultant force. This allows for uniform wear in both the faces.

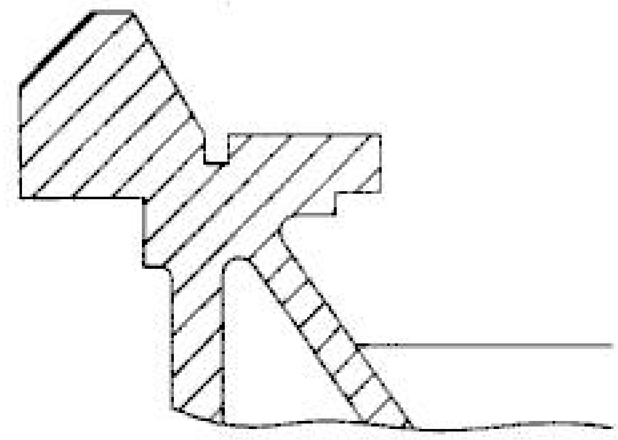

Fig. 3.25 *Single V slideway used in machine bed.*

Flat slideways Flat slideways as shown in Fig. 3.24b, are easier to manufacture and are able to provide a large amount of bearing area. However, the locational accuracy and other advantages provided by the V slideways are missing. Hence, the flat slideways are used in conjunction with the V slideways. The most common arrangement found in lathes is shown in Fig. 3.26. Similar arrangement is also used in planers and horizontal boring machines.

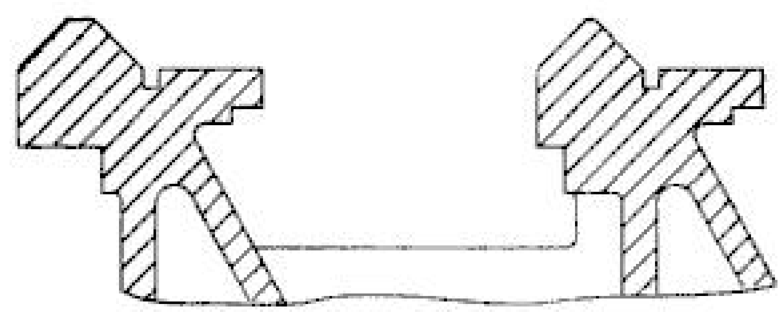

Fig. 3.26 *Asymmetric V slideway used in machine tool bed.*

Round slideways Round slideways, as shown in Fig. 3.24c, are kinematically sound, since they constrain all possible motions except the direction required, but are only used in vertical type of machines, such as drilling (radial and pillar). The main reasons for their non-acceptance are

- low rigidity,
- difficulties in manufacture according to the given accuracy, and
- difficulties in assembling and the resultant accuracy in motion.

Dovetail slideways Dovetail slideways, as shown in Fig. 3.24d, are compact but difficult to manufacture. These are generally used for vertical movement and where space is at a premium. However, they provide good rigidity and alignment. They are generally used in carriage of lathe for moving the knee of a milling machine.

Materials for slideways Generally, cast iron is used as the bed material, and hence cast iron is used for slideways. However, cast iron is poor in wear resistance and has to be induction hardened. Alternatively, separate steel guideways can be used, which can be welded in case of welded bed construction. Steel guideways have all the requisite properties, and are easier to manufacture and maintain accuracy.

A very high level of friction is encountered in slideway systems, as shown in the above varieties, because of the metal-to-metal contact existing between the members. Also, because of the large variation in the static and dynamic friction coefficient, stick-slip phenomenon would be observed with metal-to-metal contact. This is undesirable, particularly for high speed operations, such as those found in the modern machine tools.

A method often tried to minimise the stick-slip motion, and provide some measure of damping capacity, and improve the wear resistance, composite materials of small thickness are provided in between the moving members of a slideway system. The slideway composite materials are made from two or more materials, so that one of them provides the friction reduction capability, and others increase the strength, wear resistance, and load bearing capacity. Another advantage is when this material wears out, the composite material can be repasted. A slideway system with composite material is shown in Fig. 3.27. A number of composite materials are commercially available, such as Turcite-B, SKC-3, and Ferobestos LA3.

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Clamps The table of machine tools generally have a flat surface with accurately machined T-slots, which are generally used for the work holding purpose. Various clamps and locating elements are available to hold complex surfaces on these surfaces. These are discussed in later chapters that relate to specific machine tools.

Summary

Machine tools are mainly used to provide higher accuracy that is essential in the manufacturing industry. A machine tool is able to hold a cutting tool, and removes material from the stock to get the required part geometry.

- Machine tools are classified into different types based on the application, such as general purpose, production, and special purpose machine tools.
- Part geometry can either be generated or formed.
- Depending on the surface, a large number of different motions are used based on the type of tools in operation.
- There is a large variation possible in accuracy and surface finish between the different operations.
- All the machine tools have work holding, tool holding, support, and work and tool motion mechanisms built in them.
- There is a variety of support structures used in machine tools depending on the type of motions required.
- Lead screws are used in machine tools to convert rotary motion to linear motion, which is used to move the table or cutting tool depending on the type of machine tool.
- Re-circulating ball screws are used for more efficient load transmission.
- Anti-friction guideways are used in a majority of the modern machine tools. The conventional guideways are also used.
- A number of work holding systems are possible based on part geometry.

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Questions

1. How do you classify the various machine tools based on the motions used for generating the surfaces? Explain with the help of a suitable block diagram.
2. What are the various methods available for generating plane (flat) surfaces with machine tools?

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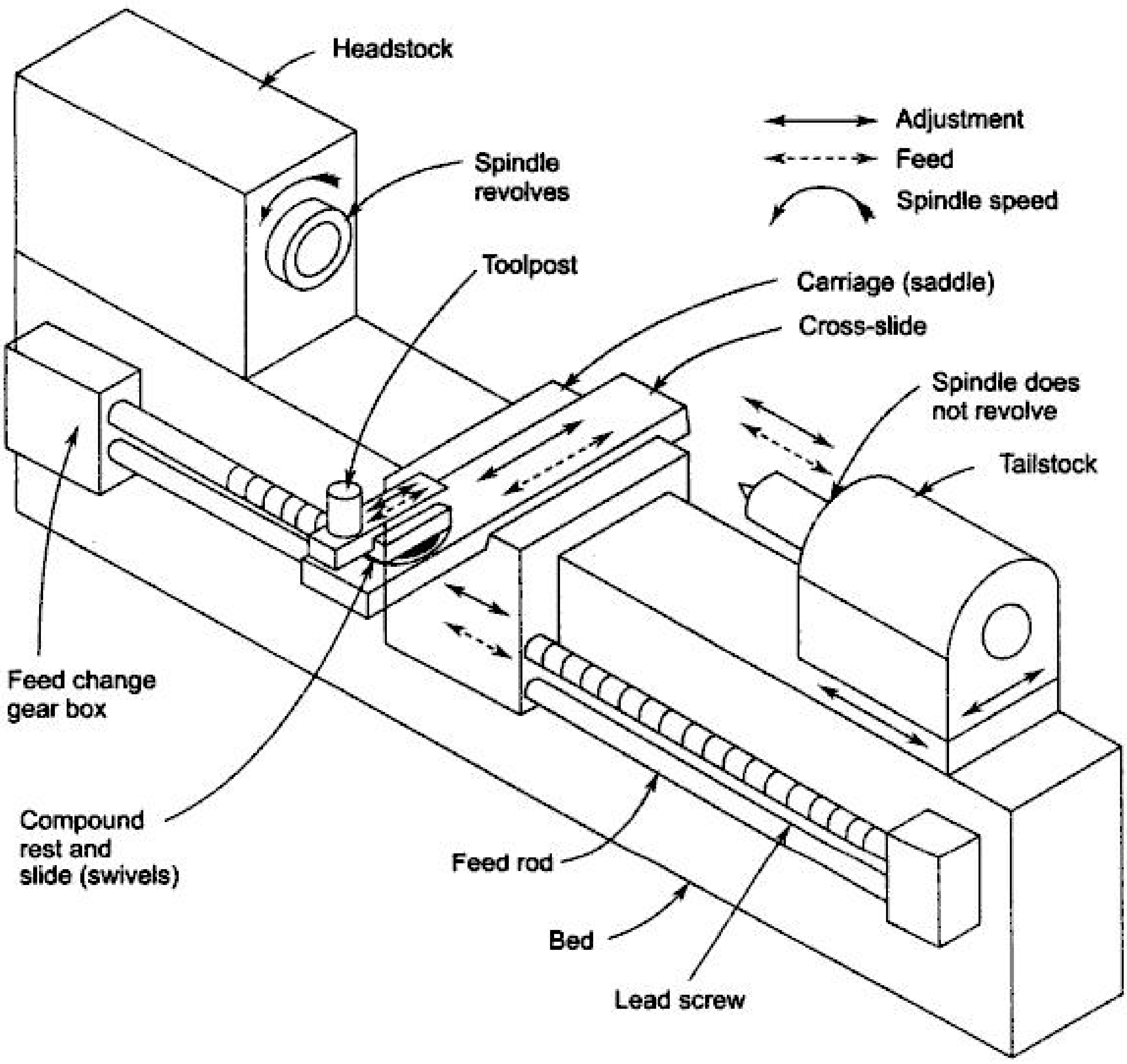

Fig. 4.2 *General view of a centre lathe showing various mechanisms and features.*

The headstock is towards the left-end on the bed and is fixed to it, which houses the power source, the power transmission, gear box, and the spindle. The spindle is hollow and should be sufficiently rigid to provide accurate rotary motion, and maintains perfect alignment with the lathe axis. A live centre fits into the morse taper in the spindle hole for the purpose of locating the workpiece axis.

The main gear box provides the necessary spindle speeds, considering the range of materials to be turned in the lathe. The headstock also houses the feed gear box to provide the various feed rates and thread cutting ranges.

The tailstock is towards the right-end on the bed, which provides a tailstock spindle for the purpose of locating the long components by the use of centres. The tailstock is movable on the inner guideways provided on the bed to accommodate the different lengths of workpieces. It also serves the purpose of holding tools, such as centre drill, twist drill, reamer, etc., for making and finishing holes in the components, which are located in line with the axis of rotation.

The third major element in the lathe mechanism is the carriage, which provides the necessary longitudinal motion to the cutting tool to generate the necessary surfaces. This also houses the cross-slide for giving the motion (cross feed) to the cutting tool, in a direction perpendicular to the axis of rotation, the compound-

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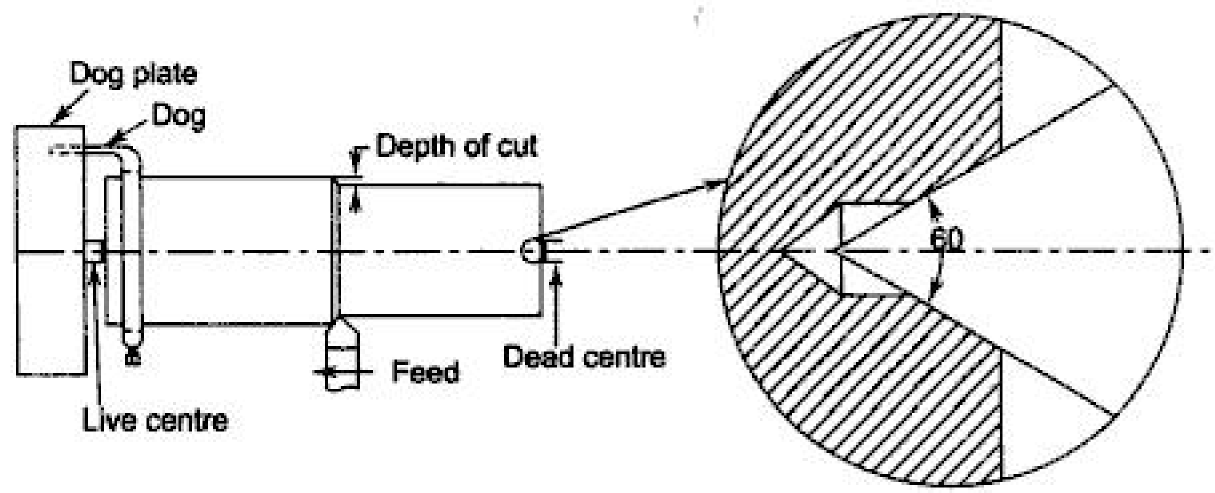


Fig. 4.7 *Centre hole locating between centres.*

Centres as shown in Fig. 4.7, are able to locate the central axis of the workpiece. However centres would not be able to transmit the motion to the workpiece from the spindle. For this purpose, a carrier plate and a dog, as shown in Fig. 4.8, are used. The centre located in the spindle is termed as live centre, while that in the tailstock is termed as dead centre. The shank of the centre is generally finished with a morse taper which fits into the tapered hole of the spindle or tailstock.

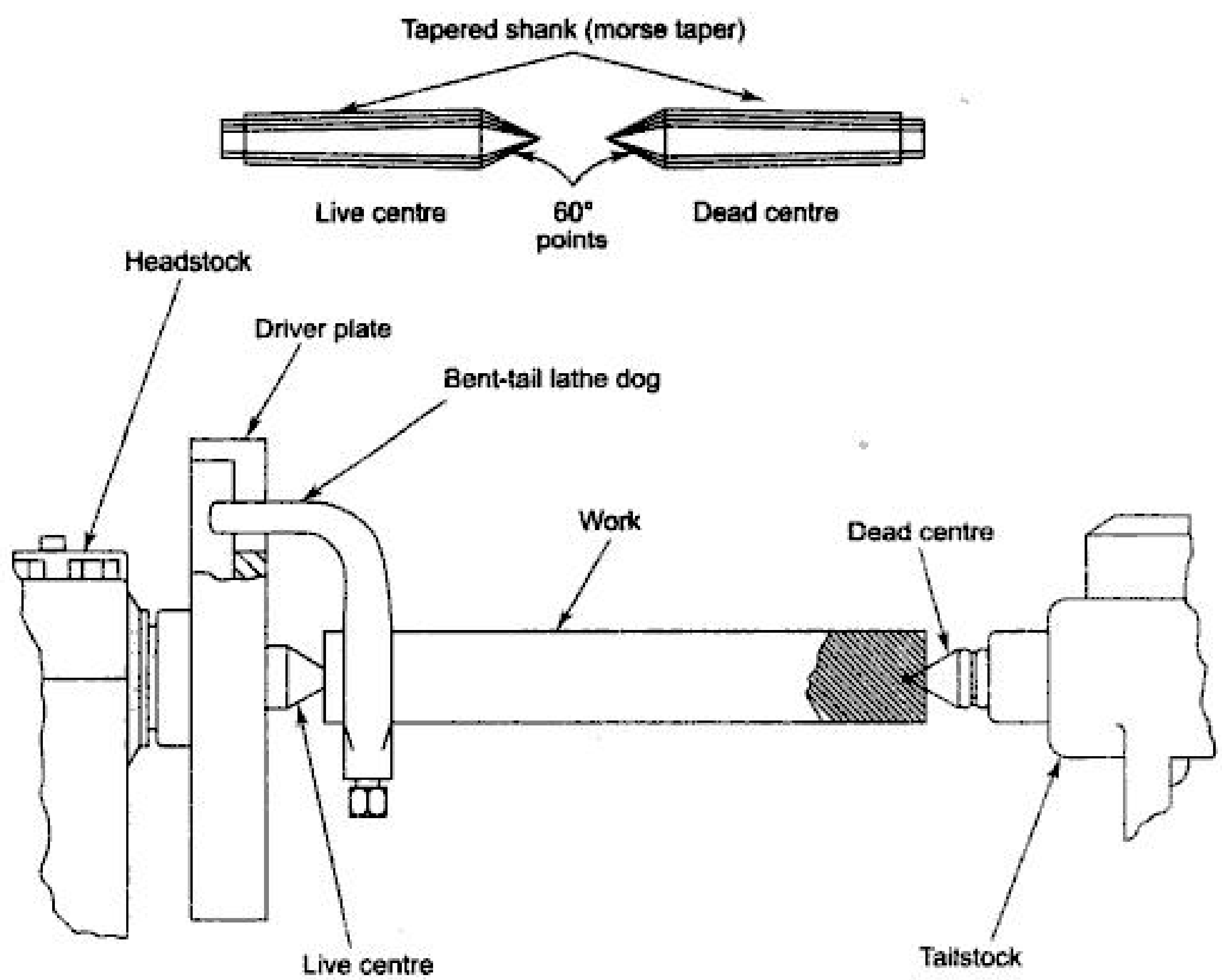


Fig. 4.8 *Dog carrier and revolving centre, half centre, steady.*

Live centre rotates with the workpiece, and hence it remains soft. Whereas, the dead centre does not rotate, hence it is hardened as it forms the bearing surface. However, in case of heavier workpieces, the relative movement between the workpiece and the dead centre generates a large amount of heat. In such cases, a revolving centre is used. In this, the centre is mounted in roller bearings, thus rotating freely, reducing the heat generation at the tailstock end. In cases where a facing operation is to be carried out with centres, a half centre is sometimes used.

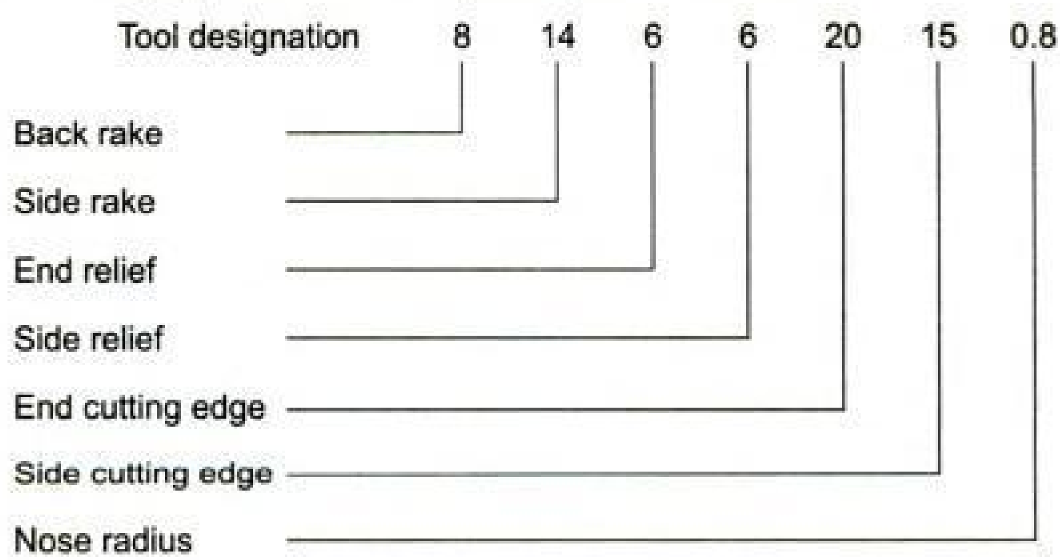
Back-rake angle is the angle between the face of the tool and the base of the shank or holder, and is usually measured in a plane through the side-cutting edge, and at right angles to the base.

Side-rake angle is the angle between the face of the tool and the base of the shank or holder, and is usually measured in a plane perpendicular to the base, to the side-cutting edge.

Side-relief angle is the angle between the portion of the side flank immediately below the side-cutting edge, and a line drawn through this cutting edge perpendicular to the base. It is usually measured in a plane perpendicular to the side flank.

End-relief angle is the angle between the portion of the end flank immediately below the end cutting edge, and a line drawn through this cutting edge perpendicular to the base. It is usually measured in a plane perpendicular to the end flank.

The tool angles are normally specified in a sequence, as shown below:



These individual angles have generally considerable influence on the cutting performance. They have to be judicially chosen for a given application. For example, the side cutting edge angle controls the width and thickness of the chips produced. A very large angle means that the uncut chip thickness reduces, resulting in higher specific cutting resistance. When it approaches zero, the radial component of the cutting force is minimum while the axial component is maximum. This is generally the preferred condition, since the vibration resistance is at its best in this condition. The recommended tool angles for various types of work and tool material combinations are given in Tables 4.1, 4.2, and 4.3.

Table 4.2 *Recommended tool angles in degrees for high speed steel cutting tools*

Work material	*Back-rake angle*	*Side-rake angle*	*Side-relief angle*	*Front-relief angle*	*Sidecutting edge angle*	*Endcutting edge angle*
Steel	8–20	8–20	6	6	10	15
Cast steel	8	8	6	6	10	15
Cast iron	0	4	6	6	10	15
Bronze	4	4	6	6	10	10
Stainless steel	8–20	8–20	6	6	10	15

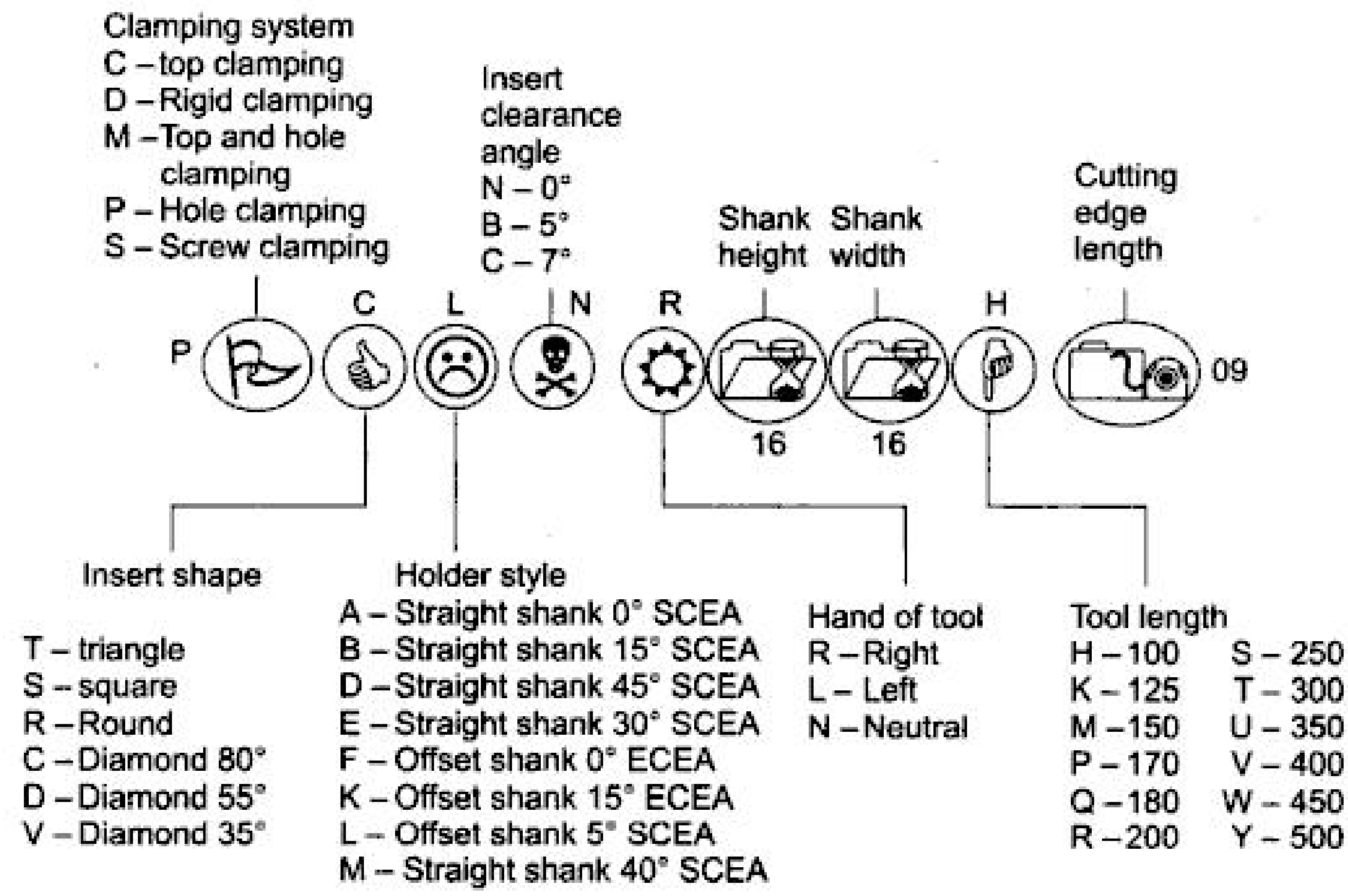


Fig. 4.17 *The ISO coding system for tungsten carbide turning tool holders used in external turning (SCEA—side cutting edge angle, ECEA—end cutting edge angle).*

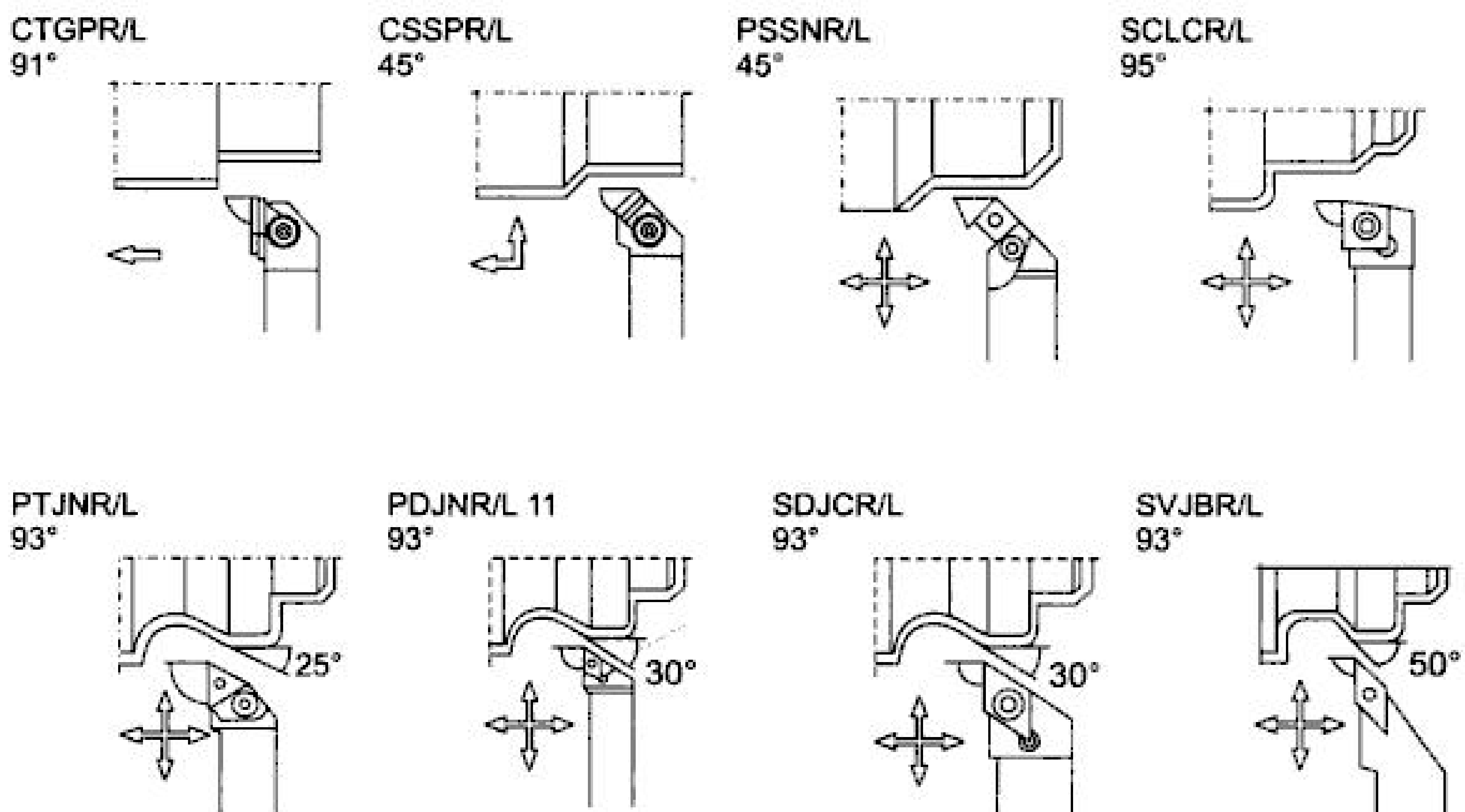


Fig. 4.18 *The typical contour capability of external turning tools (courtesy Seco Tools, Germany. Redrawn from Seco Catalogue).*

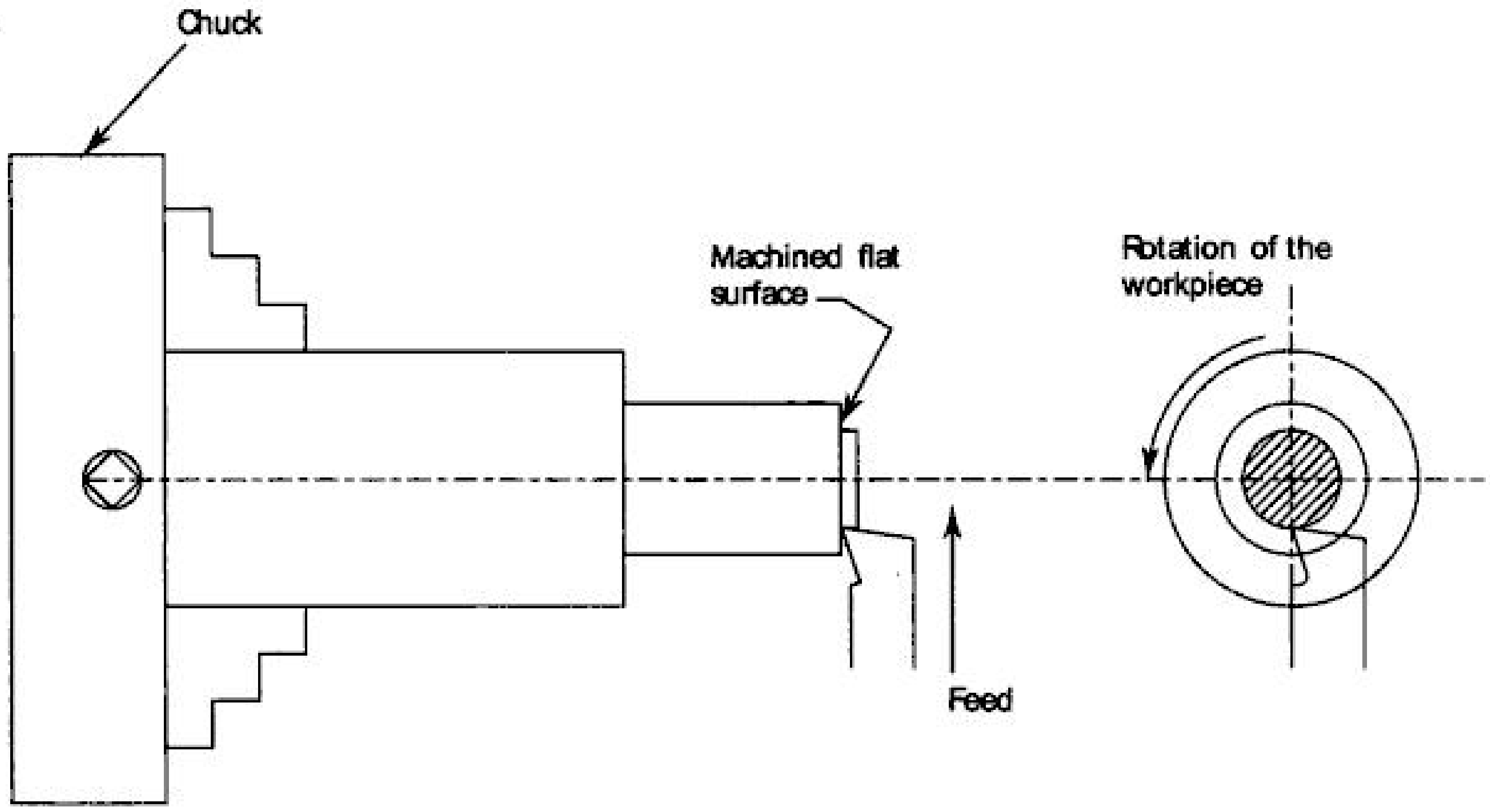


Fig. 4.23 *Facing.*

4.5.3 Knurling

Knurling is a metal working operation done in a lathe. In this, a knurling tool having the requisite serrations is forced on to the workpiece material, thus deforming the top layers, as shown in Fig. 4.24. This forms a top surface, which is rough and provides a proper gripping surface.

4.5.4 Parting

Parting and grooving are similar operations. In this, a flat-nosed tool would plunge cut the workpiece with a feed in the direction perpendicular to the axis of revolution, as shown in Fig. 4.25. This operation is generally carried out for cutting off the part from the parent material. When the tool goes beyond the centre, the part would be severed. Otherwise, a rectangular groove would be obtained. It is also possible, in similar operation, to use a special form of tool to obtain the specific groove shape.

4.5.5 Drilling

Drilling is the operation of making cylindrical holes into the solid material, as shown in Fig. 4.26. A twist drill is held in the quill of the tailstock, and is fed into the rotating workpiece by feeding the tailstock quill. Since the workpiece is rotating, the axis of the hole is well-maintained, even when the drill enters at an angle initially. The same operation can also be used for other hole making operations, such as centre drilling, counter sinking, and counter boring. This operation is limited to holes through the axis of rotation of the workpiece, and from any of the ends.

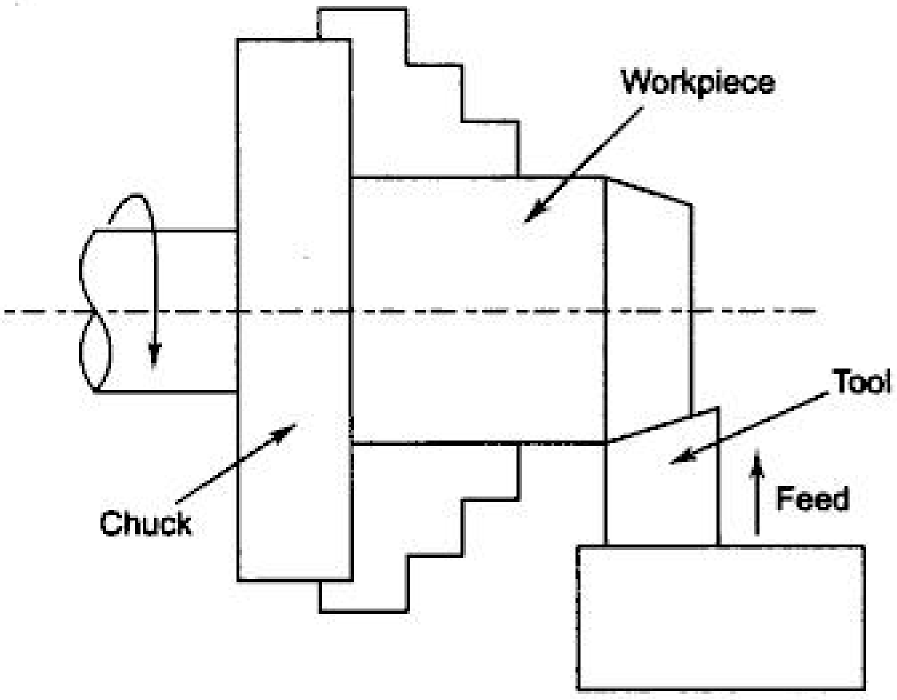


Fig. 4.29 *Taper turning using form tools.*

Referring to Fig. 4.30, the offset can be calculated as follows:

$$\sin \alpha = \frac{BC}{AB} \tag{4.4}$$

$$S = AB \sin \alpha = L \sin \alpha \tag{4.5}$$

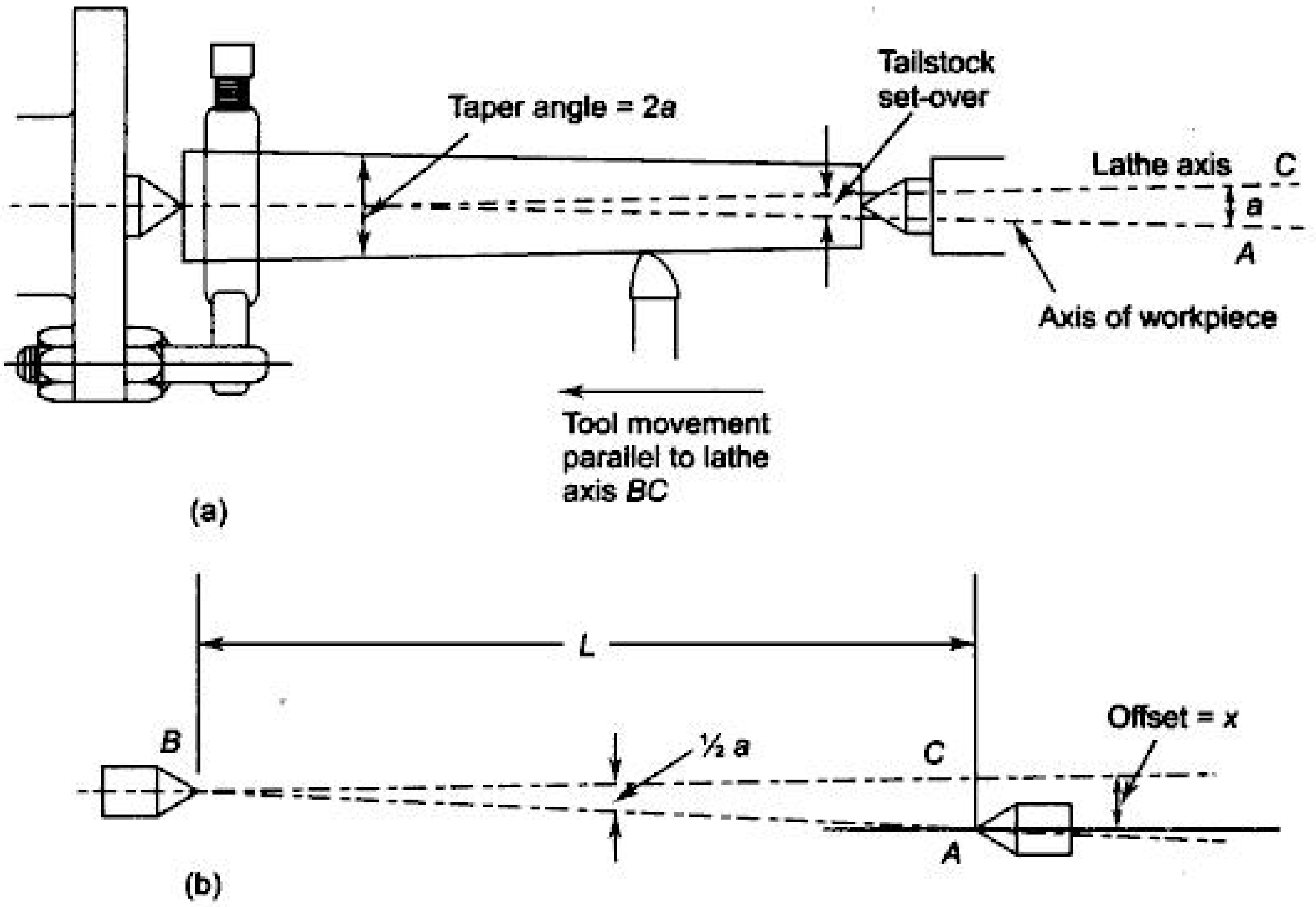


Fig. 4.30 *Tail stock offset.*

If α is very small, then we can approximate

$$\sin \alpha \approx \tan \alpha \approx \frac{D-d}{21} \tag{4.6}$$

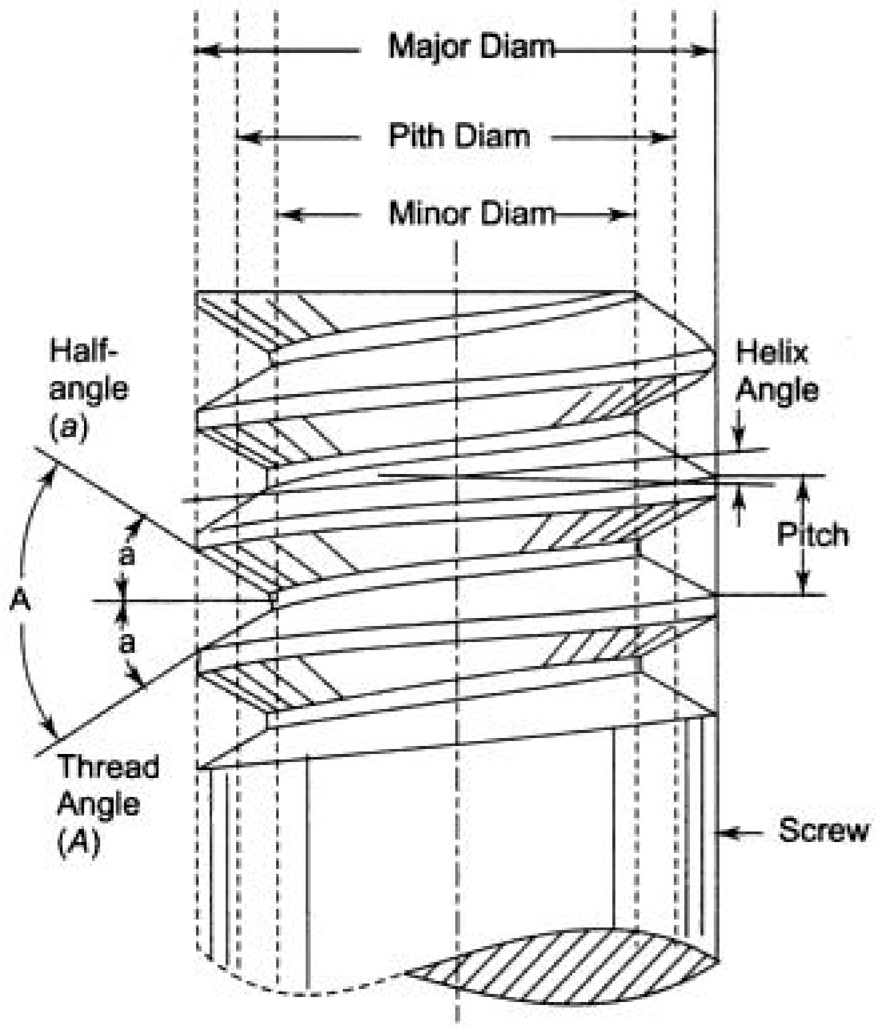


Fig. 4.33 *Simple thread definition.*

Thread cutting can be considered as turning, since the path to be travelled by the cutting tool is helical. However, there are some major differences between turning and thread cutting. In turning, the interest is in generating a smooth cylindrical surface, whereas in thread cutting, the interest is in cutting a helical thread of a given form and depth, which can be calculated from the formulae for different forms of threads, as given in Table 4.5.

Table 4.5 *Formulae for some common thread forms*

Thread form	***Formulae*** *for calculating the parameters*
British Standard Whitworth (BSW)	Depth = 0.6403 × *Pitch* Angle = 55° in the plane of the axis Radius at the crest and root = 0.137329 × *Pitch*
British Association (BA)	Depth = 0.6 × *Pitch* Angle = 47.5° in the plane of the axis Radius at the crest and root = $\frac{2 \times Pitch}{11}$
International Standards Organisation (ISO) metric thread	Max. Depth = 0.7035 × *Pitch* Min. Depth = 0.6855 × *Pitch* Angle = 60° in the plane of the axis Root radius Maximum = 0.0633 × *Pitch* Minimum = 0.054 × *Pitch*
American Standard ACME	Height of thread = 0.5 × *Pitch* + 0.254 mm Angle = 29° in the plane of the axis Width at tip = 0.3707 × *Pitch* Width at root = 0.3707 × *Pitch* – 0.132 mm

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4.8 SPECIAL ATTACHMENTS

Most of the details discussed so far allow for general purpose machining operations to be carried out using a centre lathe. In addition, it is possible to provide special enhancements to the capability of a lathe, whereby it could be used for special applications using special attachments. One such attachment discussed earlier is the taper turning attachment for obtaining cylindrical tapers or conical surfaces.

Milling attachment This is an attachment used in lathes to carry out milling operations. The attachment is provided with a separate spindle, as shown in Fig. 4.39 where the milling cutters can be located, and is attached to the cross-slide, replacing the compound-slide. The work is held between the lathe centres, as in normal centre lathes. The milling cutter can normally be fed in all the three directions, thus permitting any type of milling operation.

Grinding attachment Similar to the milling attachment, a grinding attachment is used to finish a part in the lathe by completing the required grinding operations without disturbing the setup. It can be mounted in place of the tool post on the compound-slide. These have two- or three-axis movement, and are able to perform a number of grinding operations.

Copy turning attachment Many a times, the need exists for machining complex contours, which require the feeding of the tool in two axes, *X* and *Y*, simultaneously, similar to taper turning. For such purposes, copy turning is to be used. In this, the cross-slide is directly driven by a stylus, which can trace a master for the actual contour to be produced. The cross-slide is made free, similar to the taper turning attachment.

Radius turning attachment In this attachment, the cross-slide is attached to the bed by means of a radius arm whose length is same as the radius of the spherical component to be produced, as shown in Fig. 4.40. The radius arm couples any movement of the cross-slide or the carriage, and hence the tool tip traces a radius *R*, as shown in Fig. 4.40.

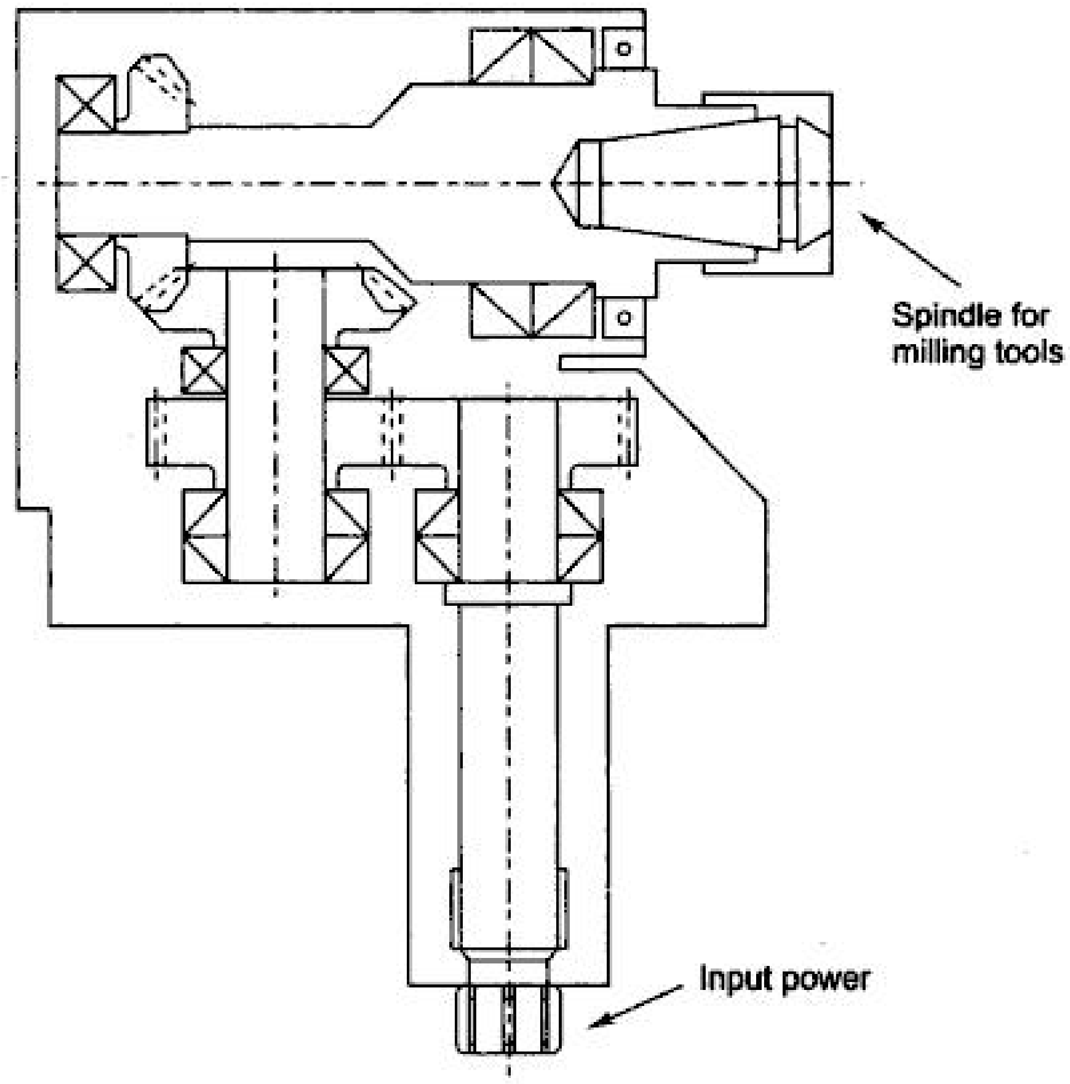

Fig. 4.39 *Schematic of a milling attachment for lathe.*

Sol.

Stock to be removed $= \dfrac{50-42}{2} = 4\text{ mm}$

Finish allowance $= 0.75\text{ mm}$

Roughing:

Roughing stock available $= 4 - 0.75 = 3.25\text{ mm}$

Since maximum depth of cut to be taken is 2 mm, there are 2 roughing passes.

Given cutting speed, $V = 30\text{ m/min}$

Average diameter $= \dfrac{50+42}{2} = 46\text{ mm}$

Spindle speed, $N = \dfrac{1000 \times 30}{\pi \times 46} = 207.59\text{ RPM}$

The nearest RPM available from the list is 176 RPM as 280 is very high compared to 207, as calculated.

Machining time for one pass $= \dfrac{(120+2)}{0.24 \times 176} = 2.898\text{ minutes}$

Finishing:

Given cutting speed, $V = 60\text{ m/min}$

Spindle speed, $N = \dfrac{1000 \times 30}{\pi \times 42} = 439.05\text{ RPM}$

The nearest RPM available from the list is 440 RPM.

Machining time for one pass $= \dfrac{(120+2)}{0.10 \times 440} = 2.77\text{ minutes}$

Total machining time $= 2 \times 2.888 + 2.77 = 8.546\text{ minutes}$

Facing In facing, the choice of the spindle speed is affected by the fact that the cutting tool is engaged with the workpiece at gradually changing radius. As a result, the actual cutting speed is changing from the highest value at the surface to almost zero at the centre. Thus, the diameter used for calculating the rpm in Eqn. (4.20) should be the average of blank diameter and the lowest diameter, zero in case of complete facing, of the face being generated.

Taper turning The time calculation of taper turning depends on the method used for the purpose. In the case of taper turning attachment, the calculation is similar to turning as the feed motion is given by the carriage parallel to the axis of rotation. However, when the tailstock offset method is used, the motion of the tool is parallel to the actual taper surface generated, and as such that length should be used in Eqn. (4.21).

All the other operations are similar to turning, where care has to be taken to find the actual distance travelled in the operation.

Carbide Tool

Assume cutting speed, $V = 145$ m/min

Feed rate, $f = 0.38$ mm/rev

Depth of cut $= 2$ mm

Power $= \dfrac{1600 \times 145 \times 0.38 \times 2}{60} = 2939\ \text{W} = 2.94\ \text{kW}$

For the second pocket also, the power required remains the same, since the processing parameters did not change.

4.10 TYPICAL SETUPS

It is necessary to consider all the factors while planning for a job to be made on any machine tool. A few examples of tool layouts are discussed that can be machined in a centre lathe.

The examples are shown in the form of process diagrams, where the material to be removed is shown in the form of a closed pocket, which is hatched. The type of tool to be chosen is based on the type of pocket to be machined.

Example 4.8 *The example is a cylindrical pin, which can be turned from a long bar, with each part being parted off. The typical sequence in which the material is produced is shown in Fig. 4.43. In the first operation, the external diameter of 16 mm is produced to the required length using a right-hand turning tool. The chamfering form tool to produce the right-hand chamfer in operation 2 will follow this. In the third operation, the undercut is produced again by using a form tool with plunge feed. Then, the part will be parted off from the bar stock with a parting tool. In the next operation, the part will be held from the other side, and then the facing and chamfering will be done to complete the job.*

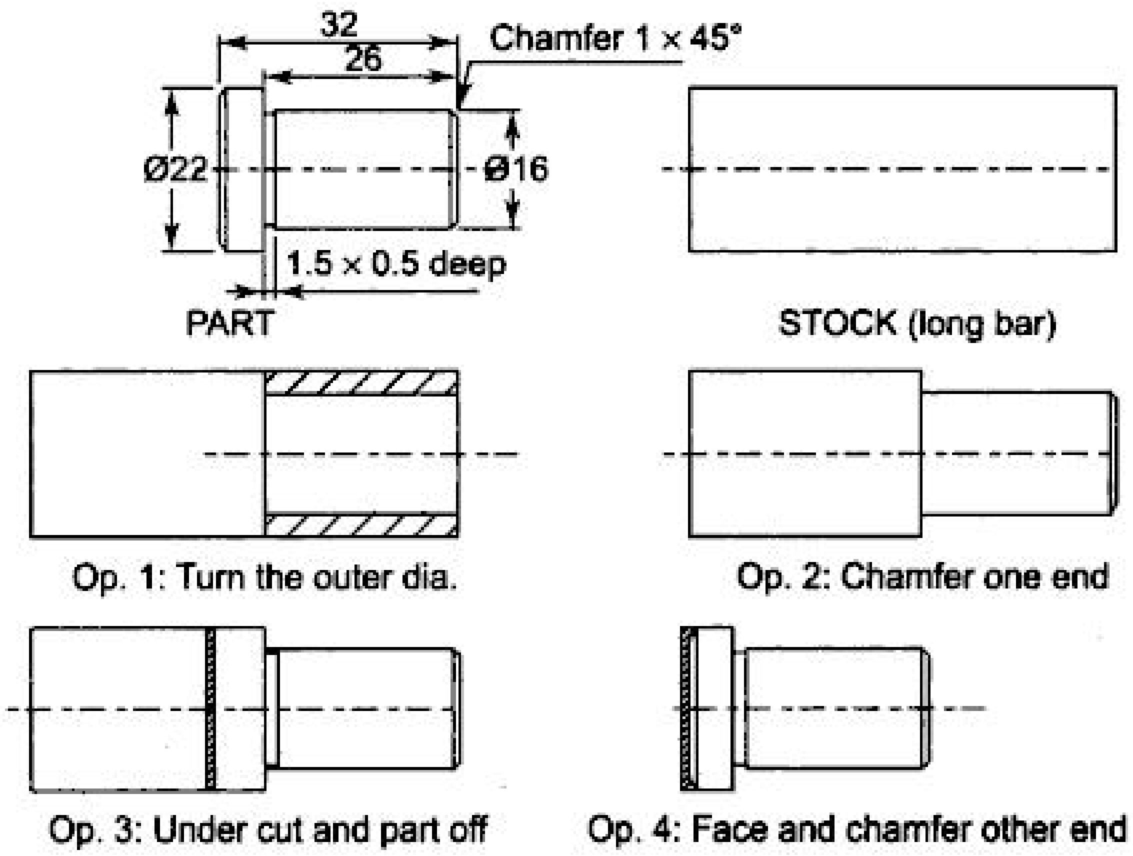

Fig. 4.43 *Typical process pictures for machining a pin from a cylindrical bar on a lathe involving only external features.*

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4. What are the applications, achievable (comparative) accuracies, and disadvantages of the following type of work holding device:
   (*a*) 3-jaw chuck (*b*) 4-jaw chuck
5. Compare the applications, accuracies, and disadvantages of 3-jaw and 4-jaw chucks.
6. What are the types of surfaces that can be generated in a centre lathe? Show with the help of sketches how these are achieved?
7. Explain the methods used for the generation of threads in a lathe.
8. How is thread chased in a lathe?
9. What are the precautions and settings to be done for cutting single start threads on a centre lathe? Give a practical method that will allow the cutting tool to follow the thread.
10. What are the various methods available for taper-turning in a lathe? Explain their specific advantages and limitations.
11. Describe the method of generation of a long and small taper in a centre lathe.
12. Explain the procedure for turning a job, which is very long. List the various operations and tools, such as cutting and holding, required for the operation.
13. What are the various methods available for taper, turning on a centre lathe? Explain in detail with a sketch, the method used for machining steep tapers of short length.
14. What are the various methods available for supporting long components and frail components in a lathe? Explain with sketches.
15. Draw a setup required for cutting external threads on a centre lathe. Explain clearly the various methods that are followed for the purpose of engaging the cutting tool for giving the depth of cut in threading.
16. What are the types of lathes that you are familiar with? Give their applications.
17. What are the applications, achievable (comparative) accuracies, and disadvantages of the following type of work holding devices when used in a centre lathe. State the precautions to be used with their application.
   (*a*) Face plate (*b*) 4-jaw chuck

Problems

1. A grey cast-iron shaft is machined in a centre lathe in 1 minute with a single cut. The shaft is 100 mm long and 75 mm in diameter. If the feed used is 0.30 mm/re-volution, what cutting speed was used?
2. In a centre lathe equipped with a taper-turning attachment, a 3 degree taper is to be produced. The small end of the workpiece is 25 mm in diameter. The taper attachment is set at 3 degrees but the tool is set 3 mm below centre. Calculate the error in taper due to the incorrect setting of the tool.
3. Calculate the maximum possible error, which is the distance from the centre of the workpiece, in setting the turning tool with a clearance angle such that, the tool starts rubbing at the clearance face, where the clearance angle become zero. The workpiece is 50 mm in diameter. If the rake angle is 10 degrees, what is the effective rake angle for this condition?
4. A high speed steel tool has a tool life of 105 minutes while turning cast iron at a cutting speed of 20 m/min. If the tool life is given by the Taylor's tool life equation as $VT^{0.1} = C$, calculate the tool life for a cutting speed of 15 m/min.
5. While taper turning a taper of 1 in 6, the tool is wrongly set at a distance of 4 mm below the workpiece centre. If the small end of the workpiece is 35 mm in diameter, calculate the actual taper obtained.
6. The taper turning attachment of a lathe is set to turn a taper of 1 in 6. The larger end of the workpiece is 50 mm in diameter and the length is 100 mm. If the tool is set 5 mm below the centre of the workpiece, calculate the actual taper produced.

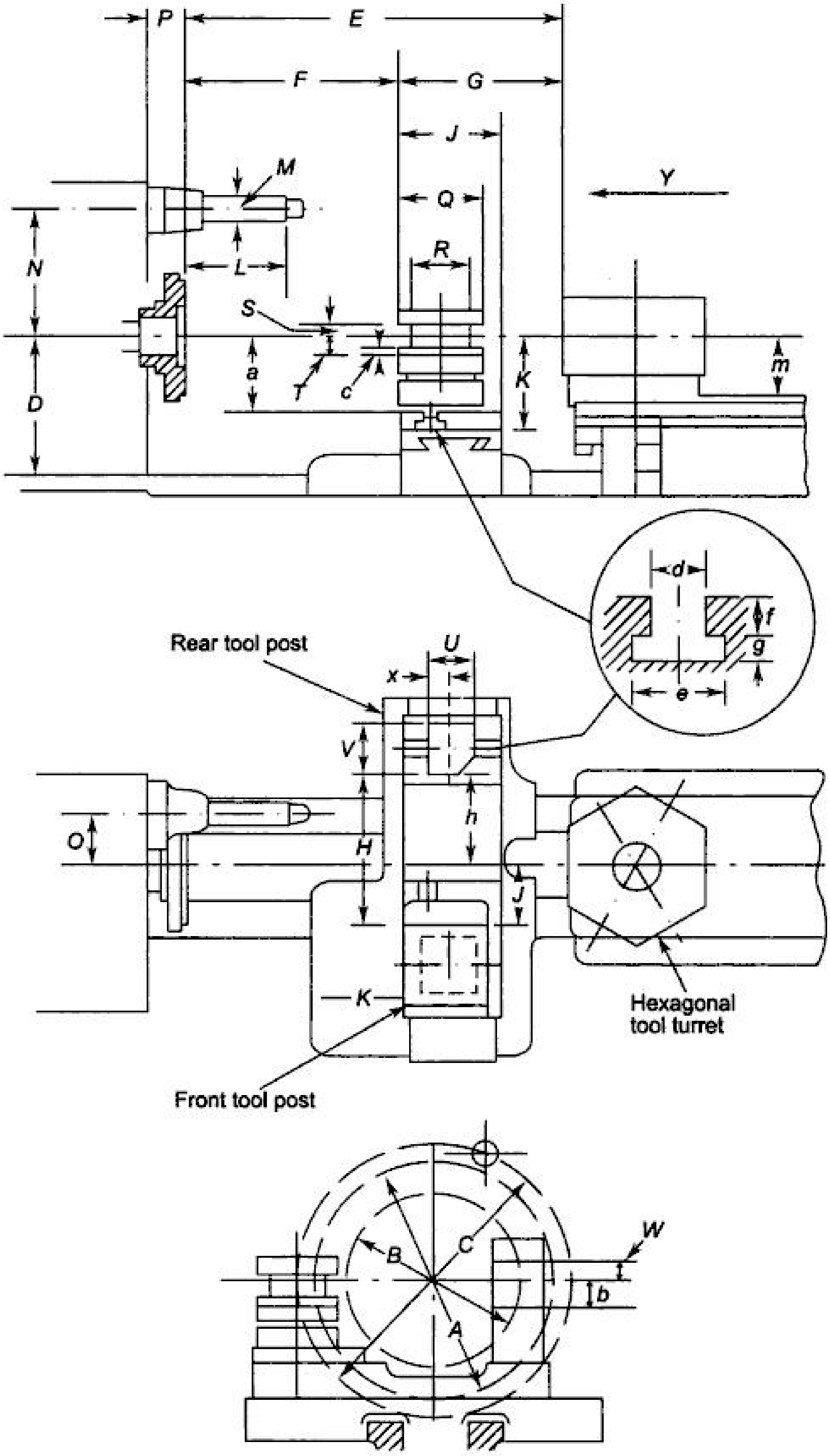

Fig. 5.1 *A view of the turret lathe.*

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5. Two or more tools mounted on a single tool face can cut simultaneously.
6. Semi-skilled operators are required.
7. Used for production operations involving better repeatability.

A variation of the turret lathe is the capstan lathe, in which the turret moves on the saddle while the saddle can itself be fixed at any position on the bed depending on the length of the job, as shown in Fig. 5.5. Thus, the tool travel length is limited to the length of the saddle. This type of arrangement is normally used for small size machines.

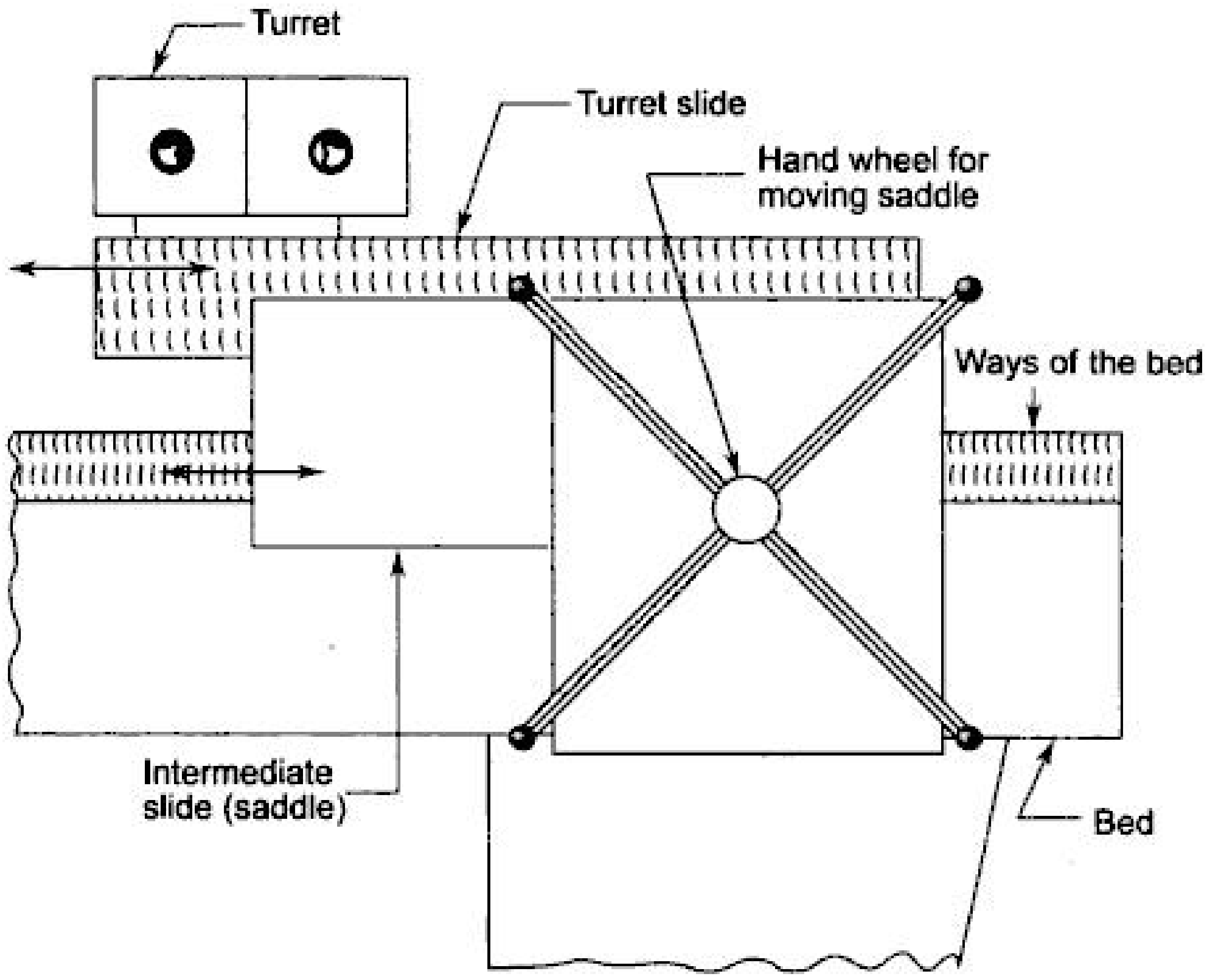

Fig. 5.5 *Intermediate slide arrangement in capstan lathe.*

The various differences between capstan and turret lathes are given in Table 5.1.

Table 5.1 *Differences between capstan and turret lathes*

Capstan lathe	Turret lathe
Short slide, since the saddle is clamped on the bed in position.	Saddle moves along the bed, thus allowing the turret to be of large size.
Light duty machine, generally for components whose diameter is less than 50 mm.	Heavy duty machine, generally for components with large diameters, such as 200 mm.
Too much overhang of the turret when it is nearing cut.	Since the turret slides on the bed, there is no such difference.

5.2.1 Typical Tool Layouts

The tool layout for a given job is the predetermined order of machining operations to be performed to produce it. An efficient tool layout produces accurate parts as per the requirements, at the most economical cost. The tool layout is generally influenced by the nature of the job, the condition of the raw material, such as casting, forging, or bar stock, the amount of stock to be removed, and the number of pieces to be produced.

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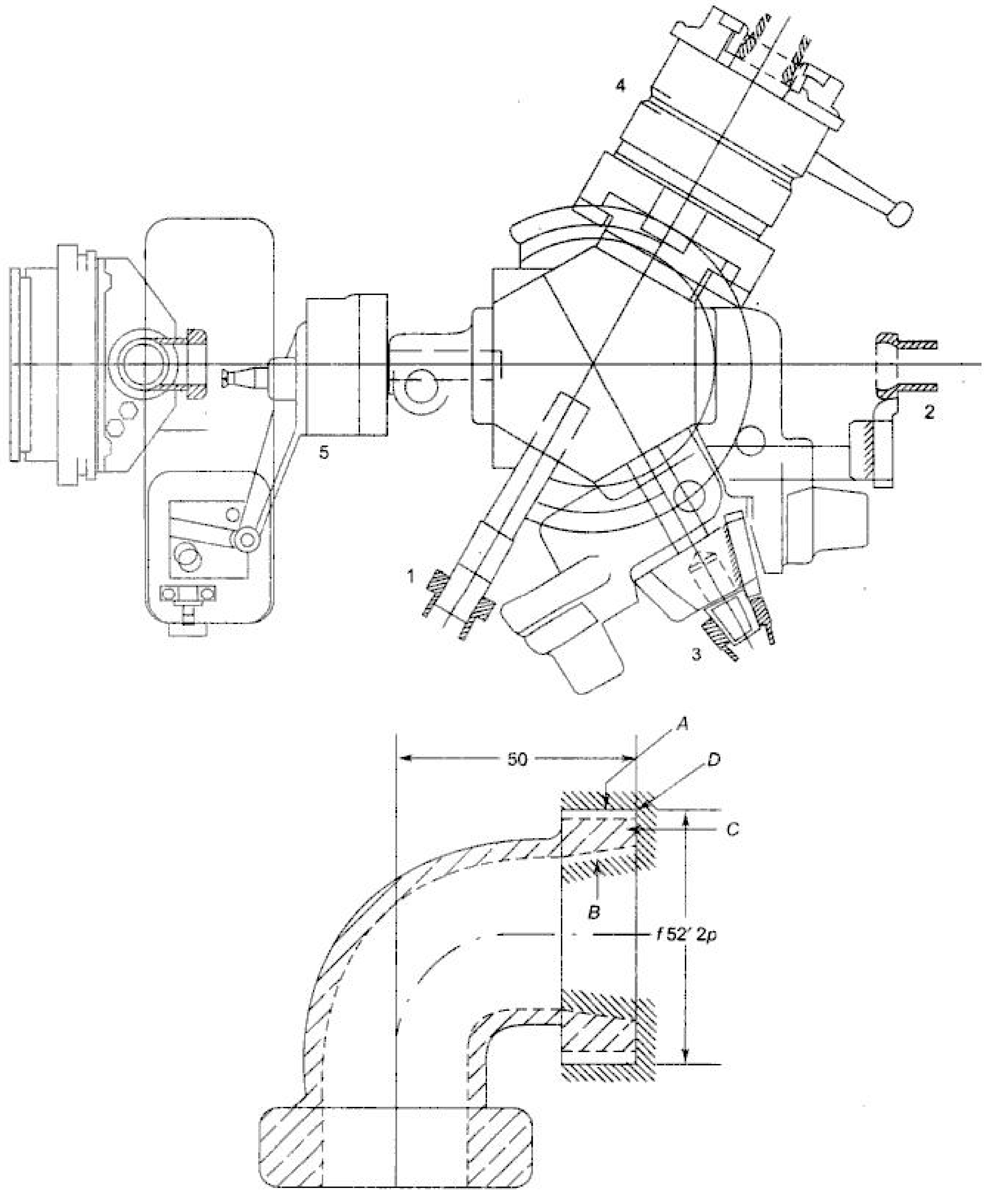

Fig. 5.8 *Tooling layout of brass pipe bend casting.*

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Drum type

Copy milling (Die sinking machines)

Keyway milling machines

Spline shaft milling machines

These machines are of a special class to provide special facilities to suit specific applications that are not catered by the other classes of milling machines.

7.2.1 Knee-and-Column Milling Machine

The knee-and-column type milling machine is the most commonly used machine in view of its flexibility, and easier setup. The typical machine construction is shown schematically in Fig. 7.2 for the horizontal axis. The knee houses the feed mechanism and mounts the saddle and table. The table basically has the T slots running along the *X*-axis for the purpose of work holding. The table moves along the *X*-axis on the saddle while the saddle moves along the *Y*-axis on the guideways provided on the knee. The feed is provided either manually with a hand wheel or connected for automatic by the lead screw, which in turn is coupled to the main spindle drive. The knee can move up and down (Z-axis) on a dovetail provided on the column.

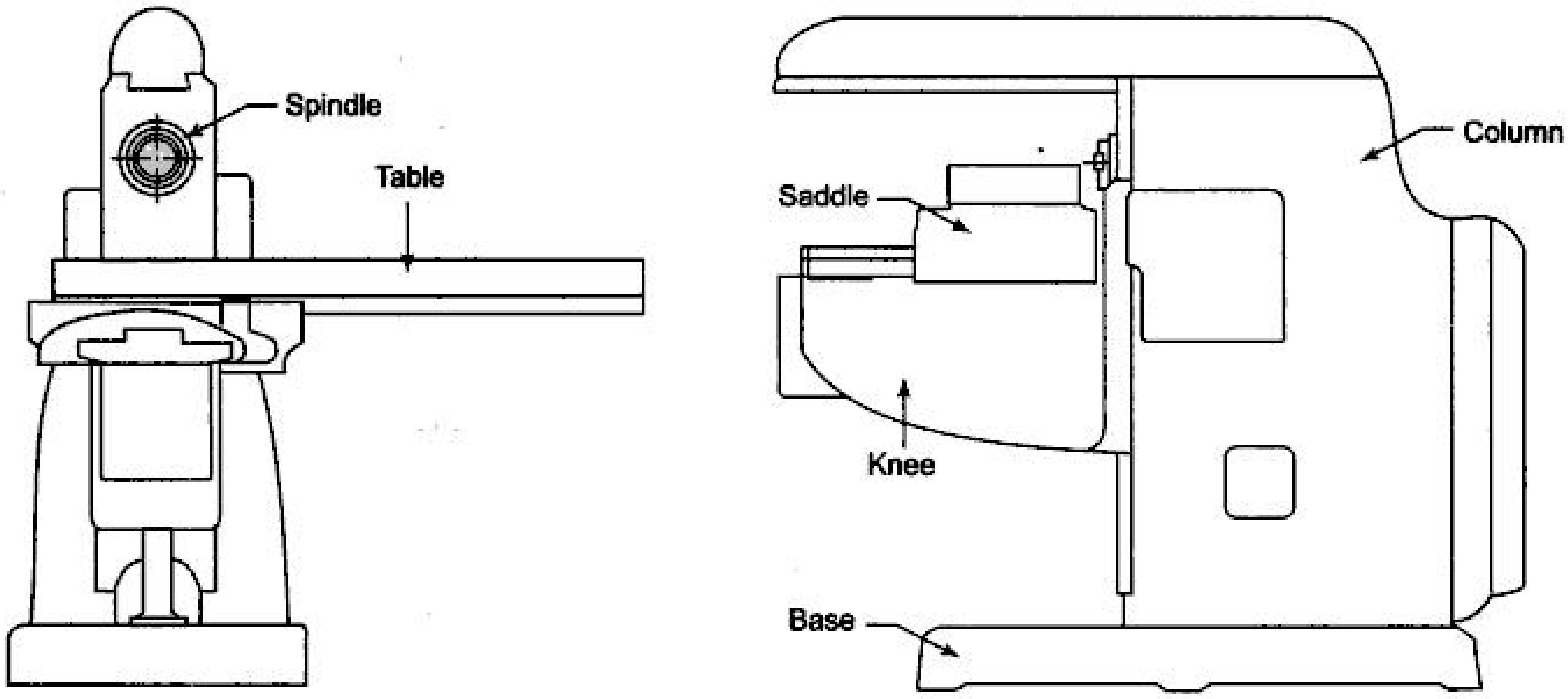


Fig. 7.2 *Horizontal knee and column type milling machine.*

The massive column at the back of the machine houses all the power train including the motor and the spindle gearbox. The power for feeding the table lead screw is taken from the main motor through a separate feed gear box. Sometimes it is possible that a separate feed motor is provided for the feed gearbox as well.

While the longitudinal and transverse motions are provided with automatic motion, the raising of the knee is generally made manually.

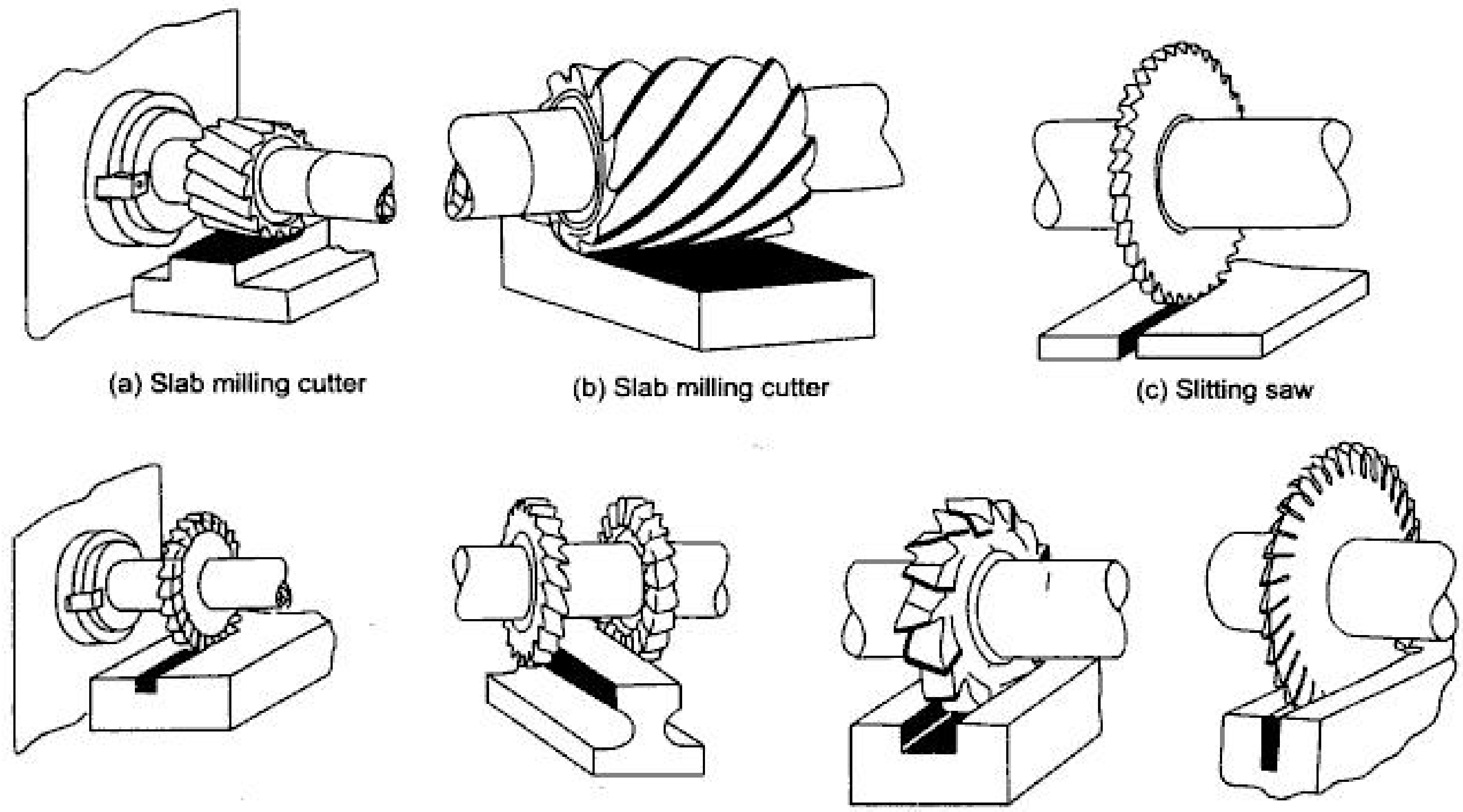
The spindle is located at the top end of the column. An arbour used to mount the milling cutters is mounted in the spindle and is provided with a support on the other end by means of an over arm with bearing to take care of the heavy cutting forces. As shown in Fig. 7.2, the over arm extends from the column with a rigid design. The spindle nose has the standard Morse taper of the suitable size, depending upon the machine size.

Based on helix

Right-hand helix

Left-hand helix

Milling cutters are generally made of high speed steel or cemented carbides. The cemented carbide cutters can be fitted with brazed tip or more commonly, with indexable tips. The indexable variety is more common since it is normally less expensive to replace the worn out cutting edges than to regrind them.



(a) Slab milling cutter (b) Slab milling cutter (c) Slitting saw

(d) Side and face cutter (e) Two side and face cutter (f) Staggered tooth cutter (g) Side and face cutter

Fig. 7.7 *Arbour mounted milling cutters (general purpose).*

Plain milling cutters These are also called as slab milling cutters and are basically cylindrical with the cutting teeth on the periphery, as shown in Fig. 7.7a. These are generally used for machining flat surfaces.

Light duty slab milling cutters generally have a face width, which is small, of the order of 25 mm. They generally have straight teeth and large number of teeth.

The heavy duty slab milling cutters come with smaller number of teeth to allow for more chip space. This feature allows taking deeper cuts and consequently high material removal rates.

Helical milling cutters have a very small number of teeth but a large helix angle. This type of cutter cuts with a shearing action, which can produce a very fine finish. The large helix angle allows the cutter to absorb most of the end load and therefore the cutter enters and leaves the workpiece very smoothly.

Side- and face-milling cutters These have the cutting edges not only on the face, like the slab milling cutters, but also on both the sides. As a result, these cutters become more versatile since they can be used for side milling as well as for slot milling.

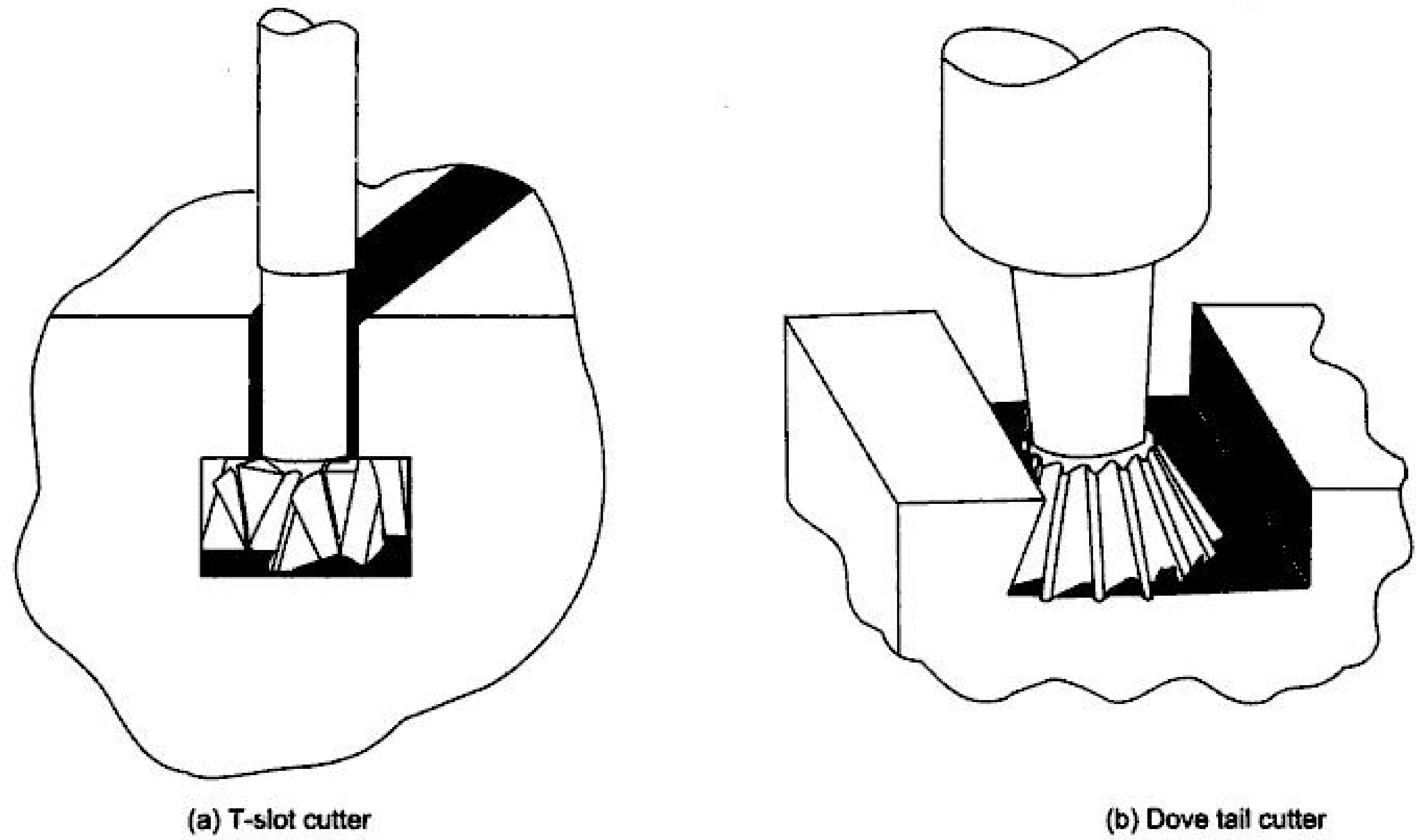


Fig. 7.11 *Special milling cutters for specific applications.*

Face milling cutters (Fig. 7.12) are used for machining large, flat surfaces. They have the cutting edges on the face and periphery. It is generally mounted directly on the nose of the spindle with entire face free for machining. The teeth on the face do most of the machining while those on the side are used for cleaning the surface. These are generally made of carbide insert variety in view of the large material removal involved, though high speed steel type are also used.

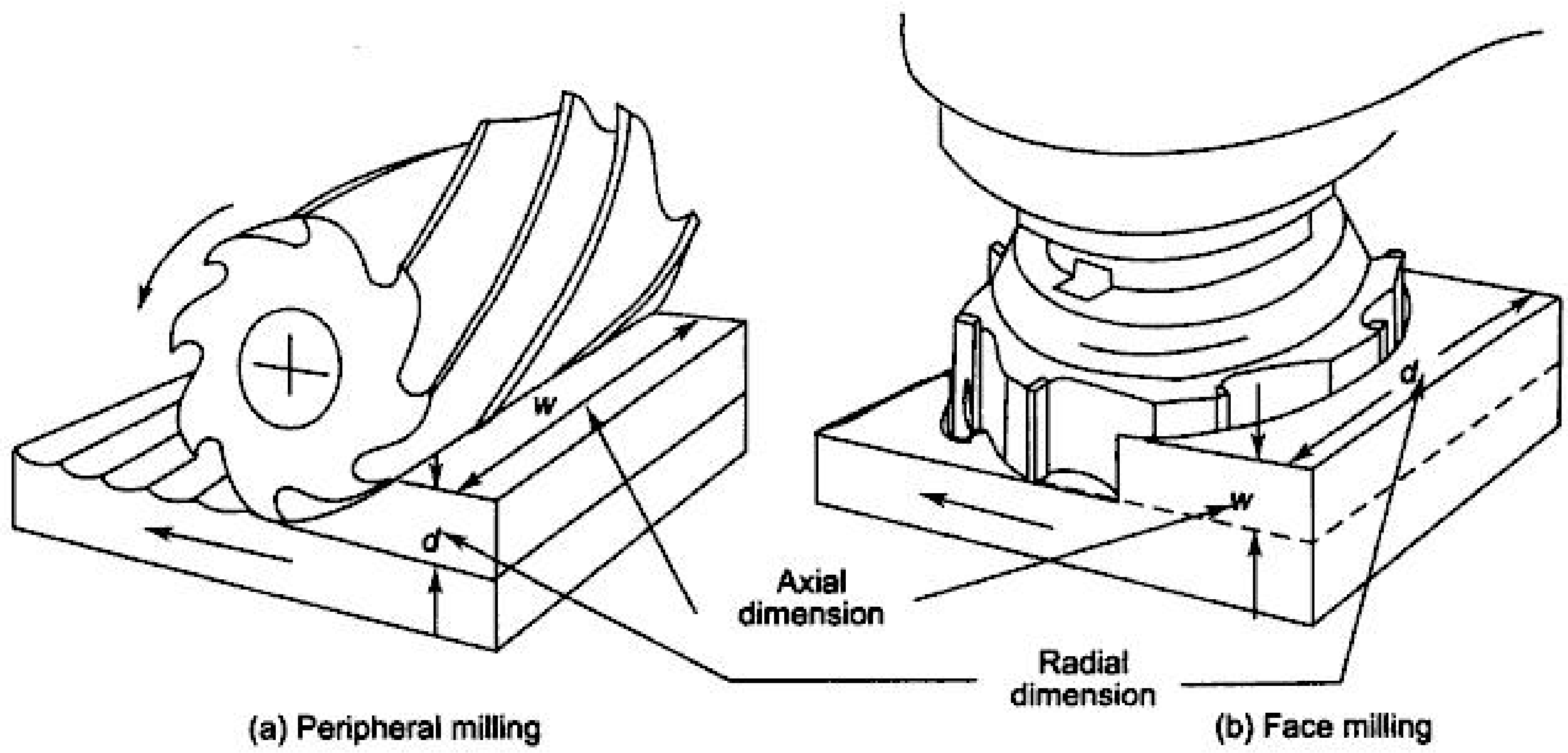


Fig. 7.12 *Generating plane surfaces in milling (using face milling).*

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5. It requires upto 20% less power to cut by this method.
6. It may be used when cutting off stock or when milling deep, thin slots.

Disadvantages

1. It cannot be used unless the machine has a backlash eliminator and the table jibs have been tightened.
2. It cannot be used for machining castings or hot rolled steel, since the hard outer scale will damage the cutter.

7.4 MILLING OPERATIONS

7.4.1 Work Holding

Milling machine table comes with precision parallel T-slots along the longitudinal axis. The workpiece therefore can be mounted directly on the table using these T-slots. Alternatively, a variety of work holding devices can be used for holding the workpiece, depending upon the type of workpiece and the type of milling to be done.

Vice is the most common form of work holding device used for holding small and regular workpieces. The vice is mounted on the table using the T-slots. A variety of vice jaws are available to suit different workpiece geometries.

Universal chuck is used for holding round workpieces for machining of end slots, splines, etc.

Fixtures are the most common form of work holding devices used in production milling operations. These become almost a necessity to reduce the setup time and increase the locational accuracy and repeatability.

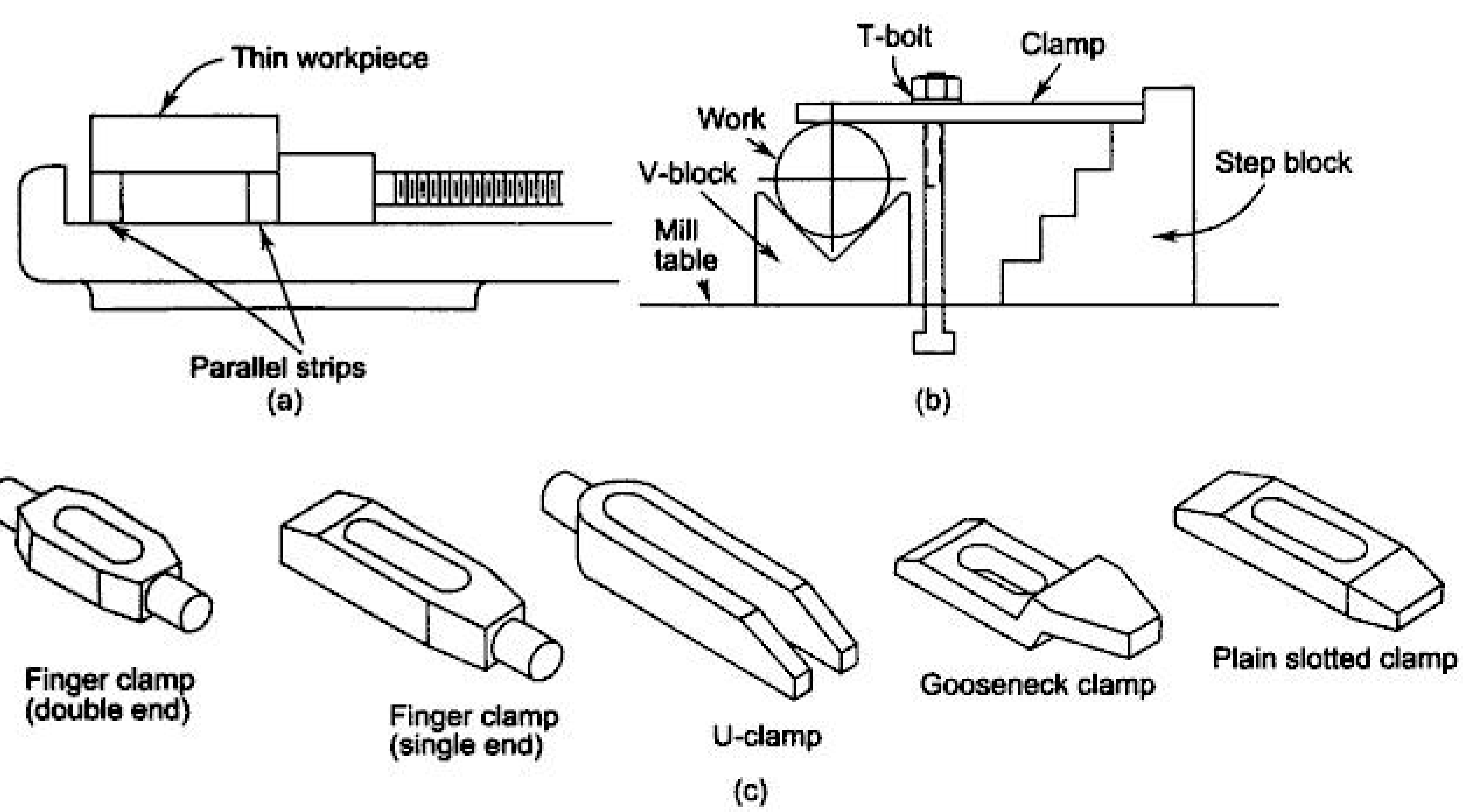

Fig. 7.16 *Common work holding methods in milling.*

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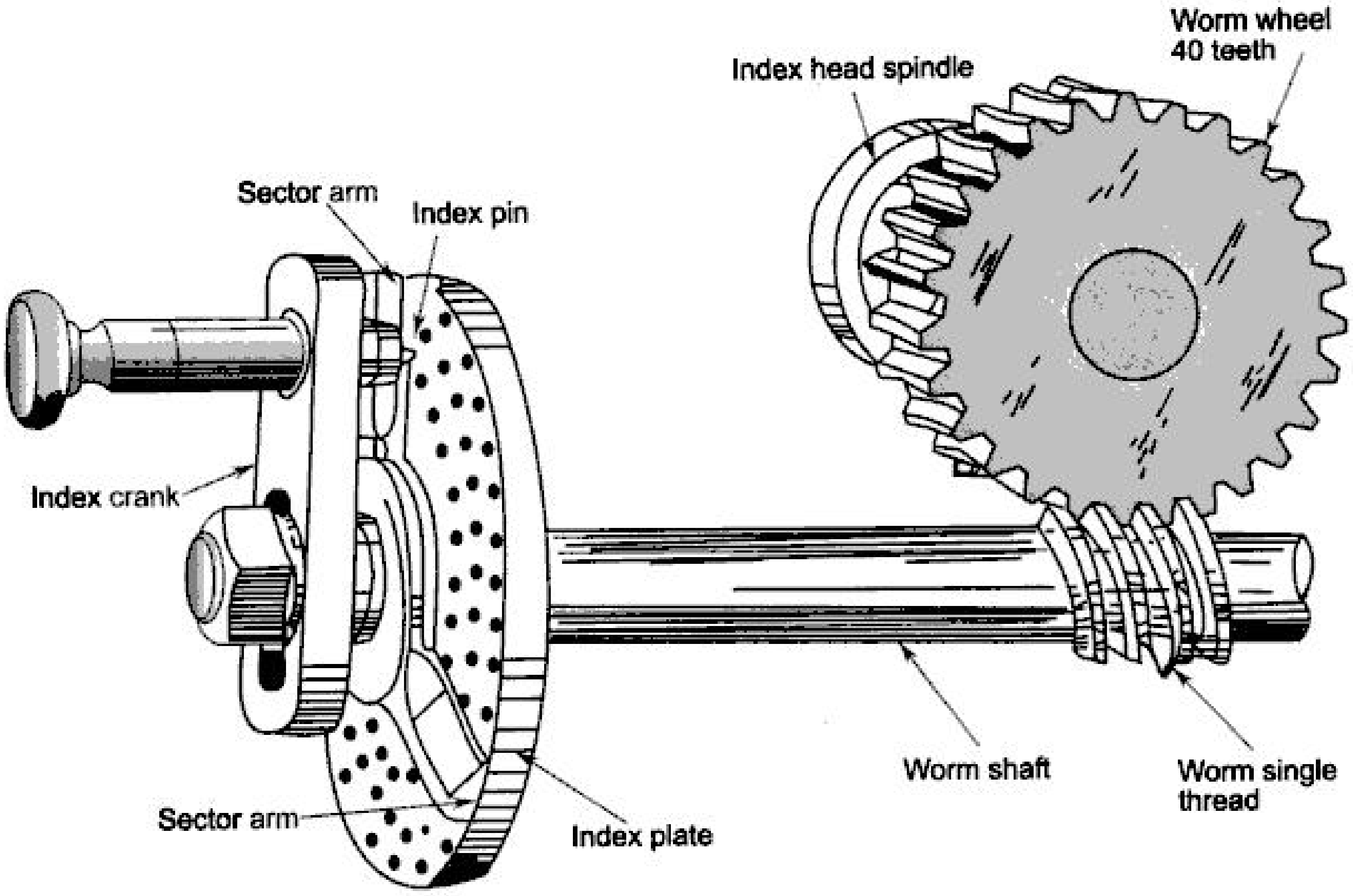

Fig. 7.21 *Indexing method of the dividing head.*

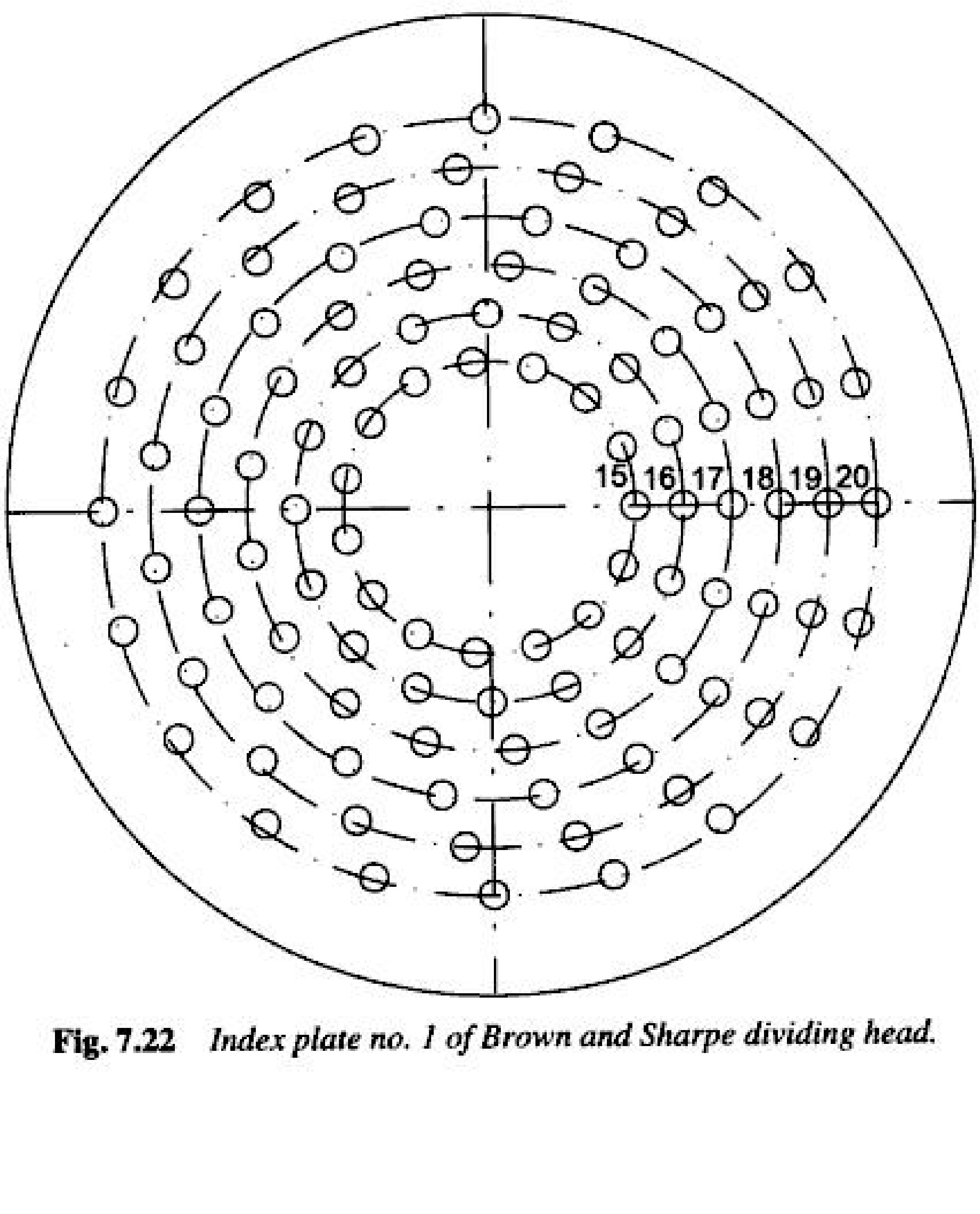

Fig. 7.22 *Index plate no. 1 of Brown and Sharpe dividing head.*

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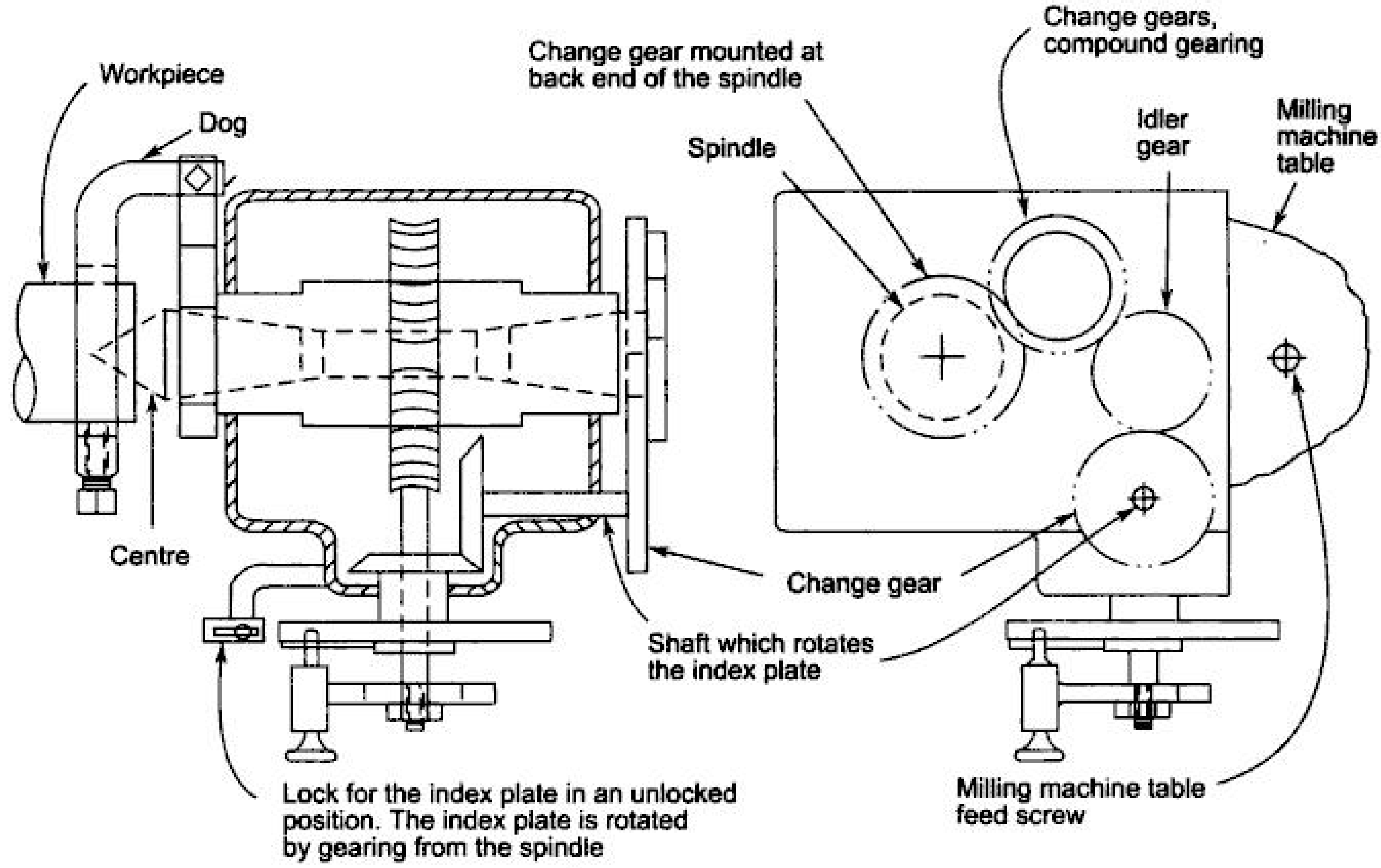

Fig. 7.24 *Dividing head setup for differential indexing.*

In differential indexing, the index plate is made free to rotate. A gear is connected to the back end of the dividing head spindle while another gear is mounted on a shaft, and is connected to the shaft of the index plate through bevel gears as shown in Fig. 7.24. When the index crank is rotated, the motion is communicated to the workpiece spindle. Since the workpiece spindle is connected to the index plate through the intermediate gearing as explained above, the index plate will also start rotating. If the chosen indexing is less than the required one, then the index plate will have to be moved in the same direction as the movement of the crank to add the additional motion. If the chosen indexing is more, then the plate should move in the opposite direction to subtract the additional motion.

The direction of the movement of the index plate depends upon the gear train employed. If an idler gear is added between the spindle gear and the shaft gear in case of a simple gear train, then the index plate will move in the same direction as that of the indexing crank movement. In the case of compound gear train, an idler gear is to be used when the index plate is to move in the opposite direction. The procedure of calculation is explained with the following example.

The change gear set available is

24, 24, 28, 32, 40, 44, 48, 56, 64, 72, 86 and 100

Example 7.8 *Obtain the indexing for 97 divisions.*

Required indexing is $\frac{40}{97}$ which cannot be obtained with any of the index plates available. Choose the nearest possible division. For example, the indexing decided is $\frac{40}{100} = \frac{2}{5} = \frac{8}{20}$.

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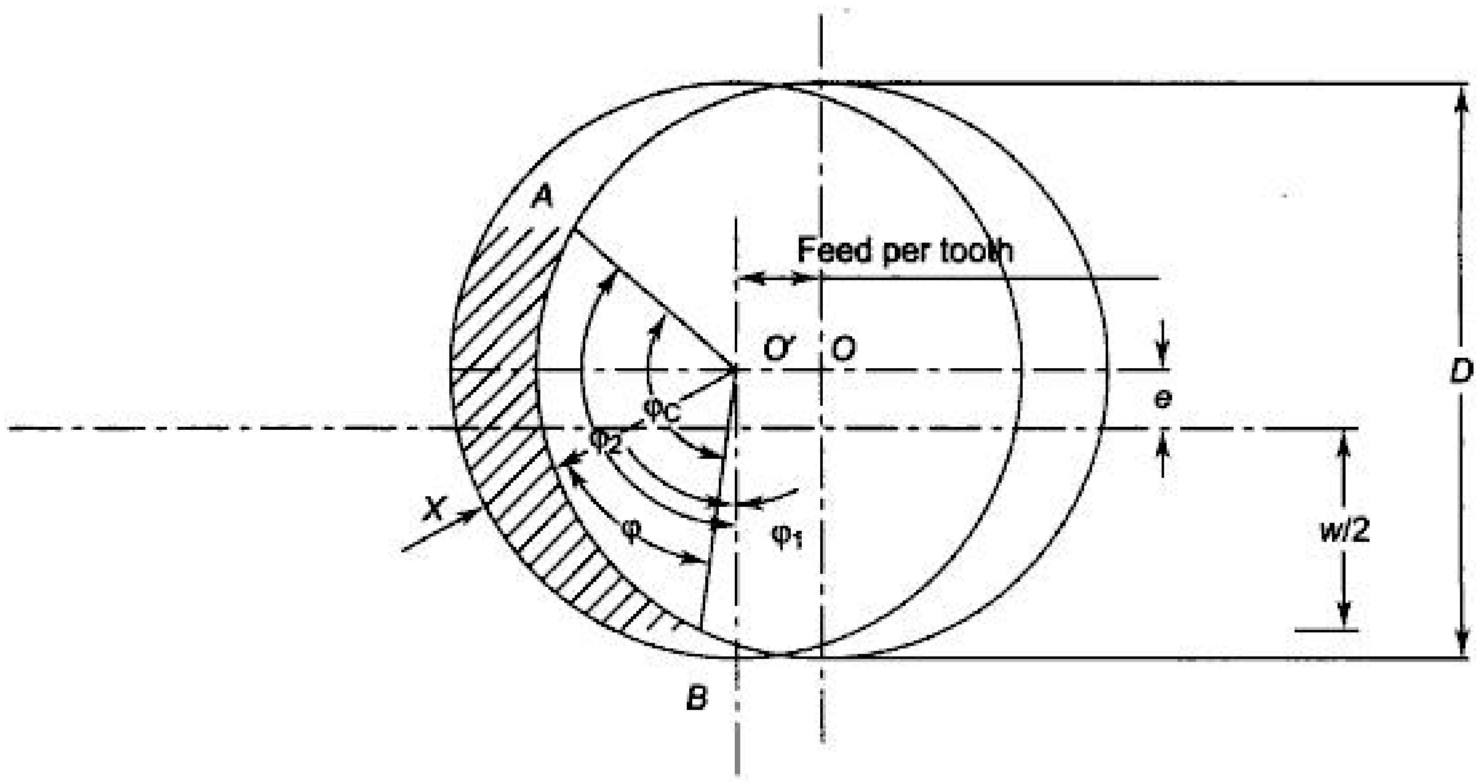

Fig. 7.27 *Cross-section of chip produced by milling using a face milling cutter with unsymmetrical cut.*

7.7 MILLING TIME AND POWER ESTIMATION

7.7.1 Milling Time Estimation

Typical process parameters used in milling operation are given in Table 7.1. The cutting speed in milling is the surface speed of the milling cutter. Thus,

$$V = \frac{\pi D N}{1000}$$

where, V = cutting speed (surface), m/min

D = diameter of the milling cutter, mm

N = rotational speed of the milling cutter, rpm

Flat surfaces can be generated by using the slab milling as well as face milling. However, each of these operations is different in terms of the actual machining time required. Schematically the slab milling operation is shown in Fig. 7.28. All other milling operations using the arbour mounted milling cutters will be similar in approach. The milling cutter will have to traverse beyond the actual workpiece by a distance termed as the approach allowance, A, which is given by

Approach distance, $$A = \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - d\right)^2} = \sqrt{d\,(D - d)}$$

where D = diameter of the slab milling cutter

d = depth of cut

Time for one pass $$= \frac{1 + 2 \times A}{f Z N} \text{ minutes}$$

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Table 7.2 *Power constant for milling (Machinery's handbook)*

Work material	Hardness BHN	Power constant
Plain Carbon Steel	100–120	1.80
	120–140	1.88
	140–160	2.02
	160–180	2.13
	180–200	2.24
	200–220	2.32
	220–240	2.43
Alloy Steel	180–200	1.88
	200–220	1.97
	220–240	2.07
	240–260	2.18
Cast iron	120–140	0.96
	140–160	1.04
	160–180	1.42
	180–200	1.64
	200–220	1.94
	220–240	2.48
Malleable iron	150–175	1.15
	175–200	1.56
	200–250	2.24
	250–300	3.22

Table 7.3 *Feed factors for power calculation (Machinery's handbook)*

Feed, mm/tooth	Feed factor	Feed, mm/tooth	Feed factor
0.02	1.70	0.22	1.06
0.05	1.40	0.25	1.04
0.07	1.30	0.28	1.01
0.10	1.25	0.30	1.00
0.12	1.20	0.33	0.98
0.15	1.15	0.35	0.97
0.18	1.11	0.38	0.95
0.20	1.08	0.40	0.94

Table 7.4 *Tool wear factors for power calculation (Machinery's handbook)*

Operation	Tool wear factor
Slab milling and End milling	1.10
Light and Medium face milling	1.10 to 1.25
Heavy face milling	1.30 to 1.60

Example 7.14 *Calculate the power required to rough mill a surface 115 mm wide and 250 mm long with a depth of cut of 6 mm by a 16-tooth cemented carbide face mill with a 150-mm diameter. The work material is alloy steel (200 BHN).*

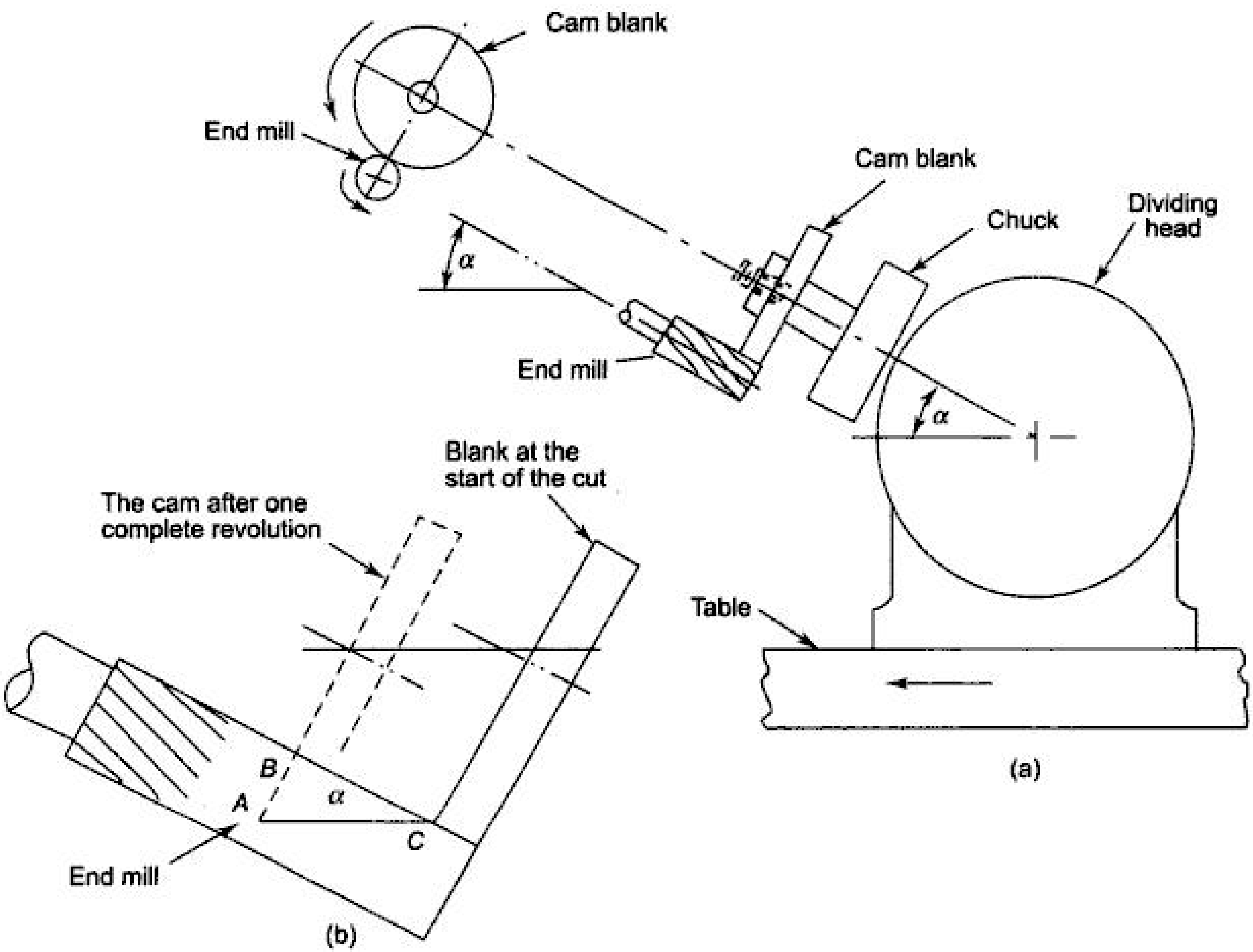

Fig. 7.31 *Cam milling setup.*

The shaft of the dividing head index plate is connected to the table lead screw by gears, as in spiral milling. The plate cam blank is held in the spindle of the dividing head, which is inclined to the horizontal at an angle, α. The end mill is also inclined at the same angle such that the axis of the cutter and axis of the cam to be milled are parallel. As the table starts moving, the plate cam rotates through the dividing head spindle and the distance between the cutter and the cam becomes smaller, thereby machining the cam profile. Since the lead of the table lead screw is constant, the rise or fall of the cam machined also becomes constant, the actual value depending upon the machine setting.

The inclination angle, α, that is set can be calculated as follows.

$$\sin \alpha = \frac{\text{Lead of the cam} \times \text{Gear ratio}}{\text{Machine lead}}$$

If the setting angle is zero, the lead of the cam becomes zero as shown in Fig. 7.32. Any suitable gear ratio can be used.

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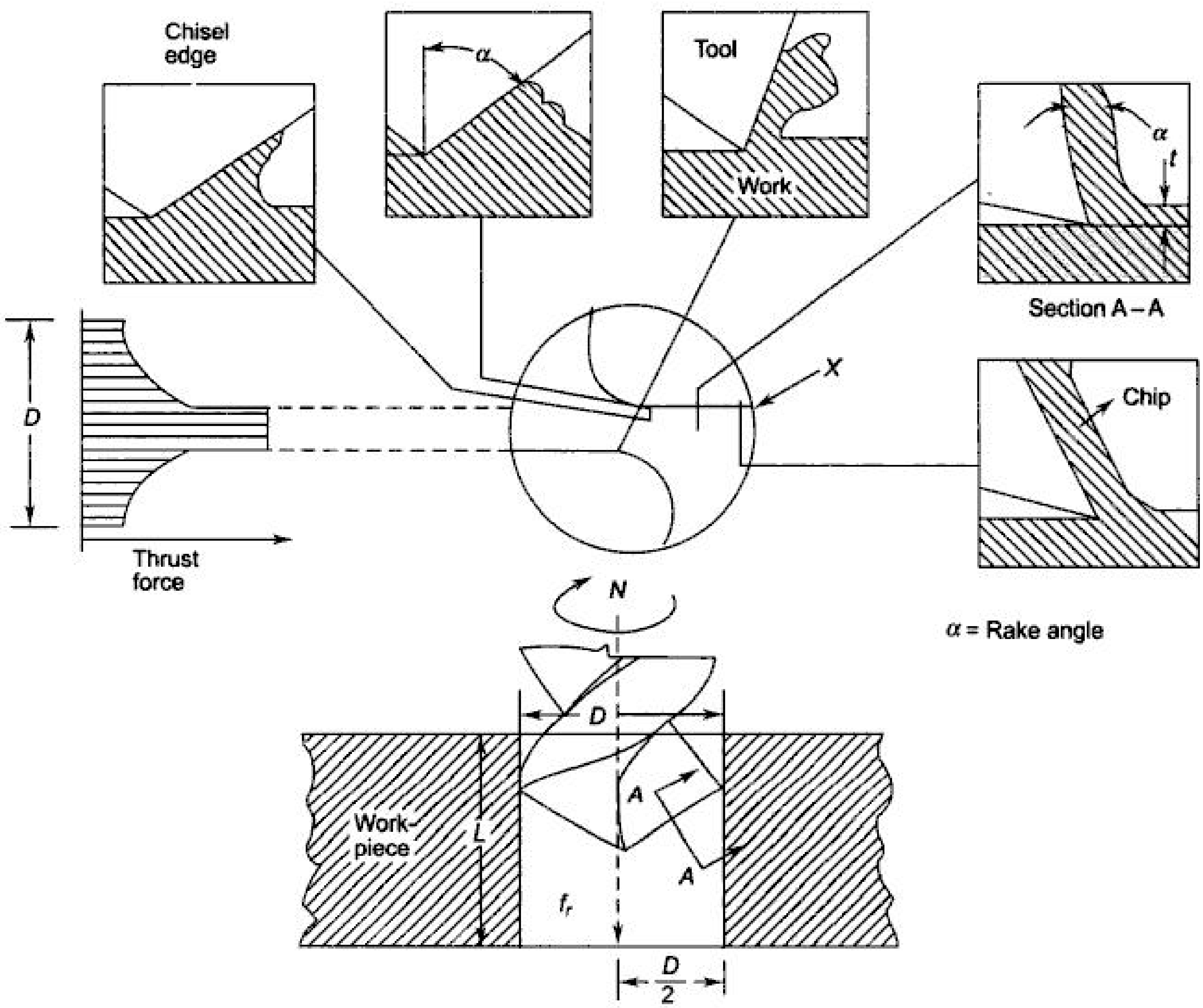

Fig. 8.3 *The rake angle in case of a twist drill.*

Since the web does not cut, sometimes direct drilling of large diameter holes makes it difficult to achieve the positional tolerance. For such a situation, a centre hole is made first, with a centre drill or a small hole drill, as a pilot hole. The size of the pilot hole drilled takes care of the web portion and thereby allows for more accurate location of the hole.

Twist drills are designed with the web, which gradually thickens as it moves from the point along the length of the flutes, as shown in Fig 8.4. This is necessary for providing strength and rigidity to the cutting tool. A twist drill is reground at the cutting lip to remove the worn out portion. This gradually decreases the total length of the drill. However, along with it the web thickness also increases as shown in Fig 8.4. As explained above, the web will only compress the material and as a result, the thrust on the drill increases with an increase in the web thickness. Also it is likely that out-of-round and over-sized holes may result in due to the additional thrust.

After some time, it therefore becomes necessary to thin the web. Web thinning has to be carefully done so that the thinning is blended evenly into the flutes. Also, the chisel edge should not be excessively reduced, so equal amounts of material should be carefully removed from either side. Some of the ways in which the web thinning is done are shown in Fig. 8.5.

Radial Drilling The radial drilling machine is more versatile than the drill press described earlier. The schematic of radial drilling machine, showing the principal parts and motions, is shown in Fig. 8.8. The drill head can move along the radial arm to any position while the radial arm itself can rotate on the column, thus allowing for reaching any position in the radial range of the machine. A radial drilling machine is more convenient to be used for large workpieces, which cannot be moved easily because of their weight. In such a case, the drill head itself is moved to the actual location on the workpiece, before carrying the drilling operation. In addition to the twist drills, other hole-making tools can also be used.

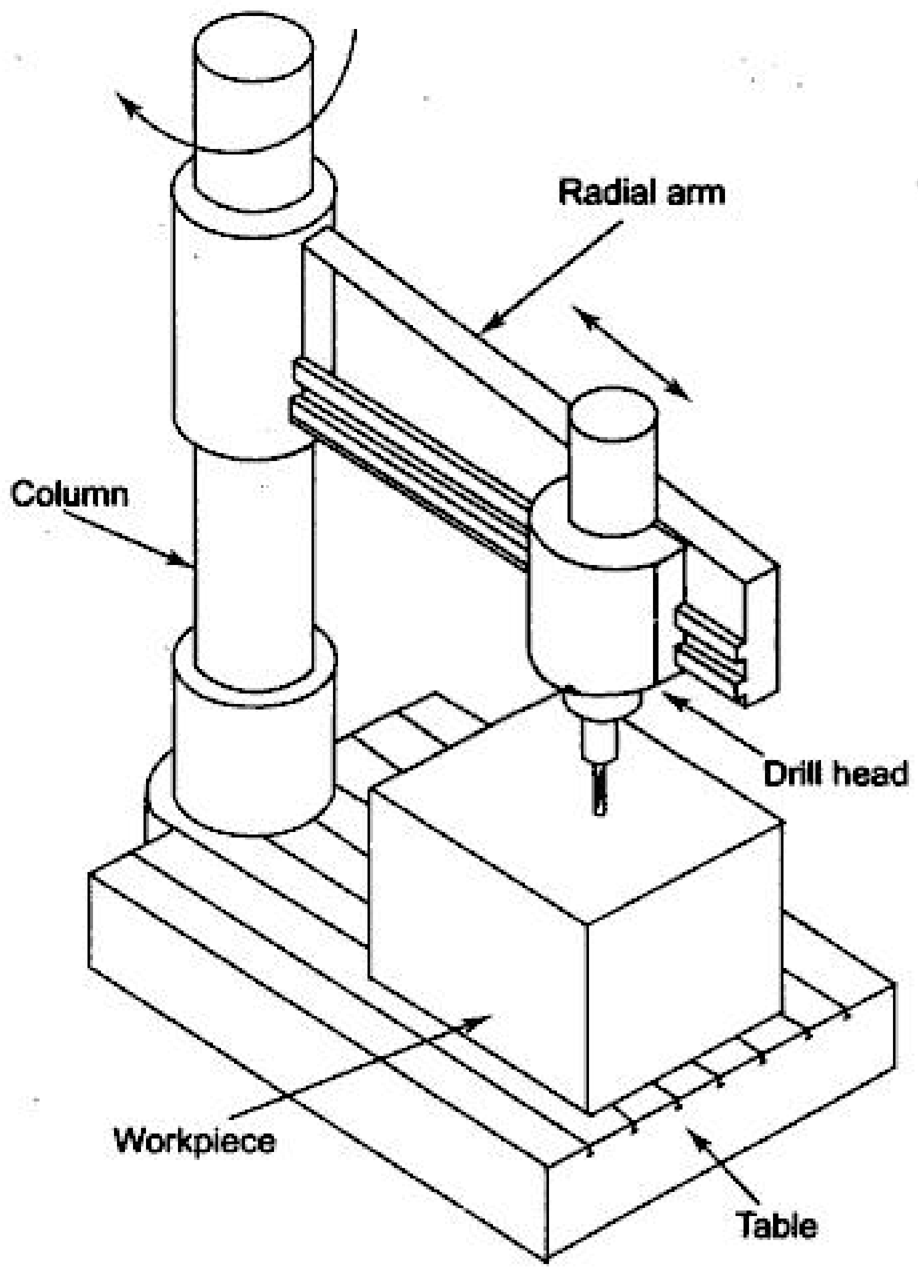

Fig. 8.8 *The radial drilling machine.*

Multiple-Spindle Drilling For production operations, it is necessary to carry out a large number of operations simultaneously, which can be done by the multiple-spindle drilling machines. In the drilling heads of these machines, by more than one drill can be located, with each of them getting the power from the same spindle motor. The use of these machines becomes more economical for large volume production of identical parts. These machines are capable of producing a large number of holes in a short time. Some machines have a fixed number of spindles in fixed locations while the others have the number fixed but their locations can be changed to suit the workpiece geometry. The later models of machines are more versatile.

Gang Drilling Gang drilling machines are the equivalent of the progressive action-type multiple-spindle lathes. These consists of a number of spindles (often equal to four) laid out in parallel. Each of the spindles can have different drills or other hole-making operation tools fixed in sequence. The workpiece will move from one station to the other, with each completing the designated hole-making operation. These are used for

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Problems

1. A series of 5 mm holes (total number 6) are to be drilled in a circle with 150-mm diameter on a 6-mm thick glass sheet. Describe the method of manufacture to be used with a neat sketch of the setup. What are the process variables to be controlled? Give their effect on the final hole quality and the production rate?
2. A hole with 25-mm diameter and 35-mm depth is to be drilled in mild steel component. The cutting speed can be taken as 35 m/min and the feed rate as 0.20 mm/rev. Calculate the machining time and the material removal rate.
3. Calculate the drilling torque and thrust force acting in the above example.
4. In C40 steel sheet of 25-mm thickness, 3 holes with 15-mm diameter are to be drilled. The cutting speed can be taken as 30 m/min and the feed rate as 0.15 mm/rev. Calculate the machining time and the material removal rate.

Coarse grains are good for higher material removal rates. They have better friability and as a result are not good for intermittent grinding where they are likely to chip easily.

9.2.3 Bond

The function of the bond is to keep the abrasive grains together under the action of the grinding forces. The commonly used bond materials are:

Vitrified
Silicate
Synthetic resin
Rubber
Shellac, and
Metal.

Vitrified This is the most commonly used bond. The bond is actually clay mixed with fluxes, such as feldspar, which hardens to a glass-like substance on firing to a temperature of about 1250°C, which develops its strength. This bond is strong, rigid and porous, and not affected by fluids. However, this bond is brittle and hence sensitive to impacts. This bond is also called ceramic bond.

Silicate This is sodium silicate ($NaSiO_3$) or water glass and hardens when heated. However, it is not as strong as vitrified bond. This can be used in operations that generate less heat. It is affected by dampness but is less sensitive to shocks. Hence, it is relatively less used.

Synthetic resin or resinoid These bonding materials are thermosetting resins, such as phenol formaldehyde. This bond has good strength and more elasticity than the vitrified bond. However, it is not heat and chemical resistant. It is generally used for rough grinding, parting off and high speed grinding (50 to 65 m/s). It can also be used for fine finishing of roll grinding.

Rubber Of all the bonds used, this is the most flexible. The bond is made up of natural or synthetic rubber. The strength is developed with vulcanisation. This bond has high strength and is less porous. However, it is affected by dampness and alkaline solutions. It is generally used for cutting off wheels, regulating wheels in centre-less grinding and for polishing wheels.

Shellac This bond is relatively less used. It is used generally for getting very high finish. Typical applications are rolls, cutlery, and cam shaft finishing.

Metal This is used in the manufacture of diamond and CBN wheels. The wheel can be made of any high thermal conductive metals, such as copper alloys or aluminium alloys. The periphery of the wheel, up to a small depth of the order of 5 mm or less, contains the abrasive grit. The choice of the metal depends on the required strength, rigidity and dimensional stability. In view of the strong bond, the grit will not be knocked out till it is fully utilised. Powder metallurgy techniques are used to make the abrasive periphery.

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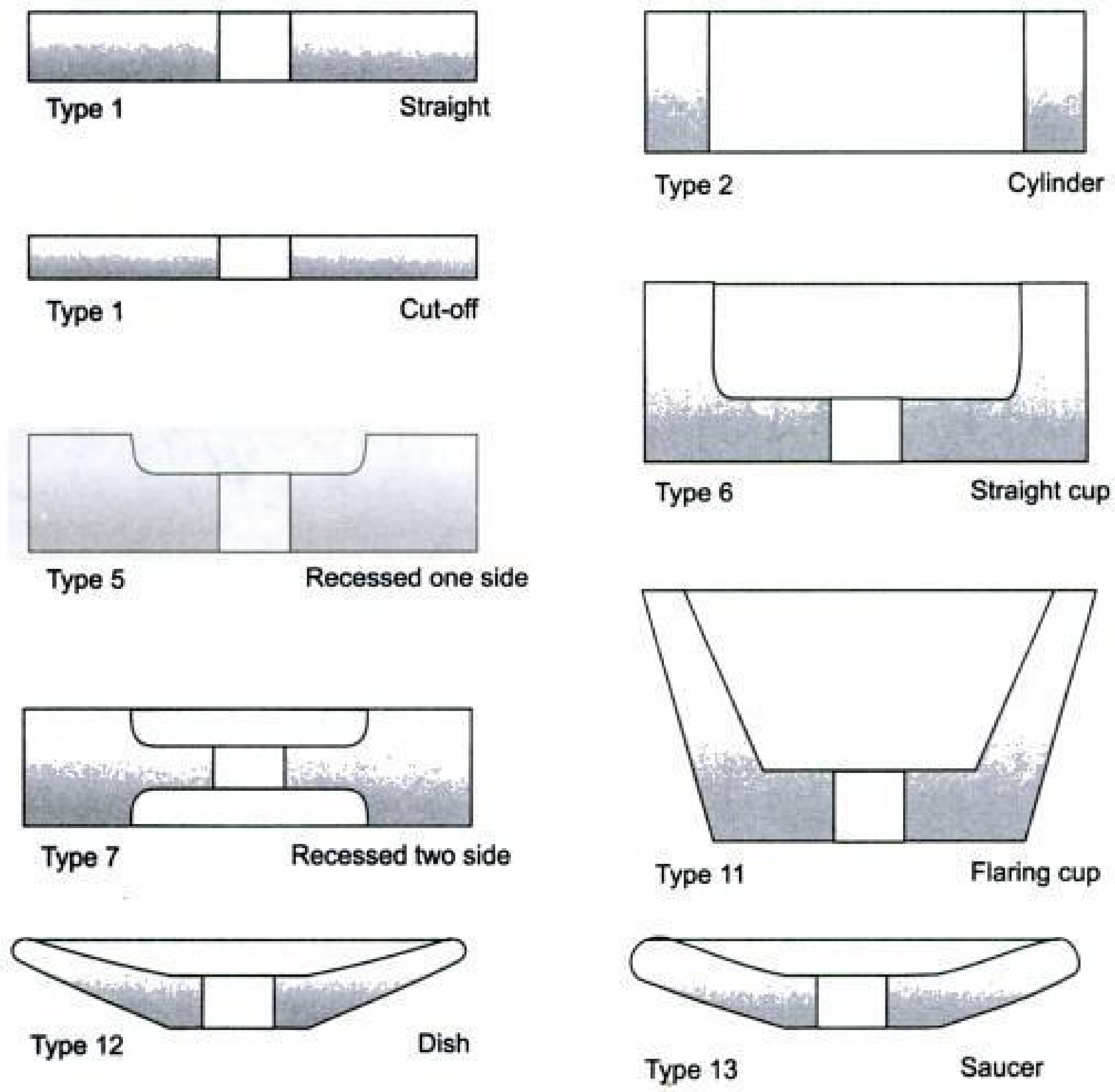

Fig. 9.4 *Grinding wheel shapes.*

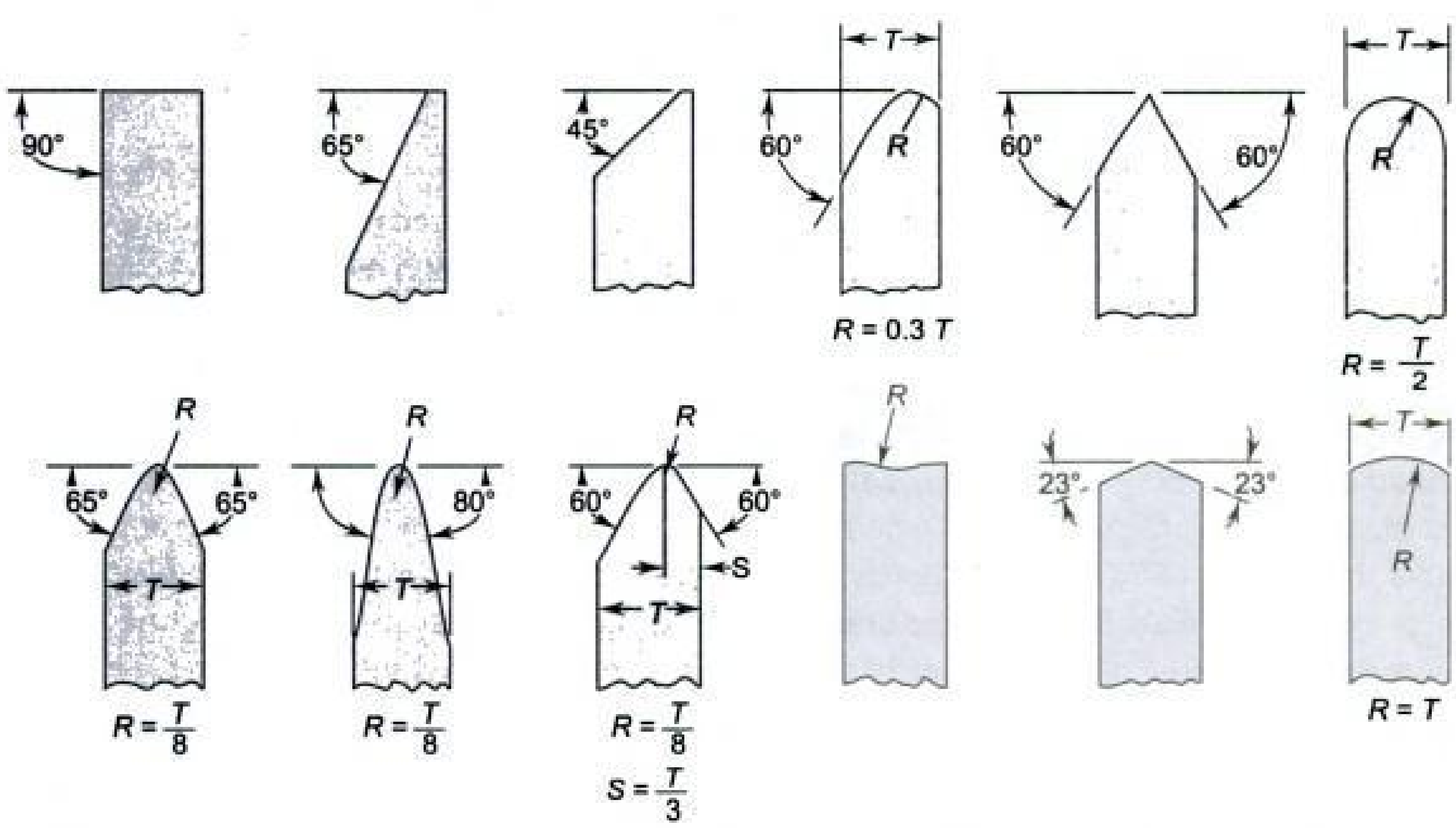

Fig. 9.5 *Various faces of grinding wheel form for the straight (Type 1) wheel shown in Fig. 9.4.*

- Horizontal spindle and rotating table
- Vertical spindle and rotating table
- Horizontal spindle and reciprocating table
- Vertical spindle and reciprocating table

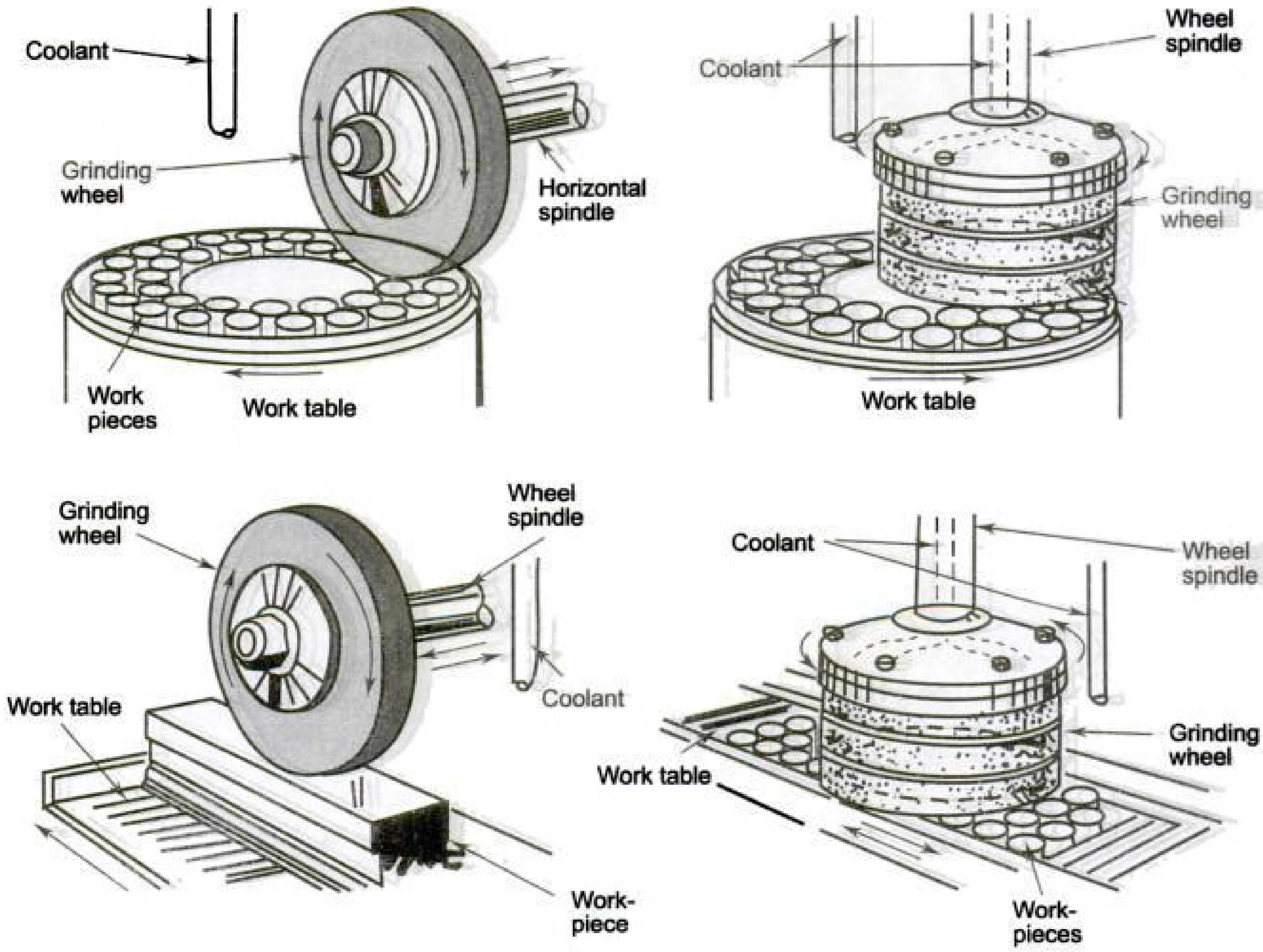

Fig. 9.11 *Different surface grinding operations.*

Horizontal spindle and rotating table In this machine, the grinding wheel cuts on its periphery, while the spindle traverses horizontally from the edge to the centre of the table. Feed is accomplished by moving the work mounted on the table up into the wheel with the table moving in a rotary fashion. Since the table and work rotate in a circle beneath the grinding wheel, the surface pattern is a series of intersecting arcs. This machine is used for round, flat parts because the wheel is in contact with the work at all times.

Vertical spindle and rotating table Vertical spindle machines generally have a bigger capacity. Complete machining surface is covered by the grinding wheel face. They are suitable for production grinding of large flat surfaces. In this machine, both the work and the wheel rotate and feed into each other. By taking deep cuts, this machine removes large amounts of material in a single pass. The side or the face of the wheel does the grinding. The wheel can be either complete solid or split into segments to save wheel material and in the process also provides cooler grinding action. In the case of small parts, the surface patterns created are a

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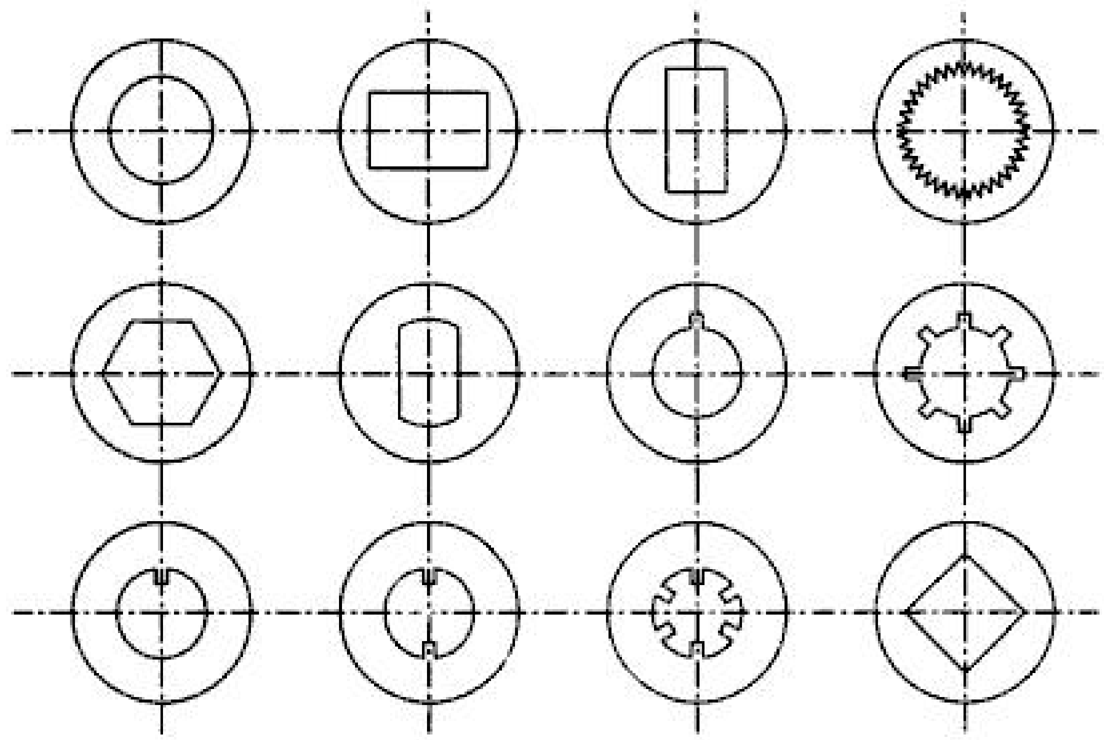

Fig. 10.10 *Some typical internal profiles that can be broached.*

10.2.1 Broach Construction

Though in the above figure, the material being removed is shown in an exaggerated fashion for the sake of clarity, in actual broach, there are a large number of teeth, each of which removes a small amount of material, so that by the time the broach completes the operation, the component is completely machined. A typical broach is shown in Fig. 10.11. Broaching was originally developed for machining internal keyways, but looking at the advantages, it has been extensively used in the mass production of automobile component manufacture for various other surfaces as well.

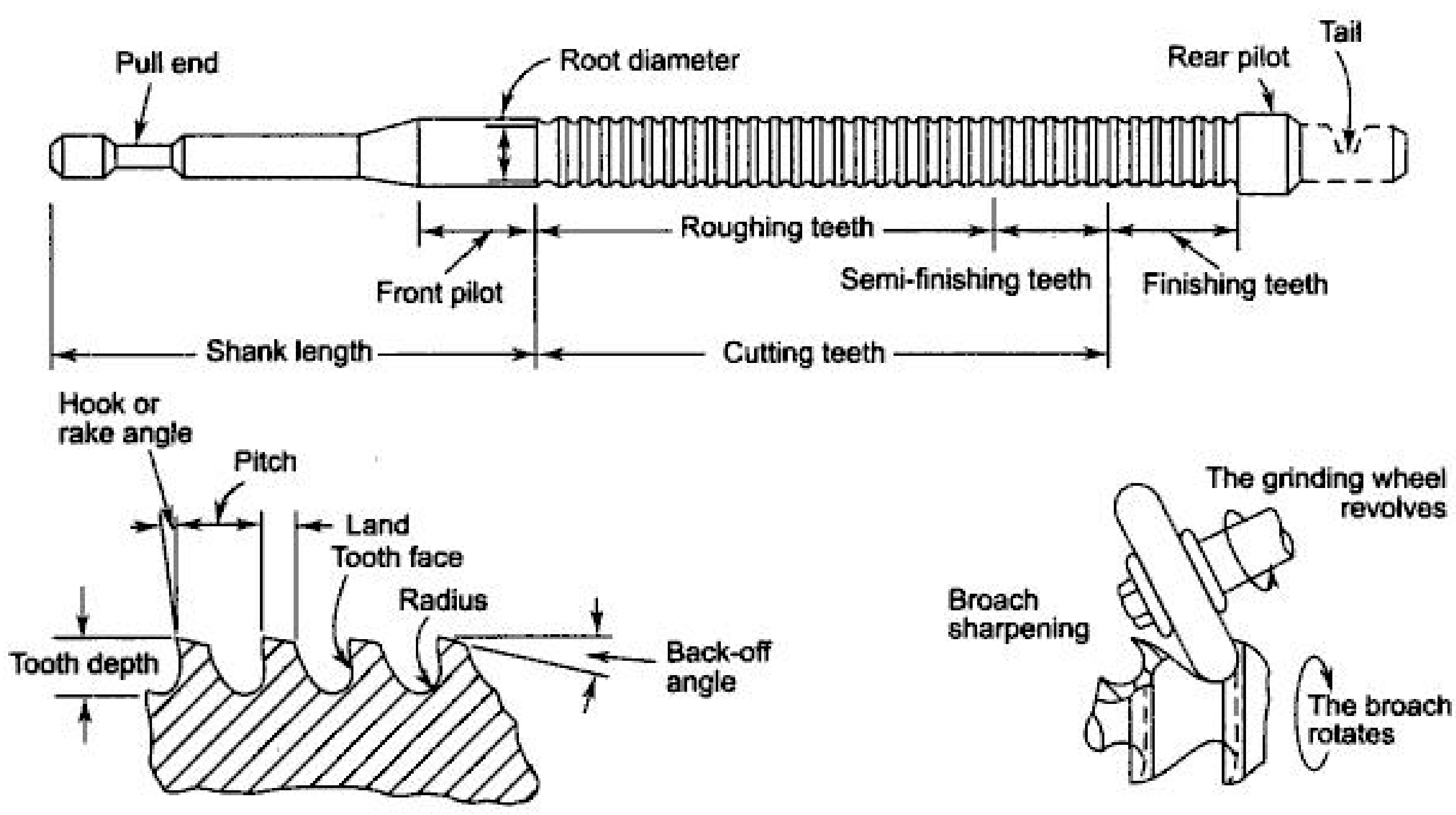

Fig. 10.11 *Typical construction of a pull broach.*

an involute curve along which they roll and slide while transmitting the motion. An involute is generated by unwinding a tautly held string from a base circle. The involute curve is chosen because it is simple, easy to manufacture and allows the centre lines to be varied between the mating gears.

Pitch circle, which is an imaginary circle on the gear, corresponds to the diameter of the wheel. For proper operation, the two pitch circles must be tangential at the point where the centre line connecting the two centres of rotation intersects the pitch circle. To reduce the friction, gears are designed such that the teeth have rolling motion rather than the sliding motion. Gear tooth size is identified as module. Some important parameters of gears that are relevant for gear manufacture are given below. The rest of the details will be found in gear design books.

Pitch diameter	= No. of teeth $\times$ module
Tooth thickness	= $0.5 \times \pi \times$ module
Total depth	= $2.25 \times$ module

Spur gear is the most common and easiest to make. It has straight teeth on the periphery of a cylinder. It transmits motion between two parallel shafts. A rack is a gear with infinite radius, having teeth that lie in a straight line. These are used for converting rotary motion to a straight line, or vice versa.

10.3.1 Gear Forming

This is a process of machining gears using a form milling cutter in a milling machine. Gears can be cut using a form milling cutter, which has the shape of the gear teeth. The form milling cutters, called DP (diametral pitch, used in inch systems, which is equivalent to inverse of module), cutters have the shape of the teeth similar to the tooth space with the involute form of the corresponding size gear. The commercial gear milling cutters are available as a set for a given module or diametral pitch. These can be used on either horizontal axis or vertical axis milling machines, though horizontal axis is more common. The vertical axis cutters are similar to end mills with tooth profile on the cutting edge.

The cutting tool as shown in Fig. 10.15 is fed radially into the workpiece till the full depth is reached. Then the workpiece is fed past the cutter to complete machining of one tooth space.

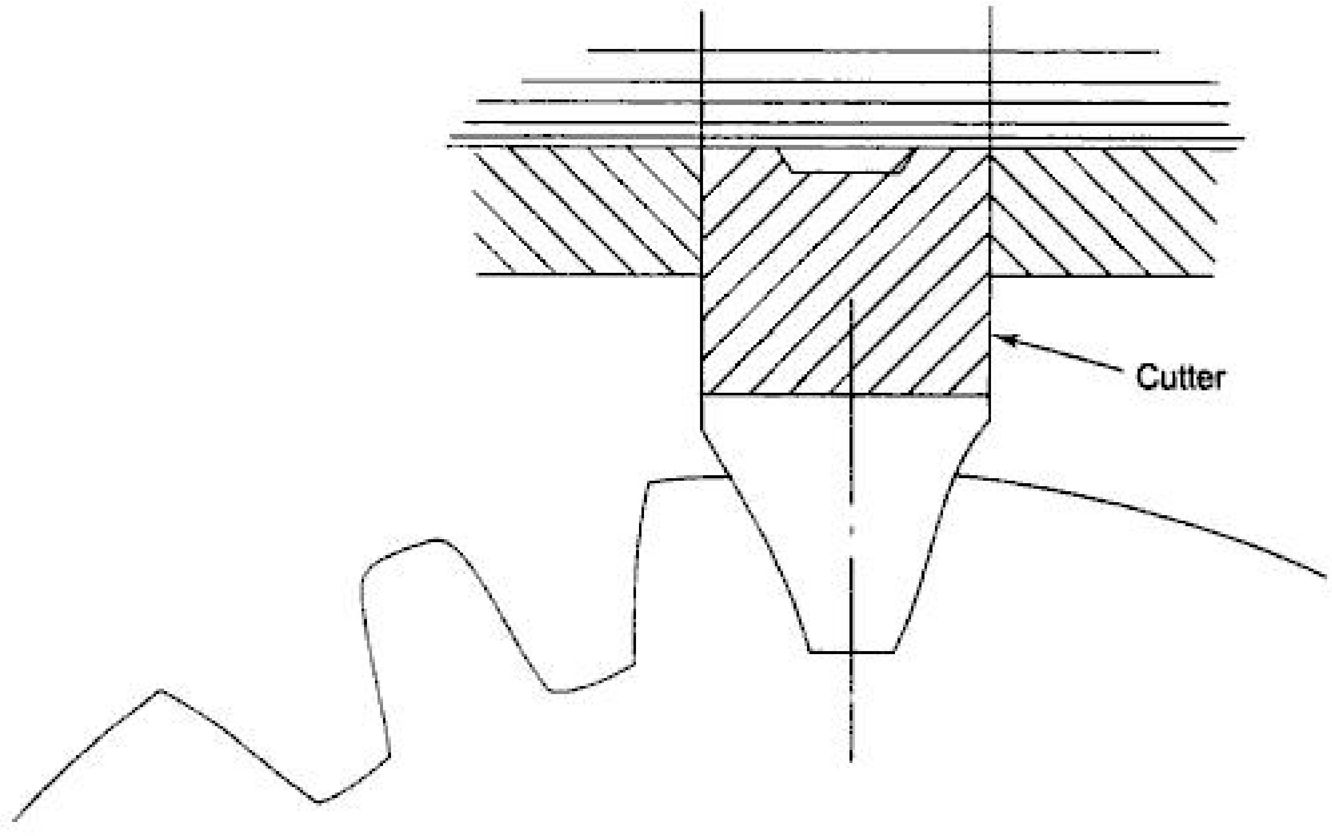

Fig. 10.15 *Form milling for spur gears*

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11

Unconventional Machining Processes

Objectives

Unconventional machining processes were developed initially to machine very hard materials that are almost impossible to be machined economically by the conventional methods. After completing the chapter, the reader will be able to understand the following.

- Need for inventing the unconventional processes, and their range of applications.
- Principles and applications of electric discharge machining.
- Principles and applications of electrochemical machining.
- Principles and applications of ultrasonic machining.
- Principles and applications of chemical machining.
- Principles and applications of laser beam machining.
- Principles and applications of abrasive water jet machining.

11.1 NEED FOR UNCONVENTIONAL PROCESSES

Conventional machining processes utilise the ability of the cutting tool to stress the material beyond the yield point to start the material removal process. This requires that the cutting tool material is harder than the workpiece material. New materials which are having high strength-to-weight ratio, heat resistance and hardness, such as nimonic alloys, alloys with alloying elements such as tungsten, molybdenum, columbium are difficult to machine by the traditional methods. Machining of these materials by the conventional methods is very difficult as well as time consuming, since the material removal rate reduces with an increase in the work material hardness. Hence, there is the need for development of non-traditional machining processes which utilise other methods such as electro-chemical processes for the material removal. As a result, these processes are termed as unconventional or non-traditional machining methods.

The complex shapes in these materials are either difficult to machine or time consuming by the traditional methods. In such cases, the application of the non-traditional machining processes finds extensive use. Further, in some applications a very high accuracy is desired besides the complexity of the surface to be

Due to the inertia of the surrounding fluid, the pressure within the spark becomes quite large and may possibly assist in 'blasting' the molten material from the surface leaving a fairly flat and shallow crater. The amount of metal removed per spark depends upon the electrical energy expended per spark and the period over which it is expended.

Thus, the sequence of events in EDM can be summarized as follows.

"1. *With the application of voltage, an electric field builds up between the two electrodes at the position of least resistance. The ionization leads to the breakdown of the dielectric which results in the drop of the voltage and the beginning of flow of current.*

2. *Electrons and ions migrate to anode and cathode respectively at very high current density. A column of vapour begins to form and the localized melting of work commences. The discharge channel continues to expand along with a substantial increase of temperature and pressure.*

3. *When the power is switched off, the current drops; no further heat is generated, and the discharge column collapses. A portion of molten metal evaporates explosively and/or is ejected away from the electrode surface. With the sudden drop in temperature, the remaining molten and vaporized metal solidifies. A tiny crater is thus generated at the surface.*

4. *The residual debris is flushed away along with products of decomposition of dielectric fluid. The application of voltage initiates the next pulse and the cycle of events.*"

Also, due to the inertia of the surrounding fluid, the pressure within the spark becomes quite large and may possibly assist in 'blasting' the molten material from the surface leaving a fairly flat and shallow crater. The amount of metal removed per spark depends upon the electrical energy expended per spark and the period over which it is expended.

At any given time, only one spark will be made between the tool and workpiece at the shortest path as shown in Fig. 11.3. As a result of this spark, some volume of metal is removed from both the tool and the workpiece. Then the spark will move to the next closest distance as shown in Fig. 11.4. This process continues till the required material is removed from the workpiece.

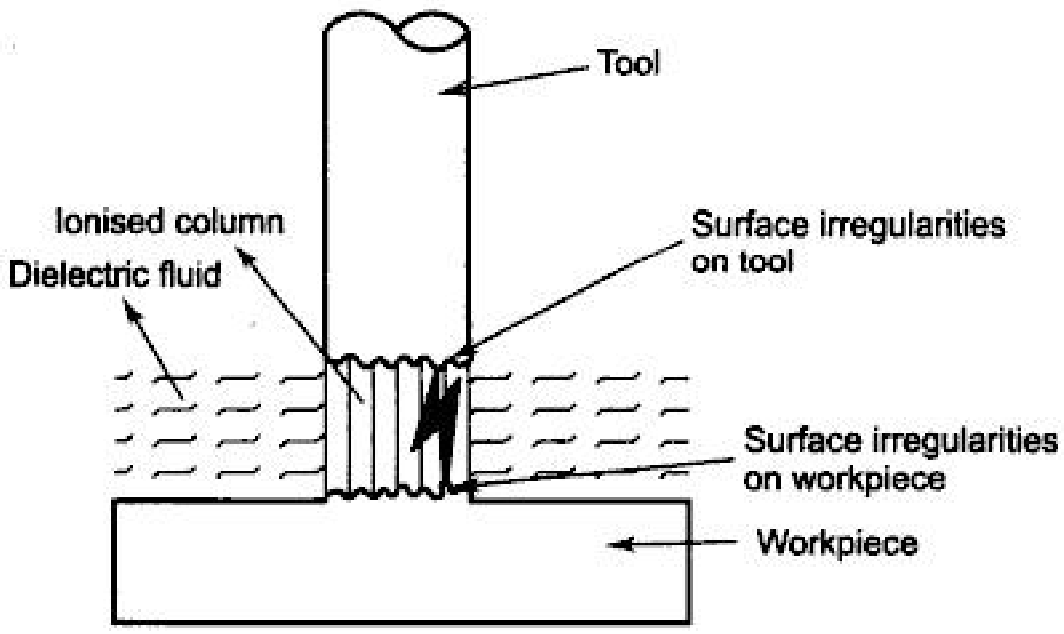

Fig. 11.3 *Schematic diagram of the arc forming at the smallest distance between the tool and the workpiece in the EDM process*

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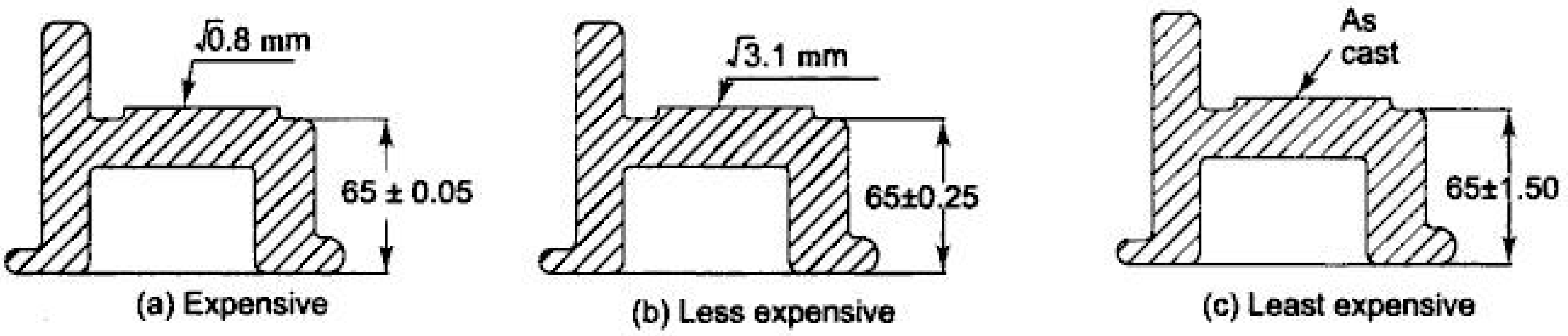

Fig. 13.2 *Type of tolerances and surface finishes that necessitates machining Decreasing them may reduce the cost of machining or can eliminate it*

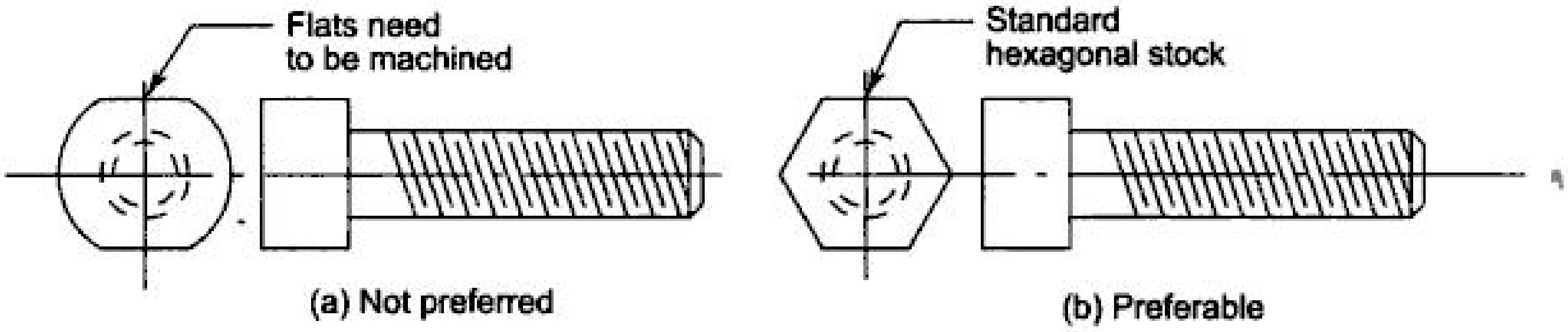

Fig. 13.3 *Use of standard stock to reduce the cost of machining*

3. Limit the manufacturing processes to those with already available expertise. This will make the available expertise to be better utilised while reducing the cost of acquiring new methods and technologies. However, care has to be taken while applying this principle, since sometimes adopting a new technology may be expensive initially, but may reduce the overall costs in the long run.
4. Reduce the variety of machining processes used. The total cost of machining increases with the number of setups used which automatically increases with the variety of processes used. Also, the tolerances start increasing with the variety of processes used.
5. Use standard (off-the-shelf available) components in the design. Off-the-shelf components such as bearings, bolts and nuts, are normally produced in large volumes which allow for higher tolerances and lower costs which cannot be achieved by the small batch volumes.
6. Provide liberal tolerances such that overall manufacturing cost could be lowered (Fig. 13.2).
7. Use more standard shapes such as rectangular or circular shapes, which can be easily produced by the simple motions with the conventional machine tools. Surfaces such as tapers and contours call for special tools or special attachments, which increase the machining cost.
8. Use materials that have better manufacturability.
9. The cutting forces in machining are generally very high and will be acting on the parts. Hence the part which is required to be produced by machining needs to be rigid enough to withstand these forces. As shown in Fig. 13.4(a), the cutting force is likely to deflect the thin rib.

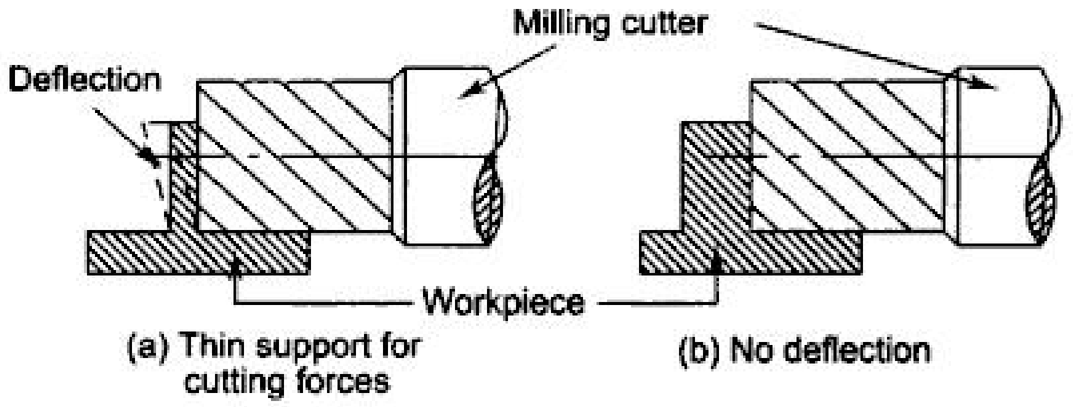

Fig. 13.4 *Parts to be machined should be rigid enough to withstand the cutting forces*

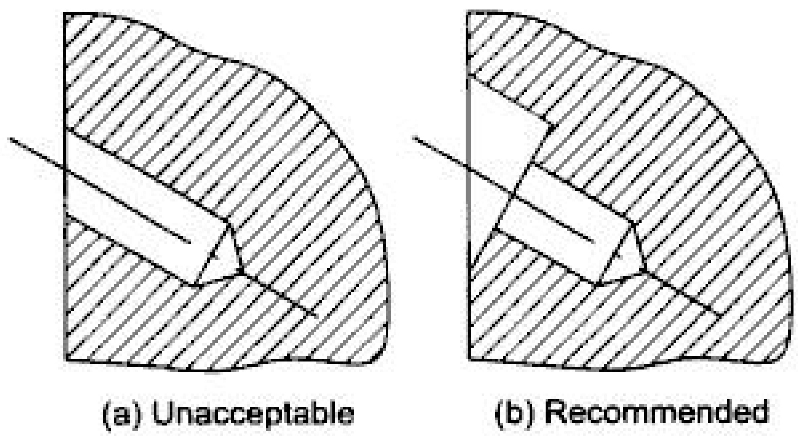

Fig. 13.14 *Parts to be machined should be rigid enough to withstand the cutting forces*

7. Drilled holes should not preferably have interrupted surfaces during the drilling process. The interrupted surface as shown in Fig. 13.15(a), will allow the material to be removed only by one of the cutting edges, thus providing an unbalanced force on the drill. This would cause the drill to deflect.

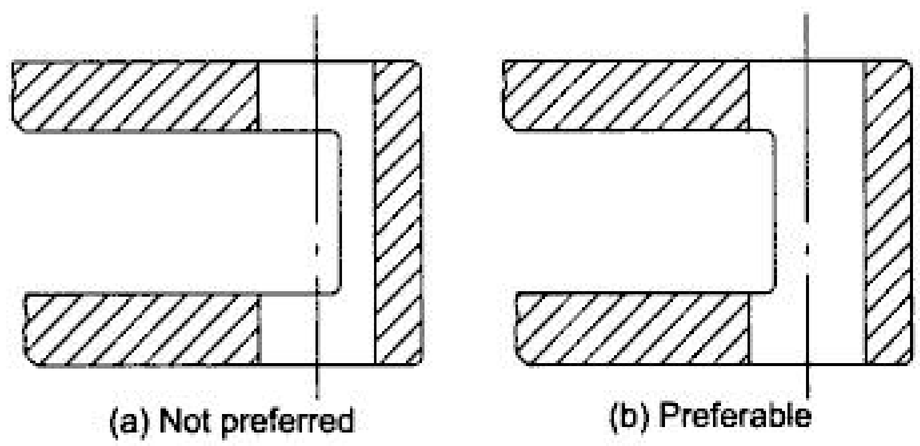

Fig. 13.15 *No interrupted surfaces in drilling*

8. Deep holes more than three times the diameter of the hole are difficult to be produced by conventional drilling. This is because of the large volume of chips generated. The work materials that produce continuous chips will further compound this problem. Special deep hole drilling methods are to be used which are expensive.
9. Deep holes that are to be bored should not be more than five times the diameter, since the boring bar becomes very slender causing chatter. Special boring bars are to be used for such purposes.
10. Production drilling operations require that jigs be used for hole-making operations. The jig bush is used to locate and support the drill during the drilling operation. This requires that the jig be designed in such a way that access of the jig bush to as close a position to the hole is possible, as shown in Fig. 13.16(b).

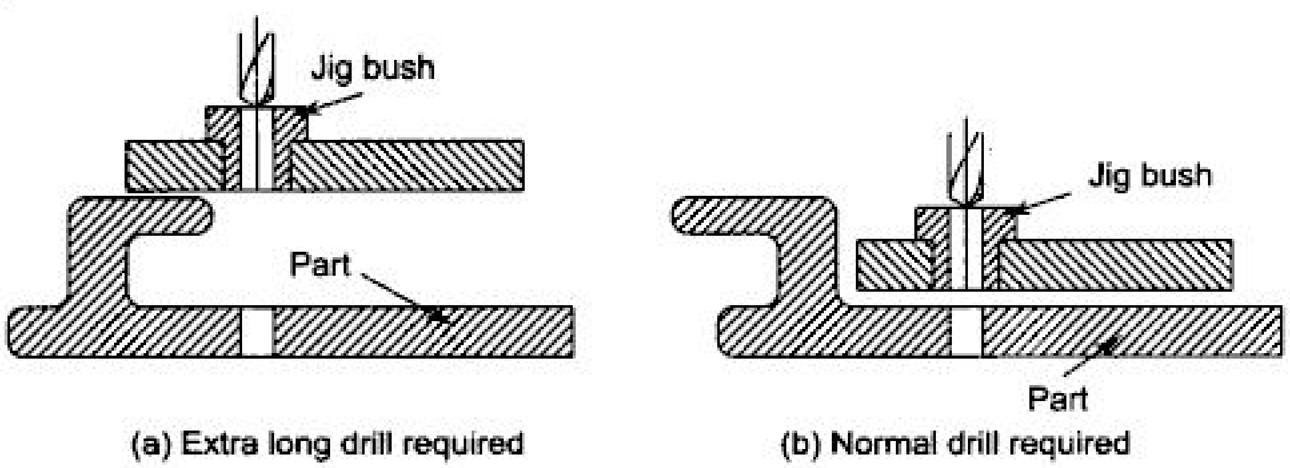

Fig. 13.16 *Provision for jig bush to stay as close to the hole entry surface should be ensured*

geometry of the workpiece. The motion of the cutting tool is more complex, involving the movement in two different axes and hence cannot be guided like a drill. These will be provided with setting blocks for the tool setting. The fixtures are generally identified by the machine tool in which they will be used along with the type of machining to be performed. For example, milling fixture or string milling fixture can be used to completely classify the operation performed.

Modular fixtures In Chapter 3, some general-purpose work holders were discussed. These are used for all types of workpieces and as such, are inexpensive in the long run. However, they require a lot of time for setting up and therefore cannot be used even for small-volume manufacture. For small-volume manufacture, a dedicated fixture may become expensive in terms of cost as well as lead time involved.

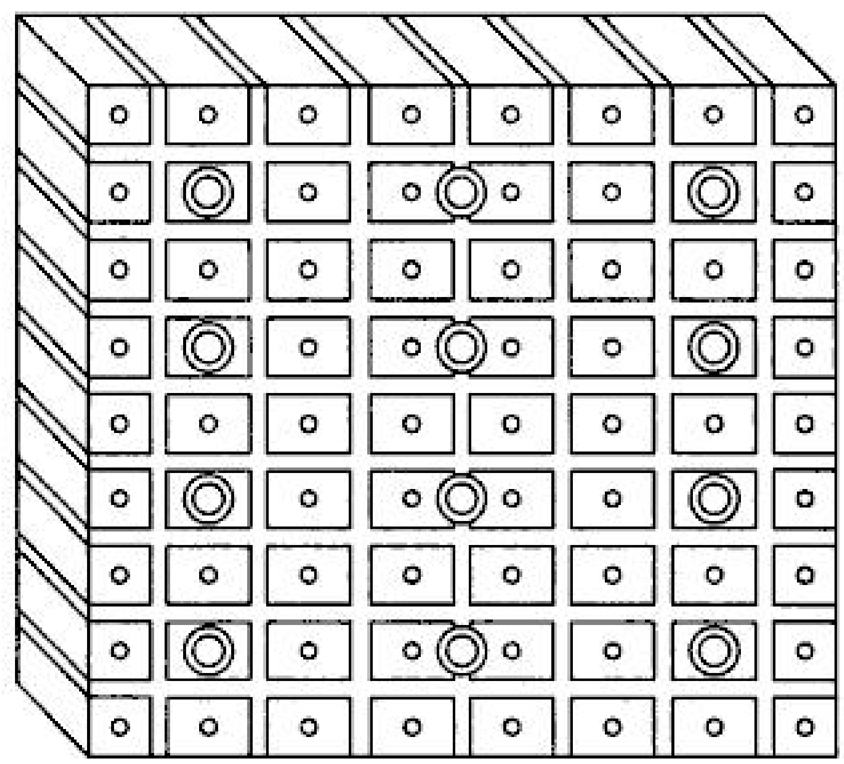

Fig. 14.3 *A grid plate with holes which can be used as a machine table*

Modular fixturing is used for quickly rigging up a fixture for a specific component using the off-the-shelf components. Modular elements are available such as grid plates shown in Fig. 14.3. Grid plates are generally used as one of the fixturing bases. The grid plates are provided with precisely drilled and tapped holes to facilitate the clamping operation. Since the holes on these grid plates are made at precise positions, the operator would know the exact location of the component depending upon the position he is clamping. These grid plates can be permanently clamped on the machine tool table, if necessary.

In addition to these standard fixture bases, a large number of fixture elements such as angle blocks, base elements, locators, and clamping elements (Fig. 14.4) are available for assembling a fixture. Depending upon the outer contour of the component, it is possible to identify the various elements required from the stock elements and assemble a fixture. Since these elements are reusable, the overall cost of fixturing is less.

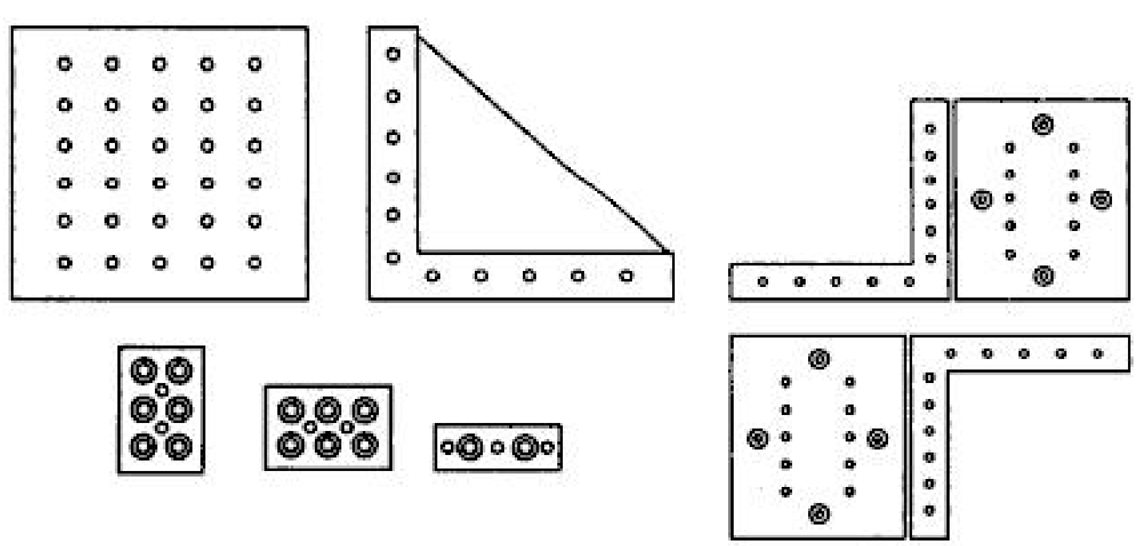

Fig. 14.4 *Modular fixture elements used for supporting complex workpieces*

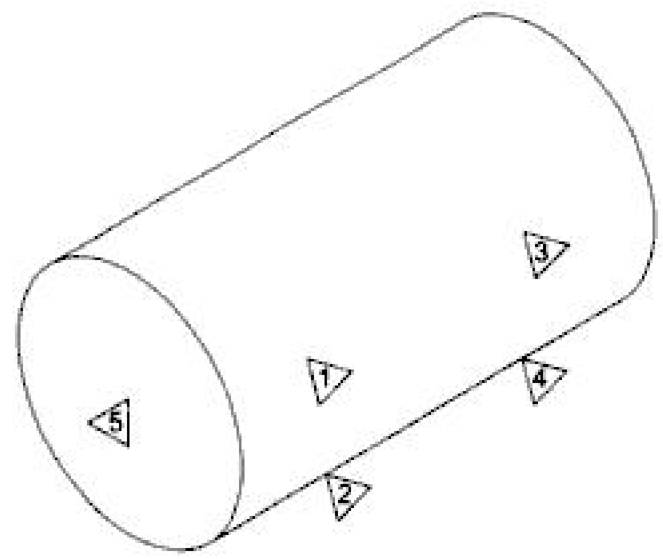

Fig. 14.12 *Location method for a long cylindrical component*

Component with holes The same principles can be applied to components where through holes are present, and the hole is to be used for location. For a short workpiece with a hole, the location method is similar to the short cylindrical case. The three locators would locate the end plane whereas the two locators placed inside the hole would locate the axis of the workpiece. For long workpiece with through holes the concept of a long cylinder can be used where the four locators would now be placed inside the hole. The fifth locator may be placed on one of the end faces.

Conical surfaces would have similar arrangement to that of cylindrical surfaces. Though the arrangements shown appear to be closed than other text above are general and would be useful for finalising the location arrangement for a majority of workpieces, the odd-shaped components require careful analysis to see how the location surfaces can be identified.

14.4 LOCATING DEVICES

It is important that the fixture should locate that part consistently with respect to the workpiece quickly and easily. This will help in achieving the required accuracy of the machining operation with a very small amount of time spent in the setting up of the workpiece. (The six degrees of movement of the workpiece need to be arrested by the appropriate choice of locators.)

Depending upon the nature of surface to be located, there are three general forms of location: plane, concentric, and radial. *Plane locators* are used to locate a flat surface on a workpiece. The surface may be flat, curved, or have an irregular contour and the locators are accordingly used to nest that surface as shown in Fig. 14.13(a). *Concentric locators* on the other hand locate a workpiece from its axis. The most common type of concentric

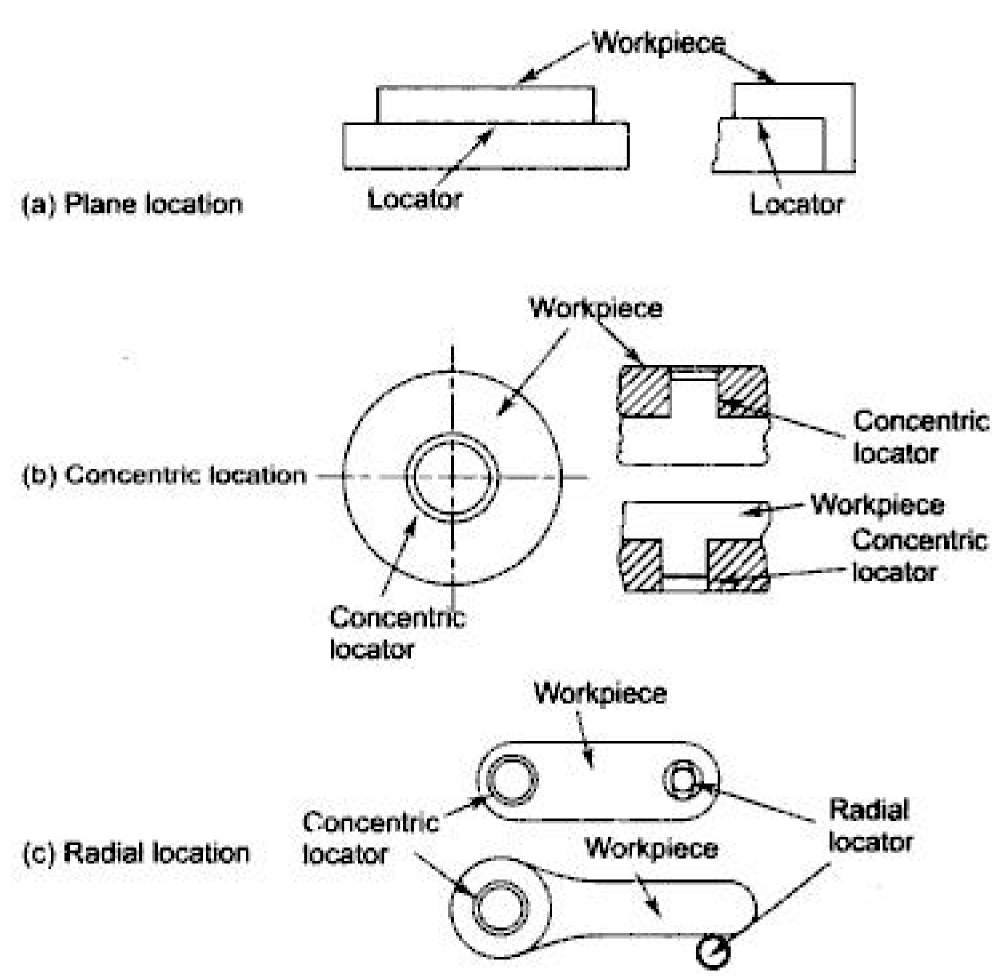

Fig. 14.13 *Three types of locators used in various fixtures*

3. The type of clamp required is determined by the kind of operation to which it is applied. A clamp suitable for holding a drill jig leaf may not be strong enough for a milling fixture.
4. Clamps should not make loading and unloading of the work difficult, nor should they interfere with the use of hoists and lifting devices for heavy work.
5. Clamps that are apt to move on tightening, such as plain straps, should be avoided for production work.
6. The anticipated frequency of set-ups may influence the clamping means. For example, the use of hydraulic clamps, even if simple and of low cost might be inadvisable if frequent installation and removal of piping and valves is necessary.

14.5.1 Basic Type of Clamps

There are a number of types of clamps that are used by tool designers for clamping the part properly as follows.

- Strap clamps
- Screw clamps
- Cam clamps
- Toggle clamps
- Equalizers

The tool designer has to choose the type of clamp that is simple and easier to use and at the same time provide the kind of productivity.

Strap Clamps By far, these are the simplest type of clamps used in jigs and fixtures. There are a variety of designs possible to be used. Most of these clamps are based upon the lever principles to amplify the clamping force required. A typical strap clamp application is shown in Fig. 14.27. By tightening the stud in Fig.14.27, the clamping force is transferred to the part. Heel pin is the fulcrum about which the lever acts while the clamping force is applied at the stud by tightening the screw. The actual force transmitted to the part at the end of the strap as indicated in Fig. 14.27.

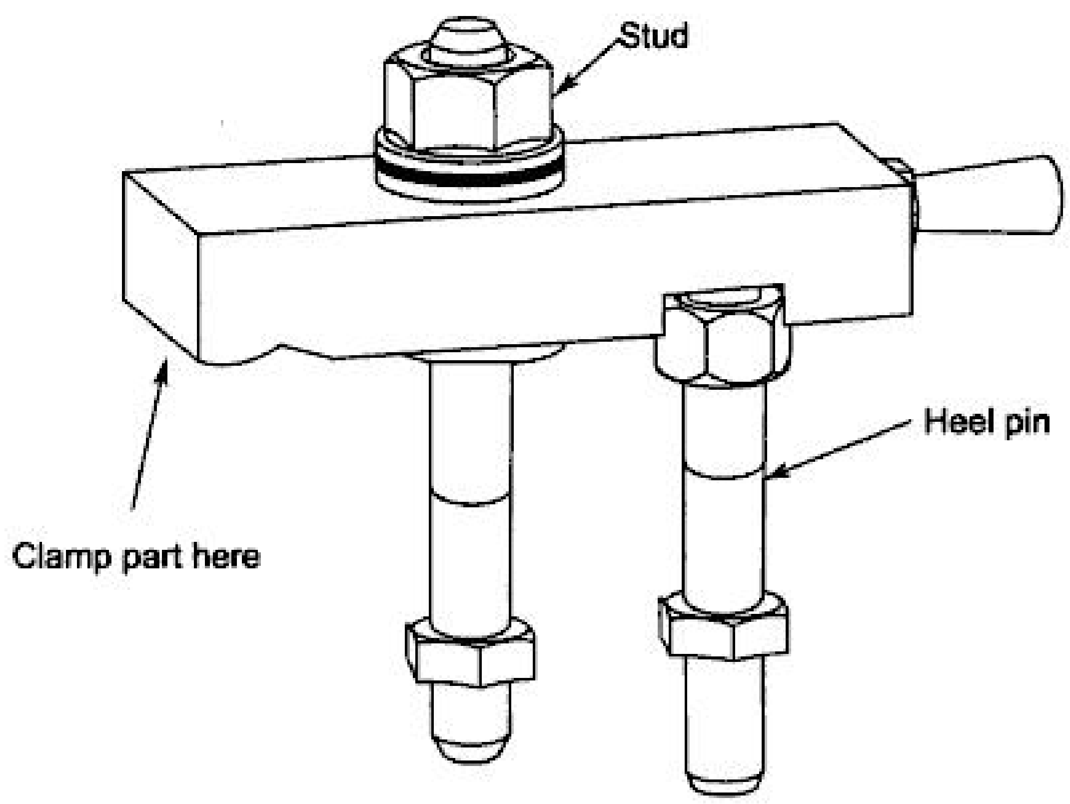

Fig. 14.27 *Strap clamp used for clamping in fixtures*

The actual amplification of the applied force depends upon the distance between the stud and the heel pin (B), and that between the stud and the part (A) as shown in Fig.14.28. The distance A should be made as small as possible compared to B to increase the mechanical advantage of the clamp to increase the clamping force on the part. A variety of strap designs as shown in Fig.14.29 are used in strap clamps. The choice of these depends upon the clamping requirement, part geometry and the relationship of the cutter in relation to the clamping surface.

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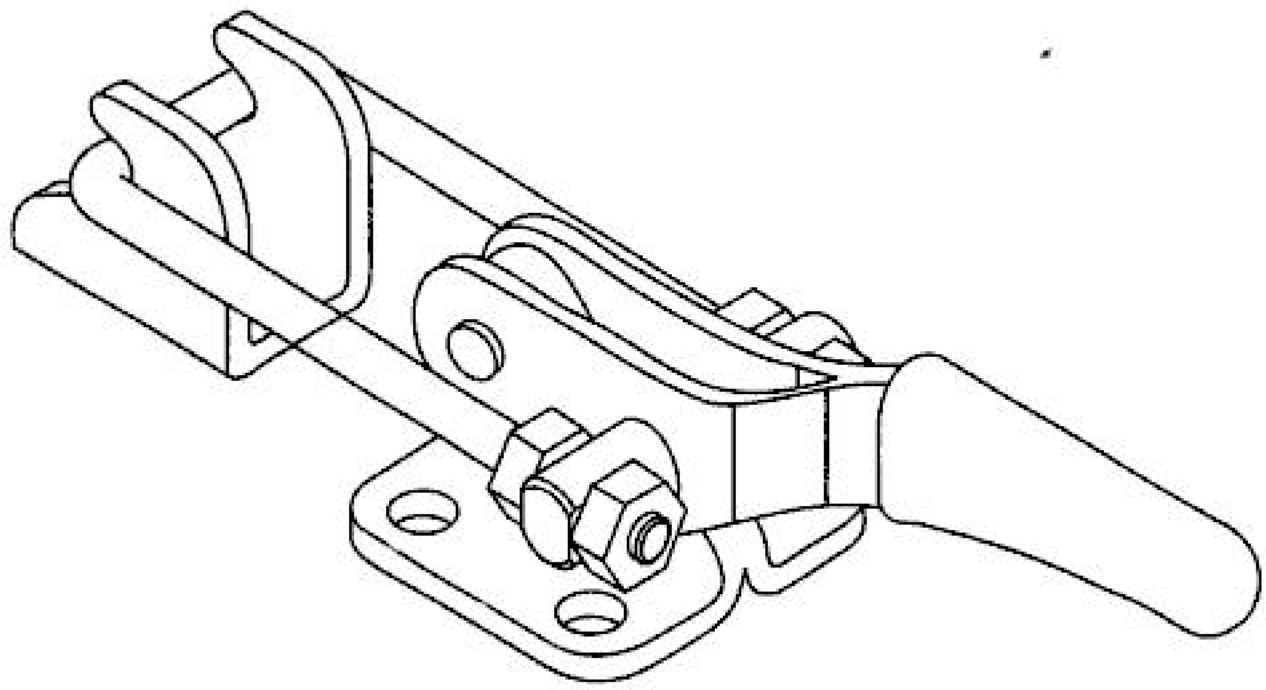

Fig. 14.36 *A push-pull type toggle clamp*

Equalizers When the clamping force is to be applied at more than one location then an equalizing clamp is useful. In this type of clamp as shown in Fig.14.37, the link arm system is being used to apply an equally divided clamping force to a pair of clamps acting on the same component. It is also possible to use this system of clamping to clamp two parts. This is particularly useful in a condition where the operator may be denied easy access to one or other of the clamps.

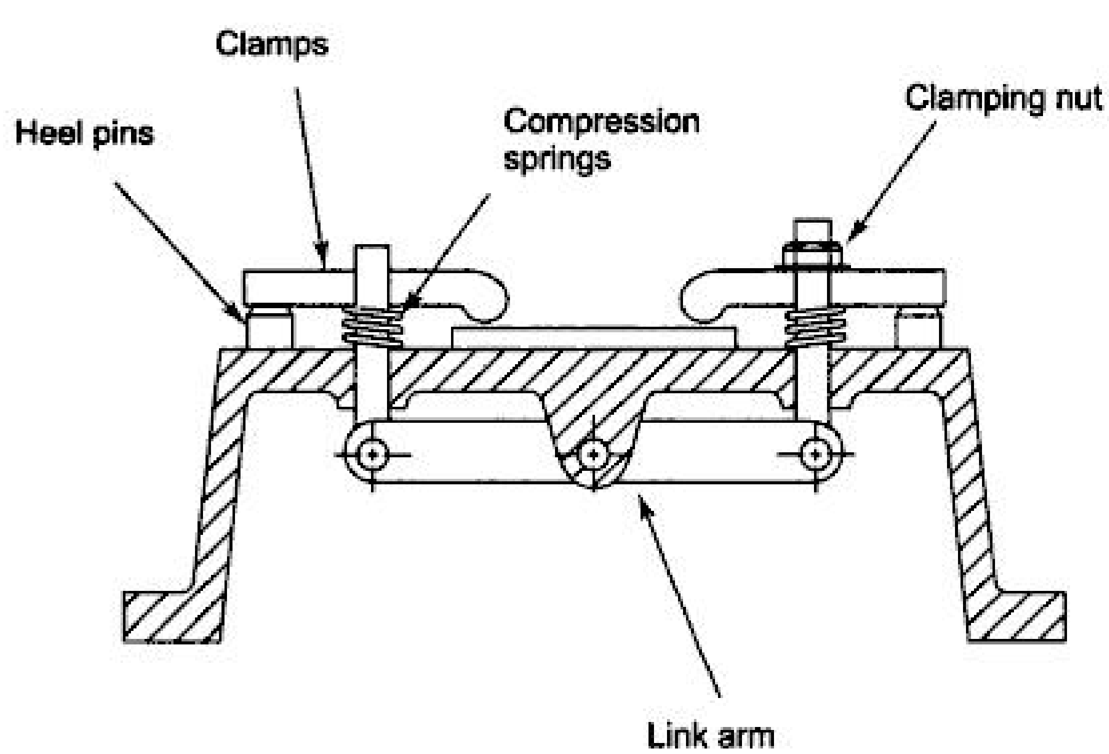

Fig. 14.37 *An equalizing clamp*

14.6 JIGS

A fixture is a device used to securely fasten a part to the machine tool table to accurately locate, support and hold the part during the machining operation. A jig is a special class of fixture, which in addition to providing

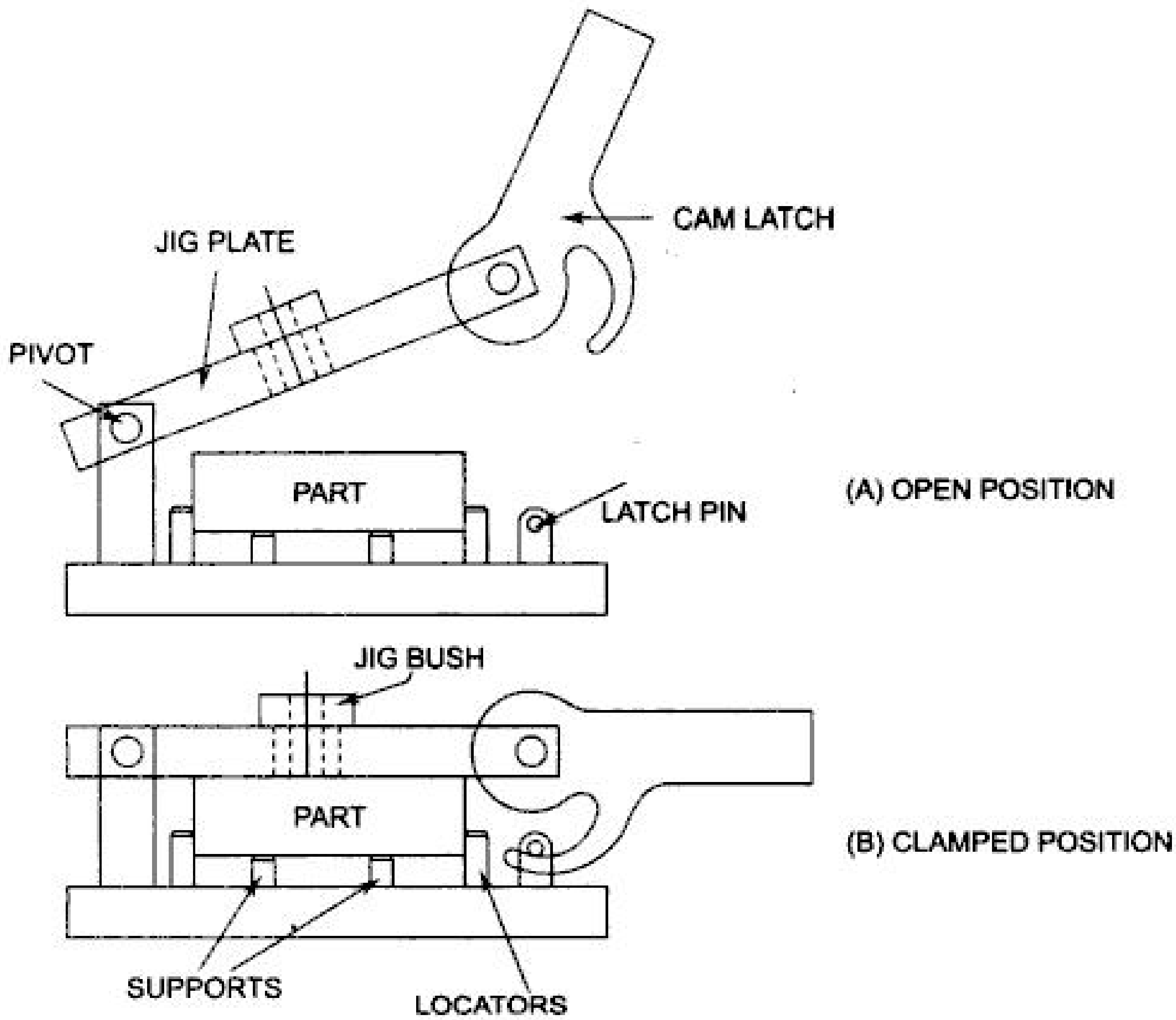

Fig. 14.45 *A leaf jig*

The hinged leaf with bushes will also apply the clamping force. Most of the designs are normally limited to small and simple parts for easy handling. The main disadvantage is that as wear or distortion takes place in the pivot pins, the accuracy of machining deteriorates.

Channel and tumble jigs Channel and tumble jigs allow for drilling in more than one surface in a part without relocating it in the jig. As a result, the accuracy of the part is higher, and less handling of the part is required to complete the machining operations. However, the jigs are more complicated and expensive compared to other jigs discussed so far. A simple channel jig is shown in Fig.14.46.

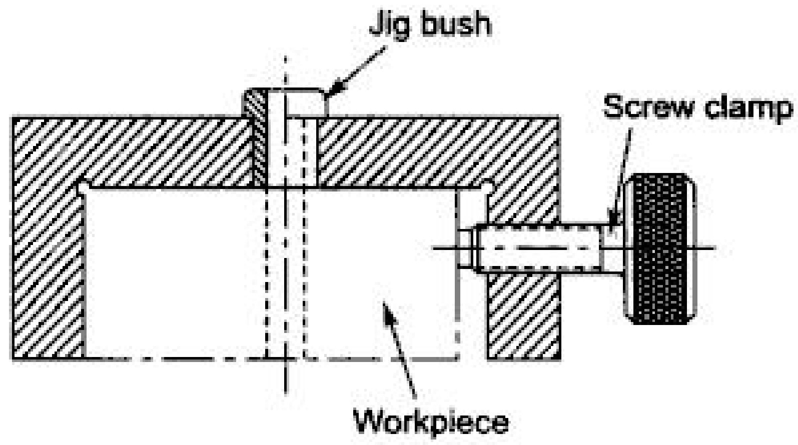

Fig. 14.46 *A channel jig*

Indexing jigs Indexing jigs are used to drill holes in a pattern. The location for the subsequent holes are normally done through the prior hole drilled. An indexing arrangement will be provided in the jig from an appropriate datum to ensure the required accuracy. An example is shown in Fig.14.47, where the part is located from the central hole and then indexed about its axis by means of a plunger located to the left side to drill the four holes around the cylindrical surface.

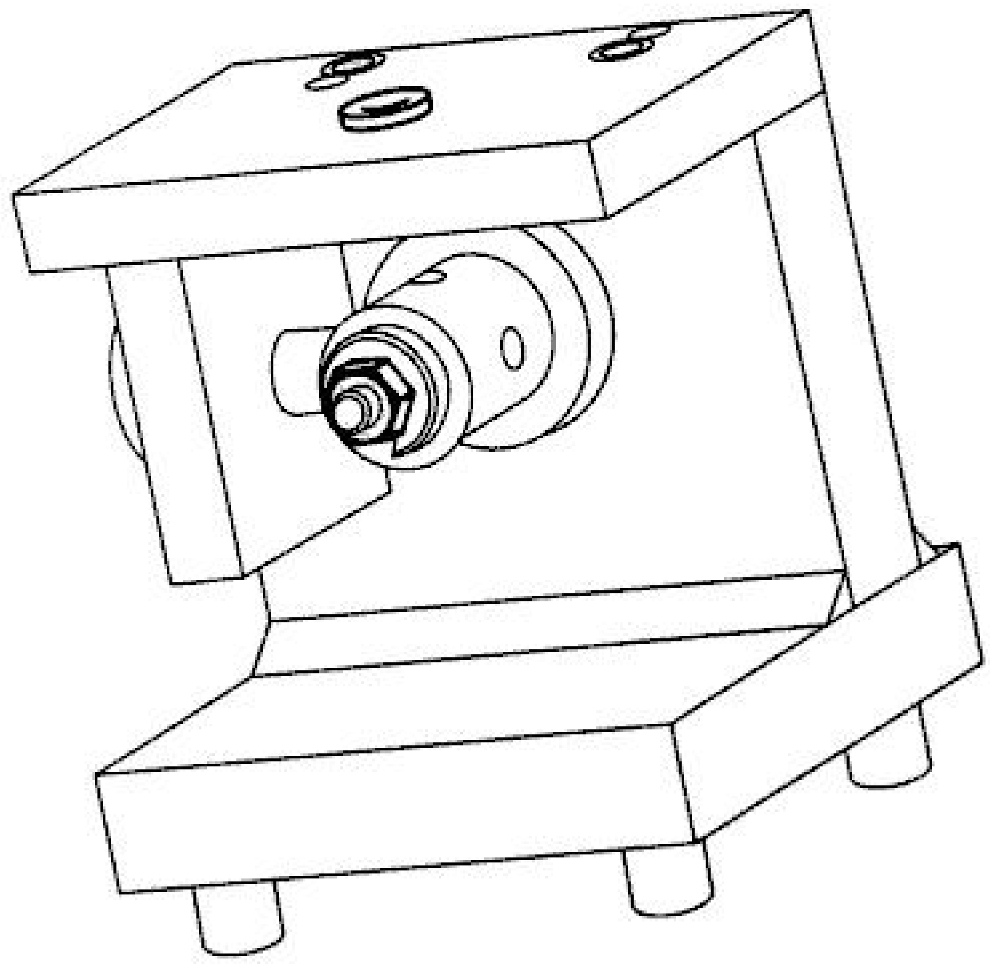

Fig. 14.57 *Completed jig with a sample part loaded in the jig for the part shown in Fig.14.48*

A few principles are enunciated below that could be adhered which will ensure a better designed drill jig.

1. Drill jigs should be as light as possible and consistent with rigidity to facilitate handling.
2. A jig, which is not bolted to the machine table, should be provided with feet, preferably four, opposite all surfaces containing jig bushes.
3. Make the jig foolproof so that the component cannot be loaded in the wrong way.
4. Clearance holes or burr slots should be provided in the jig to allow for the burr formed when the drill breaks through the component and for scarf clearance, particularly from locating faces.
5. Make all component-clamping devices as quick acting as possible.
6. Locate clamps so that they will be in the best position to resist the pressure of the cutting tool when at work.
7. Avoid complicated clamping and locating arrangements, which are liable to wear or need constant attention.
8. Make, if possible, all locating points visible to the operator when placing the component in position in the jig so that the component can be seen to be correctly located. The operator should also be able to have an unobstructed view of the clamps.
9. Clamps should be positioned above the points supporting the component, in order to avoid distortion and should be strong enough to hold the component without bending.
10. The process of inserting and withdrawing the component from the jig should be as easy as possible. Ample space should be left between the jig body and the component for hand movements.

14.8 FIXTURES

As explained earlier, the function of a fixture is to securely fasten the part to the machine tool table with accurate location of the part during the machining operation. In addition to the function of holding the

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Most of the progress that is achieved in the industrial manufacturing is credited to the interchangeable manufacture. The concept was originally attempted by a Frenchman named La Blanc who attempted it about 1775 A.D. However, historically Eli Whitney has been credited with introducing it in the early 1800s when he produced 10,000 muskets using interchangeable parts. The success of interchangeable manufacture depends upon the ability to specify the limits on the dimensions and a way to measure that dimensional acceptance. However, it was only in the twentieth century that interchangeable manufacture really flourished with the availability of a large number of dimensional gauging methods at low cost.

Gauging is defined as the acceptability of a given dimension, whether it lies in its specified or allowable limits or not. The cost and ease of manufacture are greatly controlled by the limits that can be imposed on dimensions at the design stage. The limits should be as wide as possible to decrease the cost of manufacture. However, from the performance and maintenance point of view, the limits should be as close as possible. The designer therefore has to strike a balance between the ease of manufacture and ease of maintenance depending upon the product requirements.

A few of the terminologies that need to be understood in the learning of metrology are given below.

Accuracy It is the agreement of the result of a measurement with the true value of the measured quantity. It refers to the condition whether a particular dimension is within its stated size.

Precision It refers to the exactness of the dimension or the repeatability of a measuring process. It depends upon the overall size that is being measured. If a dimension is being measured in m, then a precision of mm may be sufficient. However, if the dimension is being measured in mm, then a precision in μm is suitable. But a precision in μm for measurement in m will be meaningless.

Reliability It is the ability to obtain the desired result to the degree of precision required.

Discrimination Discrimination refers to the degree to which a measuring instrument divides the basic unit.

15.1.1 Surface Plate

Surface plate is an important tool for precision-measuring applications in a shop. It provides an accurate flat reference plane for many inspection requirements. Metallic surface plates are made of either steel or cast iron castings. The castings will be allowed to age sufficiently and then stress relieved so that all the residual stresses are relieved to ensure the desired degree of flatness. These are then ground and scraped to get the necessary flatness. Then they are mounted on heavy stands. Granite surface plates are superior since granite is harder, denser and impervious to water. It possesses greater temperature stability than the metallic counterparts.

15.2 TOLERANCES, LIMITS AND FITS

The basic or nominal size of a component dimension is arrived as a convenient size for represention based on the design process. However, it is almost impossible to produce any component to the exact dimension through any of the known manufacturing processes. Even if a component is perceived to be made to the exact dimension by the manual processes, the actual measurement with a high resolution measuring device will show that it is not so.

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centre attains the position *M*, such that *LM* is perpendicular to the direction of the next move, i.e., tangent to the circle (block N160). In the block N100, the compensation is deactivated by the word *G40* which is entered after the programmed position *B*. The cutter stops at *K*, such that *KB* is perpendicular to the direction of the previous move, i.e., *EB*. *KA* is called 'Ramp-off-move'.

In the blocks N110 and N180, T0 causes cancellation of the compensation values for the tool in action at that time. Radius compensation is also used when similar profiles are to be cut with different depths of cut, e.g., rough cut and finish cut. When a rough cut is made, a compensation, equal to the thickness of the material to be left for finish, is entered and during the finish cut, this compensation is taken off. In view of identical programmed paths in roughing and finishing, such programming is done by using subroutines. For the roughing cut, the subroutine is called in the main program using the compensation and for the finish cut, the same subroutine is called using the same tool without compensation.

Compensation for tool length and radius can be specific to a tool and if so, when the word T03 occurs in a block, it calls the tool number 3 into action with the compensation pre-registered for it. However, in many CNC systems, the compensation values (MDI entry) are stored separately, irrespective of the tools being used. This helps in calling different compensation values even with the same tool when used on different occasions. For example, T0104 word would mean that tool number 01 would be used with the compensation value, entered in the register against identifier 04. Before commencing work on the machine, the operator must examine the compensation values stored and verify them with the list of values supplied to him. Negligence on this count could be very serious.

In some of the popular control systems, the pre-registered compensation values are called in the program block by the words *D*... and *H*... which refer to the tool radius and length compensations respectively. For example,

N017 M06 T02

N018 G81 X170.0 Y100.0 Z65.0 R48.0 H07 F100 M03

would mean that the drilling operation will take place with tool number 02 with a length compensation corresponding to the entry against the identifier 07. Similarly,

N074 M06 T06

N075 G01 X70.0 D03 F150 M03

would mean that milling will take place with tool number 06 with a radius compensation corresponding to the entry in the register against the identifier 03.

16.5.11 Canned Cycles

It is found many a times that a series of motions are to be repeated a number of times, many of which are fairly common to all the positions. For example, in the case of drilling operation the tool (twist drill) has to position a little above the hole in rapid position, then move to the required depth with the given feed rate and then the tool has to return to the top of the hole. The same actions are to be repeated for each of the holes. For each of the operation three NC blocks are to be written, out of which two blocks need to be repeated without any change for each of the hole to be drilled in the same plane. It, therefore, is possible to define a canned cycle or fixed cycle which can repeat all these motions without having to repeat the same information for each of the hole. The most common cycles that would be useful are for the hole-making operations such as drilling,

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