2

METAL CUTTING AND CUTTING TOOLS

2.1 INTRODUCTION

In the metal-working industry workpieces of most different shapes and dimensions and of different materials are worked. The various working processes fall into two groups, the group of *non-cutting shaping*, e.g. forging, pressing, drawing, etc. and that of *cutting shaping* by which finish surface of desired shape and dimension is obtained by separating a layer from the parent workpiece in the form of chips, e.g. turning, drilling, milling, etc. These two groups may be sub-divided as shown in Fig.2.1.

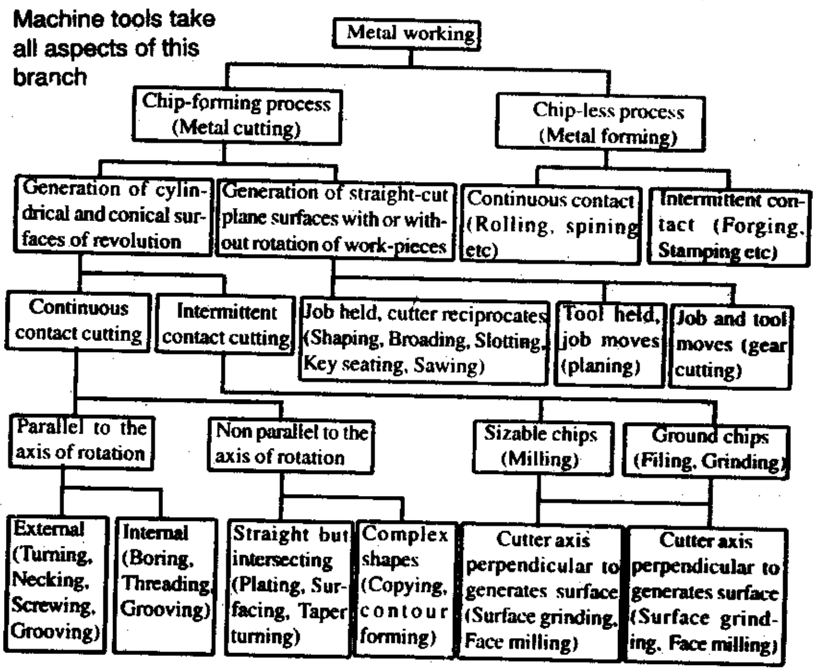

Figure 2.1 Metal working process

The process of metal cutting in which chip is formed is affected by a relative motion between the workpiece and the hard edge of a cutting tool held against the workpiece. Such relative motion is produced by a combination of rotary and translating movements either of the workpiece or of the cutting tool or of both. Depending on the nature of this relative motion, metal cutting processes are called by names example : turning, planing, boring etc. Nature of relative motion for various continuous cutting operation is listed in Table 2.1.

TABLE 2.1 NATURE OF RELATIVE MOTION FOR VARIOUS CUTTING OPERATIONS

Operation	*Motion of job*	*Motion of cutting tool*
Turning	Rotary	Forward translation
Boring	Forward translation	Rotation
Drilling	Fixed	Rotation as well as translatory feed
Planing	Translatory	Intermittent translation
Milling	Translatory	Rotation

2.2 TYPES OF CUTTING TOOLS

A cutting tool may be used either for cutting apart, as with a knife, or for removing chips. Parts are produced by removing metal mostly in the form of small chips.

Chip removal in the metal-cutting process may be performed either by cutting tools having distinct cutting edges or by abrasives used in grinding wheels, abrasive sticks, abrasive cloth, etc. These abrasives have a very large number of hard grains with sharp edges which remove metal from the workpiece surface in such operations as grinding.

All cutting tools can be divided into two groups. These are :

1. Single-point tools. 2. Multi-point tools.

Single-point cutting tools having a wedge-like action find, a wide application on lathes, and slotting machines. Multi-point cutting tools are merely two or more single-point tools arranged together as a unit. The milling cutter and broaching tool are good examples of this type.

The simplest form of cutting tool is the single-point tool. The cutting process as performed by multi-point tools closely resembles machining as performed by single-point tools. In this text the cutting action of a single-point tool is dealt with elaborately.

2.3 ORTHOGONAL AND OBLIQUE CUTTING

The two basic methods of metal cutting using a single-point tool are the orthogonal or two-dimensional, and the oblique or three-dimensional. Orthogonal cutting takes place when the cutting face of the tool is 90° to the line of action or path of the tool. If, however, the cutting face is inclined at an angle less than 90° to the path of the tool, the cutting action is known as oblique. Orthogonal and oblique cutting action are illustrated in Fig.2.2, which shows two bars receiving identical cuts. The depth of cut is the same in both cases, and so is the feed, but the force which cuts or shears the metal acts on a larger area in the case of the oblique tool. The oblique tool will, thus, have a longer life as the heat developed per unit area due to friction along the tool-workpiece interface is considerably small. Alternatively, the oblique tool will remove more metal in the same life as an orthogonal tool.

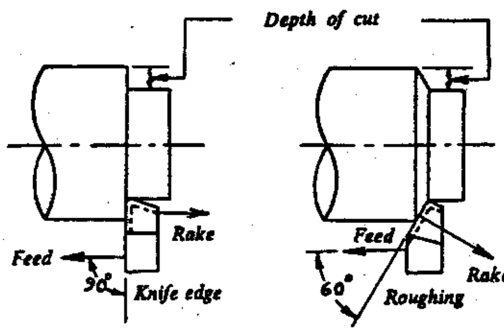

Figure 2.2 Orthogonal and oblique cutting

Fig.2.3 shows the chip flow in orthogonal and oblique cutting. In orthogonal cutting shown at (a) where the cutting edge of the tool *OC* is at right angles to the direction of the relative velocity *V* of the work, the chip coils in a tight, flat spiral. In oblique cutting as shown at (b) and at (c) where the cutting edge of the tool is inclined at the angle *i*, the chip flows sideways in a long curl. The inclination angle *i* is defined as the angle between the cutting edge and the normal to the direction of the velocity *V* of the work. An angle of interest in oblique cutting is the chip flow angle

η_c, which is defined as the angle measured in the plane of the cutting face between the chip flow direction and the normal to the cutting edge. In orthogonal cutting, $i = 0, \eta_c = 0$.

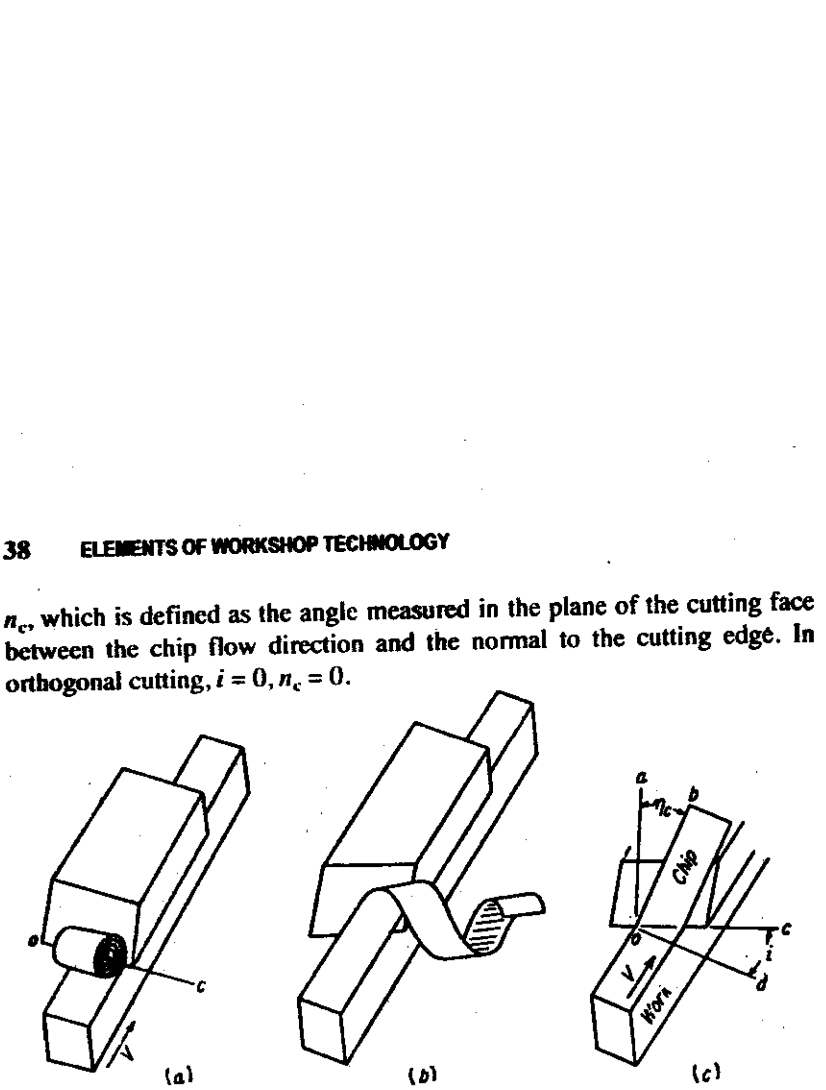

Figure 2.3 Direction of chip flow in orthogonal and oblique cutting

Orthogonal cutting in the machine shop is confined mainly to such operations as knife turning, broaching and slotting, the bulk of machining being done by oblique cutting. But orthogonal cutting is the simplest type and is considered in the major part of this Chapter. The principles developed for orthogonal cutting apply generally to oblique cutting.

2.4 MECHANICS OF CUTTING AND CHIP FORMATION

In Fig.2.4 the tool is considered stationary, and the workpiece moves to the right. The metal is severely compressed in the area in front of the cutting tool. This causes high temperature shear, and plastic flow if the metal is ductile. When the stress in the workpiece just ahead of the cutting tool reaches a value exceeding the ultimate strength of the metal, particles will shear to form a chip element which moves up along the face of the work. The outward or shearing movement of each successive element is arrested by work hardening and the movement transferred to the next element. The process is repetitive and a

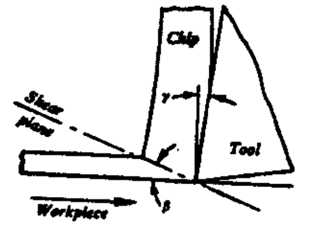

Figure 2.4 Shear plane in metal cutting

continuous chip is formed having a highly compressed and burnished underside, and a minutely serrated top side caused by the shearing action. The place along which the element shears is called the ***shear plane***. Thus the chip is formed by plastic deformation of the grain structure of the metal along the shear plane as shown in Fig.2.4.

Actually, the deformation does not occur sharply across the shear plane, but rather it occurs along a narrow band. The structure begins elongating along the line *AB* below the shear plane and continue to do so until it is completely deformed along the line *CD* above the shear plane in Fig.2.5. The region between the lower surface *AB*, where elongation of the grain structure begins, and the upper surface *CD*, where it is completed and the chip is born, is called the ***shear zone*** or ***primary deformation zone***.

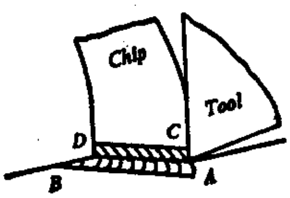

Figure 2.5 Shear zone during metal cutting

In Fig.2.5 the shear zone is included between two parallel lines *AB* and *CD*. Actually, however, these two lines may not be parallel but may produce a wedge-shaped zone which is thicker near the tool face at the right than at the left. This is one of the causes of curling of chips in metal cutting. In addition, owing to the non-uniform distribution of forces at the chip-tool interface and on the shear plane the shear plane must be slightly curved concave downward. This also causes the chip to curl away from the cutting face of the tool.

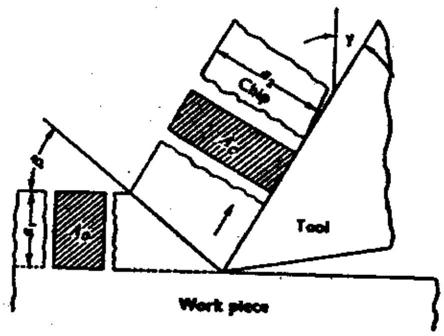

Figure 2.6 Geometry of chip formation in orthogonal cutting

2.5 CHIP THICKNESS RATIO

The outward flow of the metal causes the chip to be thicker after separation from the parent metal. That is, the chip produced is thicker than the depth of cut as shown in Fig.2.6.

Let, a_2 = thickness of chip
a_1 = uncut thickness (feed–in case of turning)

From the Geometry of Fig.2.6,

$$a_2 = a_1 \frac{\cos(\beta - \gamma)}{\sin\beta}$$

If the degree of reduction or chip reduction coefficient is designated r_c,

$$r_c = \frac{a_2}{a_1} = \frac{\cos(\beta - \gamma)}{\sin\beta} \qquad 2.1$$

from which,

$$\tan\beta = \frac{\cos\gamma}{r_c - \sin\gamma} \qquad 2.2$$

The chip reduction coefficient can also be estimated in a different manner by measuring the length of the chip (l_c) when :

$$r_l = \frac{l_o}{l_c}$$

where , r_l = chip reduction coefficient from length measurements.
l_0 = original length of uncut material in mm.

Form constancy of volume removal,

$$r_l = \frac{l_o}{l_c} = \frac{a_c . b_c}{a_0 . b_0} = \frac{A_c}{A_0} = r_a \qquad 2.3$$

where, A_0 = uncut area of layer to be removed in mm^2
A_c = area of the chip cross-section in mm^2
r_a = chip reduction coefficient from area measurement.

If there is no side flow of the chips,

$$b_c = b_0$$

when $r_l = r_a = r_c$

It is difficult to measure the cross-section of chip accurately since one side of the chip is usually rough. Hence r_c is often determined from length measurement.

The density of metal may be used to find the chip reduction coefficient thus :

$$r_c = \frac{t.w.\rho}{m}$$

where, w = width of chip.

ρ = density of metal.

m = weight per unit length of the metal.

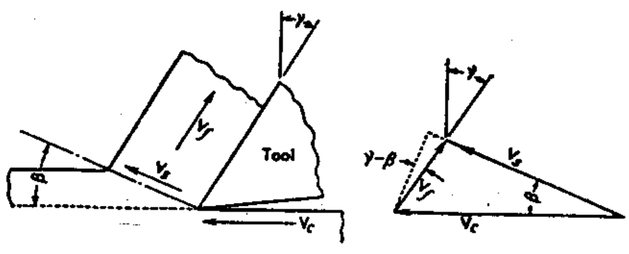

Figure 2.7 Velocity relationship during chip-removal

2.6 VELOCITY RELATIONSHIPS

The velocity relationships for orthogonal cutting are illustrated in Fig.2.7 where V_c is the cutting velocity, V_s is the velocity of shear and V_f is the velocity of chip-flow up the tool face. Therefore, from Fig.2.7 :

$$V_s = V_c \frac{\cos\gamma}{\cos(\beta-\gamma)} \qquad 2.5$$

$$V_f = V_c \frac{\sin\beta}{\cos(\beta-\gamma)} \qquad 2.6$$

or from eqn. (2.1), $V_f = \frac{V_c}{r_c}$

It can be inferred from the principle of kinematics that the relative velocity of two bodies (here tool and the chip) is equal to the vector difference between their velocities relative to the reference body (the workpiece).

So,

$$V_c = V_s + V_f \qquad 2.7$$

2.7 CUTTING FORCES IN ORTHOGONAL CUTTING

The force system in the general case of conventional turning process is shown in Fig.2.8. The resultant cutting force R may be resolved into three components : P_x, known as the "feed force" acting in a horizontal plane,

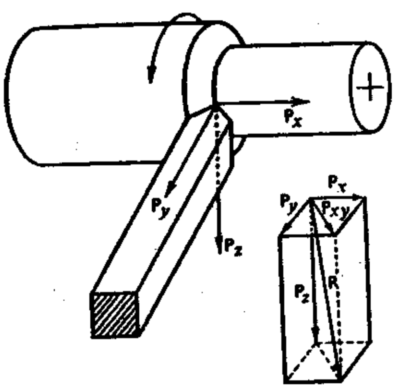

Figure 2.8 Cutting forces in conventional turning process

but in the direction opposite to the feed; P_y called "thrust force" acting in the direction perpendicular to the generated surfaces ; and P_z, the "cutting force" or the "main force" acting in the direction of the main cutting motion.

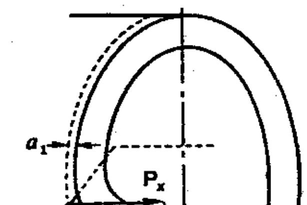

Figure 2.9 2-dimensional force system in orthogonal cutting

The largest in magnitude is the vertical force P_z which, in turning, is about 2 or 3 times larger than thrust force P_y and from 4 to 10 times larger than the feed force P_x.

In case of orthogonal cutting when i=0, ϕ=90, the force system is reduced to a 2-dimensional system as indicated in Fig.2.9.

The forces acting on the chip in orthogonal cutting are shown in Fig.2.10. They are as follows : P_s, which acts along the shear plane, is the resistance to shear of the metal in forming the chip, P_n is normal to the shear plane. This is a 'backing-up' force on the chip provided by the workpiece. Force F is the frictional resistance of the tool acting downward against the motion of the chip as it moves upward along the tool force. Force N acting on the chip is normal to the cutting face of the tool and is provided by the tool.

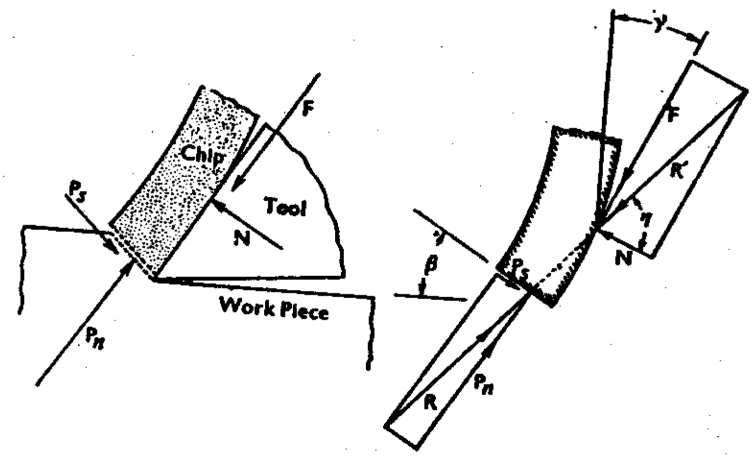

Figure 2.10 Forces on chip

Fig.2.10 is depicted to show the forces acting on the chip in which forces P_s and P_n may be replaced by their resultant R and so the forces F and N by their resultant R'. These resultant forces R and R' are equal in magnitude, opposite in direction and collinear. Therefore, for purpose of analysis the chip is regarded as an independent body held in mechanical equilibrium by the action of two equal and opposite forces R which the workpiece exerts upon the chip and R' which the tool exerts upon the chip.

$$R' = \vec{N} + \vec{F} \quad \text{and} \quad R = P_s + P_n$$

Fig.2.11 shows a circle diagram which is convenient to determine the relations between the various forces and angles. In the diagram, two force triangles of Fig.2.10 have been combined, and R and R' together have been replaced by R. Now the force R can be resolved into two component forces : P_s, the cutting force of the tool on the workpiece, and P_x , the feed force.

The cutting force P_z and feed force P_x can be determined by the use of force dynamometer. After P_z and P_x are determined they can be laid of as in Fig.2.11 and their resultant is the diameter R of the circle.

$$\vec{R} = \vec{P_z} + \vec{P_n}$$

The rake angle can be laid off or measured from the tool, and forces F and N can then be determined. The shear angle β can be measured approximately from a photomicrograph or from the relation (2.2). After these forces are known, all the component forces on the chip may be determined from the geometry of Fig.2.11.

From the force system shown in Fig.2.11, the following relationships are evident :

$$F = P_x \cos \gamma + P_z \sin \gamma \qquad 2.8$$
$$N = P_z \cos\gamma + P_x \sin \gamma \qquad 2.9$$

where, F = Frictional resistance at the rake surface in kgf.
N = Normal force on the rake surface in kgf.

Hence, average kinetic coefficient of friction (μ) can be estimated by :

$$\mu = \tan \eta = \frac{F}{N} = \frac{P_z + P_z \tan\gamma}{P_z - P_x \tan\gamma} \qquad 2.10$$

where, η = mean angle of friction at the rake surface.

Similarly, $$P_s = P_z \cos \beta - P_x \sin \beta \qquad 2.11$$
$$P_n = P_x \cos \beta + P_z \sin \beta \qquad 2.12$$
$$= P_s \tan (\beta+\eta-\gamma) \qquad 2.13$$

Merchant has developed a relationship between the shear angle β, the angle of friction η and the cutting rake angle γ as follows :

$$2\beta+\eta-\gamma = C$$

where C is a *machining constant* for the work material dependent on the rate of change of the shear strength of the metal with applied compressive stress, besides taking the internal coefficient of friction into account.

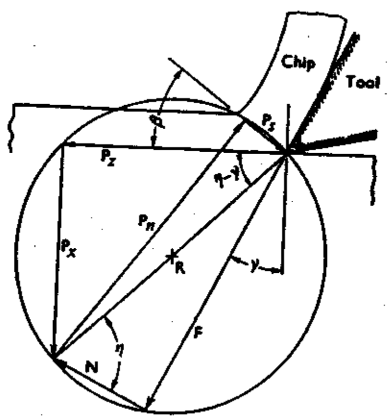

Figure 2.11 Merchant's circle diagram for cutting forces

2.8 STRESS IN SHEAR PLANE

Let, A_0 = area of chip before removal

A_s = area of the shear plane

P_s = shearing force

S = shear stress on shear plane in kgf/mm^2

$$S = \frac{P_s}{A_s}$$

but $$A_s = \frac{A_0}{\sin\beta}$$

Hence $$S = P_s \frac{\sin\beta}{A_0}$$

From equation (2.11),

$$S = \frac{(P_z \cos\beta - P_x \sin\beta)\sin\beta}{A_0} = \frac{(P_z \cos\beta \sin\beta - P_x \sin^2\beta)}{A_0} \qquad 2.14$$

2.9 WORK DONE AND POWER REQUIRED IN CUTTING

In general, power equals force times velocity. In the calculation of power requirements only that force components in the direction of the cutting speed should be considered as the effect upon the power required of the force component in the direction of feed and depth of cut is negligible and

equals zero respectively. In orthogonal cutting, vertical component P_z should be used. This force component is tangential to the machined surface produced in the cutting speed direction.
The total work done in cutting :

$$W_c = \text{cutting force} \times \text{cutting speed}$$
$$= P_z V_c \text{ kgfm.}$$

The work done in shear :

$$W_S = \text{shearing force} \times \text{velocity of the chip relative to the work}$$
$$= P_s V_s \text{ kgf,}$$

The work done in friction :

$$W_f = \text{friction force} \times \text{velocity of the chip relative to the cutting tool}$$
$$= V_f \text{ kgfm.}$$

The total work done in cutting :

$$W_c = W_s + W_f$$

$$h.p_c = \frac{P_z V_c}{60 \times 75 \times 136} \text{ kW} \quad 2.15$$

But the cutting power $h.p_c$ can be estimated by measuring the gross horse-power $h.p_g$ and tare horse power $h.p_t$, when

$$h.p_c = h.p_g - h.p_t.$$

So $$P_z = h.P_c \times 6120/V_c \text{ kgf}$$

Again, $$\eta = \frac{h.p_c}{h.p_g}$$

Torque and power in drilling : The torque T in drilling equals the product of the circumferential force Q and the arm of the couple :

$$T = Q \frac{d}{2} \text{ kg.mm}$$

The torque is also determined from the formula :

$$T = cd^{1.9} s^{0.8}$$

The thrust in drilling is determined from the formula :

$$B = kds^{0.78}$$

where d = diameter of the drill in mm, and s = feed in mm, and c = 34 and k = 85 for steel of ultimate strength of 75 kg/mm^2.

The total net horsepower developed at the drill point equals the horsepower due to the torque plus the horsepower due to the thrust as follows :

$$h.p_c = \frac{2\pi Tn}{1000\times 60\times 102} + \frac{Bsn}{1000\times 60\times 102} \text{ kW.}$$

Torque and power in milling : The torque in milling is determined from the formula :

$$T = \frac{P_z d}{2}$$

where d = diameter of the cutter in mm.

$$h.p_c = \frac{2\pi Tn}{1000\times 60\times 102} \text{ kW}$$

2.10 CUTTING FORCES IN OBLIQUE CUTTING

As stated earlier, orthogonal cutting is confined mainly to few operations as there are certain practical limitations to orthogonal cutting. In most cases, e.g. in drilling, milling, etc. oblique cutting is employed. Fig.2.8 shows the force system in oblique cutting.

$R = \sqrt{P_x^2 + P_y^2 + P_z^2}$ gives the resultant force acting on the tool face.

The component of force P_{xy} is given by :

$$P_{xy} = \sqrt{P_x^2 + P_y^2}$$

The force system is drilling process : The resultant force R required for the plastic deformation of the layer under drilling can be resolved into a tangential component, P_z, and thrust force, P_{xy} perpendicular to the cutting edge as shown in Fig.2.12. The force P_x is required for calculating the torque required in drilling. The force P_{xy} can further be resolved into a radial component P_x and a vertical component P_y acting axially along the drill. This force, P_y is commonly known as "thrust" in drilling.

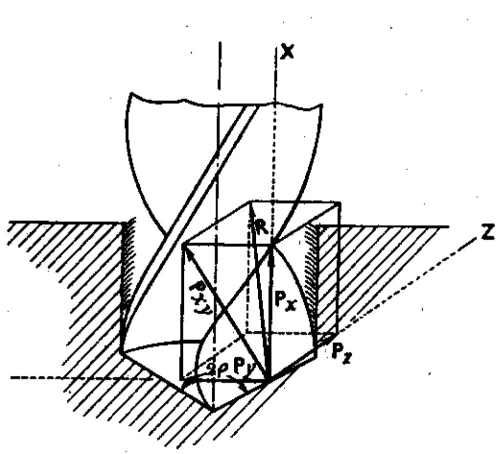

Figure 2.12 Force system in drilling

The force system in milling process : The periodic chip-discontinuity inherent with the milling chip formation and associated changing geometry of the cutter lead to cyclic conditions of force. Such periodically varying forces produce torsional vibration of the arbor that leads to variation in cutting speed with consequent lesser cutter life. The variable radial and axial forces may also have a damaging effect on the surface finish. Further, the cyclic variation of the force can provide the necessary energy to excite a natural mode of vibration in any part of the machine.

Fig.2.13 shows the forces acting on the tooth point of a plain slab cutter. The resultant force R could be resolved into a vertical force P_y horizontal force P_z and an axial thrust P_x as shown, when :

$$R = \sqrt{P_x^2 + P_y^2 + P_z^2}$$

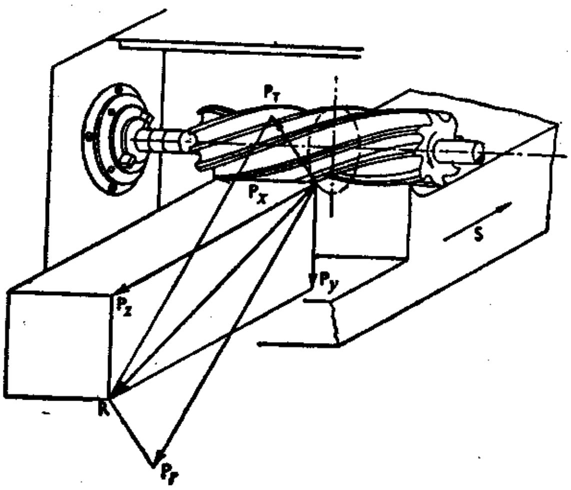

Figure 2.13 Force system in slab milling

2.11 MEASUREMENT OF FORCES

There are several important reasons for measuring forces which include :

1. To estimate the various power required in a machine tool.
2. To estimate the forces acting on the tool, that must be resisted by the machine tool components, bearings, etc.
3. To survey the characteristics of new work and tool materials.

Cutting forces or power at the cutting tool may be measured in various ways, such as :

1. Dynamometer
2. Ammeter
3. Wattmeter
4. Calorimeter
5. Thermocouple

Direct measurements by dynamometers have won general acceptance. Mechanical and strain-gauge dynamometers are most commonly used for measuring forces in metal cutting. The common feature in all type of dynamometers is the measuring springs whose deflections are proportional to cutting forces. The major difference in the design of various dynamometer lies in the technique employed to measure spring deflection.

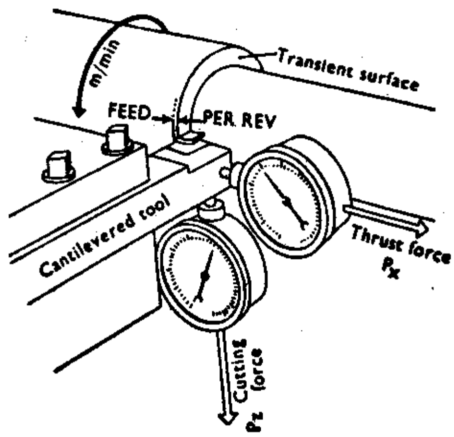

Figure 2.14 Mechanical tool force dynamometer

A mechanical tool force dynamometer which is shown in Fig.2.14 measures deflection on the tool holder by the use of sensitive dial indicators. Another way the sensitivity can be achieved by using a lever system that can magnify the deformation. Various researchers utilized this methodology by combining a sensitive dial gauge and a lever, the end of which is connected with the tool using a roller and a screw.

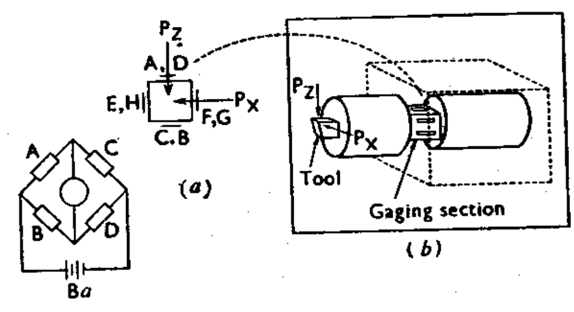

Figure 2.15 Strain gauge turning dynamometer

The basic principle of a strain gauge dynamometer is illustrated in Fig.2.15 with respect to a turning dynamometer designed by Shaw. The unbalance of the Wheatstone Bridge indicates the cutting forces. Each of the two sets of four gauges are connected into two bridge circuits to enable the determination of P_x and P_y. The strain-gauge dynamometer is more accurate and is in common use.

2.12 TYPES OF CHIP

The form and dimension of a chip in metal machining indicate the nature and quality of a particular machining process, but the type of chip formed is greatly influenced by the properties of the material cut and various cutting conditions.

In engineering manufacture particularly in metal machining processes hard brittle metals have a very limited use, and ductile metals are mostly used. Chips of ductile metals are removed by varying proportions of tear, shear, and flow. This results in three general types or shapes (Fig.2.16) :

1. The discontinuous or segmental form.
2. The continuous or ribbon type.
3. The continuous with built-up edge.

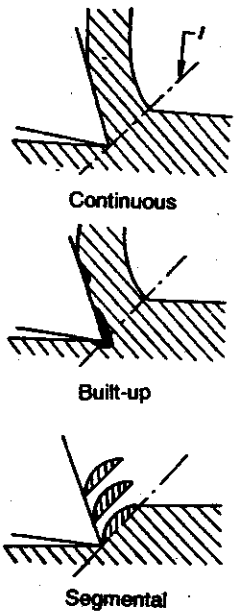

Figure 2.16 Basic chip forms
1. Shear plane

Discontinuous or *segmental chips* consist of elements fractured into fairly small pieces ahead of the cutting tool. This type of chip is obtained in machining most brittle materials, such as cast iron and bronze. These materials rupture during plastic deformation, and form chips as separate small pieces. As these chips are produced, the cutting edge smoothes over the irregularities, and a fairly good finish is obtained. Tool life is also reasonably good, and the power consumptions low. Discontinuous chips can also be formed on some ductile metals only under certain conditions particularly at very low speeds and if the coefficient of friction is low. With ductile metals, however, the surface finish is bad and the tool life is short.

Conditions tending to promote its formation include : brittle metal, greater depth of cut, low cutting speed and small rake angle.

Continuous chips consist of elements bonded firmly together without being fractured. Under the best conditions the metal flows by means of plastic deformation, and gives a continuous ribbon of metal which, under the microscope, shows no signs of tears or discontinuities. The upper side of a continuous chip has small notches while the lower side, which slides over the tool face, is smooth and shiny. The continuous form is considered most desirable for low friction at the tool-chip interface, lower power consumption, long tool life and good surface finish.

Factor favourable to its formation are : ductile metal, such as mild steel, copper, etc., fine feed, high cutting speed, large rake angle, keen cutting edge, smooth tool face and an efficient lubrication system.

The term *built-up edge* implies the building up of a ridge of metal on the top surface of the tool and above the cutting edge. It appears that, when the cut is started in ductile metals, a pile of compressed and highly stressed metal forms at the extreme edge of the tool. Owing to the high heat and pressure generated there, this piled up metal is welded to the cutting tip and forms a "false" cutting edge to the tool. This is usually referred to as the "built up edge". This weld metal is extremely strain hardened and brittle. So the weaker chip metal tears away from the weld as the chip moves along the tool face. The built-up becoming unstable, breaks down and some fragments leave with the chip as it passes off and the rest adheres to the work surface producing the characteristic rough surface. The built-up edge appears to be a rather permanent structure as long as the cut is continuous at relatively high speeds and has the effect of slightly altering the rake angle. At very high speeds, usually associated with sintered-carbide tools, the built-up edge is very small or nonexistent, and a smooth machined surface results.

Conditions tending to promote the formation of built-up edges include : low cutting speed, low rake angle, high feed, lack of cutting fluid and large depth of cut.

2.13 CHIP BREAKERS

A continuous-type chip from a long cut is usually quite troublesome. Such chips foul the tools, clutter up the machine and workplace, besides being extremely difficult to remove from the swarf tray. They should be broken into comparatively small pieces for ease of handling and to prevent it from becoming a work hazard., Hence chip breakers are used to reduce the swarf into small pieces as they are formed. The fact that the metal is already work-hardened helps the chip breaker to perform effectively. Various types of chip breakers are made, but all of them consist mainly of a step or groove ground into the leading edge of the tool or a piece of cutting-tool material clamped on top of the cutting-tool (see Fig.2.17)

Step type Groove type Clamp type

Figure 2.17 Chip breakers

In normal shop practice common methods of breaking the chips are summarized as follows :

1. By clamping a piece of sheet metal in the path of the coil.
2. By a *stepped type breaker* in which a step is ground on the face of the tool along the cutting edge.
3. By a *groove type breaker* in which a small groove is ground behind the cutting edge.
4. By a *clamp type breaker* in which a thin-carbide plate or clamp is brazed or screwed on the face of the tool.

Effective control of the chip, as it moves across the face of the tool, may also be achieved by proper selection of tool angle, feed, depth of cut and cutting fluids used. A large positive front rake gives rise to a looser chip formation, which flows down the face of the tool, and away from the workpiece, leaving the newly cut surface unscratched. A small positive or negative side rake has the effect of decreasing the radius at which the chip coils. Hence the tendency to produce short, easily managed chip. Slightly increased feed gives a thicker chip which breaks more quickly. A small depth of cut with a fine feed allows the chip to form into comparatively small pieces or direct it into the swarf tray. The use of a good stream of coolant that acts as a quenching medium causes the hot chip to become harder and break into small pieces.

2.14 CUTTING–TOOL NOMENCLATURE

Cutting-tool nomenclature means systematic naming of the various parts and angles of a cutting-tool. The surfaces on the point of a tool bear definite relationship to each other that are defined by angles. The principles underlying cutting-tool angles are the same whether the tool is a single-point tool, a multipoint tool, or a grinding wheel. Since a single-point tool is the easiest to understand, it will be discussed in greater detail. The basic angles needed on a single-point tool may be best understood by removing the unwanted surface from an oblong tool blank of square section. However, the complete nomenclature of the various parts of a single-point tool is shown in Fig.2.18. These are : shank, face, flank, heel, nose, base, back rake, side rake, side clearance, end cutting edge, wide cutting edge, and lip angle. These elements define the shape of a tool.

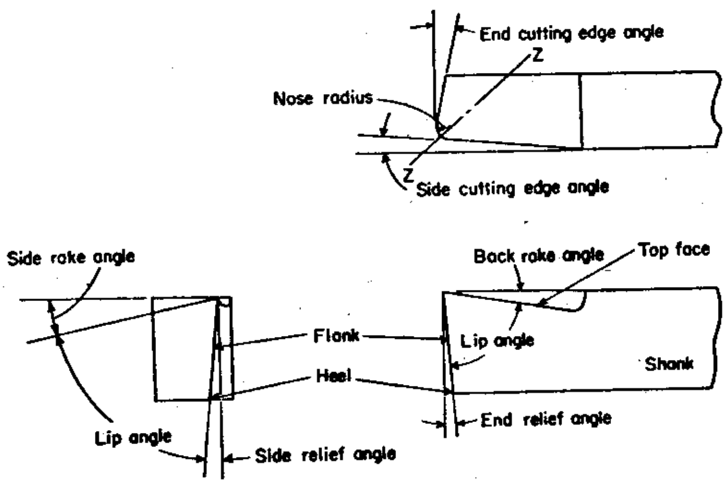

Figure 2.18 Tool nomenclature and tool angles (sec. 3.50 for tool signature)

The *Shank* is that portion of the tool bit which is not ground to form cutting edges and is rectangular in cross-section.

The *face* of the cutting-tool is that surface against which the chip slides upward.

The *flank* of a cutting-tool is that surface which face the workpiece.

The *heel* of a single point tool is the lowest portion of the side-cutting edges.

The *nose* of a tool is the conjunction of the side- and end-cutting edges. A nose radius increases the tool life and improves surface finish.

The *base* of a tool is the under-side of the shank.

The *rake* is the slope of the top away from the cutting edge. The larger the rake angle, the larger the shear angle and subsequently the cutting force and power reduce. A large rake angle is conducive to good surface finish. Each tool has a side and back rake. *Back rake* indicates that the plane which forms the face or top of a tool has been ground back at an angle sloping from the nose. *Side rake* indicates that the plane that form the face or top of a tool has been ground back at an angle sloping from the side cutting edge. Side rake is more important than back rake for turning operations.

The *side clearance* or *side relief* indicates that the plane that forms the flank or side of a tool has been ground back at an angle sloping down form the side cutting edge. Likewise, *the end clearance* or *end relief* indicates that the nose or end of a tool has been ground back at an angle sloping down from the end cutting edge.

The *end cutting edge angle* indicates that the plane which forms the end of a tool has been ground back at an angle sloping form the nose to the side of the shank, whereas the *side cutting edge angle* indicates that the plane which forms the flank or side for a tool has been ground back at an angle to the side of the shank. In the main, chips are removed by this cutting edge.

The *lip* or *cutting angle* is the included angle when the tool has been ground wedged-shaped.

Multipoint tools : Cutters like twist drills, reamers, taps, milling cutters have two or more tool points each. They differ in overall appearance and purposes, but each cutting blade acts as and has the basic features of a single-point tool. The milling cutter, and drill like a single point tool, have various angles of importance. A milling cutter has *clearance* ; it often has both a secondary and a primary clearance. A *land* also exists on a milling cutter and a drill. This is the narrow surface resulting from providing a primary clearance. They may have different rakes depending on the intended use. These kinds of tools have been described in more detail in connection with these machines in later chapters.

2.15 GEOMETRICAL CONTROL OF TOOL ANGLES

Geometrical control of the cutting edge means control or influence of the cutting edge including the various angles in a cutting tool in the effective machining of a metal. A tool is ground to a given form to produce a cutting edge of a given shape in a given position in relation to the shank of the tool, and to produce a form that will permit the cutting edge to be fed into the workpiece so that it can cut efficiently. To grind the tool properly the edge must keep its shape-flat or curved as the case may be. Also, to cut well, the surfaces that form edge must be ground to "certain angles". These angles are measured in degrees.

The exact shape of a cutting tool depends upon the kind of metal being cut. This applies particularly to the keenness or cutting angle of the tool. Hard materials require a greater lip angle than soft materials because of the strength inherent in the cutting edge with the greater angle. However, since an increase in the lip angle also increases the amount of force necessary to cut the metal, it is advisable to compromise the two factors to obtain the best results.

Experience and study have established that certain shapes of tools are more satisfactory for certain types of work than others. Besides the variation of cutting angles required for different materials, tool shapes are designed in working these materials to secure the best possible finish, the longest tool life, and the most rapid cutting. The rake, relief, side- and end-cutting edge angles each influence tool performance to a considerable extent. Therefore, their values should be selected with great care and consideration. A general discussion of the tool performance with reference to these angle is presented in Art.3.43.

2.16 THE CUTTING ACTION OF HAND TOOLS

As described in Art.2.2, all hand tools may also be classified as single-point tools and multi-point tools, and the action of removing metal is one of shear. The fundamental cutting form that has been described before, applies, in principle, on every type of cutting edge used for metal cutting,

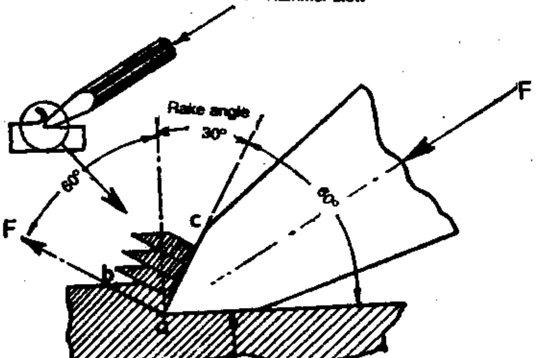

Figure 2.19 Shearing action of a cold chisel

whether at the bench or in a machine tool. In some cases, at the first instance, it appears that the principle of cutting perhaps does not apply, but upon more detailed examination the fundamental rake or clearance may be found out. In the subsequent paragraphs a few of the more common hand tools are described.

The flat chisel : A flat cold chisel is a single-point tool used at the bench and the point is considered as a wedge. A diagram of a chisel point in the action of cutting is shown at Fig.2.19, where the angle of rake and wedge angle are indicated. For mild steel a rake angle of 30° and wedge angle of 60° are recommended. The chisel is seen flat on the work and there is no clearance angle. This ensures that the depth of cut can be maintained. It should be understood that the clearance angle takes on actual part in the cutting or shearing action, but is given on a tool to remove the loss of energy caused by frictional resistance. Using a cold chisel with no clearance angle, the loss through friction is small as one cutting point is in contact with the metal. It is, therefore, better to use the chisel as in Fig.2.19, for the loss of energy due to friction at the heel of the chisel is less than that by the maintenance of the depth of the cut giving a little amount of clearance angle.

The force of the hammer blow *F* is transmitted at approximately 90° to the cutting face *ac*, and this sets up shear stress across the shear plane *ab*. Provided the hammer blow is heavy enough, the metal will shear across the shear plane and move up the face *ac* as a continuous chip. The energy required to shear the metal will be the shearing force along the shear plane *ab* and this force is proportional to the length of the shear plane, and the greater the energy required to shear the metal.

The hack saw blade : A hack saw blade is a multi-point tool and has a very large number of wedge-like points each with its own rake and clearance angle. The rake and clearance angle of a hack saw blade is shown in Fig.2.20. The rake is necessary but too much rake makes the tooth weak . It is also necessary to have clearance angles on these wedge-like points. A large amount of energy would be lost in overcoming the frictional forces set up if there were no clearance.

The hollow space between each tool is sloped more sharply to give the form as shown in Fig.2.20. If this would be too shallow it would have clogged with chips of the metal being cut. The radiussed portion in the upper part of the hollow space adds strength.

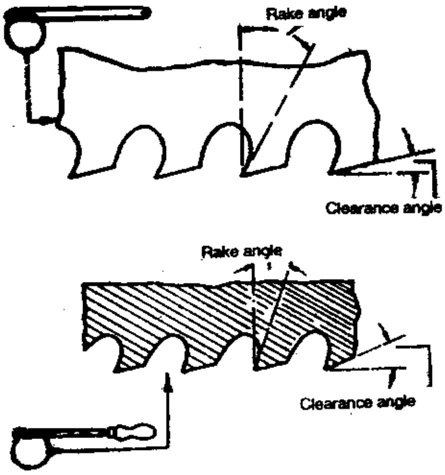

Figure 2.20 Rake and clearance angles on hack saw blade and file

The file : A file is also a multi-point tool and has a large number of wedge like points as in the case of a hack saw blade. The most usual form of file is that with cross-cut teeth and the grooves in the face run in two directions dividing it up into small diamond shaped teeth. In a single-cut file there is only one series of grooves . The result of the two sets of cuts is to raise teeth in the form of small pyramids with edged tops turned back towards the direction in which the file must cut. An enlarged view of the teeth of a file with rake and clearance angle is shown in Fig.2.20.

Taps and dies : Taps used for cutting internal threads are hardened and tempered, and are of relatively small cross-section. They may be easily broken if excessive torque or turning moment is applied. The rake angles on the flutes of a tap will reduce the shear forces so that less torque is required to shear the metal. But there is no clearance angle on hand taps and that the frictional forces set up will increase the turning moment and tend to cause breakage. The cross-

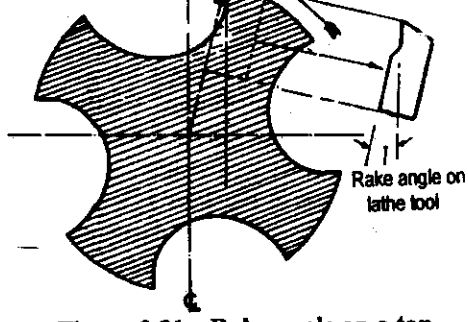

Figure 2.21 Rake angle on a tap

section of a tap is shown in Fig.2.21. It will be seen that the rake angle is obtained by offsetting the flutes.

The rake angle of a die used for cutting external threads is shown in Fig.2.22. This is obtained by the position of the four holes in a die.

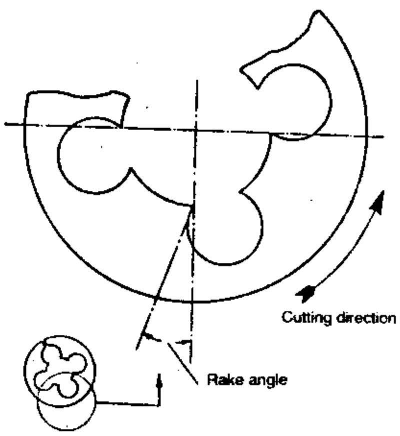

Figure 2.22 Rake angle on a die

2.17 CUTTING SPEEDS AND FEEDS

The *cutting speed* of a cutting tool may be defined as the speed at which the cutting edge passes over the material. Cutting speed is ordinarily expressed in metre per minute, often referred to as surface speed in meter per minute.

The *feed* of a cutting tool is the distance the tooi advances into or along the workpiece each time the tool point passes a certain position in its travel over the surface. In the case of turning on a lathe, the feed is the distance that the tool advances in one revolution of the workpiece. On a shaper, the feed is the distance the work is moved relative to the tool for each cutting stroke. For single-points tools, feed is specified in millimeters per revolution, millimeters per stroke, etc. It also may be expressed as millimeters per tooth for milling cutters and broaches.

Since so many factors are required to be considered, it is difficult to state definitely what the speed and feeds for a given material should be. In general, the speed and feed are determined by the following factors :

1. *Kind of material being cut.* The harder the material, the more force required to remove the chip and the more rapid the wear on the tool. For this reason, hard materials are to be machined at lower cutting speeds and smaller feeds than soft materials.
2. *Kind of material and life of the tool.* An increase in cutting speed will result in more intensive heat generation, consequently, more heat resistant tool materials should be used when machining at high cutting speeds. Carbon steel tools car

take about one half the cutting speed of a high-speed steel tool. Stellite and carbide and carbide tools will stand still greater speeds. These heat resistant tools may be used under heavier feeds than other tool materials.

3. *Shape (angles) and dimension of the cutting elements.* A change in the chief angles of the tool will correspondingly change the forces due to the cutting action, as well as the conditions for heat transmission through the cutting elements of the tool. The heavier the cutting elements, the easier the heat will flow to the body of the tool. Therefore, tooi wear will vary for various shapes and dimensions of the cutting elements and even of the body of the tool. Forming tools, taps, and other tools that are expensive and difficult to sharpen should be operated at speeds and feeds that insure long life.
4. *Size of chip cross-section.* The size of chip cross-section affects the forces due to cutting and, consequently the amount of heat generated. Tool wear is more rapid with an increase in cutting speed than with an increase in chip cross-section. For this reason, an increase in production capacity at a given tool life can be provided by increasing the cross-section of the chip removed and not the cutting speed. In such cases, the cross-section of the chip should be increased by increasing the depth of cut and not the feed.
5. *Types of finish desired.* In general, high cutting speeds and fine feeds give the best finish.
6. *Rigidity of the machine.* No work should be done at speeds and feeds that cause vibration in the machine.
7. *Types of coolant used.* Cooling with cutting fluids is not only for carrying away the heat generated, but also because of the lubricating effect of the fluid on the working surface of the tool. When a cutting fluid is used in machining tough material, the productivity may be increased from 15 to 30 % and more in comparison with dry operation. So higher cutting speeds and larger feeds may be given using a suitable cutting fluid.

2.18 FRICTION AND HEAT SOURCES IN CUTTING

All the mechanical work done in cutting metal is converted into an equivalent amount of heat.

The work (W) done in cutting depends upon the cutting force P_z and the cutting speed v. It is determined from the formula :

$$W = P_z v \text{ kgfm per min.}$$

The amount of heat Q generated in a unit of time (one minute) by metal cutting is based upon the thermal equivalent of work, equal to 427 kgfm per kcal ; then

$$Q = \frac{W}{427} = \frac{P_z v}{427} \text{ kcal per min.}$$

The generated heat is distributed between the workpiece, chip and tool : only a negligible amount of heat is dissipated to the ambient air.

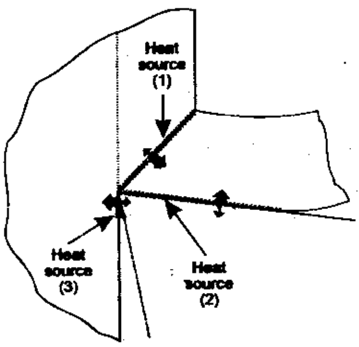

Figure 2.23(a) Source of heat in metal cutting

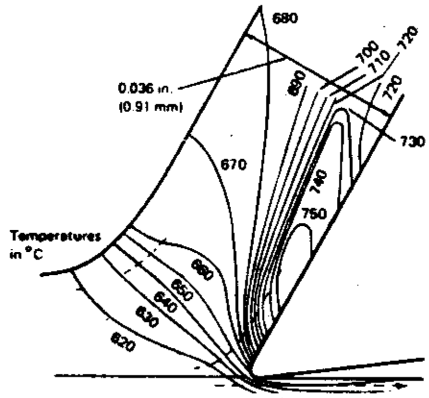

Figure 2.23(b) Temperature distribution in cutting zone

The main sources of heat in metal cutting are shown in Fig.2.23(a). These three distinct heat sources are :

1. ***The shear zone, 1***, where the main plastic deformation takes place due to shear energy. This heat raises the temperature of the chip. Part of this heat is carried away by the chip when it moves upward along the tool.

Considering a continuous type chip, as the cutting speed increases for a given rate of feed, the chip thickness decreases and less shear energy is required for chip deformation so the chip is heated less from this deformation.

2. ***The chip-tool interface zone, 2***, where secondary plastic deformation due to friction between heated chip and tool takes place. This causes a further rise in the temperature of the chip.

The frictional heat increases with increasing cutting speed. The tool-chip interface temperature increases with the cutting speed and the work hardness because the heat is concentrated upon a smaller area even though the quantity of heat transferred to be remained constant. The tool-chip temperature rise but less rapidly than for a rise in the cutting speed. Changes in the depth of cut is appreciably greater than the nose radius. Less heat is generated when higher feed rates are used but the surface quality is adversely affected.

3. *The work-tool interface zone, 3,* at flanks where friction rubbing occurs.

Fig.2.23(b) shows the temperature distribution during cutting operation.

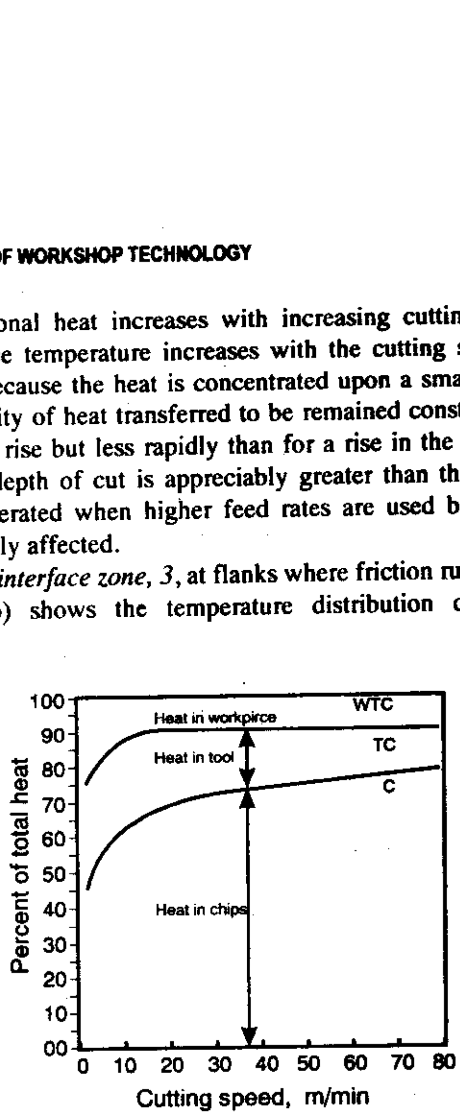

Figure 2.24 Distribution of heat during metal cutting
WTC = 100% total heat, TC = total heat in tool and chip, C = heat in chips.

In machining steel with a single-point tool having a cemented-carbide tip, the relative amount of heat passing into the chip, workpiece, and tool at different cutting speeds is illustrated in Fig.2.24. It is seen that as the cutting speed increases, proportionately more heat is carried away by the chip and less is transferred to the work-piece and the tool. The fact that at high cutting speeds most of the heat energy is carried away by the chip leads to the advantage and practicability of the tool is tolerable.

2.19 TOOL LIFE AND WEAR

The tool life is an important factor in a cutting tool performance since considerable time is lost whenever tool is ground and re-set.

A tool cannot cut for an unlimited period of time. It has its definite life. If a cutting tool is to have a long life it is essential that the face of the tool be as smooth as possible. Tool life is the time a tool will operate satisfactorily until it is dulled. A blunt tool causes chatter in machining, poor surface finish, increase in cutting forces and power consumption, overheating of the tool.

Tool failure : The failure of cutting tools may be the result of :

1. *Wear on the flank of the tool* (Fig.2.25). Flank Wear is a flat portion worn behind the cutting edge which eliminates some clearance or relief. Flank wear takes place when machining brittle materials like C.I. or when feed is less than 0.15 mm/rev. The worn region at the flank is called the wear land. The wear land width is measured accurately with a Brinel microscope. Increased wear land means that frictional heat will cause excessive temperature of the tool at its cutting point ; it will rapidly loose its hardness, and catastrophic failure of the tool will be imminent. In the meantime, the burnishing action of the tool at its wear land will mean poor surface finish on the workpiece.

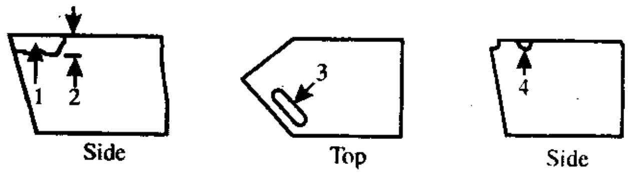

Figure 2.25 Common types of tool failure
1. Flank wear, 2. Wear land, 3. Crater, 4. Chipping.

A quantitative term setting the limit of the permissible value of wear is known as "criterion of wear". The criterion of wear for different tool materials is given below in Table 2.2.

2. *Wear at the tool-chip interface* occurs in the form of a depression or crater (Fig.2.25). This is caused by the pressure of the chip as it slides up the face of the cutting tool . Both flank and crater wear take place when feed is greater than 0.15 mm/rev at low or moderate speeds. Actually a limited amount of cratering or depression improve the cutting action. but as the crater is further

enlarged, some material which supports the cutting edge is removed. This eventually will cause the cutting edge to be weakened so that it will break. This type of failure occurs when high speed steel, stellite, or sintered-carbide tools turn ductile metals.

TABLE 2.2 CRITERION OF WEAR IN CUTTING TOOLS

Tool Material	*Job Material*	*Cutting Condition*	*Predominant Wear*	*Criterion of Wear*
h.s.s.	C.I.	Semi-rough	flank	1.5 to 2 mm
h.s.s.	Steel	Semi-rough	flank	0.6 to 1.0 mm
Cemented carbide	Steel	$s > 0.3$ mm	flank	1.4 to 1.7 mm
Cemented carbide	C.I.	$s < 0.3$ mm	flank	0.8 mm to 1.0 mm
Ceramic tool	C.I., Steel	—	flank	0.6 mm

3. *A combination of flank wear and cratering.*
4. The *spalling* or *crumbling* of the cutting edge (Fig.2.25) as when cutting extremely hard material. A cutting tool that has improperly ground relief angles will either rub on the material or be weak because of excessive clearance angles. If the cutting edges are not well supported, they will be subject to cracking and spalling. The proper setting of the tool is, therefore, an important consideration.

Other factors that cause the tool to chip or spall are excessive chip loads, intermittent heating and cooling, and interrupted cutting. Excessive chip loads are caused by too fast a feed or too deep a cut. Intermittent heating and cooling result because the cutting fluid is not able to cover the cutting point constantly, and because the tool keeps entering and leaving the material. Interrupted cutting is caused by a tool entering and leaving the work as in milling or planing. Hard grades of carbide are likely to chip under these conditions.

5. The *loss of hardness* because of excessive heat but under cutting conditions when the temperature and stresses are high, plastic deformation may cause loss of "form stability", i.e. cutting ability of the tool. Various tool materials can withstand various heating temperatures (critical temperatures) before they lose the required

hardness– 200° to 250°C for carbon tool steels, 560°C for high-speed steels and 800° to 1,000°C for cemented carbides.
6. *Fracture by a process of mechanical breakage* when the cutting force is very large or by developing fatigue cracks under chatter conditions.

Frequently in the formation of chips, high-frequency vibration occurs when the tool or work is not supported rigidly, because of the sliding of the chip elements into sections, because of the flank wear, or because of the periodic sloughing off of the built-up edge. These work, or even the whole machine, which in turn may cause a disagreeable noise called *chatter*.

Factors affecting tool life : The life of a tool is affected by many factors such as : cutting speed, feed, depth of cut, chip thickness tool geometry, material of the cutting fluid and rigidity of the machine. Physical and chemical properties of work materials influence tool life by affecting form stability and rate of wear of tools. The nose radius also tends to affect tool life. Researchers have identified a number of factors which are established by experimental verification. Some of them are briefly described in the subsequent paragraphs.

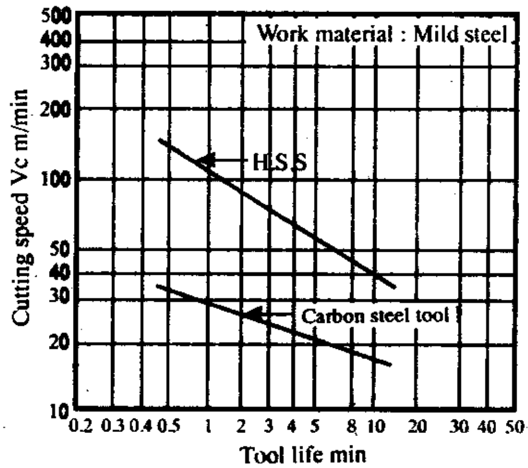

Figure 2.26 Tool life vs cutting speed

Cutting speed : Cutting speed has the greatest influence on tool life. As the cutting speed increases the temperature also rises. The heat is more concentrated on the tool than on the work and the hardness of the tool matrix changes so the relative increase in the hardness of the work accelerates the abrasive action. The criterion of wear is dependent on cutting speed because the predominant wear may be wear for flank or crater if cutting speed is increased. It has been found that at cutting speeds greater than 100 m per min in carbide turning of steel, crater wear may become predominant.

The relation of the cutting speed to the tool life is expressed by the formula :

$$VT^n = C$$

where, V = cutting speed in m per min.
T = tool life in minutes.
n = exponent which depends on the tool and the workpiece. The value of exponent n is about 0.1 for high-speed steel tool, 0.20 to 0.25 for carbide tools, and 0.4 to 0.55 for ceramic tools.
C = constant which is numerically equal to cutting speed that gives a tool life of one minute.

A typical V vs. T relationship is shown in Fig.2.26 which indicates that as cutting speed increases, tool life decreases. Obviously, if a very low cutting speed is used, the tool will last a long life. In case of carbide tools very low cutting speed, usually below 30 m per min, may reduce tool life. However, an intricate cutting tool that is difficult to sharpen should be run at a low speed so that it does not have to be sharpened again.

Feed and depth of cut : The tool life is influenced by the feed rate also. With a fine feed the area of chip passing over the tool face is greater than that of a coarse feed for a given volume of swarf removal, but to offset this chip will be greater. Hence the resultant pressure will nullify the advantage ; it is, however, possible to balance the two opposing influences to obtain an optimum feed rate.

The effect of feed and depth of cut on tool life is given by :

$$V = \frac{257}{T^{0.19} \times s^{0.36} \times t^{0.08}} \text{ m per min.}$$

where, s = feed in mm per min,
and t = depth of cut in mm.

Another relation between cutting speed for a given tool life, depth of cut and feed is given by :

$$V_t = \frac{C_v}{t^x . s^y} \text{ m per min.}$$

where, V_t = cutting speed for a given tool life in m per min,
C_v = a coefficient depending upon machine and workpieces variables,
x,y = exponents which depend on the mechanical properties of the material being machined.

The above relation shows that for a constant tool life cutting speed decreases with the increase of feed and depth of cut.

Tool geometry : The tool life is also affected by tool geometry. A tool with large rake angle becomes weak as a large rake reduces the tool cross-section and the amount of metal to absorb the heat. It is –5° and +10° for turning austenitic steel by a carbide tool. The nose radius tends to improve tool life and is evident from the relation :

$$VT^{0.0927} = 331 \, R^{0.244}$$

where R = nose radius of h.s.s. tool. But the size of the radius is limited by vibration. The effect of clearance is to improve tool life at first and then tool life decreases because of decreased strength. The optimum clearance is between 10° to 15°. Side cutting edge angle (ϕ_s) may improve tool life under non-chatter conditions :

$$VT^{0.11} = 78(\phi_s + 15°)^{0.264}$$

where ϕ_s = side cutting edge angle of h.s.s. tool cutting steel. With cemented carbide, side cutting edge angle varies between 3° to 25°. The effect of end cutting edge angle is to improve surface finish, rigidity and equivalent speed. The optimum end cutting edge angle is 4° to 10°. Similarly, the clearance is seen to be optimum for 12° to 15°.

Tool material : The effect of tool material on tool life is shown in Fig.2.27 which indicates that higher cutting speed is not the only criteria considered for removing large volume of metal. What is most desirable is the high rate at which the stock will be removed per cutting edge or tool-life. An ideal tool would remove the same amount of metal per cutting edge at any speed.

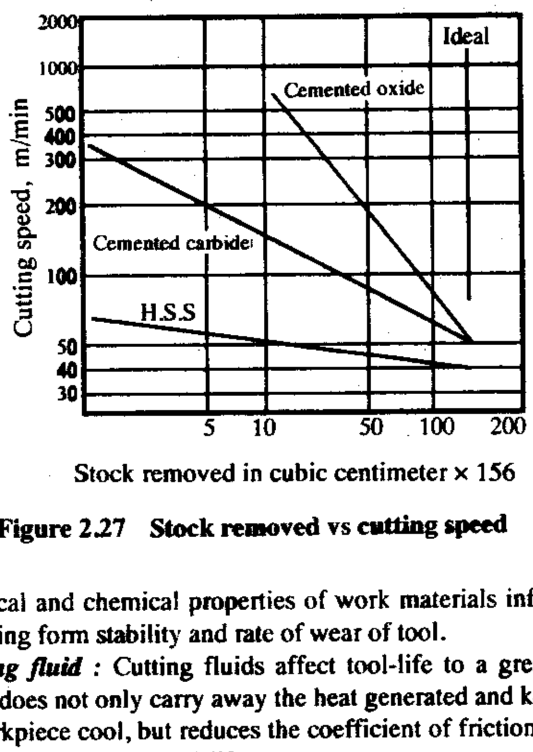

Figure 2.27 Stock removed vs cutting speed

Physical and chemical properties of work materials influence tool-life by affecting form stability and rate of wear of tool.

Cutting fluid : Cutting fluids affect tool-life to a great extent. A cutting fluid does not only carry away the heat generated and keep the tool, chip and workpiece cool, but reduces the coefficient of friction at the chip-tool interface and increases tool-life.

Measuring tool-life : Tool-life is the time elapsed between two successive grinding of a cutting tool. Tool-life may be measured in the following ways :

1. Number of pieces machined between tool sharpenings.
2. Time of actual operation, viz., the time the tool is in contact with the job.
3. Total time of operation.
4. Equivalent cutting speed.
5. Volume of material removed between tool sharpenings.

In practice it is more profitable to assess the tool-life in terms of the volume of metal removed because the wear is related to the area of the chip passing over the tool surface. The volume of metal removed from the workpiece between tool sharpenings for a definite depth of cut, feed, and cutting speed can be determined as follows :

Notation :

t = depth of cut in mm
S = feed in mm per rev
d = diameter of the workpiece in mm
V = cutting speed in m per min
T = time to tool failure in min
n = revolution per min of the workpiece
L = tool-life in terms of metal removed until tool fails in mm^3.

Cross sectional area of chip	$= ts\ mm^2$
Length of chip in one revolution	$= \pi d$ mm
∴ Volume of metal removed / rev	$= \pi dts\ mm^3$
Volume of metal removed / min	$= \pi dtsn\ mm^3/min$
Volume of metal removed until tool fails	$= \pi dtsnT\ mm^3$

$$\therefore \quad L = \pi dtsnT$$

$$V = \frac{\pi dn}{1{,}000} \text{ m/min}$$

$$\therefore \text{ Too-life, } L = 1{,}000\, tsVT \text{ mm}^3/\text{min}$$

2.20 MACHINABILITY

The 'ease' with which a given material may be worked with a cutting tool is machinability. Machinability depends on :

1. Chemical composition of workpiece material.
2. Micro-structure.
3. Mechanical properties.
4. Physical properties.
5. Cutting conditions.

In evaluating machinability the following criterion may be considered :

1. Tool-life between grinds.
2. Value of cutting forces.
3. Quality of surface finish.
4. Form and size of chips.
5. Temperature of cutting.
6. Rate of cutting under a standard force.
7. Rate of metal removal.

The main factor to be chosen for judging machinability depends on the type of operation and production requirements.

Some factors that are used to predict and calculate machinability are tensile strength, Brinell hardness and shear angle. The shear angle of a given material may be calculated, as explained before, by comparing chip thickness before removal a_1 with the chip thickness after removal a_2, i.e., in terms of a_2/a_1. In terms of shear angle this is found by use of the formula (Refer section 2.5):

$$\tan\beta = \frac{\cos\gamma}{r_c - \sin\gamma}$$

Machinability index : Good machinability implies satisfactory results in machining. But this machinability is not a basic standard, but is relative. The rated machinability of two or more metals being compared may vary for different processes of cutting, such as heavy turning, light turning, forming, milling, drilling, etc. Good machinability indicates many aspects, but many times one or more objectives must be sacrificed to obtain others.

The machinability of different metals to be machined may be compared by using the machinability index of each. This is defined as follows :

Machinability index,

$$\text{MI}\,\% = \frac{\text{cutting speed of metal investigated for 20 min. tool-life}}{\text{cutting speed of standard steel for 20 min. tool-life}}$$

A free-cutting steel, which is machined relatively easily and machinability index of which is arbitrarily fixed at 100 per cent, is considered a standard steel. This steel has carbon contents of 0.13 maximum, manganese of 0.06 to 1.10 and sulphur of 0.08 to 0.03 per cent.

2.21 CUTTING TOOL-MATERIALS

Characteristic : The characteristics of the ideal material are :

1. *Hot hardness.* The material must remain harder than the work material at elevated operating temperatures.
2. *Wear resistance.* The material must withstand excessive wear even though the relative hardness of the tool-work materials changes.
3. *Toughness.* The term 'toughness' actually implies a combination of strength and ductility. The material must have sufficient toughness to withstand shocks and vibrations and to prevent breakage.
4. *Cost and easiness in fabrication.* The cost and easiness of fabrication should have within reasonable limits.

Type of Tool Materials : The selection of proper tool material depends on the type of service to which the tool will be subjected. No material is superior in all respects, but rather each has certain characteristics which limits its field of application.

The principal cutting materials are :

1. Carbon steels.	5. Cemented carbides.
2. Medium alloy steels.	6. Ceramics.
3. High-speed steels.	7. Diamonds.
4. Stellites.	8. Abrasives.

1. *Carbon steels* : Carbon steels contain carbon in amounts ranging from 0.08 to 1.5 per cent. A disadvantage of carbon tool steels is their comparatively low-heat and wear-resistance. They lose their required hardness at temperatures from 200° to 250°C. Therefore, they may only be used in the manufacture of tools operating at low cutting speeds (about 12m/min) and of hand operated tools. But they are comparatively cheap, easy to forge, and simple to harden.

2. *Medium alloy steels* : The high carbon medium alloy steels have a carbon content akin to plain carbon steels, but in addition there is, say, up to 5 per cent alloy content consisting of tungsten, molybdenum, chromium and vanadium. Small additions of one or more of these elements improve the performance of the carbon steels in respect of hot hardness, wear resistance, shock and impact resistance and resistance to distortion during heat treatment. The alloy carbon steels, therefore, broadly occupy a midway performance position between plain carbon and high speed steels. They lose their required hardness at temperatures from 250° to 350°C.

These tool steels are of two types ; (1) Type – O tool steels, (2) Type – A tool steels.

Type – O tool steels are oil quenched for hardening. It has C-0.90%, Mn-1.00%, W-0.5% and Cr-0.5%. Punching dies are generally manufactured from this steel.

Type – A tool steels are hardened by slow cooling in a current of air after heating it to a high temperature (1100°C to 1300°C). The composition of this type of steel is C-1.0%, Cr-5%,. It is mainly used to manufacture thread rolling dies, coining dies and guages.

3. ***High-speed steels :*** High-speed steel (h.s.s) is the general purpose metal for low and medium cutting speeds owing to its superior hot hardness and resistance to wear. High-speed steels operate at cutting speeds 2 to 3 times higher than for carbon steels and retain their hardness up to about 900°C. It is used as a popular operations of drilling, tapping, hobbing, milling, turning etc. There are three general types of high-speed steels; high tungsten, high molybdenum, and high cobalt. Tungsten in h.s.s. provides hot hardness and form stability, molybdenum or vanadium maintains keenness of the cutting edge, while addition of cobalt improves hot hardness and makes the cutting tool more wear resistant. Three general types of high-speed steels are as follows :

a. 18-4-1 *high-speed steels (T-series).* This steel containing 18 per cent tungsten, 4 per cent chromium and 1 per cent vanadium, is considered to be one of the best of all purpose tool steels. In some steels of similar composition the percentage of vanadium is slightly increased to obtain better results in heavy-duty work.

b. *Molybdenum high-speed-steel (M-series).* This steel containing 6 per cent molybdenum, 6 per cent tungsten, 4 per cent chromium and 2 per cent vanadium have excellent toughness and cutting ability.

There are other molybdenum high speed steels now marketed, having various tungsten-molybdenum ratios, with or without cobalt, or with variations in percentages of the minor alloys chromium and vanadium.

c. *Cobalt high-speed steels :* This is sometimes called super high-speed steel. Cobalt is added from 2 to 15 per cent to increase hot hardness and wear resistance. One analysis of this steel contains 20 per cent tungsten, 4 per cent chromium, 2 per cent vanadium and 12 per cent cobalt.

Table 2.3 shows the compositions of selected types of h.s.s.

TABLE 2.3 COMPOSITIONS OF H.S.S

Designation	Percentages of contributions					
	C	W	Mo	Cr	V	Co
T–1	0.75	18.00	–	4.00	1.00	–
T–2	0.85	18.00	–	4.00	2.00	–
T–5	0.80	18.00	–	4.25	2.00	8.00
T–15	1.50	12.00	–	4.50	5.00	5.00
M–1	0.80	1.75	8.50	3.75	1.20	–
M–2	0.85	6.00	5.00	4.00	2.00	–
M–10	0.90	–	8.00	4.00	2.00	–
M–45	1.25	8.25	5.00	4.25	1.60	5.50

4. *Stellites* : Stellite is the trade name of a nonferrous cast alloy composed of cobalt, chromium and tungsten. The range of elements in these alloys is 40 to 48 per cent cobalt, 30 to 35 per cent chromium, and 12 to 19 per cent tungsten. In addition to one or more carbide forming elements, carbon is added in amounts of 1.8 to 2.5 per cent. They can not be forged to shape, but may be deposited directly on the tool shank in an oxy-acetylene flame, alternately, small tips of cast stellite can be brazed into place. Stellites preserve hardness up to 1000°C and can be operated on steel at cutting speeds 2 times higher than for high-speed steel. These materials are not widely used for metal cutting since they are very brittle, however, they are used extensively in some non-metal cutting application, such as in rubbers, plastics, where the loads are gradually applies and the support is firm and where wear and abrasion are problems.

5. *Cemented carbides* : Cemented carbides are so named because they are composed principally of carbon mixed with other elements. The basic ingredient of most cemented carbides is tungsten carbide which is extremely hard. Pure tungsten powder is mixed under high heat, at about 1500°C, with pure carbon (lamp black) in the ratio of 94 per cent and 6 per cent by weight. The new compound, tungsten carbide, is then mixed with cobalt until the mass is entirely homogeneous. This homogenous mass is pressed, at pressures from 1,000 to 4,200 kg/cm^2, into suitable blocks and then heated in hydrogen. Boron, titanium and tantalum are also used to form carbides. The amount of cobalt used will regulate the toughness of the tool. A typical analysis of a carbide suitable for steel machining is 82 per cent tungsten carbide, 10 per cent titanium carbide and 8 per cent cobalt.

Carbide tools are made by brazing or silver-soldering the formed inserts on the ends of commercial steel holders. The most important properties of cemented carbides are their very high heat and wear resistance. Cemented carbide tipped tools can machine metals even when their cutting elements are heated to a temperature of 1,000°C. They can withstand cutting speed 6 per cent or more than 6 times higher manufactured material and has extremely high compressive strength. However, it is very brittle, has low resistance to shock, and must be very rigidly supported to prevent cracking.

The two types of cemented carbides are the tungsten and titanium tungsten varieties. The *tungsten-type cemented carbides* are less brittle than the titanium-tungsten type; they contain 92 to 98 per cent tungsten carbide and from 2 to 8 per cent cobalt. These cemented carbides are designed chiefly for machining brittle metals such as cast iron, bronze, but they may also be used for non-ferrous metals and alloys, steel, etc. The *titanium-tungsten type* are more wear-resistant. They contain 66 to 85 per cent tungsten carbide, 5 to 30 per cent titanium carbide and 4 to 10 per cent cobalt. These cemented carbides are designed for machining tougher materials chiefly for various steels.

6. *Ceramics* : The latest development in the metal-cutting tools uses aluminium oxide generally referred to as ceramics. Ceramics tools are made by composing aluminium oxide powder in a mould at about 280 kg/cm^2 or more. The part is then sintered at 2200°C. This is known as cold pressing. Hot pressed ceramics are more expensive owing to higher mould costs. Ceramic tool materials are made in the form of tips that are to be clamped on metal shanks. Other materials used to produce ceramic tools include sillicon carbide, boron carbide, titanium carbide and titanium boride.

These tools have very low heat conductivity and extremely high compressive strength. But they are quite brittle and have a low bending strength. For this reason, these materials can not be used for tools operating in interrupted cuts, with vibrations as well as for removing a heavy chip. But they can withstand temperatures up to 1200°C and can be used at cutting speeds 4 times that of cemented carbides, and up to about 40 times that of high-speed cutting tools. They are chiefly used for single-point tools in semi-finish and finish turning of cast iron, plastics, and other work, but only when they are not subject to impact loads. To give them increased strength often ceramic with a metal bond, known as "cermets" is used. Because of the high compressive strength and brittleness the tips are given a 5 to 8° negative rake for carbon steel and zero rake for cast iron and for non-metallic materials to strengthen their cutting edge and are well supported by the tool holder. Heat conductivity of ceramics being very low the tools are generally used without a coolant.

7. ***Diamond*** : The diamonds used for cutting tools are industrial diamonds, which are naturally occurring diamonds containing flaws and therefore of no value as gemstones. Alternatively they can be also artificial. The diamond is the hardest known material and can be run at cutting speeds about 50 times greater than that for h.s.s. tool, and at temperatures up to 1650°C. In addition to its hardness the diamond is incompressible, is of a large grain structure, readily conducts heat, and has a low coefficient of friction. Diamonds are suitable for cutting very hard materials such as glass, plastics, ceramics and other abrasive materials and for producing fine finishes. The maximum depth of cut recommended is 0.125 mm with feeds of say, 0.05 mm.

8. ***Abrasive*** : Abrasive grains in various forms–loose, bonded into wheels and stone, and embedded in papers and cloths–find wide application in industry. They are mainly used for grinding harder materials and where a superior finish is desired on hardened or unhardened materials.

For most grinding operations there are two kinds of abrasives in general use, namely aluminium oxide (carborundum) and silicon carbide. The aluminium oxide abrasives are used for grinding all high tensile materials, whereas silicon carbide abrasives are more suitable for low tensile materials and non-ferrous metals.

9. ***Cubic boron nitride*** (CBN) : This material, consisting atoms of boron and nitrogen, is considered as the hardest tool material available next to diamond. It is having high hardness, high thermal conductivity and tensile strength. In certain application a thin layer (0.5 mm) of CBN is applied on cemented carbide tools to obtain better machining performance. It can also be made in terms of indexable inserts in standard form and size. This material is traded in the name of 'BOROZON'.

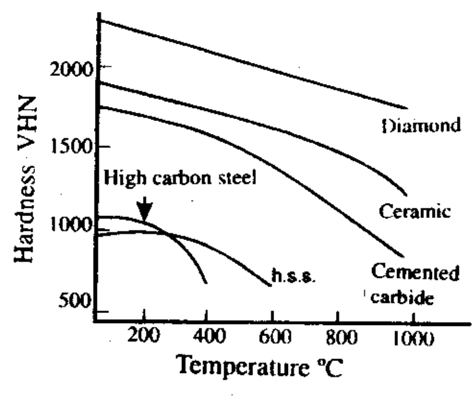

Figure 2.28 Hardness profiles of cutting tool materials

10. ***Coated carbide tools*** : For coated carbide tools, a thin chemically stable, shock resistance refractory coatings of TiC, Al_2O_3 and TiN are applied on the tungsten carbide inserts, using chemical vapour deposition method (CVD). In this coating first layer is of TiC, second layer is of Al_2O_3 and the top thin layer is of TiN. This process makes the insert two to three times stronger for wear resistance

The variations of hardness of a few of the tool materials with temperatures are shown in Fig.2.28.

2.22 CUTTING FLUIDS

Cutting fluids, sometimes referred to as lubricants or coolants are liquids and gases applied to the tool and workpiece to assist in the cutting operations.

Purpose of Cutting Fluids : Cutting fluids are used for the following purposes :

1. *To cool the tool.* Cooling the tool is necessary to prevent metallurgical damage and to assist in decreasing friction at the tool-chip interface and at the tool-workpiece interface. Decreasing friction means less power required to machine, and more important, increased tool life and good surface finish. The cooling action of the fluid is by direct carrying away of the heat developed by the plastic deformation of the shear plane and that due to friction. Hence, a high specific heat and high heat-conductivity together with a high film-coefficient for heat transfer is necessary for a good coolant. For cooling ability, water is very effective, but is objectionable for corrosiveness and lack of friction reducing wear.
2. *To cool the workpiece.* The role of the cutting fluid in cooling the workpiece is to prevent its excessive thermal distortion.
3. *To lubricate and reduce friction. (a)* The energy or power consumption in removing metal is reduced : *(b)* abrasion or wear on the cutting tool is reduced thereby increasing the life of the tool ; *(c)* by virtue of lubrication, less heat is generated and the tool, therefore, operates at lower temperatures with the tendency to extend tool life ; and *(d)* chips are helped out of the flutes of drills, taps, dies, saws, broaches, etc. An incidental improvement in the cutting operation is that the built-up edge will be reduced, which, in turn, will decrease friction at the tool-workpiece area and contribute toward a cooler tool. It is, therefore, evident that the proper choice of lubricant is important to give the optimum

cooling effect and lubrication condition in metal cutting.

4. *To improve surface finish.*
5. *To protect the finished surface from corrosion.* To protect the finished surface from corrosion, especially in cutting fluids made up of a high percentage of water, corrosion inhibitors are effective in the form of sodium nitrate or triethanolamine.
6. *To cause chips break up into small parts* rather than remain as long ribbons which are hot and sharp and difficult to remove from the workpiece.
7. *To wash the chips away from the tool.* This is particularly desirable to prevent fouling of the cutting tool with the workpiece.

Properties of Cutting Fluids : A cutting fluid should have the following properties :

1. *High heat absorption* for readily absorbing heat developed.
2. *Good lubricating qualities* to produce low-coefficient of friction.
3. *High flash point* so as to eliminate the hazard of fire.
4. *Stability* so as not to oxide in the air.
5. *Neutral* so as not to react chemically.
6. *Odorless* so as not to produce any bad smell even when heated.
7. *Harmless to the skin of the operators.*
8. *Harmless to the bearings.*
9. *Non-corrosive* to the work or the machine.
10. *Transparency* so that the cutting action of the tool may be observed.
11. *Low viscosity* to permit free flow of the liquid.
12. *Low priced* to minimize production cost.

Choice of cutting fluids : The choice of cutting fluid depends upon the following factors.

1. Type of operation.
2. The rate of metal removal.
3. Material of the workpiece.
4. Material of the tool.
5. Surface finish requirement.
6. Cost of cutting fluid.

Type of Cutting Fluids : The type of cutting fluid to be used depends upon the work material and the characteristic of the machining process. For some machining processes, a cutting fluid which is predominantly a lubricant is desirable. With other machining processes, a cutting fluid which is predominantly a coolant should be used. Cutting fluids are classified in seven main groups. These include water, soluble oils, straight oils, mixed oils, chemical additive oils (sulphurized and chlorinated), chemical compounds and solid lubricants.

1. *Water :* Water, either plain or containing an alkali, salt or water-soluble additive but little or no oil or soap are sometimes used only as a coolant. But water alone is, in most cases, objectionable for its corrosiveness.
2. *Soluble oils :* Soluble oils are emulsions composed of around 80 per cent or more water , soap and mineral oil. The soap acts as an emulsifying agent which break the oil into minute particles to dispose them throughout water. The water increases the cooling effect, and the oil provides the best lubricating properties and ensures freedom from rust. By mixing various proportions of water with soluble oils and soaps, cutting fluids with a wide range of cooling and lubricating properties can be obtained.
3. *Straight oils :* The straight oils may be (a) straight mineral (petroleum) oils, kerosene, low-viscosity petroleum fractions, such as mineral seal, or higher-viscosity mineral oils, (b) straight fixed or fatty oils consisting animal, vegetable, or synthetic equivalent, lard oil, etc. They have both cooling and lubricating properties and are used in light machining operations.
4. *Mixed oils :* This is a combination of straight mineral and straight fatty oil. This blend makes an excellent lubricant and coolant for automatic-screw-machine work and other light machining operations where accuracy and good finish are of prime importance.
5. *Chemical-additive oil :* Straight oil or mixed oil when mixed up with sulphur or chlorine is known as chemical additive oil. Sulphur and chlorine are used to increase both the lubricating and cooling qualities of the various oils with which they are combined. Sulfurized mineral oils are commonly used for machining the tough, stringy, low-carbon steels. Chlorinated mineral oils are particularly effective in promoting anti-weld characteristics.
6. *Chemical compounds :* These compounds consist mainly of a rust inhibitor, such as sodium nitrate, mixed with a high

percentage of water. Chemical compounds have grown in favour as coolants, particularly in grinding and on machined surfaces where formation of rust is to be avoided.

7. *Solid lubricants :* Stick waxes and bar soaps are sometimes used as a convenient means of applying lubrication to the cutting tool.

Table 2.3 shows different types of coolants and lubricants used for different machining operations.

Theory of Cutting Fluid : The basic function of an effective cutting fluid is to reduce kinetic coefficient of friction, Dr. Merchant, one of the pioneers in the theory of metal cutting, has suggested a theory to explain the penetration of cutting fluid. It is assumed that minute capillaries exist at the tool-chip interface as shown in Fig.2.29 on a submicroscopic scale. As the chip move up the tool face, it contacts mainly the tops of the asperities in the point contact zone creating capillaries between the chip and the tool. These capillaries draw in the cutting fluid which chemically reacts to produce a solid low-shear strength film. Under the condition of high pressure and temperature at the "nascent" chip surface the highly reactive chemical action produces relatively weak solid providing a "sandwich filling" to keep the chip and tool apart thereby reducing friction. It is well established that small change in tool temperature can produce considerable change in tool life. Cutting fluids directly control the amount of heat at the chip tool face and thereby increase tool life.

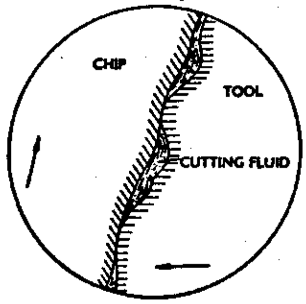

Figure 2.29 Penetration of cutting fluid

2.23 ECONOMICS OF MACHINING

All the foregoing information is of little use unless it is intelligently applied to obtain the *lowest possible unit cost and highest possible production rate for any given operation.* It is known that, at high cutting speeds, one may expect increased tool cost owing to shorter tool life. At the same time, it is expected that the machining cost per piece to go down. So much emphasis has been given on tool-life that sometimes other factors fade into the background.

The lowest possible unit cost and highest possible production cost depend on a particular machining process. However, the total cost per piece is based on idle cost, tool changing cost, and tool grinding cost. Fig.2.29 schematically shows optimum cutting speed for minimum production.

Cutting cost per piece depends on the time the tool is actually cutting. This time can be reduced by removing metal at a higher rate. In proportion to total cost, cutting cost is small in small job shops but may be proportionately larger in production work. The cutting-cost curve in Fig.2.30 shows the reduction in cutting cost as the cutting speed increases.

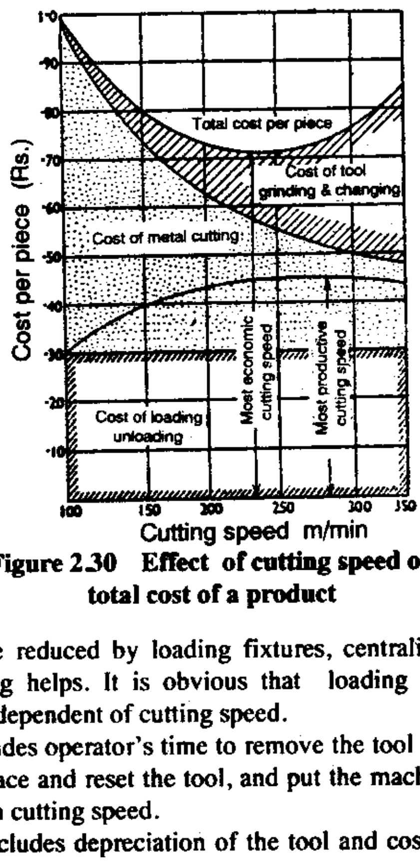

Figure 2.30 Effect of cutting speed on total cost of a product

Idle costs include costs for time spent in loading and unloading the piece, for crane time and for tool approach. This can be reduced by loading fixtures, centralized controls, and other time saving helps. It is obvious that loading and unloading costs per piece are independent of cutting speed.

Tool-changing cost includes operator's time to remove the tool and to grind it, if necessary, to replace and reset the tool, and put the machine in operation. This increases with cutting speed.

Tool-regrinding cost includes depreciation of the tool and cost of regrinding. This cost may become excessive at high cutting speed.

The *total cost* curve is the sum of the individual curves for optimum cutting speeds.

W.W. Gilbert evaluated tool-life for (a) minimum cost and for (b) maximum production.

Cost per piece = Idle cost per piece + Cutting cost per piece + Tool changing cost per piece + Tool grinding cost per piece.

$$= K_T(idle\,time) + K_1 \frac{\pi DL}{1000s} + K_1 \frac{\pi DLV^{\frac{1}{n}-1}}{1000sC^{\frac{1}{n}}}(TCT) + K_2 \frac{L\pi DV^{\frac{1}{n}-1}}{1000sC^{\frac{1}{n}}}$$

where,
K_1 = directed labour rate + overhead rate in Rs/min,
K_2 = tool cost per grind in Rs/tool,
L = length of machining in mm,
D = diameter of machined part in mm,
V = cutting speed in m/min,
s = feed in mm/rev,
VT^n = C, tool-life equation,
TCT = tool changing time.

TABLE 2.3 COOLANTS AND LUBRICANTS FOR DIFFERENT OPERATIONS

	Coolants and lubricants					
Material	*Turning & boring*	*Threading*	*Drilling*	*Reaming*	*Shaping, Planing Slotting*	*Milling*
Cast iron	Dry	Dry	Dry	Dry, Tallow, Lard oil	Dry	Dry
Soft steel	Cutting compound, Cutting oil, Soap-water	Cutting compound, Cutting oil, Soap-water	Any coolant	Cutting compound	Soap-water, Soda water	Soluble sulphurized, or mineral oil
Hard steel	Mineral lard oil	Mineral lard oil	Kerosene, Strong soda water	Mineral lard oil	Mineral lard oil	Soluble sulphurized, or mineral oil, mineral lard oil
Brass	Dry	Dry, Kerosene, Turpentine	Dry	Dry, kerosene, turpentine	Dry	Dry
Bronze	Mineral lard oil	Mineral lard oil	Dry or any coolant	Dry, Mineral lard oil	Dry	Soluble sulphurized, mineral lard oil
Aluminium	Kerosene	Kerosene	Dry, Kerosene	Kerosene with 25% soluble cutting oil	Kerosene	Soluble sulphurized, or mineral oil and kerosene
Copper	Mixture of lard oil and turpentine	Dry or a mixture of lard oil and turpentine	Dry, cooling compound, lard oil and turpentine	Dry or a coolant	Dry	Soluble sulphurized or mineral lard oil

REVIEW QUESTIONS

1. Differentiate between orthogonal and oblique cutting. What is the utility of orthogonal cutting ?
2. Derive the expression of chip reduction coefficient in single point cutting. State the assumptions used.
3. Considering the various forces acting on the chip, draw Merchant force diagram. State the assumptions made.
4. Derive the formula for stress developed in shearing zone for orthogonal cutting.
5. Establish average kinetic coefficient of friction for orthogonal cutting.
6. Derive the formulae for work done and power needed in orthogonal cutting.
7. Establish the formula for torque and power required in drilling.
8. Why cutting forces are measured ? What ate the different ways to measure cutting forces ?
9. List the various types of chips produced during metal cutting. Describe the conditions in which these types of chips are produced. Why discontinuous chips are preferred over the continuous type ?
10. List various types of chip breakers. Why they are used ?
11. What do you understand by cutting - tool nomenclature ? Sketch and label tool angles/tool nomenclatures.
12. List various hand tools and discuss their cutting actions.
13. How do you define cutting speed and feed ? State various factors that may be considered to fix cutting speed and feed.
14. Why heat is generated in cutting. Label various heat sources (and zones) in metal cutting ? Draw a sketch to show heat distribution to various elements during metal cutting.
15. Why tools fail during cutting ? Explain, giving reasons of tool wear.
16. What are the factors that affect tool life ? Briefly describe their influence.
17. Describe in brief how you measure tool life. What is machinability and what is machinability index ?
18. What are the desirable characteristics of cutting tool materials ? Describe them in brief.
19. Name various cutting tool materials. Briefly describe one important tool materials along with its characteristics and usability.
20. Briefly describe the properties of high speed steel as tool material. Name various types of high speed steels.
21. Why cemented carbide is considered as an useful tool material ?
22. What are the purposes of cutting fluids ? What are the types ?
23. What do you understand by economics of machining ? How do you evaluate machining cost.
24. Discuss the role of the tungşten, chromium and vanadium in h.s.s.
25. What are the significant characteristics of h.s.s. ?