COURSE CODE: *MCE 501*
COURSE TITLE: *Production Engineering 1*
NUMBER OF UNITS: *2 Units*
COURSE DURATION: *Two hours per week*

COURSE DETAILS:

Course Coordinator: **Dr Salami Olasunkanmi ISMAILA** *ND, BSc, MSc, PhD*
Email: ismailaso@unaab.edu.ng; ismailasalami@yahoo.com
Office Location: **Room 1, PG Building**
Other Lecturers: **None**

COURSE CONTENT:

The role of production engineering in the mechanical engineering profession. Mechanics and kinematics of machine tools. Tool geometry and chip formation. Mechanics of cutting with single-point tools. Merchant's analysis. Other theories. Economics of cutting: Time and cost estimates. Variables affecting metal removal rate, economic cutting speeds, cutting tool materials, cutting fluids. Principles of metal cutting with multi-point tools: milling, grinding, drilling, boring, etc.

COURSE REQUIREMENTS:

This a compulsory course for all students in the Department of Mechanical Engineering. Students are expected to participate in all course activities and have minimum of 75% attendance to be able to write the final examination.

READING LIST:

1. Adejuyigbe S.B. (2007). *Applied Manufacturing Engineering Processes*. TOPFUN Publications Ventures. P.O. Box 1129, Akure, Nigeria.

2. Boothroyd G. and Knight W.A. (1989), *Fundamentals of Machining and Machine Tools*, 2nd edition. Marcel Dekker.

3. Dieter, G.E.(1986), *Mechanical Metallurgy*, Third Ed., McGraw-Hill Publishing Co., New York.

4. Groover M.P. (2007), *Fundamentals of Modern Manufacturing*. John Wiley & Sons Inc.

5. Schmid R.S. and Kalpakjian S. (2006), *Manufacturing Engineering and Technology*, 5th edition, Pearson Prentice Hall, Upper Saddle River, NJ 07458.

6. Sharma P.C. (2004), *A textbook of Production Technology (Manufacturing Processes)*, 5th edition. S. Chand and Company Ltd., Ram Nagar, New Delhi-110055.

LECTURE NOTES

1.0 THE ROLE OF PRODUCTION ENGINEERING

Mechanical engineers play a key role in the production of goods by working closely with other engineers and specialists in corporate management, finance, marketing, and packaging. Mechanical Engineers design products, select materials and processes, and convert them to finished products. They design and manufacture machine tools -- literally the machines that make machines and design entire manufacturing processes, aided by the latest technologies in automation and robotics. Finally, the finished products are transported in equipment designed by mechanical engineers. This is the largest area of employment for mechanical engineers, especially when the process and textile industries are included. A finished product requires the right materials, a viable plant and equipment, and a manufacturing system. This all comes within the purview of mechanical, manufacturing and industrial engineers.

About half of all Mechanical Engineer's work in companies that manufacture products such as consumer goods, transportation, or industrial equipment. Another 16% work in the process industries, like petrochemical or pharmaceutical. The challenges are as diverse as the products and calls for knowledge of materials, manufacturing processes, thermal processes, controls, electronics, and, as in all of engineering --- teamwork skills. Production engineering is a completely production oriented course. The quality of the products produced is to a large extent dependent on production engineering and with quality comes standard. Therefore the production engineering lands in the standard arena which in turn is related to the price control chains. Thus the course in turn is influencing the delicate balance of demand-supply chain which is very critical in the present world. The list of influenced factor is very long, thus these facts alone creates the opportunities to understand the role of production engineering in the present world. Industrial Engineering and Production engineering course has a wide scope in manufacturing and automation field. Production engineers work in all branches and industries in which products are manufactured in industrial processes. Employment opportunities are to be found in mechanical and plant engineering, in automobile engineering, in power-generating, in the electrical industry, in the precision engineering industry, in the chemical and pharmaceutical industry, in the textile industry, the paper industry, iron and steel industry, food and semi-luxury foods and tobacco industry. The industry offers a wide choice of options extending across many interdisciplinary interdependent specialties.

2.0 MECHANICS OF CUTTING TOOLS

Metal ahead of the cutting tool is compressed which results in the deformation or elongation of the crystal structure—resulting in a shearing of the metal. As the process continues, the metal above the cutting edge is forced along the "chip-tool" interference zone and is moved away form the work.

The cutting of metal is by a relative motion between the work piece and the hard edge of a cutting tool. The cutting of metal could be done by either a single point cutting tool or a multi point cutting tool. There are two basic types of metal cutting by a single point cutting tool namely orthogonal and oblique metal cutting.

In orthogonal cutting, unwanted material is removed from the work piece by a cutting edge that is perpendicular to the direction of relative motion between tool and the work piece as shown in Figure 1.

Orthogonal cutting occurs if the cutting face of the tool is at 90^o to the direction of the tool travel while oblique cutting occurs if the cutting face of the tool is inclined at less than 90^o to the path of the tool. The differences between orthogonal and oblique cutting is given in Table 1.

Table 2.1: Differences between orthogonal and oblique cutting

Orthogonal metal cutting	**Oblique metal cutting**
Cutting edge of the tool is perpendicular to the direction of tool travel.	The cutting edge is inclined at an angle less than 90^o to the direction of tool travel.
The direction of chip flow is perpendicular to the cutting edge.	The chip flows on the tool face making an angle.
The chip coils in a tight flat spiral	The chip flows side ways in a long curl.
For same feed and depth of cut the force which shears the metal acts on smaller areas. So the life of the tool is less.	The cutting force acts on larger area and so tool life is more.
Produces sharp corners.	Produces a chamfer at the end of the cut
Smaller length of cutting edge is in contact with the work.	For the same depth of cut greater length of cutting edge is in contact with the work.
Generally parting off in lathe, broaching and slotting operations are done in this method.	This method of cutting is used in almost all machining operations.

In oblique cutting, the major cutting edge is inclined to direction of the cutting velocity with an inclination angle.

Most of the metal cutting operations are oblique but orthogonal cutting has been extensively studied because of its simplicity and good approximations.

The chip formation of oblique and orthogonal cutting is approximately identical.

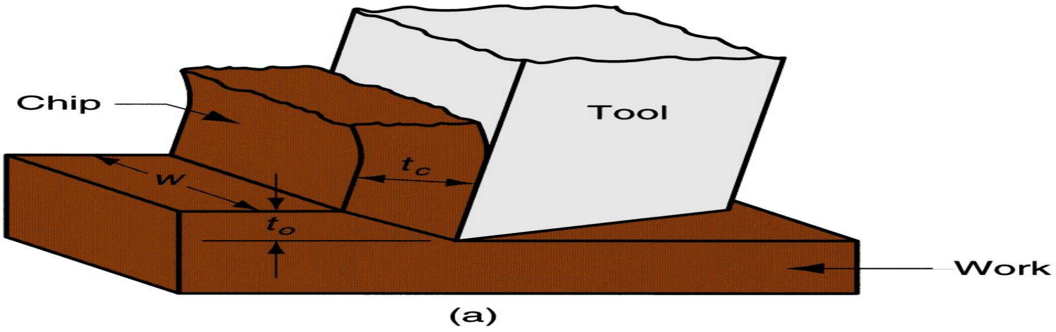


Figure 2.1: Orthogonal cutting: (a) as a three-dimensional process.

3.0 TOOL GEOMETRY AND CHIP FORMATION

3.1 Tool geometry

Large rake angle reduces the tool cross section. Area of the tool, which will absorb heat, is reduced. So the tool will become weak. Hence correct rake angle must be used for longer tool life. If the cutting angle increases, more power will be required for cutting. Clearance angle of 10^{o} to 15^{o} is optimal.

Other factors include the material of tool (Carbon steel, medium alloy steel, high speed steel, molybdenum high speed steel, cobalt high speed steel, stellites, carbides, ceramics and diamond are the commonly used tool materials.), use of cutting fluids and work material.

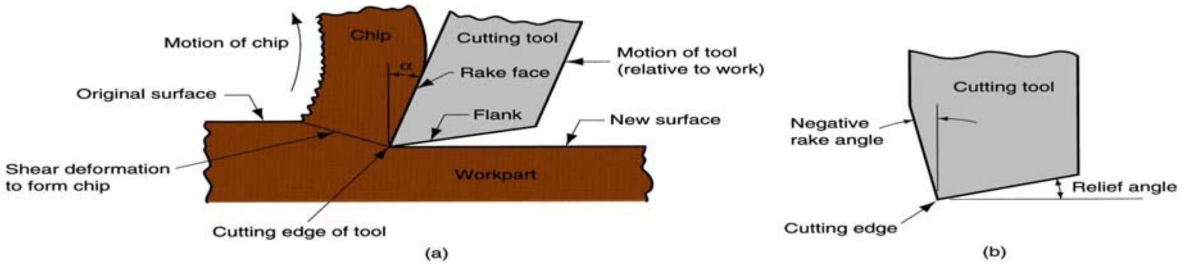


Figure 3.1 (a) A cross-sectional view of the machining process, (b) tool with negative rake angle; compare with positive rake angle in (a).

3.1.1. Major Classifications of Cutting Tools

Two types of cutting tools may be identified namely:

1.Single-Point Tools (Figure 3.2 (a)) with one dominant cutting edge, which is usually rounded to form a nose radius. They are useful for turning.

2.Multiple Cutting Edge Tools (Figure 3.2 (b)) have more than one cutting edge with a motion relative to work achieved by rotating. They are useful for drilling and milling.

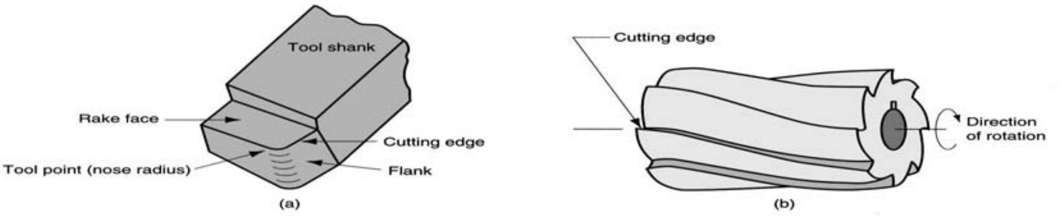


Figure 3.2: (a) A single-point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges.
Source: Groover (2007)

All tools have a major and minor cutting edge. The major cutting edge removes bulk of material while the minor cutting edge gives good surface finish.

3.2 Chip Formation

The type of chip produced depends on the material being machined and the cutting conditions at the time. These conditions include the type of tool used tool, rate of cutting condition of the machine and the use or absence of a cutting fluid.

When the tool advances into the work piece, the metal in front of the tool is severely stressed. The cutting tool produces internal shearing action in the metal. The metal below the cutting edge yields and flows plastically in the form of chip. Compression of the metal under the tool takes place. When the ultimate stress of the metal is exceeded, separation of metal takes place. The plastic flow takes place in a localized area called as shear plane. The chip moves upward on the face of the tool.

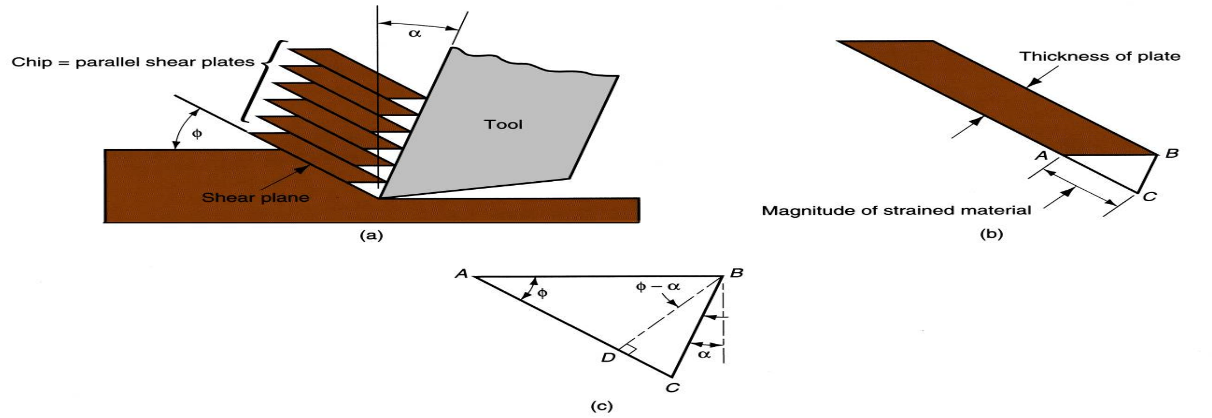


Figure 3.3: Shear strain during chip formation: (a) chip formation depicted as a series of parallel plates sliding relative to each other, (b) one of the plates isolated to show shear strain, and (c) shear strain triangle used to derive strain equation.
Source: Groover (2007)

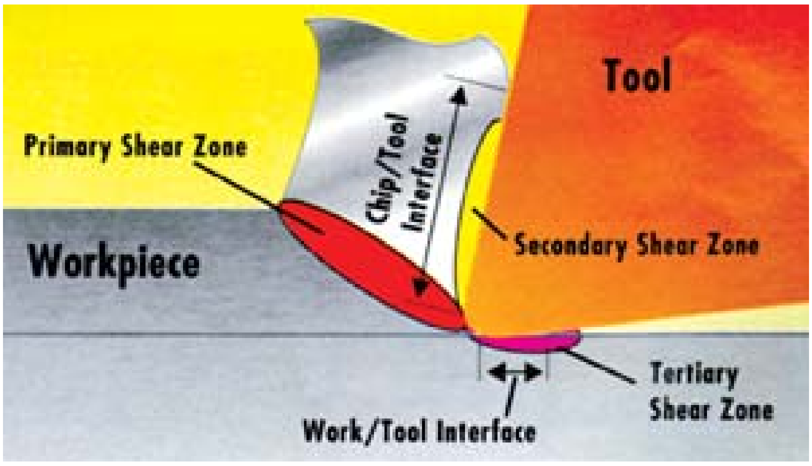


Figure 3.4: Realistic view of chip formation, showing shear zones: primary, secondary and tertiary rather than shear plane resulting from tool-chip friction.
Source: Groover (2007)

Chip Thickness Ratio

The chip thickness ratio is given by

$$r = \frac{t_o}{t_c}$$

where r = *chip thickness ratio*; t_o = thickness of the chip prior to chip formation; and t_c = chip thickness after separation

The chip thickness after cut is always greater than before, so chip ratio is always less than 1.0.

Using the geometric parameters of the orthogonal model, the shear plane angle ϕ (Figure 3.5) can be determined as:

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

where r = chip ratio, and α = rake angle

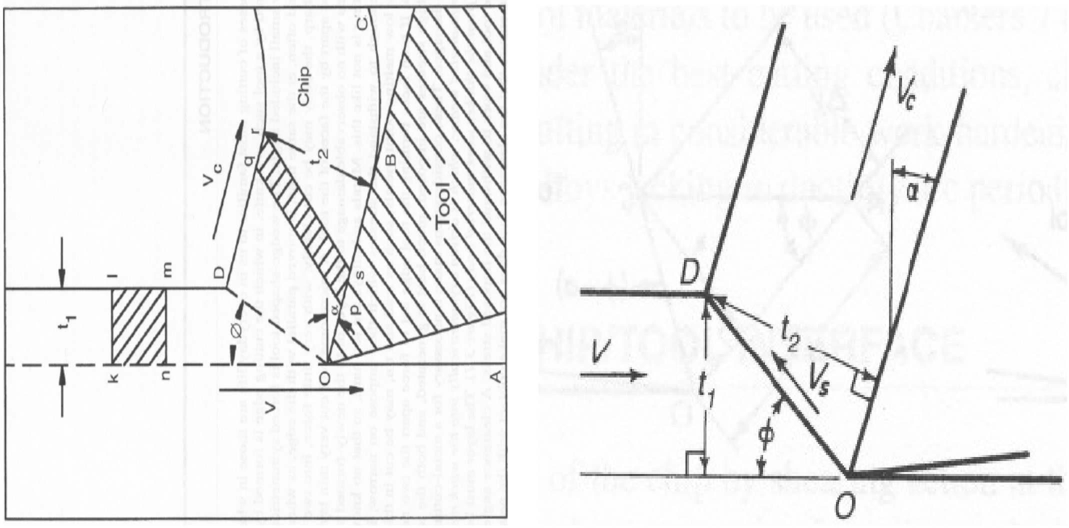


Figure 3.5: Geometry of Chip formation

$$OD = \frac{t_1}{\sin\varphi} = \frac{t_2}{\cos(\varphi - \alpha)} \quad \text{…………………………………………..} \quad (3.1)$$

$$\frac{t_1}{\sin\varphi} = \frac{t_2}{\cos\varphi\cos\alpha - \sin\varphi\sin\alpha} \quad \text{…………………………………..} \quad (3.2)$$

$$\tan\alpha = \frac{r\cos\alpha}{1 - r\sin\alpha} \quad \text{……………………………………………………} \quad (3.3)$$

There are four different types of chips that are produced during machining. They are
(a) Discontinuous chips
(b) Continuous chips
(c) Continuous chips with built up edge.
(d) Serrated chip

(a) Discontinuous chips

These chips are produced when cutting more brittle materials like bronze, hard brass and gray cast iron. Since there chips break up into small segments the friction between chip and tool reduces resulting in better surface finish. These chips are convenient to handle and dispose off.

Discontinuous chips are produced in ductile materials under the conditions such as large chip thickness, low cutting speed, small rake angle of tool etc.

Brittle materials lack the ductility necessary for appreciable plastic chip deformation. The amount of deformation, which the chip undergoes, by deformation is limited by repeated fracturing.

If these chips are produced from brittle materials, then the surface finish is fair, power consumption is low, tool life is reasonable however, with ductile materials, the surface finish is poor, and tool wear is excessive.

(b) Continuous chips

The conditions that favor the production of continuous chips is small chip thickness, high cutting speed, sharp cutting edge, large rake angle in cutting tool and fine feed, smooth tool face and efficient lubricating system. Such chips are produced while machining ductile materials like mild steel, copper and aluminum. Because of plastic deformation of ductile material long and continuous chips are produced. This is desirable because it produces good surface finish, low power consumption and longer tool life.

These chips are difficult to handle and dispose off. Further the chips coil in a helix, curl around work and tool, and may injure the operator when it is breaking. The tool face is in contact for a longer period resulting in more frictional heat. However, this problem could be rectified by the use of chip breakers.

Chip breakers

During machining, long and continuous chip will affect machining as it may spoil tool, work and machine. It will also be difficult to remove metal and dangerous. The chip should be broken into small pieces, for ease of removal, safety and prevent damage to machine and work. The function of chip breakers is to reduce the radius of curvature of chips and thus break it. The upper side of continuous chips notches while the lower side, which slides over the face tool, is smooth and shiny. The chips have the same thickness through.

(c) Continuous chips with built up edge

This is nothing but a small built up edge sticking to the nose of the cutting tool. These built up edge occurs with continuous chips.

When machining ductile materials, the high local temperature, extreme pressure at the cutting zone and high friction in the tool chip interface may make the work material to weld to the cutting edge of tool and thus forming built up edges. This weld metal is extremely hard and brittle. This welding may affect the cutting action of tool.

Successive layers are added to the build up edge. When this edge becomes large and unstable it is broken and part of it is carried up, the face of the tool along with chip while remaining is left in the surface being machined thus contributing to the roughness of surface.

Thus the size of the built up edge, varies during the machining operation. It first increases, then decreases and again increases.

This built up edge protects the cutting edge of tool, thus changing the geometry of the cutting tool.

Low cutting speeds lead to the formation of built up edge, however with high cutting speeds associated with sintered carbide tools, the build up edge is negligible or does not exist. Conditions favoring the formation of build up edge are low cutting speed, low rake angle, high feed and large depth of cut. This formation can be avoided by the use of coolants and taking light cuts at high speeds. This leads to the formation of crater on the surface of the tool.

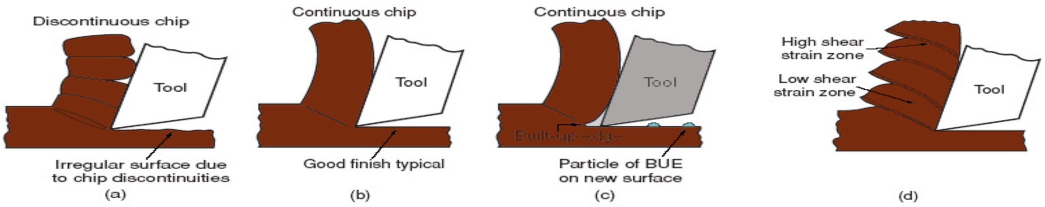


Figure 3.6: Four types of chip formation in metal cutting: (a) discontinuous (b) Continuous (c) Continuous with Built up edge (d) Serrated Chips
Source: Groover (2007)

(d) Serrated Chips

These are semi-continuous, saw-tooth in appearance and cyclical chips form with alternating high shear strain then low shear strain. They are associated with difficult-to-machine metals at high cutting speeds.

4.0 MECHANICS OF CUTTING WITH SINGLE-POINT TOOLS

The usual conception of cutting suggests clearing the substance apart with a thin knife or wedge. When metal is cut, the action is rather different and although the tool will always be wedge shaped in the cutting area and the cutting edge should always be sharp the wedge angle will be far too great for it to be considered knife shaped. Consequently, a shearing action takes place when the work moves against the tool. Figure 4.1 shows a tool being moved against a fixed work piece. When the cut is in progress, the chip presses heavily on the top face of the tool and continuous shearing takes place across the shear plane AB. Although the Figure shows a tool working in the horizontal plane with the work piece stationary, the same action takes place with the work piece revolving and the tool stationary.

Table 4.1 states the parts of a single point-cutting tool and Figure 4.2 shows the schematic diagram of the tool.

Table 4.1: Parts of a single point cutting tool

Part	**Description**
Shank	It is the body of the tool, which is ungrounded.
Face	It is the surface over which the chip slides.
Base	It is the bottom surface of the shank.
Flank	It is the surface of the tool facing the work piece. There are two flanks namely end flank and side flank.
Cutting edge	It is the junction of the face ends the flanks. There are two cutting edges namely side cutting edge and end cutting edge.
Nose	It is the junction of side and end cutting edges.

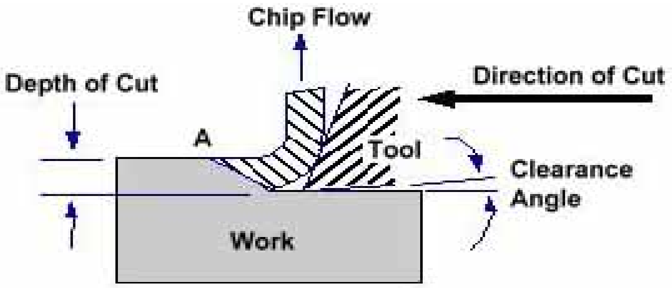


Figure 4.1: Basic Metal Cutting Theory

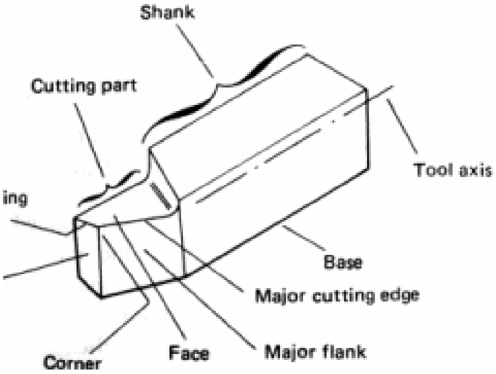


Figure 4.2: Schematic diagram of a single point tool

The forces acting on a chip are (Figure 4.3):

(i) Friction force F

(ii) Normal force to friction N

(iii) Shear force F_s

(iv) Normal force to shear F_n

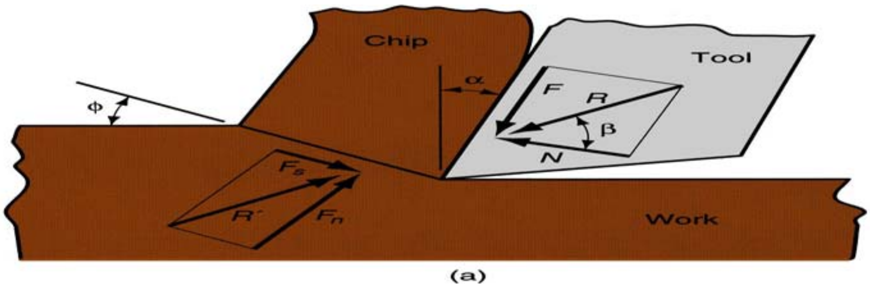


Figure 4.3: Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting

There are three important angles in the construction of a cutting tool rake angle, clearance angle and plan approach angle.

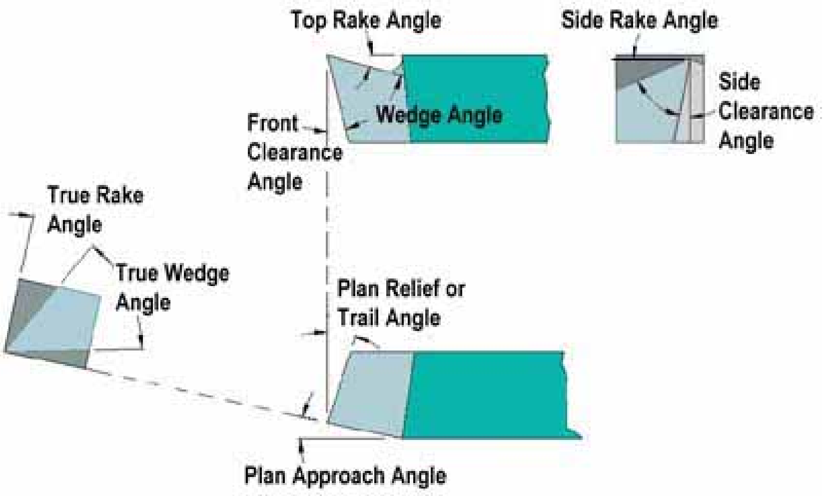


Figure 4.4: Orthographic views showing the tool geometry

Rake angle is the angle between the top face of the tool and the normal to the work surface at the cutting edge. In general, the larger the rake angle, the smaller the cutting force on the tool, since for a given depth of cut the shear plane AB decreases as rake angle increases. A large rake angle will improve cutting action, but would lead to early tool failure, since the tool wedge angle is relatively weak. A compromise must therefore be made between adequate strength and good cutting action.

Clearance angle is the angle between the flank or front face of the tool and a tangent to the work surface originating at the cutting edge. All cutting tools must have clearance to allow cutting to take place. Clearance should be kept to a minimum, as excessive clearance angle will not improve cutting efficiency and will merely weaken the tool. Typical value for front clearance angle is 6° in external turning.

Table 4.2: Typical value for top rake angle

Metal Being Cut	Cast Iron	Hard Steel / Brass	Medium Carbon Steel	Mild Steel	Aluminium
Top Rake Angle	0°	8°	14°	20°	40°

Table 4.3: Important angles of a single point cutting tool

Angle	**Details**
Top rake angle	It is also called as back rake angle. It is the slope given to the face or the surface of the tool. This slope is given from the nose along the length of the tool.

Side rake angle	It is the slope given to the face or top of the tool. This slope is given from the nose along the width of the tool. The rake angles help easy flow of chips
Relief angle	These are the slopes ground downwards from the cutting edges. These are two clearance angles namely, side clearance angle and end clearance angle. This is given in a tool to avoid rubbing of the job on the tool.
Cutting edge angle	There are two cutting edge angles namely side cutting edge angle and end cutting edge angle. Side cutting edge angle is the angle, the side cutting edge makes with the axis of the tool. End cutting edge angle is the angle, the end cutting edge makes with the width of the tool.
Lip angle	It is also called cutting angle. It is the angle between the face and end surface of the tool.
Nose angle	It is the angle between the side cutting edge and end cutting edge.

Vector addition of F and N = resultant R
Vector addition of F_s and F_n = resultant R'
Forces acting on the chip must be in balance:
R' must be equal in magnitude to R
R' must be opposite in direction to R
R' must be collinear with R

The coefficient of friction between tool and chip can be described as:

$$\mu = \frac{F}{N}$$

The friction angle, β is related to the coefficient of friction as:

$$\mu = \tan\beta$$

The shear stress acting along the shear plane is described by the following equation:

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

where As = area of the shear plane

$$A_s = \frac{t_o w}{\sin\phi}$$

Shear stress = shear strength of work material during cutting.

The F, N, F_s, and F_n cannot be directly measured but the cutting force F_c and Thrust force F_t acting on the tool can be measured.

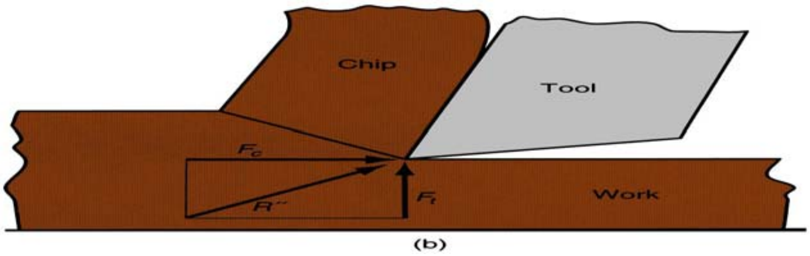


Figure 4.5: Forces in metal cutting: (b) forces acting on the tool that can be measured

Equations can be derived to relate the forces that cannot be measured to the forces that can be measured:

$$F = F_c \sin\alpha + F_t \cos\alpha$$
$$N = F_c \cos\alpha - F_t \sin\alpha$$
$$Fs = F_c \cos\phi - F_t \sin\phi$$
$$Fn = F_c \sin\phi + F_t \cos\phi$$

Based on these calculated force, shear stress and coefficient of friction can be determined

Elements of Metal Cutting

Cutting speed: It is the distance traveled by work surface related to the cutting edge of Tool
$v = \pi dN / 1000$ m / min

Feed (s): The motion of cutting edge of tool with reference to one revolution of work piece.

Depth of cut (t): It is measured perpendicular to axis of work piece and in straight turning in one pass. This can be estimated from the relation
$t = (D - d) / 2$ mm

Undeformed chip (F_c): The cross sectional area of chip before it is removed from work piece. it is equal to the product of feed and depth of cut.
$F_c = s \times t$ mm^2

4.1 Merchant's Analysis

Of all the possible angles at which shear deformation can occur, the work material will select a shear plane angle ϕ that minimizes energy and is given by the following equation by Eugene Merchant based on orthogonal cutting, but which validity extends to 3-D machining:

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

The Merchant's equation tells us that to increase the shear plane angle, there should be an increase in the rake angle and there should be a reduction in friction angle (or coefficient of friction).

Higher shear plane angle means smaller shear angle, which means lower shear force, cutting forces, power, and temperature as shown in Figure 4.6.

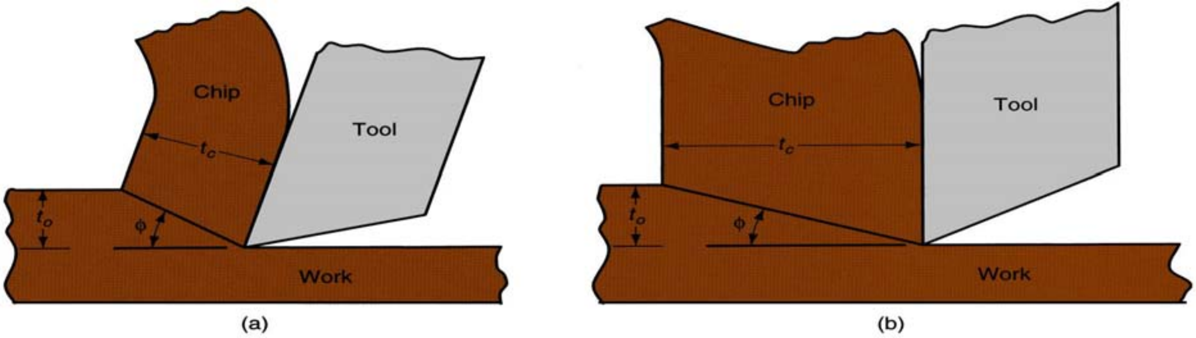


Figure 4.6: Effect of shear plane angle ϕ : (a) higher ϕ with a resulting lower shear plane area; (b) smaller ϕ with a corresponding larger shear plane area. Note that the rake angle is larger in (a), which tends to increase shear angle according to the Merchant equation

4.2 Ernst and Merchant Theory of Metal cutting

Ernst and Merchant made the following assumptions:

(i) A single unique shear (not sliding or deformation) plane exists all the time during cutting as shown in Figure 4.7.

(ii) A unique shear velocity V_S, which is the relative velocity between the unreformed work material and the chip on the shear plane, exist along this plane, this velocity is constant, and remains the same all the time during cutting.

(iii) The chip has chip velocity V_C and thus moves up.

(iv) Because the velocity of deformation on the shear plane is constant, the shearing force F_S acting along this plane and this force should remain constant over the time of existence of this shear plane.

(v) Because the shear deformation on the shear plane is a result of material compression, the normal force F_n that is perpendicular to the shear plane should be considered. The sum of the shear and normal forces is the force R that the tool exerts on the chip. Force R may be resolved along the direction of motion of the tool relative to the work piece into a component F_C, the cutting force, which is responsible for the total work done in cutting, and into component F_t, the trust force, which is perpendicular to F_C

The shearing force is calculated as

$$F_s = \frac{\tau_y A_c}{\sin\varphi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where $A_C = t_1 \cdot b_C$ is the uncut chip cross-sectional area (Figure 4.7); τ_y is the shear strength of the work material.

Ernst and Merchant made one assumption that is more indirect, namely, the work material deforms when the stress on the shear plane reaches the shear strength of the work material. In other words, no strain hardening of the work material is allowed and thus the work material is elastic- perfectly-plastic. Although some metals may exhibit such behavior (for example, low carbon steels), the onset of plastic deformation, however, occurs at the stress which is significantly higher than the yield strength (the so-called upper yield point) so that the shearing force Fs cannot be constant even for these specific materials. For the steels, used in the experiments Ernst and Merchant, strain-hardening takes place and thus the so-called flow shear stress is much higher than the yield strength of the work material.

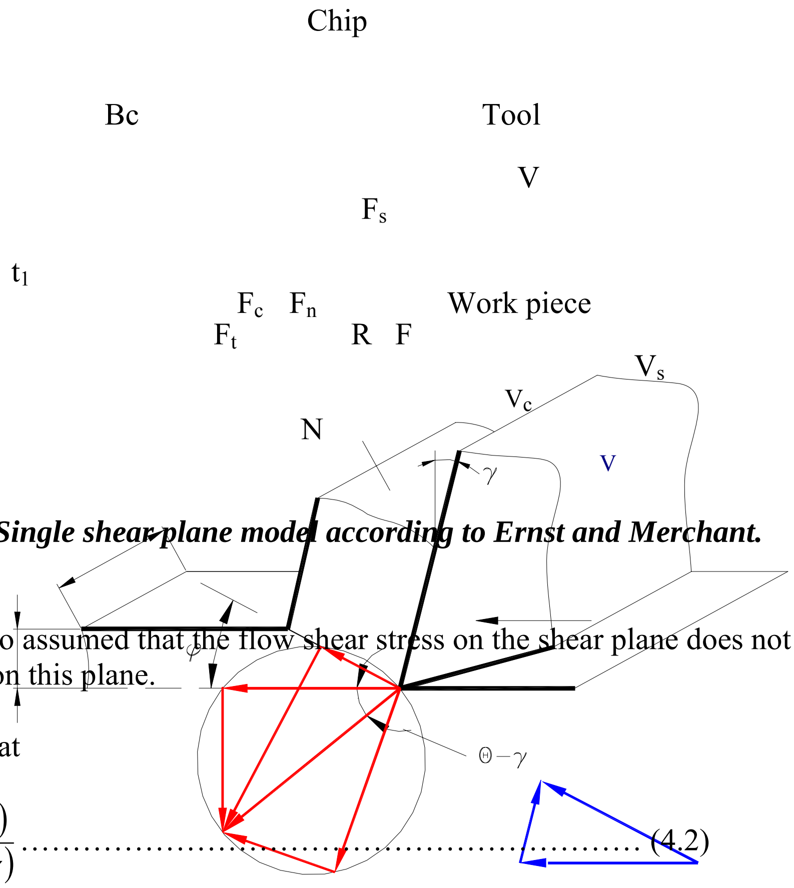


Figure 4.7: Single shear-plane model according to Ernst and Merchant.

Besides, it was also assumed that the flow shear stress on the shear plane does not depend on the normal stress on this plane.

It follows from, that

$$F_c = \frac{F_s \cos(\theta-\gamma)}{\cos(\varphi+\theta-\gamma)} \quad \text{(4.2)}$$

Equation (2) may be re-written using equation (1) as follows:

$$F_c = \frac{\tau_y A_c \cos(\theta-\gamma)}{\sin\varphi\cos(\varphi+\theta-\gamma)} \quad \text{(4.3)}$$

The work spent in cutting is calculated as $U_c = F_c V$

According to the principle of minimum work, the work done in cutting should be at minimum, and thus its derivative should be zero, i.e.

$$\frac{\partial}{\partial\varphi}(U) = \frac{\partial}{\partial\varphi}(F_c V) = V\frac{\partial}{\partial\varphi}(F_c) = 0 \quad \text{(4.4)}$$

Since the cutting velocity cannot be equal to 0, it means that

$$\frac{\partial}{\partial \varphi}(F_c) = 0$$

Ernst and Merchant concluded that $\tau_y A_c \cos(\theta - \gamma)$ is a non-zero constant, thus one can obtain

$$\frac{\partial}{\partial \varphi}(F_c) = \frac{\partial}{\partial \varphi}\left(\frac{\tau_y A_c \cos(\theta - \gamma)}{\sin \varphi \cos(\varphi + \theta - \gamma)}\right) = \tau_y A_c \cos(\theta - \gamma)\frac{\partial}{\partial \varphi}\left(\frac{1}{\sin \varphi \cos(\varphi + \theta - \gamma)}\right) = 0 \ldots (4.5)$$

Ernst and Merchant solution to the equation is

$$2\varphi_{sp} + \theta - \gamma = \frac{\pi}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

Merchant realized that this solution is in very poor agreement with experimental results. He, therefore, tried to 'adjust' the behaviour of the work material suggesting that the shear strength of the work material depends linearly on the normal stress on the shear plane. He thought that that this might account for the fact that his experimental results were not in agreement with equation (4.6). The modified version of equation (4.3) is

$$F_c = \frac{\tau_y A_c \cos(\theta - \gamma)}{\sin \varphi \cos(\varphi + \theta - \gamma)[1 - k_1 \tan(\varphi + \theta - \gamma)]} \ldots\ldots\ldots\ldots\ldots\ldots (4.7)$$

Applying the principle of minimum energy and following the same procedure as before, that is, minimizing F_c with respect to φ in order to obtain an expression for φ, it can be readily shown that

$$2\varphi + \theta - \gamma = c_1 \text{ and } c_1 = \cot^{-1} k_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.8)$$

k_1 is a constant for the material. This solution is known as the modified Merchant solution that was obtained earlier on the basis of pure geometrical considerations.

4.3 Lee and Shafer's Theory

Ernst and Merchant in their studies never considered the state of stress (and strain) in the work material ahead of the tool, in the chip, and at the tool/chip interface. In other words, it was not their concern to understand how the force exerted by the tool rake face is transmitted to the shear plane.

The first attempt to solve this problem was made by Lee and Shafer. For their modeling, Lee and Shafer considered the following:

(i) Method of machining: Orthogonal cutting as the simplest case.

(ii)Work material: A rigid-perfectly plastic solid (no work hardening was allowed). It was considered as a good approximation for steels and cast irons for three reasons. Firstly, work hardening of steels decreases rapidly with increasing strain and this in the large strains, which occur in metal cutting, the material yields at a fairly constant stress for most of the strains. Secondly, since the effect of high strain rate is to raise the yield strength of a material with respect of its ultimate stress, then at high strain rates of the order of 10^5 s^{-1}, which exists in the cutting operation, the stress-strain curve of the work material would tend to that of a non-work hardening material. Thirdly, since the elastic yield-point strain of most materials is of the order 10^{-3}, it can be safety neglected in analyzing large plastic deformations.

(iii)State of strain: Plane strain conditions because it was observed that no sideways spread occurs (apart from an edge effect).

Lee and Shafer developed a model of chip formation shown where the work piece is stationary and the tool moves from right to left. Because a steady-state problem was kept in mind, the model was considered when the tool advances far enough that the stress in the deformation zone reaches the yield point. The shear plane separates the undeformed work material from the chip. Its orientation was chosen to give the minimum machining force. As a result, when an infinitesimal element of work material crosses the shear plane, it rapidly sheared into the chip. In this process, it acquires that the velocity, which makes it move up the tool and the stress falls to zero. This rapid onset of deformation and velocity occurs at the edge shear plane of the slip- line field that was deduced by Lee and Shafer.

Lee and Shafer concluded that the slip lines (as the lines of maximum shear) meet the tool face at angle $\eta = 45^o - \theta$, and so the lower boundary of the slip-line field meets the tool face at an angle $(90^o - \eta)$. Further, after passing the slip- line field the chip is subjected to no forces and so no stresses is transmitted across the upper boundary. Therefore, the slip lines must meet at 45^o. Using this consideration, a location of point *e* on the Mohr circle was determined by the angle η (Figure 4.8). Having determined this location, Lee and Shafer used the similarity of the Mohr circle to determine the friction angle θ at the tool/chip interface as shown in Figure 4.8.

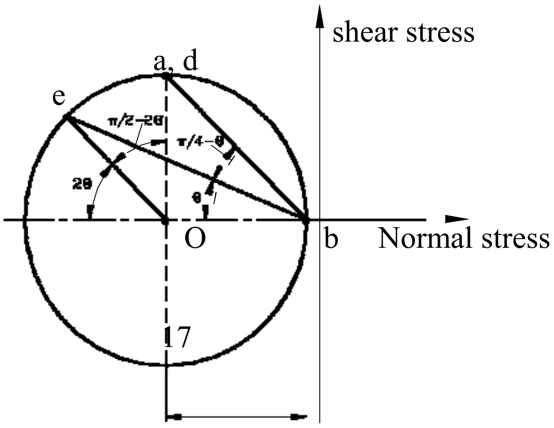
Therefore, the friction coefficient $\mu = \tan\theta$ was defined as the ratio of the shear and normal stresses at the tool/chip interface.

From the pure geometrical considerations, the Lee and Shafer solution gives the following expression for the shear angle

$$\varphi + \theta - \gamma = 45$$

The horizontal (power) component of the cutting force is

$$F_c = \tau_y t_1 b_c (1 + \cot\varphi) = \tau_y t_1 b_c \left(1 + \cot\left[\frac{\pi}{4} - \theta + \gamma \right] \right) \quad \text{……………………… (4.9)}$$



c, f p=k

Figure 4.8: Mohr's circle diagram for Lee and Shafer's solution with no built-up edge.

The chip thickness ratio can then be calculated as

$$r_c = \frac{t_2}{t_1} = \frac{\sin\left(\frac{\pi}{4} - \theta + \gamma\right)}{\cos\left(\frac{\pi}{4} - \theta\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.10)}$$

It may be seen that if γ is negative by considering equations (4.9) and (4.10) say -10^o, and with, say $\theta = 35^o$, $\cot(\pi/4 - \theta + \gamma)$ becomes infinite so do F_c and t_2.

5.0 ECONOMICS OF CUTTING WITH SINGLE POINT TOOLS

5.1 Basis

The economics cost of cutting can be based on any of the criteria shown in Figure 10. The costs of consists of machining cost, set up cost and tooling cost.

(i) Machining cost consists of
- Labor cost
- Machine overhead
- Time to machine

(ii) Set up cost consists of
- Cost of setting up machine
- Cost of loading, unloading tools and work piece

(iii) Tooling Cost consists of
- Cost of tool
- Cost of regrinding tool
- Cost of tool regrinding machine

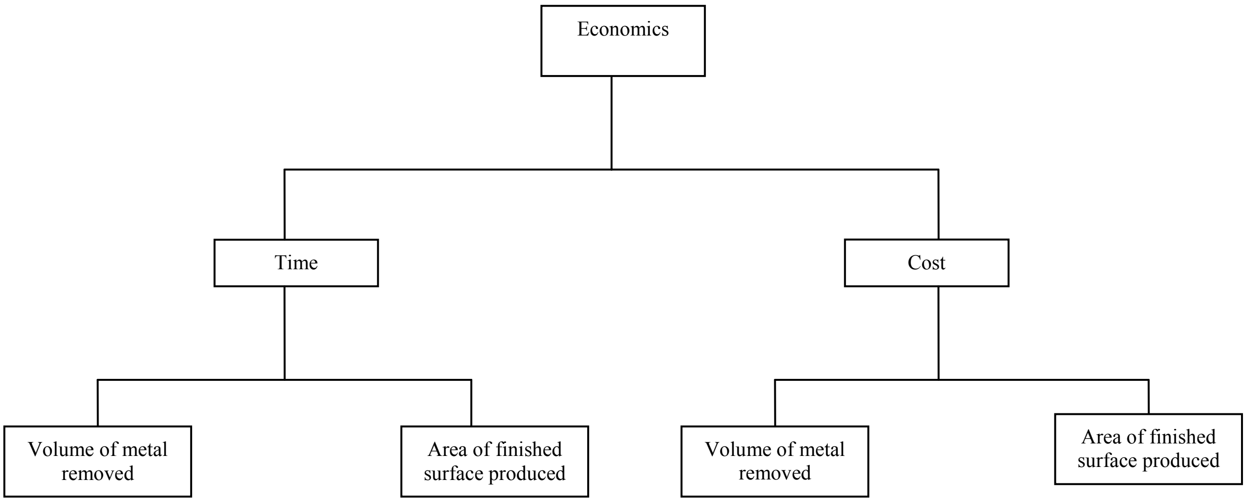


Figure 5.1: Basis of economics cost of cutting

5.2 Variables affecting metal removal rate

The metal removal rate, ω is given by

$$\omega = V \times d \times f \quad \ldots\ldots (5.1)$$

where d = depth of cut (mm), f = feed rate (mm) and V = Cutting velocity (mm/min)

Metal removal rate can be estimated by:

(i) horsepower available at the spindle of the machine.

(ii) tool life specified

The Taylor's (empirical) law states that if feed, rake angle etc are kept constant,

$$VM^{n} = C \quad \text{------} (5.2)$$

where M = Tool life (min.), C and n are constants which can be obtained from cutting tools and depending on the cutting tool material and the material being cut.

For High speed Steel (HSS) tools, $n \approx \frac{1}{8}$ and for Tungsten Carbide tools, $n \approx \frac{1}{5}$

Increase of cutting speed affects the economics of cutting by:

(i) increasing the metal removal rate (lowering the direct cost of metal removal)

(ii) decreasing the tool life (increase the costs of servicing and replacing worn-out tools)

Tool life: It is an important factor in cutting tool performance. The tool cannot cut effectively for an unlimited period of time. It has a definite life. Tool life is the time for which the tool will operate satisfactorily until it becomes blunt. It is the time between two successive grinds. Following are the factors influencing tool life.

Cutting speed: It has the greatest influence. When the cutting speed increases, the cutting temperature increases. Due to this, hardness of the tool decreases. Hence the tool flank wear and crater wear occurs easily. The relation ship between tool life and cutting speed is given by the Taylor's formula which states that $VM^{n} = C$

V is the cutting speed in meters / minute

M is the tool life in minutes.

n depends on the tool and work.
C a constant.

Feed and depth of cut: The tool life depends upon the amount of material removed by the tool per minute. For a given cutting speed if the feed or depth of cut is increased, tool life will be reduced.

5.3 Economic Relationships of cutting with single point tools

Let H = hourly cost of running the machine (operator's wage and overheads)
J = total cost per tool change (tool grinding, setting and eventual replacement costs)
P_m = cost of machining metal per unit volume
P_t = cost of servicing tools per unit volume of metal cut
P = total cost per unit volume of metal cut ($P_m + P_t$)
ω = metal removal rate
d = depth of cut (mm)
f = feed rate (mm)
V = Cutting velocity (mm/min)
M = tool life (min)

Time (minutes) to machine a unit volume of material is given by

$$\frac{1}{\omega} = \frac{1}{V \times d \times f} = \frac{k}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

where k = constant

Cost of machining per unit volume of metal cut,

$$P_m = \frac{H \times k}{60 \times V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.4)$$

The number of tool changes in $\frac{k}{V}$ minutes is $\frac{k}{M \times V}$ …………….. (5.5)

But from Taylor's equation,

$$M = \left(\frac{c}{V}\right)^{\frac{1}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.6)$$

Cost of tool servicing per unit volume of metal cut,

$$P_t = \frac{J \times k}{V}\left(\frac{V}{c}\right)^{\frac{1}{n}} = \frac{J \times k \times V^{\frac{1-n}{n}}}{c^{\frac{1}{n}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.7)$$

Adding equations (5.4) and (5.7)

The total cost per unit volume of metal cut, P= $P_m + P_t$

$$P = \frac{H \times k}{60 \times V} + \frac{J \times k \times V^{\frac{1-n}{n}}}{c^{\frac{1}{n}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.8)$$

Differentiating equation (5.8) with respect to V and equating to zero, we have

$$\frac{dP}{dV} = \frac{-H \times k}{60 \times V^2} + \frac{1-n}{n} \times \frac{J \times k}{c^{\frac{1}{n}}} \times V^{\frac{1-2n}{n}} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.9)$$

i.e. $\frac{H\times k}{60\times V^{2}} = \frac{J\times k}{c^{\frac{1}{n}}}\times V^{\frac{1-2n}{n}}\left(\frac{1-n}{n}\right)$ .... (5.10)

since k ≠ 0,

$$\frac{-H}{60\times V^{2}} + \frac{1-n}{n}\times\frac{J}{c^{\frac{1}{n}}}\times V^{\frac{1-2n}{n}} = 0 \ldots\ldots\ldots\ldots \quad (5.11)$$

$$\frac{H}{60\times V^{2}} = \frac{1-n}{n}\times\frac{J}{c^{\frac{1}{n}}}\times V^{\frac{1-2n}{n}} \ldots\ldots\ldots\ldots \quad (5.12)$$

$$\frac{H}{60} = \frac{1-n}{n}\times\frac{J}{c^{\frac{1}{n}}}\times V^{\frac{1-2n}{n}}\times V^{2} \ldots\ldots\ldots\ldots \quad (5.13)$$

$$\frac{H}{60} = \frac{1-n}{n}\times\frac{J}{c^{\frac{1}{n}}}\times V^{\frac{1}{n}} \ldots\ldots\ldots\ldots \quad (5.14)$$

$$\frac{H}{60} = \frac{1-n}{n}\times J\times\left(\frac{V}{c}\right)^{\frac{1}{n}} \ldots\ldots\ldots\ldots \quad (5.15)$$

But $\frac{1}{M} = \left(\frac{V}{c}\right)^{\frac{1}{n}}$ .... (5.16)

Therefore, $\frac{H}{60}\times\frac{M}{J} = \frac{1-n}{n}$ .... (5.17)

Equation (5.17) represents the economic cutting conditions.

Since $\frac{H}{60}\times M$ is the cost of operating the machine between tool changes and J is the total cost per tool change, equation (5.17) can be written as

$$\frac{\cos tof}{} = \frac{1-n}{n}$$

Cost of operating between tool changes $= \frac{1-n}{n}$

Total cost of a tool change

The ratio $\frac{1-n}{n}$ is called the costs ratio for economic cutting

5.4 Power and Energy Relationships

A machining operation requires power and the power to perform machining can be computed from:

$P_c = F_c V$, where P_c = cutting power; F_c = cutting force; and V = cutting speed.

In U.S. customary units, power is traditional expressed as horsepower (dividing ft-lb/min by 33,000)

$$HP_c = \frac{F_c v}{33{,}000}$$

where HP_c = cutting horsepower, hp.

Gross power to operate the machine tool P_g or HP_g is given by

$P_g = \frac{P_c}{E}$ or $HP_g = \frac{HP_c}{E}$, where E = mechanical efficiency of machine tool Typical E for machine tools ~ 90%. Useful to convert power into power per unit volume rate of metal cut is called *unit power*, P_u or *unit horsepower*, HP_u

$P_u = \frac{P_c}{R_{MR}}$ or $HP_u = \frac{HP_c}{R_{MR}}$, where R_{MR} = material removal rate

The unit power is also known as the *specific energy U* that is defined as

$$U = P_u = \frac{P_c}{R_{MR}} = \frac{F_c V}{v t_o w}$$

Units for specific energy are typically N-m/mm3 or J/mm3 (in-lb/in3)

5.5 Cutting Temperature

Approximately 98% of the energy in machining is converted into heat and this can cause temperatures to be very high at the tool-chip. The remaining energy (about 2%) is retained as elastic energy in the chip.

Cutting temperatures are important as high cutting temperatures (i) reduce tool life (ii) produce hot chips that pose safety hazards to the machine operator and (iii) can cause inaccuracies in part dimensions due to thermal expansion of work material.

Nathan Cook derived an analytical method to determine cutting temperature from dimensional analysis using experimental data for various work materials as:

$$T = \frac{0.4U}{\rho C}\left(\frac{Vt_o}{K}\right)^{0.333}$$

where T = temperature rise at tool-chip interface; U = specific energy; v = cutting speed; t_o = chip thickness before cut; ρC = volumetric specific heat of work material; K = thermal diffusivity of work material. Experimental methods can be used to measure temperatures in machining using the *tool-chip thermocouple.* Using this method, Ken Trigger determined the speed-temperature relationship to be of the form:

$T = KV^m$, where T = measured tool-chip interface temperature, and V = cutting speed.

6.0 REQUIRED PROPERTIES OF CUTTING TOOL MATERIAL:

6.1 Requirements of cutting tool materials

The cutting tool materials must possess a number of important properties to avoid excessive wear, fracture failure, and high temperatures in cutting. The following characteristics are essential for cutting materials to withstand the heavy conditions of the cutting process and to produce high quality and economical parts:

(i) *hardness* at elevated temperatures (so-called *hot hardness*) so that hardness and strength of the tool edge are maintained in high cutting temperatures. This is the ability of the material to with stand very high temperature without loosing its cutting edge. The hardness of the tool material can be improved by adding molybdenum, tungsten, vanadium, chromium etc that form hard carbides. High hardness gives good wear resistance but poor mechanical shock resistance.

(ii) *toughness*: ability of the material to absorb energy without failing. Cutting if often accompanied by impact forces especially if cutting is interrupted, and cutting tool may fail very soon if it is not strong enough. This property possesses limitation on the hardness of the tool because of very high hardness the material becomes brittle and weak.

(iii) *wear resistance*: although there is a strong correlation between hot hardness and wear resistance, later depends on more than just hot hardness. The ability of the tool to withstand wear is called as wear resistance. During the process of machining, the tool is affected because of the abrasive action of the work piece. If the tool does not have sufficient wear resistance then there are possibilities of failure of cutting edge. Lack of chemical affinity between the tool and work piece improve wear resistance.

(iv) Should be easy to regrind and easy to weld the tool.

(v) *chemical inertness* of the tool material with respect to the work material, and

(vi) *thermal conductivity* of the tool material, which affects the maximum value of the cutting temperature at tool-chip interface. In order to have a low tool wear and better surface finish the co-efficient of friction between the tool and chip must be low. The thermal conductivity must be high for quick removal of heat from chip tool interface.

(vii)Mechanical and thermal shock resistance.

However, no single material fulfills all the above requirements.

6.2 Types of cutting tool materials

Carbon Steels

It is the oldest of tool material. The carbon content is 0.6~1.5% with small quantities of silicon, chromium, manganese, and vanadium to refine grain size. Maximum hardness is about HRC 62. This material has low wear resistance and low hot hardness. The use of these materials now is very limited.

High-speed steel (HSS)

This was first produced in 1900s. They are highly alloyed with vanadium, cobalt, molybdenum; tungsten and chromium added to increase hot hardness and wear resistance. Can be hardened to various depths by appropriate heat treating up to cold hardness in the range of HRC 63-65. The cobalt component gives the material a hot hardness value much greater than carbon steels. The high toughness and good wear resistance make HSS suitable for all type of cutting tools with complex shapes for relatively low to medium cutting speeds. The most widely used tool material today for taps, drills, reamers, gear tools, end cutters, slitting, broaches, etc.

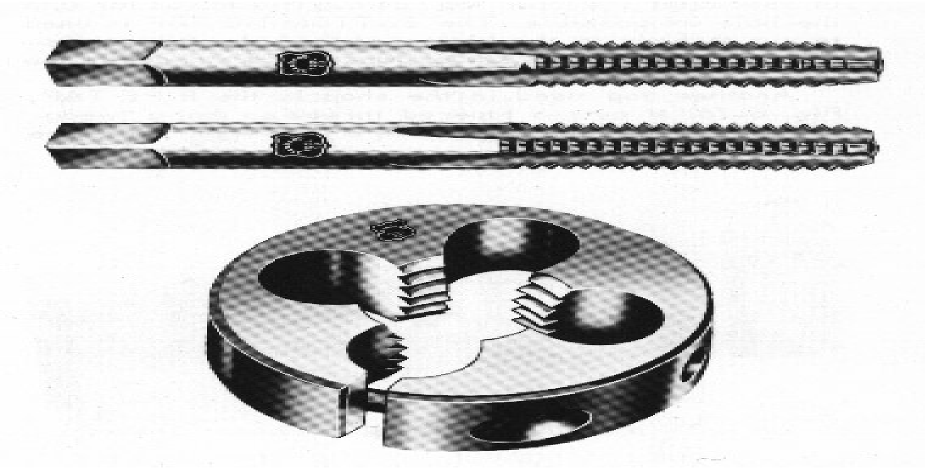


Figure 6.1: Thread tap and die made of high-speed steel

Cemented Carbides

Cemented carbides were introduced in the 1930s. These are the most important tool materials today because of their high hot hardness and wear resistance. The main disadvantage of cemented carbides is their low toughness. These materials are produced by powder metallurgy methods, sintering grains of *tungsten carbide* (WC) in a *cobalt* (Co) matrix (it provides toughness). There may be other carbides in the mixture, such as *titanium carbide* (TiC) and/or *tantalum carbide* (TaC) in addition to WC.

Figure 6.2: Various Inserts

In spite of more traditional tool materials, cemented carbides are available as inserts produced by powder metallurgy process. Inserts are available in various shapes, and are usually mechanically attached by means of clamps to the tool holder, or brazed to the tool holder. The clamping is preferred because after a cutting edge is worn, the insert is indexed (rotated in the holder) for another cutting edge. When all cutting edges are worn, the insert is thrown away. The indexable carbide inserts are never reground. If the carbide insert is brazed to the tool holder, indexing is not available, and after reaching the wear criterion, the carbide insert is reground on a tool grinder.

One advance in cutting tool materials involves the application of a very thin coating (~ 10 μm) to a K-grade substrate, which is the toughest of all carbide grades. Coating may consists of one or more thin layers of wear-resistant material, such as *titanium carbide* (TiC), *titanium nitride* (TiN), *aluminium oxide* (Al_2O_3), and/or other, more advanced materials. Coating allows increasing significantly the cutting speed for the same tool life.

Ceramics
Ceramic materials are composed primarily of fine-grained, high-purity aluminum oxide (Al2O3), pressed, and sintered with no binder. Two types are available:
(i) *white*, or *cold-pressed ceramics*, which consists of only Al_2O_3 cold pressed into inserts and sintered at high temperature.
(ii) *black*, or *hot-pressed ceramics*, commonly known as *cermets* (from ceramics and metal). This material consists of 70% Al_2O_3 and 30% TiC.
Both materials have very high wear resistance but low toughness; therefore they are suitable only for continuous operations such as finishing turning of cast iron and steel at very high speeds. There is no occurrence of built-up edge, and coolants are not required.

Cubic boron nitride (CBN) and synthetic diamonds
Diamond is the hardest substance ever known of all materials. It is used as a coating material in its polycrystalline form, or as a single-crystal diamond tool for special applications, such as mirror finishing of non-ferrous materials. Next to diamond, CBN is the hardest tool material. CBN is used mainly as coating material because it is very brittle. In spite of diamond, CBN is suitable for cutting ferrous materials.

7.0. CUTTING FLUIDS

Cutting fluid (*coolant*) is any liquid or gas that is applied to the chip and/or cutting tool to improve cutting performance. A very few cutting operations are performed dry, i.e., without the application of cutting fluids. Generally, it is essential that cutting fluids be applied to all machining operations.

7.1 Functions of cutting fluids

Cutting fluids serve the following functions:
(i) to cool the tool and work piece and carry away the heat generated from cutting zone. It is essential to maintain a temperature of 200^o C for carbon tools and 600^o C for HSS.
(ii) to improve surface finish. At low speeds, the surface finish obtained by using cutting fluids is better than what is obtained without using cutting fluids.
(iii) to wash away the chips and keep the cutting region free. This action is applicable to small, discontinuous chips only. Special devices are subsequently needed to separate chips from cutting fluids.
(iv) it helps to keep the freshly machined surface bright by giving a protective coating against atmospheric oxygen and thus protect the finished surface from corrosion.
(v) cutting fluids improves machinability and reduces machining forces.
(vi) to cause the chips to break into small parts rather than remain as long ribbons, which are hot, sharp, and difficult to remove from work piece.

7.2 Requirements of cutting fluid

A cutting fluid should posses the following properties:
(i) high heat absorption to remove the heat developed immediately,

(ii) good lubricating properties to have a low coefficient of friction,
(iii) high flash point to avoid fire hazard,
(iv) stability must be high to that it does not oxidize with air,
(v) it must not react with chemical and must be neutral,
(vi) Odourless, so that at high temperatures, it does not give a bad smell,
(vii) harmless to the skin of operators,
(viii) harmless to the bearings,
(ix) should not have a corrosive action on the machine or work piece,
(x) should have low viscosity to permit the free flow of the cutting tool and
(xi) it must be economical.

The choice of a cutting fluid depends upon type of operation, material of tool and work piece, rate of metal removal and cost of cutting fluid.

7.3 Types of cutting fluids

(i) Cutting Oils (Oils)

Cutting oils are cutting fluids based on mineral or fatty oil mixtures. They include mineral, animal, vegetable, compounded, and synthetic oils that are used for low-speed cutting where temperature rise is not significant. Chemical additives like sulphur improve oil lubricant capabilities. Areas of application depend on the properties of the particular oil but commonly, cutting oils are used for heavy cutting operations on tough steels.

(ii) Soluble Oils (Emulsions)

They are mixtures of oil and water and are generally for high-speed cutting because temperature rise is significant. The most common, cheap and effective form of cutting fluids consisting of oil droplets suspended in water in a typical ratio water to oil 30:1. Emulsifying agents are also added to promote stability of emulsion. For heavy-duty work, extreme pressure additives are used. Oil emulsions are typically used for aluminium and cooper alloys.

(iii) Chemical fluids (Semi synthetics)

These cutting fluids consist of chemical diluted in water with additives that reduce the size of oil particles, making them more effective. They possess good flushing and cooling abilities. Tend to form more stable emulsions but may have harmful effects to the skin.

(iv) *Synthetics*

These are chemicals with additives that are diluted in water but contain no oil.

7. 4 Effect of cutting fluid on cutting speed, tool life and chip concentration

Cutting speed: Cutting fluids are not only used to carry away the heat generated but also to lubricate the working surface of the tool. When a cutting fluid is used for machining tough material the productivity may be increased from 15% to 30% more when compared with dry operation. But using cutting fluids, high speeds may be used.

Tool life: By using cutting fluids effectively during machining operations, the tool life increases. Carbon steel rods have less heat resistant and thus have maximum increase in tool life for HSS it is around 25%.

Chip concentration: Without the use of cutting fluid chips are accumulated near the work tool interface and are difficult to remove because of its high temperature. By the use of cutting fluid, the temperature of the chip is reduced and the chips are washed away from the work tool interface.

7.5 Environmental issues

Cutting fluids become contaminated with garbage, small chips, bacteria, etc., over time. Alternative ways of dealing with the problem of contamination are:
(i) replace the cutting fluid at least twice per month,
(ii) machine without cutting fluids (dry cutting),
(iii) use a filtration system to continuously clean the cutting fluid.
Disposed cutting fluids must be collected and reclaimed. There are a number of methods of reclaiming cutting fluids removed from working area. Systems used range from simple settlement tanks to complex filtration and purification systems. Chips are emptied from the skips into a pulverizer and progress to centrifugal separators to become a scrap material. Neat oil after separation can be processed and returned, after cleaning and sterilizing to destroy bacteria.

7.6 Application of cutting fluids

The cutting fluids may be applied to the cutting tool in the following ways.
For effective use of cutting fluid and for heavy and continuous cutting the fluid should penetrate into the cutting zone. The following are the famous methods of cutting fluid application:

(i)Manual application

This is the application of a fluid from a can manually by the operator. It is not acceptable even in job-shop situations except for tapping and some other operations where cutting speeds are very low and friction is a problem. In this case, cutting fluids are used as *lubricants*.

(ii) Flood application (Hi-jet application)

Here there is a continuous stream of cutting fluid is directed to the cutting zone with the help of nozzle. The used cutting fluid drops into a tank at the bottom. Before it is re-circulated by the pump, it passes through many filters to remove chips and dirt. Flow rates typically range from 10L/min for single point tools to 225 L/min per cutter for multi – points cutter. In some drilling and milling operations, fluid pressure in the range of 700 to 14,000 kPa are used to flush away, the chips produced to prevent interfering with the operation. to the operation.

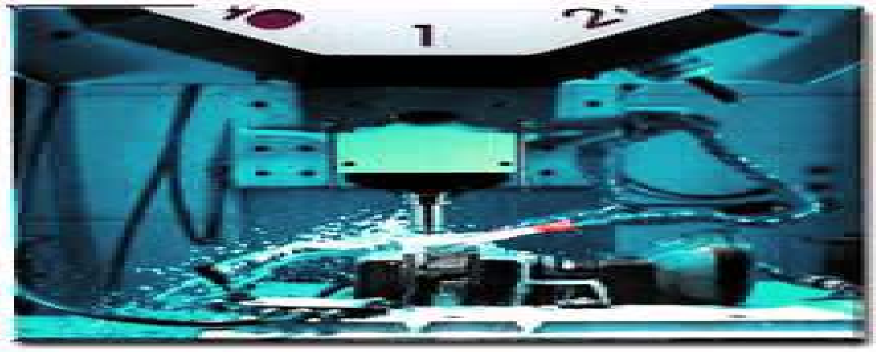


Figure 7.1: Application of flooding in milling

(iii) Mist method of application

This type of cooling supplies fluid to inaccessible areas, similar to using aerosol can, and provides better visibility of the work piece being machined as compared to flood cooling. It however has limited cooling capacity. Mist application requires venting to prevent the inhalation of airborne fluid particles by the machine operator and other workers that are nearby.

(iv)High pressure systems

Due to the increase in speed and power of modern, computer-controlled machine tools, heat generation is an important factor in machining. High-pressured refrigerated systems in the range of 5.5 to 35 MPa to increase the rate of heat removal from the cutting zone and act as chip breaker are employed.

(v)Through the cutting tool system.

For a more effective application of cutting fluid, narrow passages can be produced in cutting tools, as well as in tool holders, through which cutting fluid can be applied under high pressure.

Example

1. The useful tool life of a HSS tool at 18 m/min is 3 hours. Calculate the tool life when the tool operates at 24 m/min.

Solution:

VTn = C

V = 18 m/min
T = 3 x 60 = 180 min
Constant C = 18 x (180) 0.125 = 34.45 (Here n = 0.125)
Now V = 24 m/min.
T = (34.45 / 24) 1/0.125
= 18 minutes.

8.0 PRINCIPLES OF METAL CUTTING WITH MULTI-POINT TOOLS

Cutters, which present more than one cutting edge, usually have a higher metal removal rate than single point tools and have increased life between regrinds due to the number of cutting edges.

8.1 Classification of Multi-edges cutting tools

Group	Machines	Cutters
1	Drilling, Boring, Reaming machines, Capstan Lathes, Turret Lathes	Twist Drills, Reamers, Multi-flute cone drills, counter-bores, spot facing cutters.
2	Milling Machines	Slotting cutters, side-and-face cutters, slab mills, end mills, face mills.
3	Grinding machines	Grinding cutters
4	Threading machines	Taps and Dies

8.2 Principles of Operation

Group 1 Tools: These groups of tools have their cutting edges in continuous engagement with the work and are fed axially at a uniform feed per revolution. The undeformed chip thickness is therefore constant and directly proportional to the feed/revolution. The geometry and mechanics of cutting are then identical to those for single-point tools.

Group 2 Tools: Have their cutting edges intermittently engaged with the work and are fed in a plane parallel or perpendicular to the cutter axis of rotation. The geometry of chip formation for this cutter is more complex than group 1 or single-point tools.

Group 3 Tools: Have geometry of chip formation similar to that of milling. The grit edges, which project from the surfaces of the wheel, act as very small cutting teeth.

The principal differences between the cutting action of grinding wheel and of milling are:

(i) grinding grits are sufficiently hard to cut fully-hardened steels.
(ii) The cutting angles of the grits have a random geometry.
(iii)The pitch of the grit cutting edges is much smaller than the pitch of the milling-cutter teeth.
(iv)The size of the chips is very small for grinding as compared with milling.

Group 4 Tools: An internal thread is produced by rotation through a hole of a hard-steel form tool in the shape of the required thread. The tap has a screw-like appearance with breaks in the threaded portion by flutes or clearance grooves to permit cutting action by faces at 90^0 to the material being cut.

An external thread is cut by the action of hard metal shaped to the form to be produced in the work piece. The die features, a hardened steel nut of the required thread form in a single piece, but with a split on one edge so that one can adjust it. For larger threads, the die is in two separate pieces held side-by –side in a stock provided with handles for turning the die about the work piece.

8.3 Principle of Milling

Milling is a process of producing flat and complex shapes with the use of multi-tooth cutting tool, which is called a *milling cutter* and the cutting edges are called *teeth*. The axis of rotation of the cutting tool is perpendicular to the direction of feed, either parallel or perpendicular to the machined surface.

The machine tool that traditionally performs this operation is a *milling machine*.

Milling is an interrupted cutting operation: the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects the teeth to a cycle of impact force and thermal shock on every rotation. The tool material and cutter geometry must be designed to withstand these conditions. Cutting fluids are essential for most milling operations.

In milling, each tooth on a tool removes part of the stock in the form of a chip.

Cutting velocity V is the peripheral speed of the cutter is defined by

$$V = \pi DN$$

where D is the cutter outer diameter and N is the rotational speed of the cutter.

Cutting speeds are usually in the range of 0.1~4 m/s, lower for difficult-to-cut materials and for rough cuts, and higher for non-ferrous easy-to-cut materials like aluminium and for finishing cuts.

Three types of *feed* in milling can be identified:

feed per tooth f_z: the basic parameter in milling equivalent to the feed in turning. Feed per tooth is selected with regard to the surface finish and dimensional accuracy required.

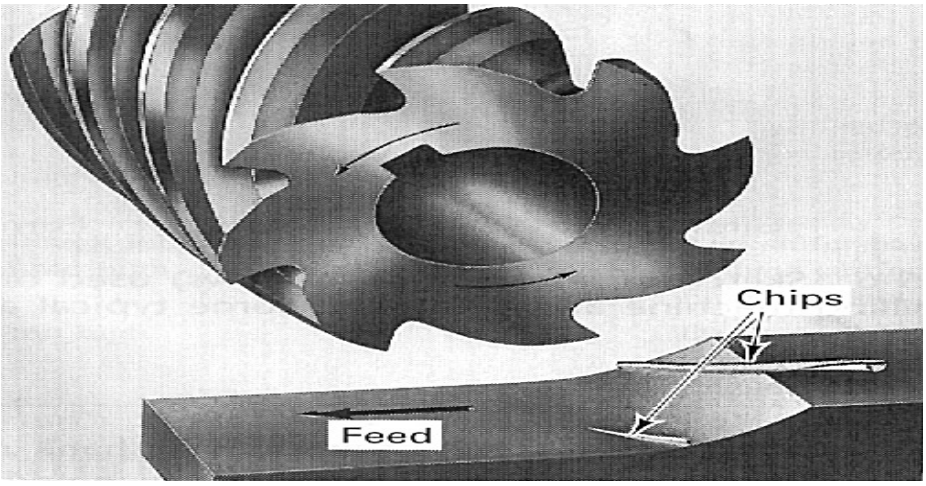


Figure 8.1: Milling operation. The cutter is lifted to show the chips, and the work, transient, and machined surfaces.

Feeds per tooth are in the range of 0.05~0.5 mm/tooth, lower feeds are for finishing cuts.
feed per revolution f_r: it determines the amount of material cut per one full revolution of the milling cutter. Feed per revolution is calculated as $f_r = f_z z$, z being the number of the cutter's teeth.
feed per minute f_m: Feed per minute is calculated taking into account the rotational speed N and number of the cutter's teeth z,
$f_m = f_z zN = f_r N$
Feed per minute is used to adjust the feed change gears.

8.3.1 Milling Operations

Owing to the variety of shapes possible and its high production rates, milling is one of the most versatile and widely used machining operations. The geometric form created by milling fall into three major groups:
(i) *Plane surfaces*: the surface is linear in all three dimensions. The simplest and most convenient type of surface;
(ii) *Two-dimensional surfaces*: the shape of the surface changes in the direction of two of the axes and is linear along the third axis. Examples include cams;
(iii) *Three-dimensional surfaces*: the shape of the surface changes in all three directions. Examples include die cavities, gas turbine blades, propellers, casting patterns, etc.

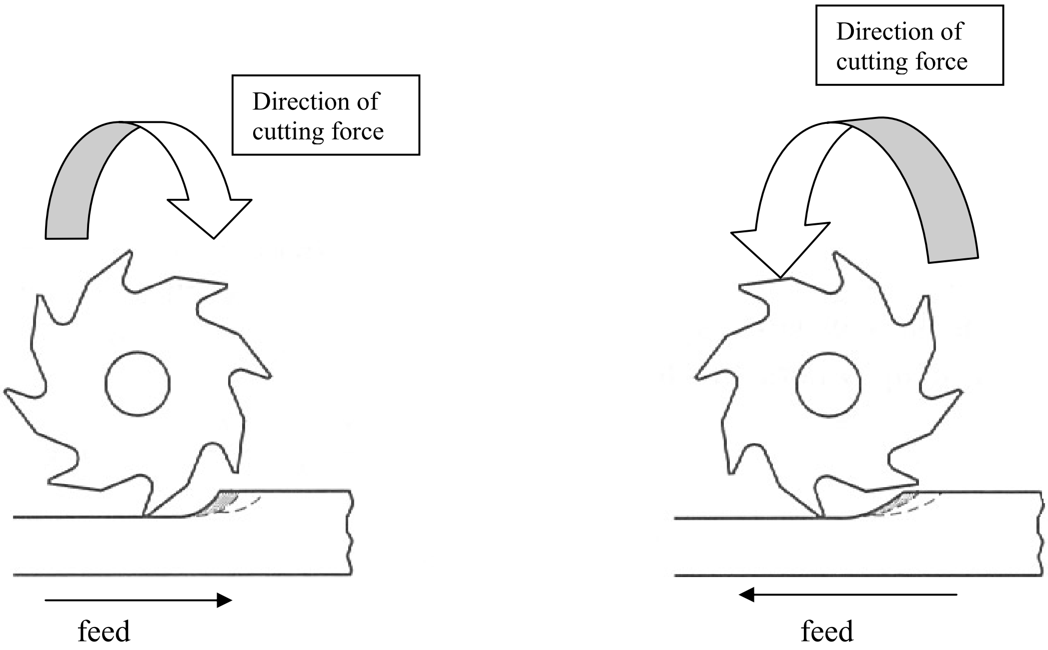
8.3.1.1Peripheral Milling

In *peripheral milling*, also called *plain milling*, the axis of the cutter is parallel to the surface being machined, and the operation is performed by cutting edges on the outside periphery of the cutter. The primary motion is the rotation of the cutter.

Main types of peripheral milling

There are two basic types of milling, as shown in Figure 8.2:
(i) *Down (climb) milling*, when the cutter rotation is in the same direction as the motion of the work piece being fed. In down milling, the cutting force is directed into the worktable, which

allows thinner work parts to be machined. Better surface finish is obtained but the stress load on the teeth is abrupt, which may damage the cutter.
(ii) *Up (conventional) milling*, in which the work piece is moving towards the cutter, opposing the cutter direction of rotation. In up milling, the cutting force tends to lift the work piece. The work conditions for the cutter are more favourable. Because the cutter does not start to cut when it makes contact (cutting at zero cut is impossible), the surface has a natural waviness. Up-cut milling is the conventional method of milling in which the rotation of the cutter is in opposite direction to the feed of the worktable. The tangential force not only shears the metal but also overcomes the feed force of the worktable.



Down-cut Milling ***Up-cut Milling***

Figure 8.2: Two types of peripheral milling

Several types of peripheral milling are shown in Figures 8.3 and 8.4 are:
(i) *slab milling*, the basic form of peripheral milling in which the cutter width extends beyond the work piece on both sides;
(ii) *slotting*, also called *slot milling*, in which the width of the cutter, usually called *slotter*, is less than the work piece width, creating a slot in the work piece. The slotter has teeth on the periphery and over the both end faces. When only the one-side face teeth are engaged, the operations is known as the *side milling*, in which the cutter machines the side of the work piece;
(iii) *straddle milling*, which is the same as side milling, only cutting takes place on both sides of the work. In straddle milling, two slotters mounted on an arbour work together;
(iv) when the slotter is very thin, the operation called *slitting* can be used to mill narrow slots (slits) or to cut a work part into two. The slitting cutter (*slitter*) is narrower than the slotter and has teeth only on the periphery.

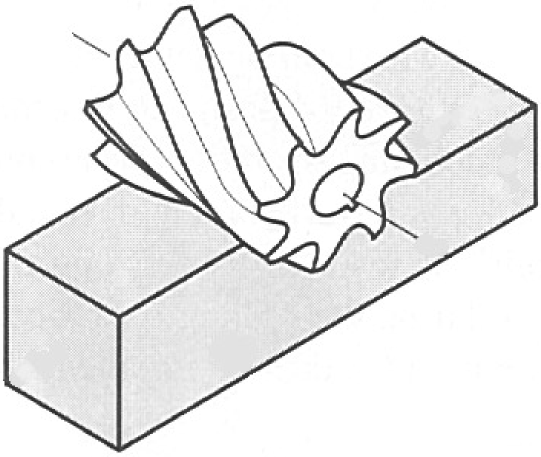
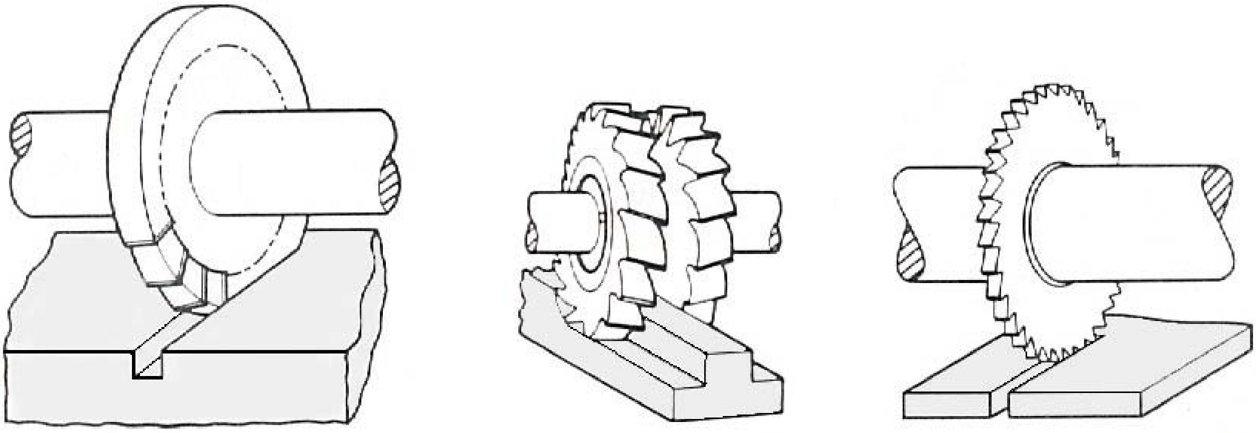


Figure 8.3: Peripheral slab milling operation



(a) (b) (c)

Figure 8.4: Peripheral milling operations with narrow cutters: (a) slotting, (b) straddle milling, and (c) slitting.

Some of the advantages of peripheral milling include,
(i) More stable holding of the cutter. There is less variation in the arbour torque;
(ii) Lower power requirements;
(iii) Better work surface finish.

8.3.1.2 Face milling

In *face milling*, cutter is perpendicular to the machined surface. The cutter axis is vertical, but in the newer CNC machines, it often is horizontal. In face milling, machining is performed by teeth on both the end and periphery of the face-milling cutter. Again up and down types of milling are available, depending on directions of the cutter rotation and feed.

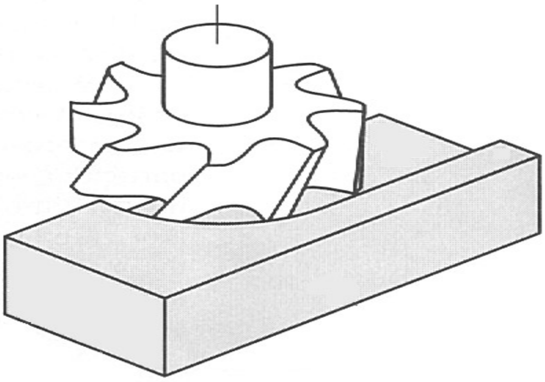


Figure 8.5: Partial face milling operation.
The face-milling cutter machines only one side of the work piece.

Face milling is usually applied for rough machining of large surfaces. Surface finish is worse than in peripheral milling, and feed marks are inevitable. One advantage of the face milling is the high production rate because the cutter diameter is large and as a result, the material removal rate is high. Face milling with large diameter cutters requires significant machine power.

8.3.1.3 End milling

In *end milling*, the cutter, called *end mill*, has a diameter less than the work piece width. The end mill has helical cutting edges carried over onto the cylindrical cutter surface. End mills with flat ends (so called *squire-end mills*) are used to produce pockets, closed or end key slots, etc.

Figure 8.6: End milling operation used to cut an aluminium work part.

8.3.2 Milling machines

The conventional milling machines provide a primary rotating motion for the cutter held in the spindle, and a linear feed motion for the work piece, which is fastened onto the worktable. Milling machines for machining of complex shapes usually provide both a rotating primary motion and a curvilinear feed motion for the cutter in the spindle with a stationary work piece. Various machine designs are available for various milling operations. The main types of milling machines in general use are:

(i) horizontal milling machine
(ii) vertical milling machine

The term horizontal and vertical, refer to the axis of the spindle for the technique underlying the generating, copying, or forming of geometric surfaces. Using a milling machine consists of rotation of the cutting tool in conjunction with a feed movement of the worktable. Although the vertical milling machine is capable of a more versatile range of work, the horizontal machine is preferred for heavy-cuts, because of the greater support and rigidity afforded to the milling cutter by the arbour and its support.

The universal milling machine may be considered as a combination of both horizontal and vertical types, with provision for adjustment of the line of motion or feeding direction of the worktable. The increased tool and table movements make possible a wide range of milling operation not applicable with a straight vertical or horizontal type machine. The universal milling machine is a horizontal milling machine with the following attachments:

(i) vertical milling attachment
(ii) slotting attachment (for machining slots and keyways)
(iii) the dividing head (for location and holding of work in order that machining may take place by suitable division of the work piece, a most versatile work holding device, capable of holding cylindrical work with the axis horizontal, vertical or at any angle between the horizontal and the vertical)

Other classifications of milling machines are:

(i) Column-and-knee milling machines;
(ii) Bed type-milling machines;
(iii) Machining centres.

Column-and-knee milling machines

The *column-and-knee milling machines* are the basic machine tool for milling. The name comes from the fact that this machine has two principal components, a *column* that supports the spindle, and a *knee* that supports the worktable. There are two different types of column-and-knee milling machines according to position of the spindle axis: horizontal, and vertical.

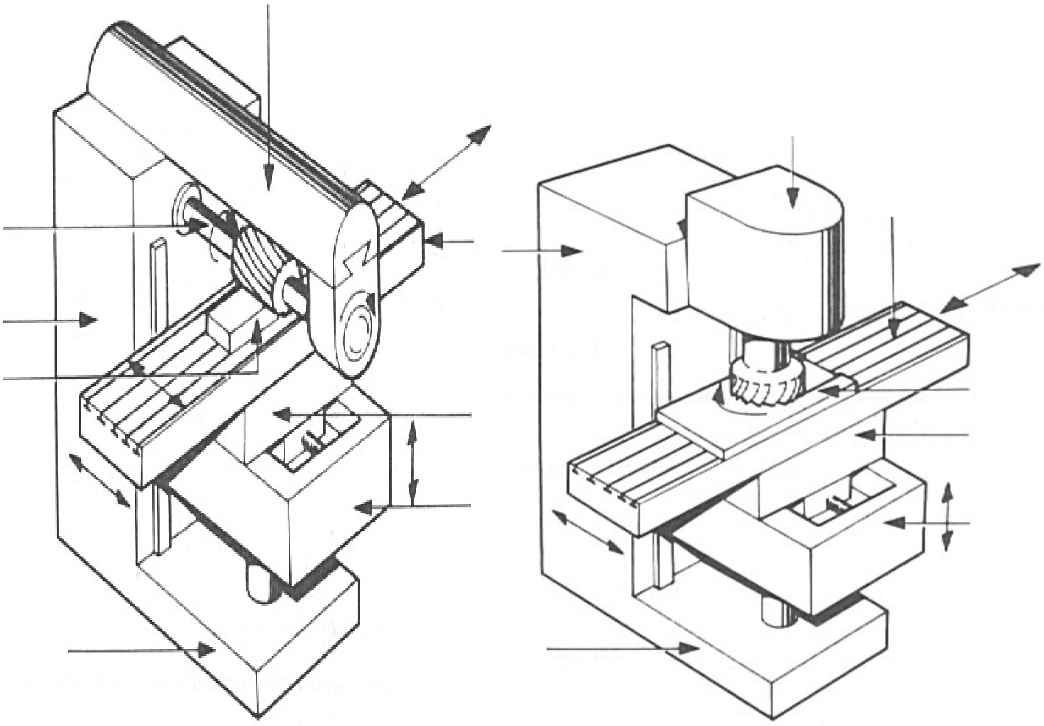


Figure 8.7: Two basic types of column-and-knee milling machines, (Left) horizontal, and (Right) vertical.

Bed type machines
In bed type milling machines, the worktable is mounted directly on the bed that replaces the knee. This ensures greater rigidity, thus permitting heavier cutting conditions and higher productivity. These machines are designed for mass production.

Machining centres
A machining centre is a highly automated machine tool capable of performing multiple machining operations under CNC control. The features that make a machining centre unique include the following:
(i) tool storage unit called *tool magazine* that can hold up to 120 different cutting tools.
(ii) *automatic tool changer*, which is used to exchange cutting tools between the tool magazine and machining centre spindle when required. The tool changer is controlled by the CNC program.
(iii) *automatic workpart positioning*. Many of machining centres are equipped with a rotary worktable, which precisely position the part at some angle relative to the spindle. It permits the cutter to perform machining on four sides of the part.

Milling cutters
Classification of milling cutters according to their design includes the following:
HSS cutters: Many cutters like end mills, slitting cutters, slab cutters, angular cutters, form cutters, etc., are made from high-speed steel (HSS).

Brazed cutters: Very limited numbers of cutters (mainly face mills) are made with brazed carbide inserts. This design is largely replaced by mechanically attached cutters.
Mechanically attached cutters: The vast majority of cutters are in this category. Carbide inserts are either clamped or pin locked to the body of the milling cutter.
Classification of milling cutters may also be associated with the various milling operations. Figure 8.8 illustrate two of the most important types of milling cutters, end mills, and ball-end mills.

Figure 8.8: Two of the most widely used types of milling cutters with mechanically attached carbide inserts, (Left) end mills, and (Right) ball-end mills

8.4 Grinding

Abrasive machining uses tools that are made of tiny, hard particles of crystalline materials – abrasive particles have irregular shape and sharp edges; the work piece surface is machined by removing very tiny amounts of material at random points where a particle contacts it. By using a large number of particles, the effect is averaged over the entire surface, resulting in ***very good surface finish*** and ***excellent dimension control***, even for hard, brittle work pieces. Grinding is also used to machine brittle materials (such materials cannot be machined easily by conventional cutting processes, since they would fracture and crack in random fashion).

1. To improve the surface finish of a part manufactured by other processes
Examples:
(i) A steel injection moulding die is machined by milling; the surface finish must be improved for better plastic flow, either by manual grinding using shaped grinding tools, or by electro-grinding.
(ii) The internal surface of the cylinders of a car engine is turned on a lathe. The surface is then made smooth by grinding, followed by honing and lapping to get an extremely good, mirror-like finish.
(iii) Sand-paper is used to smooth a rough-cut piece of wood.

2. To improve the dimensional tolerance of a part manufactured by other processes
Examples:
(i) ball-bearings are formed into initial round shape by a forging process; this is followed by a grinding process in a specially formed grinding die to get extremely good diameter control ($\leq 15\mu m$).

(ii) Knives are made from forged steel; the steel is then hardened; finally, a grinding operation is used to give a sharp cutting edge.

3. To cut hard brittle materials
Example: Most semiconductor IC chips are made from silicon; the starting point is a long bar of a crystal of silicon (the diameter is usually 8cm, 15cm or 30cm, and length up to 200 cm). This rod must by sliced into thin circular slices; each slice is used to make a large number of ICs. A diamond abrasive wheel is used to cut the rod into slices.

4. To remove unwanted materials of a cutting process
Example: Drilling and milling often leave tiny, sharp chips along the outer edges of the surface created by the tool – these are called burrs. Tapered grinding wheels are used to remove the burr (the process is called deburring).

8.4.1 Abrasive materials

Common abrasive materials are Aluminium Oxide and Silicon Carbide. For harder materials and high precision applications, super abrasives (Cubic Boron Nitride, or CBN, and diamond powder), which are extremely hard materials, are used.

Abrasive materials have two properties: high hardness, and high friability. Friability means that the abrasive particles are brittle, and fracture after some amount of use, creating new sharp edges that will again perform more abrasion.

8.4.2 Abrasive tools

Figure 8.9 shows several types of abrasive tools. They all contain abrasive grains that are glued together using resin or hardened rubber. Sometimes, the abrasive particles may be embedded in metal or ceramic. It is important for the bonding material to be softer than the abrasive. In addition, the bonding material is selected to release the abrasive particles and wear away after some amount of use – this keeps exposing fresh abrasive particles to the work piece continuously. The mean size of abrasive particle used in each tool determines the rate at which it will cut, and the quality of surface finish it will provide. Low material removal rate means better surface, which is achieved by using very fine grains. Grain size is expressed using numbers, small numbers like 10 mean large grains, and large numbers, e.g. 100 mean fine grains. You can see this in the grades of sandpaper.

8.4.3 Grinding machines

There are several types of grinding machines. The main ones are surface grinders, grinding wheels, cylindrical grinders and centerless grinders. The figure below shows examples of a few of these. Surface grinders produce flat surfaces. The part is held on the flat table (steel parts can be held by a magnetic force – this is called ***magnetic chucking***). The table moves in a reciprocating motion (±X-axis), and the rotating wheel is lowered (Z-axis) so that it just scrapes along the surface. After each reciprocating cycle, the part is fed by a small amount along the Y-axis.

To improve dimension control on cylindrical parts, centerless grinders, which use long cylindrical wheels, are employed. The axis of the regulating wheel and grinding wheel are slightly misaligned, causing the part to travel slowly in the axial direction, and after some time, the part automatically moves beyond the length of the wheel. Controlling the angle of misalignment can control the time that the part is subjected to grinding.

If a turned part of complex shape (e.g. stepped shafts) are to be ground, then cylindrical grinding is used, which employs specially made grinding wheels, whose profile fits the profile of the part to be ground.

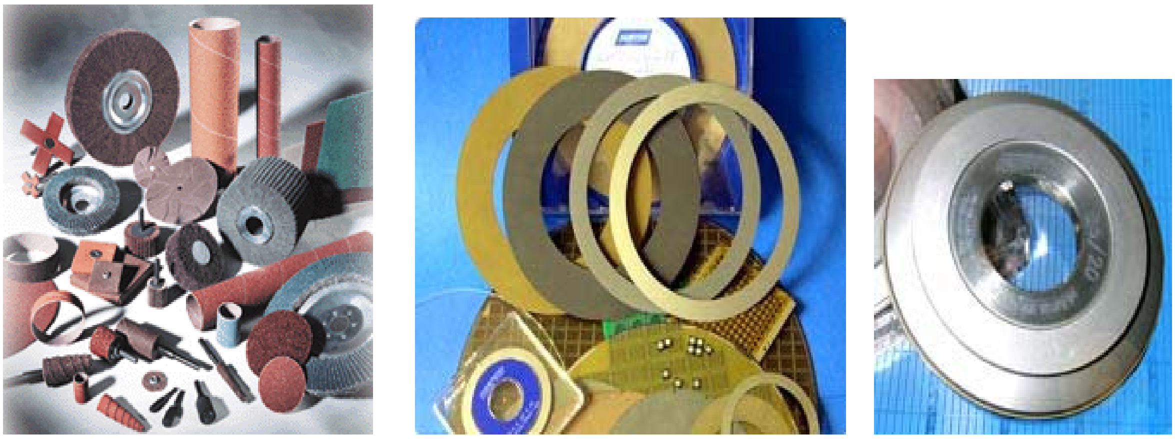


Figure 8.9: Types of Abrasive Tools

8.5 Drilling

The geometry of the common twist drill tool (called *drill bit*) is complex; it has straight cutting teeth at the bottom – these teeth do most of the metal cutting, and it has curved cutting teeth along its cylindrical surface (Figure 8.10). The grooves created by the helical teeth are called flutes, and are useful in pushing the chips out from the hole as it is being machined. Clearly, the velocity of the tip of the drill is zero, and so this region of the tool cannot do much cutting. Therefore, it is common to machine a small hole in the material, called a center-hole, before utilizing the drill. Special drills called centre-drills make centre-holes; they also provide a good way for the drill bit to be aligned with the location of the centre of the hole. There are hundreds of different types of drill shapes and sizes.

Common ***drill bit materials*** include hardened steel (High Speed Steel, Titanium Nitride coated steel); for cutting harder materials, drills with hard inserts, e.g. carbide or CBN inserts, are used. In general, drills for cutting softer materials have smaller point angle, while those for cutting hard and brittle materials have larger point angle. If the Length/Diameter ratio of the hole to be machined is large, then we need a special guiding support for the drill, which itself has to be very long; such operations are called ***gun-drilling***. This process is used for holes with diameter of few mm or more, and L/D ratio up to 300 and are used for making barrels of guns. Drilling is not useful for very small diameter holes (e.g. < 0.5 mm), since the tool may break and are stuck in the work piece. Usually, the size of the hole made by a drill is slightly larger than the measured diameter of the drill – this is mainly because of vibration of the tool spindle as it rotates possible misalignment of the drill with the spindle axis, and some other factors. For tight dimension control on hole diameter, we first drill a hole that is slightly smaller than required size (e.g. 0.25 mm smaller), and then use a special type of drill called a ***reamer***. Reaming has very low material removal rate, low depth of cut, but gives good dimension accuracy. Spade drills make large and deep holes.

Coutersink/***counterbore*** drills have multiple diameters – they make a chamfered/stepped hole, which is useful for inserting screws/bolts – the larger diameter part of the hole accommodates the screw/bolt head. Internal threads can be cut into holes that mate with screws/bolts and are cut by using tapping tools.

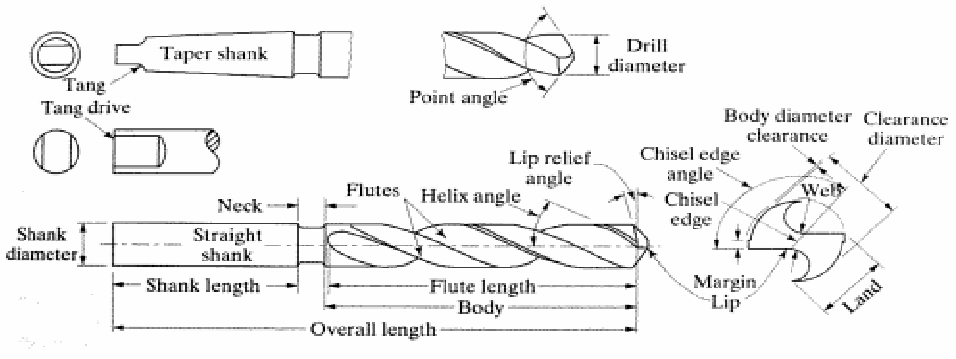


Figure 8.10: Geometry of a drill bit

(a) Twist drill *(b) Spade drill* *(c) Step drill* *(d) Reamer* *(e) Center drill*

Figure 8.11: Types of drills

(a) Countersink *(b) Counter bore*

Figure 8.11: Two types of drilling operations

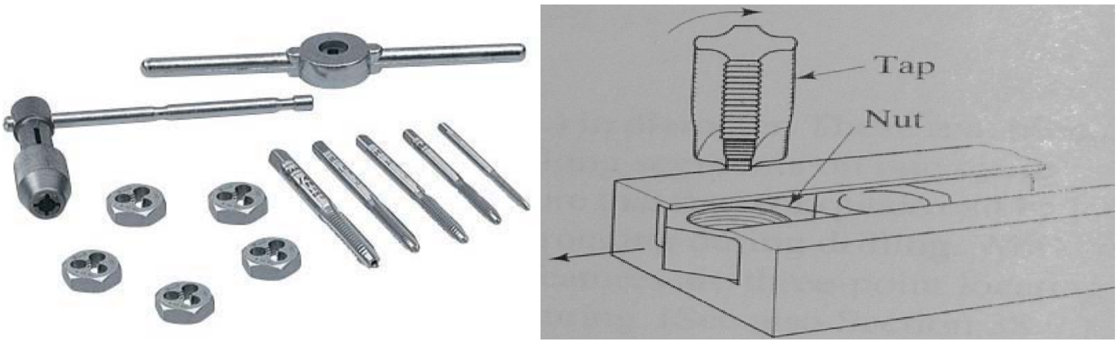


Figure 8.12: ***Thread-cutting. A drilled hole can be given internal threads by using a tapping tool; external threads on a cylindrical shape are made using a tapping die. The left image shows manual tool set for making external and internal threads. The right image shows a schematic for automatic tapping of threads in nuts.***

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