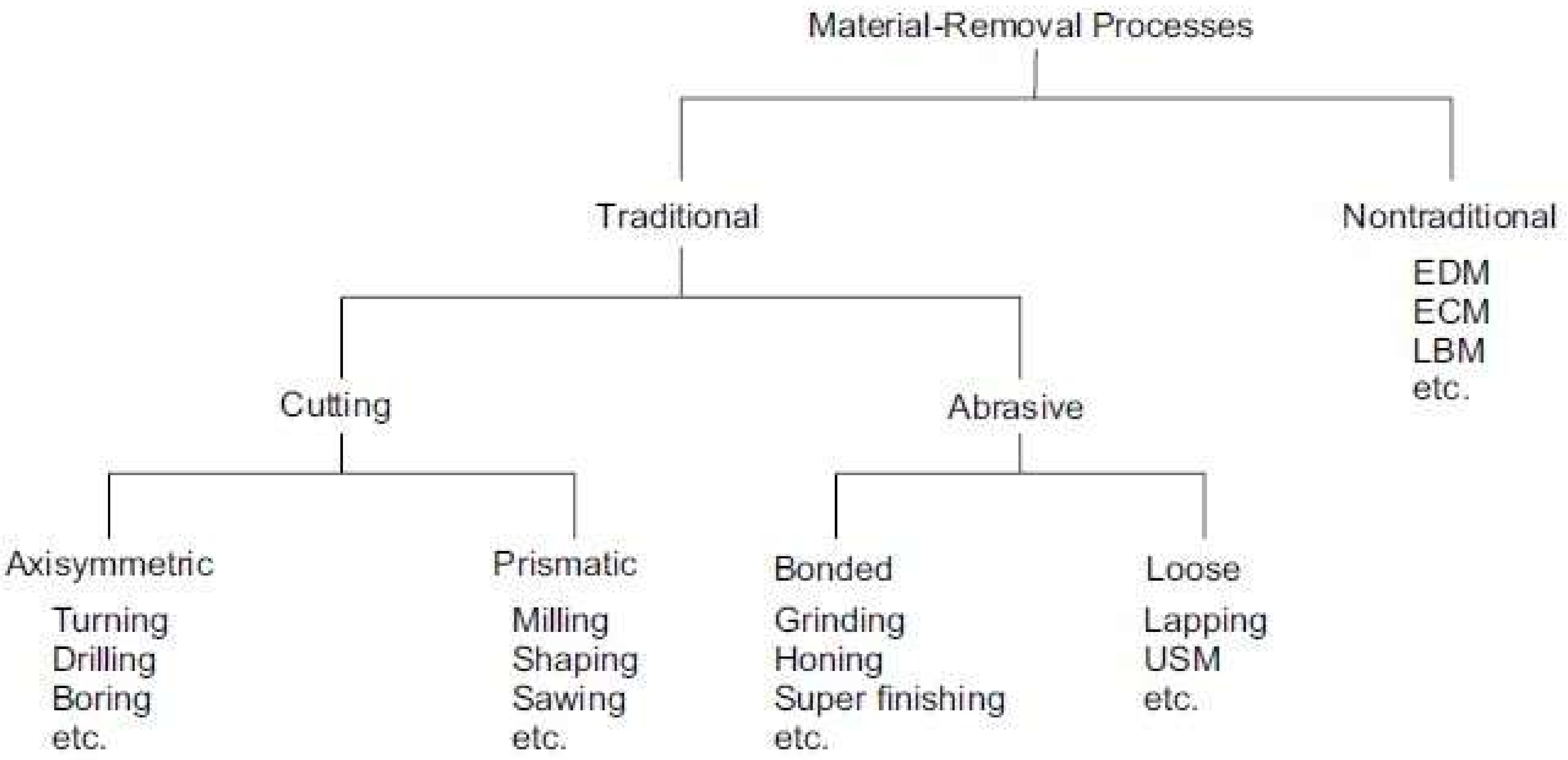
Machining Science and Technology

(RME6C002)
Part - I

MODULE-I (13 hrs)

- Geometry of cutting tools in ASA and ORS.
- Effect of Geometrical parameters on cutting force and surface finish
- Mechanics of chip formation,
- Merchant’s theory, Force relationship and velocity relationship,
- Cutting tool materials.
- Types of Tool Wear: Flank wear, Crater wear, Wear measurement
- Cutting fluid and its effect; Machinability Criteria,
- Tool life and Taylor's equation,
- Effect of variables on tool life and surface finish
- Measurement of cutting force, Lathe tool dynamometer, Drill tool dynamometer.
- Economics of machining.

Machining Process



Material-Removal Processes

Traditional

Cutting

Axisymmetric
- Turning
- Drilling
- Boring
- etc.

Prismatic
- Milling
- Shaping
- Sawing
- etc.

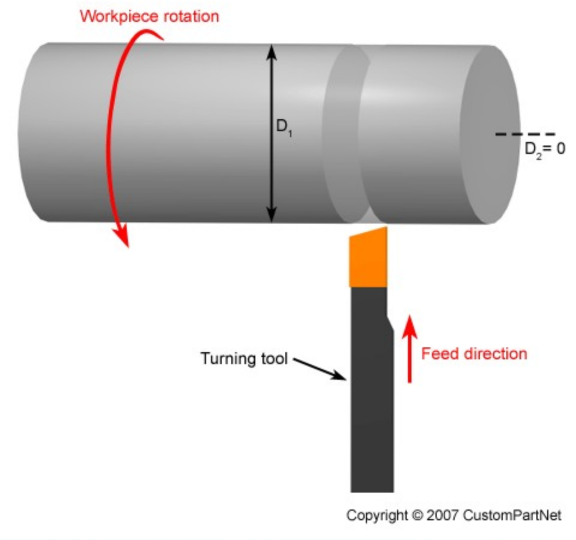
Abrasive

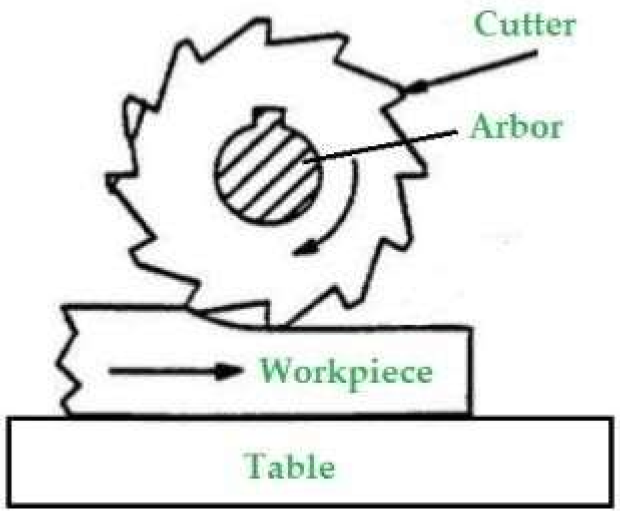
Bonded
- Grinding
- Honing
- Super finishing
- etc.

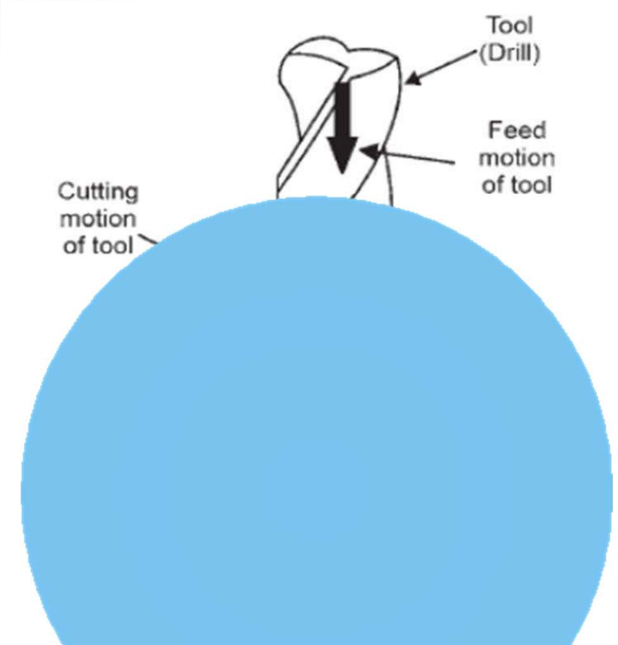
Loose
- Lapping
- USM
- etc.

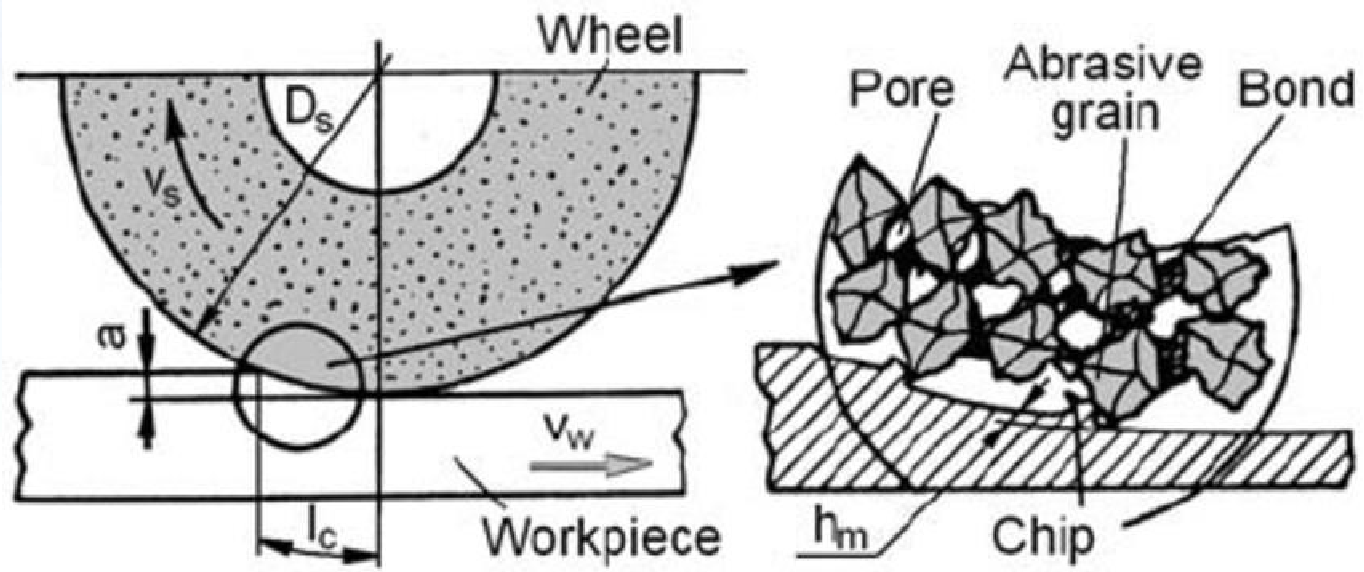
Nontraditional
- EDM
- ECM
- LBM
- etc.

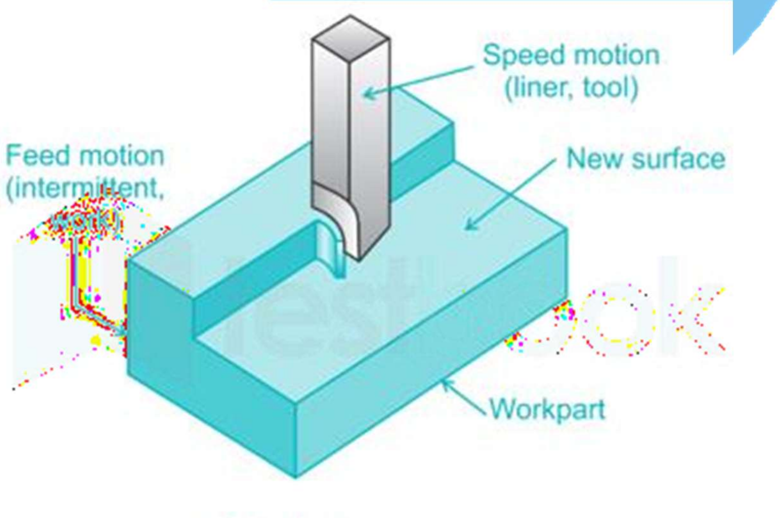
Basic Machining Process





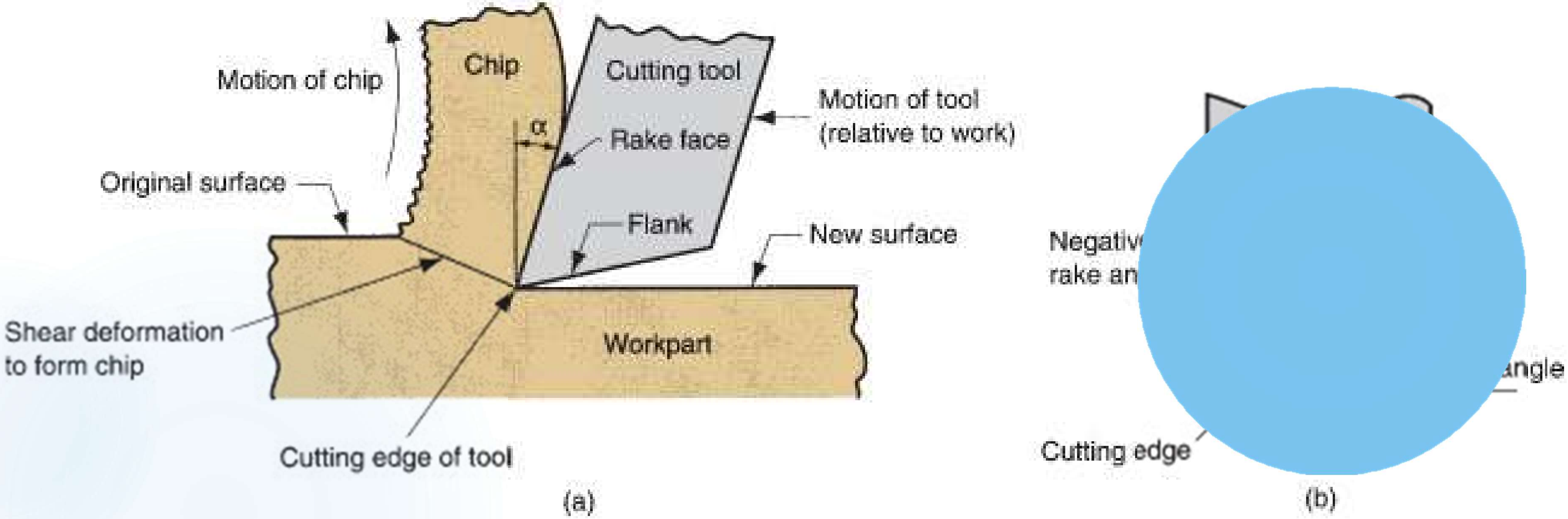






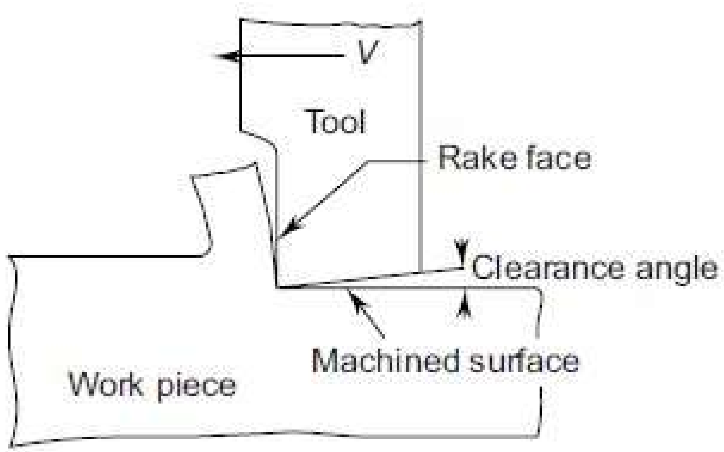
a) Shaping

Cross-sectional view of the machining process.

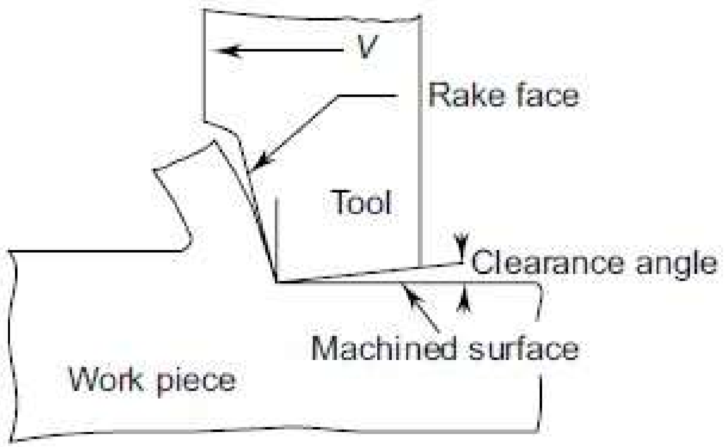


Rake angle

- It is the angle between the face of the tool called the rake face and the normal to the machining direction.
- This angle specifies the ease with which a metal is cut. Higher the rake angle better is the cutting and less is the cutting force.
- Increasing the rake angle reduces the metal back up available at the tool rake face. This reduces the strength of the tool tip as well as the heat dissipation through the tool.
- The maximum limit to the rake angle and is generally of the order of 15° for high speed steel tools cutting mild steel.
- Zero or negative rake angle are generally used in the case of highly brittle tool materials such as car bides or diamond for giving extra strength to the tool tip.



(b) Zero rake angle



(c) Negative rake angle

Clearance angle:(Relief Angle)

- This is the angle between the machined surface and the under side of the tool called the flank face.
- The clearance angle is provided such that the tool will not rub or spoil the machined surface, but at the same time will increase the cutting forces.
- A very large clearance angle reduces the strength of the tool tip, hence normally an angle of the order of 5 to 6° is generally used.

Geometry of cutting tools in ASA and ORS

- American Standard Association (ASA)
- Orthogonal Rake System (ORS)

Cutting tool geometry is a very important aspect that has to be carefully considered. The two considerations that need to be considered (**Armarego and Brown**) are:

- The ease with which the tool geometry can be maintained through the grinding and inspection process,

and

- The mechanics of the process and its relationship with the tool geometry.

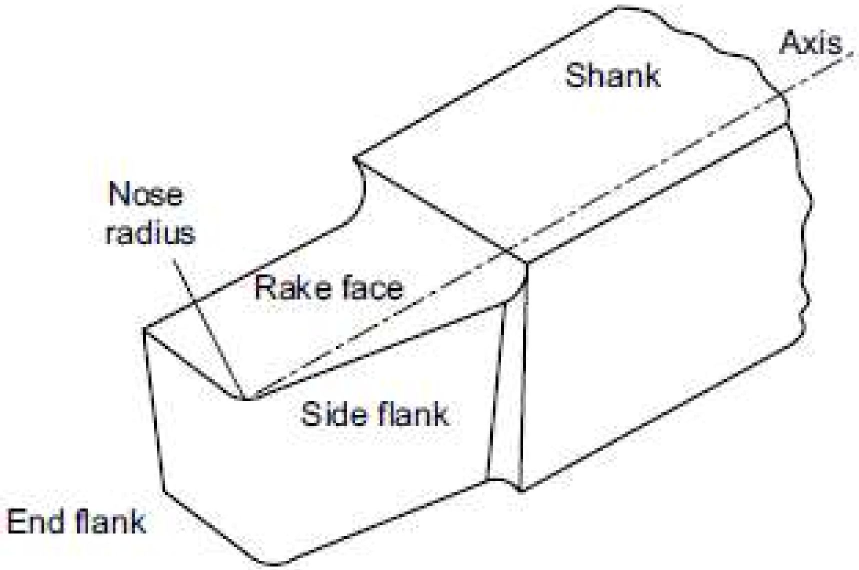
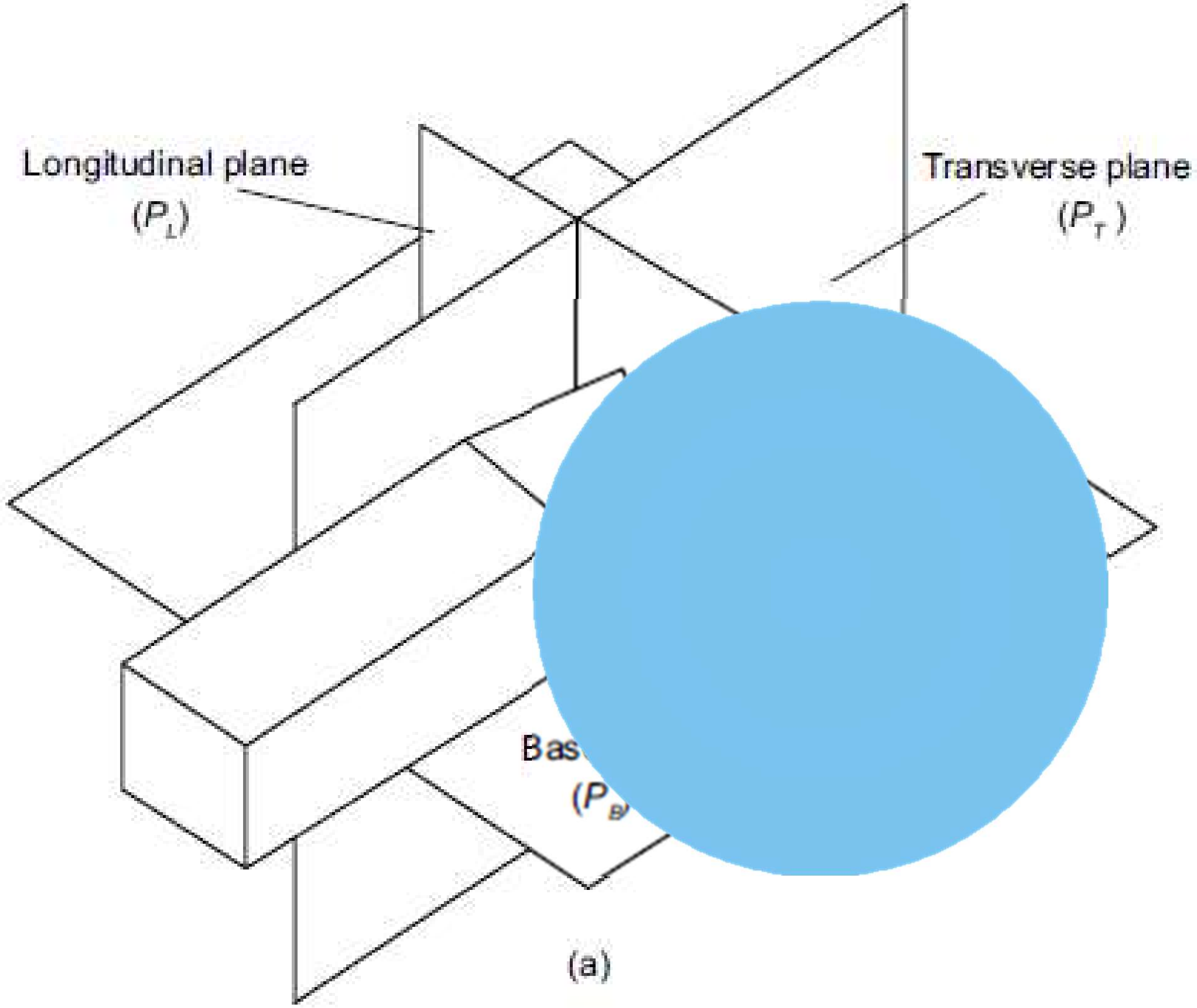


FIG. 2.25 *A typical single point cutting tool with various features and their nomenclature.*

American Standard Association (ASA)

This tool nomenclature is purely geometrical in nature and is not related to the mechanics of the process. ASA system specifies the tool geometry with two intersecting orthogonal planes; one parallel to and the other perpendicular to the axis of the cutting tool. Both of these orthogonal planes are perpendicular to the base of the tool.

- PB – Base plane; plane perpendicular to the velocity vector
- PL – Machine longitudinal plane; plane perpendicular to PB and taken in the direction of assumed longitudinal feed
- PT – Machine Transverse plane; plane perpendicular to both PB and PL



The main advantage of the system is the ability to set the angles on a tool and cutter grinder for grinding the tool angles. However a tool cannot be ground accurately to the back rake and side rake without using equations or curves.

The various tool angles as specified in ASA system are:

- **Back rake angle (α_b)** – angle of inclination of the rake surface from the base plane (PB) and measured on Machine Transverse plane, PT.
- **Side rake angle (α_s)**– angle of inclination of the rake surface from the base plane (PB) and measured on Machine Longitudinal Plane, PL.
- **End relief angle (ϕ_e)–** angle of inclination of the principal flank from the machined surface and measured on PT plane.
- **Side relief angle (ϕ_s)** – angle of inclination of the principal flank from the machined surface and measured on PL plane.
- **End cutting edge angle (C_e)** – angle between the end cutting edge (its projection on PB) from PL and measured on PT.
- **Side cutting edge angle (C_s)** – angle between the principal cutting edge (its projection on PB) and PT and measured on PB

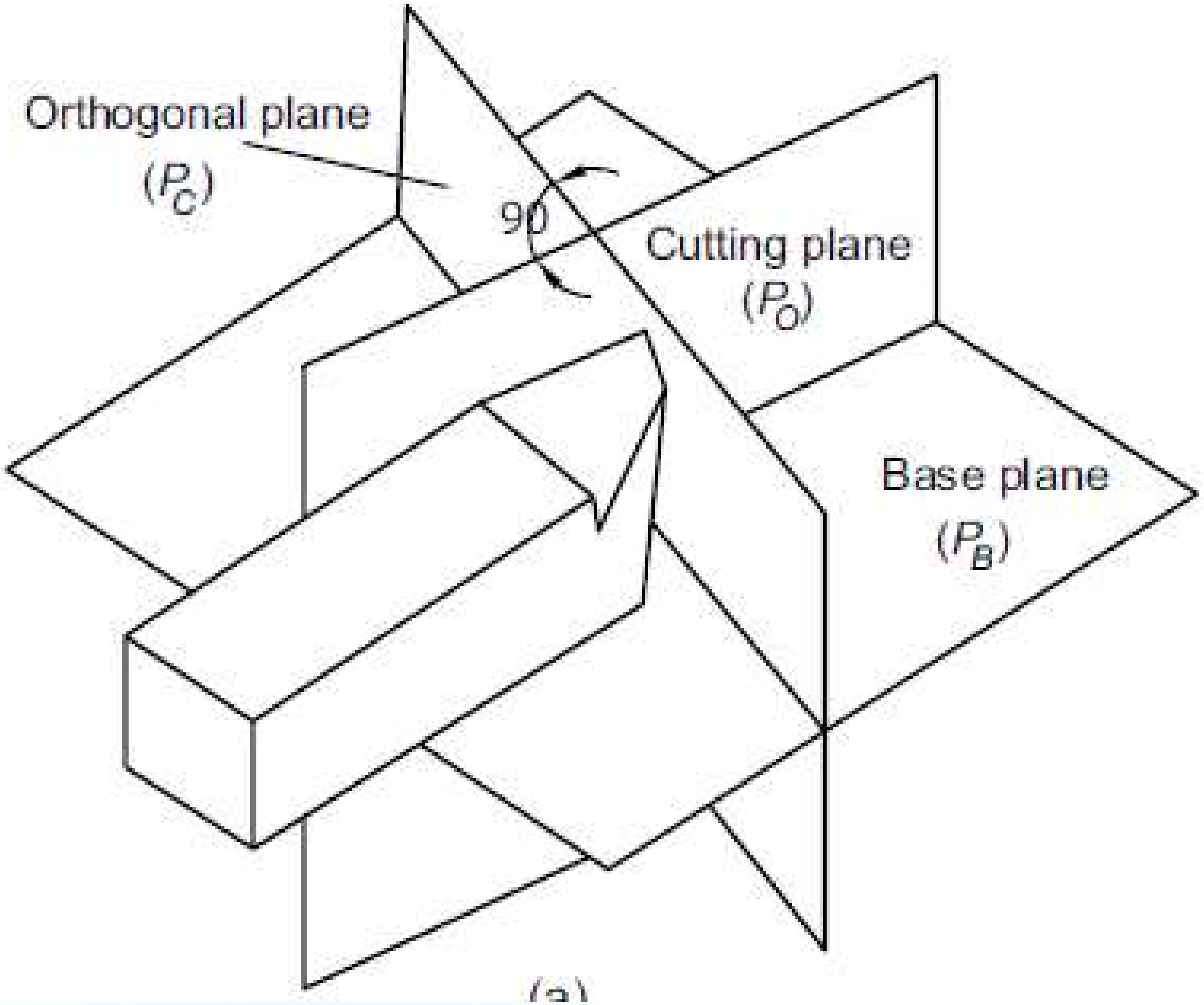
Tool signature: $\alpha_b - \alpha_s - \phi_e - \phi_s - C_e - C_s - \mathrm{r}$

where r is the nose radius.

Orthogonal Rake System (ORS)

- The ASA system is that it utilizes the rectangular coordinate system but not the actual cutting planes of the cutting tool.
- In the ORS system (also called as the old ISO system) the actual cutting plane is utilized and all the angles are measured in the planes corresponding to the cutting tools.
- A base plane is defined as the plane where the base of the cutting tool is present.
- The cutting plane is defined as the plane normal to the base plane and passing through the principal cutting edge (side cutting edge angle Cs in ASA). A third plane called the orthogonal plane is perpendicular to these two planes

- Base plane – (P_B)– perpendicular to the cutting velocity vector.
- Cutting plane – (P_C) – plane perpendicular to PB and taken along the principal cutting edge
- Orthogonal plane – (P_0) – plane perpendicular to both PB and PC and the axes



(a)

The various angles identified and defined are as follows:

- **Inclination angle (i)** – angle between P_C from the direction of assumed longitudinal feed (P_L) and measured on P_C .
- **Orthogonal rake angle (α_0)** – angle of inclination of the rake surface from base plane, P_B and measured on the orthogonal plane,
- **Orthogonal clearance of the principal flank angle (ϕ_0)** – angle of inclination of the principal flank from P_C and measured on P_0
- **Auxiliary orthogonal clearance angle (ϕ'_0)** – angle of inclination of the auxiliary flank from auxiliary cutting plane, P'_C and measured on auxiliary orthogonal plane, P'_0
- **Auxiliary cutting angle (C')** – angle between P'_C and P_L and measured on P_B
- **Principal cutting edge angle (C)** – angle between   and the direction of assumed longitudinal feed or P_L and measured on P_B
- **Nose radius (r)** – radius of curvature of tool tip

Tool signature i, α_0, ϕ_0, ϕ'_0, C', C, r (mm)

Equations for conversion between ASA and ORS system are as follows:

$\tan \alpha_b = \sin C_S \tan \alpha_0 + \cos C_S \tan i$

$\tan \alpha_S = \cos C_S \tan \alpha_0 - \sin C_S \tan i$

$\tan i = -\tan \alpha_S \sin C_S + \tan \alpha_b \cos C_S$

$\tan \alpha_0 = \tan \alpha_S \cos C_S + \tan \alpha_b \sin C_S \; P_0$

Effect of Geometrical parameters on cutting force and surface finish

❑ Rake Angles (back and side)

- These can be positive, zero, or negative. As seen earlier in orthogonal cutting mechanics, shear angle is directly affected by the rake angle.
- Larger rake angles are beneficial for machining efficiency giving rise to lower cutting force and power. However, increasing to a very high value decreases the strength of the tool tip.
- Small rake angles are used for cutting hard materials while large angles are used for cutting soft and ductile materials. An exception is brass where, to prevent digging of tool in work, it is machined with small rake angles.

❑ Side Cutting-Edge Angle

- Side Cutting-Edge Angle (SCEA) prevents the sudden engagement of the entire depth of cut when the tool enters the work material. As a result it affects the resulting tool life, and surface finish. It can vary from 0° to 90°.
- When it is zero, the entire cutting edge will engage at the same time with the work piece. It is used to produce square shoulders. It is particularly desirable while machining castings and forgings that normally have hard and scaly skins.
- When the SCEA is increased the entry of the tool is smooth to start the cut since the depth of cut will gradually increase until the entire cutting edge is in contact with the work piece.
- The chip produced is thinner and wider, with increased SCEA. This helps in distributing the produced heat over a larger cutting edge.
- With larger SCEA, the radial component of the cutting force increases thereby promoting the possibility of chatter.
- The complimentary angle (90° – CS) of SCEA is called plan approach angle.

❑ End Cutting-Edge Angle

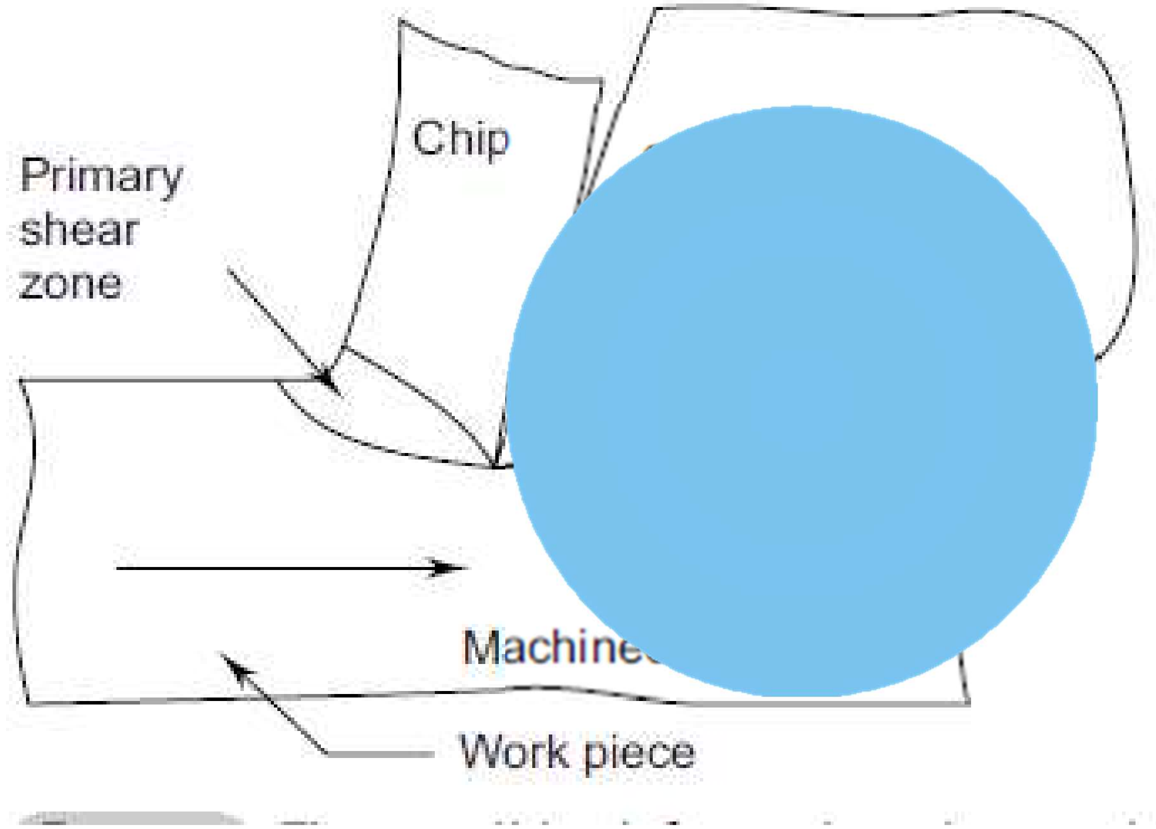
- The purpose of the End Cutting-Edge Angle (ECEA) is to relieve the trailing end of the cutting edge to prevent rubbing the machined surface.
- To that extent only a small angle is sufficient for this purpose.
- It is not desirable to have a large ECEA as it takes away material that supports the cutting edge and hinders the conduction of heat away from the point.
- In most cases, values of 8° to 15° have been found satisfactory for boring and turning tools.

❑ Relief Angles (Side and End)

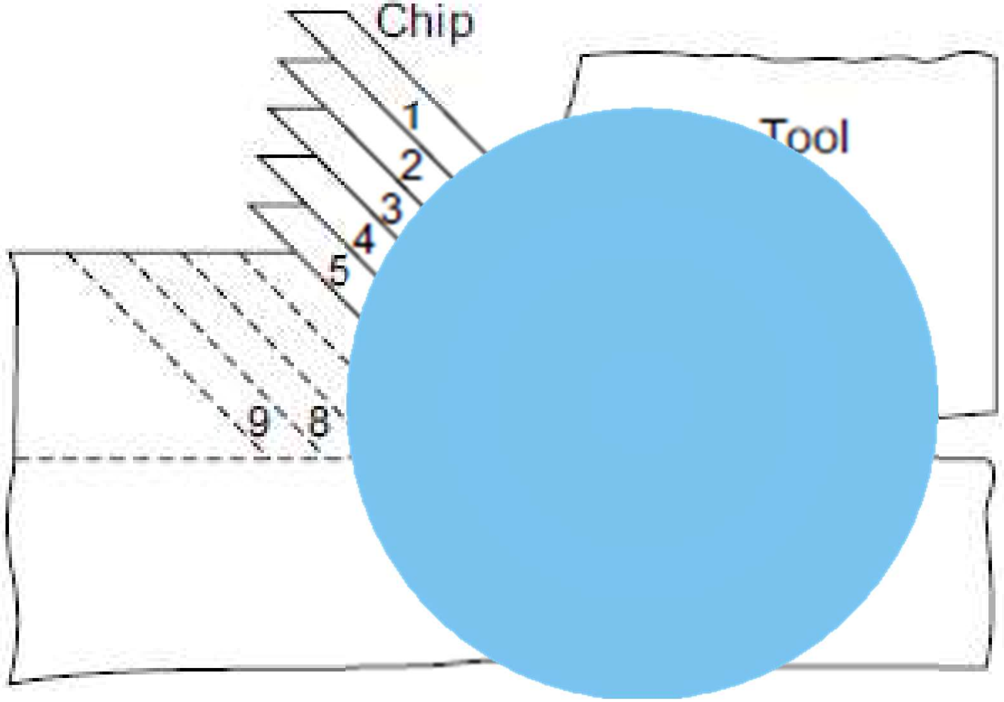
- The function of the relief angles is to prevent the rubbing of the flank of the tool with the machined surface. In general, turning relief angles ranging from 5° to 15° are used.
- Small relief angles give strength to the cutting edge when machining hard and strong materials.
- Increased values of relief angles allow the tool to penetrate and cut the work piece material more efficiently, thereby reducing the cutting forces.
- However too large relief angles weaken the cutting edge and are not desirable.

Mechanics of chip formation

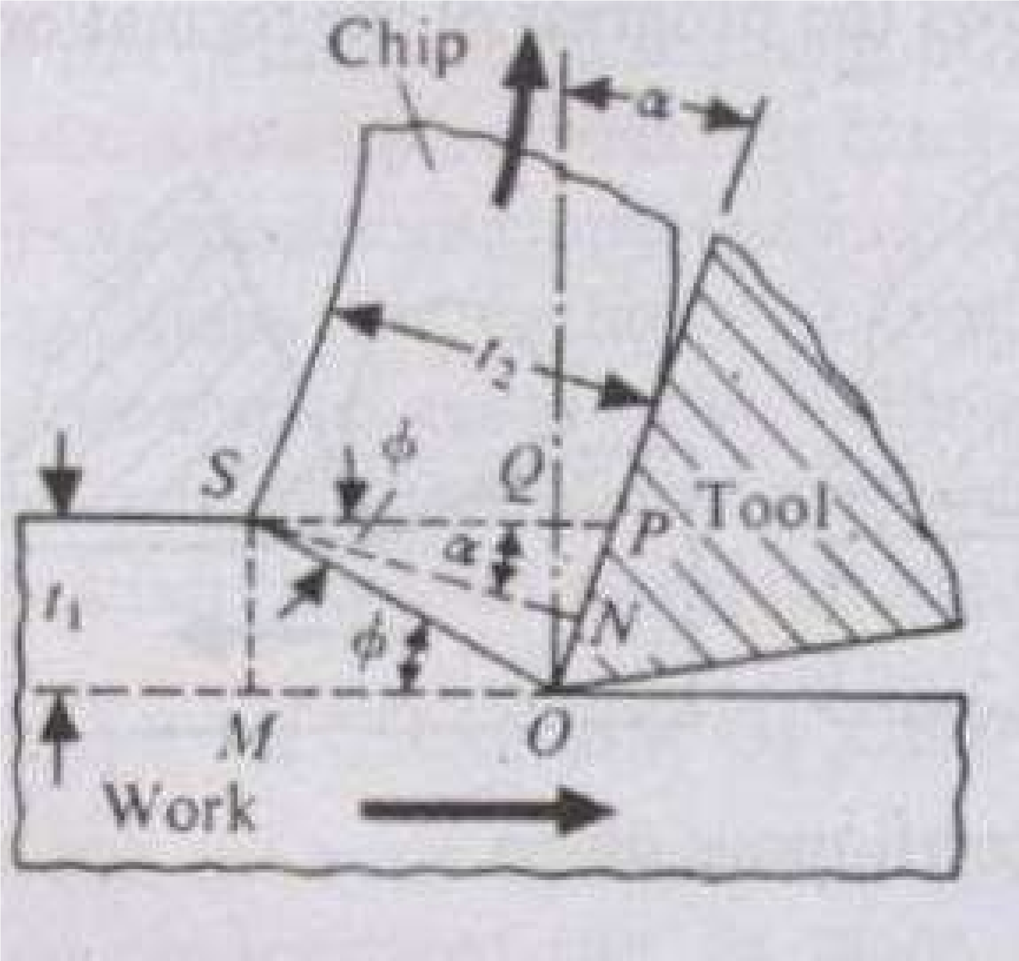
- The metal in front of the tool rake face gets immediately compressed first elastically and then plastically. This zone is traditionally called the shear zone.
- The material in the final form would be removed by shear from the parent metal..
- If the friction between the tool rake face and the underside of the chip (deformed material) is considerable, then chip gets further deformed, which is termed as secondary deformation.
- The chip after sliding over the tool rake face would be lifted away from the tool, and the resultant curvature of the chip is termed as chip curl



- Plastic deformation can be caused by yielding, in which case strained layers of material would get displaced over other layers along the slip-planes which coincide with the direction of maximum shear stress.
- **Piispanen** presented an interesting mechanism to account for the deformation process taking place at the cutting edge.
- He considered the undeformed metal as a stack of cards which would slide over one another as the wedge shaped tools moves under these cards as shown in Fig.
- Though this idea is an over simplified one, it would account for a number of features that are found in practice.



A simplified model of machining is available that neglects many of the geometric complexities, yet describes the mechanics of the process quite well. It is called the ***orthogonal*** cutting model.



Let t_1 = Uncut chip thickness
t_2 = Chip thickness
ϕ = Shear angle

$$\text{Chip thickness ratio (r)} = \frac{\text{Uncut chip thickness}}{\text{Chip thickness}} = \frac{t_1}{t_2}$$

To establish relationship between α, ϕ, t_1 and t_2 let us drop two perpendicular SM and SN from S on the extension of the machined surface and rake face of the tool. Further SP is drawn parallel to OM and Q is the intersection of SP with the normal drawn at O to OM.

Considering two right angle triangles ΔSNO and ΔQPO

$$\angle PSN = \angle QPO = \alpha$$

$\angle NSO = \angle PSO - \angle PSN = \phi - \alpha$

Again,

$$\cos(\phi - \alpha) = \frac{SN}{OS} \implies OS = \frac{t_2}{\cos(\phi - \alpha)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and

$$\sin\phi = \frac{SM}{OS} \implies OS = \frac{t_1}{\sin\phi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From eq (1) and (2)

$$\frac{t_1}{\sin\phi} = \frac{t_2}{\cos(\phi - \alpha)}$$

or

$$\frac{t_1}{t_2} = \frac{\sin\phi}{\cos(\phi - \alpha)} = r$$

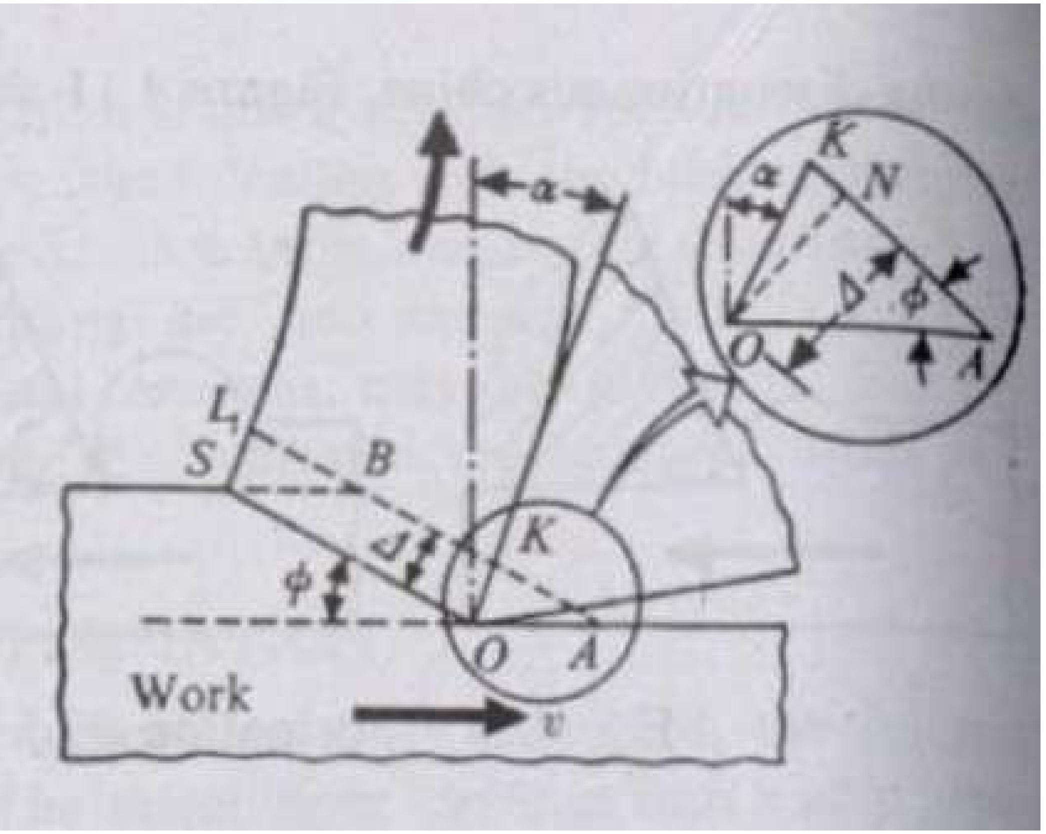
$$\boxed{\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}}$$

Shear strain can be determined

Let us consider an element of the undeformed work material ABSO of thickness Δ. Due to the presence of the tool, this is sheared to shape KLSO.

So that Shear Strain is given by

$$\Upsilon = \frac{AK}{\Delta.}$$



From Fig

$$\angle KAO = \phi$$

Thus $$\frac{\pi}{2} + \alpha = \angle OKA + \phi$$

or $$\angle OKA = \frac{\pi}{2} + \alpha - \phi$$

Now

$$\Upsilon = \frac{AK}{\Delta} = \frac{AN+NK}{ON} = \cot \emptyset + \tan(\phi - \alpha)$$

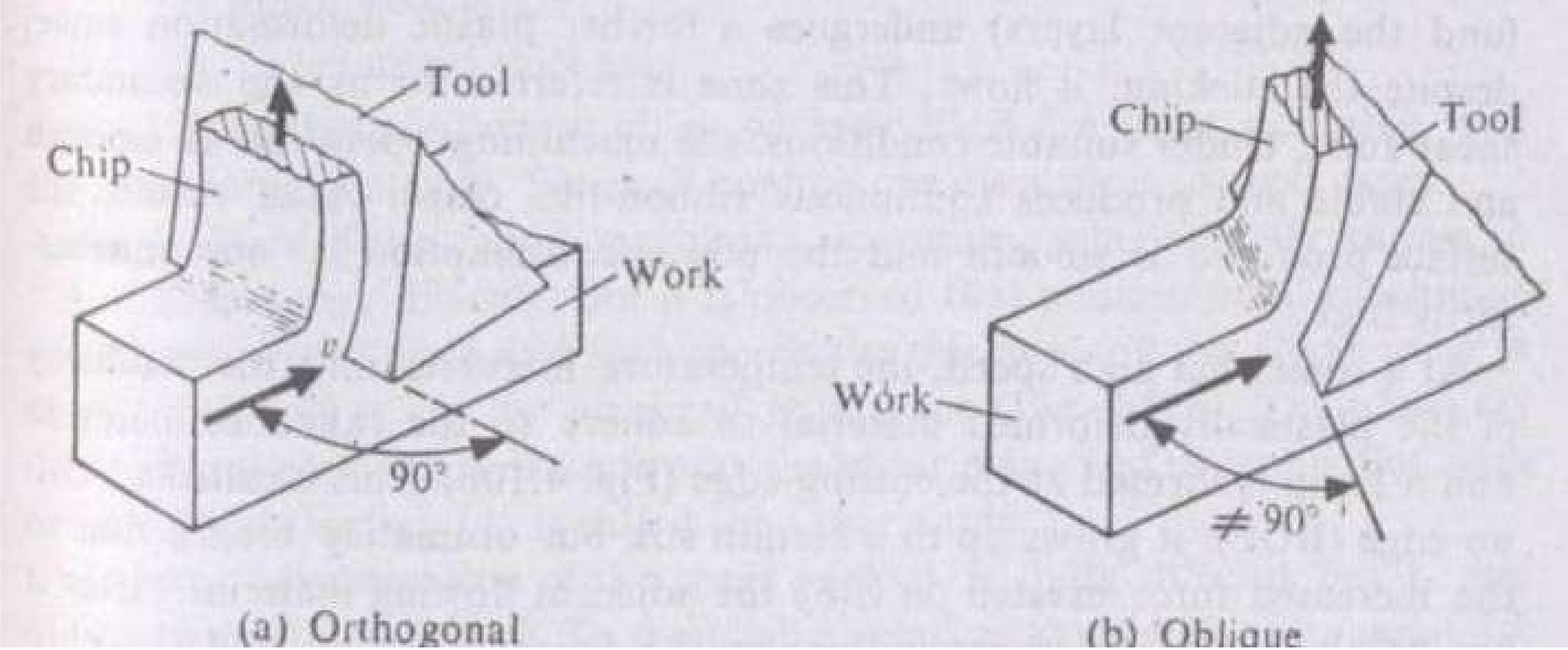
Hence,

$$\boxed{\Upsilon = \cot\phi + \tan(\phi - \alpha)}$$

Orthogonal Cutting and Oblique Cutting operations

Orthogonal Cutting: When the cutting edge is straight and the relative velocity of the work and tool is perpendicular to the cutting edge.

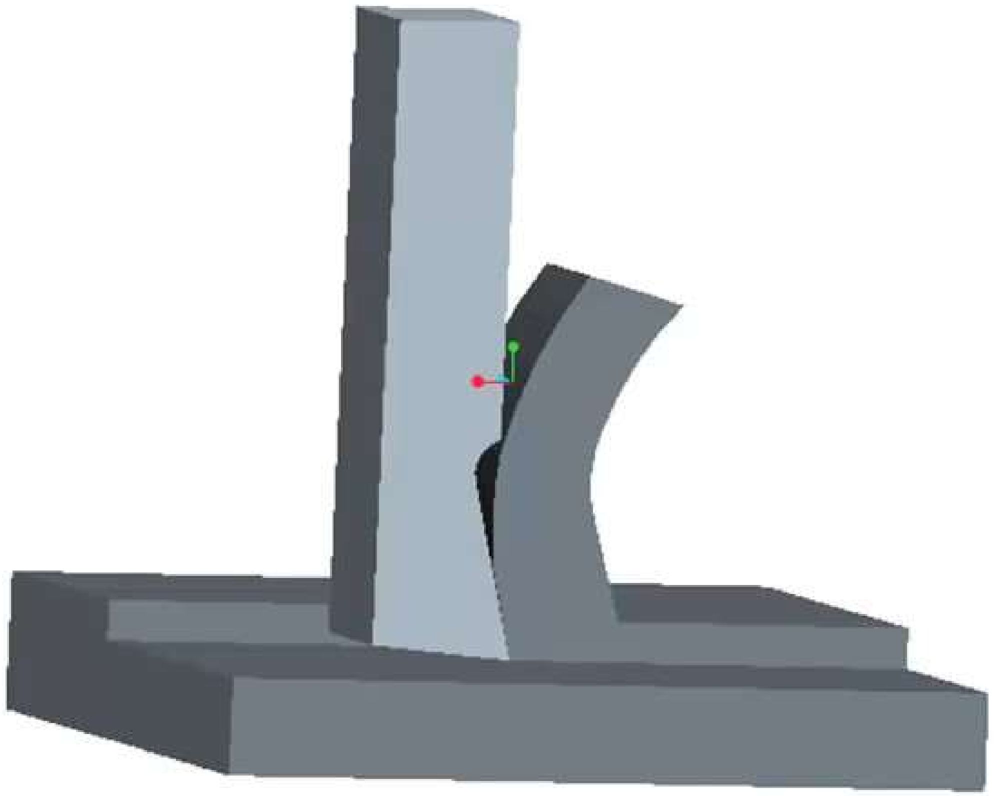
Oblique Cutting: When the relative velocity of the work and tool is not perpendicular to the cutting edge, all the work and chip material particles do not move in parallel planes, and thus a two dimensional representation of the operation is not possi



(a) Orthogonal (b) Oblique

Merchant’s theory, Force relationship and velocity relationship

CUTTING FORCE ANALYSIS



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Cutting Tool Materials

What are the important characteristics expected of a cutting tool material:

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

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

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

(iv) Toughness – Even though the tool is hard, it should have enough toughness to withstand the impact loads at the beginning of the cut or to force fluctuations due to imperfections in the work material. This requirement is more useful for interrupted cutting, e.g. milling.

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

(vi) Better thermal characteristics – Since huge amount of heat is generated at the cutting zone, it is necessary that the tool material should have higher thermal conductivity to dissipate this heat in the shortest time.

Tool Materials

- Carbon Tool Steels
- High Speed Steel
- Cast Cobalt Alloys
- Cemented Carbides
- Coated Carbides
- Ceramics
- Diamond
- Cubic Boron Nitride (CBN)

Summary of applications for various cutting tool materials

Tool Material	Work Materials	Remarks
Carbon steels	Low strength, softer materials, nonferrous alloys, plastics	Low cutting speeds, low strength materials
Low/medium alloy steels	Low strength, softer materials, nonferrous alloys, plastics	Low cutting speeds, low strength materials
HSS	All materials of low and medium strength and hardness	Low to medium cutting speeds, low to medium strength materials
Cemented carbides	All materials up to medium strength and hard ness	Not suitable for low speed application
Ceramics.	Cast iron, Ni-base super alloys, nonferrous alloys, plastics	Not for low speed operation or interrupted cut ting. Not for machining Al, Ti alloys
CBN	Hardened alloy steels, HSS, Ni-base super alloys, hardened chill cast iron, commercially pure nickel	High strength, hard materials
Diamond	Pure copper, pure aluminium, Al-Si alloys, cold pressed cemented car bides, rock, cement, plastics, glass-epoxy composites, non-ferrous alloys, hardened high carbon alloy steels (for burnishing only), fibrous composites	Not for machining low carbon steels, Co, Ni, Ti, Zr.

- very high stress gradients

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

- Flank wear,
- Crater wear

- ☐ **Flank wear:** Flank wear or wear land is on the clearance surface of the tool. The wear land can be characterized by the length of wear land, (w). It modifies the tool geometry and changes the cutting parameters such as depth of cut. Flank wear directly affects the component dimensions. Thus there is always a close limit on the value of the wear land. In addition, as the wear land progresses, the tool tip becomes weak because of the progress of crater wear.

- ☐ **Crater wear:** The crater is on the rake face and is more or less circular. The crater does not always ex tend to the tool tip, but may end at a distance from the tool tip. It increases the cutting forces, modifies the tool geometry, and softens the tool tip. During cutting as the depth increases the friction increases, the chip contact length increases and consequently the decrease in the machining performance. Ultimately with very large crater depth (KT), the tool tip weakens and fails catastrophically

A ***cutting fluid*** is any liquid or gas that is applied directly to the machining operation to improve cutting performance.

The functions of cutting fluids are:

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

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

- cooling action
- lubricating action

- It is designed to reduce the effects of heat in the machining operation. They carry away the heat that is generated, thereby reducing the temperature of tool and workpiece. This helps to prolong the life of the cutting tool.
- The capacity of a cutting fluid to reduce temperatures in machining depends on its thermal properties. Specific heat and thermal conductivity are the most important properties.
- Water has high specific heat and thermal conductivity relative to other liquids, which is why water is used as the base in coolant-type cutting fluids.
- Coolant-type cutting fluids seem to be most effective at relatively high cutting speeds in which heat generation and high temperatures are problems.
- They are most effective on tool materials that are most susceptible to temperature failures, such as high-speed steels, and are used frequently in turning and milling operations in which large amounts of heat are generated.

- It is usually oil-based fluids (because oils possess good lubricating qualities) formulated to reduce friction at the tool–chip and tool–work interfaces.
- Lubricant cutting fluids operate by ***extreme pressure lubrication***, a special form of lubrication that involves formation of thin solid salt layers on the hot, clean metal surfaces through chemical reaction with the lubricant.
- Compounds of sulfur, chlorine, and phosphorous in the lubricant cause the formation of these surface layers, which act to separate the two metal surfaces (i.e., chip and tool).
- These extreme pressure films are significantly more effective in reducing friction in metal cutting than conventional lubrication, which is based on the presence of liquid films between the two surfaces.
- Lubricant-type cutting fluids are most effective at lower cutting speeds. They tend to lose their effectiveness at high speeds, above about 120 m/min (400 ft/min.
- In addition, high cutting temperatures at these speeds cause the oils to vaporize before they can lubricate. Machining operations such as drilling and tapping usually benefit from lubricants. In these operations, built-up edge formation is retarded, and torque on the tool is reduced.

There are four categories of cutting fluids according to chemical formulation:
(1) cutting oils,
(2) emulsified oils,
(3) semi chemical fluids,
(4) chemical fluids.

All of these cutting fluids provide both coolant and lubricating functions. The cutting oils are most effective as lubricants, whereas the other three categories are more effective as coolants because they are primarily water.

Cutting oils

- It is based on oil derived from petroleum, animal, marine, or vegetable origin. Mineral oils (petroleum based) having desirable lubricating characteristics.
- To achieve maximum lubricity, several types of oils are often combined in the same fluid.
- Chemical additives are also mixed with the oils to increase lubricating qualities.
- These additives contain compounds of sulfur, chlorine, and phosphorous, and are designed to react chemically with the chip and tool surfaces to form solid films (extreme pressure lubrication) that help to avoid metal-to-metal contact between the two.

- It consist of oil droplets suspended in water.
- promote blending and stability of the emulsion.
- A typical ratio of water to oil is 30:1.
- Chemical additives based on sulfur, chlorine, and phosphorous are often used to promote extreme pressure lubrication. Because they contain both oil and water, the emulsified oils combine cooling and lubricating qualities in one cutting fluid

Chemical fluids

- It is chemicals in a water solution rather than oils in emulsion.
- The dissolved chemicals include compounds of sulfur, chlorine, and phosphorous, plus wetting agents.
- The chemicals are intended to provide some degree of lubrication to the solution.
- Chemical fluids provide good coolant qualities but their lubricating qualities are less than the other cutting fluid types.

Semichemical fluids

- It have small amounts of emulsified oil added to increase the lubricating characteristics of the cutting fluid. In effect, they are a hybrid class between chemical fluids and emulsified oils.

❖ Machinability is the characteristic of the work material expressing its ease of machining.

There are various criteria used to evaluate machinability, the most important of which are
(1) tool life,
(2) forces and power,
(3) surface finish, and
(4) Ease of chip disposal.

Although machinability generally refers to the work material, it should be recognized that machining performance depends on more than just material. The type of machining operation, tooling, and cutting conditions are also important factors. In addition, the machinability criterion is a source of variation. One material may yield a longer tool life whereas another material provides a better surface finish. All of these factors make evaluation of machinability difficult.

Machinability testing usually involves a comparison of work materials. The machining performance of a test material is measured relative to that of a base (standard) material.

Possible measures of performance in machinability testing include
(1) tool life,
(2) tool wear,
(3) cutting force,
(4) power in the operation,
(5) cutting temperature, and
(6) material removal rate under standard test conditions.

The relative performance is expressed as an index number, called the machinability rating (MR).