Module 5

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Metal Cutting

Classification of material removal processes

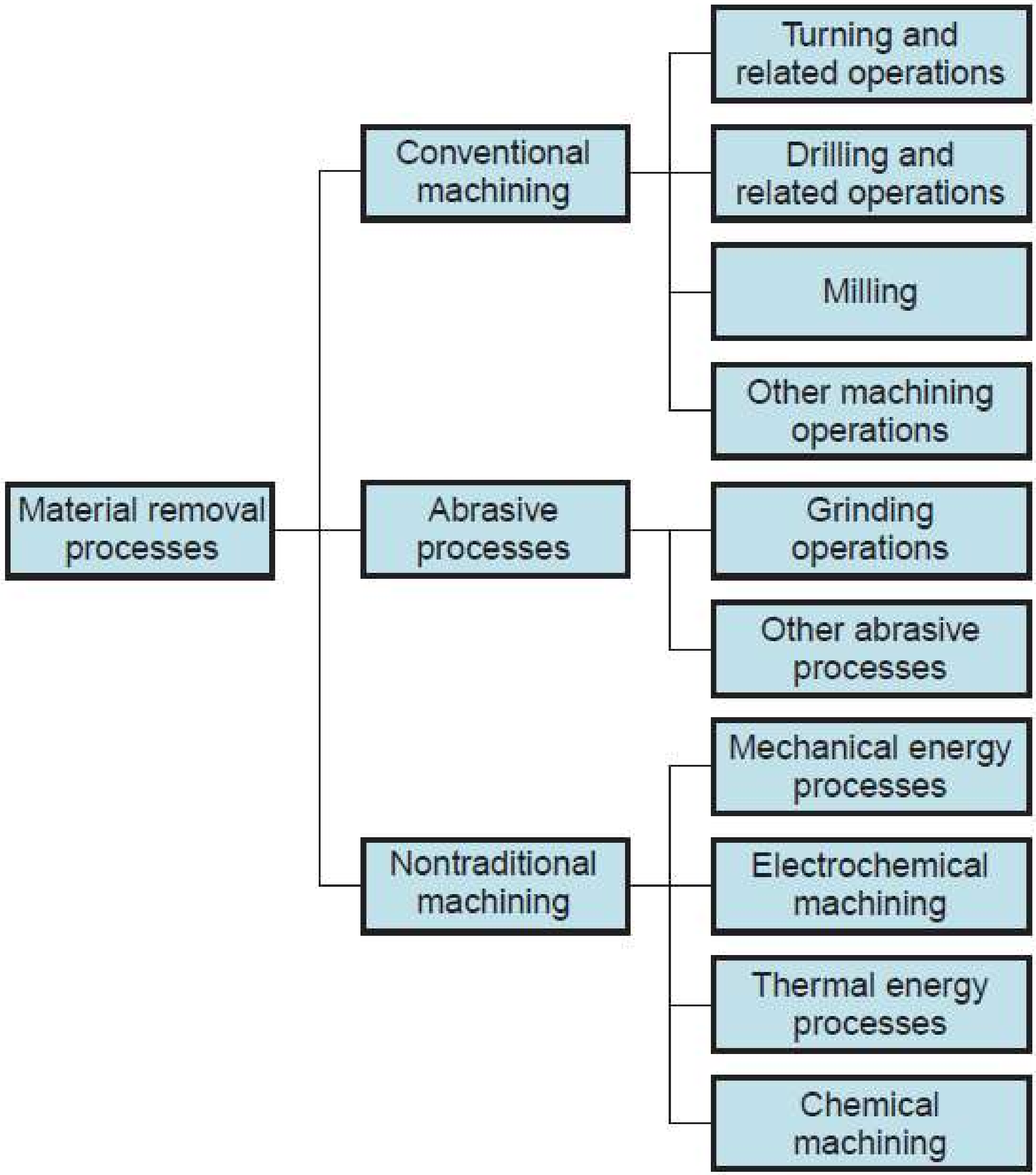
Material removal process: Operations in which excess material is removed from a starting workpart so that what remains is the desired final geometry.

Conventional machining: A sharp cutting tool is used to mechanically cut the material to achieve the desired geometry.

Abrasive machining processes: Mechanically remove material by the action of hard, abrasive particles.

Non-traditional machining processes: Various energy forms other than a sharp cutting tool or abrasive particles to remove material. The energy forms include mechanical, electrochemical, thermal, and chemical.

Classification of material removal processes



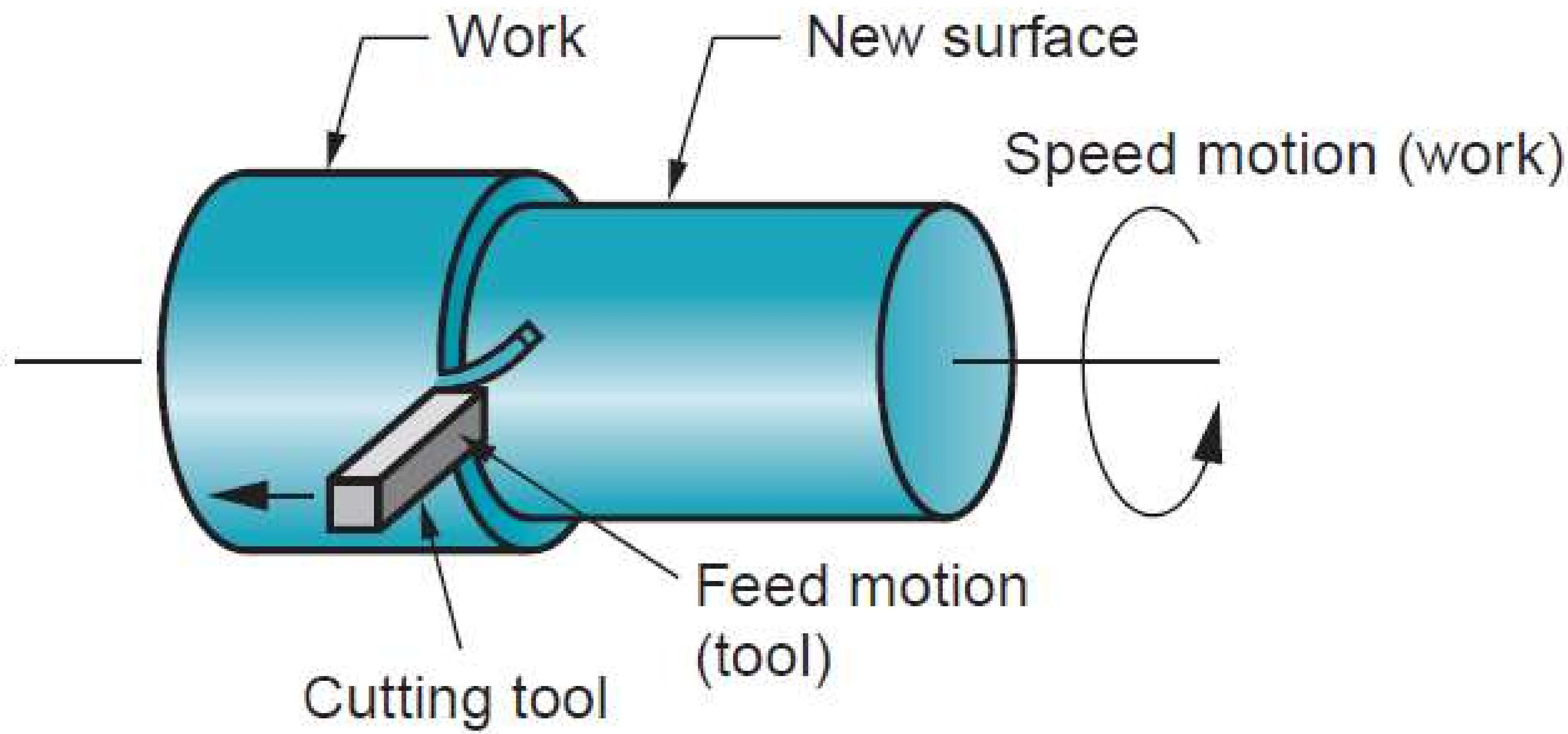
Machining

- ***Machining*** is a manufacturing process in which a sharp cutting tool is used to cut away material to leave the desired part shape.
- The predominant cutting action in machining involves ***shear deformation*** of the work material to form a **chip**
- **Advantages** of *machining* as a manufacturing process:
  - Variety of work **materials** can be machined
  - Variety of part **shapes and geometric features** can be obtained
  - Better **dimensional accuracy** can be attained
  - Better **surface finish** can be attained
- **Limitations** of *machining* as a manufacturing process:
  - Material **wastage**
  - **Expensive** machinery and cutting tools
  - **Time** consuming

Machining is generally performed **after** other manufacturing processes such as casting or bulk deformation (e.g., forging, bar drawing).

The other processes create the **general shape** of the starting workpart, and machining provides the **final** geometry, dimensions, and finish.

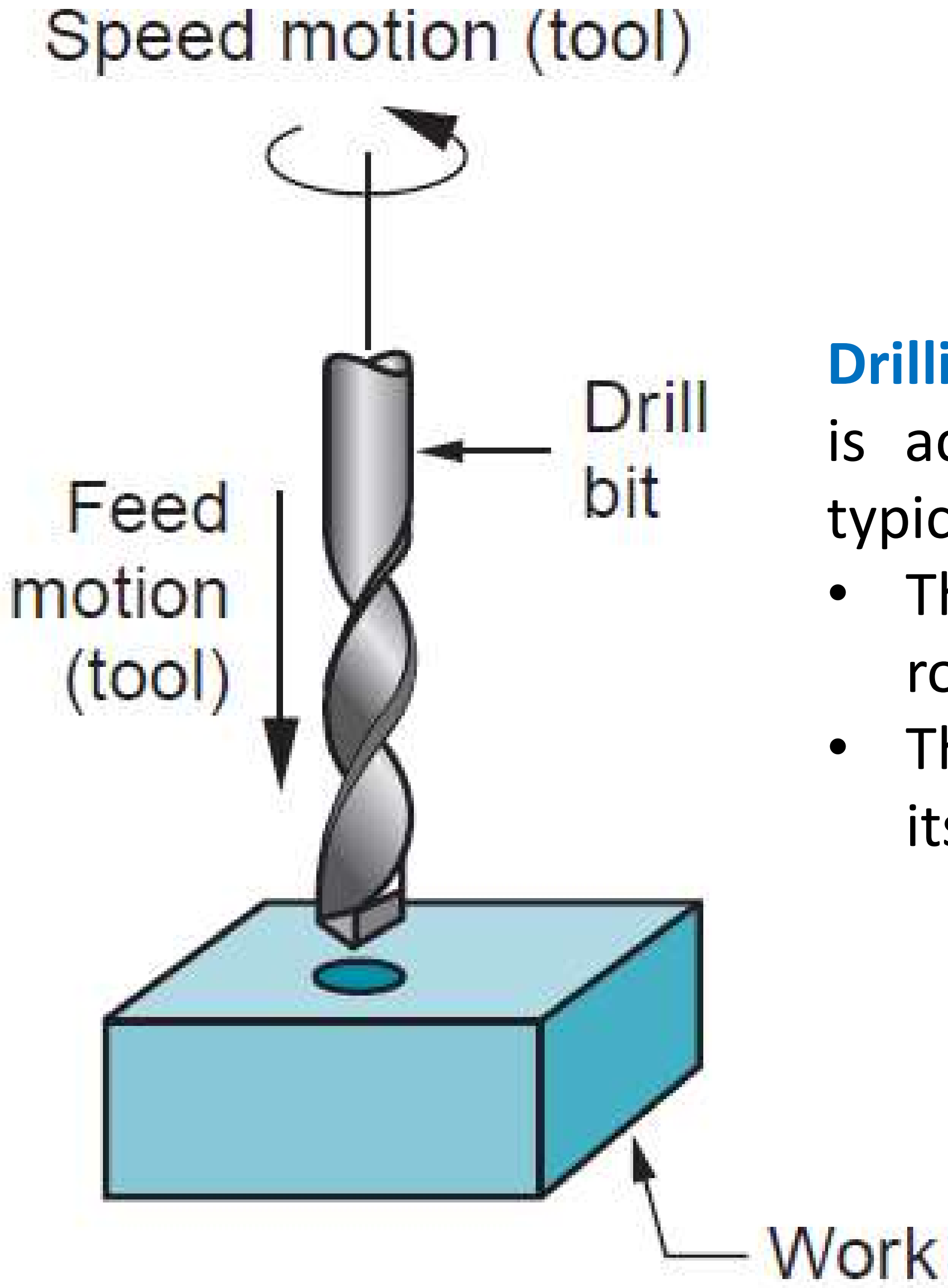
Types of Machining Operations: Turning



Turning: A cutting tool with a **single cutting edge** is used to remove material from a rotating workpiece to **generate a cylindrical shape**

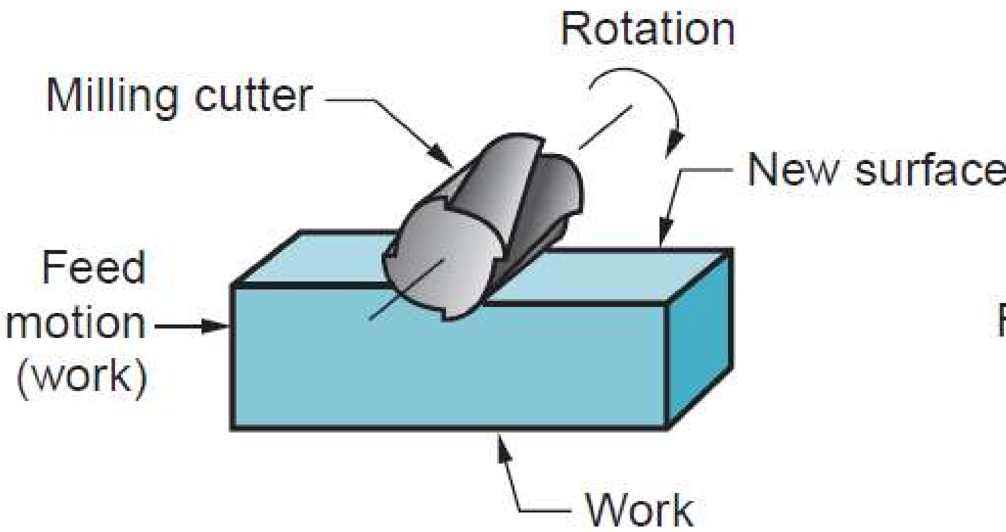
- The **speed** motion is provided by the rotating workpart
- The **feed** motion is achieved by the cutting tool moving slowly in a direction parallel to the axis of rotation of the workpiece

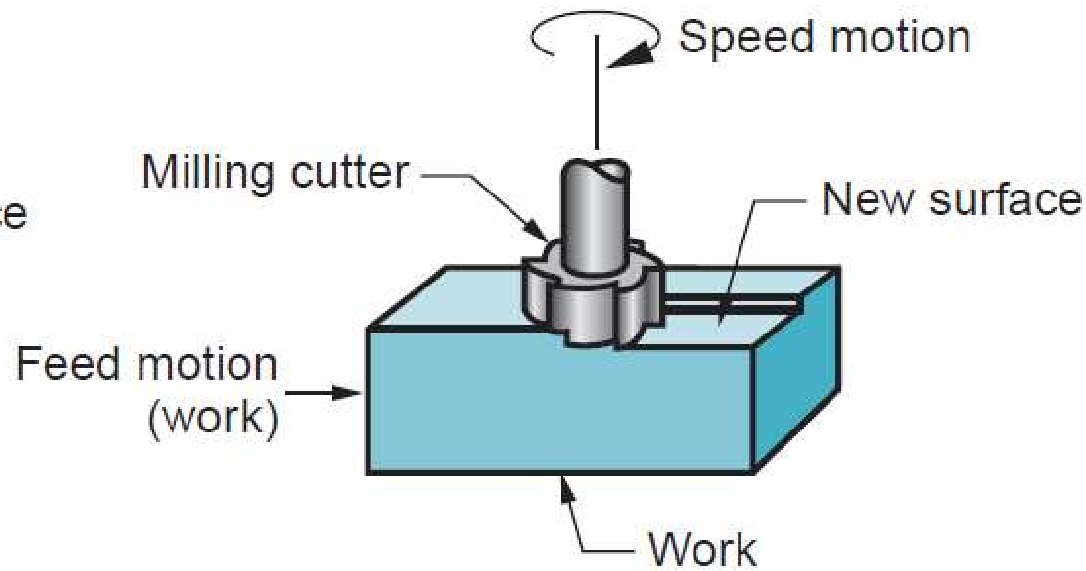
Types of Machining Operations: Drilling



Drilling: It is used to **create a round hole**. It is accomplished by a **rotating tool** that typically has **two cutting edges**

- The **speed** motion is provided by the rotating tool (called as **drill bit**)
- The tool is **fed** in a direction parallel to its axis of rotation





Milling: a **rotating tool** with **multiple cutting edges** is fed slowly across the work material to **generate a plane or straight surface**

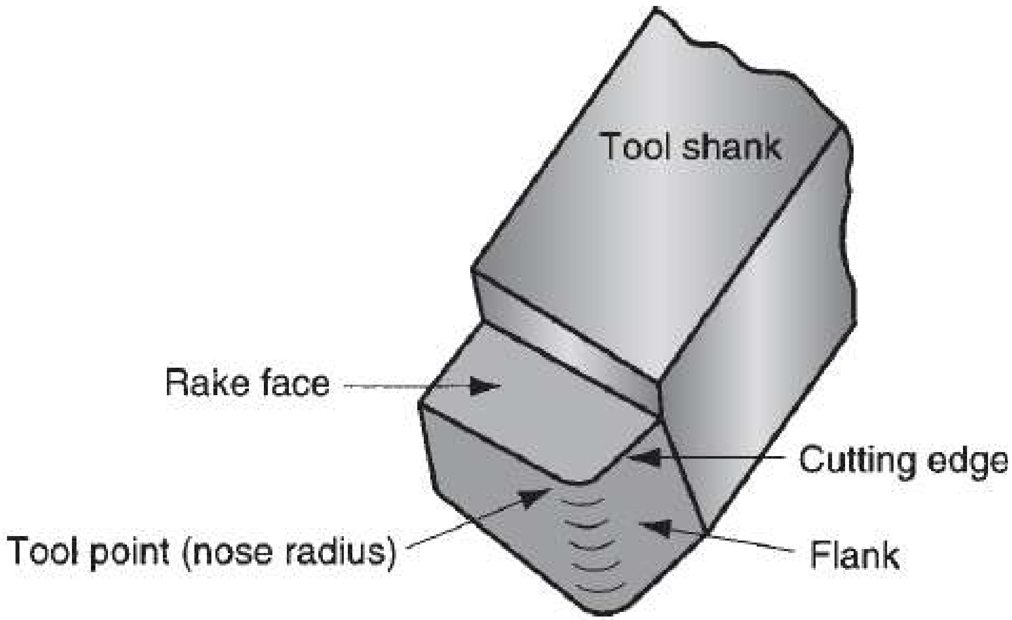
- The **speed** motion is provided by the rotating **milling cutter**
- The direction of the **feed** motion is **perpendicular to the tool's axis of rotation**.
- The two basic forms of milling are **peripheral milling** (left image) and **face milling** (right side image)

Other conventional machining operations

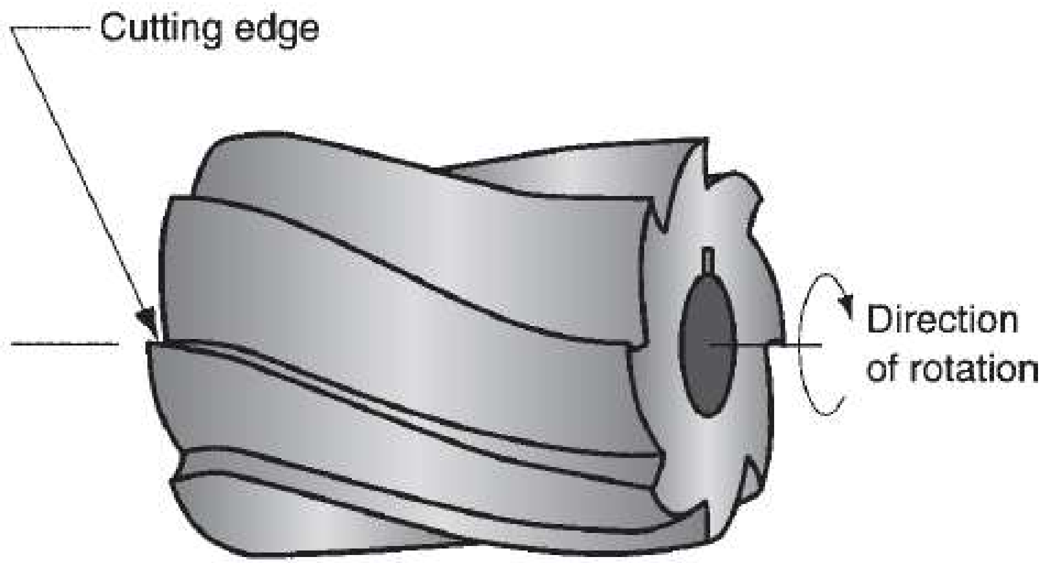
- Other conventional machining operations include **shaping, planing, broaching, and sawing.**
- **Grinding and similar abrasive operations** are often included within the category of machining. These processes commonly follow the conventional machining operations and are used to achieve a superior surface finish on the workpart.

The Cutting Tool

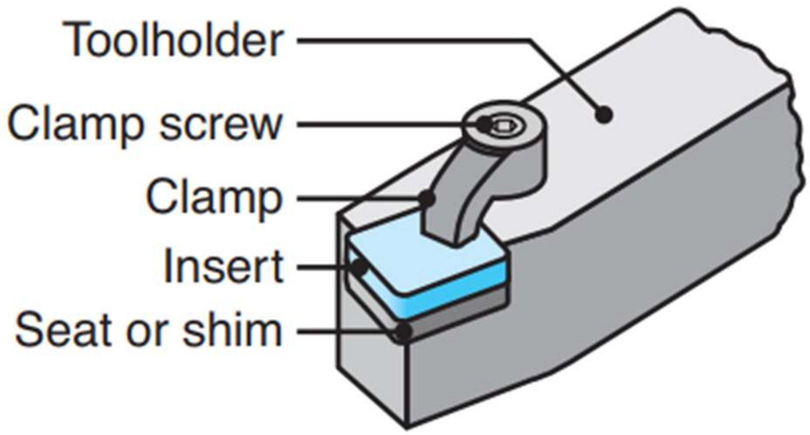
- A cutting tool has one or more sharp cutting edges and is made of a material that is harder than the work material.



A single-point tool



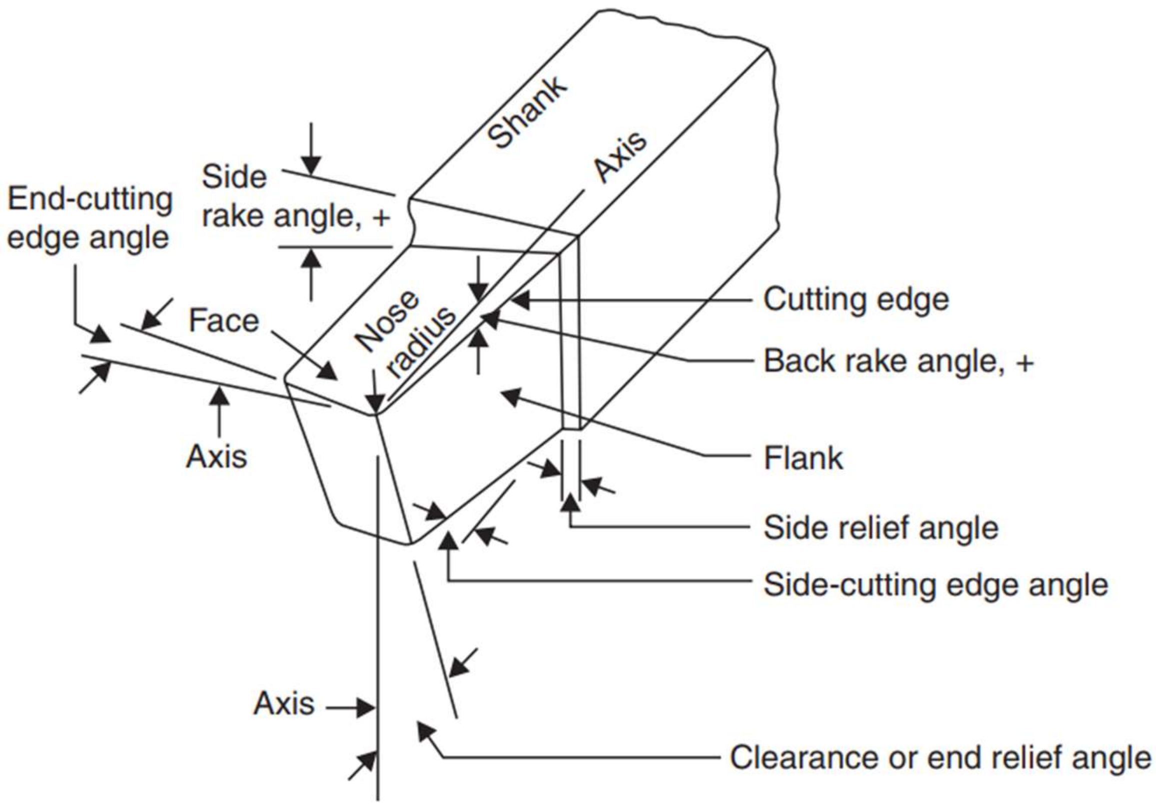
Tools with multiple cutting edges



Inserts made of carbides and other materials of various shapes and sizes.

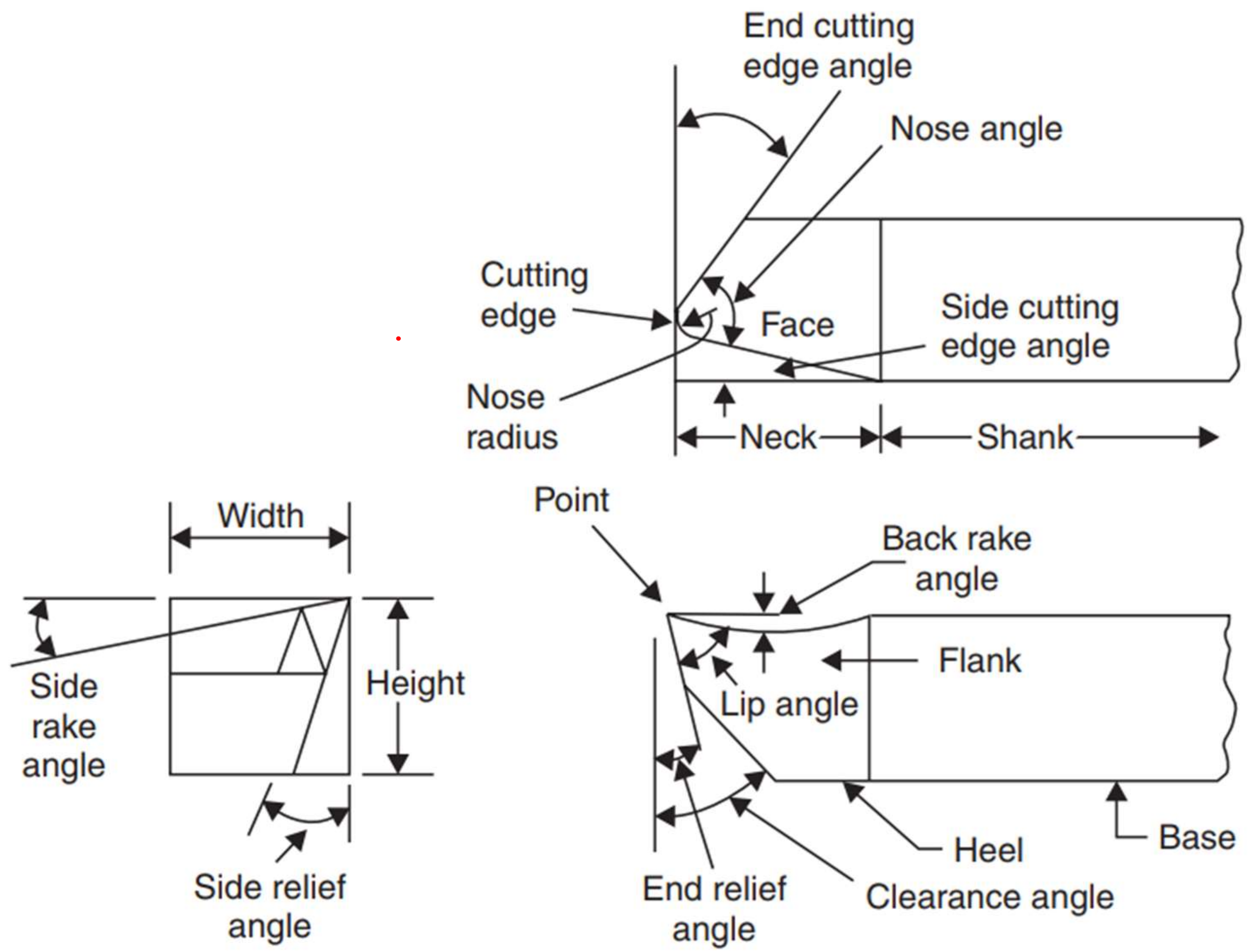
GEOMETRY - Single Point Cutting Tool

Single Point Cutting Tool



Single point right-hand cutting tool.

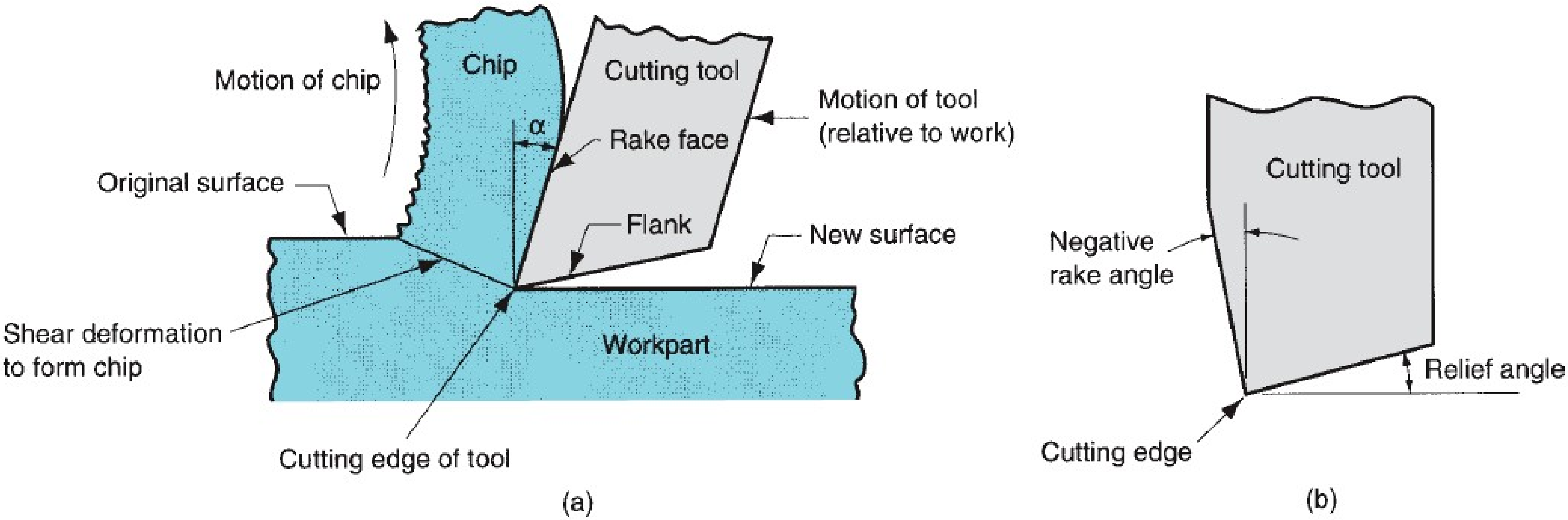
Single Point Cutting Tool – 3D Animation



Various angles of a single point tool.

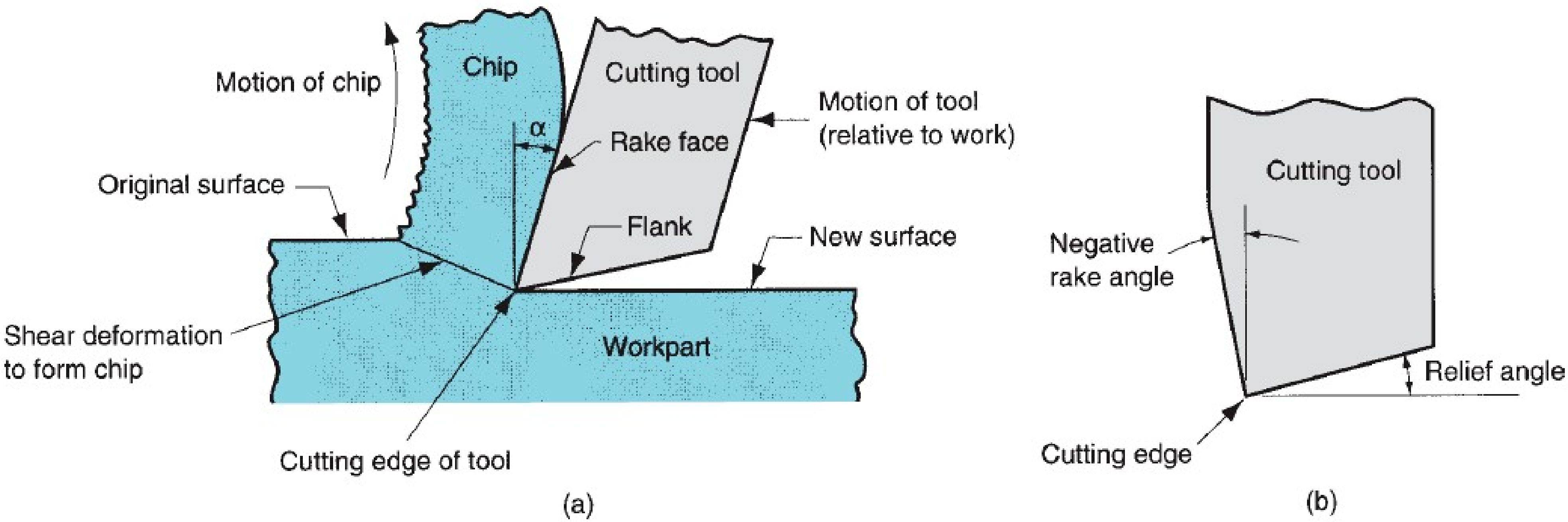
Rake angle

- The **rake face**, which directs the flow of the newly formed chip, is oriented at a certain angle called the ***rake angle α***.
- Rake angle is measured **relative to a plane perpendicular to the work surface**.
- The rake angle can be **positive**, as in Fig. a, or **negative** as in Fig. b

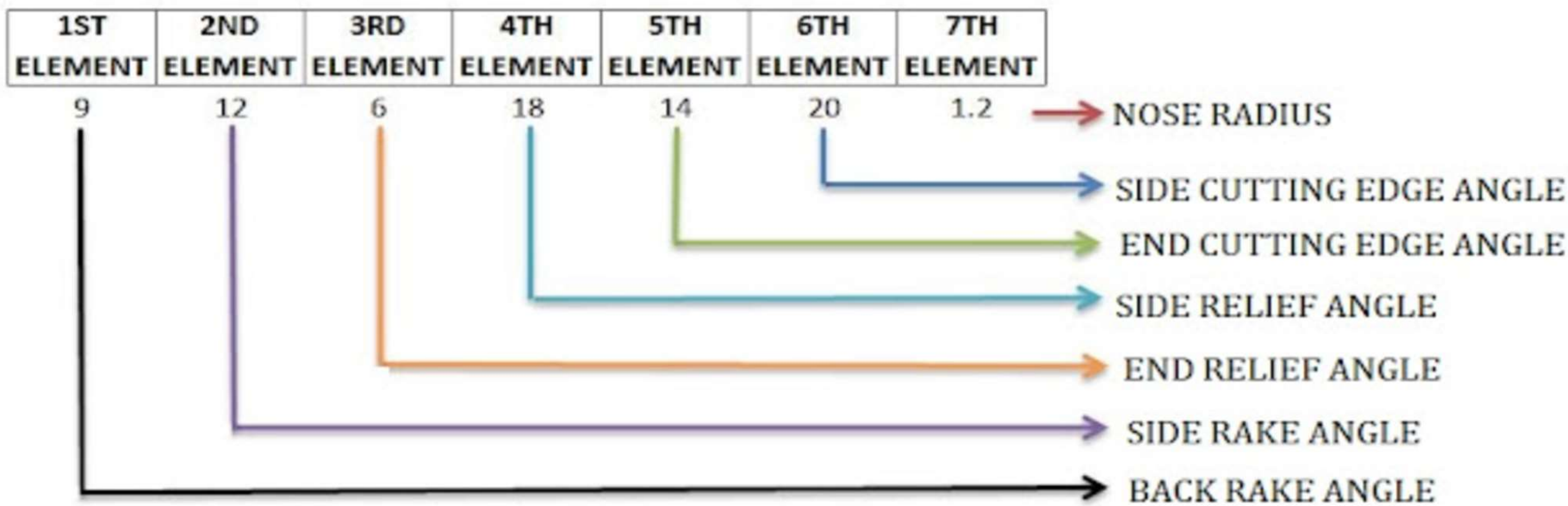


Relief angle

- The **flank** of the tool provides a clearance between the tool and the newly generated work surface, thus protecting the surface from abrasion, which would degrade the finish
- This flank surface is oriented at an angle called the **relief angle.**



TOOL SIGNATURE: - (7 Elements)



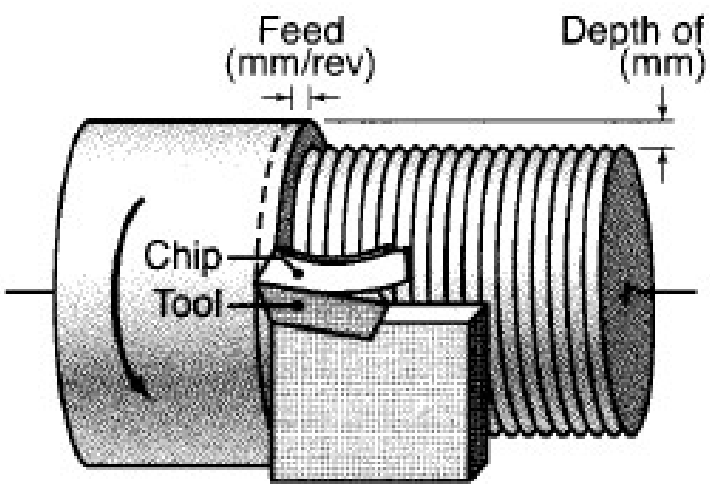
A typical tool designation (signature) is :

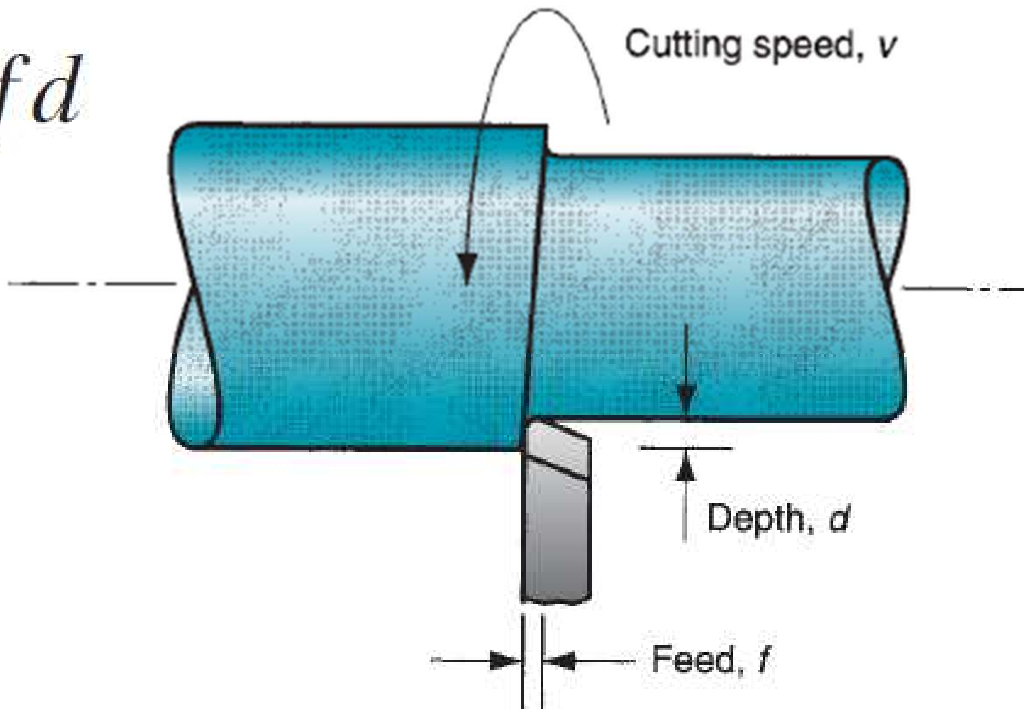
0—10—6—6—8—90—1 mm.

Cutting Conditions

- The primary motion is accomplished at a certain **cutting speed *v***
- In addition, the tool must be moved laterally across the work. This is a much slower motion, called the **feed *f*.**
- The remaining dimension of the cut is the penetration of the cutting tool below the original work surface, called the **depth of cut *d***.

Material removal rate: $R_{MR} = vfd$





Roughing vs. Finishing and Cutting fluid

- **Roughing** cuts are used to remove large amounts of material from the starting workpart as rapidly as possible, in order to produce a shape close to the desired form, but leaving some material on the piece for a subsequent finishing operation.
  - performed at high feeds and depths—feeds of 0.4 to 1.25 mm/rev and depths of 2.5 to 20 mm are typical
- **Finishing** cuts are used to complete the part and achieve the final dimensions, tolerances, and surface finish.
  - feeds of 0.125 to 0.4 mm and depths of 0.75 to 2.0mm are typical
- A **cutting fluid** is often applied to the machining operation to cool and lubricate the cutting tool

Factors that influence the cutting process

- Independent variables

  (a) tool material and coatings;

  (b) tool shape, surface finish, and sharpness;

  (C) workpiece material and condition;

  (d) cutting speed, feed, and depth of cut;

  (e) cutting fluids;

  (f) characteristics of the machine tool; and

  (g) work holding and fixturing

Factors that influence the cutting process

- Dependent variables

  (a) type of chip produced,

  (b) force and energy dissipated during cutting,

  (c) temperature rise in the workpiece, the tool, and the chip,

  (d) tool wear and failure, and

  (e) surface finish and surface integrity of the workpiece.

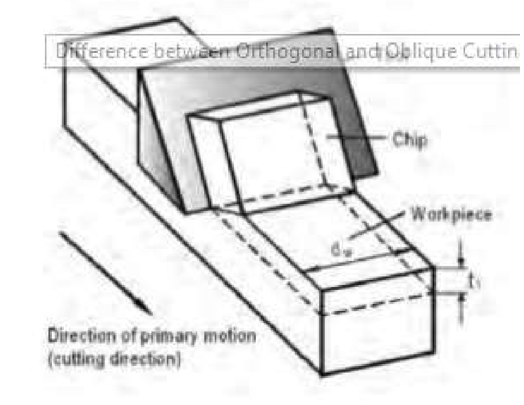
Factors that influence the cutting process

Factors Influencing Machining Operations

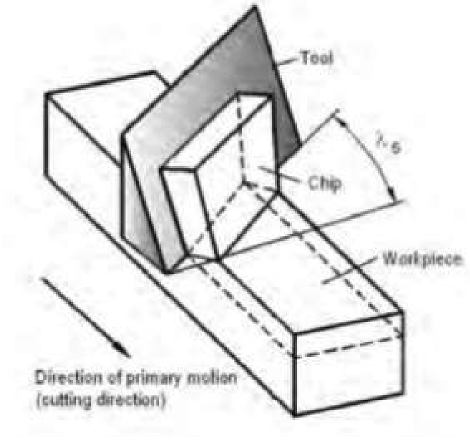
Parameter	Influence and interrelationship
Cutting speed, depth of cut, feed, cutting fluids	Forces, power, temperature rise, tool life, type of chip, surface finish and integrity
Tool angles	As above; influence on chip flow direction; resistance to tool wear and chipping
Continuous chip	Good surface finish; steady cutting forces; undesirable, especially in automated machinery
Built-up edge chip	Poor surface finish and integrity; if thin and stable, edge can protect tool surfaces
Discontinuous chip	Desirable for ease of chip disposal; fluctuating cutting forces; can affect surface finish and cause vibration and chatter
Temperature rise	Influences tool life, particularly crater wear and dimensional accuracy of workpiece; may cause thermal damage to workpiece surface
Tool wear	Influences surface finish and integrity, dimensional accuracy, temperature rise, forces and power
Machinability	Related to tool life, surface finish, forces and power, and type of chip

Orthogonal and Oblique cutting

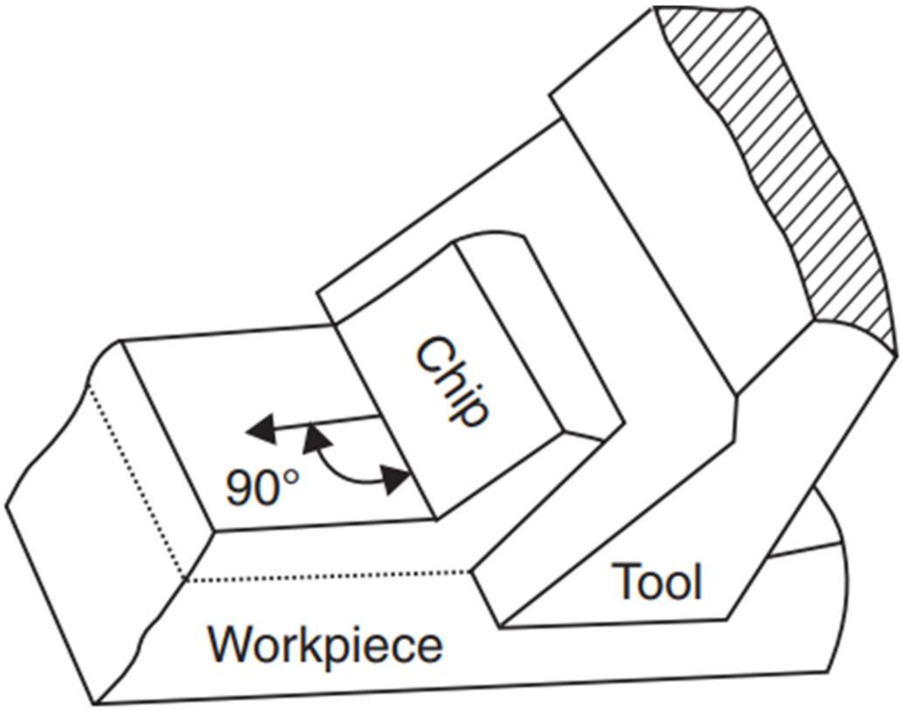
1. **Orthogonal cutting** is a type of metal cutting in which the cutting edge of wedge shaped cutting tool is perpendicular to the direction of tool motion. In this cutting, the cutting edge is wider than width of cut. This cutting is also known as 2D cutting because the forces developed during cutting can be ploted on a plane or can be represented by 2D coordinate system.
2. **Oblique cutting** is another type of cutting in which the cutting edge of wedge shaped cutting tool make an angle except right angle to the direction of tool motion. This will affect the cutting conditions. It is also known as 3D cutting because the cutting force developed during cutting cannot be represented by 2D coordinate system and is represented by 3D coordinate system.



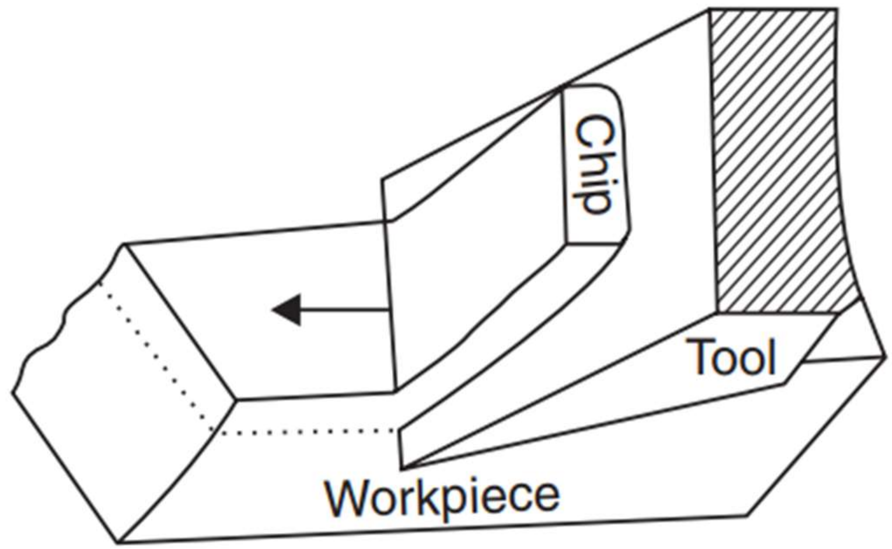
Orthogonal Cutting



Oblique Cutting



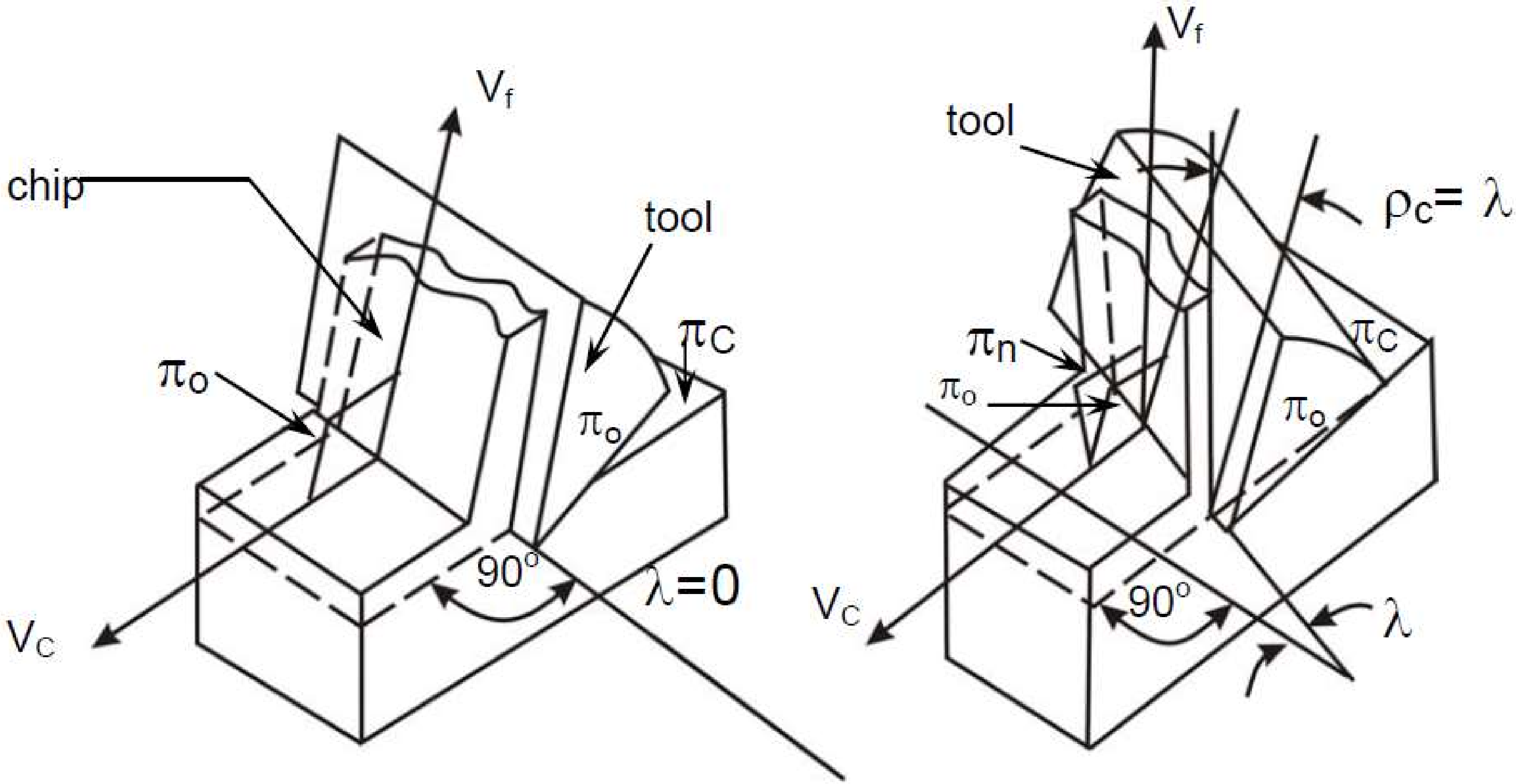
Orthogonal cutting.



Oblique cutting.

ORTHOGONAL AND OBLIQUE CUTTING

Role of inclination angle, λ on chip flow direction:



(a) $\lambda = 0$ (b) $\lambda \neq 0$

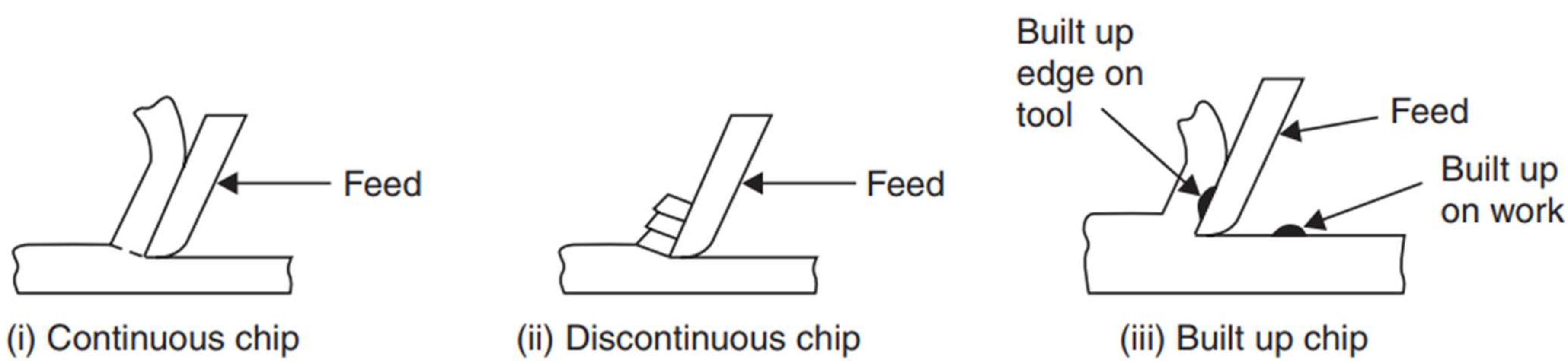
Orthogonal and Oblique cutting

The role of inclination angle, λ on the direction of chip flow

- **When $\lambda=0$, the chip flows along orthogonal plane, i.e, $\rho_c = 0$**
- **When $\lambda \neq 0$, the chip flow is deviated from π_o and $\rho_c = \lambda$ where ρ_c is chip flow deviation (from π_o) angle**
- **Orthogonal cutting:** when chip flows along orthogonal plane, π_o, i.e., $\rho_c = 0$
- **Oblique cutting:** when chip flow deviates from orthogonal plane, i.e. $\rho_c \neq 0$

Types of chips

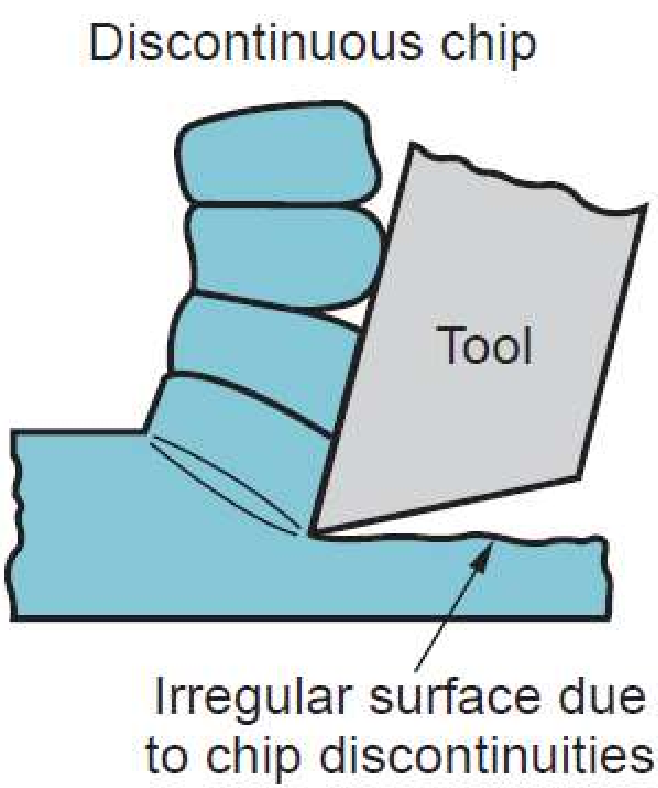
1. Discontinuous chip
2. Continuous chip
3. Continuous chip with built-up edge
4. Serrated (shear-localized) chips



Types of chips.

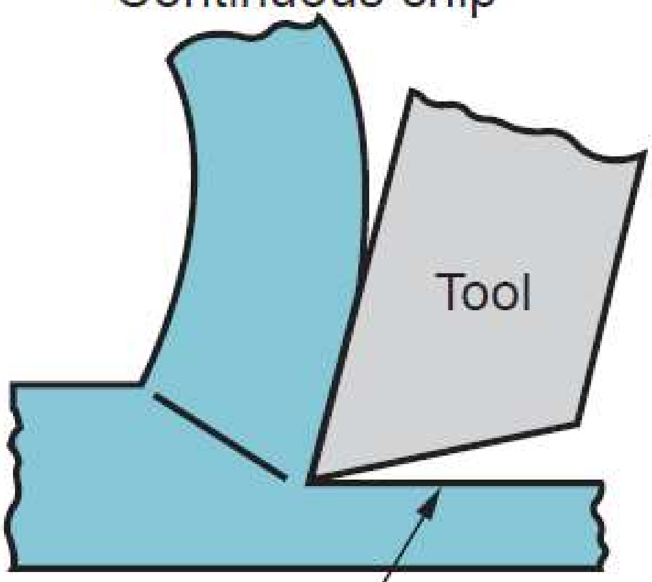
Discontinuous chip

- Forms when relatively brittle materials (e.g., cast irons) are machined at low cutting speeds
- High tool–chip friction and large feed and depth of cut promote the formation of this chip type.
- the chips often form into separate segments (sometimes the segments are loosely attached). This tends to impart an irregular texture to the machined surface



Continuous chip

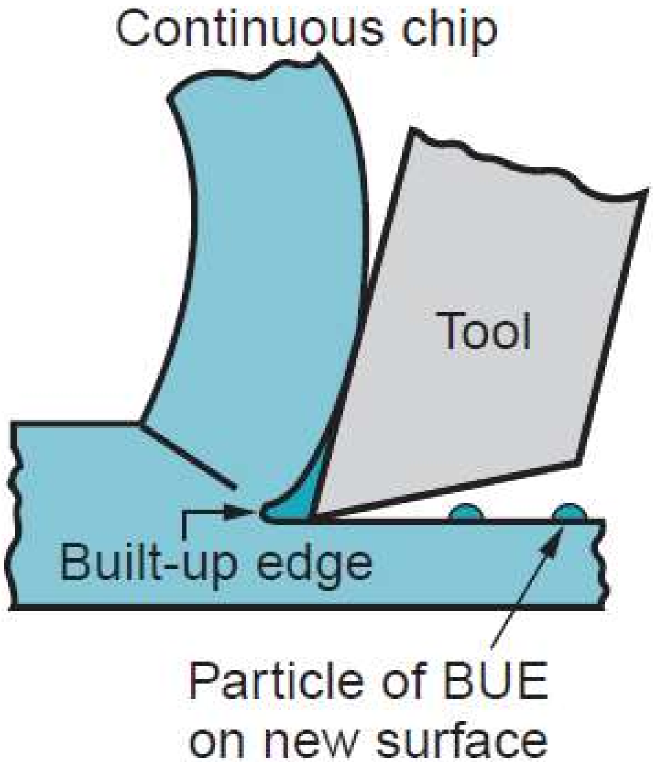
- When ductile materials are cut at high speeds and relatively small feeds and depths, long continuous chips are formed.
- A good surface finish typically results when this chip type is formed.
- A sharp cutting edge on the tool and low tool–chip friction encourage the formation of continuous chips.



- **Long, continuous chips (as in turning) can cause problems with regard to chip disposal and/or tangling about the tool.**
- **To solve these problems, turning tools are often equipped with *"chip breakers"*.**

Continuous chip with built-up edge

- When machining ductile materials at low-to-medium cutting speeds, friction between tool and chip tends to cause portions of the work material to adhere to the rake face of the tool near the cutting edge. This formation is called a ***built-up edge (BUE)***.
- The formation of a BUE is cyclical; it forms and grows, then becomes unstable and breaks off. Much of the detached BUE is carried away with the chip, sometimes taking portions of the tool rake face with it, which reduces the life of the cutting tool.

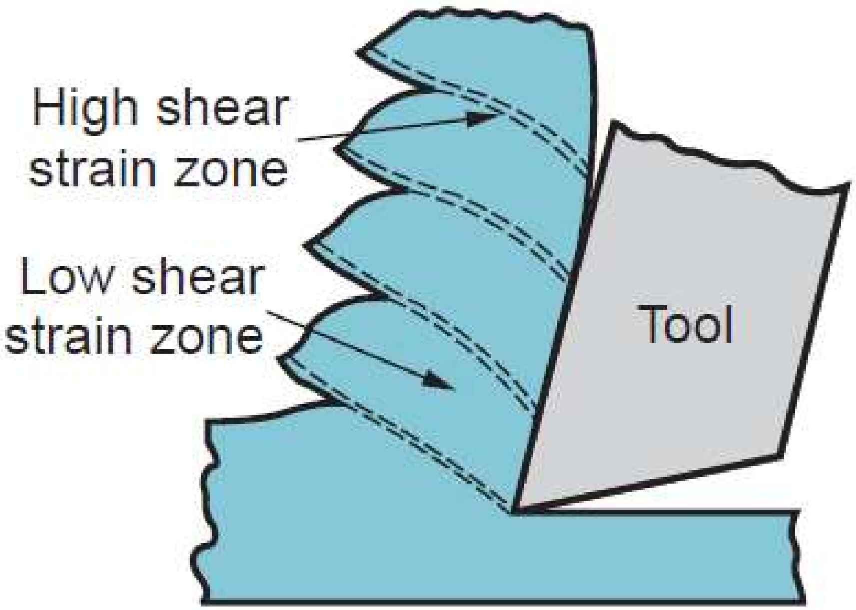


Continuous chip with built-up edge (continued)

- Portions of the detached BUE that are not carried off with the chip become **imbedded** in the newly created work surface, causing the surface to become rough.

Serrated (shear-localized) chips

- These chips are semi-continuous in the sense that they possess a saw-tooth appearance that is produced by a cyclical chip formation of alternating high shear strain followed by low shear strain.
- This type of chip is most closely associated with certain difficult-to-machine metals such as titanium alloys, nickel-base superalloys, and austenitic stainless steels when they are machined at higher cutting speeds.



Cutting tool materials

Cutting tool materials

The cutting-tool material must possess the following characteristics:

a. **Hot hardness**, so that the hardness, strength, and wear resistance of the tool are maintained at the temperatures encountered in machining operations.
b. **Toughness and impact strength**, so that impact forces on the tool that are encountered repeatedly during cutting operations do not chip or fracture the tool.
c. **Thermal shock resistance**, to withstand the rapid temperature cycling encountered in interrupted cutting.
d. **Wear resistance**, so that an acceptable tool life is obtained before replacement is necessary.
e. **Chemical stability and inertness** with respect to the material being machined, to avoid or minimize any adverse reactions, adhesion, and tool-chip diffusion that would contribute to tool wear.

Cutting tool materials

- **Hardness and strength are important with respect to the mechanical properties of the workpiece material to be machined.**

- **Impact strength is important in making interrupted cuts in machining, such as in milling.**

- **Melting temperature of the tool material is important as compared to the temperatures developed in the cutting zone.**

- **The physical properties of thermal conductivity and coefficient of thermal expansion are important in determining the resistance of the tool materials to thermal fatigue and shock.**

Cutting tool materials

General Characteristics of Tool Materials

Property	High-speed steels	Cast-cobalt alloys	Carbides WC	Carbides TiC	Ceramics	Cubic boron nitride	Single-crystal diamond*
Hardness	83–86 HRA	82–84 HRA 46–62 HRC	90–95 HRA 1800–2400 HK	91–93 HRA 1800–3200 HK	91–95 HRA 2000–3000 HK	4000–5000 HK	7000–8000 HK
Compressive strength, MPa	4100–4500	1500–2300	4100–5850	3100–3850	2750–4500	6900	6900
Transverse rupture strength, MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
Impact strength, J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	<0.1	<0.5	<0.2
Modulus of elasticity, GPa	200	—	520–690	310–450	310–410	850	820–1050
Density, kg/m^3	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
Volume of hard phase, %	7–15	10–20	70–90	—	100	95	95
Melting or decomposition temperature, °C	1300	—	1400	1400	2000	1300	700
Thermal conductivity, W/m K	30–50	—	42–125	17	29	13	500–2000
Coefficient of thermal expansion, $\times 10^{-6}$/°C	12	—	4–6.5	7.5–9	6–8.5	4.8	1.5–4.8

*The values for polycrystalline diamond are generally lower, except for impact strength, which is higher.

Cutting tool materials

General Characteristics of Cutting-tool Materials (These Tool Materials Have a Wide Range of Compositions and Properties; Overlapping Characteristics Exist in Many Categories of Tool Materials)

	High-speed steels	Cast-cobalt alloys	Uncoated carbides	Coated carbides	Ceramics	Polycrystalline cubic boron nitride	Diamond
Hot hardness							→
Toughness	←						
Impact strength	←						
Wear resistance							→
Chipping resistance	←						
Cutting speed							→
Thermal-shock resistance	←						
Tool material cost							→
Depth of cut	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Very light for single-crystal diamond
Processing method	Wrought, cast, HIP* sintering	Cast and HIP sintering	Cold pressing and sintering	CVD or PVD†	Cold pressing and sintering or HIP sintering	High-pressure, high-temperature sintering	High-pressure, high-temperature sintering

CUTTING TOOL MATERIALS

1. High Speed Steel
2. Cemented Carbide
3. Diamond
4. Boron Nitride
5. Ceramics

1. High Speed Steel (HSS)

High speed steel is a tool steel with a high hardness, high wear resistance and high heat resistance by adding more alloy elements such as tungsten, molybdenum, chromium, and vanadium.

2. Cemented Carbide

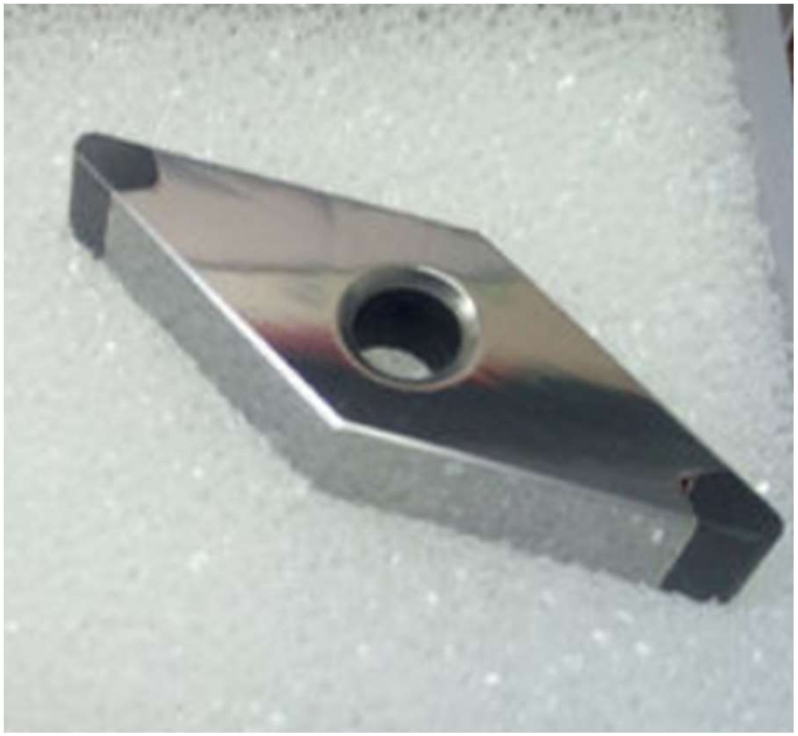
Cemented carbide is widely used as a tool material. It can also be used to cut difficult-to-machine materials such as heat-resistant steel, stainless steel, high manganese steel as well as tool steel.

3. Diamond

Cemented carbide is widely used as a tool material. It can also be used to cut difficult-to-machine materials such as heat-resistant steel, stainless steel, high manganese steel as well as tool steel.

4. Boron Nitride

It has high hardness, good abrasion resistance, excellent chemical stability, much higher thermal stability than diamond tools.



5. Ceramics

The main advantages of ceramic tool materials are: high hardness and abrasion resistance, minimal reduction in bending strength and bending resistance at high temperatures.

Cutting tool materials: overview

General Operating Characteristics of Cutting-tool Materials

Tool materials	General characteristics	Modes of tool wear or failure	Limitations
High-speed steels	High toughness, resistance to fracture, wide range of roughing and finishing cuts, good for interrupted cuts	Flank wear, crater wear	Low hot hardness, limited hardenability, and limited wear resistance
Uncoated carbides	High hardness over a wide range of temperatures, toughness, wear resistance, versatile, wide range of applications	Flank wear, crater wear	Cannot use at low speeds because of cold welding of chips and microchipping
Coated carbides	Improved wear resistance over uncoated carbides, better frictional and thermal properties	Flank wear, crater wear	Cannot use at low speeds because of cold welding of chips and microchipping
Ceramics	High hardness at elevated temperatures, high abrasive wear resistance	Depth-of-cut line notching, microchipping, gross fracture	Low strength and low thermomechanical fatigue strength
Polycrystalline cubic boron nitride (cBN)	High hot hardness, toughness, cutting-edge strength	Depth-of-cut line notching, chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperature
Diamond	High hardness and toughness, abrasive wear resistance	Chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperatures

Machining: unacceptable scenarios

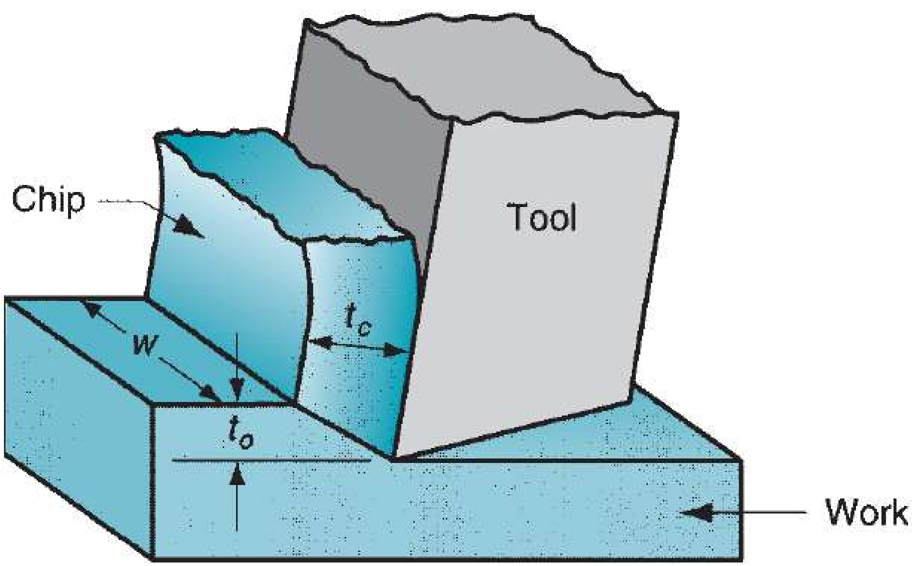
1. The surface finish of the workpiece being cut is unacceptable
2. The cutting tool wears rapidly and becomes dull
3. The workpiece becomes very hot
4. The tool begins to vibrate and chatter

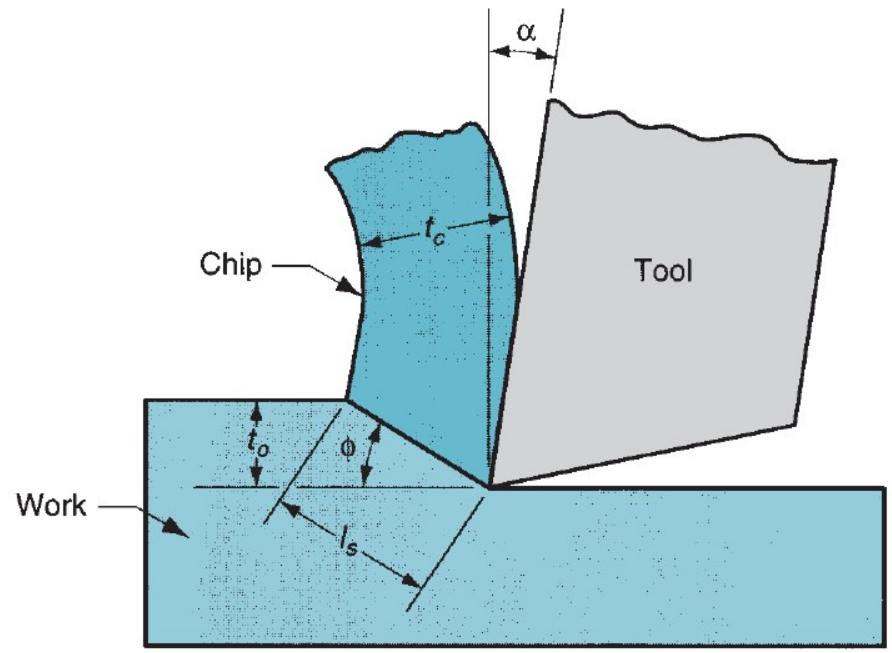
The Orthogonal Cutting Model (M. E. Merchant model)

1. Simple model
   a. neglects many of the geometric complexities, yet
   b. describes the mechanics of the process quite well
2. Developed in the early 1940s
3. This model is known as orthogonal cutting model, because
   a. It is two dimensional and
   b. the forces involved (as we later see) are perpendicular to each other.
4. The cutting tool has a **rake angle (α)** and a **relief or clearance angle**.

The Orthogonal Cutting Model (M. E. Merchant model)

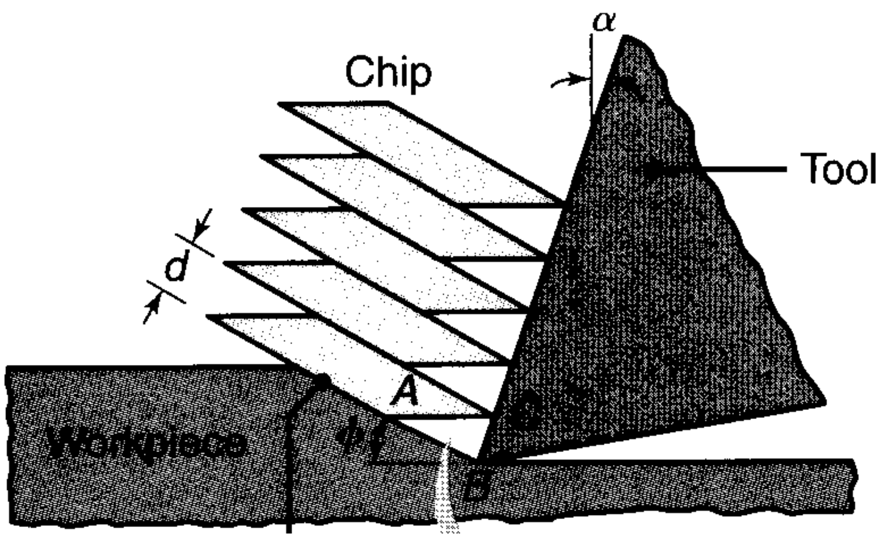
By definition, orthogonal cutting uses a wedge-shaped tool in which the ***cutting edge is perpendicular to the direction of cutting speed***.

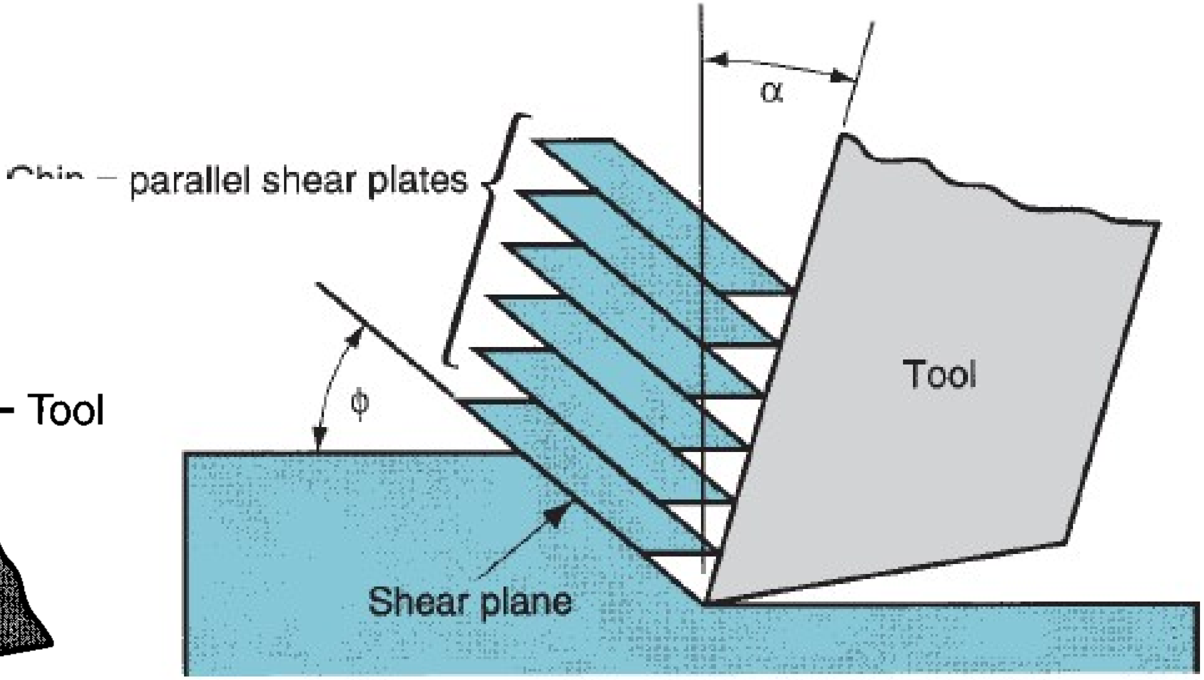




The Orthogonal Cutting Model (M. E. Merchant model)

1. As the tool is forced into the material, the chip is formed by ***shear deformation*** along a plane called the ***shear plane***, which is oriented at an angle **Ø** with the surface of the work.
2. Below the shear plane, the workpiece remains undeformed; above it, the chip that is already formed moves up the rake face of the tool.





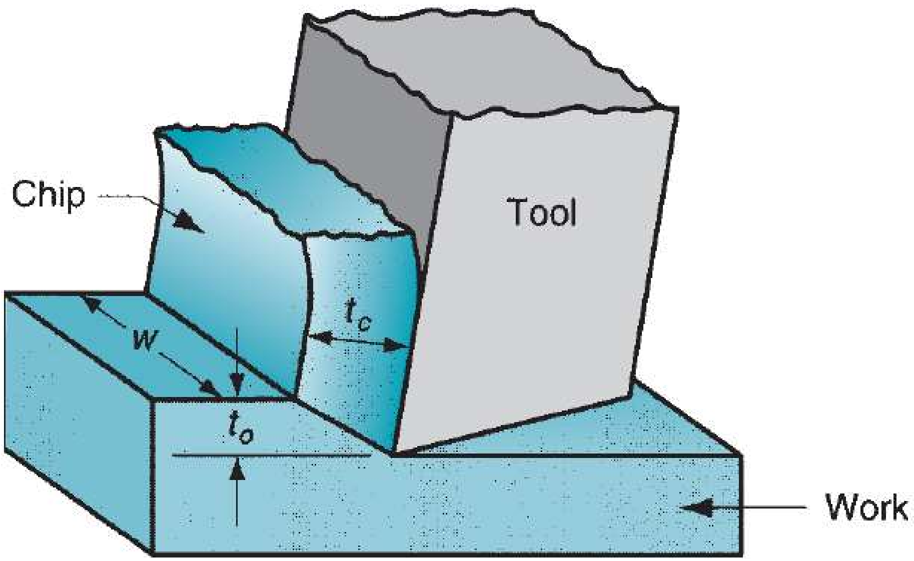
The Orthogonal Cutting Model (M. E. Merchant model)

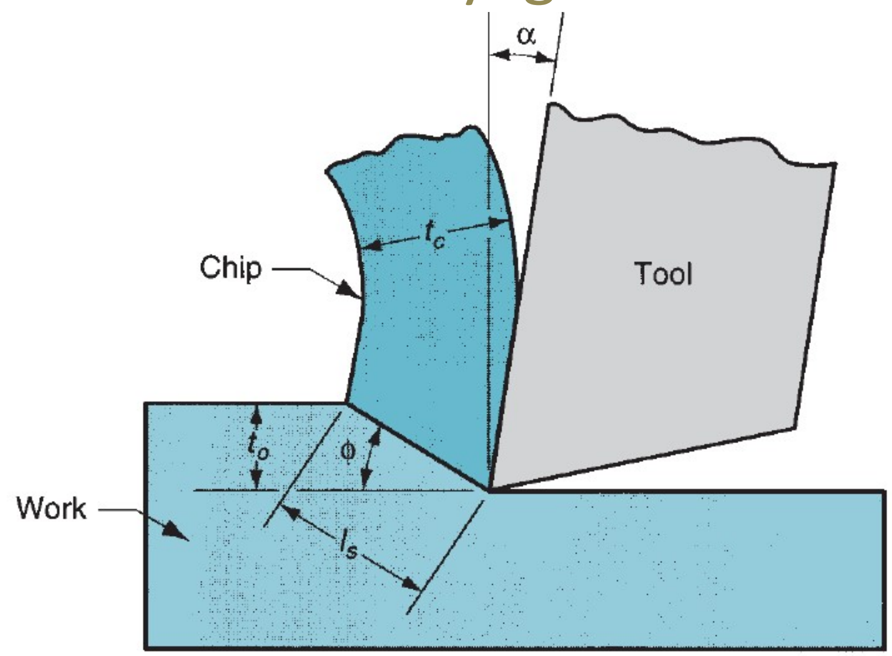
The tool in orthogonal cutting has only two elements of geometry:

(1) **rake angle**

(2) **clearance angle**

The rake angle α determines the direction that the chip flows as it is formed from the workpart; and the clearance angle provides a small clearance between the tool flank and the newly generated work surface.

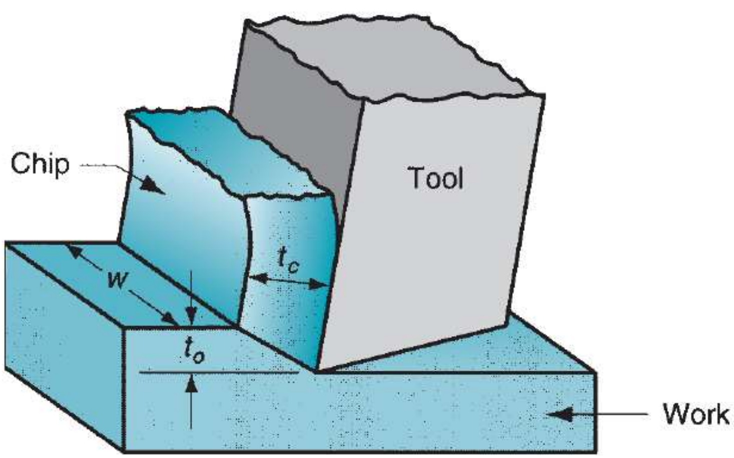




Chip thickness ratio

- During cutting, the cutting edge of the tool is positioned a certain distance below the original work surface. This corresponds to the thickness of the chip prior to chip formation, t_o.
- As the chip is formed along the shear plane, its thickness increases to t_c.
- The ratio of t_o to t_c is called the ***chip thickness ratio*** (or ***cutting ratio*** or simply the ***chip ratio***) ***r***:

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



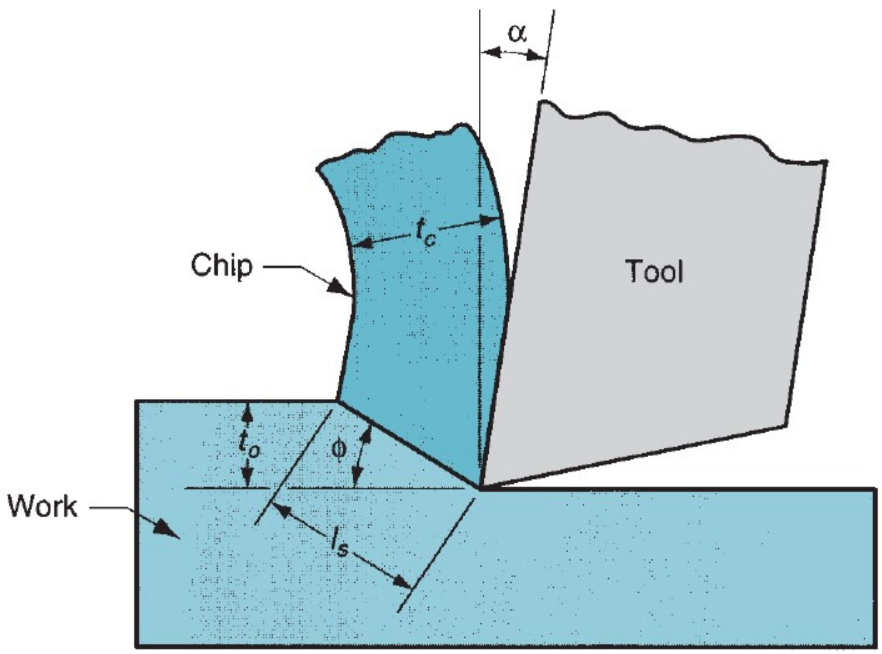
Note

Since the chip thickness after cutting is always greater than the corresponding thickness before cutting (WHY ?),

the chip ratio will always be less than 1.0

The Orthogonal Cutting Model (M. E. Merchant model)

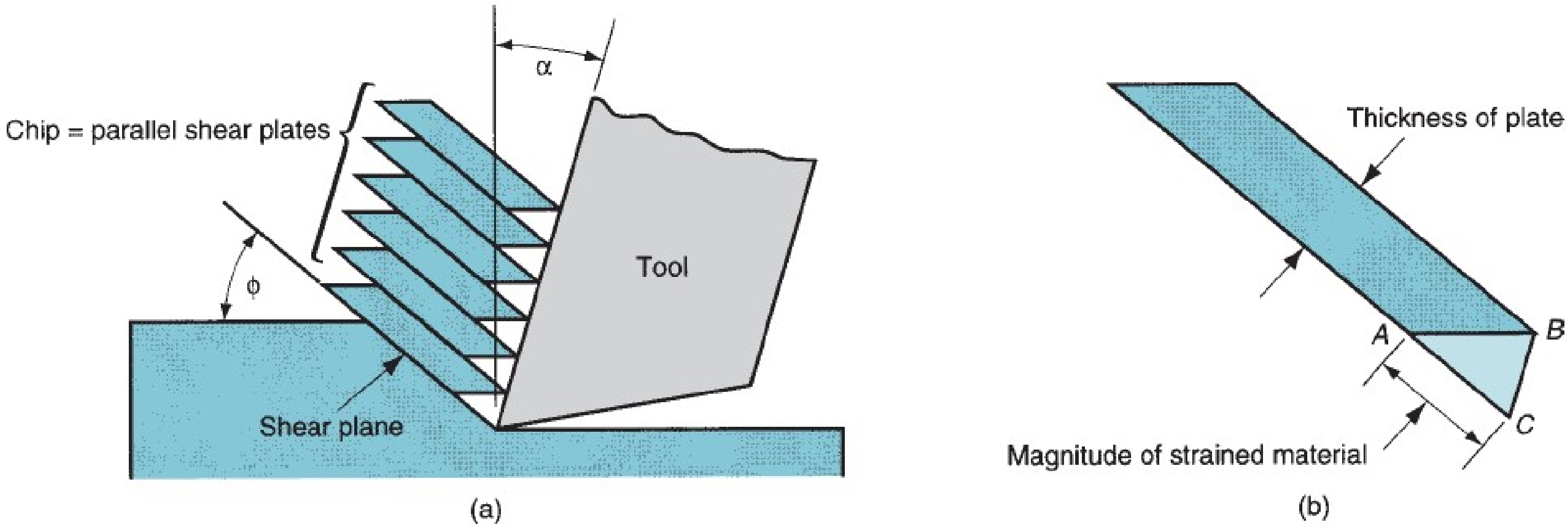
The geometry of the orthogonal cutting model allows us to establish an important relationship between the ***chip thickness ratio***, the ***rake angle***, and the ***shear plane angle***.



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

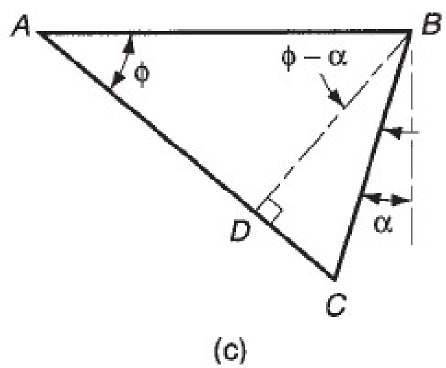
$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha}$$

Shear strain



$$\gamma = \frac{AC}{BD} = \frac{AD + DC}{BD}$$

$$\gamma = \tan(\phi - \alpha) + \cot\phi$$



Torque developed on the workpiece,

$$T = \frac{F_t \times D}{2 \times 1000} \text{ Nm (neglecting the components } F_a \text{ and } F_r\text{)}$$

where, D = Diameter of the workpiece in mm.

Heat produced (= work done in metal cutting)

$$= \frac{F_t \times V}{60 \times 1000} \text{ kN m/s} \quad \text{or} \quad \text{kJ/s or kW}$$

where, V = Cutting speed in m/min.

$$\textit{Power required} = \frac{F_t \times V}{60 \times 1000 \times \eta} \text{ kW}$$

where, η = Efficiency of the machine.

Velocity Relationship in Orthogonal Cutting

In an orthogonal cutting processes, there are three velocities ; these are :

1. *Cutting velocity (V)*—Velocity of tool relative to the workpiece.
2. *Velocity of chip (V_c)*—Velocity with which the chip moves over the rake face of the cutting tool.
3. *Velocity of shear (V_s)*—Velocity with which metal of the workpiece shears along the shear plane.

$$V_c = \frac{V \sin \phi}{\cos (\phi - \alpha)}$$

$$V_s = \frac{V \cos \alpha}{\cos (\phi - \alpha)}$$

1. In a machining operation that approximates orthogonal cutting, the cutting tool has a rake angle 10º. The chip thickness before the cut t_o = 0.50 mm and the chip thickness after the cut t_c = 1.125 mm. Calculate the shear plane angle and the shear strain in the operation.

Chip ratio: $$r = \frac{t_o}{t_c}$$ $$r = \frac{0.50}{1.125} = 0.444$$

Shear angle: $$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$ $$\tan\phi = \frac{0.444\cos 10}{1 - 0.444\sin 10} = 0.4738$$ $$\phi = 25.4^\circ$$

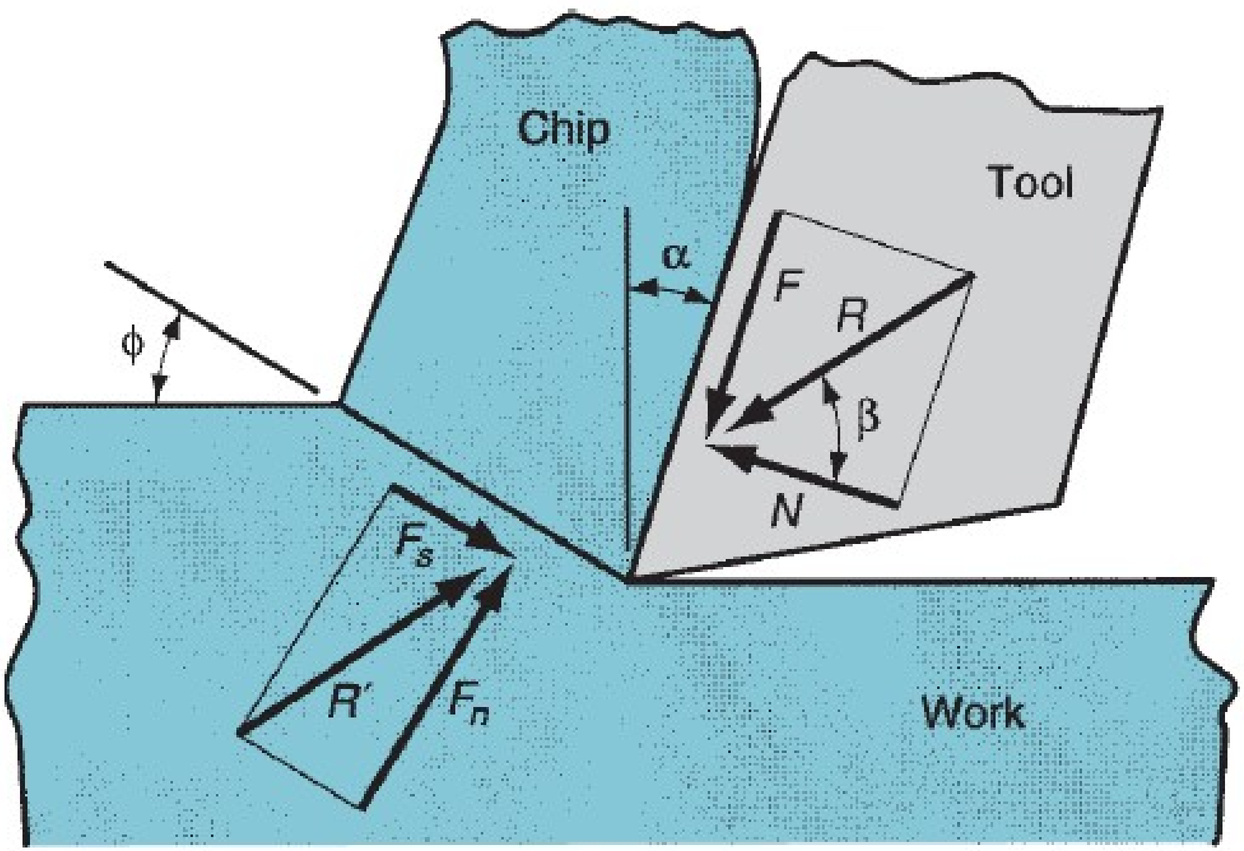
Shear strain: $$\gamma = \tan(\phi - \alpha) + \cot\phi$$ $$\gamma = \tan(25.4 - 10) + \cot 25.4$$ $$\gamma = 0.275 + 2.111 = 2.386$$

FORCE OF A SINGLE-POINT TOOL – **ANIMATION 1**

FORCE OF A SINGLE-POINT TOOL – **ANIMATION 2**

Force relationships and the Merchant equation

1. The forces applied against the chip by the tool can be separated into two mutually perpendicular components: ***friction force (F)*** and ***normal force (N)*** to friction



1. These two components can be used to define the coefficient of friction between the tool and the chip:

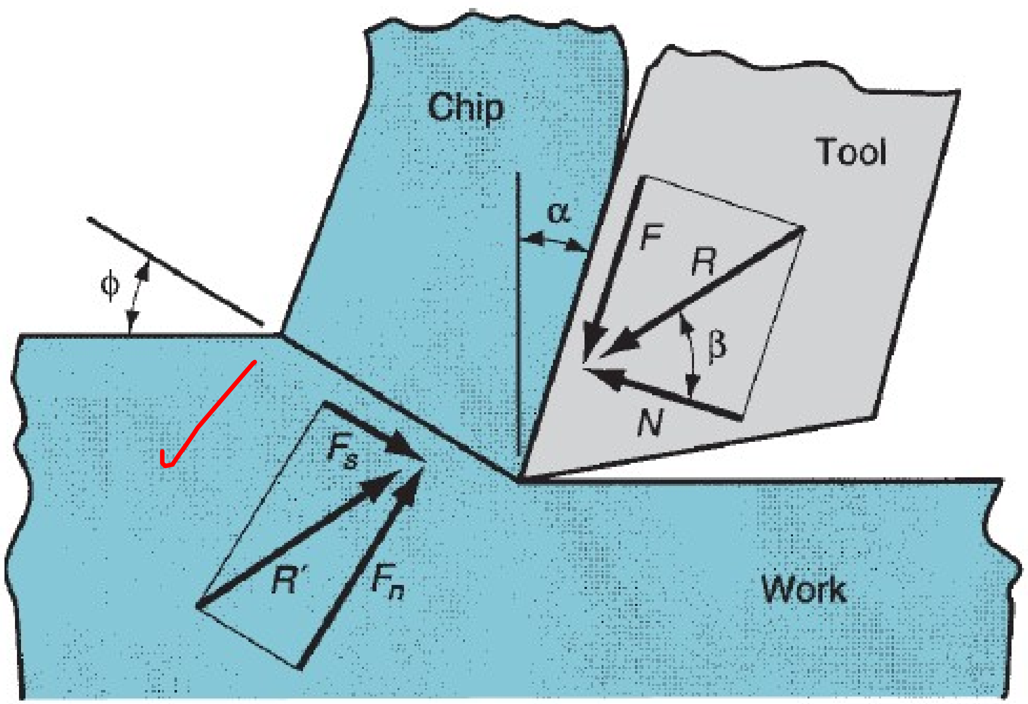
$$\mu = \frac{F}{N}$$

2. The friction force and its normal force can be added vectorially to form a resultant force R, which is oriented at an angle **β** with respect to the normal force, called the ***friction angle***. The friction angle is related to the coefficient of friction as

$$\mu = \tan \beta$$

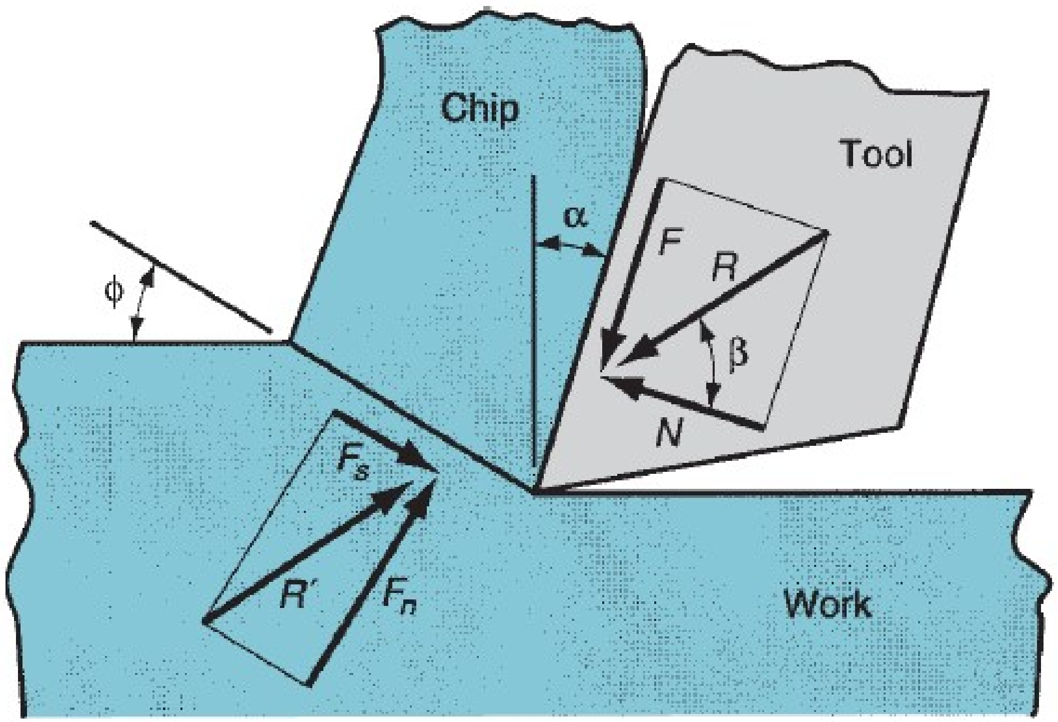
Force relationships and the Merchant equation

1. In addition to the tool forces acting on the chip, there are two force components applied by the workpiece on the chip: shear force and normal force to shear.
2. The ***shear force (F_s)*** is the force that causes shear deformation to occur in the shear plane, and the ***normal force to shear (F_n)*** is perpendicular to the shear force.



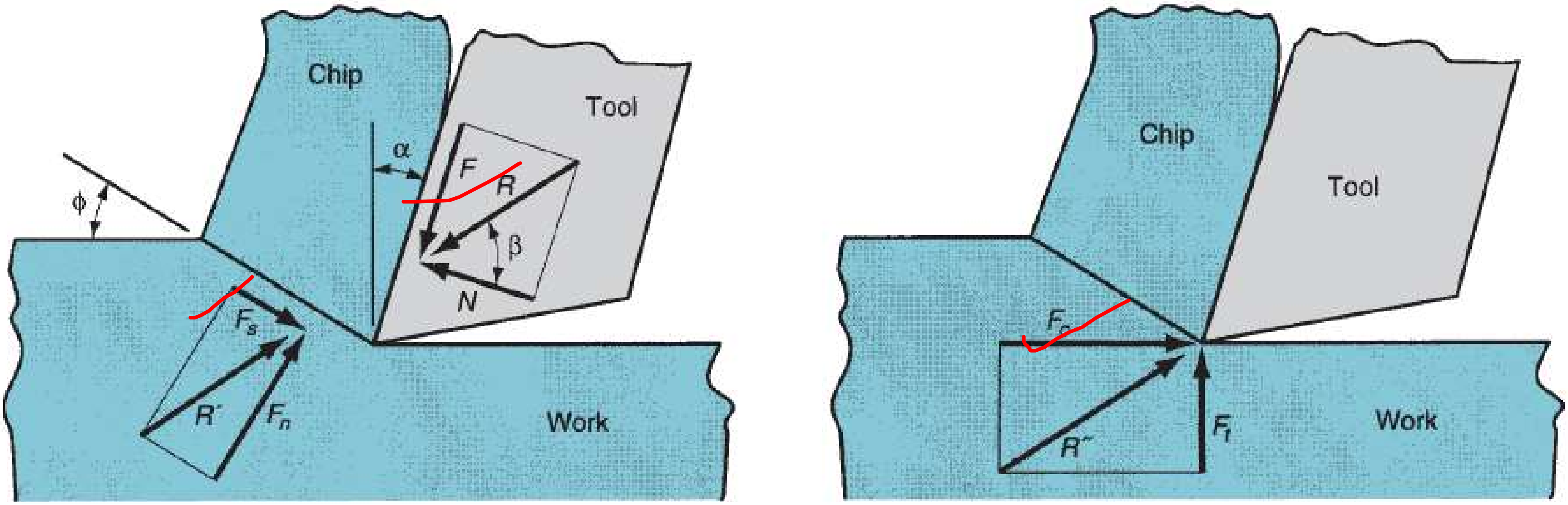
Force relationships and the Merchant equation

1. Vector addition of the two force components F_s and F_n yields the resultant force R'.
2. In order for the forces acting on the chip to be in balance, this resultant R' must be equal in magnitude, opposite in direction, and collinear with the resultant R.

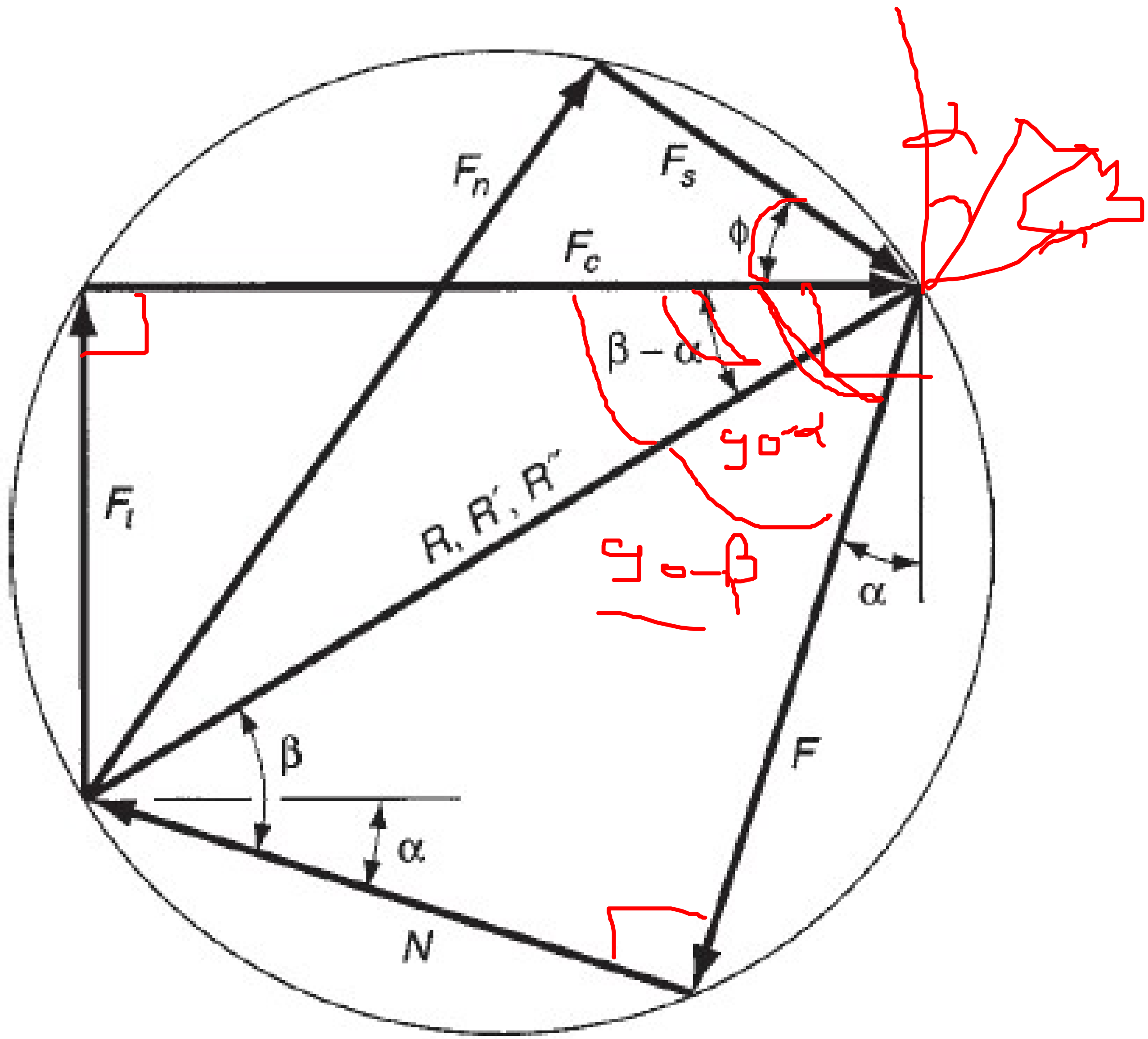


Force relationships and the Merchant equation

1. None of the four force components F, N, F_s, and F_n can be directly measured in a machining operation, because the directions in which they are applied vary with different tool geometries and cutting conditions.
2. However, it is possible for the cutting tool to be instrumented using a force measuring device called a dynamometer, so that two additional force components acting against the tool can be directly measured: **cutting force and thrust force**.
3. The cutting force F_c is in the direction of cutting, the same direction as the cutting speed v, and the thrust force F_t is perpendicular to the cutting force and is associated with the chip thickness before the cut t_0.


Chip
Tool
α
F
R
β
N
ϕ
F_s
R'
F_n
Work
Chip
Tool
F_c
F_t
R''
Work

Force relationships and the Merchant equation



Force relationships and the Merchant equation

$$F = F_c \sin\alpha + F_t \cos\alpha$$

$$N = F_c \cos\alpha - F_t \sin\alpha$$

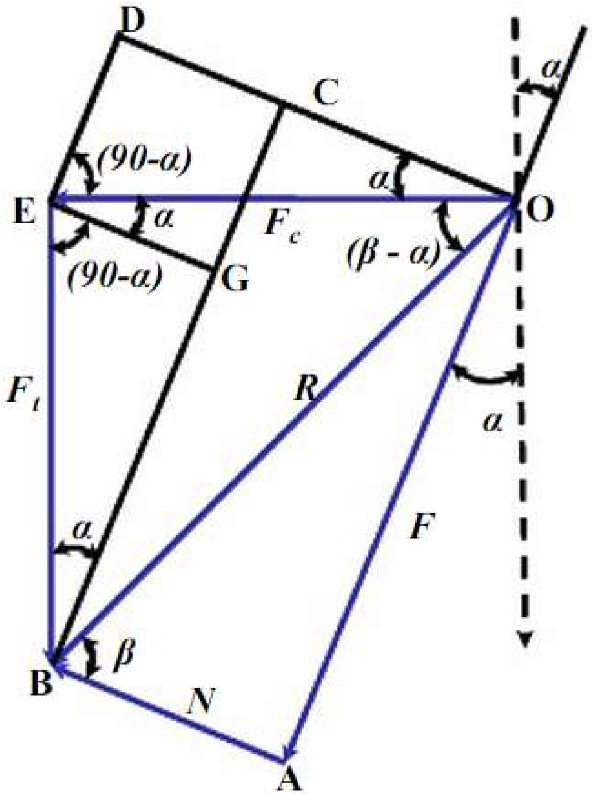
$$F_s = F_c \cos\phi - F_t \sin\phi$$

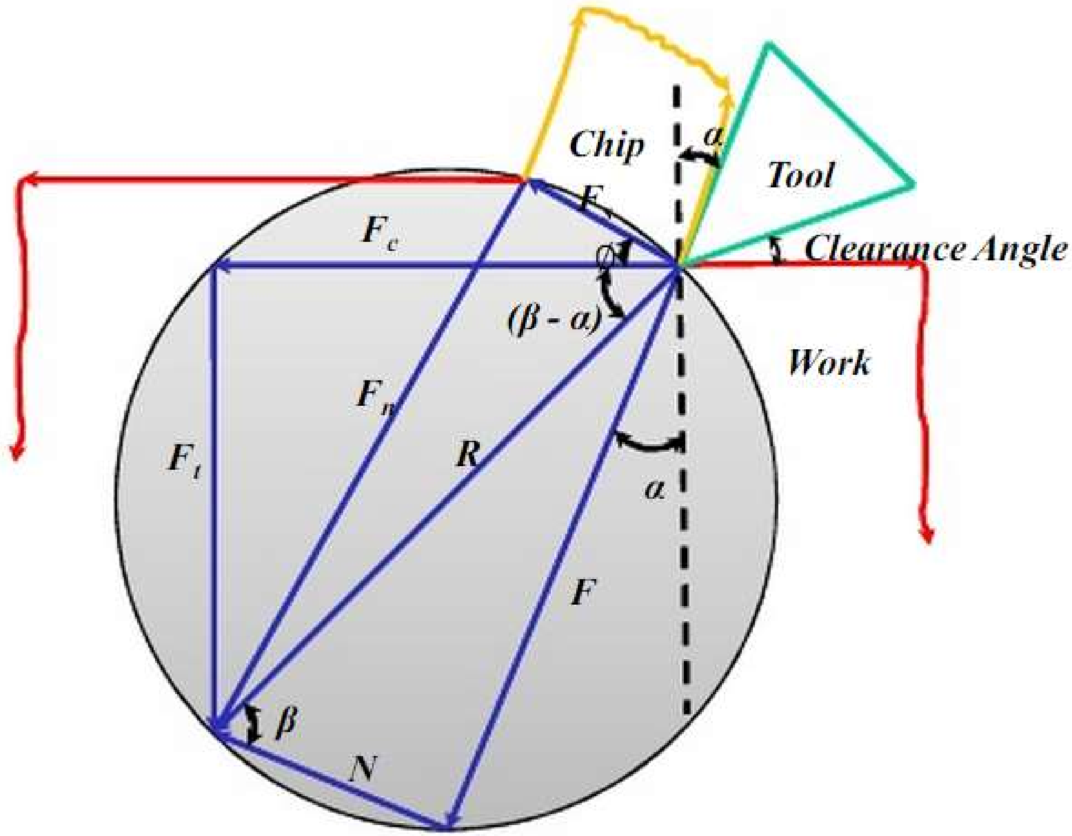
$$F_n = F_c \sin\phi + F_t \cos\phi$$

$\beta = \tan^{-1}\left(\frac{F}{N}\right)$

$$F_C = F_s \left[\frac{\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} \right]$$

Frictional Force System





$$F = OA = CB = CG + GB = ED + GB$$

$$\Rightarrow F = F_C \sin\alpha + F_t \cos\alpha$$

$$N = AB = OD - CD = OD - GE$$

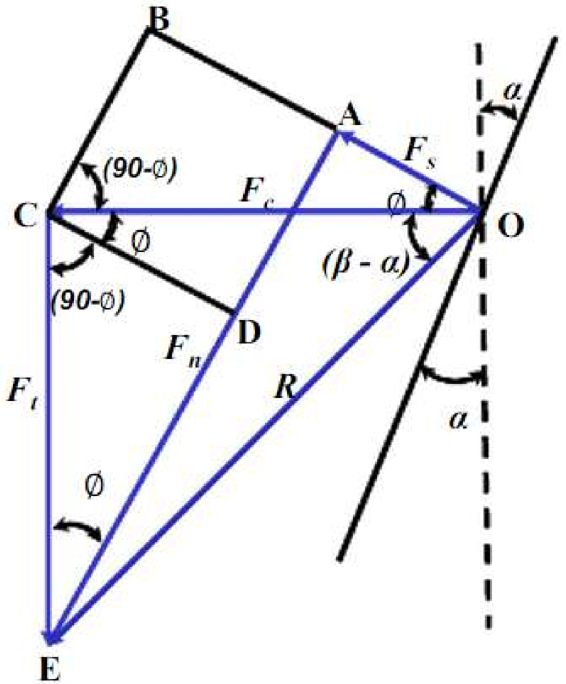
$$\Rightarrow N = F_C \cos\alpha - F_t \sin\alpha$$

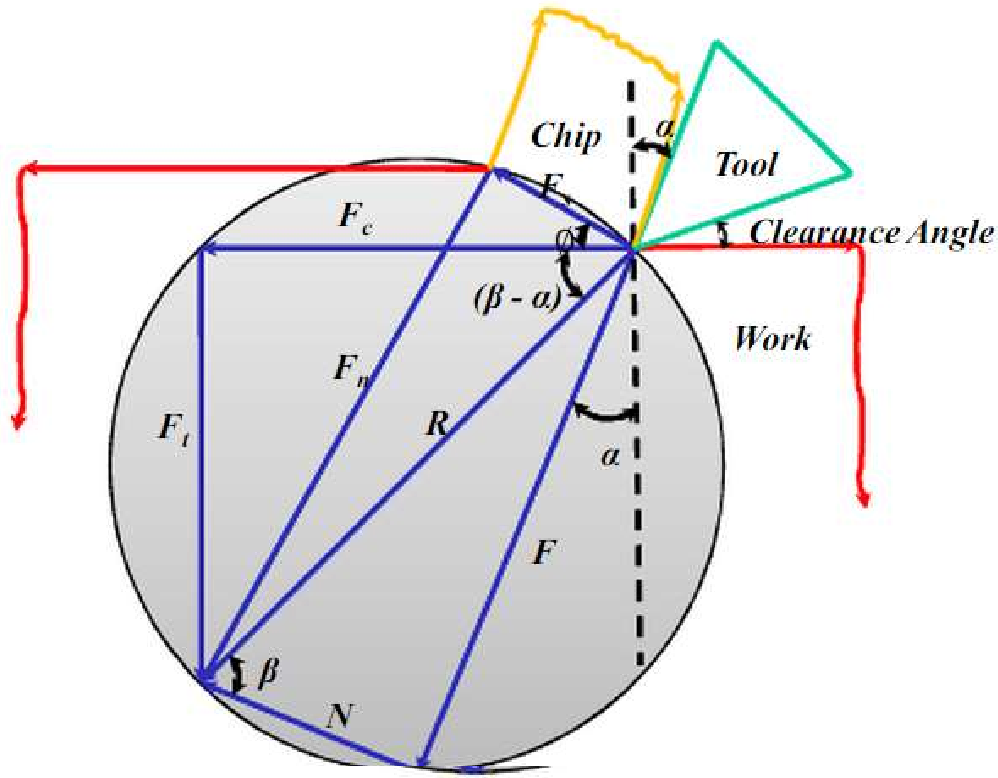
The coefficient of friction

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

Where β = *Friction angle*

Shear Force System





$$F_S = OA = OB - AB = OB - CD$$

$$\Rightarrow F_S = F_C \cos\phi - F_t \sin\phi$$

$$F_N = AE = AD + DE = BC + DE$$

$$\Rightarrow F_N = F_C \sin\phi + F_t \cos\phi$$

Also:

$$\boxed{F_N = F_S \tan(\phi + \beta - \alpha)}$$

1. Suppose in previous example, the cutting force and thrust force are measured during an orthogonal cutting operation: F_c = 1559 N and F_t = 1271 N. The width of the orthogonal cutting operation w = 3.0 mm. Based on these data, determine the shear strength of the work material.

rake angle 10º

$$\phi = 25.4^\circ$$

$$F_s = 1559 \cos 25.4 - 1271 \sin 25.4 = 863 \text{ N}$$

$$A_s = \frac{t_o w}{\sin \phi} \qquad A_s = \frac{(0.5)(3.0)}{\sin 25.4} = 3.497 \text{ mm}^2$$

$$\tau = S = \frac{863}{3.497} = 247 \text{ N/mm}^2 = 247 \text{ MPa}$$

THE MERCHANT EQUATION

1. Shear angle Ø is the angle at which shear stress is just equal to the shear strength of the work material, and so shear deformation occurs at this angle.
2. In effect, the work material will select a shear plane angle that minimizes energy.
3. This angle can be determined by taking the derivative of the shear stress S with respect to Ø and setting the derivative to zero. Solving for Ø, we get the relationship named after Merchant:

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

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

$$F_s = F_c \cos\phi - F_t \sin\phi$$

$$\tau = \frac{F_c \cos\phi - F_t \sin\phi}{(t_o w/\sin\phi)}$$

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

1. Using the data and results from our previous examples, determine (a) the friction angle and (b) the coefficient of friction.

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

$$\beta = 2(45) + 10 - 2(25.4) = 49.2^{\circ}$$

$$\mu = \tan 49.2 = 1.16$$

Lessons Based on the Merchant Equation

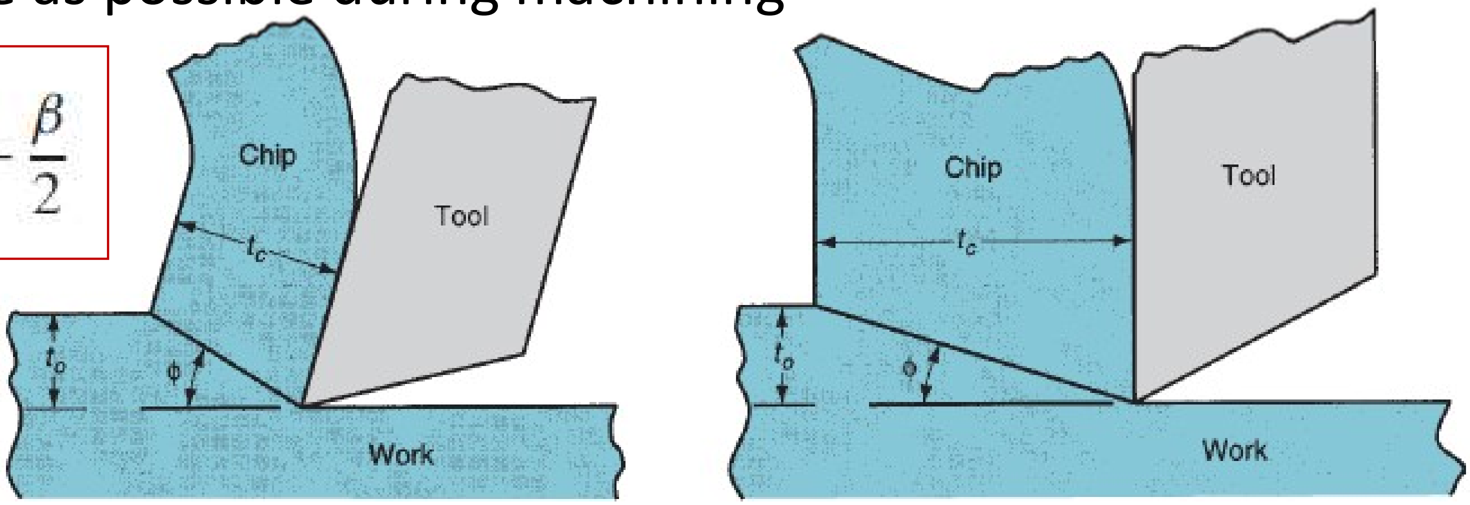
$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

1. The importance of the Merchant equation is that it defines the general relationship between ***rake angle, tool–chip friction***, and ***shear plane angle***.
2. The shear plane angle can be increased by
   a. *increasing the rake angle* and
   b. *decreasing the friction angle (and coefficient of friction)* between the tool and the chip.
3. Rake angle can be increased by proper tool design
4. Friction angle can be reduced by using a lubricant cutting fluid

The importance of increasing the shear plane angle

1. If all other factors remain the same, a higher shear plane angle results in a smaller shear plane area.
   a. The shear force required to form the chip will decrease when the shear plane area is reduced.
   b. Hence results in lower cutting energy and power requirements, and lower cutting temperature
   c. These are good reasons to try to make the shear plane angle as large as possible during machining

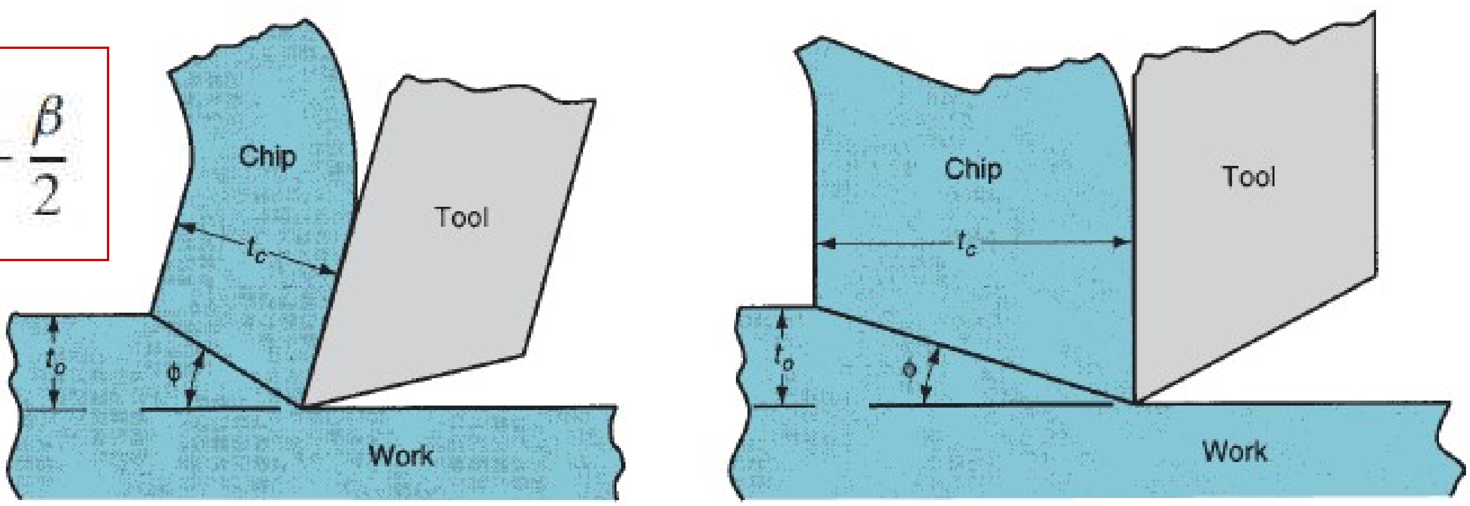
$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

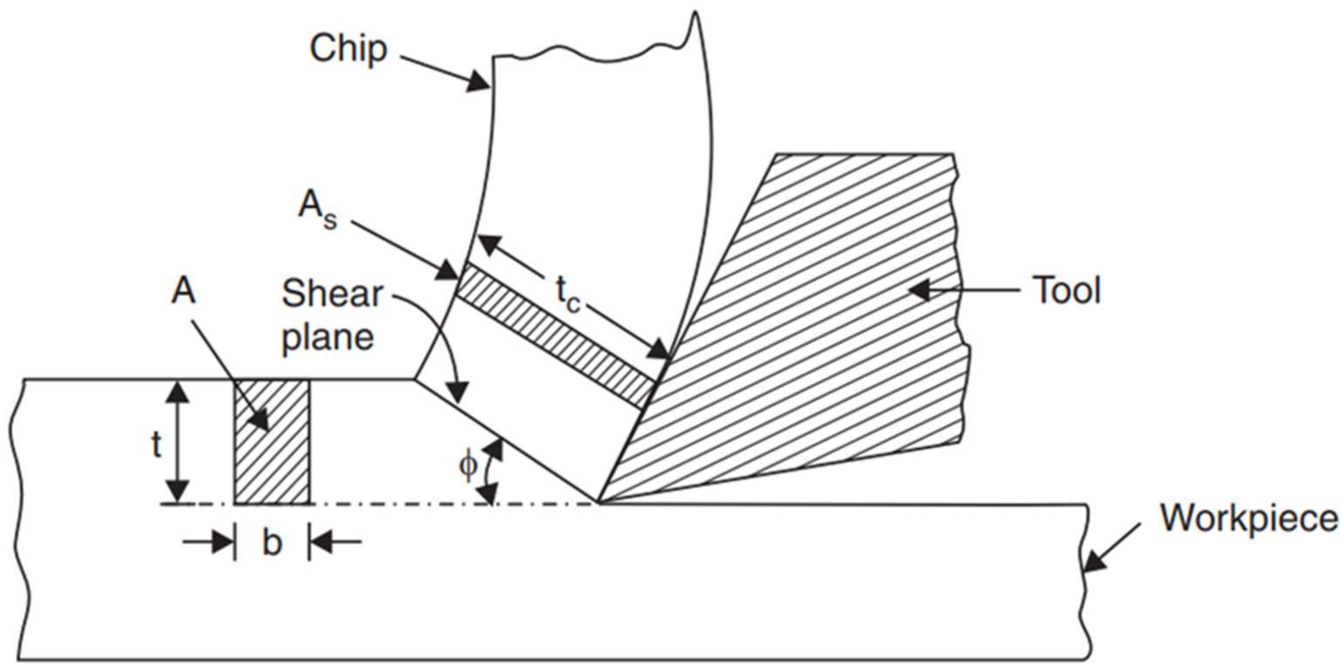


Note

If all other factors remain the same, a higher shear plane angle results in a smaller shear plane area. Since the shear strength is applied across this area, the shear force required to form the chip will decrease when the shear plane area is reduced. A greater shear plane angle results in lower cutting energy, lower power requirements, and lower cutting temperature. These are good reasons to try to make the shear plane angle as large as possible during machining.

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





Geometry of chip formation.

A_s = Area of shear plane

b = Width of cut

$A = b \times t$

= Cross-sectional area of uncut chip (*i.e.*, before cutting)

$= A_s \sin \phi$

Mean normal stress (σ) **:**

$$\sigma = \frac{F_c}{A_s} = \frac{F_c}{(A/\sin\phi)} = \frac{F_c \cdot \sin\phi}{A}$$

$$\sigma = \frac{(F_f \cos\phi + F_t \sin\phi)\sin\phi}{A}$$

Mean shear stress (τ) **:**

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

$$\tau = \frac{F_s \sin\phi}{A}$$

$$F_s = \frac{\tau \cdot b \cdot t}{\sin\phi}$$

$$(MRR)_{\max} = \frac{\text{Max. power available at machine spindle}}{\text{Power required/cm}^3\text{/min}}$$

$$(MRR)_{\max} = V.t.f$$

SHEAR STRAIN

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

SPECIFIC CUTTING ENERGY

$$E_{sp} = \frac{\tau\cos(\beta-\alpha)}{\sin\phi\,.\,\cos(\phi+\beta-\alpha)}$$

SHEAR ANGLE

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha)$$

Power and Energy Relationships in Machining

1. A machining operation requires power.
2. The cutting force in a production machining operation might exceed 1000 N
3. Typical cutting speeds are several hundred m/min.
4. The product of cutting force and speed gives the power (energy per unit time) required to perform a machining operation:

$$\boxed{P_c = F_c v}$$

where P_c = cutting power, N-m/s or W (ft-lb/min);
F_c = cutting force, N (lb); and
v = cutting speed, m/s (ft/min).

Gross power

$$P_g = \frac{P_c}{E}$$

where P_g = gross power of the machine tool motor
E = mechanical efficiency of the machine tool.
Typical values of E for machine tools are around 90%.

Unit power

It is often useful to convert *power* into *power per unit volume rate of metal cut*. This is called the ***unit power***, P_u

$$P_u = \frac{P_c}{R_{MR}}$$

where R_{MR} = material removal rate, mm^3/s (in^3/min).
The material removal rate can be calculated as the product of v, t_o and w.
v = cutting speed
t_o = Initial chip thickness
w = width

Unit power (Specific energy)

Unit power is also known as the ***specific energy, U***.

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

- The units for specific energy are typically N-m/mm^3 (in-lb/in^3).
- However, at the units might be reduced to N/mm^2

Unit power (Specific energy)

Material	Brinell Hardness	Specific Energy U or Unit Power P_u		Unit Horsepower HP_u hp/(in^3/min)
		N-m/mm^3	in-lb/in^3	
Carbon steel	150–200	1.6	240,000	0.6
	201–250	2.2	320,000	0.8
	251–300	2.8	400,000	1.0
Alloy steels	200–250	2.2	320,000	0.8
	251–300	2.8	400,000	1.0
	301–350	3.6	520,000	1.3
	351–400	4.4	640,000	1.6
Cast irons	125–175	1.1	160,000	0.4
	175–250	1.6	240,000	0.6
Stainless steel	150–250	2.8	400,000	1.0
Aluminum	50–100	0.7	100,000	0.25
Aluminum alloys	100–150	0.8	120,000	0.3
Brass	100–150	2.2	320,000	0.8
Bronze	100–150	2.2	320,000	0.8
Magnesium alloys	50–100	0.4	60,000	0.15

Values of unit horsepower and specific energy for selected work materials using sharp cutting tools and chip thickness before the cut t_o = 0.25 mm (0.010 in).

PROBLEM - 1

The following observations were made during an orthogonal cutting operation :

Tool rake angle	.... $10°$
Co-efficient of friction	.... 0.85
Chip thickness	.... 2.5 mm
Width of cut	.... 15 mm
Cutting speed	.... 40 m/min
Feed	.... 1.5 mm/rev.
Shear strength	.... 650 N/mm^2

Determine the following :

(*i*) *Chip thickness ratio.*

(*ii*) *Shear angle.*

(*iii*) *Shearing force.*

(*iv*) *Friction angle.*

(*v*) *Cutting force.*

(*vi*) *Power consumed at the cutting tool.*

Solution.

Given :

$\alpha = 10°$;

$\mu = 0.85$;

$t_c = 2.5$ mm ;

$b = 15$ mm,

$V = 40$ m/min. ;

Feed, $f (= t) = 1.5$ mm/rev. ;

$\tau = 6.5$ N/mm^2

(*i*) Chip thickness ratio, *r* :

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

$$= \frac{1.5}{2.5}$$

$$= \mathbf{0.6}$$

(*ii*) **Shear angle, ϕ :**

$$\phi = \tan^{-1}\left(\frac{r\cos\alpha}{1 - r\sin\alpha}\right)$$

$$\phi = \tan^{-1}\left(\frac{0.6 \times \cos 10^\circ}{1 - 0.6 \times \sin 10^\circ}\right)$$

$$\phi = \mathbf{33.4^\circ}$$

(*iii*) **Shearing force, F_s :**

$$\tau = \frac{F_s \sin\phi}{A}$$

$$F_s = \frac{\tau . A}{\sin\phi}$$

$$= \frac{\tau . b . t}{\sin\phi}$$

$$= \frac{650 \times 15 \times 1.5}{\sin 33.4^\circ}$$

$$= 26567.7 \text{ N}$$

$$= \mathbf{26.567\ kN}$$

(*iv*) **Friction angle, β :**

$$\mu = \tan \beta$$

$$\beta = \tan^{-1} (0.85)$$

$$\beta = \mathbf{40.36°}$$

(v) Cutting force, F_t :

$$F_t = F_s \left[\frac{\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} \right]$$

$$F_t = 26.567 \left[\frac{\cos(40.36^\circ - 10^\circ)}{\cos(33.4^\circ + 40.36^\circ - 10)} \right]$$

$$F_t = 51.85 \text{ kN}$$

(*vi*) Power consumed at the cutting tool, *P* :

$$P = \frac{F_t \times V}{60}\ k\mathrm{W}$$

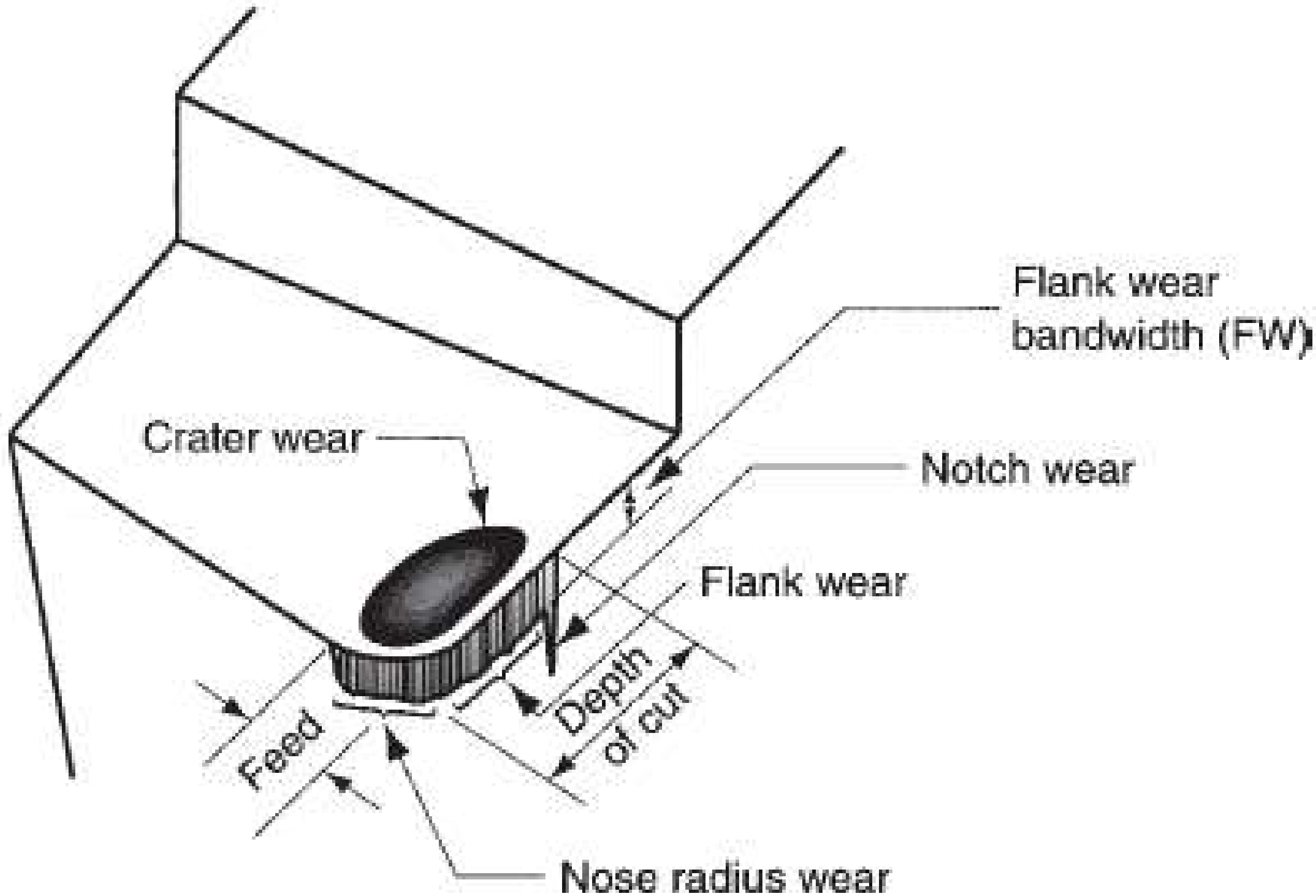
$$P = \frac{51.85 \times 40}{60}$$

$$= \mathbf{34.56\ kW}$$

Cutting tool wear & life period

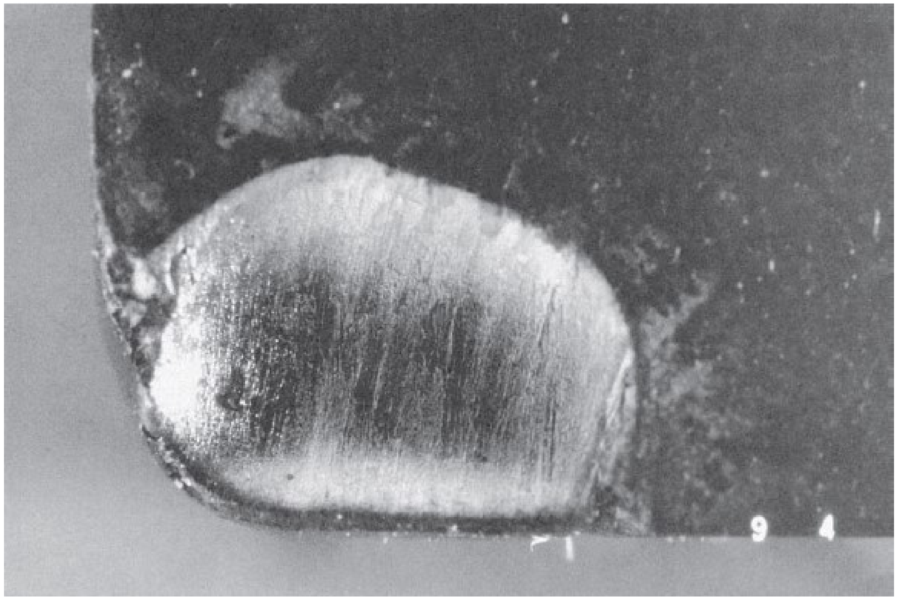
Tool Life: Wear and Failure

1. Gradual wear occurs at two principal locations on a cutting tool:
   a. The top rake face and
   b. The flank
2. Accordingly, two main types of tool wear can be distinguished:
   a. Crater wear and
   b. Flank wear


Flank wear
bandwidth (FW)
Crater wear
Notch wear
Flank wear
Depth
of cut
Feed
Nose radius wear

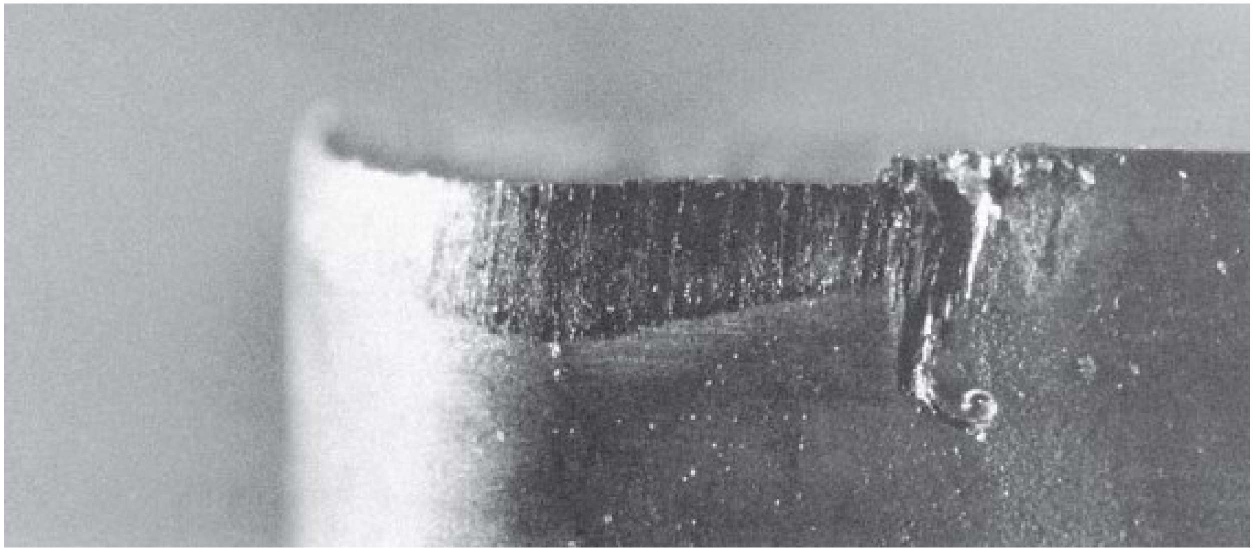
Crater Wear

1. Crater wear consists of a cavity in the rake face of the tool that forms and grows from the action of the chip sliding against the surface.
2. High stresses and temperatures characterize the tool–chip contact interface, contributing to the wearing action.
3. The crater can be measured either by its depth or its area.



Flank Wear

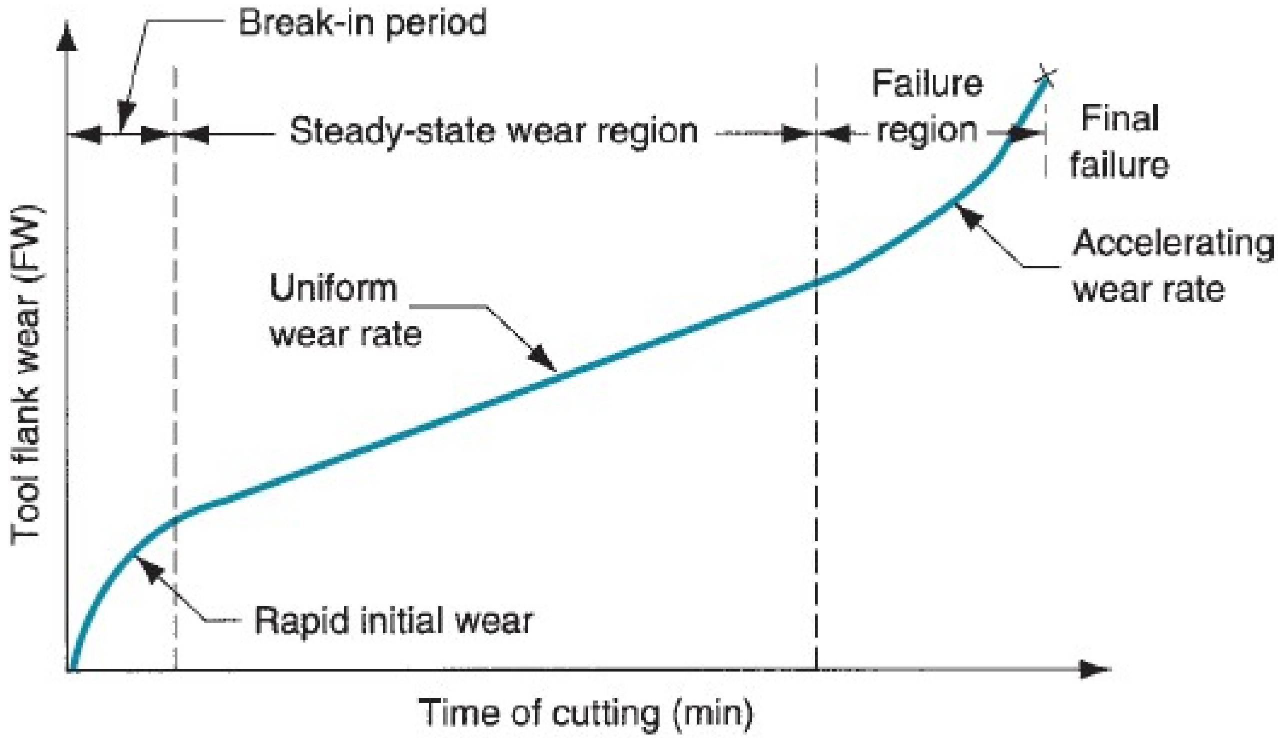
1. Flank wear occurs on the flank, or relief face, of the tool.
2. It results from rubbing between the newly generated work surface and the flank face adjacent to the cutting edge.
3. Flank wear is measured by the width of the wear band, FW.
4. This wear band is sometimes called the flank wear land.



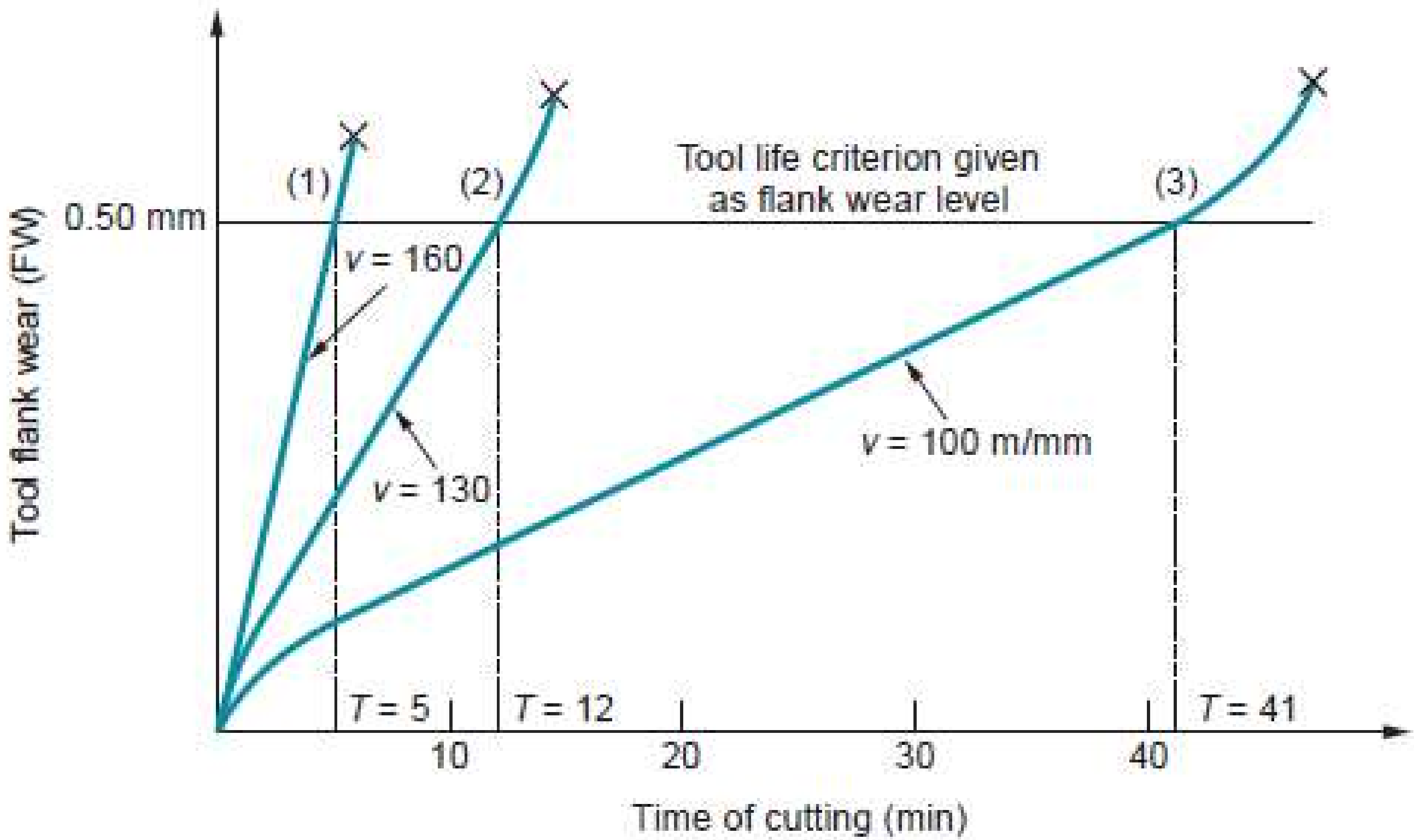
The mechanisms that cause wear at the tool–chip and tool–work interfaces

1. Abrasion
2. Adhesion
3. Diffusion
4. Chemical reactions
5. Plastic deformation

1. Tool life is defined as the length of cutting time that the tool can be used



Tool Life



Tool life criterion given as flank wear level
0.50 mm
(1)
(2)
(3)
v = 160
v = 130
v = 100 m/mm
T = 5
T = 12
T = 41
10
20
30
40
Tool flank wear (FW)
Time of cutting (min)

Taylor Tool Life Equation

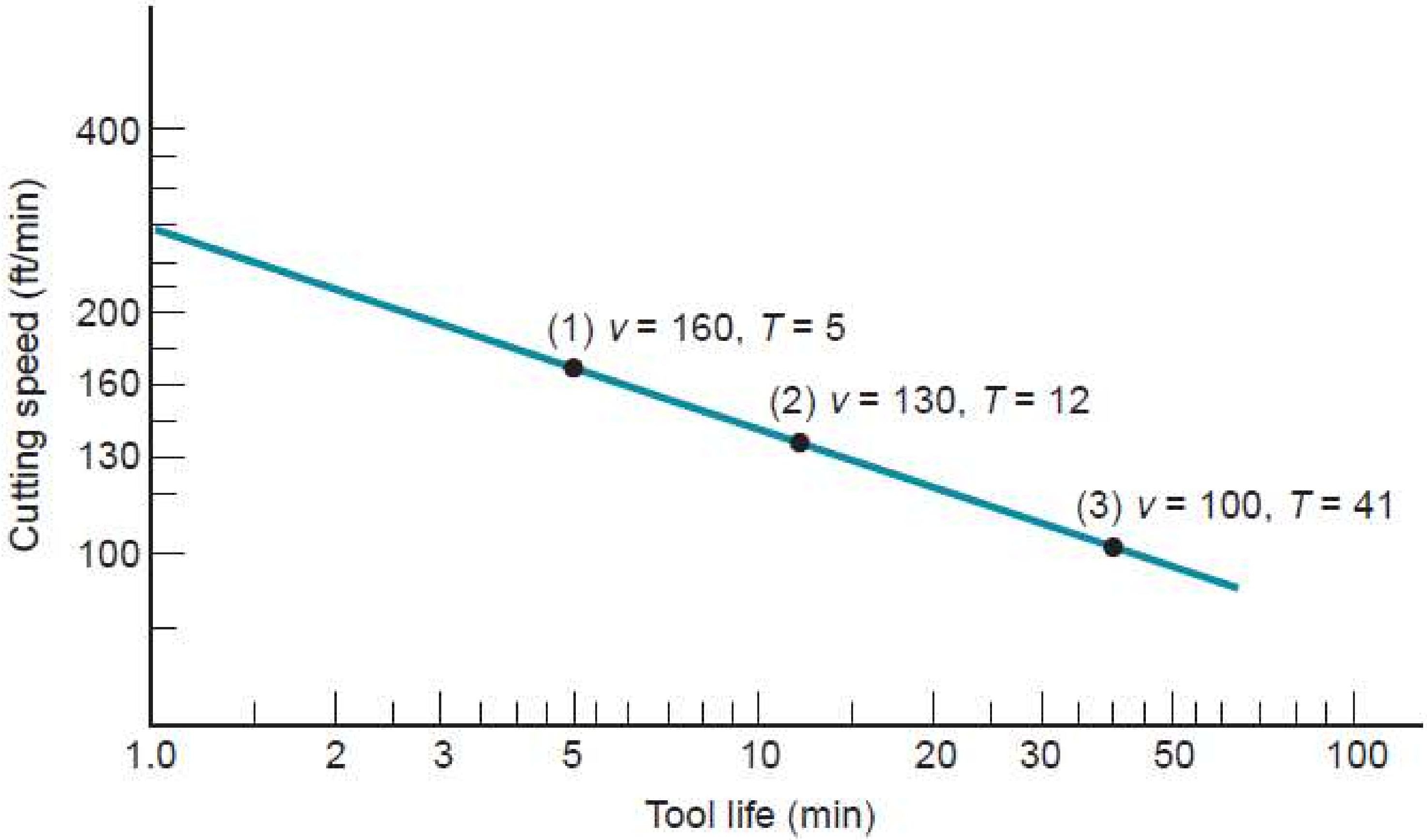
In a classic study by F.W Taylor on the machining of steels conducted in the early 1890s, the following approximate relationship for tool life, known as the Taylor tool life equation, was established:

$$vT^n = C$$

where v = cutting speed, m/min (ft/min); T = tool life, min; and n and C are parameters whose values depend on feed, depth of cut, work material, tooling (material in particular), and the tool life criterion used.

Determination of tool life using Taylor Tool Life Equation

Determine the values of C and n in the plot shown below, using two of the three points on the curve and solving simultaneous equations of the Taylor Tool Life Equation $vT^n = C$



Determination of tool life using Taylor Tool Life Equation

Solution: Choosing the two extreme points: $v = 160$ m/min, $T = 5$ min; and $v = 100$ m/min, $T = 41$ min; we have

$$160(5)^n = C$$
$$100(41)^n = C$$

Setting the left-hand sides of each equation equal,

$$160(5)^n = 100(41)^n$$

Taking the natural logarithms of each term,

$$\ln(160) + n\ln(5) = \ln(100) + n\ln(41)$$
$$5.0752 + 1.6094\,n = 4.6052 + 3.7136\,n$$
$$0.4700 = 2.1042\,n$$
$$n = \frac{0.4700}{2.1042} = 0.223$$

Substituting this value of n into either starting equation, we obtain the value of C:

$$C = 160(5)^{0.223} = 229$$

or

$$C = 100(41)^{0.223} = 229$$

The Taylor tool life equation for the given data is therefore…

$$vT^{0.223} = 229$$

PROBLEM - 1

A mild steel workpiece is being machined by two different tools A and B under indentical machining conditions. The tool life equations for these tools are :

For tool-A : $VT^{0.32} = 42.5$

For tool-B : $VT^{0.45} = 88.6$

where V and T are in m/s and s, respectively.

Determine the cutting speed above which tool-B will give better tool life.

Solution. Let, V^* = *Break-even speed* at which both the tools give the *same tool life*.

$$VT^{0.32} = 42.5$$

$$VT^{0.45} = 88.6$$

$$T = \left(\frac{42.5}{V*}\right)^{1/0.32} \quad \text{...For tool-}A$$

$$T = \left(\frac{88.6}{V*}\right)^{1/0.45} \quad \text{...for tool-}B$$

$$\left(\frac{42.5}{V*}\right)^{1/0.32} = \left(\frac{88.6}{V*}\right)^{1/0.45}$$

$$\left(\frac{42.5}{V*}\right)^{3.125} = \left(\frac{88.6}{V*}\right)^{2.22}$$

$$\frac{(V*)^{3.125}}{(V*)^{2.22}} = \frac{122663.5}{21052.5} = 5.826$$

$$(V^*)^{0.905} = 5.826$$

$$= \mathbf{7.0\ m/s}$$

PROBLEM - 2

$V = \pi D N$

$V_1 T_1^n = C$

During straight turning of a 24 mm diameter steel bar at 300 RPM with an HSS tool, a tool life of 9 min was obtained. When the same bar was turned at 250 RPM the tool life was increased to 48.5 min. What will be the tool life at a speed of 280 RPM.

$V_3 T_3^n = C$

Solution.

Given : $D = 24$ mm

$N_1 = 300$ r.p.m. $N_2 = 250$ r.p.m. $N_3 = 280$ r.p.m.

$T_1 = 9$ min $T_2 = 48.5$ min $T_3 = ?$

$$V_1 = \frac{\pi D N_1}{1000} = \frac{\pi \times 24 \times 300}{1000} = 22.62 \text{ m/min}$$

$$V_2 = \frac{\pi D N_2}{1000} = \frac{\pi \times 24 \times 250}{1000} = 18.85 \text{ m/min}$$

$$V_3 = \frac{\pi D N_3}{1000} = \frac{\pi \times 24 \times 280}{1000} = 21.11 \text{ m/min}$$

Tool life at 280 r.p.m., T_3 :

$$V_1 T_1^{\,n} = V_2 T_2^{\,n}$$

$$n = \frac{\ln(V_2/V_1)}{\ln(T_1/T_2)}$$

$$n = \frac{\ln(18.85/22.62)}{\ln(9/48.5)}$$

$$= 0.108$$

$$V_1 T_1^{\,n} = V_3 T_3^{\,n}$$

$$T_3 = \left(\frac{V_1}{V_3}\right)^{1/n} \times T_1$$

$$= \left(\frac{22.62}{21.11}\right)^{1/0.108} \times 9$$

$$= \mathbf{17.06\ min}$$

PROBLEM - 3

A carbide tool with mild steel workpiece was found to give life of 2 hours at cutting speed of 48 m/min. If Taylor's exponent n = 0.27, determine :

(i) The tool life, if the same tool is used at a speed of 20 per cent higher than the previous one.

(ii) The value of cutting speed if the tool is required to have tool life of 3 hours.

$$Given : T_1 = 2 \text{ hours} = 120 \text{ min}$$

$$V_1 = 48 \text{ m/min}$$

$$n = 0.27$$

$$V_2 = 1.2 \times 48 = 57.6 \text{ m/min}$$

$$T_2 = ?$$

$$T_3 = 3 \text{ hours} = 180 \text{ min}$$

$$V_3 = ?$$

(i) Tool life at higher speed, $\mathbf{T_2}$:

$$VT^n = C$$

$$V_1(T_1)^n = V_2\,(T_2)^n$$

$$T_2 = \left(\frac{V_1}{V_2}\right)^{1/n} \times T_1$$

$$= \left(\frac{48}{57.6}\right)^{(1/0.27)} \times 120$$

$$= \mathbf{61.08\ min}$$

(ii) **Cutting speed, $\mathbf{V_3}$:**

$$V_1(T_1)^n = V_3(T_3)^n$$

$$48 \times (120)^{0.27} = V_3 \times (180)^{0.27}$$

$$V_3 = 48 \times \left(\frac{120}{180}\right)^{0.27}$$

$$= \mathbf{43.02\ m/min}$$

Thermal aspects of metal machining

Temperatures in Cutting

1. Of the total energy consumed in machining, nearly all of it (98%) is converted into heat energy that, in turn, raises the temperature in the cutting zone.
2. This heat can cause temperatures to be very high at the tool–chip interface—over 600˚C is not unusual.
3. Temperature rise is a very important factor in machining because of its major adverse effects, such as the following:
    a. Excessive temperature lowers the strength, hardness, stiffness, and wear resistance of the cutting tool; tools also may soften and undergo plastic deformation; thus, tool shape is altered.
    b. Increased heat causes uneven dimensional changes in the part being machined, making it difficult to control its dimensional accuracy and tolerances.
    c. An excessive temperature rise can induce thermal damage and metallurgical changes in the machined surface, adversely affecting its properties.

Temperatures in Cutting

The main sources of heat in machining are:

a. The work done in shearing in the primary shear zone,
b. Energy dissipated as friction at the tool-chip interface, and
c. Heat generated as the tool rubs against the machined surface, especially for dull or worn tools.

A comprehensive expression for predicting the *mean temperature*, T_{mean}, in orthogonal cutting is

$$T = \frac{0.000665 Y_f}{\rho c} \sqrt[3]{\frac{V t_o}{K}}$$

Proposed by **Cook**, which was derived using experimental data for a variety of work materials to establish parameter values for the resulting equation.

where the mean temperature is in *Kelvins*

Y_f is the flow stress in MPa
ρc is the volumetric specific heat in kJ/m^3-K
K is the thermal diffusivity (ratio of thermal conductivity to volumetric specific heat) in m^2/s

1. to predict the increase in temperature at the tool–chip interface during machining:

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

where ΔT = mean temperature rise at the tool–chip interface, C ˚ (F ˚);
U = specific energy in the operation, N-m/mm^3 or J/mm^3 (in-lb/in^3);
v = cutting speed, m/s (in/sec);
t_o = chip thickness before the cut,m (in);
ρC = volumetric specific heat of the work material, J/mm^3-C (in-lb/in^3-F);
K = thermal diffusivity of the work material, m^2/s (in^2/sec).

Machinability

- **Machinability** denotes the relative ease with which a material (usually a metal) can be machined using appropriate tooling and cutting conditions.
- There are various criteria used to evaluate machinability, the most important of which are:

  (1) Tool life

  (2) Force and power required

  (3) Surface finish and surface integrity of the machined part

  (4) ease of chip disposal
- Thus, good machinability indicates good surface finish and surface integrity, a long tool life, and low force and power requirements.

Machinability ratings (indexes)

1. the standard material is AISI 1112 steel (resulfurized), with a rating of 100.
2. Examples of typical ratings are
   a. 3140 steel - 55
   b. free-cutting brass - 300
   c. 2011 wrought aluminum - 200
   d. pearlitic gray iron - 70
   e. precipitation-hardening 17-7 steel - 20

Cutting Fluids

Cutting Fluids

Cutting fluids have been used extensively in machining operations to..

1. Reduce friction and wear, thus improving tool life and the surface finish of the workpiece.
2. Cool the cutting zone, thus improving tool life and reducing the temperature and thermal distortion of the workpiece.
3. Reduce forces and energy consumption.
4. Flush away the chips from the cutting zone, thus preventing the chips from interfering with the cutting process, particularly in operations such as drilling and tapping.
5. Protect the machined surface from environmental corrosion.

Cutting Fluids

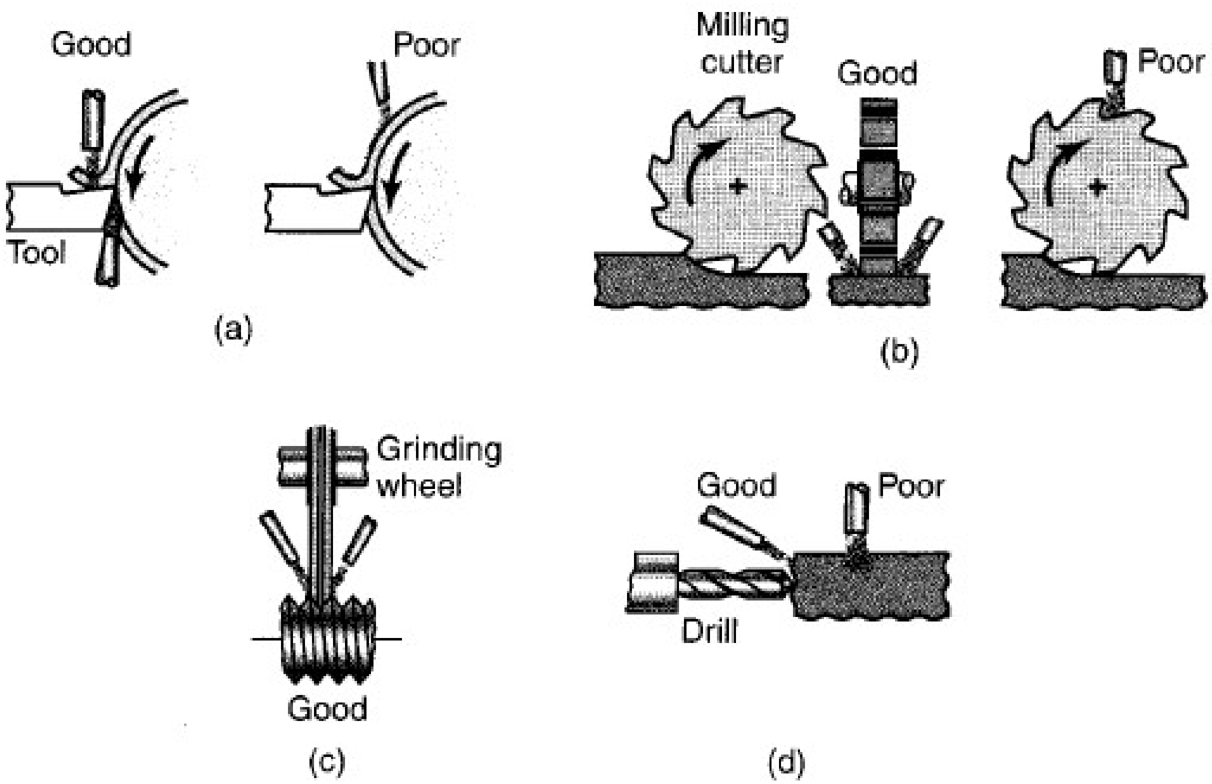
1. The cutting fluid may be a coolant, a lubricant, or both.
2. Eg. Water is an excellent coolant but is not an effective lubricant
3. There are operations, however, in which the cooling action of cutting fluids can be detrimental.
4. It has been shown that cutting fluids may cause the chip to become more curly and thus concentrate the heat closer to the tool tip, reducing tool life.
5. More importantly, in interrupted cutting operations, such as milling, cooling of the cutting zone leads to thermal cycling of the cutter teeth, which can cause thermal crac/as by thermal fatigue or thermal shock
6. beginning with the mid-1990s, there has been a major trend toward near-dry machining, meaning a minimal use of cutting fluids, as well as toward dry machining

Types of Cutting Fluids

1. **Oils** (also called straight oils), including mineral, animal, vegetable, compounded, and synthetic oils,
   a. typically are used for low-speed operations where temperature rise is not significant.
2. **Emulsions** (also called soluble oils), a mixture of oil and water and additives
   - generally are used for high-speed operations because the temperature rise is significant. The presence of water makes emulsions highly effective coolants. The presence of oil reduces or eliminates the tendency of water to cause oxidation.
3. **Semisynthetics** are chemical emulsions containing little mineral oil, diluted in water, and with additives that reduce the size of oil particles, making them more effective.
4. **Synthetics** are chemicals with additives, diluted in water, and containing no oil.

Methods of Cutting-fluid Application

1. Flooding
   a. This is the most common method.
   b. Flow rates typically range from 10 L/min for single-point tools to 225 L/min per cutter for multiple-tooth cutters, as in milling.



Methods of Cutting-fluid Application

2. Mist
   a. This type of cooling supplies fluid to inaccessible areas
   b. provides better visibility of the workpiece being machined
   c. has limited cooling capacity
   d. Problem of inhalation of airborne fluid particles by the machine operator
3. High-pressure systems
   a. high-pressure refrigerated coolant systems are highly effective in increasing the rate of heat removal from the cutting zone
   b. The pressures employed acts as a chip breaker in situations where the chips produced would otherwise be long and continuous
4. Through the cutting tool system
   a. For a more effective application, narrow passages can be produced in cutting tools,
   b. Eg. In drilling of long bars

Near-dry and Dry Machining

Major benefits

1. Alleviating the environmental impact of using cutting fluids, improving air quality in manufacturing plants, and reducing health hazards.
2. Reducing the cost of machining operations, including the cost of maintenance, recycling, and disposal of cutting fluids.
3. Further improving surface quality.

- The principle behind **near-dry cutting** is the application of a fine mist of an air-fluid mixture containing a very small amount of cutting fluid, which may be reformulated to contain vegetable oil.
- With major advances in cutting tools, **dry machining** has been shown to be effective in various machining operations (especially turning, milling, and gear cutting) on steels, steel alloys, and cast irons, but generally not for aluminum alloys.