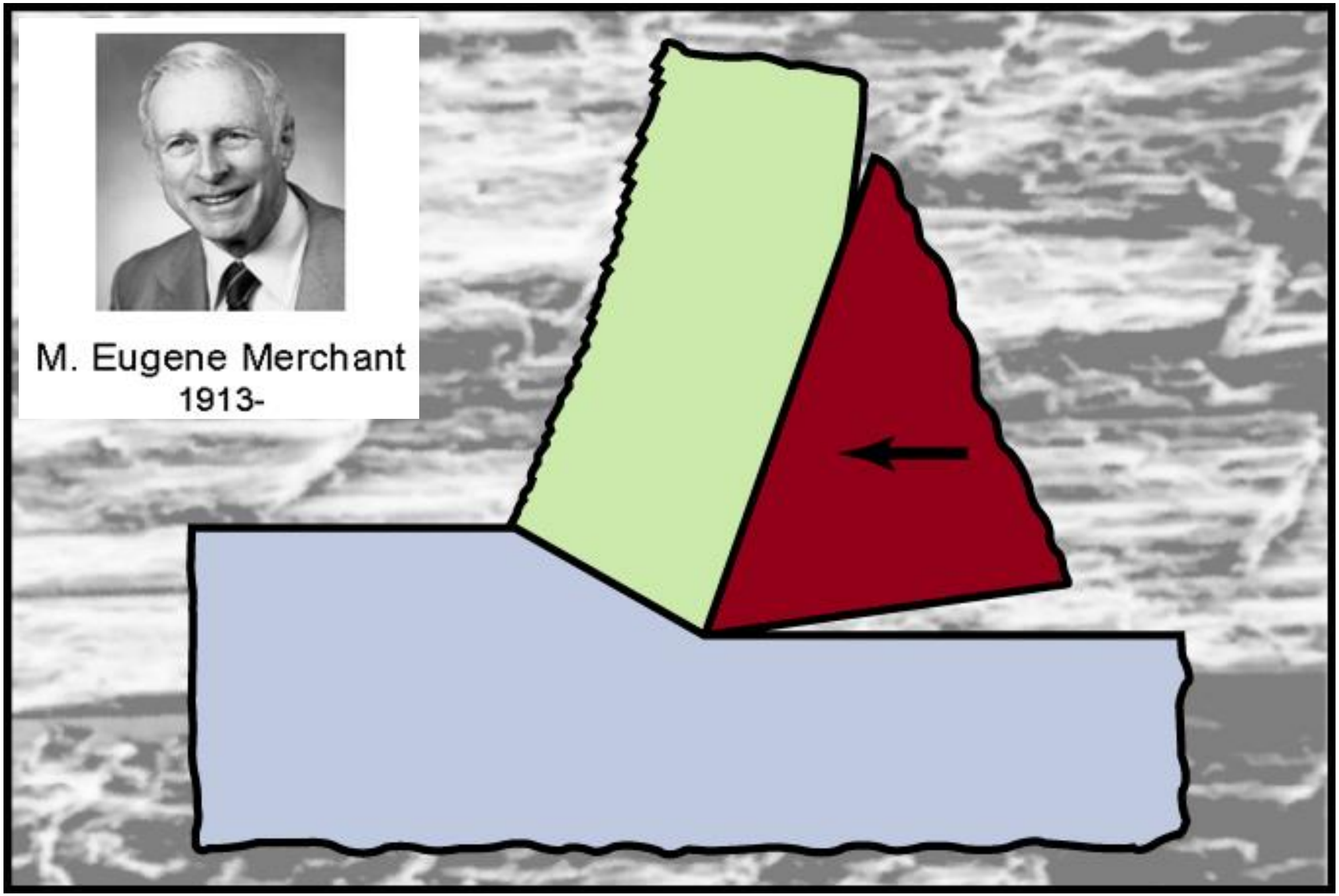
Machining
(Material Removal Processes)
(Metal Cutting)

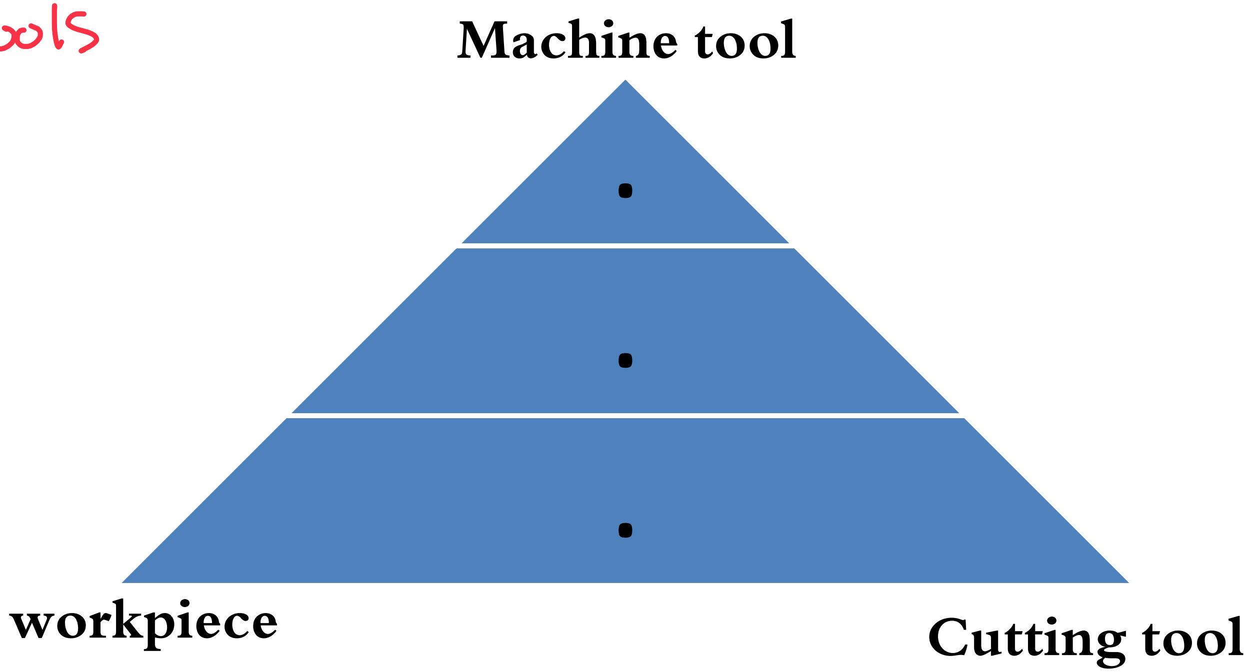
#Notes with Eng. Yara Nasan


M. Eugene Merchant
1913-

Outline

Overview of Machining Technology

can use different machining tools



Fundamentals of Manufacturing - Manufacturing Concepts

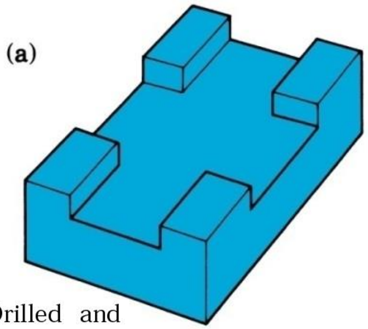
- **Castability**
- **Compactability**
- **Sinterability**
- **Weldability**

- **Formability**
- **Workablity**
- **Forgability**
- **Hardenability**
- **Machinability**

relies on the relative motion and the relative motion depends on the cutting tool's dimensions

Examples of Parts Produced Using the Machining Processes

(a)



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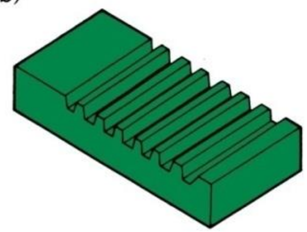

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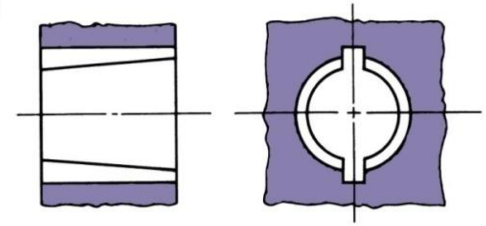

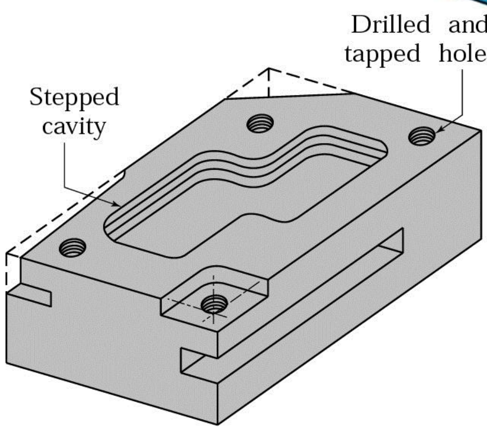

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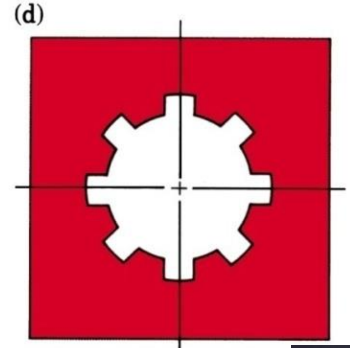

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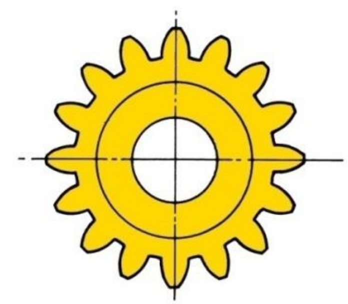


Process of Metal Cutting

- A family of shaping operations, the common feature of which is removal of material from a starting workpart so the remaining part has the desired geometry.
- Metal cutting processes consists in removing a layer of metal from blank to obtain a machine part of the required shape and dimensions and with the specified quality of surface finish.

Material Removal Processes

Material Removal

Chip removal processes

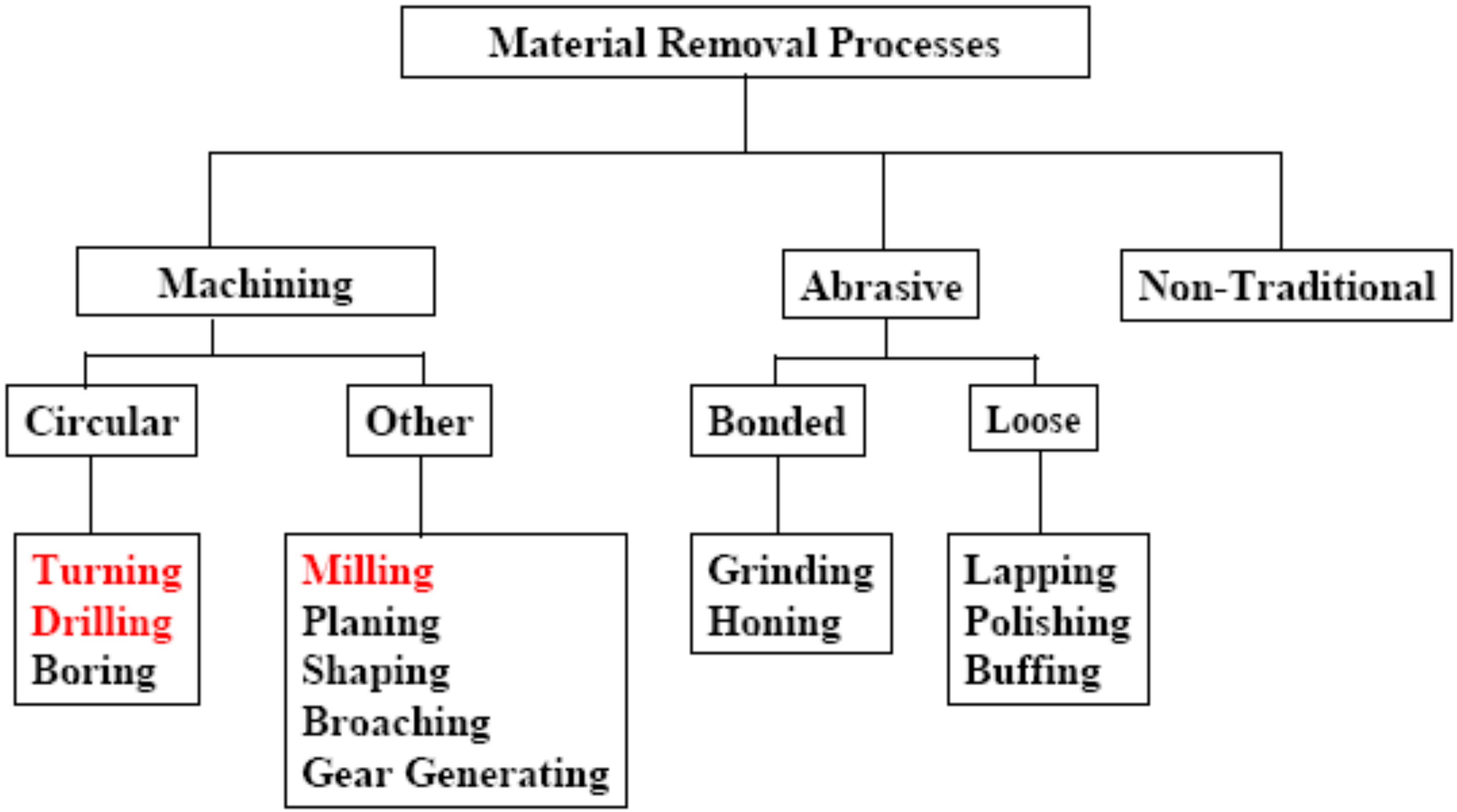
Machining – material removal by a **sharp cutting** tool, e.g., turning, milling, drilling.

Chip removal processes

Abrasive processes – material removal by **hard, abrasive particles**, e.g., grinding.

Chipless processes

Nontraditional processes - various energy forms other than sharp cutting tool to remove material, e.g. electrochemical and thermal energy processes.

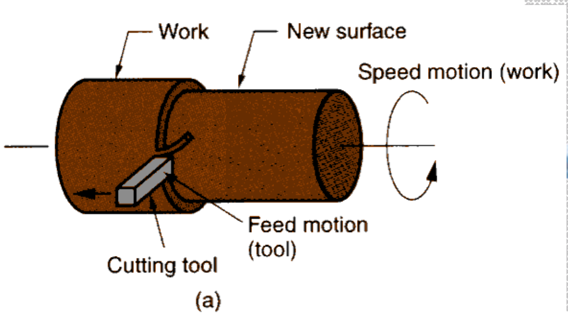

Material Removal Processes
Machining
Abrasive
Non-Traditional
Circular
Other
Bonded
Loose
Turning
Drilling
Boring
Milling
Planing
Shaping
Broaching
Gear Generating
Grinding
Honing
Lapping
Polishing
Buffing

Material Removal Processes

Traditional Chip Removal

- ✓ Turning
- ✓ Milling
- ✓ Drilling
- ✓ Boring
- ✓ Reaming
- ✓ Shaping
- ✓ Sawing
- ✓ Broaching
- ✓ Planing

- Grinding
- Honing
- Lapping



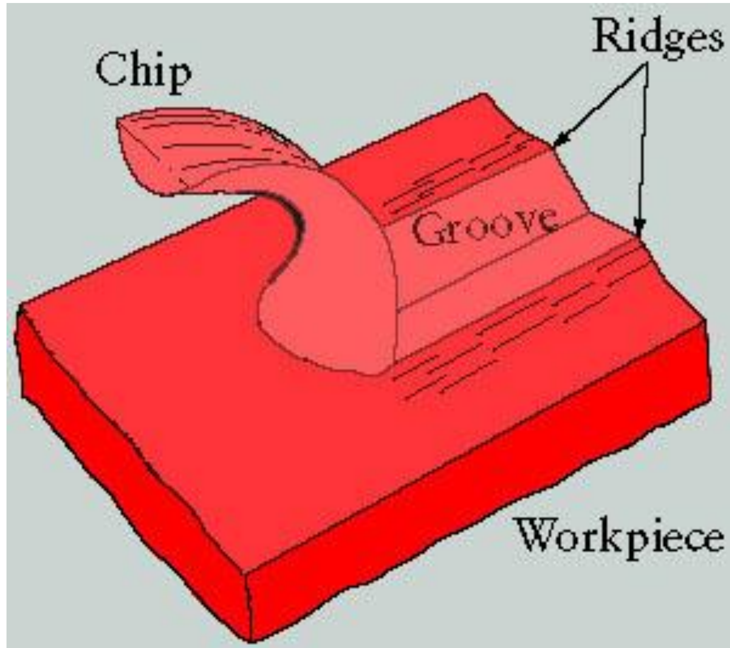
Nontraditional non chipless Machining

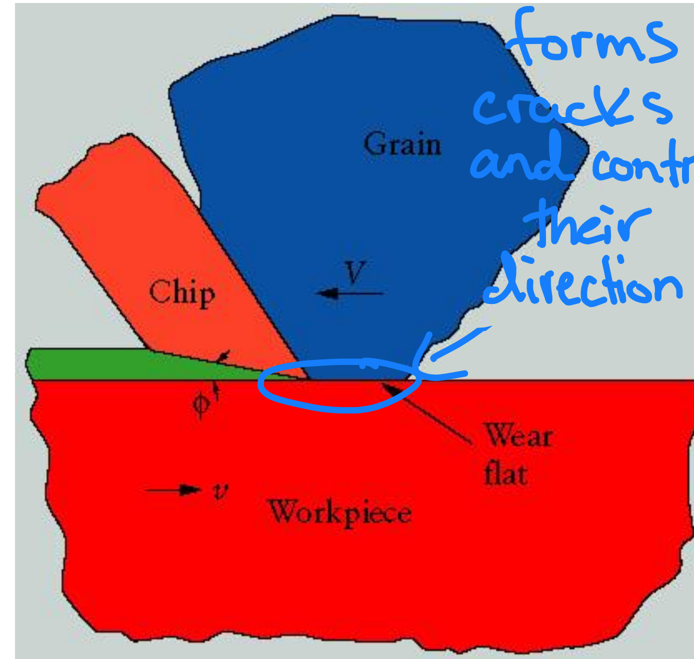
- Ultrasonic
- Electrical Discharge
- Electro-arc
- Optical Lasers
- Electrochemical
- Chem-milling
- Abrasive Jet Cutting
- Electron Beam Machining
- Plasma Arc Machining

Chip removal processes

Traditional cutting processes

(Conventional)



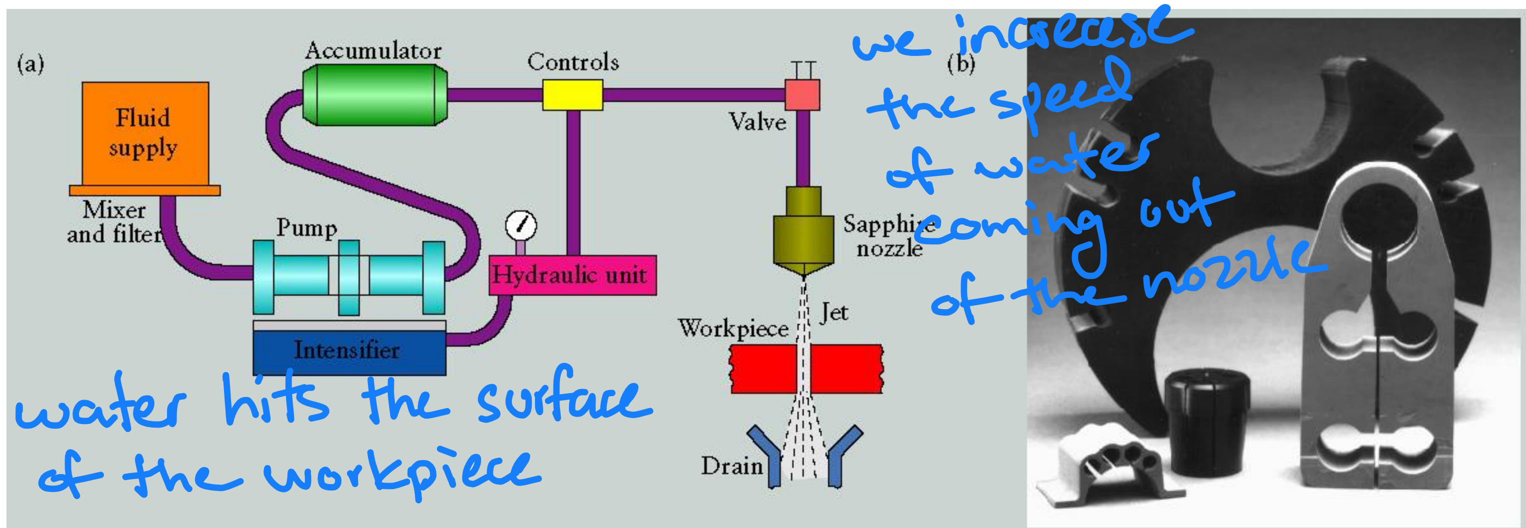


forms cracks and controls their direction

Chipless processes (Non-chip removal processes)

Nontraditional cutting processes

(Conventional)



we increase the speed of water coming out of the nozzle

water hits the surface of the workpiece

↑ water ↑ speed ↑ momentum

when the water hits the surface the speed is reduced to 0

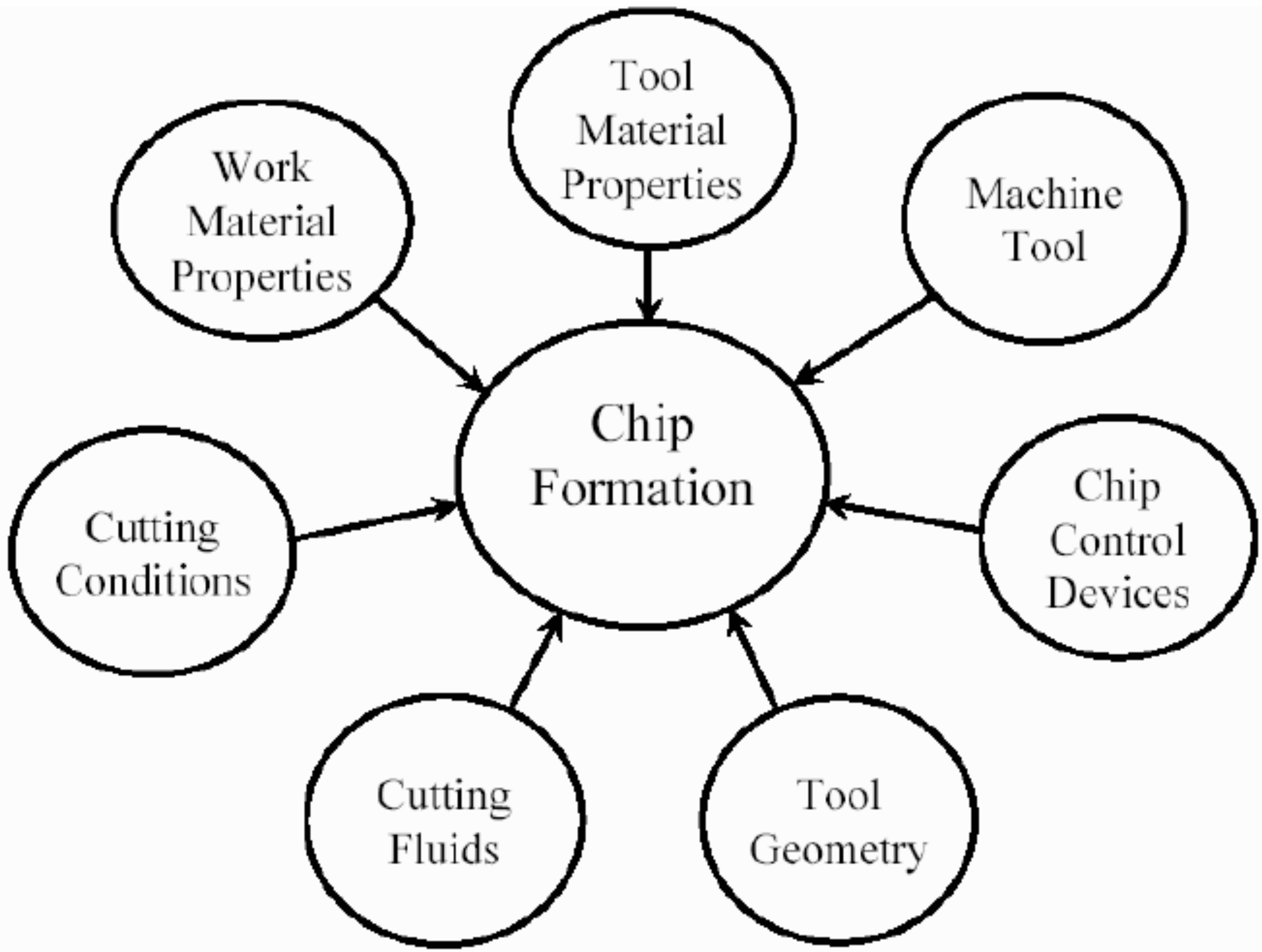
Momentum → impulse force

Machining in Manufacturing Sequence

- Generally performed after other manufacturing processes, such as casting, forging, and bar drawing
  - Other processes create the general shape of the starting workpart.
  - Machining provides the final shape, dimensions, finish, and special geometric details that other processes cannot create

Basic machining variables

Factors Influencing the Chip Formation Process

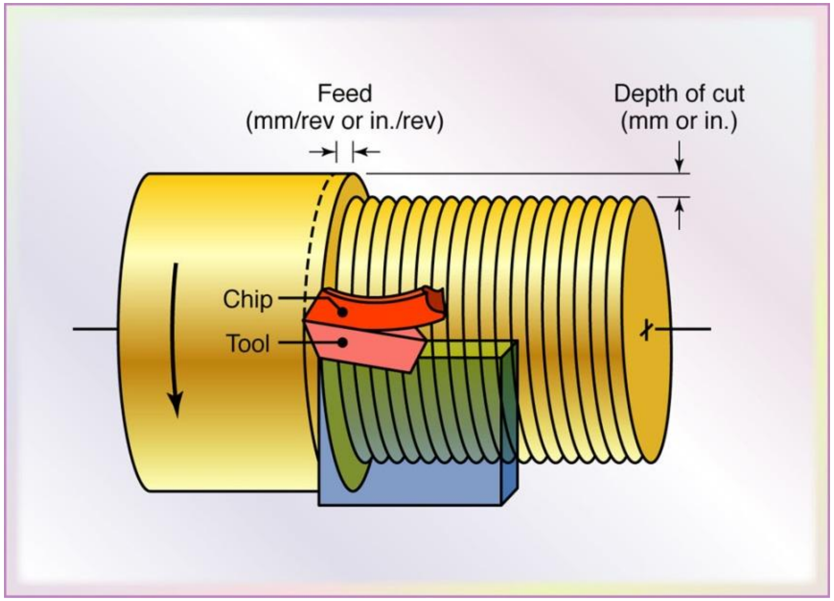


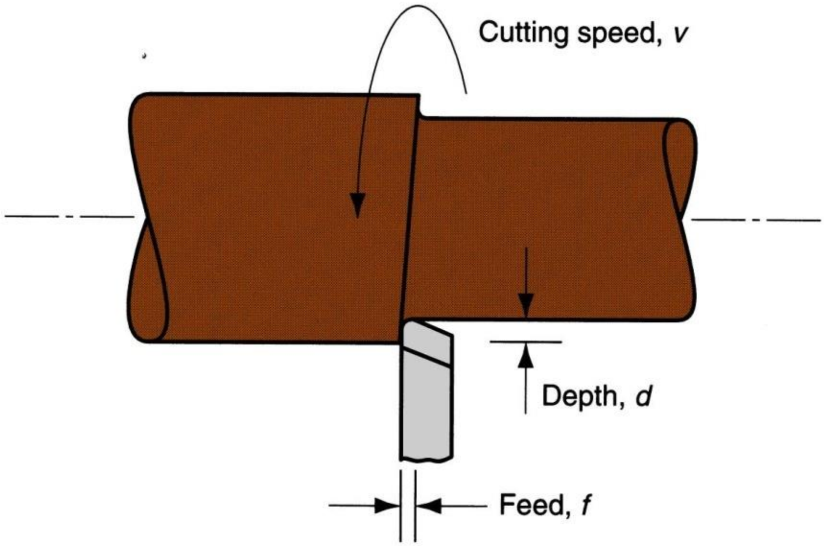
Basic machining variables

✓ **Cutting speed :**

the rate at which the workpiece passes by the cutting edge (m/s or mm/s).

defines as the speed at which the chips are removed from the surface of the workpiece. Often related to the rotational speed of the cutting tool or the workpiece in the form $V=\pi DN$ (where V is the cutting speed, D is the diameter of the tool/workpiece, and N is the rotational speed of the tool/workpiece (rpm).





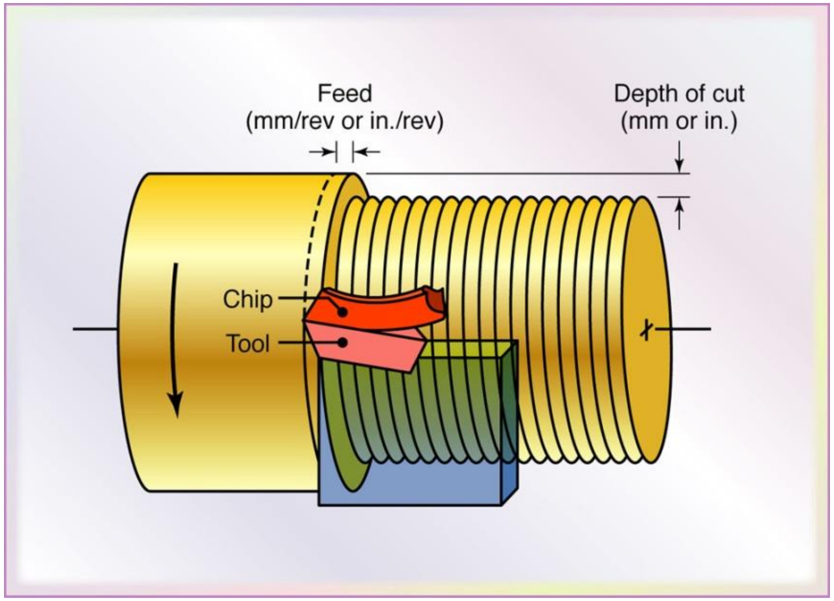
Basic machining variables

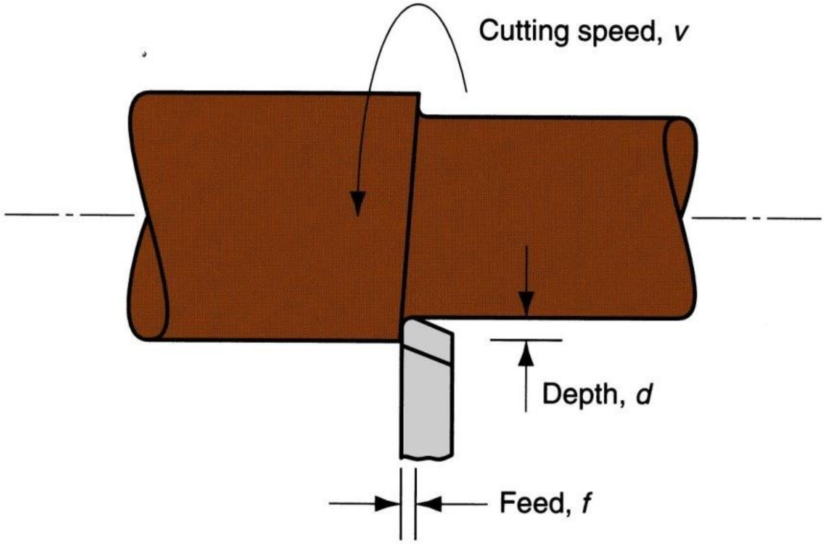
✓ **Cutting feed:**

the rate at which the cutting tool advances into workpiece mm/rev or mm/min

✓ **Depth of cut:**

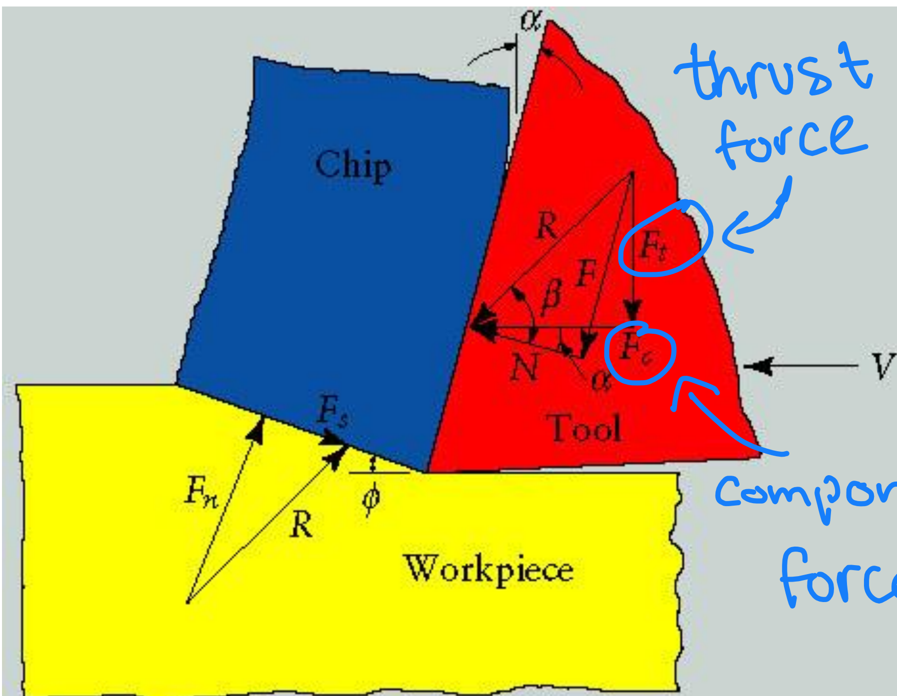
the distance the tool is set into the work.





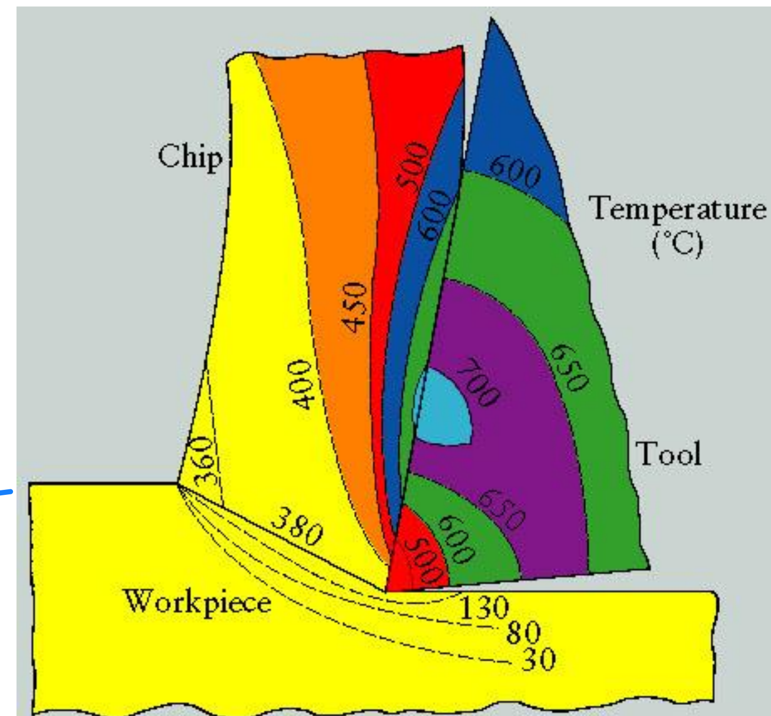
↑ friction ↑ temperatures

Mechanism of metal cutting process



thrust force

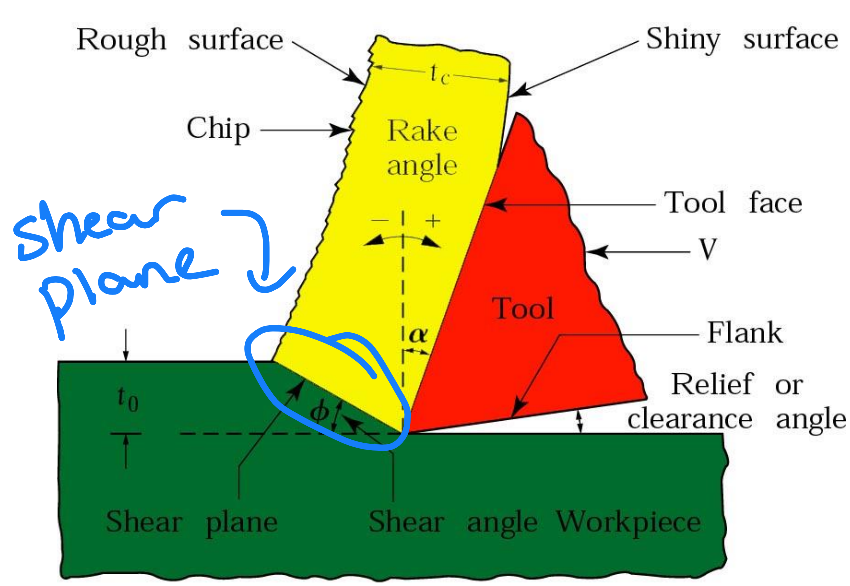
component force

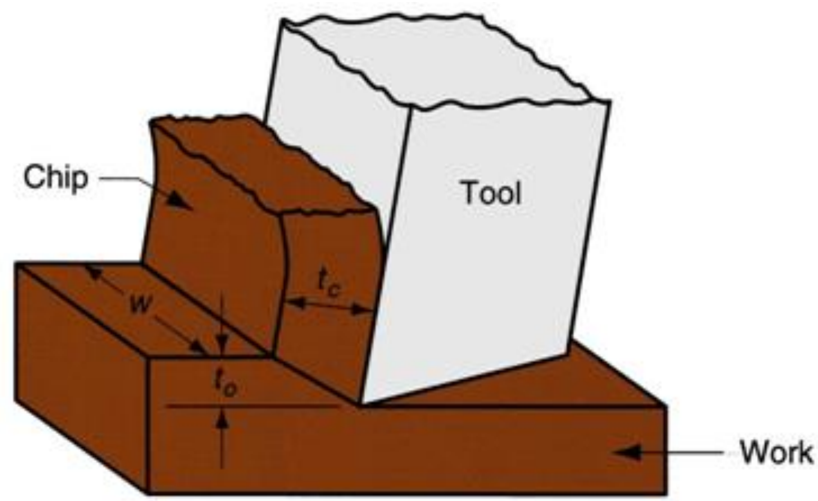


↑ chip thickness ↑ resiliance

Mechanism of metal cutting process

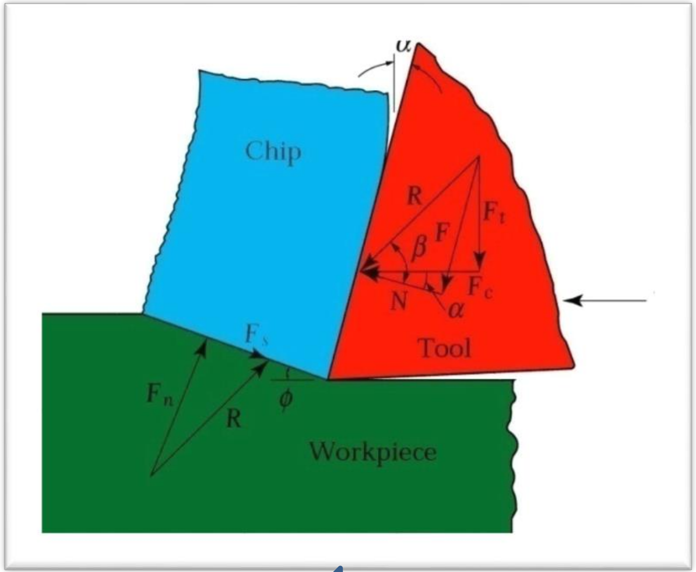
- The cutting tool exerts a compressive force on the workpiece.
- Under this force, the material of the workpiece is stresses beyond its yield point causing the material to deform plastically and shear off.
- The plastic flow takes place in a localized region called shear plane.
- The sheared material begins to flow along the cutting tool face in the form of small piece called chips.

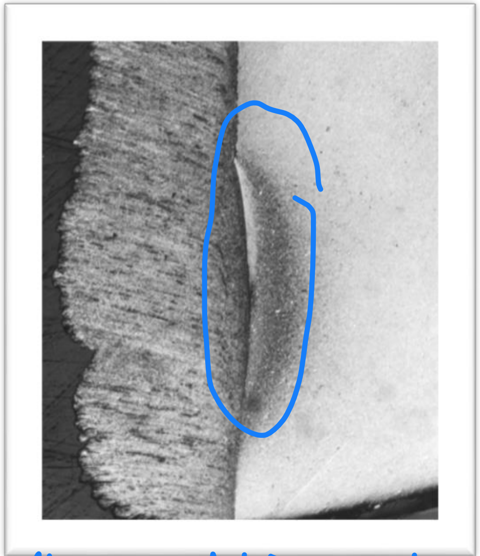




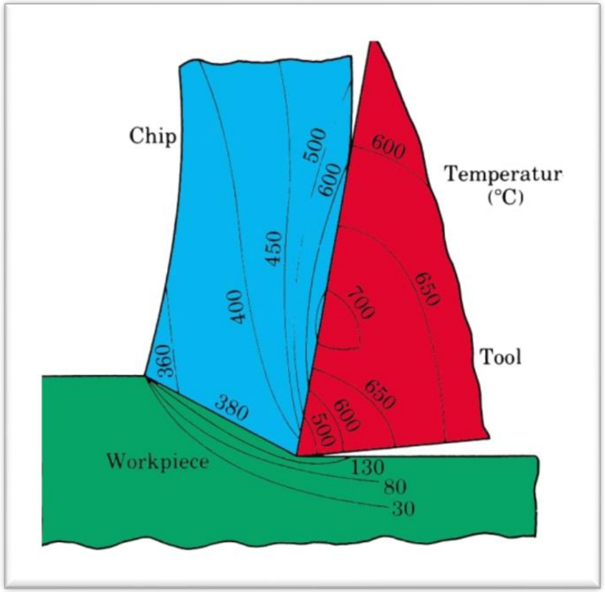
Mechanism of metal cutting process

- The compressive force applied to form the chip is called **cutting force.**
- The flowing chips **cause wear** of the cutting tool.
- Heat is produced during shearing action. The heat generated **raises** the temperature of the **work**, **cutting tool** and the **chips**. The temperature rise in the **cutting tool** tends to **soften** it.
- The **cutting forces**, **heat**, **wear** are the basic feature of the cutting process





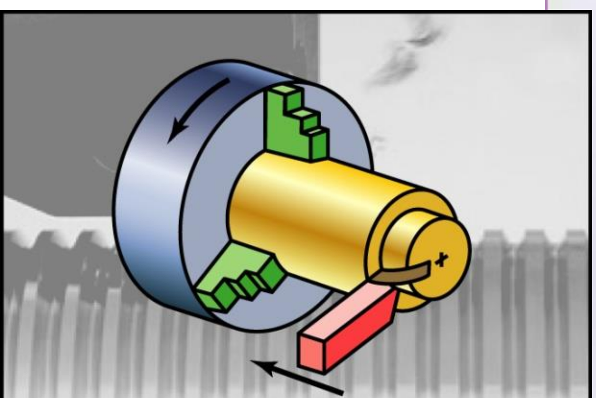
the cutting tool



is broken

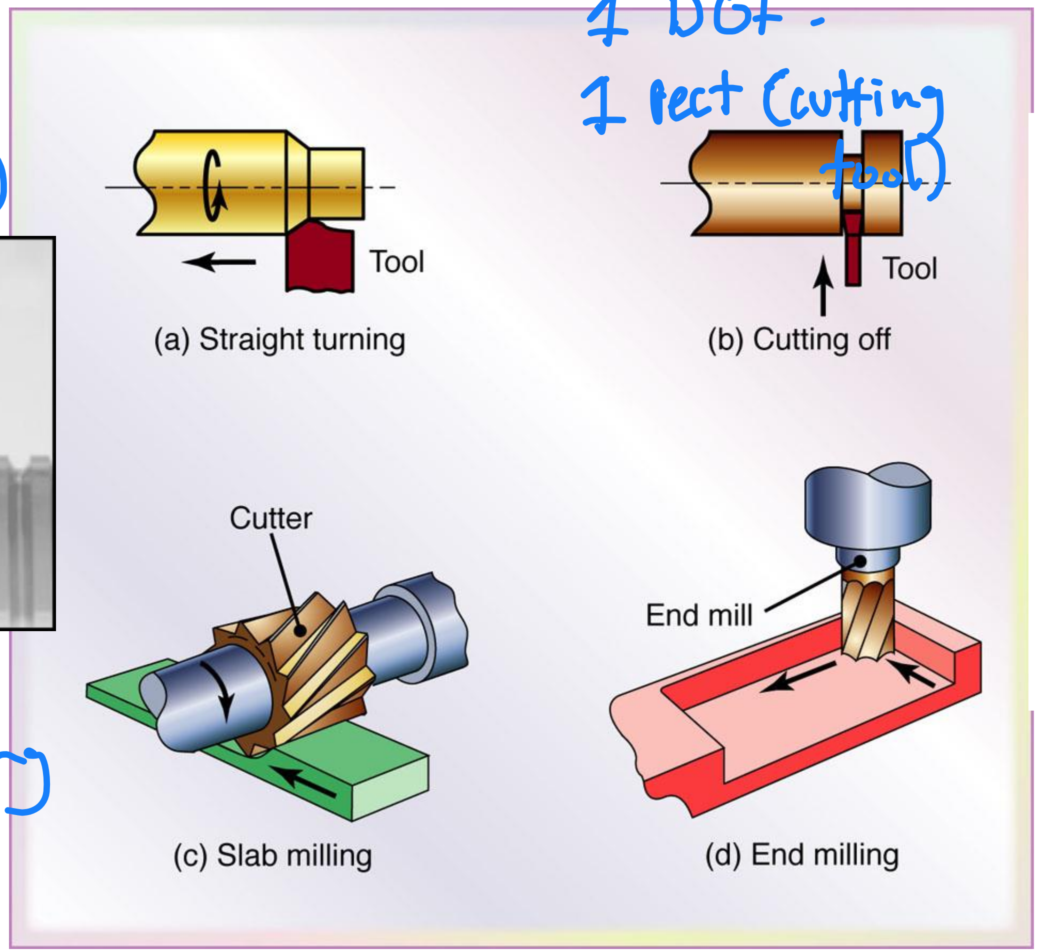
Machining Operations

2 DOF:
1 rotational (wm)
1 rect (cutting tool)

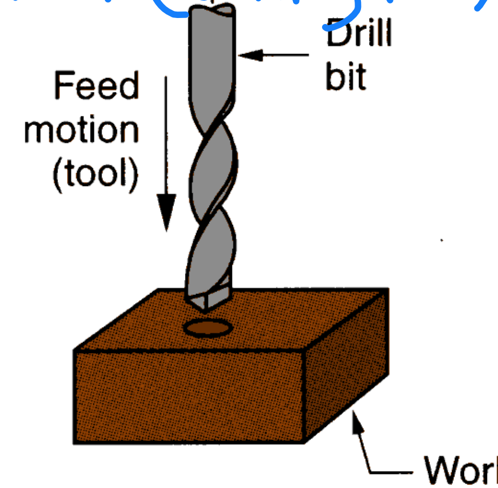


2 DOF:
1 rotational (cutting tool)
1 rect (wm)

1 DOF:
1 rect (cutting tool)



2 DOF:
1 rotational and 1 rect (cutting tool)



(b)

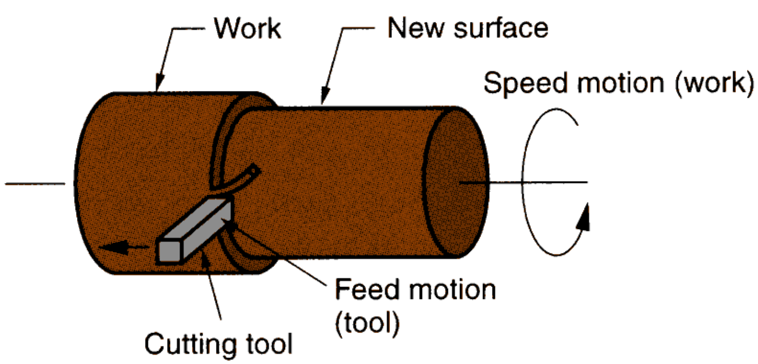
3 DOF:
1 rotational
2 rect (cutting tool)

Metal Cutting Operation Classifications

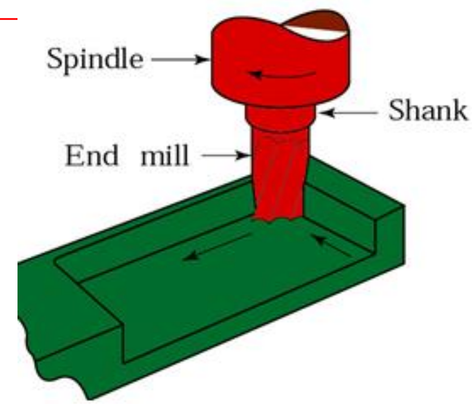
According to the Kinematics of the operation we can produce

✓Flat surfaces

✓Internal and External cylindrical and curved surfaces



(a)



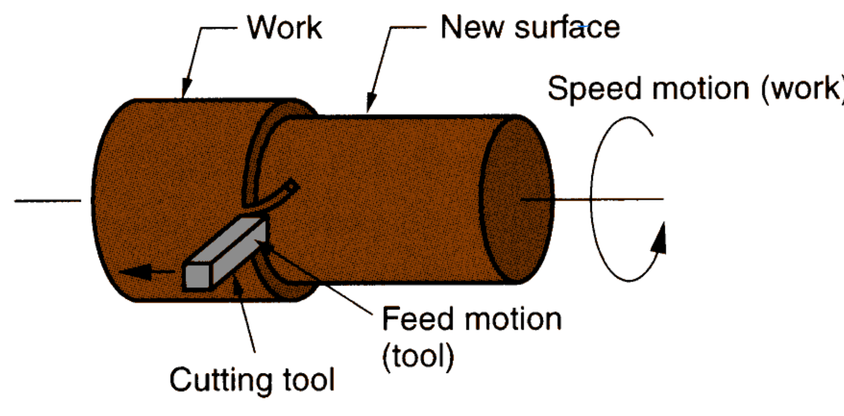
- Rotational - cylindrical or disk-like shape
- Nonrotational (also called prismatic) - block-like or plate-like

Machining Operations

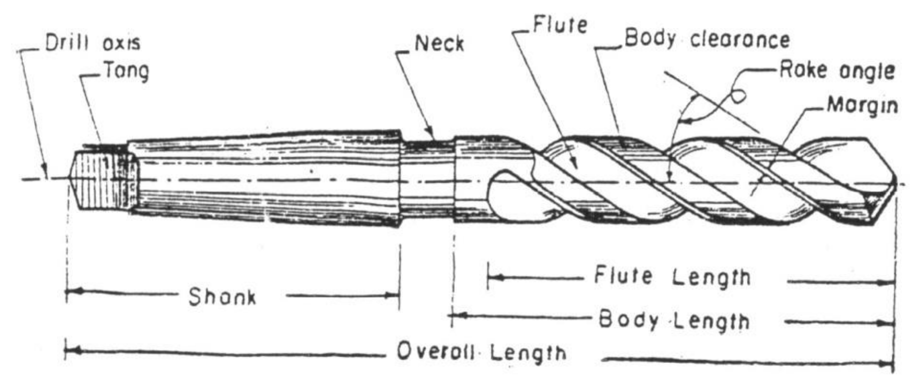
- Most important machining operations:
  - Turning
  - Drilling
  - Milling
- Other machining operations:
  - Shaping and planing
  - Broaching
  - Sawing

Cutting Tool Classification

1. Single-Point Tools
   - One dominant cutting edge
   - Point is usually rounded to form a nose radius
   - Turning uses single point tools
2. Multiple Cutting Edge Tools
   - More than one cutting edge
   - Motion relative to work achieved by rotating
   - Drilling and milling use rotating multiple cutting edge tools



(a)

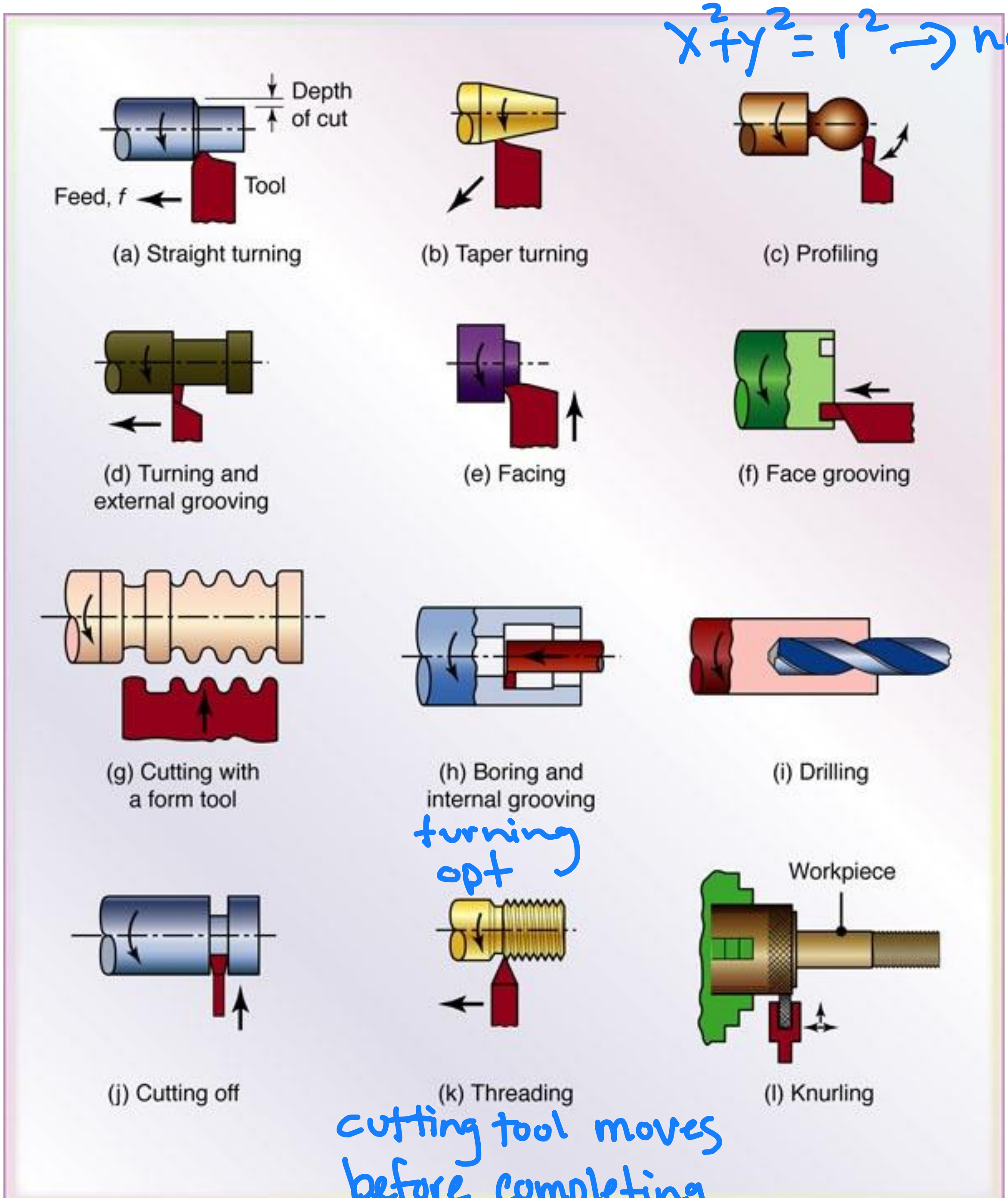


In order to create an edge two planes must intersect at a point

taper turning : 1 rotational (wm)
2 rect (cutting tool)
x, y → linear relationship

$x^2+y^2=r^2 \rightarrow$ non-linear

Lath operations



turning opt

cutting tool moves before completing a rev unlike straight turning

Internal and External cylindrical and curved surfaces

The final shape of the product depends on :

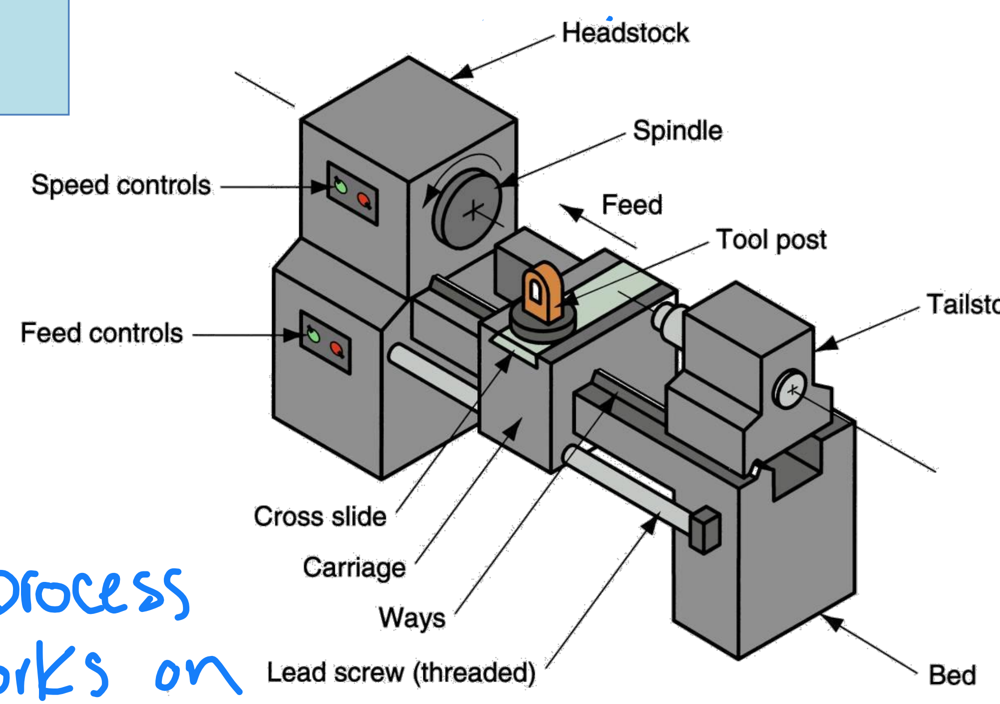
1- Relative motion between the wm and ctm

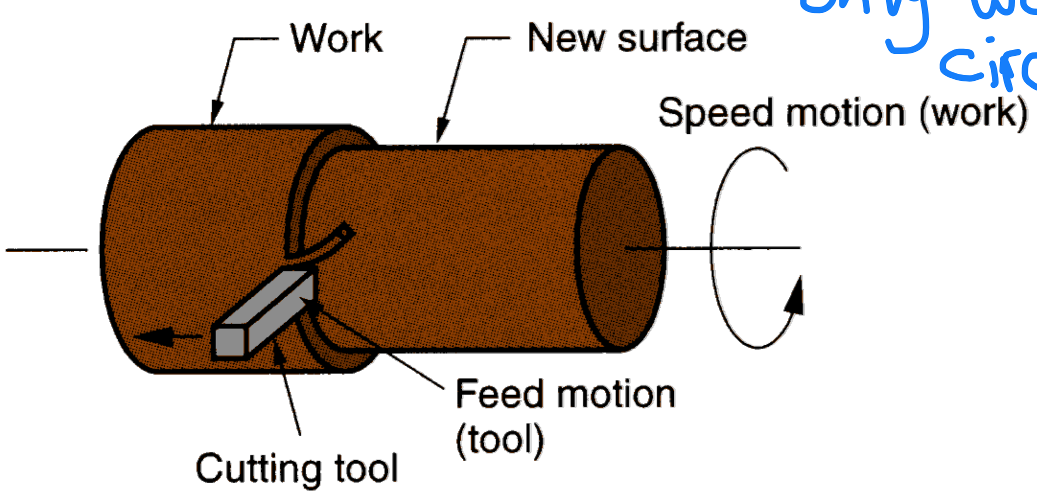
2- Kinematics of the system

Turning

Single point cutting tool removes material from a rotating workpiece to form a cylindrical shape

turning process only works on circumferences

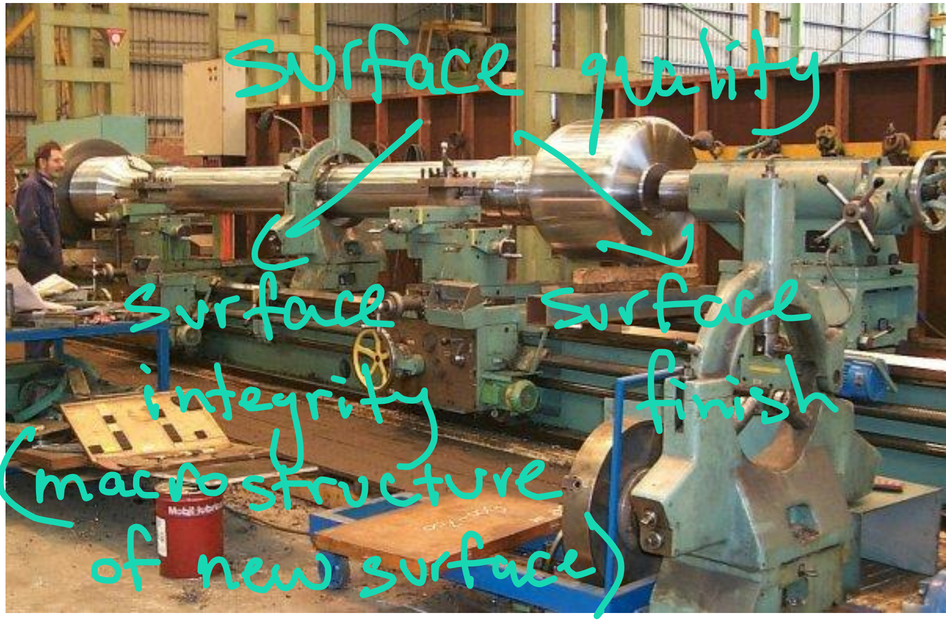




(a)

Depends on final dimensional accuracy and surface quality of the new surface

Big "Engine" Lathe



Surface quality

surface integrity (macrostructure of new surface)

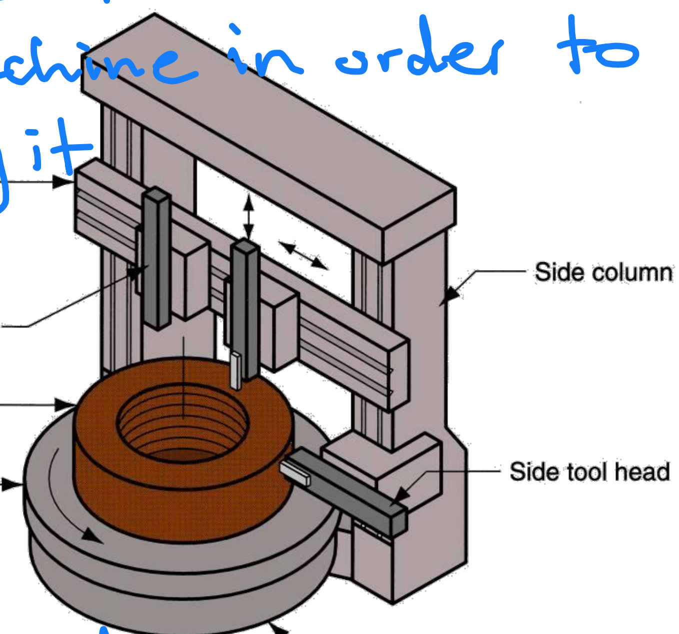
surface finish

Boring

- Internal turning operation which is performed on the inside diameter of an existing hole (Turning is performed on the outside diameter of an existing cylinder)

Spindle must be attached to the base of the machine in order to prevent deflecting it for heavy work-parts

If deflection were to happen it will happen to the entire system and will not affect the relative motion

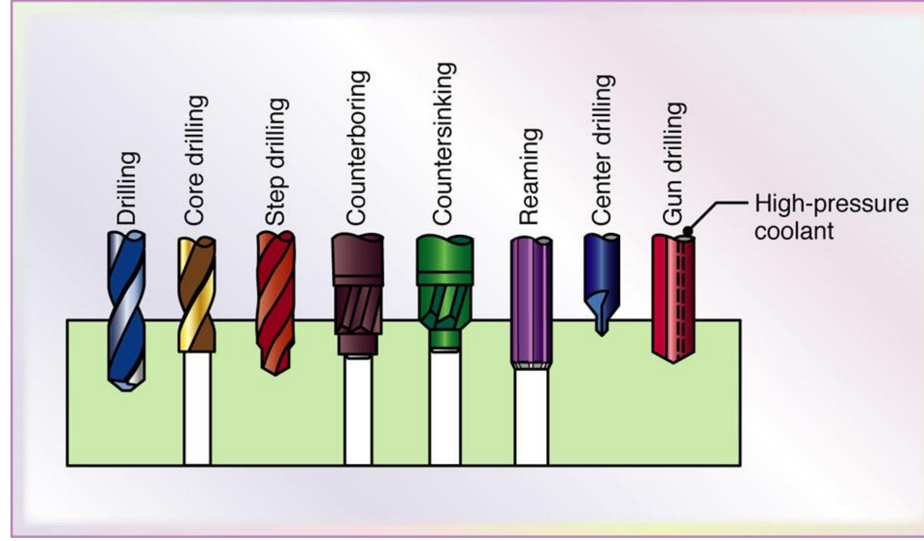


A vertical boring mill – for large, heavy workparts.

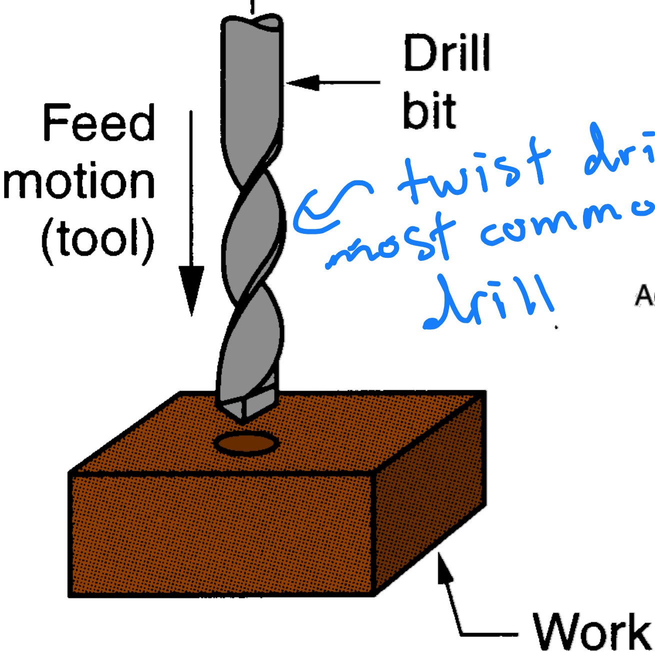
Boring!

Drilling

- Used to create a round hole, usually by means of a rotating tool with two cutting edges

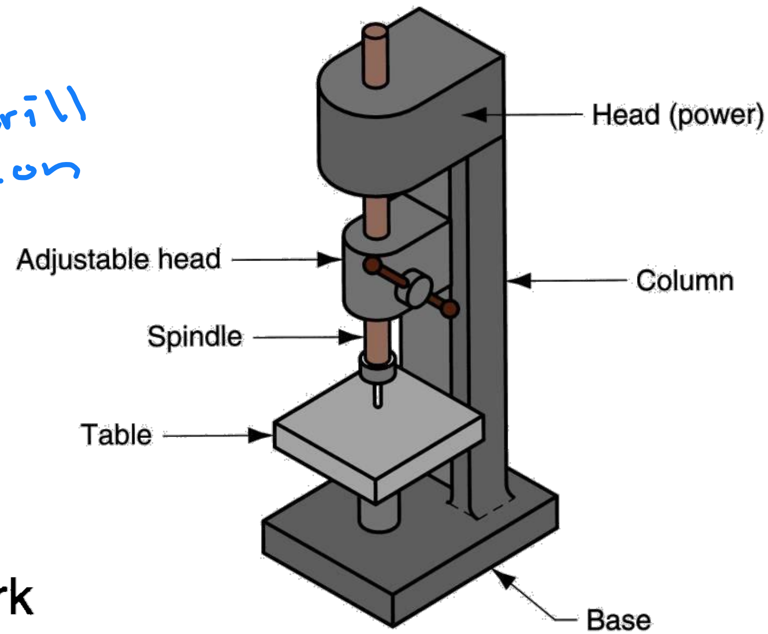


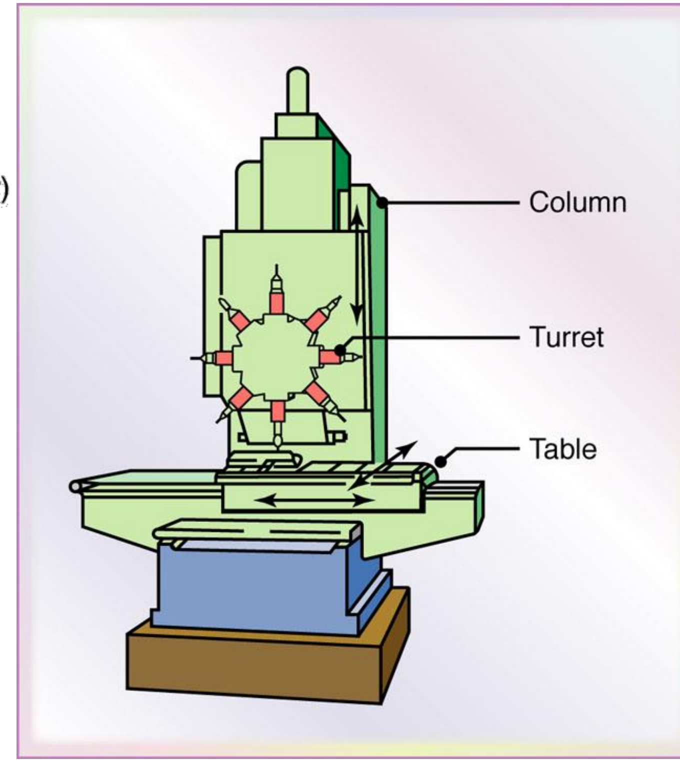
most common material associated with the twist drill is the HSS



twist drill most common drill

(b)

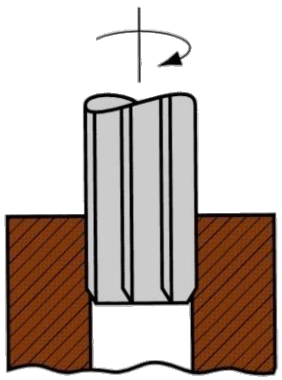




Turret: changes the active drills that are connected with the power unit

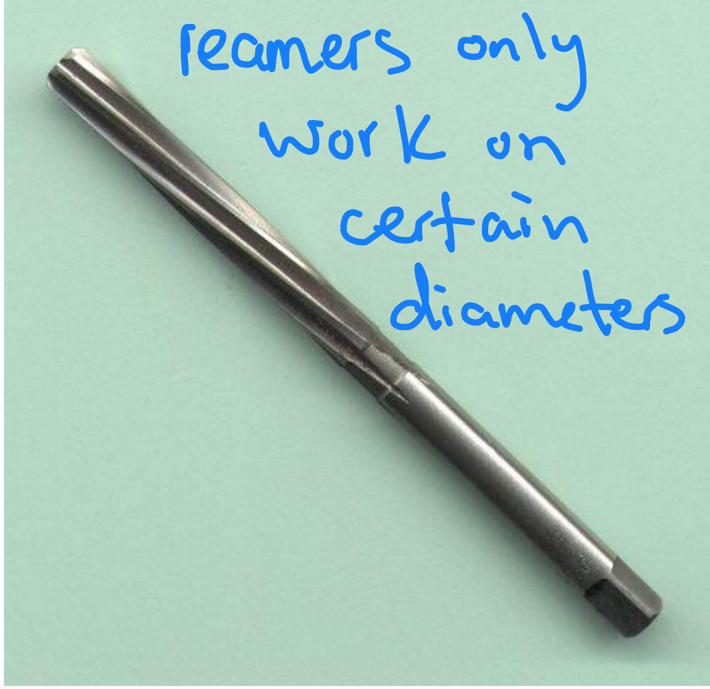
Reaming

- Used to slightly enlarge a hole, provide better tolerance on diameter, and improve surface finish. and increase dimentional accuracy of the hole



(a)

Reaming is Machining operations related to drilling

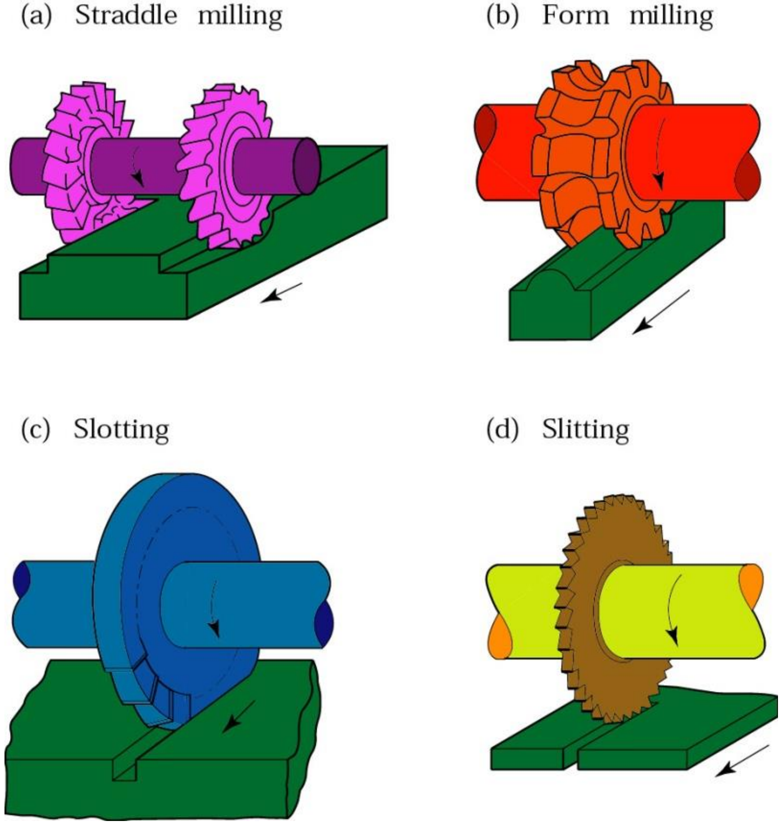


reamers only work on certain diameters

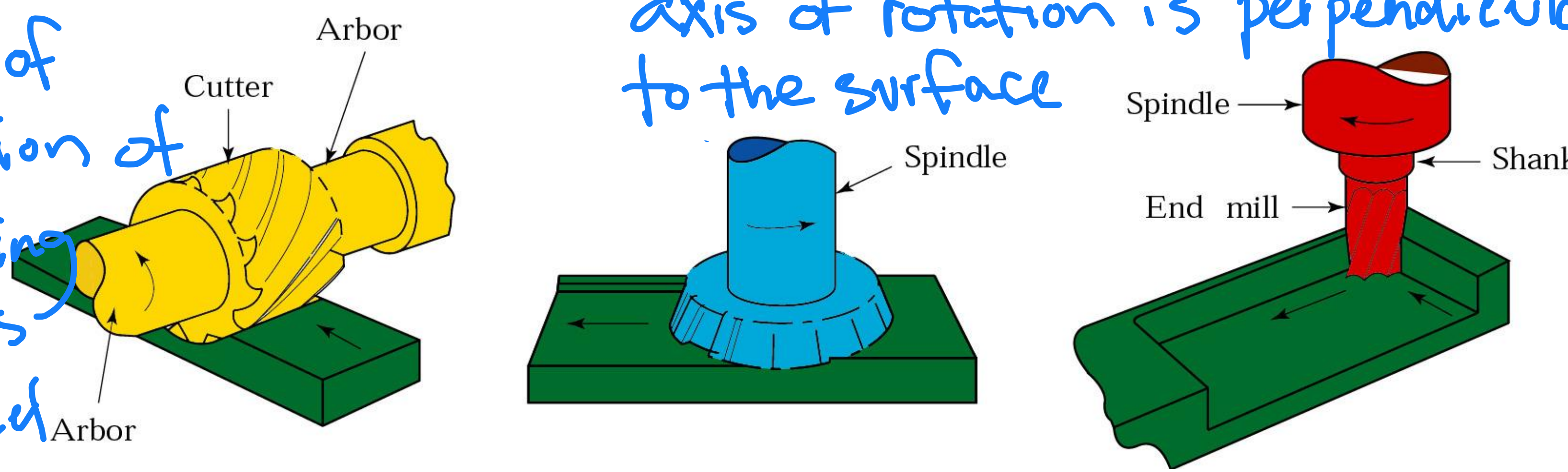
Milling operations

ما منشتغل على محيط

بينما الـ turning
لازم تشتغل عليه
سواء كان ext or int
circf



(a) Slab milling
(b) Face milling
(c) End milling

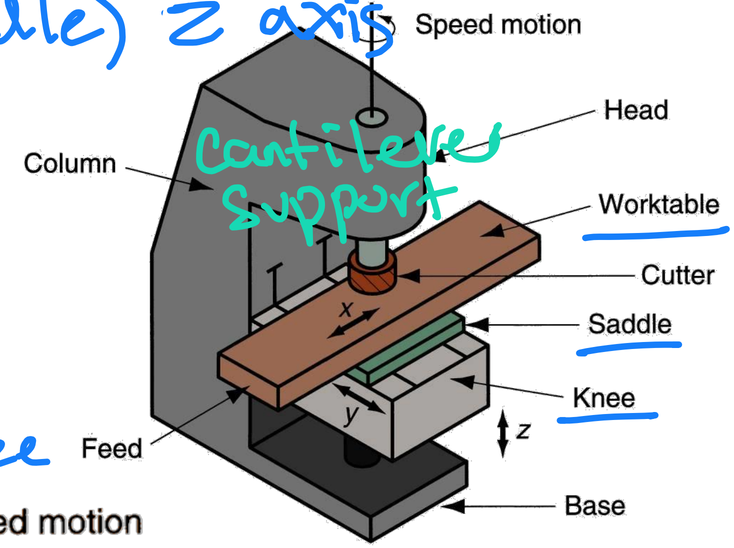


axis of rotation of cutting tool is parallel to the workpiece surface

axis of rotation is perpendicular to the surface

Milling

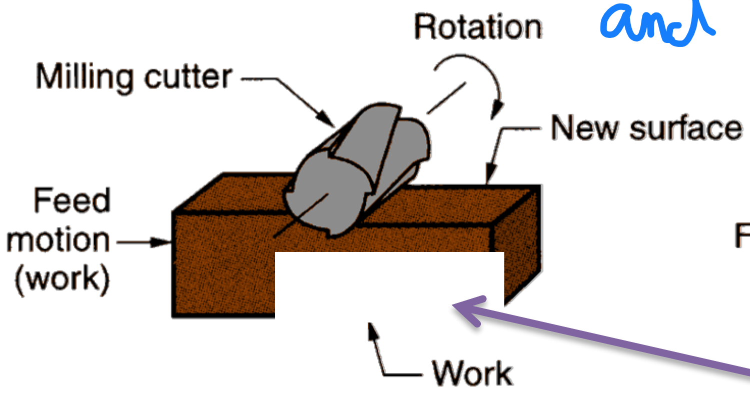
4 DOF: 1 rotational (spindle) z axis
3 rect: x, y, z



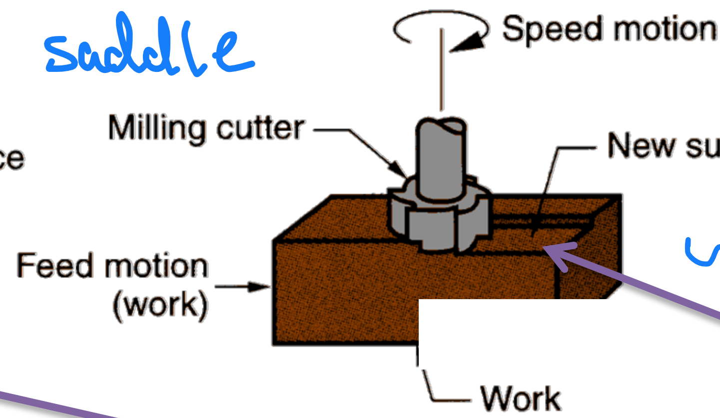
(b)

Rotating multiple-cutting-edge tool

the direction of the worktable is perpendicular to the motion of the knee and saddle



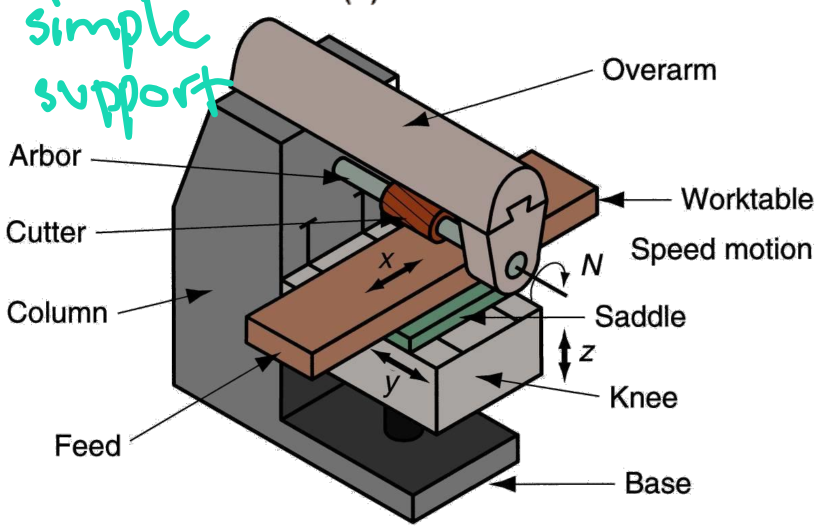
(c)



(d)

slab milling: width of the wp is greater

simple support



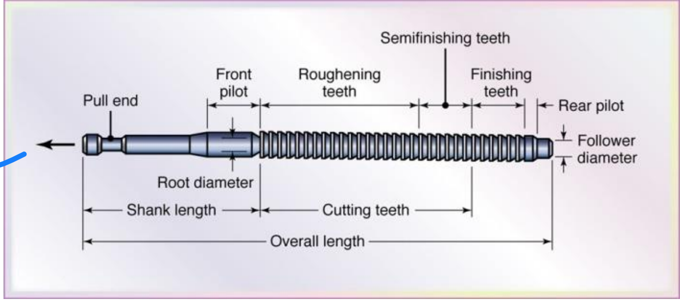
(a)

Two forms: peripheral milling and face milling

peripheral milling (Axis of the tool is parallel to the surface), and face milling (axis of the tool is perpendicular to the surface).

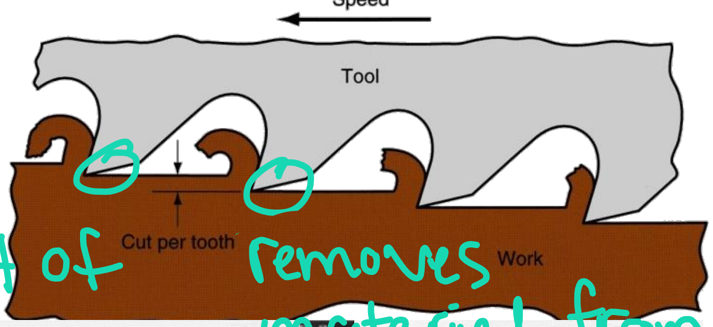
Broaching

we add a certain feature to a hole



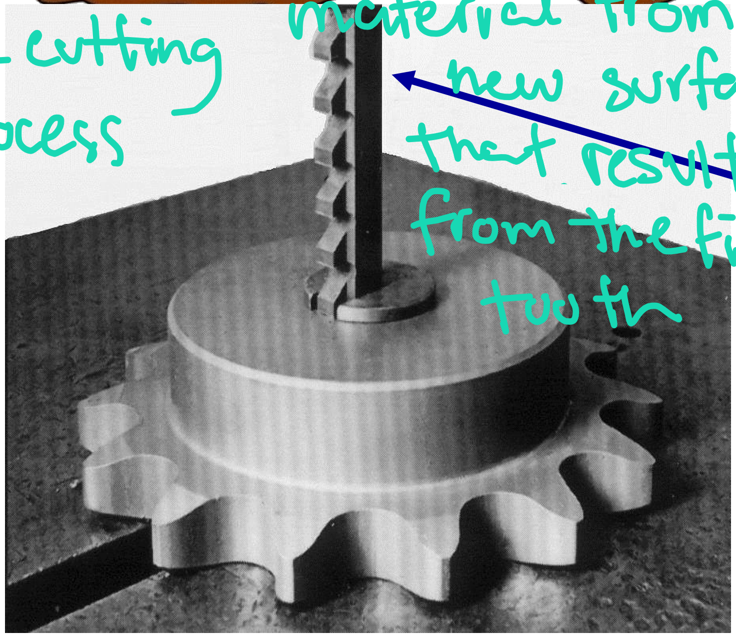
This process is performed using a multiple tooth cutting tool. The tool is moved linearly relative to the work.

depth of penetration of 1st tooth > depth of penetration of 2nd tooth

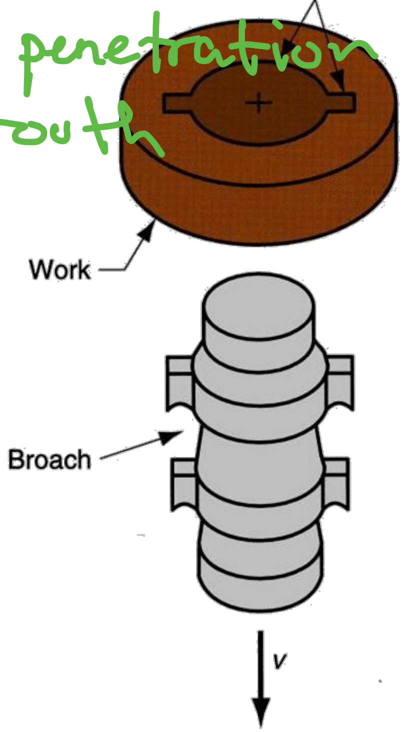


Start of the cutting process

removes material from the new surface that resulted from the first tooth



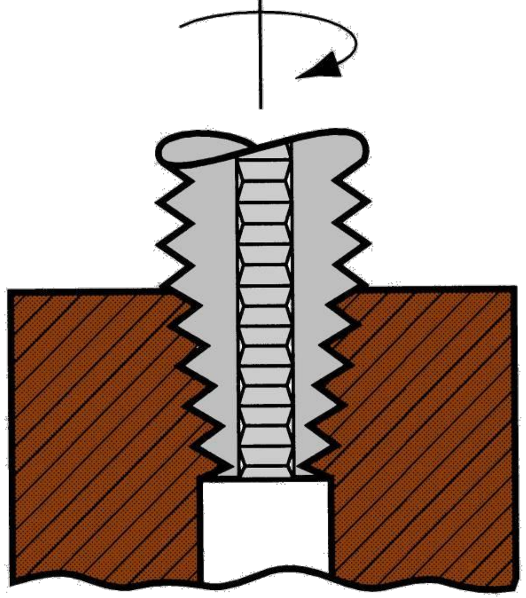
Broaching operation.
The tool is called a *broach*. The machine is called the *broaching machine*.

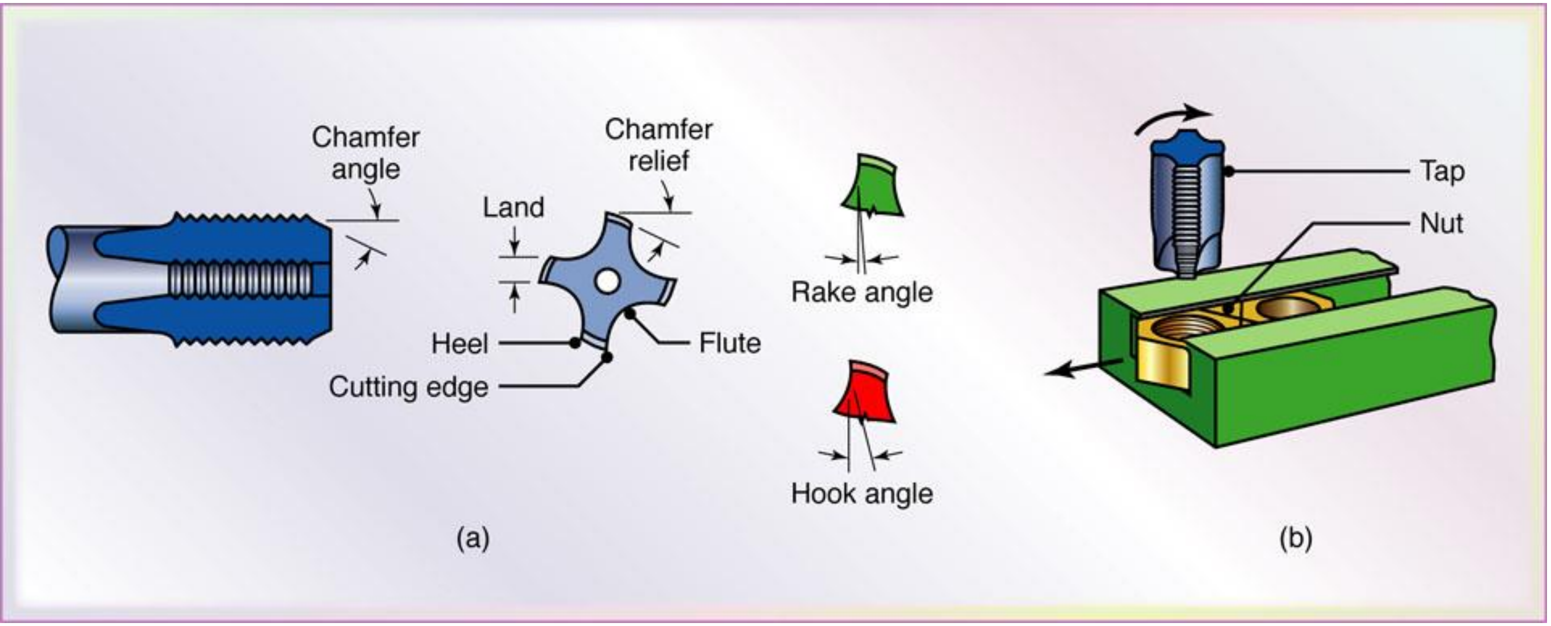


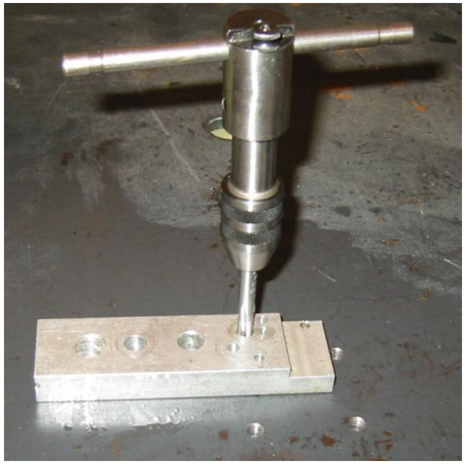
rough cutting and surface finish happen in one pass

Tapping

Used to provide internal screw threads on an existing hole





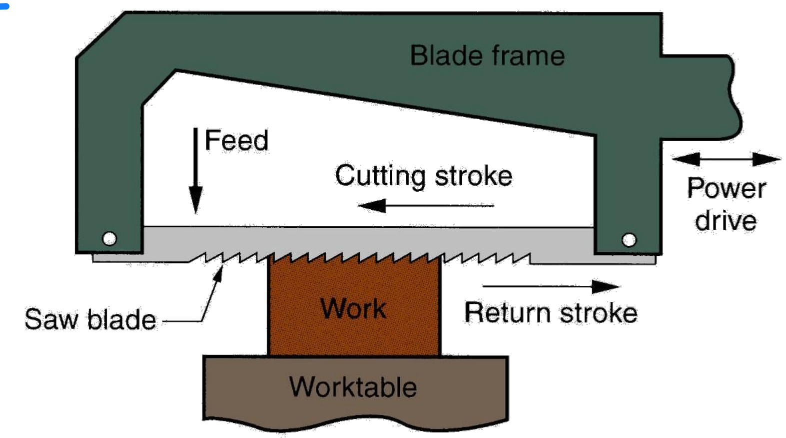


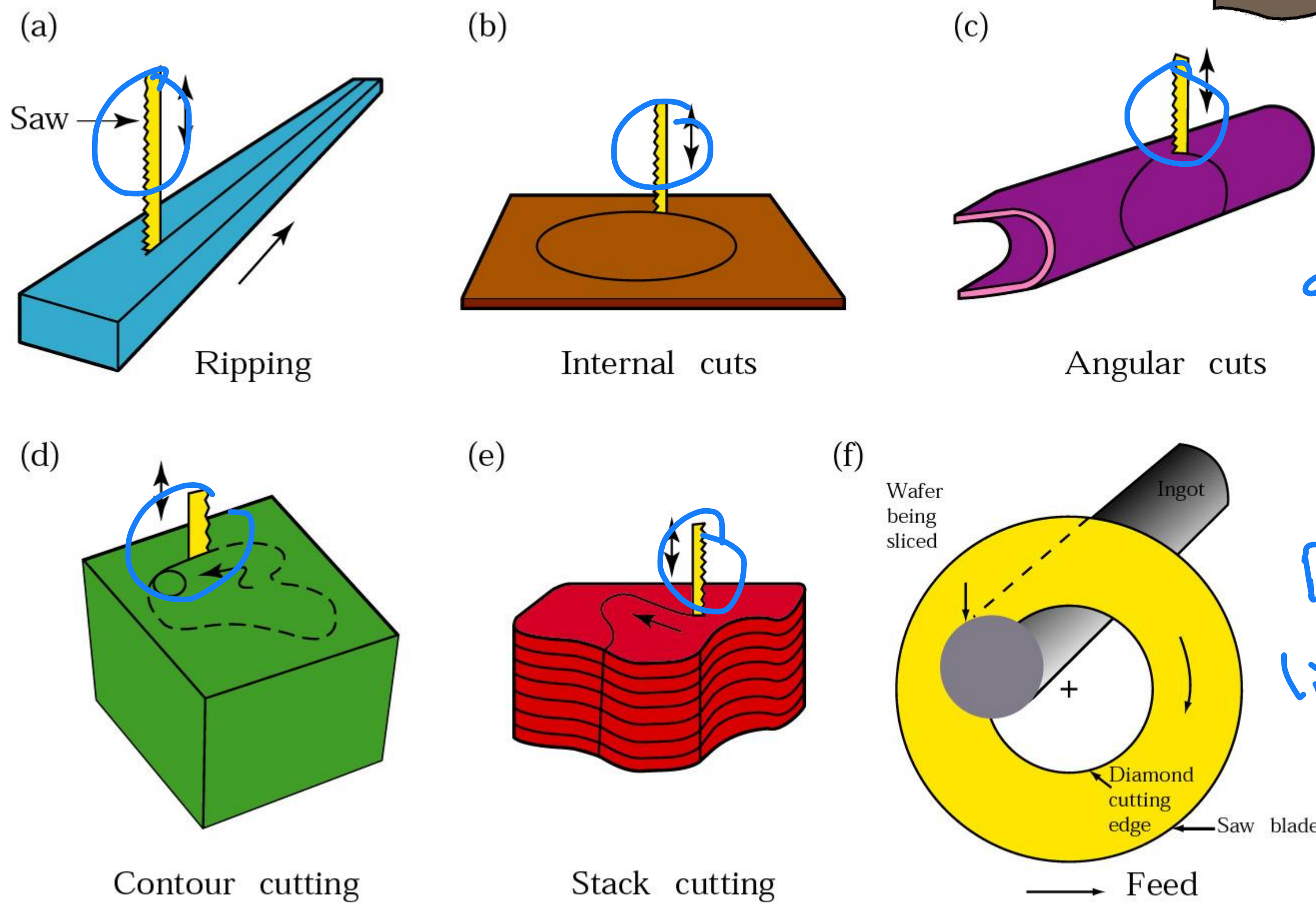
Sawing Operations

linear cuts

most important : Hack saw type of saw

cuts large bulky materials





(a)

band saw is flexible

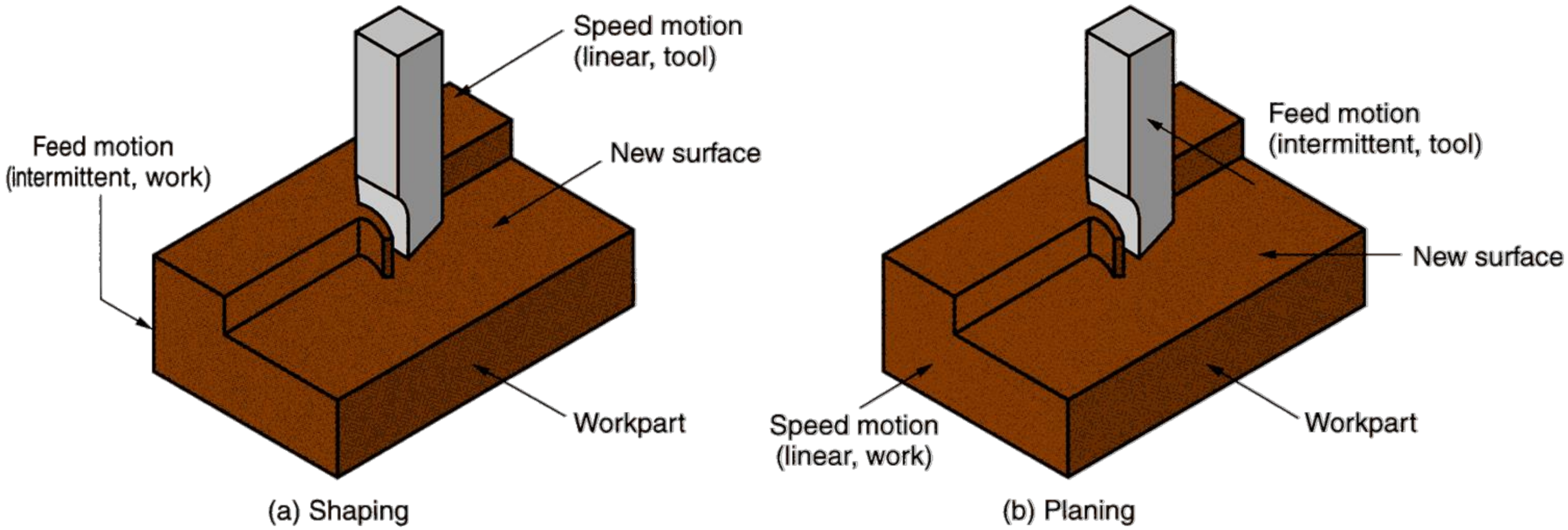
allows linear or non-linear cuts

Disk saw

linear cuts

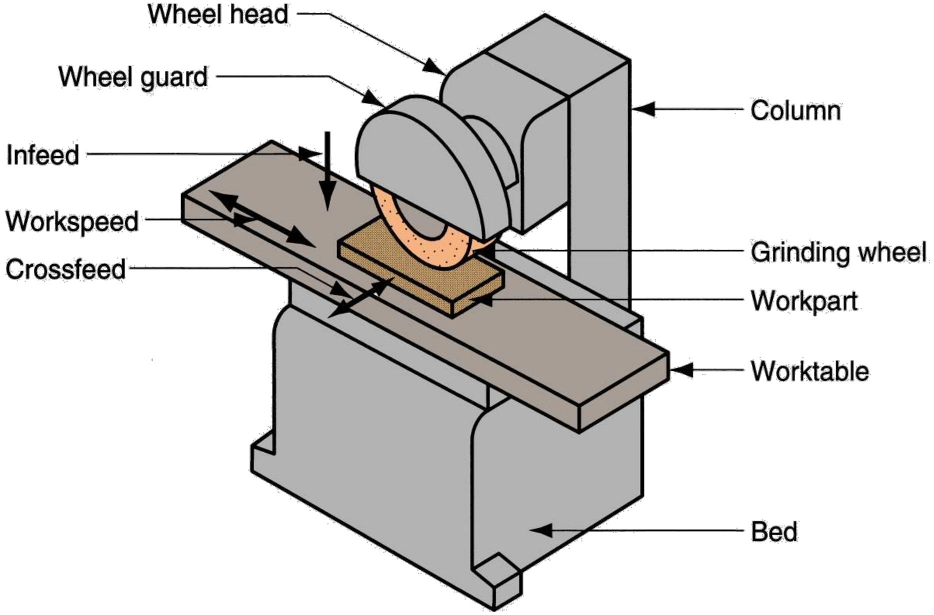
Shaping & Planing

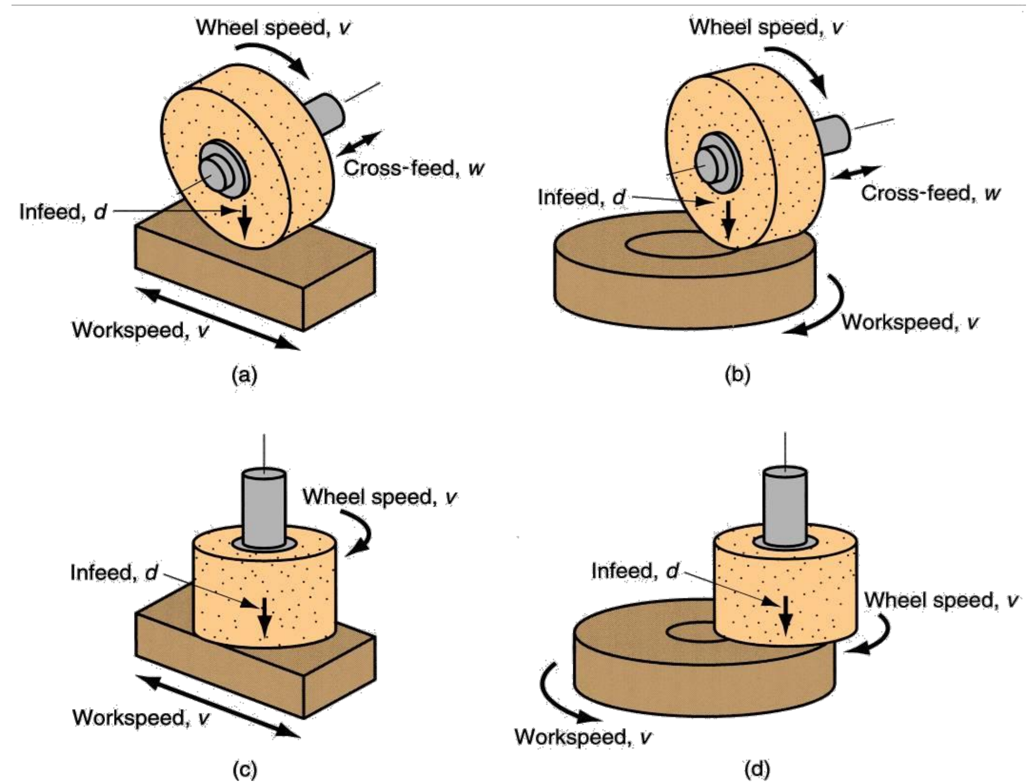
- **Shaping:** Tool has a linear speed motion. Work has occasional feed motion.
- **Planing:** Work has a linear speed motion. Tool has occasional feed motion.

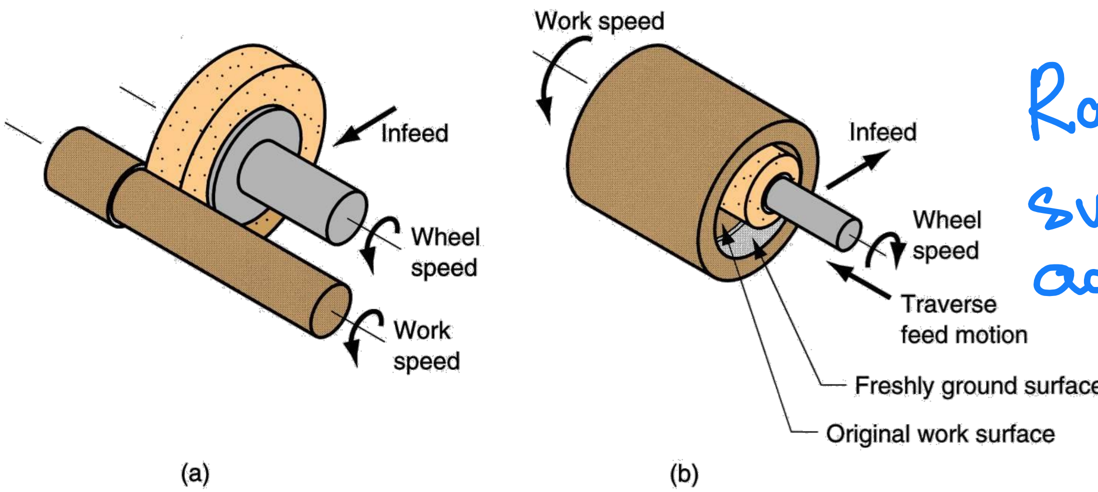


(a) Shaping (, and (b) planing.

Grinding

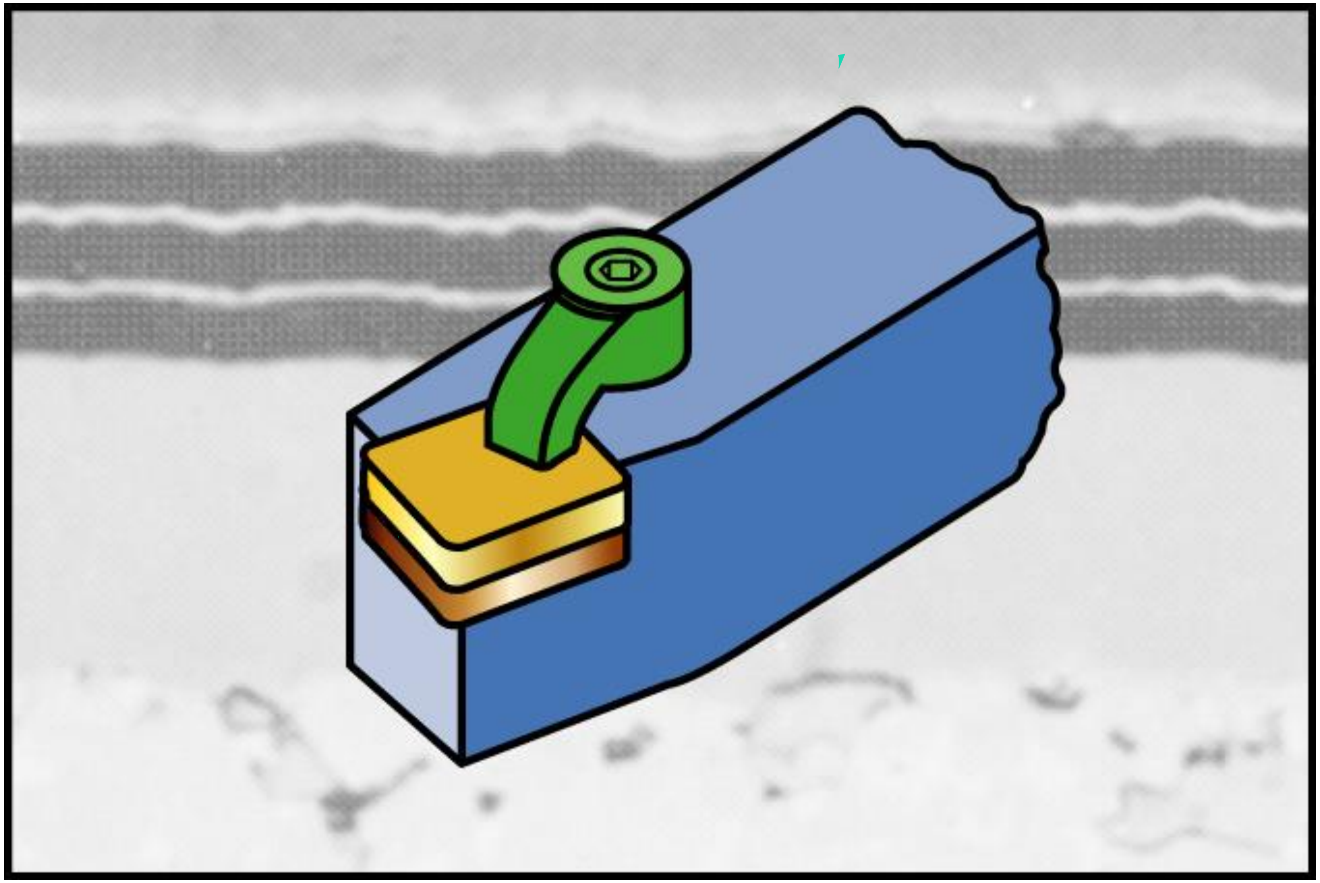




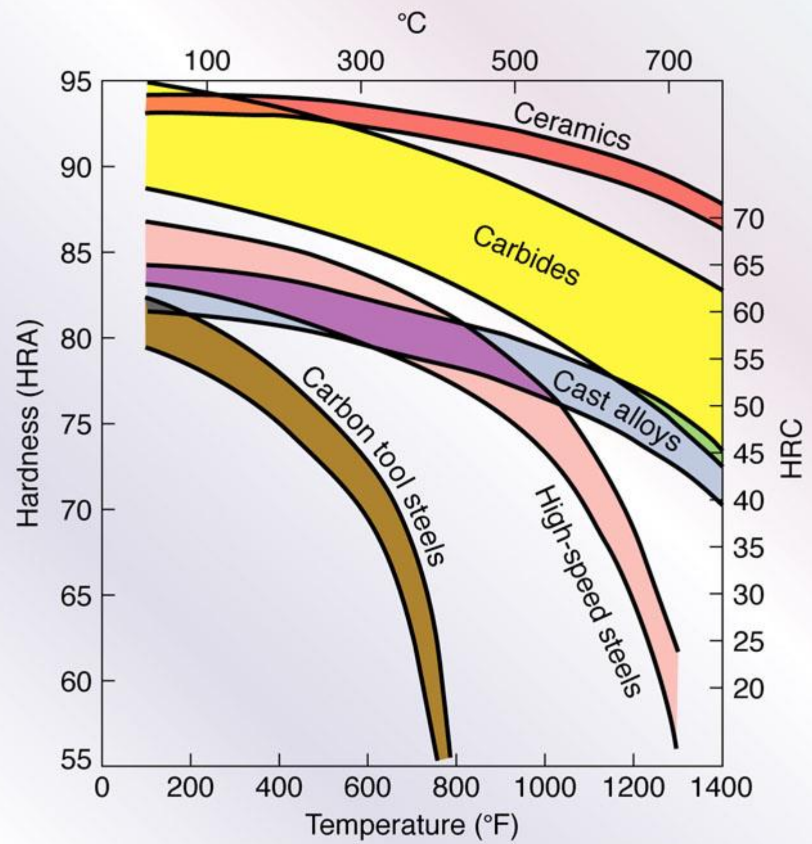


Rough cutting or improving surface finish can be accomplished with grinding

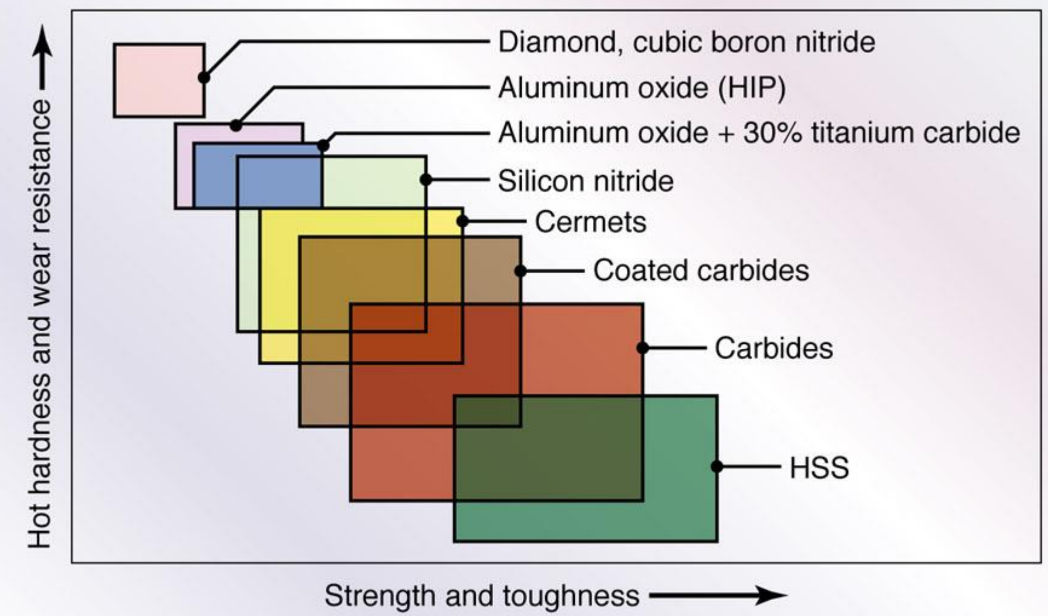
Cutting-Tool Materials



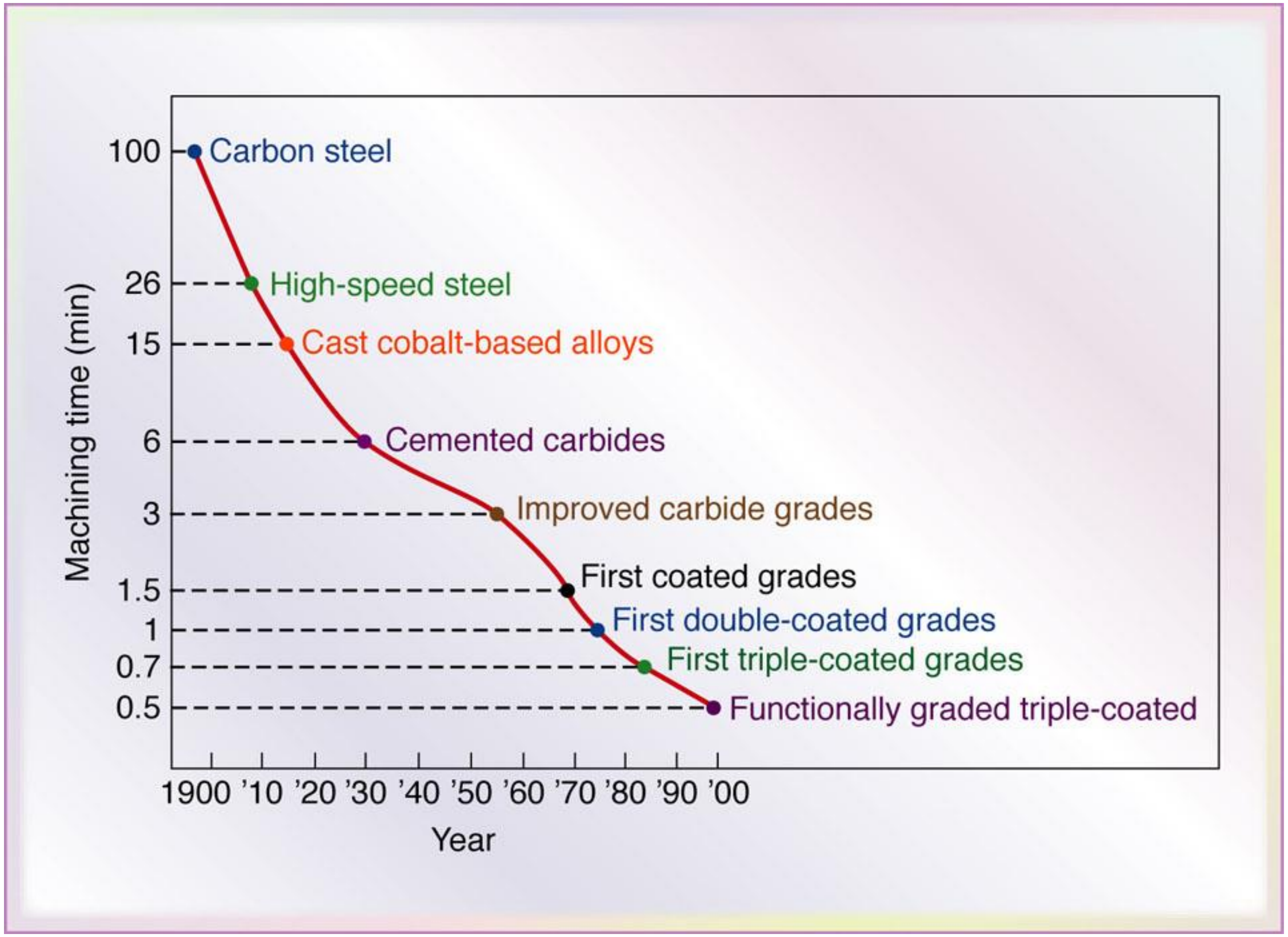
Hardness of Cutting Tool Materials as a Function of Temperature



Ranges of Mechanical Properties for Groups of Tool Materials



Relative Time Required to Machine with Various Cutting-Tool Materials



Cutting Tool Material Requirements:

1. It should be strong enough to withstand the forces being applied due the cutting i.e. bending compression, shear etc.
2. It should be tough (resistant to shock loads). It is quite important when tool is used for intermittent cutting.
3. It should be sufficient harder (resistant to wear, abrasion and indentation) the material being cut.

   used for metals

4. It should be able to resist high temperature (red hardness).

   نقطة تحول ال properties

5. It should be capable of withstanding,, the sudden cooling effect of coolant used during cutting.
6. The coefficient of friction between the chip and the tool should be as low as possible in the operating range of speed and feed.
7. should be easily formed to the required cutting shape.

friction depends on the surface

Hardness is the resistance of the localized plastic deformation

Types of cutting tool material

Several materials exhibiting above properties in varying degrees have been developed for use in cutting tools:

- Carbon tool steel.
- High speed steel (H.S.S.)
- Carbides.
- Ceramics
- Diamonds
- Cubic boron nitride.

Carbon Tool steel	H.S.S
• Carbon steels are limited in use to tools of small section operating at lower speeds. • Tools made up of plain carbon steel can be used for machining soft materials such as brass. • This material starts loosing its hardness at about 250°C and is therefore not used when the operational temperature is more.	• High speed steel tools give improved cutting performance and higher metal removal rates. • High speed steel is widely used for drills. • Although several types of high speed steels are in use but 18-4-1 high speed steel containing tungsten 18%, chromium 4% and vanadium 1% is quite commonly used. • This type of material gives excellent performance over a great range of materials and cutting speeds and it retains its hardness up to around 600°C.

mechanical properties of HSS are higher than the mechanical properties of carbon tool steels metal + carbon

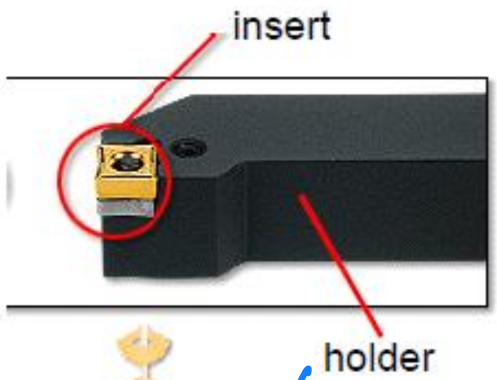
carbides

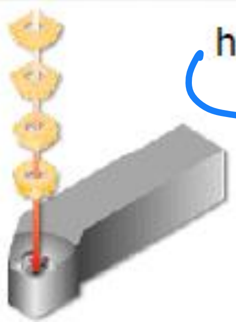
- They consist of tungsten, tantalum and titanium carbides together with a binder usually cobalt all mixed together as fine powders. These powders are compacted (compressed) into the required shape and subjected to a high temperature treatment known as sintering. During this process the cobalt binder is fused to the carbides, producing a hard, dense substance.
- Tools made up of carbides are extremely hard having Rockwell hardness varying from 90—93 HRC.
- They can be used at cutting speeds 200 to 500% greater than those used for high speed steel. They have virtually replaced high speed steels in high speed and high producing machining.

Cobalt has ↑ toughness and ↓ hardness

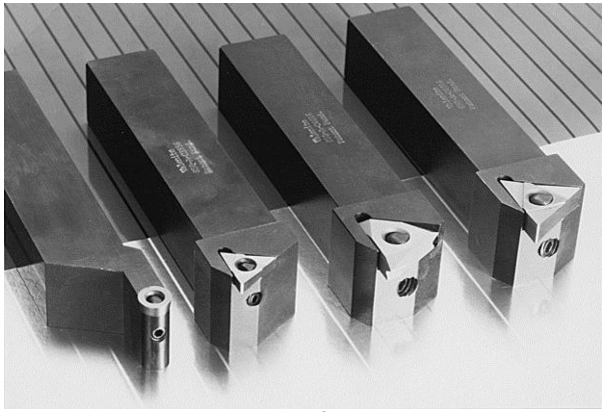
"insert"

cutting tool edge





provides tough and stiff support to the insert



cobalt provides toughness and carbides provide hardness

General characteristics of carbide tools

- They have high thermal conductivity, ~~low~~ high specific heat and low thermal expansion.
- They have high hardness over a wide range of temperature (up to 900°C). then it becomes visco elastic
- Their compressive strength is more than tensile strength.

Ceramics

- ✓ Aluminum oxide and boron nitride powders mixed together and sintered at 1700°C form the ingredients of ceramic tools.
- ✓ These materials are very hard with good compressive strength.
- ✓ Ceramics are usually in the form of disposable tips. They can be operated at from two to three times the cutting speeds of tungsten carbide and cutting speeds on cast iron in the order of 1000 m/min are not uncommon.
- ✓ They resist cratering, usually require no coolant. However in order to take full advantage of their capabilities special and more rigid machine tools are required.

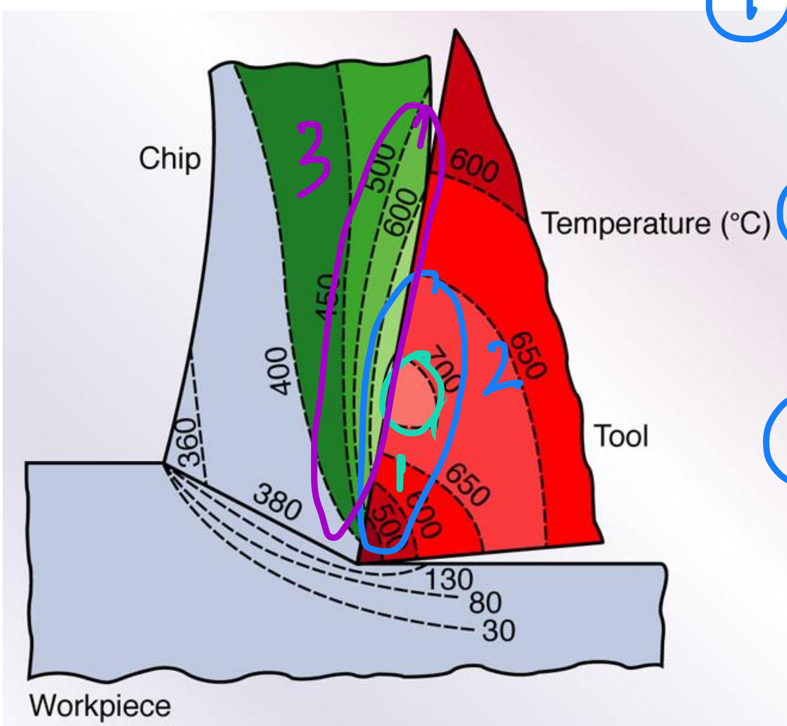
Cratering is a type of wear. It is caused by diffusion of the wm in the chip on the surface of the cutting tool.

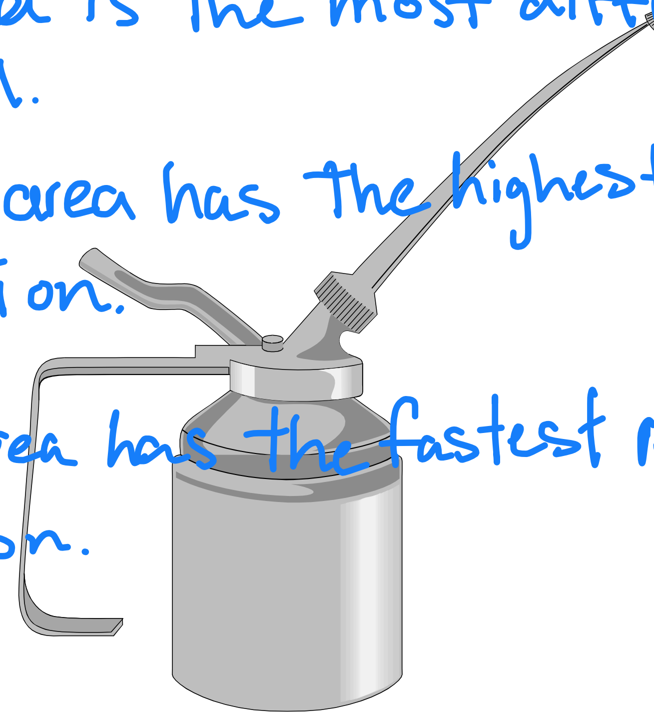
Diamonds.

- Diamond is the hardest material known.
- It has a low coefficient of friction, lowest thermal expansion, high compressive strength and is extremely wear resistant, high heat conductivity and low coefficient of friction
- It is used mainly for cutting very hard materials, such as glass, plastics, ceramics etc.
- Diamond tools produce a very good surface finish at high speeds with good dimensional accuracy.
- The main disadvantages of diamonds are their brittleness and high cost.

fluid reduces temperature

Cutting Fluid and Cutting Temperture





① This area is the most difficult to cool.

② This area has the highest friction.

③ This area has the fastest relative motion.

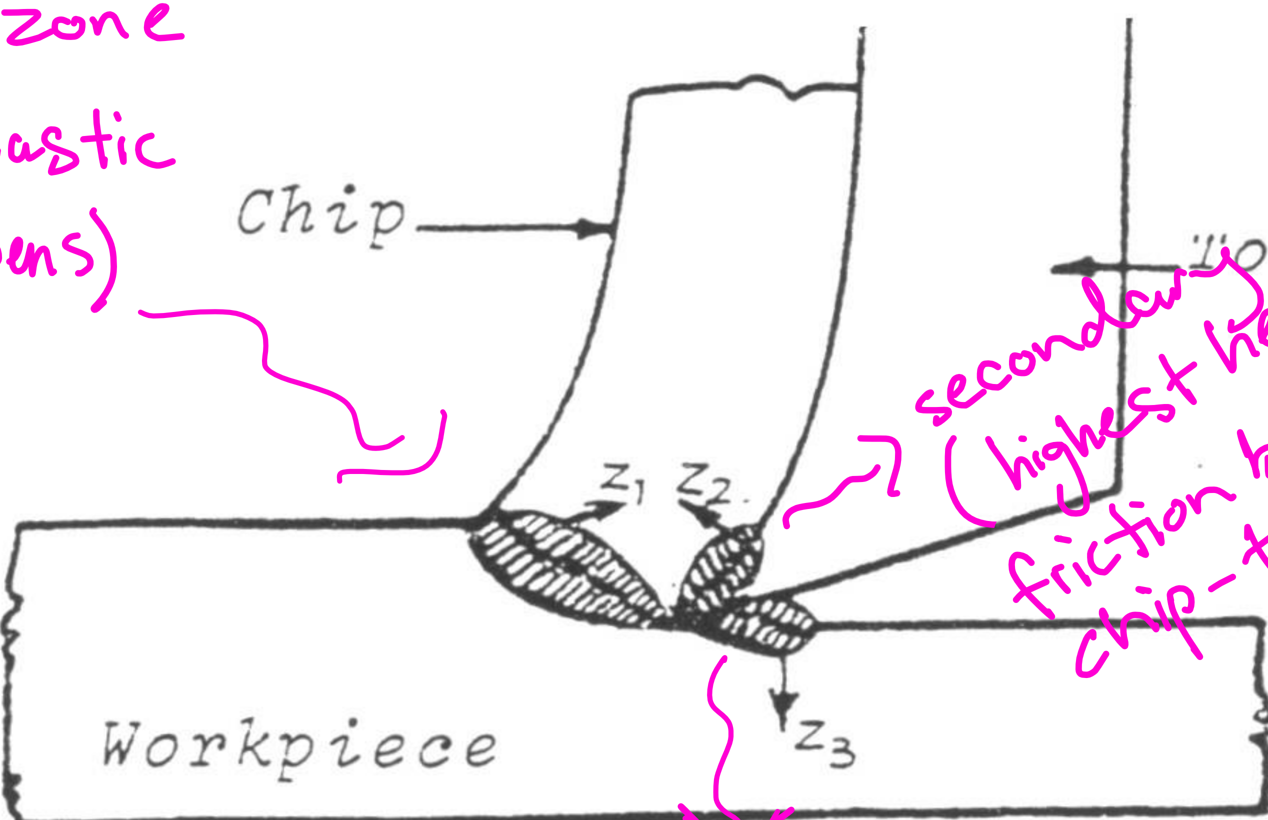
Cutting Temperatures are Important

High cutting temperatures

1. Reduce tool life because it affects the tool's mechanical properties
2. Produce hot chips that pose safety hazards to the machine operator
3. Can cause inaccuracies in part dimensions due to thermal expansion of work material

Thermal Aspects of Metal machining

primary zone (where plastic def happens)



secondary zone (highest heat generation friction between the chip-tool interface)

tertiary zone (friction between the flank surface of the cutting tool and the new surface of the wm)

Functions of Cutting Fluid

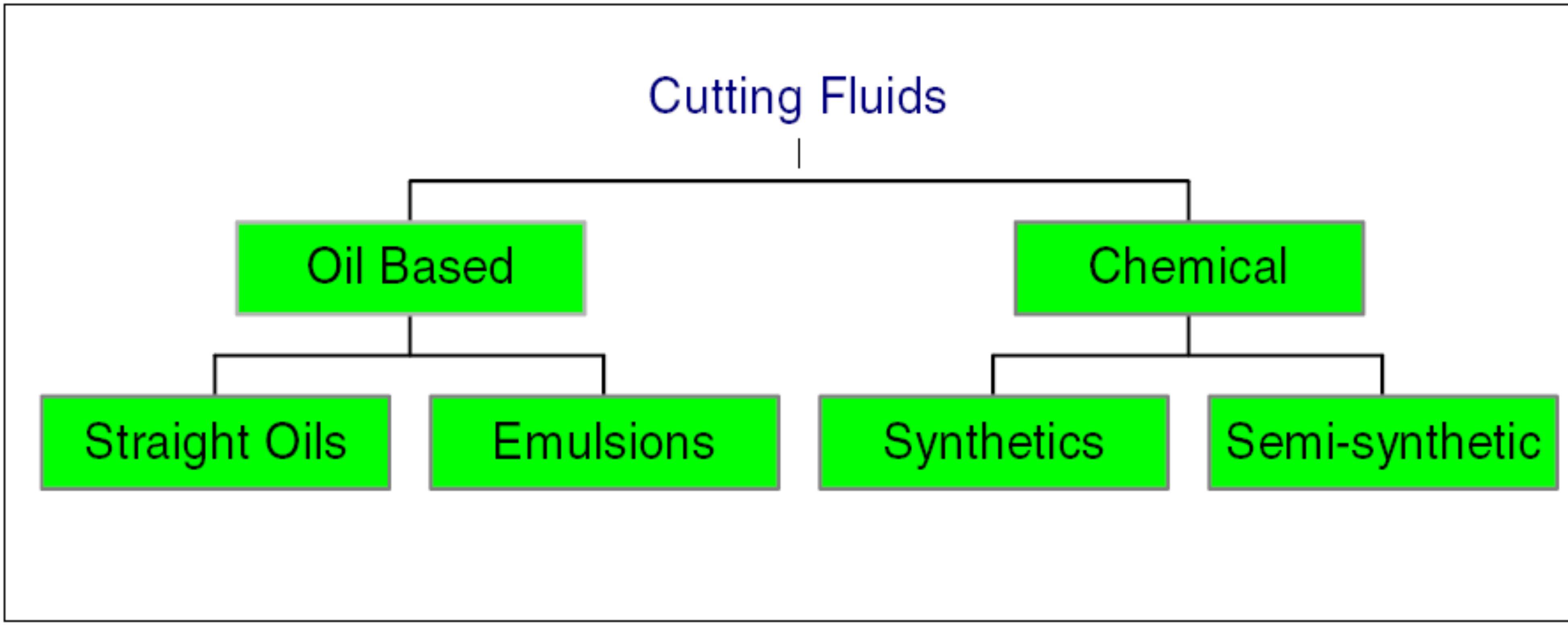
- It **cools the cutting tool and workpiece**. The fluid carries the heat produced away by supplying adequate quantity of cutting fluid. This makes more accurate production and measurement. because thermal expansion ↓
- It **lubricates the cutting tool** and thus reduces the coefficient of friction between the chip and tool. This increases tool life. heat generated and energy lost due to friction ↓
- **Reduce Wear.** because of the diff in temp
- It causes the **chips be break up** into small pieces.
- It **washes away the chips** from the tool.
- It **prevents corrosion of workpiece** and machine.
- Removal of heat from the [redacted] cutting zone also **reduces thermal distortion of the Workpiece.**

because the normal force decreases which will decrease the pressure on the cutting tool

Properties of Cutting Fluid

- It should have a high specific heat, high heat conductivity.
- It should possess good lubricating properties to reduce frictional forces and to decrease the power consumption.
- It should be odorless.
- It should be non-corrosive to workpiece and machine.
- It should he non-toxic to operating personnel.

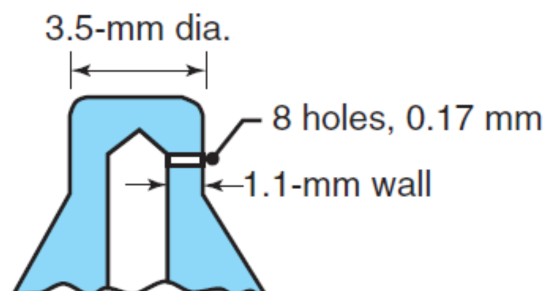
should pocess good witting properties in order to fit in suitable places

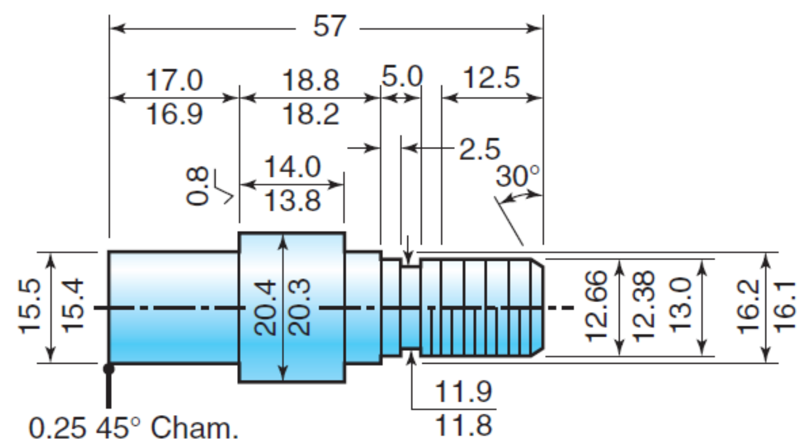


Additives: Chlorine, Sulfur, Phosphorus, Biocides, Odorants

Machining Processes

- Parts can be manufactured by casting, forming and shaping processes
- They often require further operations before the product is ready for use





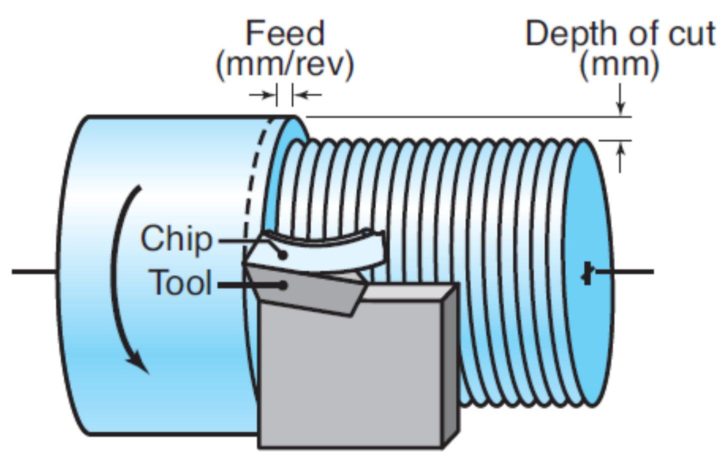
- Major types of material removal processes:

1. **Cutting**
2. **Abrasive processes**
3. **Advanced machining processes**

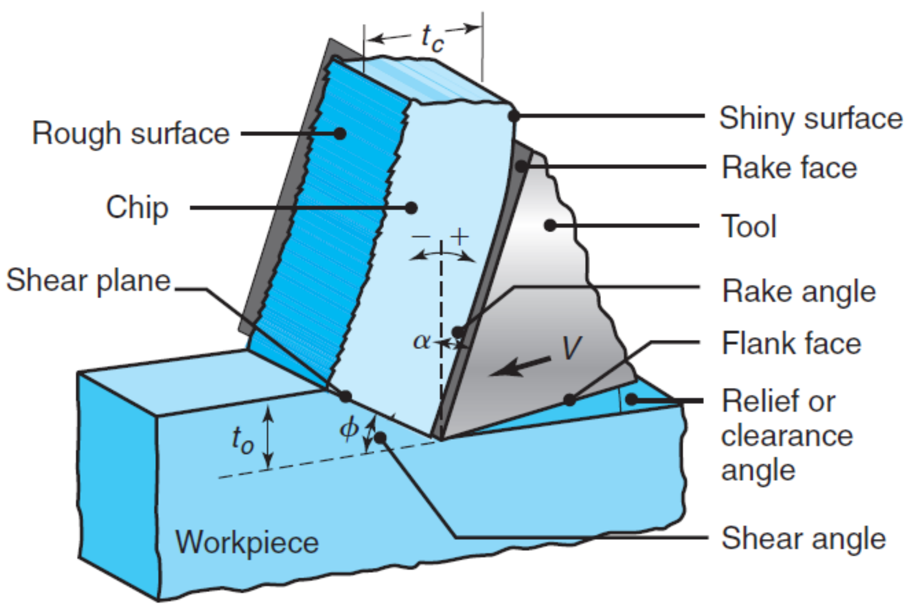
- Machining operations is a *system* consisting of the

1. *Workpiece*
2. *Cutting tool*
3. *Machine tool*
4. *Production personnel*

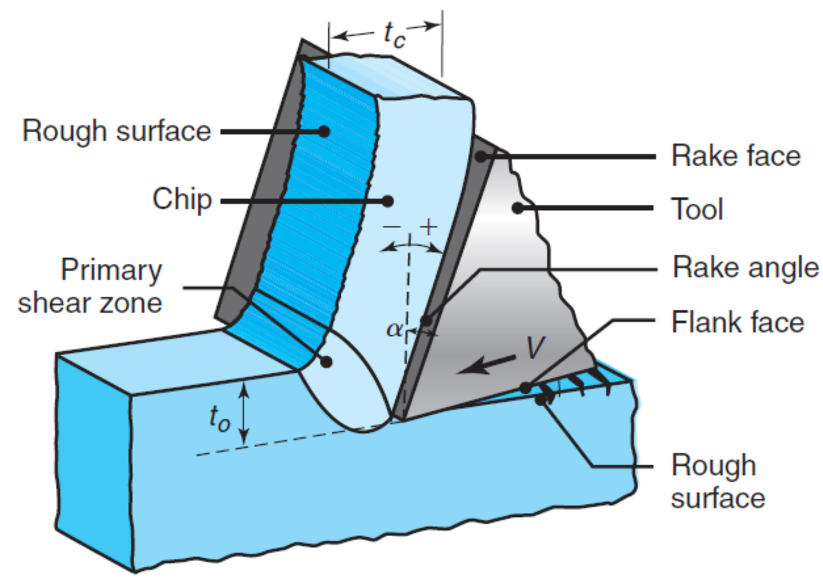
- In the turning process, the cutting tool is set at a certain *depth of cut* (mm) and travels to the left as the workpiece rotates
- *Feed*, or *feed rate*, is the distance the tool travels horizontally per unit revolution of the workpiece (mm/rev)



- In idealized model, a cutting tool moves to the left along the workpiece at a constant velocity and a depth of cut



(a)



(b)

Mechanics of Cutting

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

Mechanics of Cutting

- Major *independent variables* in the cutting process:

1. Tool material and coatings
2. Tool shape, surface finish, and sharpness
3. Workpiece material and condition
4. Cutting speed, feed, and depth of cut
5. Cutting fluids
6. Characteristics of the machine tool
7. Work holding and fixturing

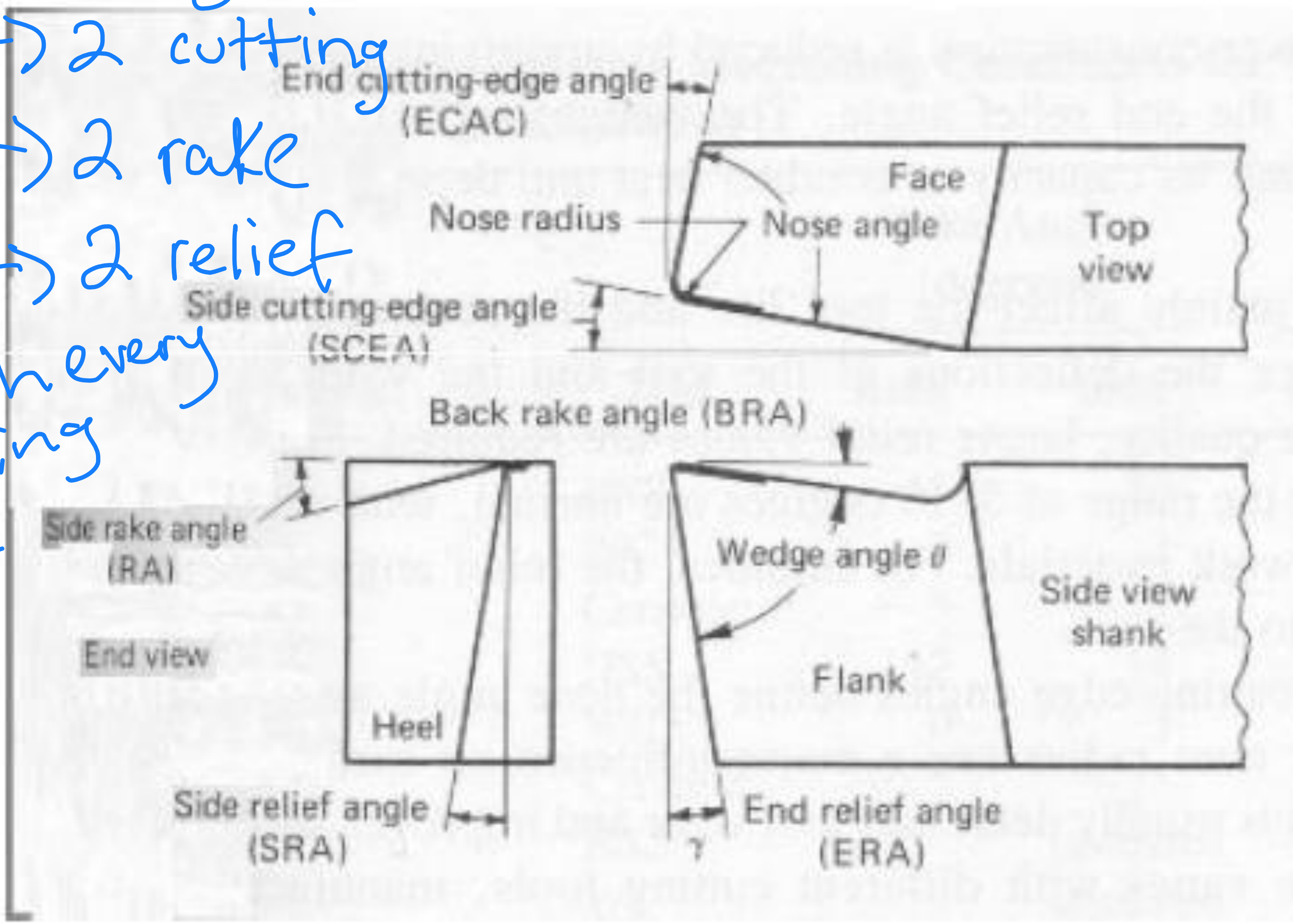
nose radius is the smooth transition between two cutting edges

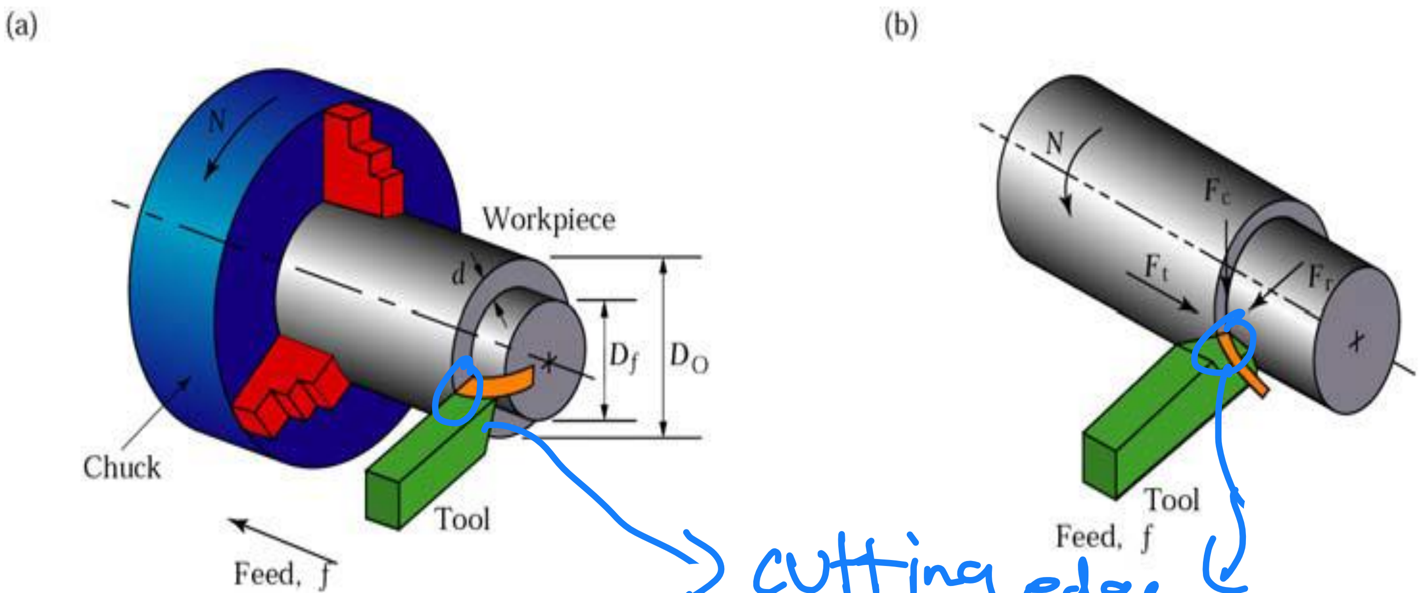
Tool Geometry for single Point Tool

6 angles and 1 nose radius

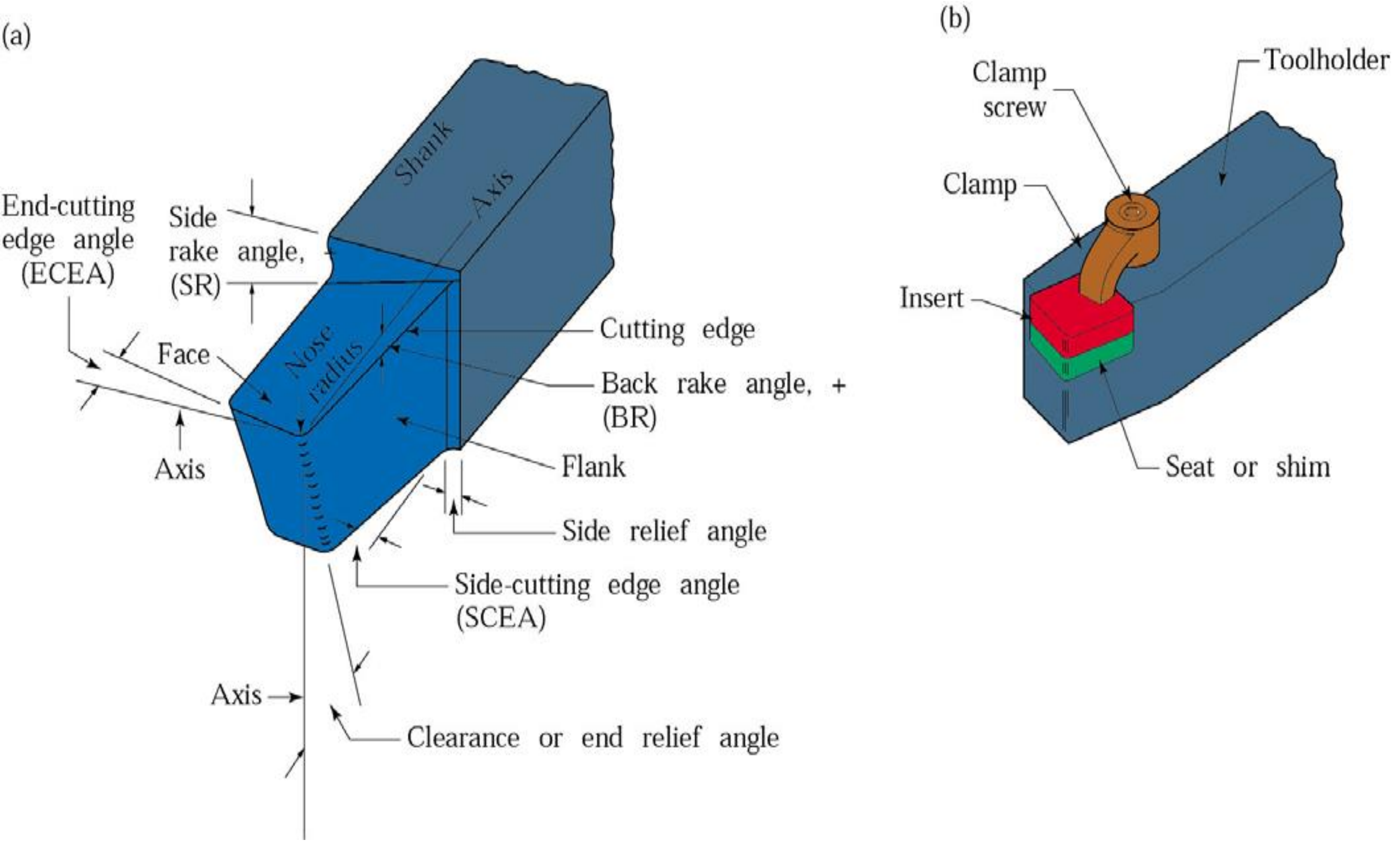
- 2 cutting
- 2 rake
- 2 relief

3 with every cutting edge



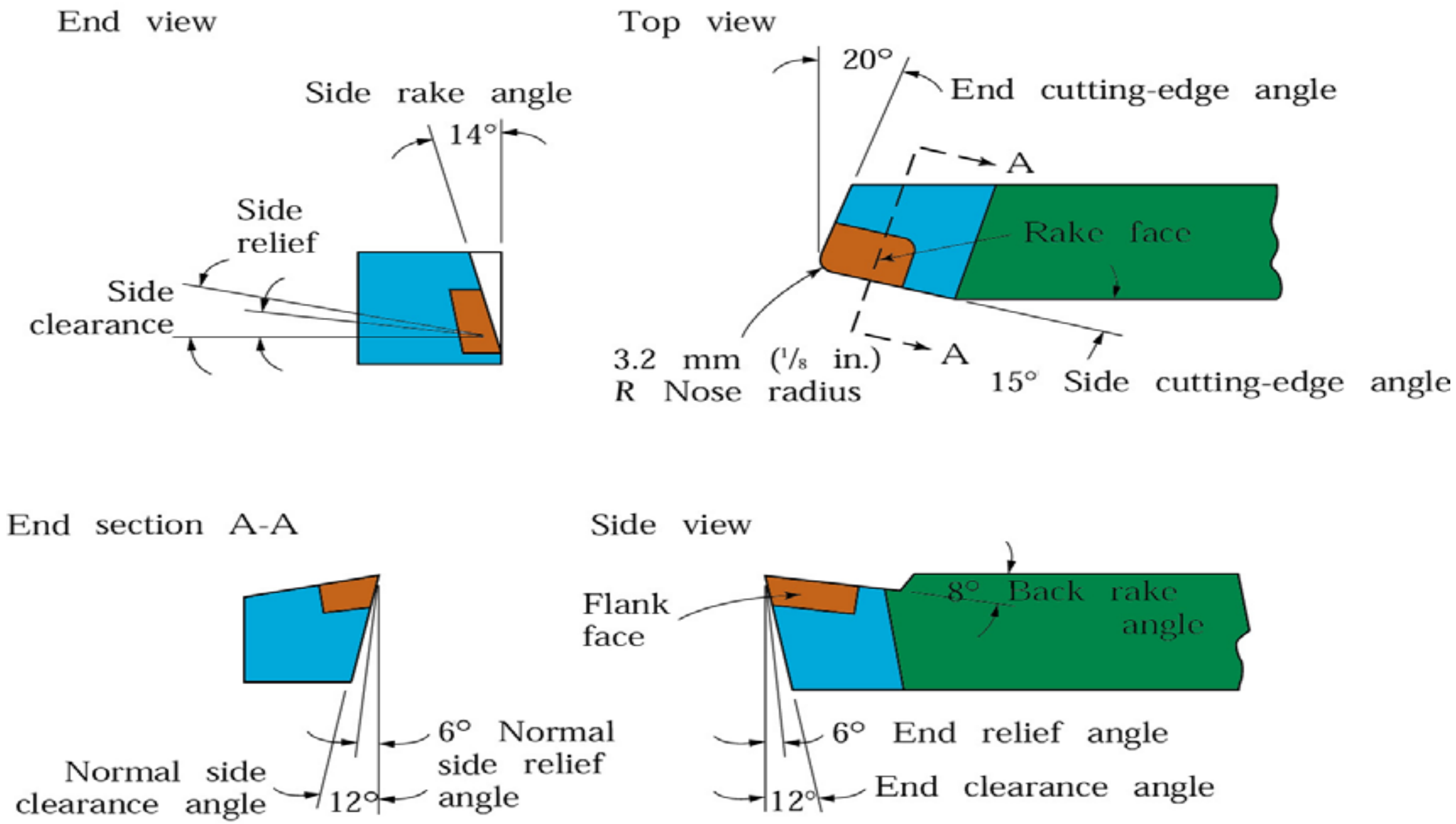


cutting edge



(a)
Shank
Axis
End-cutting
edge angle
(ECEA)
Side
rake angle,
(SR)
Face
Nose
radius
Cutting edge
Back rake angle, +
(BR)
Axis
Flank
Side relief angle
Side-cutting edge angle
(SCEA)
Axis
Clearance or end relief angle
(b)
Clamp
screw
Toolholder
Clamp
Insert
Seat or shim

(a)

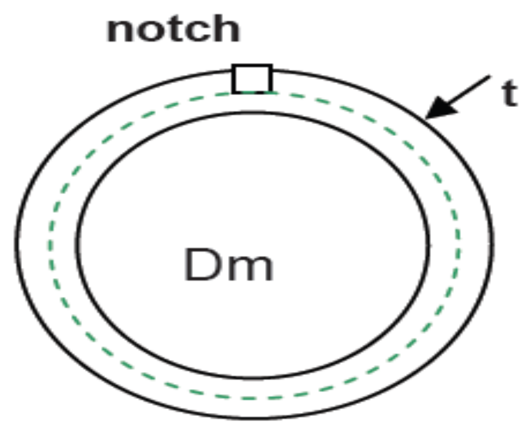


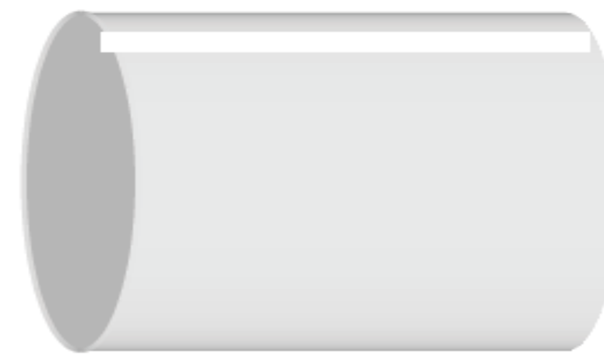
Tool Signature	Dimensions	Abbreviation
8	Back rake angle	BR
14	Side rake angle	SR
6	End relief angle	ER
12	End clearance angle	. . .
6	Side relief angle	SRF
12	Side clearance angle	. . .
20	End cutting-edge angle	ECEA
15	Side cutting-edge angle	SCEA
1/8	Nose radius	NR

t: depth of cut (thicness of chip before cutting)
tc: cut chip thickness
AB :is the shear line
α : shear angle

1- **It is noticed that tc is always greater than t**
2- **It is essential to know α since it is needed for force anlysis. It can be found by measuring t and tc and using the following derivation: A notch is marked on a rounded bar and a certain depth t is cut as shown:**

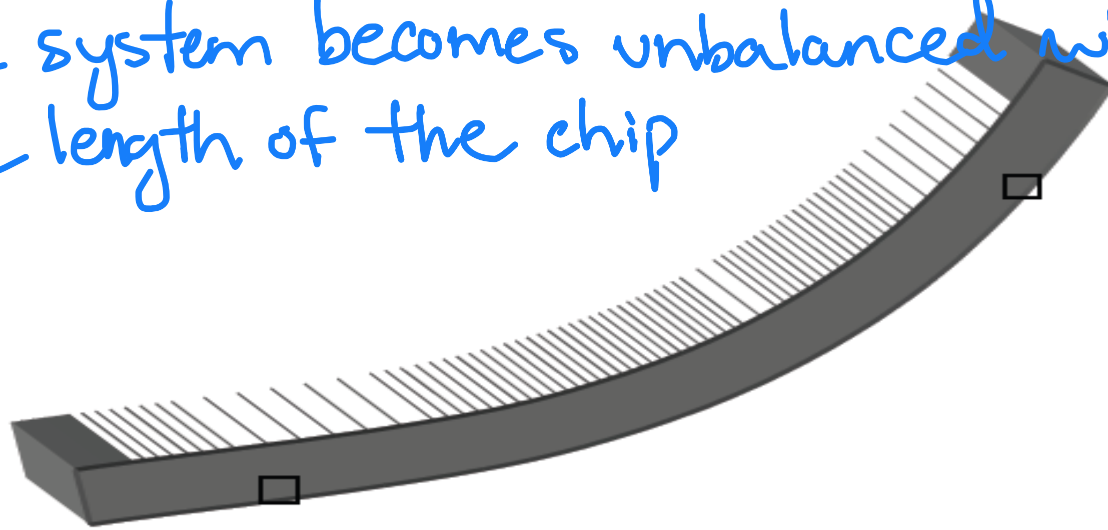
Before cutting → 1 surface

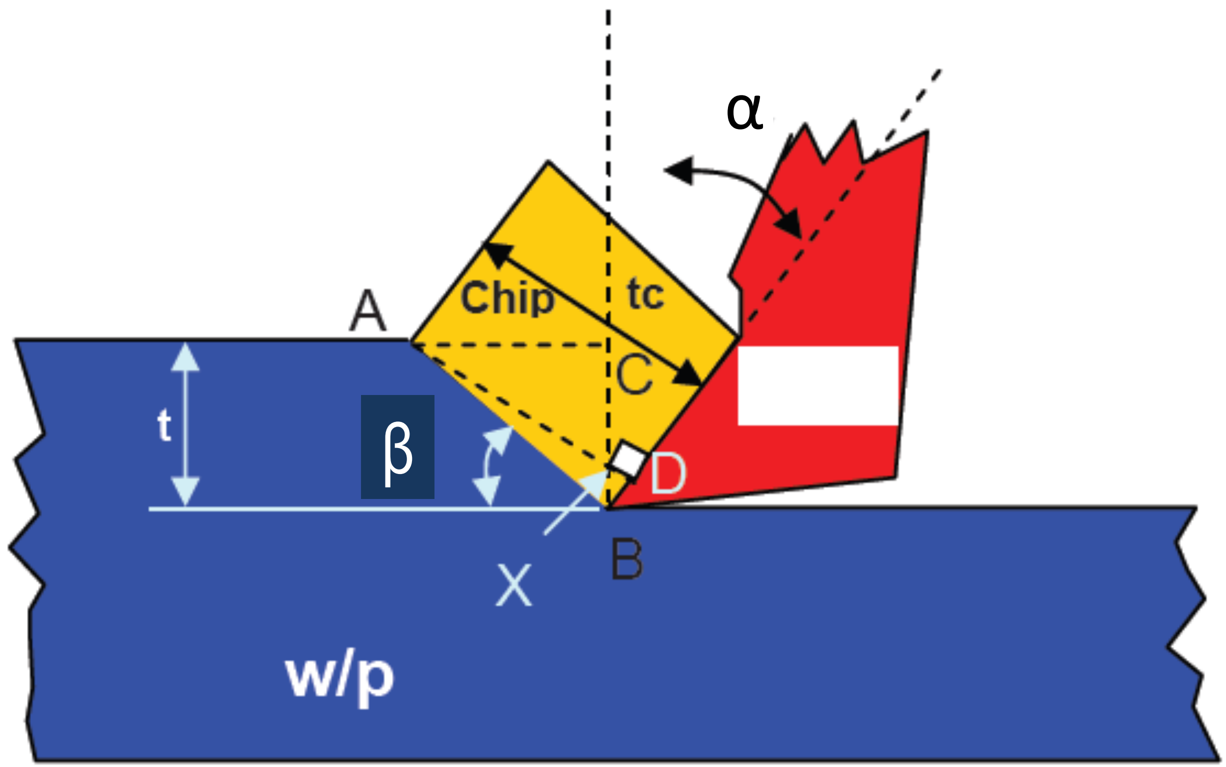




After cutting → 3 surfaces

so the system becomes unbalanced which causes shrinkage in the length of the chip





α
A
Chip
tc
C
t
β
D
B
X
w/p

Now we measure the circumference on the cut chip (the distance between 2 successive notches).

The length of the cut chip before cutting was $\boldsymbol{l_1 = \pi\, Dm}$

From the volume constancy, $l_1 t_1 = l_2 t_2$

Or,

$T_2 = L_1 T_1 / T_2$

From the similarity of the two triangles AXC and BXD, the angles

AXC=BXD

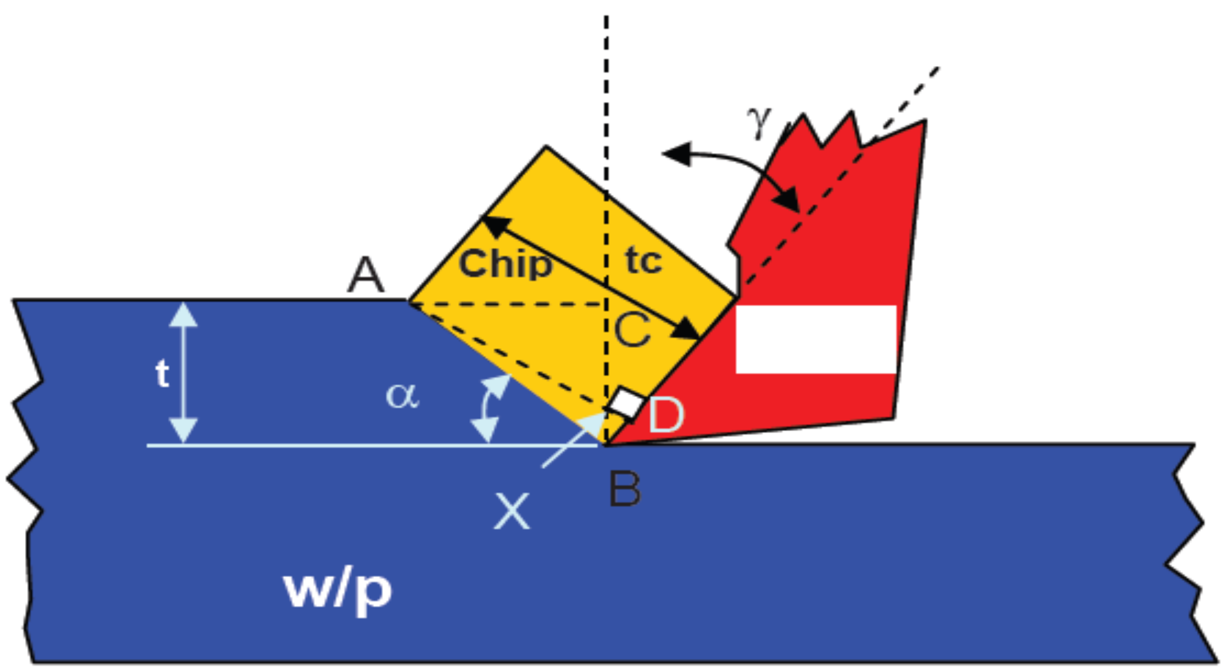
ACX=BDX

XAC=XBD=γ

CAB= α

Then BAD=CAB-XAC

= α−γ



Let $r = \frac{t}{t_c} = \frac{CB}{AD} = \frac{AB \sin\alpha}{AB\cos(\alpha-\gamma)} = \frac{\sin\alpha}{\cos(\alpha-\gamma)}$

$$\begin{aligned}\therefore \sin\alpha &= r\cos(\alpha-\gamma)\\ &= r\cos\alpha\cos\gamma + r\sin\alpha\sin\gamma\end{aligned}$$

Dividing by cos α

$$\tan\alpha = r\cos\gamma + r\tan\alpha\sin\gamma$$

$$r\cos\gamma = \tan\alpha - r\tan\alpha\sin\gamma$$

$$r\cos\gamma = \tan\alpha(1 - r\sin\gamma)$$

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

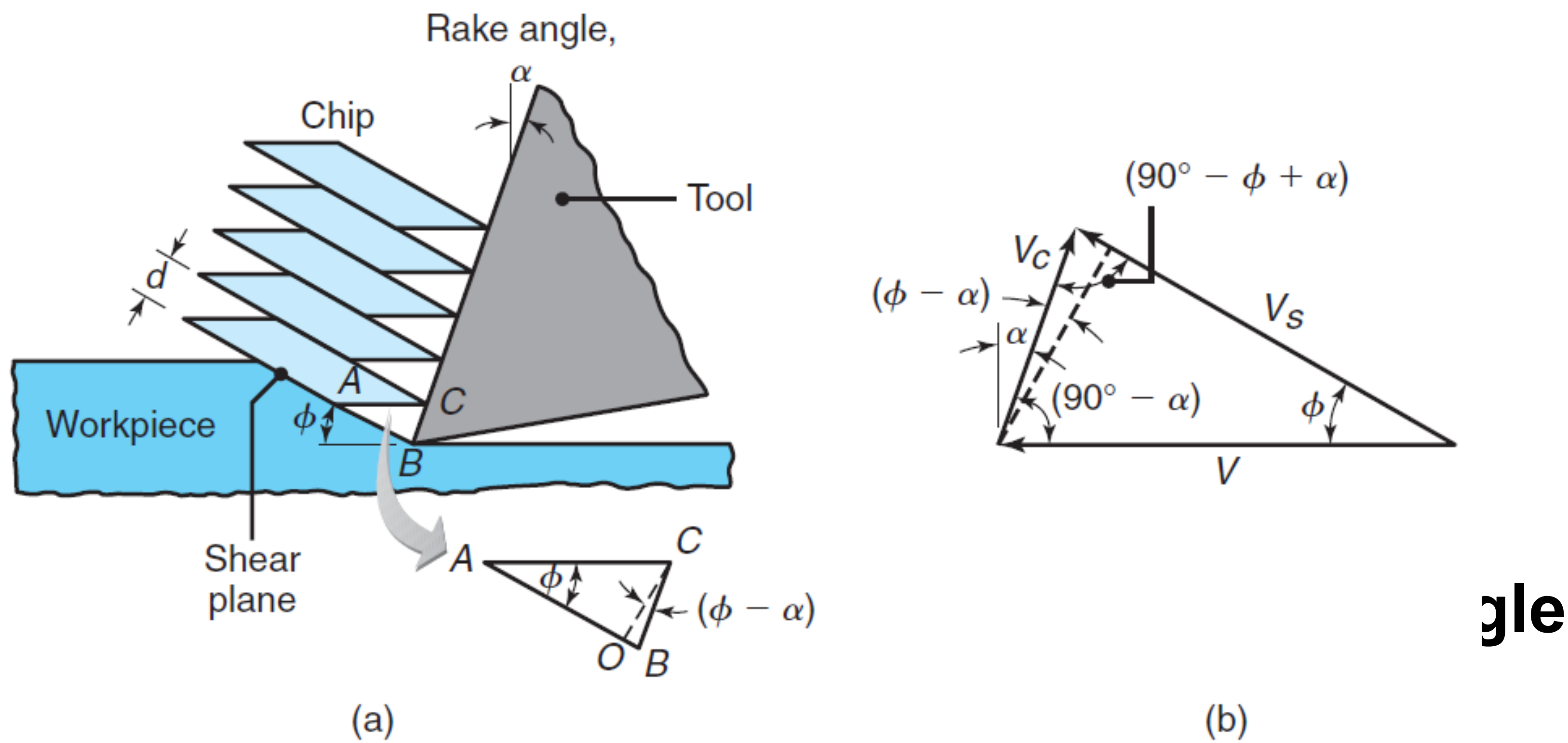
Mechanics of Cutting

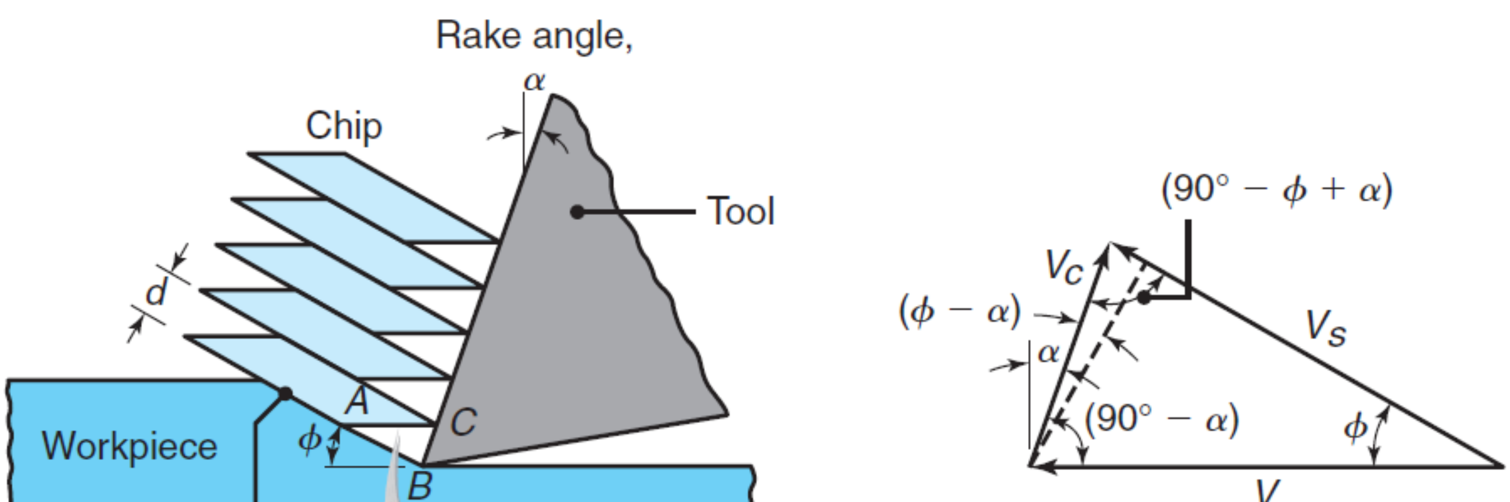
- *Dependent variables* in cutting are:

1. Type of chip produced
2. Force and energy dissipated during cutting
3. Temperature rise in the workpiece, the tool and the chip
4. Tool wear and failure
5. Surface finish and surface integrity of the work piece

Mechanics of Cutting

- M
- I
  p
- C
  c
- S … gle
  c





Mechanics of Cutting

Cutting Ratio

- The ratio is related to the two angles by

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha} \Rightarrow r = \frac{t_0}{t_c} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

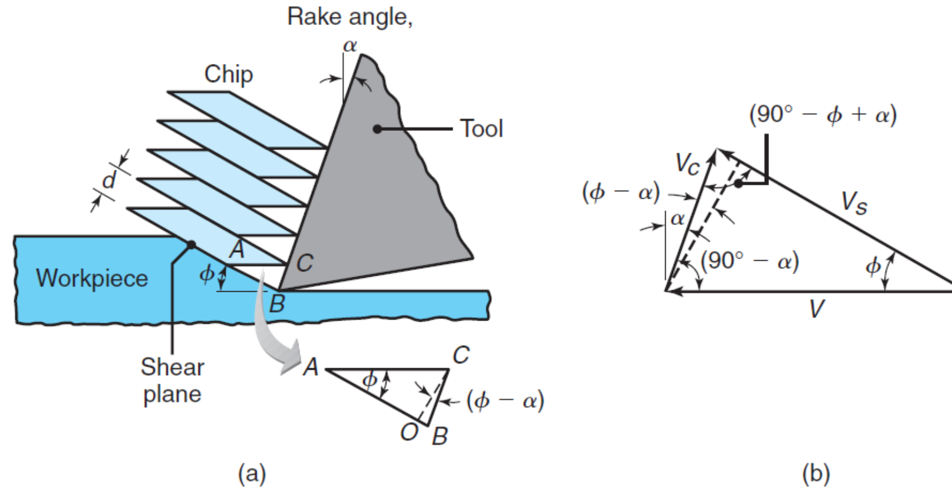
- As the chip thickness is always greater than the depth of cut, the value of *r* is always less than unity
- Reciprocal of *r* is known as the *chip-compression ratio* or *chip-compression factor*
- A measure of how thick the chip has become

Mechanics of Cutting

Shear Strain

- The **shear strain** that the
expressed as

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC} =$$



- Large shear strains are associated with low shear angles or with low or negative rake angles
- Based on the assumption that the shear angle adjusts itself to minimize the cutting force,

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

$$\Rightarrow \phi = 45° + \alpha - \beta \text{ (when } \mu = 0.5 \sim 2)$$

β = friction angle

μ = tanβ ➔ *coefficient of friction*

Mechanics of Cutting

u= spcefic power

$$u = \frac{P}{V} = \frac{P}{MRR}$$

Velocities in the Cutting Zone

- Since mass continuity is maintained,

$$Vt_0 = V_c t_c \text{ or } V_c = Vr \Rightarrow V_c = \frac{V \sin\phi}{\cos(\phi - \alpha)}$$

- From *Velocity diagram,* we can obtained equations from trigonometric relationships,

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

$MRR = w t_c V_c$

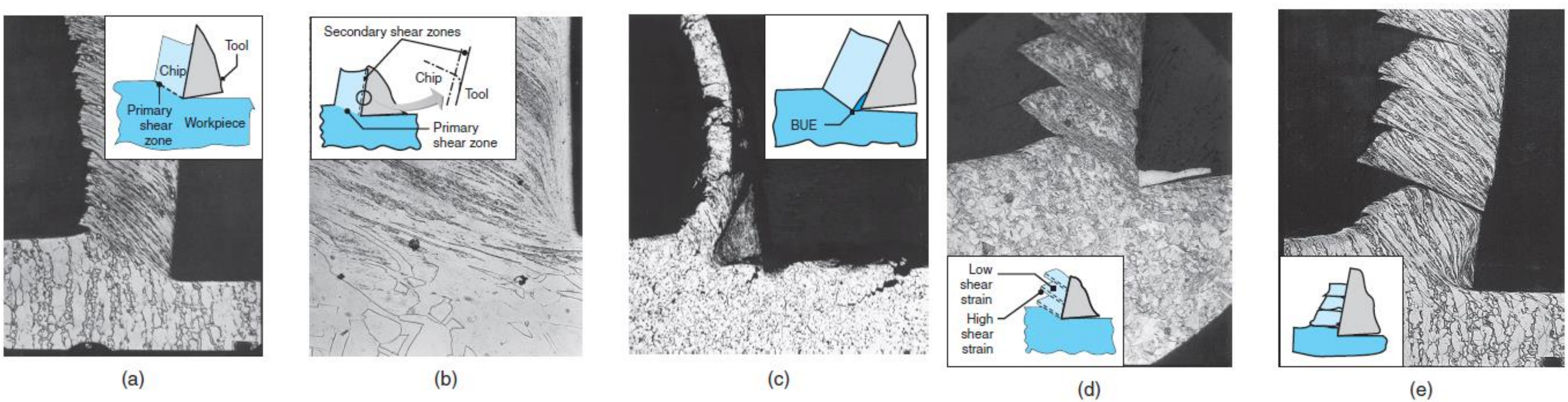
$= w t V$

- Note also that

$$r = \frac{t_0}{t_c} = \frac{V_c}{V}$$

Mechanics of Cutting: Types of Chips Produced in Metal Cutting

- Types of metal chips are commonly observed in practice
- There are 4 main types:



a) Continuous
b) Built-up edge
c) Serrated or segmented
d) Discontinuous

Mechanics of Cutting: Types of Chips Produced in Metal Cutting

machining parameters are high

Continuous Chips

- Formed with ductile materials machined at high cutting speeds and/or high rake angles
- Deformation takes place along a narrow shear zone called the (*primary shear zone*) low shear strain
- Continuous chips may develop a *secondary shear zone* due to high friction at the tool–chip interface

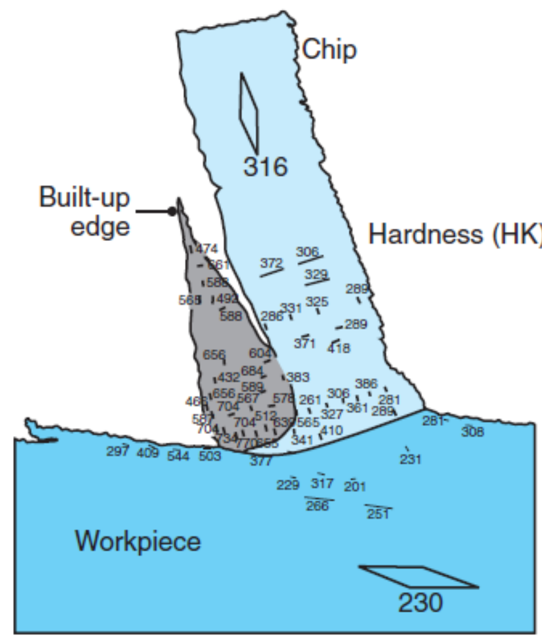
However, if chip thickness is ↑, friction is ↑ and speed is ↓ discontinuous chips are produced

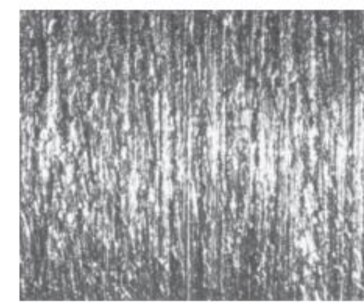
Mechanics of Cutting:
Types of Chips Produced in Metal Cutting

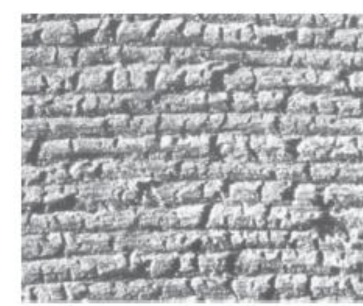
Built-up Edge (BUE) Chips

- Consists of layers of material from the workpiece that are deposited on the tool tip
- As it grows larger, the BUE becomes unstable and eventually breaks apart
- BUE can be reduced by:

1. Increase the cutting speeds
2. Decrease the depth of cut
3. Increase the rake angle
4. Use a sharp tool
5. Use an effective cutting fluid
6. Use a cutting tool that has lower chemical affinity for the workpiece material







Mechanics of Cutting:
Types of Chips Produced in Metal Cutting

Serrated Chips

- Also called *segmented* or *nonhomogeneous* chips
- They are semicontinuous chips with large zones of low shear strain and small zones of high shear strain *(shear localization)*
- Chips have a sawtooth-like appearance

Mechanics of Cutting:
Types of Chips Produced in Metal Cutting

Discontinuous Chips

- Consist of segments that attached firmly or loosely to each other
- Form under the following conditions:

1. Brittle workpiece materials
2. Materials with hard inclusions and impurities
3. Very low or very high cutting speeds
4. Large depths of cut
5. Low rake angles

low shear strain

6. Lack of an effective cutting fluid
7. Low stiffness of the machine tool

Mechanics of Cutting: Types of Chips Produced in Metal Cutting

Chip Curl

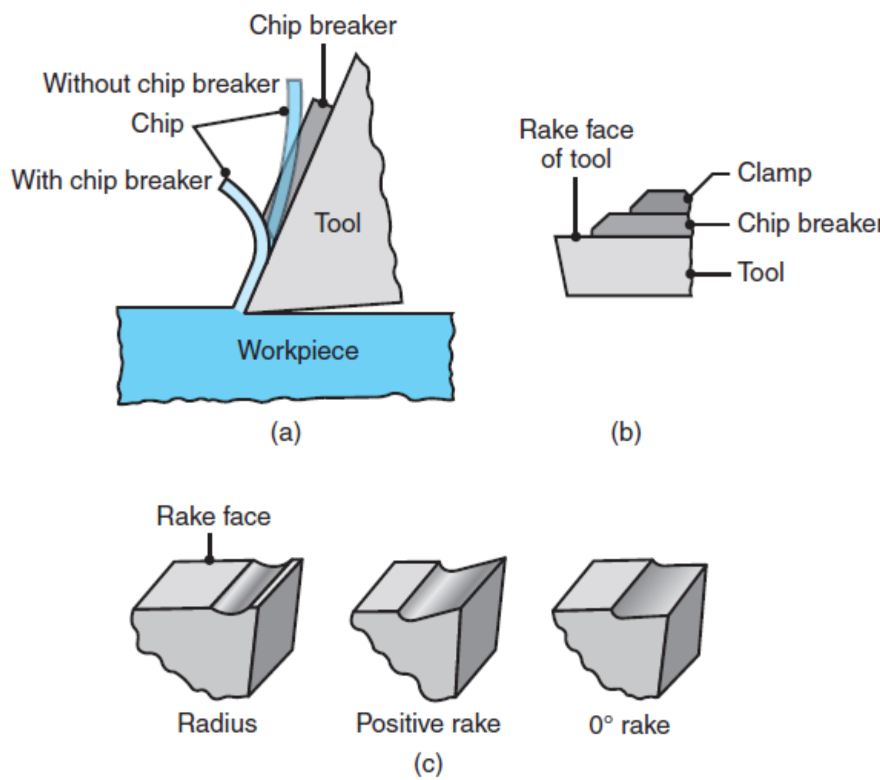
- Chips will develop a curvature (*chip curl*) as they leave the workpiece surface
- Factors affecting the chip curl conditions are:

1. Distribution of stresses in the primary and secondary shear zones.
2. Thermal effects.
3. Work-hardening characteristics of the workpiece material
4. Gometry of the cutting tool
5. Cutting fluids

Mechanics of Cutting: Types of Chips Produced in Metal Cutting

Chip Breakers

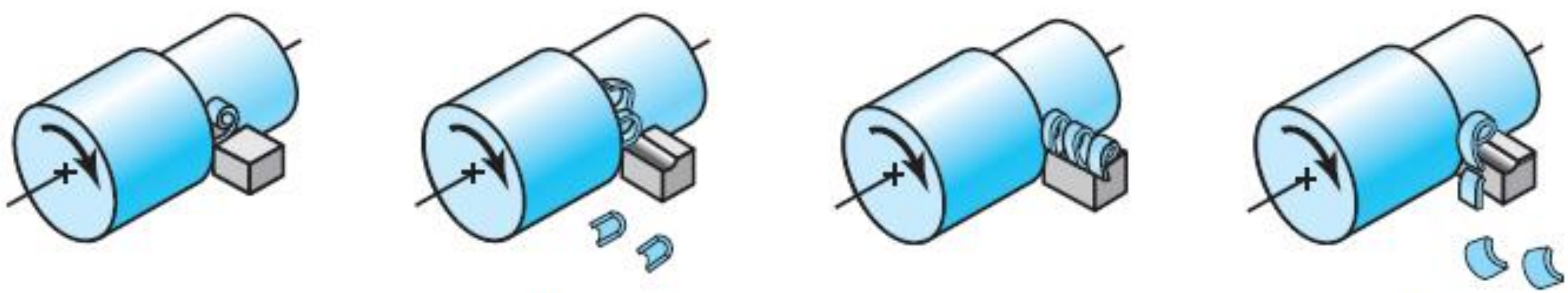
- A situation that break the chip intermittently with cutting tools have *chip-breaker* features



Mechanics of Cutting:
Types of Chips Produced in Metal Cutting

Chip Breakers

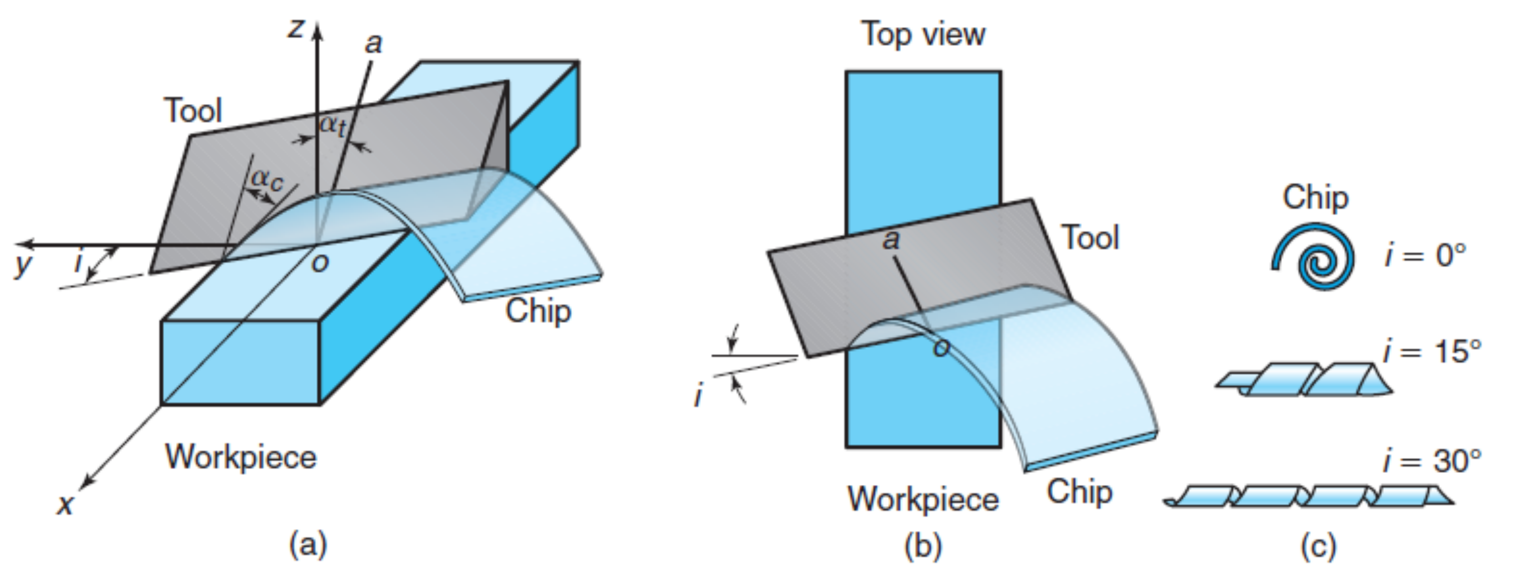
- Chips can also be broken by changing the tool geometry to control chip flow



(a) (b) (c) (d)

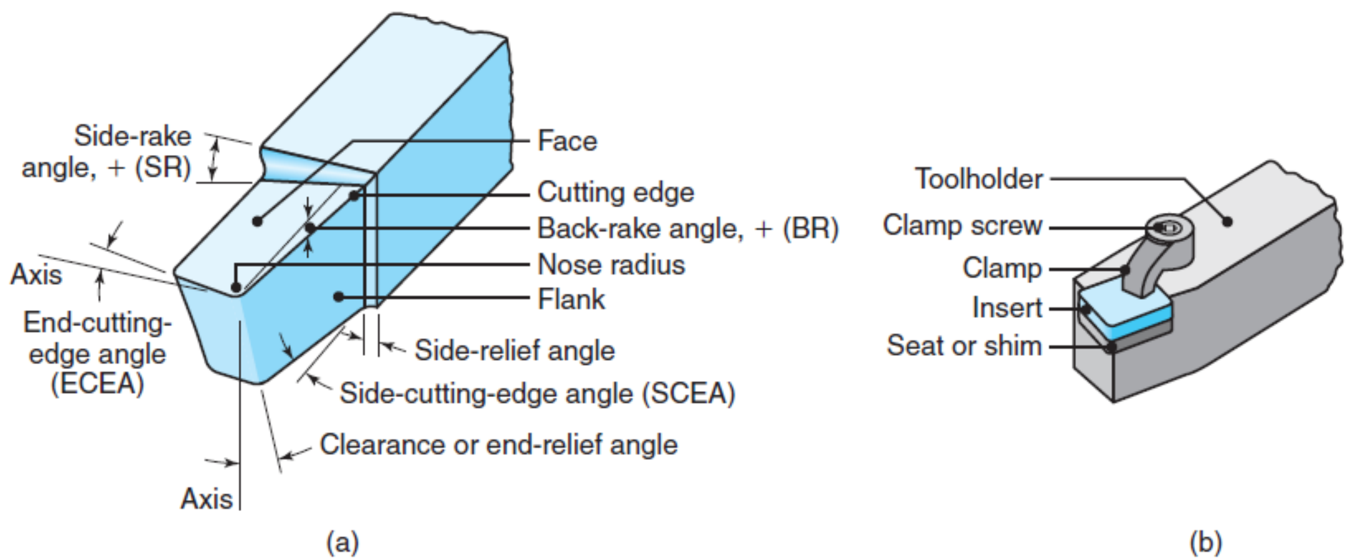
Mechanics of Cutting: Oblique Cutting

- Majority of machining operations involve tool shapes that are three dimensional where the cutting is said to be *oblique*
- There is a difference between oblique and orthogonal cutting



Mechanics of Cutting: Oblique Cutting

- Orthogonal cutting the chip slides directly up the face of the tool
- In oblique cutting, the chip is *helical* and at an **inclination** angle
- The effective rake angle is $\alpha_e = \sin^{-1}\left(\sin^2 i + \cos^2 i \sin\alpha_n\right)$



Mechanics of Cutting:
Oblique Cutting

Shaving and Skiving

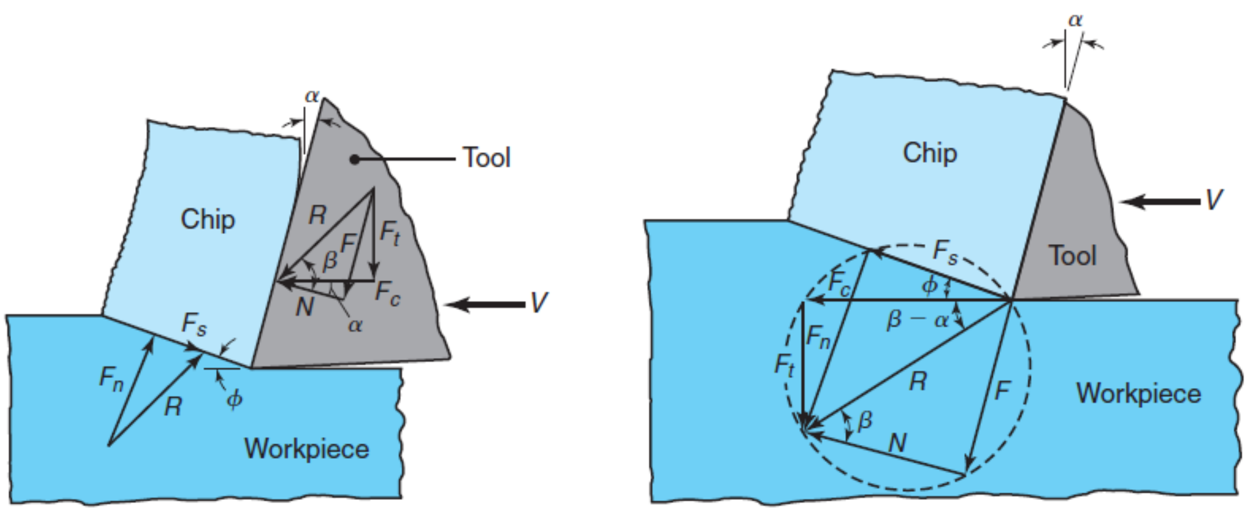
- Thin layers of material is removed from straight or curved surfaces
- *Shaving* can improve the surface finish and dimensional accuracy
- Parts that are long or combination of shapes are shaved by *skiving*
- A specially shaped cutting tool is moved tangentially across the length of the workpiece

Cutting Forces and Power

- Knowledge of the *cutting forces* and power involved:

1. Data on cutting forces
2. Power requirements

- **Cutting force** acts in the direction of the cutting speed, and supplies the energy required for cutting



(a) (b)

Cutting Forces and Power

- It can also be shown that

$$F = R\sin\beta \Rightarrow N = R\cos\beta$$

- Resultant force is balanced by an equal and opposite force along the shear plane
- It is resolved into a **shear force** and a **normal force**
- Thus,

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

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

- The magnitude of **coefficient of friction** is

$$\mu = \frac{F}{N} = \frac{F_t + F_c\tan\alpha}{F_c - F_t\tan\alpha}$$

Cutting Forces and Power

Thrust Force

- The tool holder, work-holding devices, and machine tool must be stiff to support thrust force with minimal deflections
- The effect of rake angle and friction angle on the direction of thrust force is

$$F_t = R\sin(\beta - \alpha) \text{ or } F_t = F_c\tan(\beta - \alpha)$$

- Magnitude of the cutting force is always positive as the force that supplies the work is required in cutting

Cutting Forces and Power

Power

- The power input in cutting is

$$Power = F_c V$$

- The power dissipated in the shear plane is

$$\text{Power for shearing} = F_s V_s$$

- Denoting the width of cut as *w*, the **specific energy for shearing**, is

$$\mu_s = \frac{F_s V_s}{w t_0 V}$$

Cutting Forces and Power

Power

- The power dissipated in friction is

$$\text{Power for friction} = FV_c$$

- The **specific energy for friction** is

$$\mu_f = \frac{FV_c}{wt_0V} = \frac{Fr}{wt_0}$$

- **Total specific energy** is

$$\mu_t = \mu_s + \mu_f$$

- Sharpness of the tool tip also influences forces and power

Cutting Forces and Power

Power

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (for Dull Tools, Multiply by 1.25)

Material	Specific energy $W \cdot s/mm^3$
Aluminum alloys	0.4–1
Cast irons	1.1–5.4
Copper alloys	1.4–3.2
High-temperature alloys	3.2–8
Magnesium alloys	0.3–0.6
Nickel alloys	4.8–6.7
Refractory alloys	3–9
Stainless steels	2–5
Steels	2–9
Titanium alloys	2–5

Cutting Forces and Power

Measuring Cutting Forces and Power

- Cutting forces can be measured using a **force transducer**, a **dynamometer** or a **load cell** mounted on the cutting-tool holder
- It is also possible to calculate the cutting force from the **power consumption** during cutting
- The *specific energy* in cutting can be used to calculate cutting forces

Cutting Forces and Power

EXAMPLE 21.1

Relative Energies in Cutting

In an orthogonal cutting operation, t_o=0.13 mm, V=120 m/min, α=10° and the width of cut 6 mm. It is observed that t_c=0.23 mm, F_c=500 N and F_t=200 N. Calculate the percentage of the total energy that goes into overcoming friction at the tool–chip interface.

Cutting Forces and Power

Solution

Relative Energies in Cutting

The percentage of the energy can be expressed as

$$\frac{\text{Friction Energy}}{\text{Total Energy}} = \frac{FV_c}{F_c V} = \frac{Fr}{F_c}$$

where

$$r = \frac{t_0}{t_c} = \frac{0.13}{0.23} = 0.565$$

We have

$$F = R\sin\beta \ , \ F = R\cos(\beta - \alpha) \text{ and}$$

$$R = \sqrt{\left(F_t^2 + F_c^2\right)} = \sqrt{200^2 + 500^2} = 539 \text{ N}$$

Cutting Forces and Power

Solution

Relative Energies in Cutting

Thus,

$$500 = 539\cos(\beta - 10) \Rightarrow \beta = 32^\circ$$

$$F = 539\sin 32^\circ = 286\ \mathrm{N}$$

Hence

$$\text{Percentage} = \frac{(286)(0.565)}{500} = 0.32 \text{ or } 32\%$$

Temperatures in Cutting

- *Temperature rise* - its major adverse effects:

1. Lowers the strength, hardness, stiffness and wear resistance of the cutting tool
2. Causes uneven dimensional changes
3. Induce thermal damage and metallurgical changes in the machined surface

resistance ↑
Power ↑
friction ↑

- Expression for *mean temperature* is

$$T = \frac{0.000665 Y_f}{\rho c} \sqrt[3]{\frac{V t_0}{K}}$$

Where Y_f flow stress in Mpa, K thermal diffusivity (thermal conductivity/ volumetric specific heat) m^2/s, and ρc volumetric specific heat kJ/m^3K

- *Mean temperature in turning* on a lathe is given by

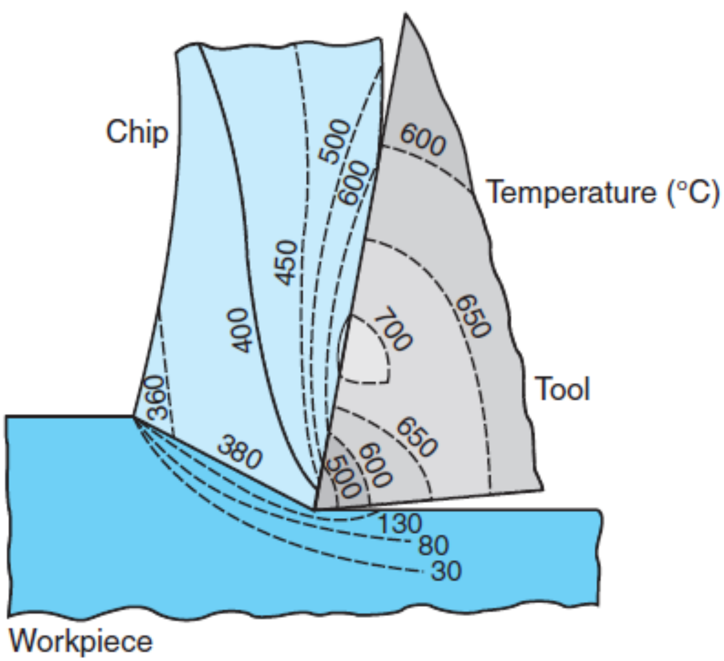
$$T_{mean} \propto V^a f^b$$

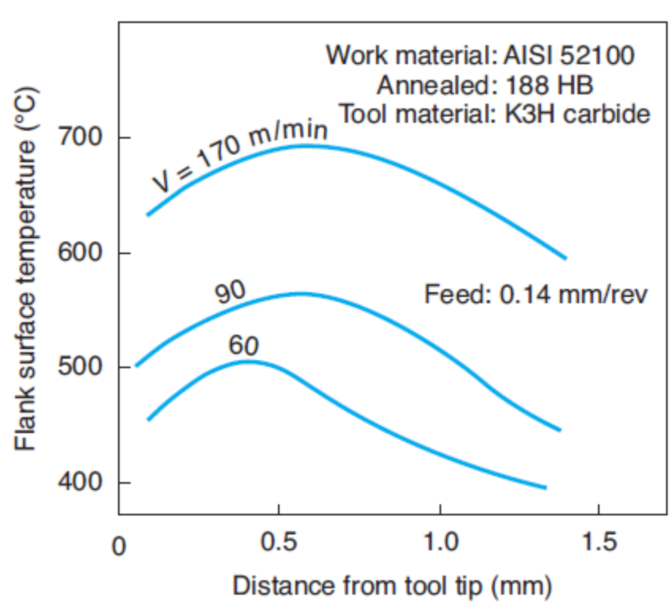
Where v is the cutting speed and f is the feed. The exponents a and b are 0.2 and 0.125 respectively for carbide tools and a=0.5 and b= 0.375 for HSS tools

Temperatures in Cutting

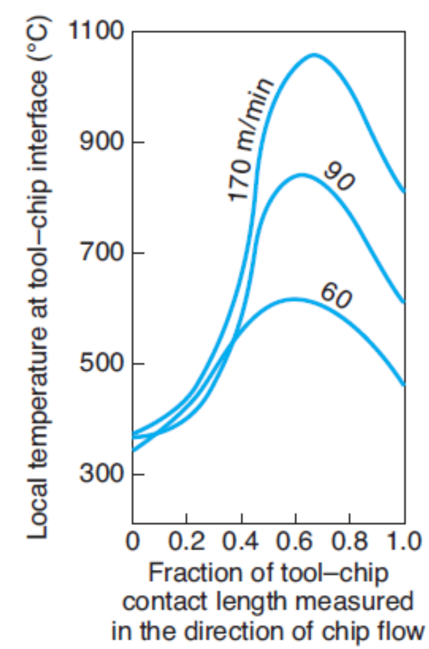
Temperature Distribution

- The sources of heat generation are concentrated in the primary shear zone and at the tool–chip interface
- There are temperature gradients in the cutting zone





(a)



(b)

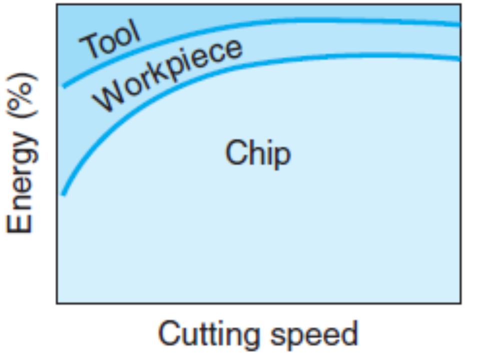
Temperatures in Cutting

Temperature Distribution

- The temperature increases with cutting speed
- Chips can become red hot and create a safety hazard for the operator
- The chip carries away most of the heat generated

Techniques for Measuring Temperature

- Temperatures and their distribution can be determined from **thermocouples**



Tool Life: Wear and Failure

- Cutting tools are subjected to:

1. High localized stresses at the tip of the tool
2. High temperatures
3. Sliding of the chip along the rake face
4. Sliding of the tool along the newly cut workpiece surface

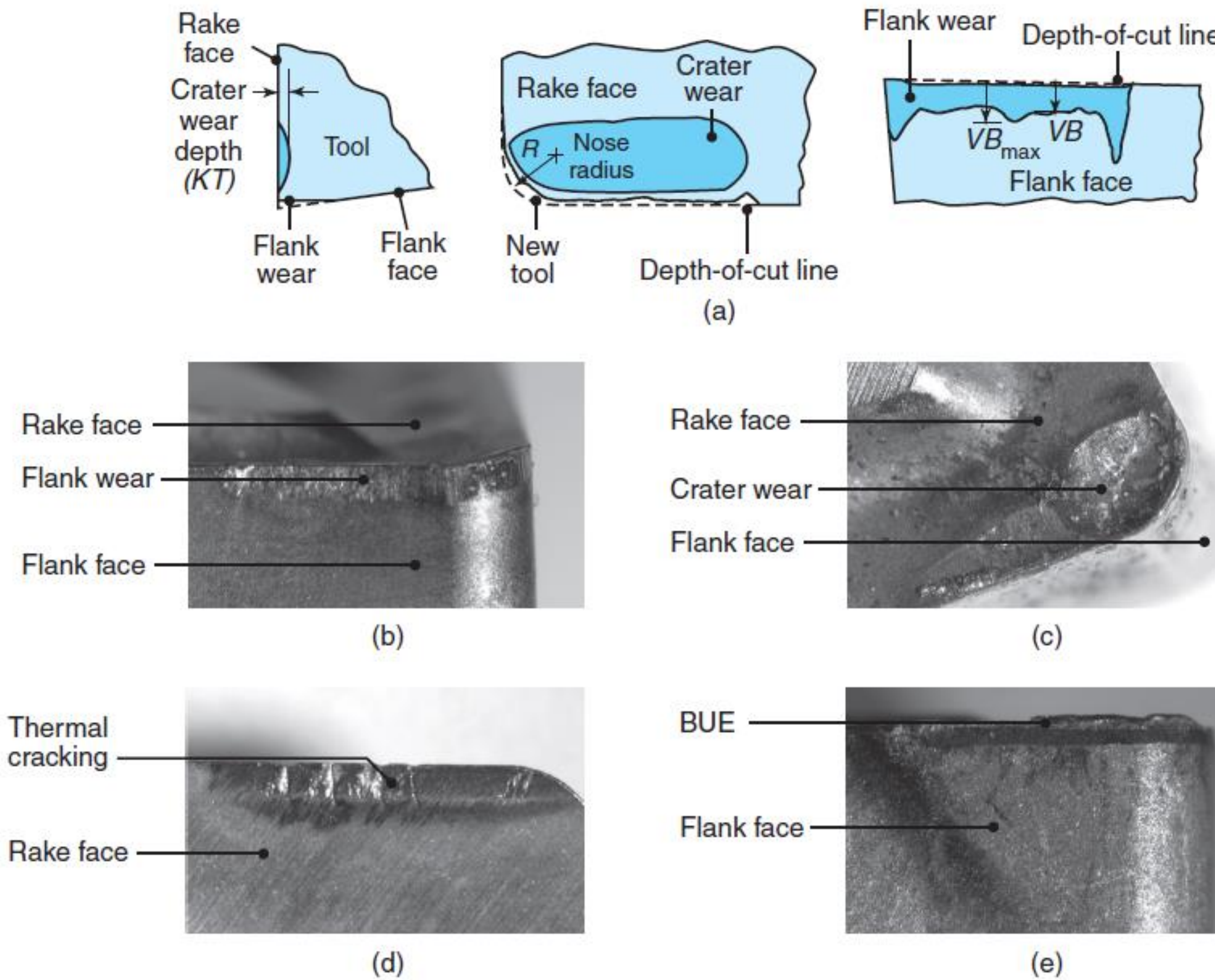
- Wear is a gradual process
- The rate of tool wear depends on tool and workpiece materials, tool geometry, process parameters, cutting fluids and the characteristics of the machine tool

Tool Life: Wear and Failure

- Tool wear and the changes in tool geometry and they are classified as:

a) *Flank wear* occurs at the new surface
b) *Crater wear* occurs at the rake face
c) *Nose wear* affects the surface finish
d) *Notching plastic deformation of the tool tip*
e) *Chipping*
f) *Gross fracture*

Tool Life: Wear and Failure



Tool Life: Wear and Failure: Flank Wear

- Occurs on the relief (flank) face of the tool
- It is due to (a) rubbing of the tool along the machined surface and (b) high temperatures
- *Taylor tool life equation* states that

$$VT^n = C$$

V = cutting speed

T = time taken to develop a certain flank **wear land**

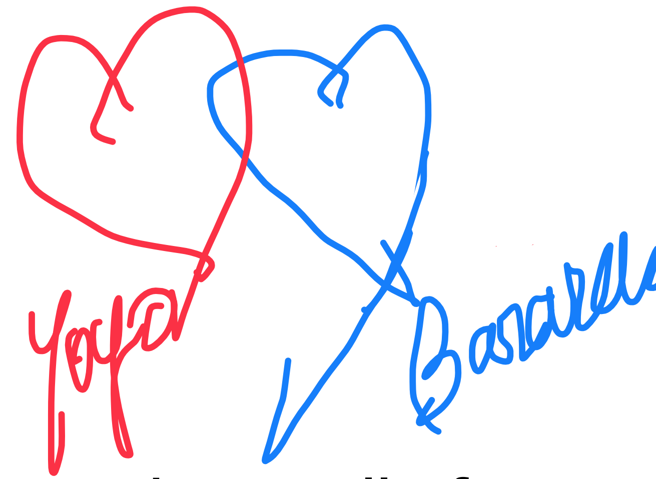
n = an exponent that depend on tool and workpiece materials and cutting conditions

C = constant

- To appreciate the importance of the exponent,

$$T = \left(\frac{C}{V}\right)^{1/n}$$

Tool Life: Wear and Failure: Flank Wear



- For turning, it can be modified to

$$VT^n d^x f^y = C$$

- Since x and y must be determined experimentally for each cutting condition, we have

$$T = C^{1/n} V^{-1/n} d^{x/n} f^{y/n}$$

Ranges of n Values for the Taylor Equation (21.20a) for Various Tool Materials	
High-speed steels	0.08–0.2
Cast alloys	0.1–0.15
Carbides	0.2–0.5
Coated carbides	0.4–0.6
Ceramics	0.5–0.7

Start with a high cutting speed but it is gradually decreased

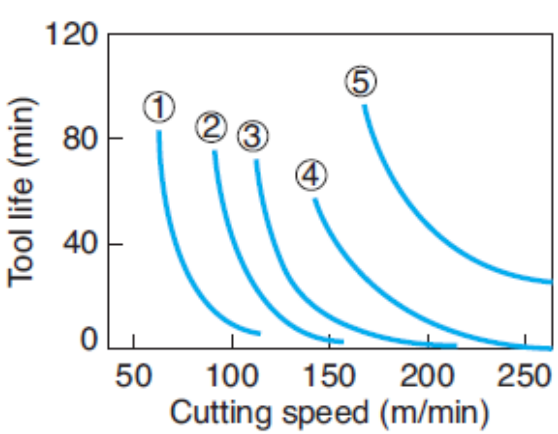
- To obtain a constant tool life:

1. The cutting speed must be decreased
2. Depending on the exponents

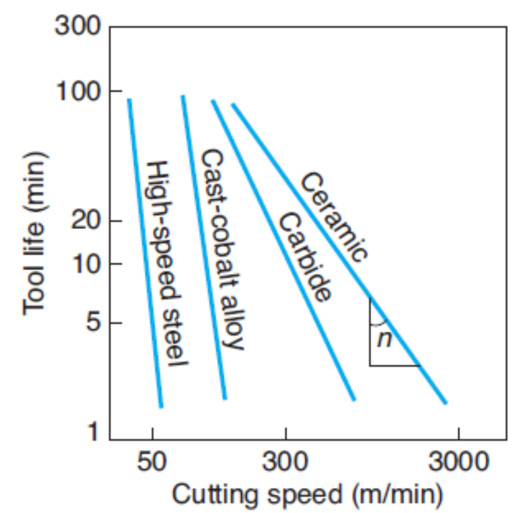
Tool Life: Wear and Failure: Flank Wear

Tool-life Curves

- *Tool-life curves* are plots of experimental data from performed cutting tests on various materials under different cutting conditions
- The exponent *n* can be determined from tool-life



	Hardness (HB)	Ferrite	Pearlite
① As cast	265	20%	80%
② As cast	215	40	60
③ As cast	207	60	40
④ Annealed	183	97	3
⑤ Annealed	170	100	—



- As temperature increases, flank wear rapidly increases

Tool Life: Wear and Failure: Flank Wear

EXAMPLE 21.2

Increasing Tool Life by Reducing the Cutting Speed

Using the Taylor Equation for tool life and letting n=0.5 and C=120, calculate the percentage increase in tool life when the cutting speed is reduced by 50%.

Solution

Since n=0.5, we have $0.5V_1\sqrt{T_2} = V_1\sqrt{T_1} \Rightarrow \frac{T_2}{T_1} = 4$

This indicates that the change in tool life is

$$\frac{T_2 - T_1}{T_1} = \left(\frac{T_2}{T_1}\right) - 1 = 3 \text{ or } 300\% \text{ increase}$$

Tool Life: Wear and Failure: Flank Wear

Allowable Wear Land

- Cutting tools need to be replaced when:

1. Surface finish of the machined workpiece begins to deteriorate
2. Cutting forces increase significantly
3. Temperature rises significantly

Allowable Average Wear Land (see *VB* in Fig. 21.15a) for Cutting Tools in Various Machining Operations

	Allowable wear land (mm)	
Operation	High-speed steel tools	Carbide tools
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

Note: Allowable wear for ceramic tools is about 50% higher. Allowable notch wear, VB_{max}, is about twice that for VB.

Tool Life: Wear and Failure: Flank Wear

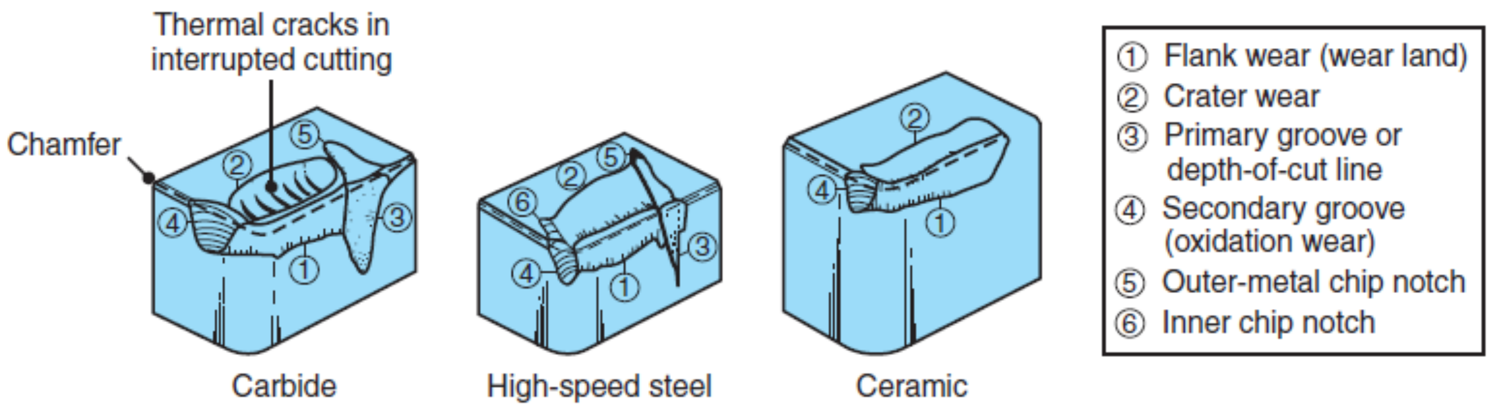
EXAMPLE 21.3

Effect of Cutting Speed on Material Removal

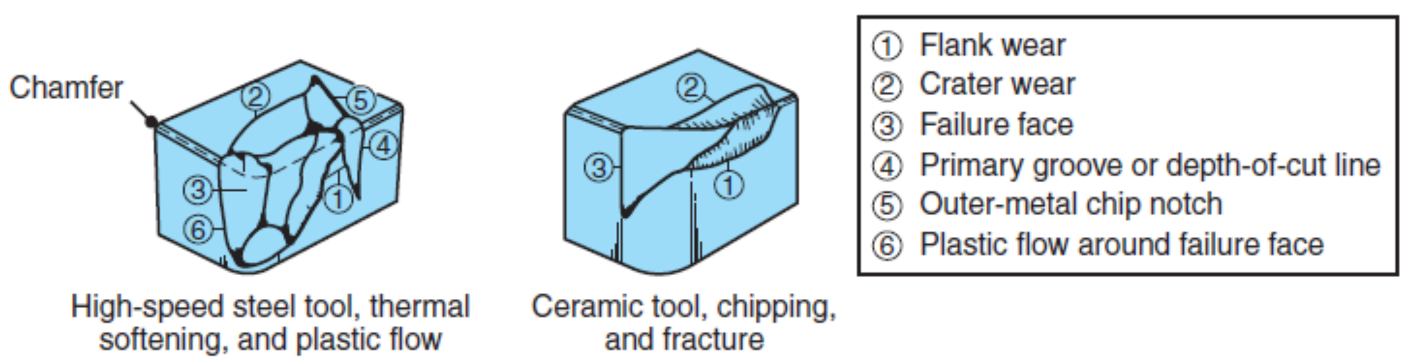
- When cutting speed is 60 m/min, tool life is 40 min
- The tool travels a distance of 60 x 40 = 2400 m
- When cutting speed is increased to 120 m/min, tool life reduced 5 min and travel 600 m
- It can be seen that by *decreasing* the cutting speed, *more* material is removed between tool changes

Tool Life: Wear and Failure: Crater Wear

- *Crater wear* occurs on the rake face of the tool



(a)



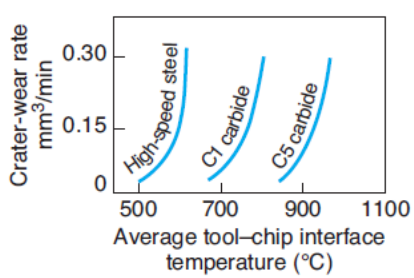
(b)

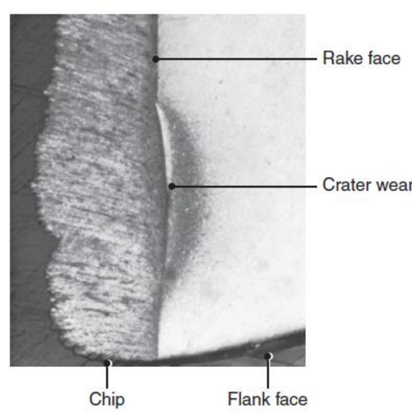
Tool Life: Wear and Failure: Crater Wear

- Factors influencing crater wear are

1. The temperature at the tool–chip interface
2. The chemical affinity between the tool and workpiece materials

- Diffusion rate increases with increasing temperature, crater wear increases as temperature increases
- Location of the max depth of crater wear, *KT*, coincides with the location of the *max temperature* at the tool–chip interface





Tool Life: Wear and Failure:
Other Types of Wear, Chipping, and Fracture

- *Nose wear* is the rounding of a sharp tool due to mechanical and thermal effects
- It dulls the tool, affects chip formation and causes rubbing of the tool over the workpiece
- Tools also may undergo *plastic deformation* because of temperature rises in the cutting zone
- Tools may undergo *chipping*, where small fragment from the cutting edge of the tool breaks away
- Chipping may occur in a region of the tool where a small crack already exists
- Two main causes of chipping: **Mechanical shock & Thermal fatigue**

Tool Life: Wear and Failure: Tool-condition Monitoring

- Tool-condition monitoring systems are integrated into computer numerical control and programmable logic controllers
- Classified into 2 categories:

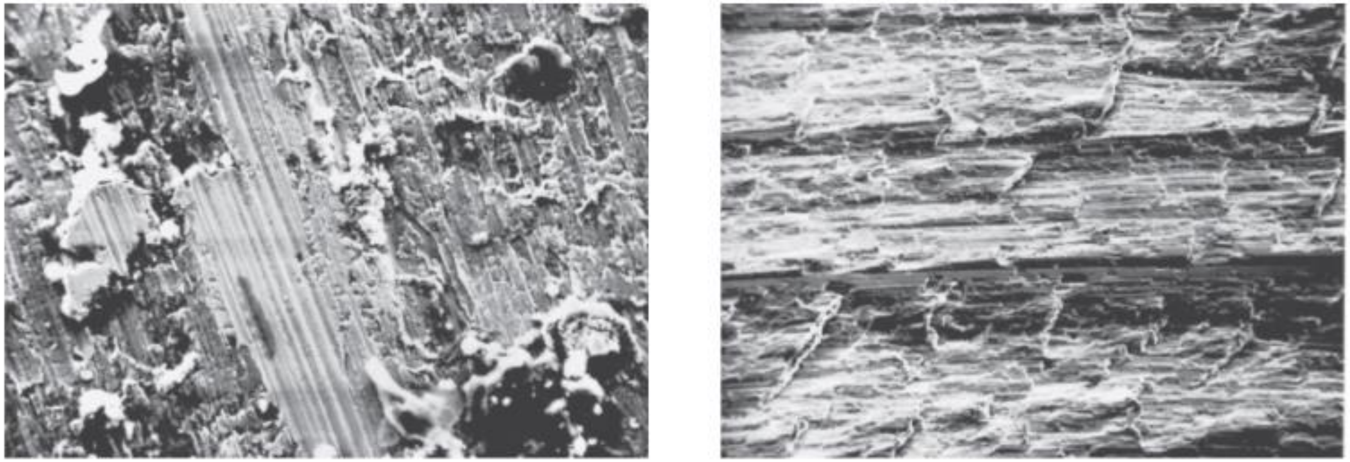
1. **Direct method** is observing the condition of a cutting tool involves optical measurements of wear
2. **Indirect methods** is observing tool conditions involve the correlation of the tool condition with parameters

- Another similar system consists of transducers, which continually monitor torque and forces during cutting

Surface Finish and Integrity

morphology of the surface

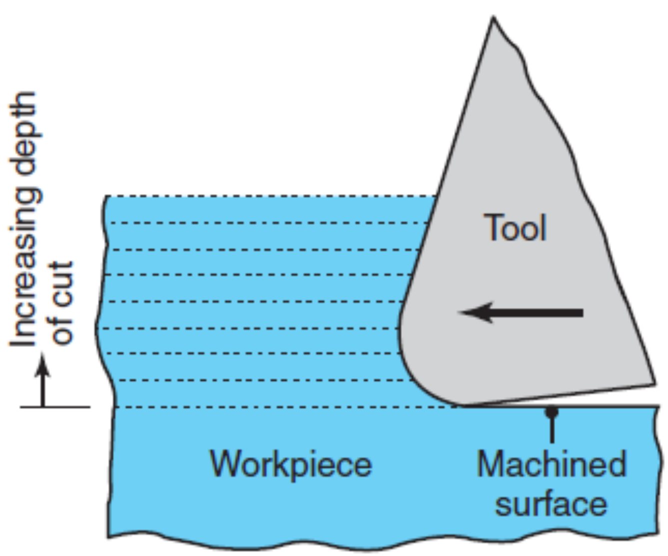
- Surface finish influences the dimensional accuracy of machined parts, properties and performance in service
- *Surface finish* describes the geometric features of a surface while *surface integrity* pertains to material properties
- The *built-up edge* has the greatest influence on surface finish

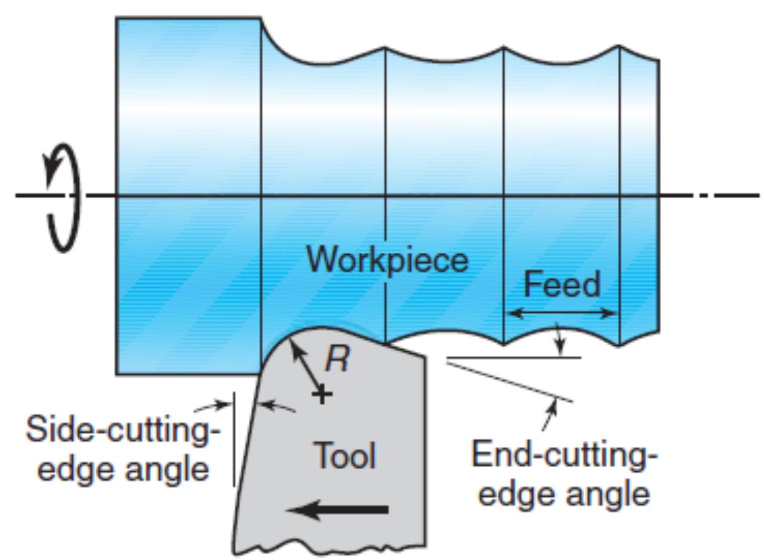


(a) (b)

Surface Finish and Integrity

- A *dull* tool has a large radius along its edges
- In a turning operation, the tool leaves a spiral profile (**feed marks**) on the machined surface as it moves across the workpiece
- Typical surface roughness is expressed as $R_t = \frac{f^2}{8R}$





Surface Finish and Integrity

microstructure of the surface

- Factors influencing *surface integrity* are:

1. Temperatures generated
2. Surface residual stresses
3. Plastic deformation and strain hardening of the machined surfaces, tearing and cracking

- 2 Finish machining is considering the surface finish to be produced
- 1 Rough machining is to remove a large amount of material at a high rate

Machinability

- *Machinability* is defined in terms of:

1. Surface finish and surface integrity high
2. Tool life high
3. Force and power required low
4. The level of difficulty in chip control low

- Good machinability indicates good surface finish and surface integrity, a long tool life, and low force and power requirements
- **Machinability ratings (indexes)** are available for each type of material and its condition

Machinability: Machinability of Ferrous Metals

Steels

- If a carbon steel is too ductile, chip formation can produce built-up edge, leading to poor surface finish
- If too hard, it can cause abrasive wear of the tool because of the presence of carbides in the steel
- In **leaded steels**, a high percentage of lead solidifies at the tips of manganese sulfide inclusions
- **Calcium-deoxidized steels** contain oxide flakes of calcium silicates (CaSiO) that reduce the strength of the secondary shear zone and decrease tool–chip interface friction and wear

Machinability:
Machinability of Ferrous Metals

Effects of Various Elements in Steels

- Presence of *aluminum* and *silicon* is harmful, as it combine with oxygen to form aluminum oxide and silicates, which are hard and abrasive
- Thus tool wear increases and machinability reduce

Stainless Steels

FCC structure

- Austenitic (300 series) steels are difficult to machine

BCC structure

- Ferritic stainless steels (also 300 series) have good machinability
- Martensitic (400 series) steels are abrasive so it's difficult to machine it. We can use an expensive cutting tool or use non-traditional machining processes

Machinability:
Machinability of Nonferrous Metals

- **Aluminum** is very easy to machine
- **Beryllium** requires machining in a controlled environment
- **Cobalt-based alloys** require sharp, abrasion-resistant tool materials and low feeds and speeds
- **Copper** can be difficult to machine because of buildup edge formation
- **Magnesium** is very easy to machine, with good surface finish and prolonged tool life best choice
- **Titanium** and its alloys have very poor thermal conductivity
- **Tungsten** is brittle, strong, and very abrasive

Machinability:
Machinability of Miscellaneous Materials

- Machining **thermoplastics** requires sharp tools with positive rake angles, large relief angles, small depths of cut and feed and high speeds
- **Polymer-matrix composites** are difficult to machine
- **Metal-matrix and ceramic-matrix composites** can be difficult to machine, depending on the properties of the matrix material and the reinforcing fibers
- polymer
  In wood, The type of chips and the surfaces produced also vary significantly, depending on the type of **wood** and its condition

composites can be separated on a macro structure level while alloys can be separated on a micro structure level

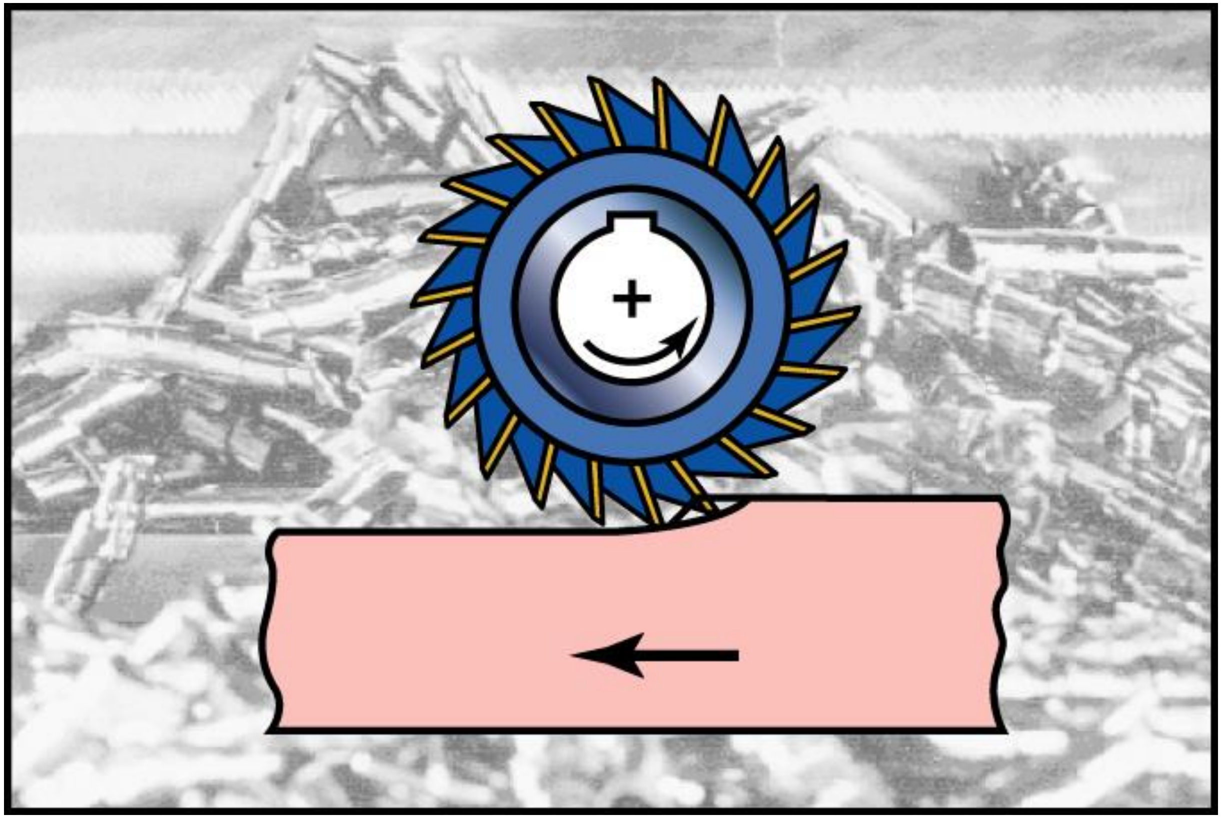
Machinability: Thermally Assisted Machining

- In *thermally assisted machining* (**hot machining**), a source of heat is focused onto an area just ahead of the cutting tool
- Advantages of hot machining are:

1. Reduced cutting forces
    1. Increased tool life
2. Higher material-removal rates
3. Reduced tendency for vibration and chatter

Chapter 24

Machining Processes Used to Produce Various Shapes: Milling



low complexity → medium complexity

Parts Made with Machining Processes of Chapter 24

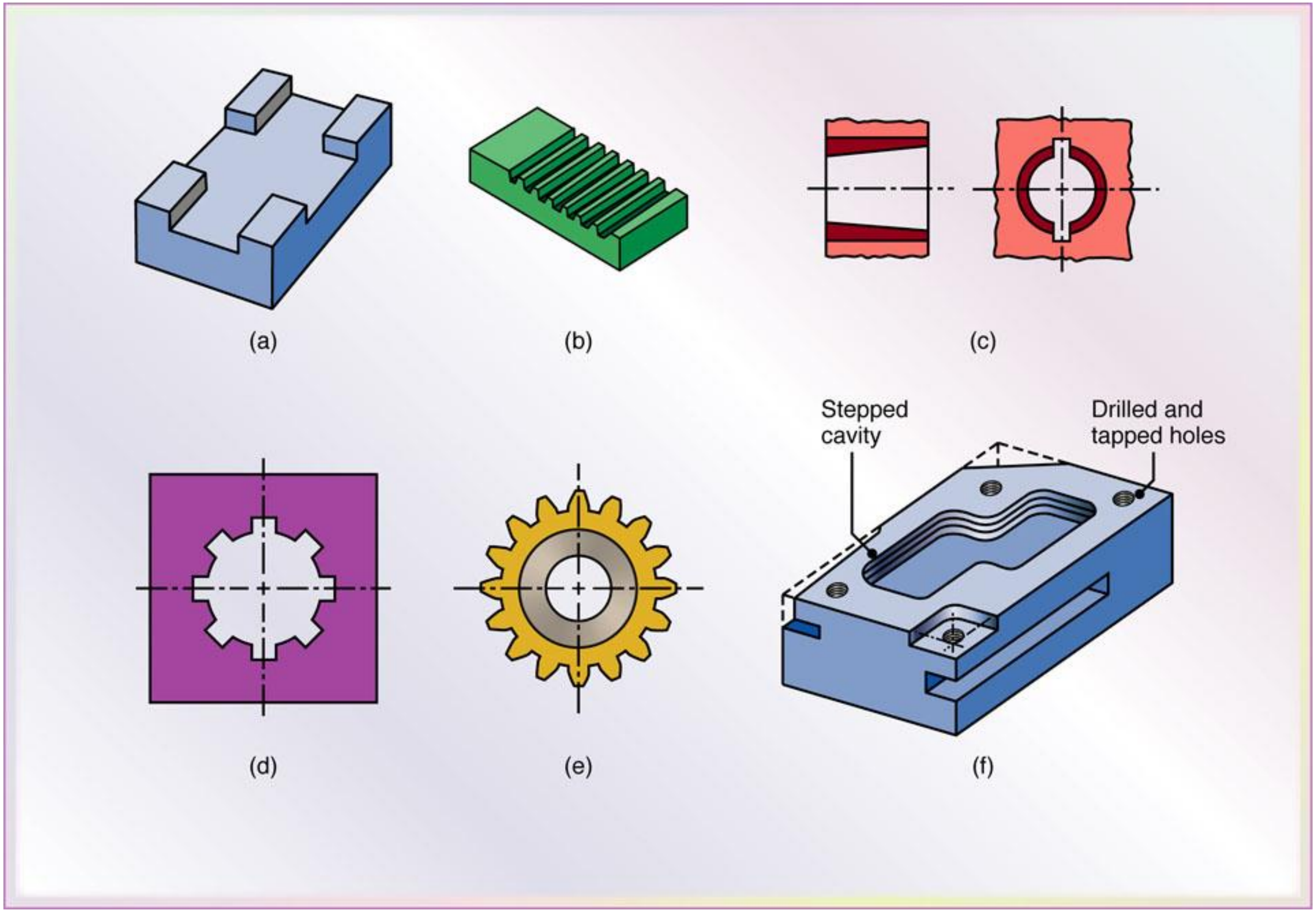


Figure 24.1 Typical parts and shapes that can be produced with the machining processes described in this chapter.

Milling and Milling Machines
Milling operations

- Milling: a process in which a rotating multi-tooth cutter removes material while traveling along various axes with respect to the workpiece.
- Figure 24.2: basic types of milling cutters & milling operations
- In peripheral milling (also called plain milling), the axis of cutter rotation is parallel to the workpiece surface. When the cutter is longer than the width of the cut, the process is called slab milling

Milling Cutters and Milling Operations

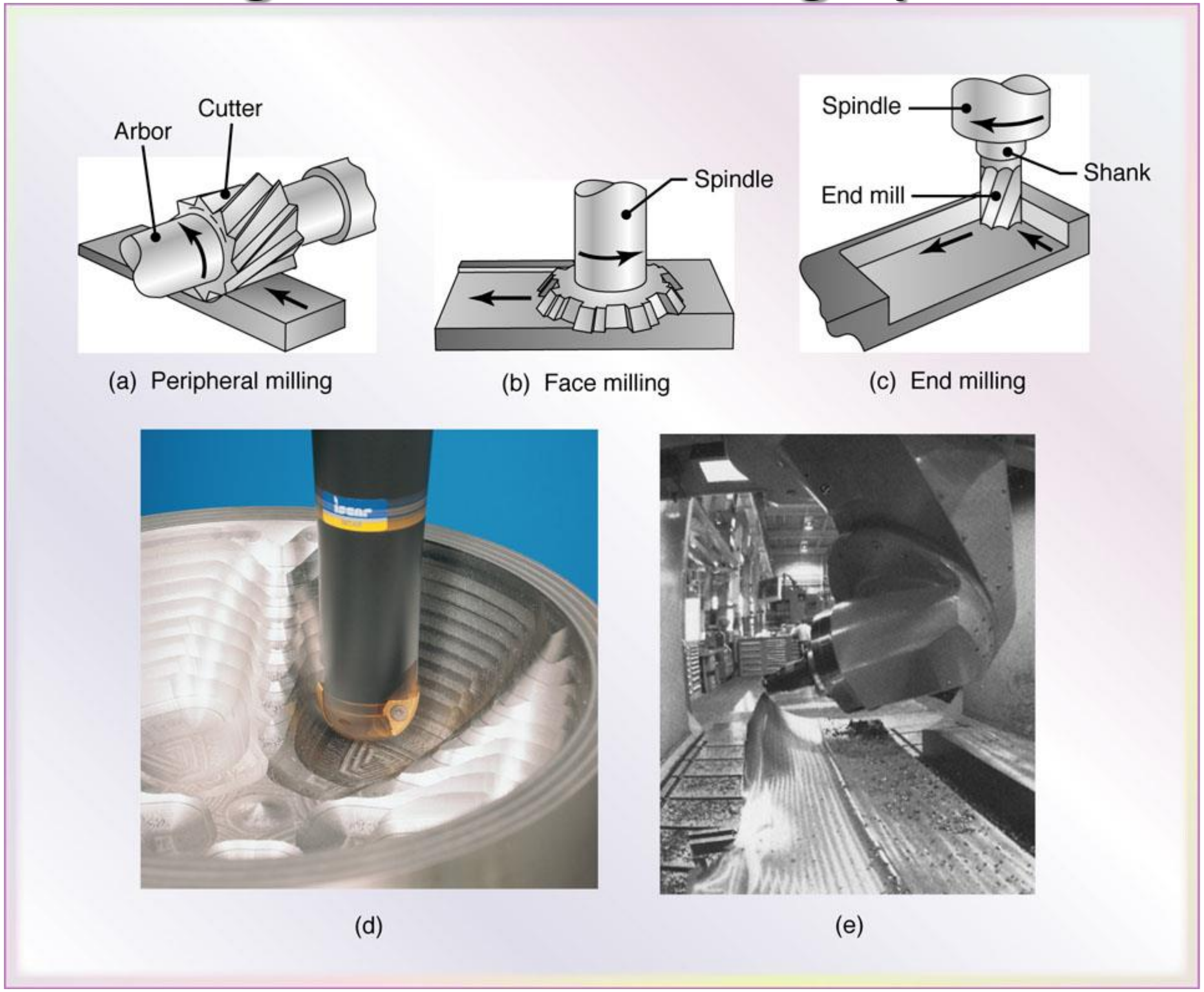


Figure 24.2 Some basic types of milling cutters and milling operations. (a) Peripheral milling. (b) Face milling. (c) End milling. (d) Ball-end mill with indexable coated-carbide inserts machining a cavity in a die block. (e) Milling a sculptured surface with an end mill, using a five-axis numerical control machine. *Source*: (d) Courtesy of Iscar. (e) Courtesy of The Ingersoll Milling Machine Co.

What is the difference between up and down milling?

Milling Operations

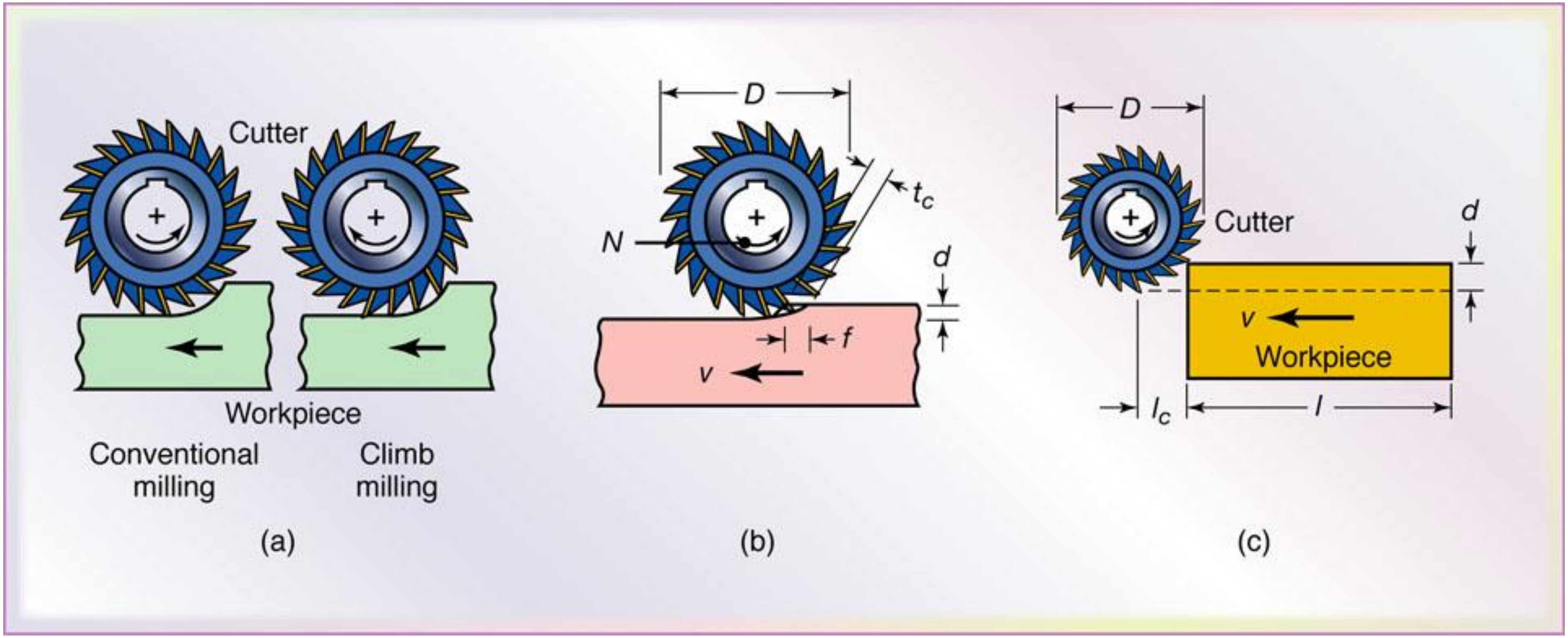


Figure 24.3 (a) Schematic illustration of conventional milling and climb milling. (b) lab-milling operation showing depth-of-cut, *d*; feed per tooth, *f*; chip depth-of-cut, t_c; and workpiece speed, *v*. (c) Schematic illustration of cutter travel distance, l_c, to reach full depth-of-cut.

Milling and Milling Machines
Milling operations: Slab milling

- **Conventional Milling (Up Milling)**
- Max chip thickness is at the end of the cut
- Advantage: tooth engagement is not a function of workpiece surface characteristics, and contamination or scale on the surface does not affect tool life.
- Cutting process is smooth
- Tendency for the tool to chatter
- The workpiece has a tendency to be pulled upward, necessitating proper clamping.

cutting starts from the side and ends at the surface

Milling and Milling Machines
Milling operations: Slab milling

- **Climb Milling (Down Milling)**
- Cutting starts at the surface of the workpiece.
- Downward compression of cutting forces hold workpiece in place
- Because of the resulting high impact forces when the teeth engage the workpiece, this operation must have a rigid setup, and backlash must be eliminated in the table feed mechanism
- Not suitable for machining workpiece having surface scale.

Milling and Milling Machines
Milling operations: Slab milling
Milling Parameters

- N = Rotational speed of the milling cutter, rpm
- f = Feed per tooth, mm/tooth (in/tooth) = υ /N n
- D = Cutter diameter, mm (in)
- n = Number of teeth on cutter
- υ = Linear speed of the workpiece or feed rate, mm/min (in/min)
- V = Surface speed of cutter, m/min (ft/min) = π D N
- l = Length of cut, mm (in)
- t = Cutting time, s or min=(l+lc) / υ
- lc =extent of the cutter's first contact with workpiece lc=$\sqrt{Dd}$
- MRR = mm3/min or in3/min = w d υ , where w is the width of cut
- Torque = N.m (lb.ft) =(Fc) (D/2)
- Power = kW (hp) = (Torque) (ω), where ω = 2π N radians/min

Milling and Milling Machines
Milling operations: Slab milling
Milling Parameters

- **EXAMPLE 24.1 Material-removal Rate, Power, Torque, and Cutting Time in Slab Milling**
- A slab-milling operation is being carried out on a 300-mm-long, 100-mm-wide annealed mild-steel block at a feed f = 0.25 mrn/tooth and a depth of cut d = 3.0 mm. The cutter is D = 50 mm in diameter, has 20 straight teeth, rotates at N = 100 rpm, and, by definition, is wider than the block to be machined, Calculate the material-removal rate, estimate the power and torque required for this operation, and calculate the cutting time.
- **Solution:**

$$v = fNn = (0.25)(100)(20) = 500 \text{ mm/min.}$$

$$\text{MRR} = \frac{lwd}{t} = wdv, \qquad \text{MRR} = (100)(3)(500) = 150{,}000 \text{ mm}^3/\text{min.}$$

From table 21.2 U=3 W.S/mm^3

Milling and Milling Machines
Milling operations: Slab milling
Milling Parameters-Example 24.2

$$\text{Power} = (3)(150{,}000)\left(\tfrac{1}{60}\right) = 7.5 \text{ kW}$$

$$\text{Torque} = \frac{\text{Power}}{\text{Rotational speed}}$$

$$= \frac{(7500)(60 \text{ N·m/min} \cdot \text{W})}{(100 \text{ rpm})(2\pi)}$$

$$= 716 \text{ N·m}$$

$$l_c = \sqrt{Dd} = \sqrt{(50)(3)} = 12.2 \text{ mm.}$$

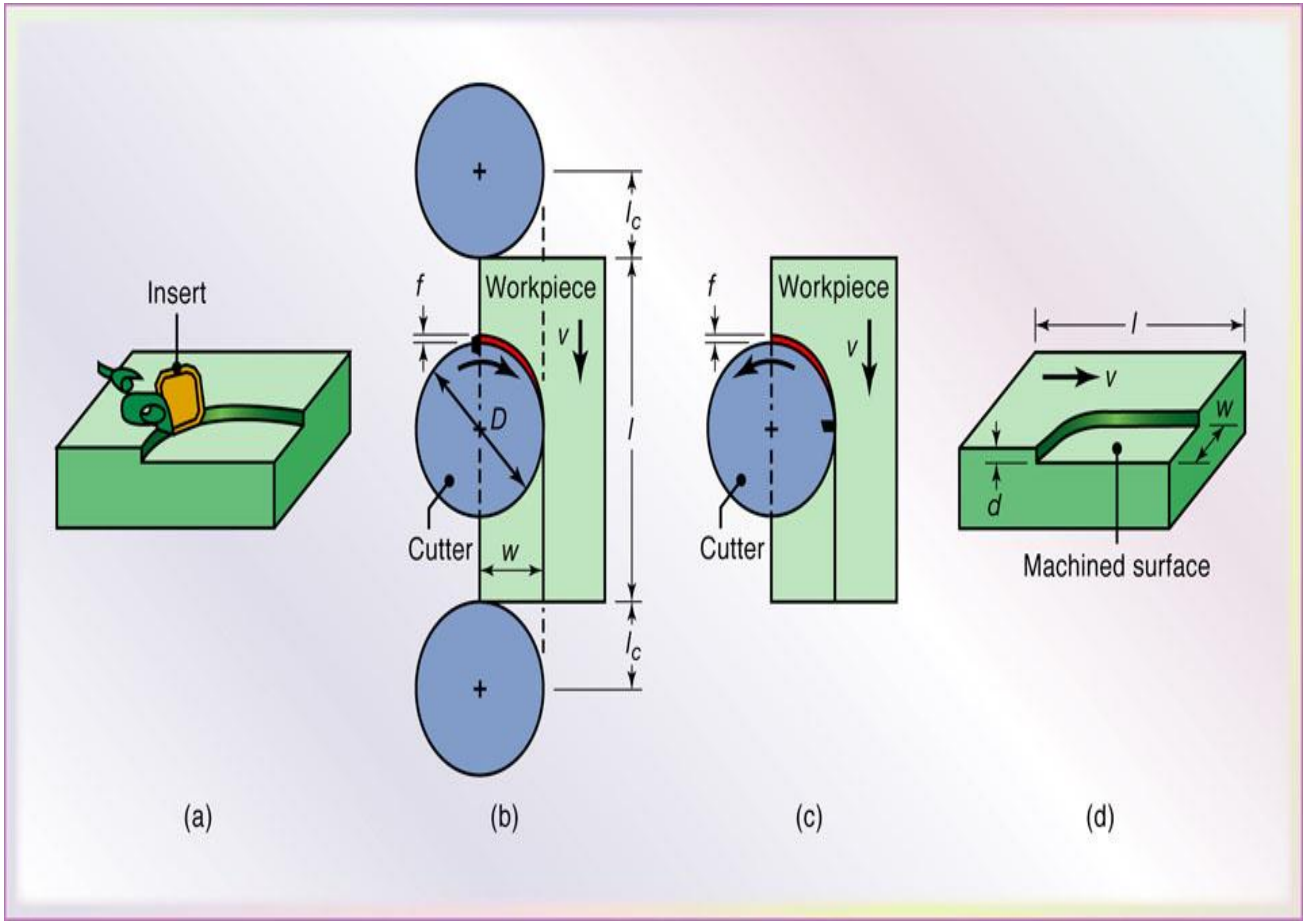
Thus, the cutting time is

$$t = \frac{300 + 12.2}{500} = 0.62 \text{ min} = 37.2 \text{ s.}$$

Face-Milling Operation

The cutter is mounted on a spindle whose axis of rotation is perpendicular to wp surface.

$L_c = D/2$



$$L_c = \sqrt{R^2 - (R-d)^2}$$

$$L_c = \sqrt{\cancel{R^2} - \cancel{R^2} + 2Rd - d^2}$$

$$L_c = \sqrt{\cancel{2}\frac{D}{\cancel{2}}d - d^2}$$

Figure 24.4 Face-milling operation showing (a) action of an insert in face milling; (b) climb milling; (c) conventional milling; (d) dimensions in face milling. The width of cut, *w,* is not necessarily the same as the cutter radius.

when depth of cut is high

Face-Milling Cutter with Indexable Inserts

Figure 24.5 A face-milling cutter with indexable inserts. *Source*: Courtesy of Ingersoll Cutting Tool Company.

Effect of Insert Shape on Feed Marks on a Face-Milled Surface

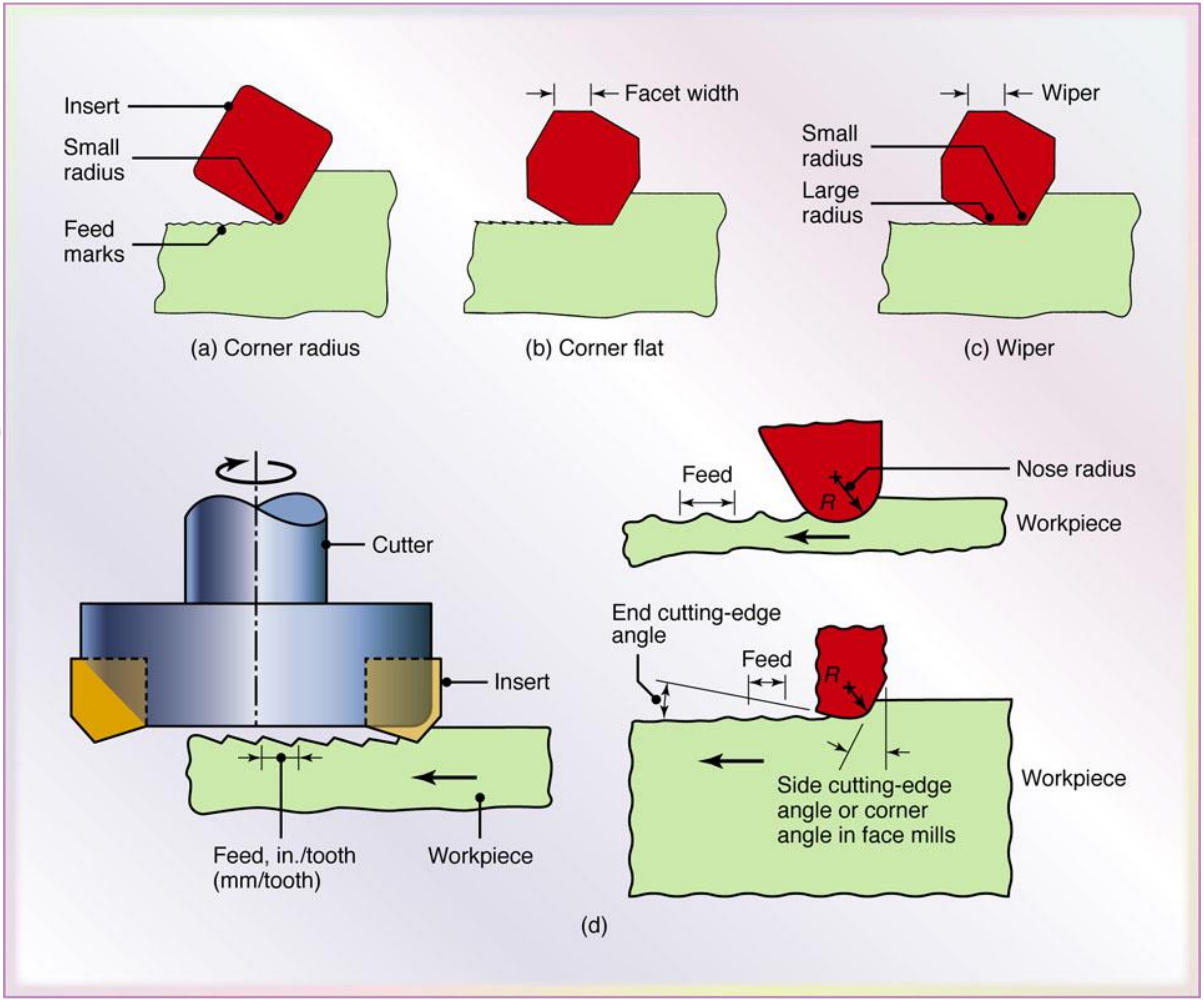


Figure 24.6 Schematic illustration of the effect of insert shape on feed marks on a face-milled surface: (a) small corner radius, (b) corner flat on insert, and (c) wiper, consisting of small radius followed by a large radius which leaves smoother feed marks. (d) Feed marks due to various insert shapes.

Face-Milling Cutter

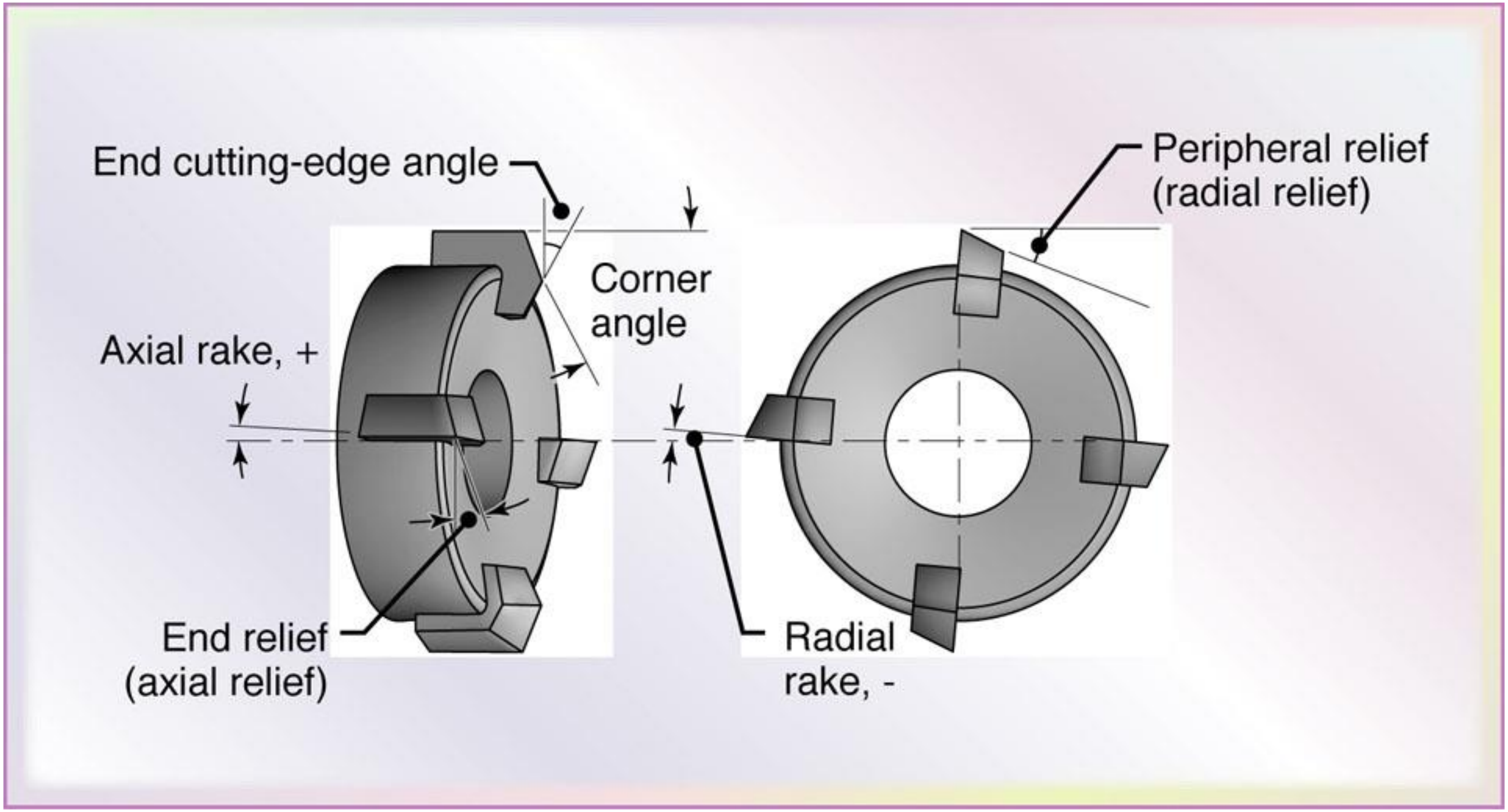


Figure 24.7 Terminology for a face-milling cutter.

Effect of Lead Angle on Undeformed Chip Thickness in Face Milling

- Lead angle of insert has a direct influence on undeformed chip thickness
- As the lead angle increases, undeformed chip thickness decreases, length of contact increases
- Range of lead angles = 0-45
- X-sectional area of undeformed chip remains constant
- As lead angle decreases, there is a smaller vertical force comp (axial force)
- Ratio of cutter diameter, D, to width of cut should be no less than 3:2

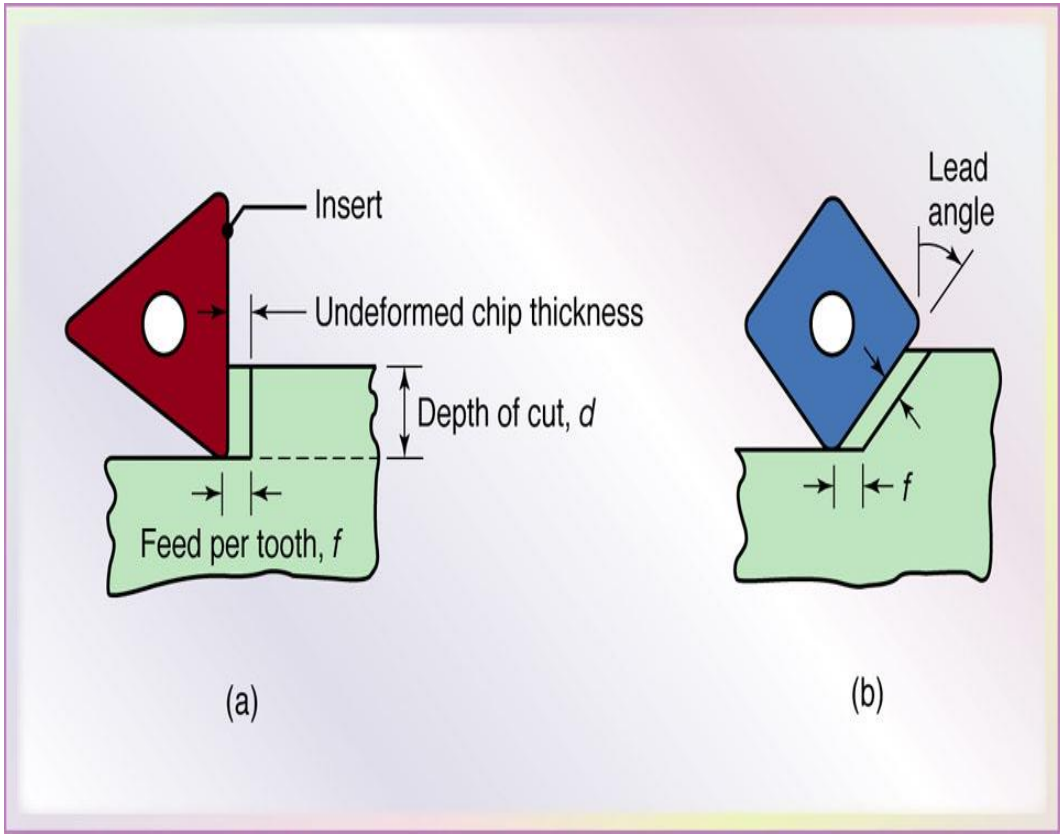


Figure 24.8 The effect of the lead angle on the undeformed chip thickness in face milling. Note that as the lead angle increases, the chip thickness decreases, but the length of contact (i.e., chip width) increases. The edges of the insert must be sufficiently large to accommodate the contact length increase.

Position of Cutter and Insert in Face Milling

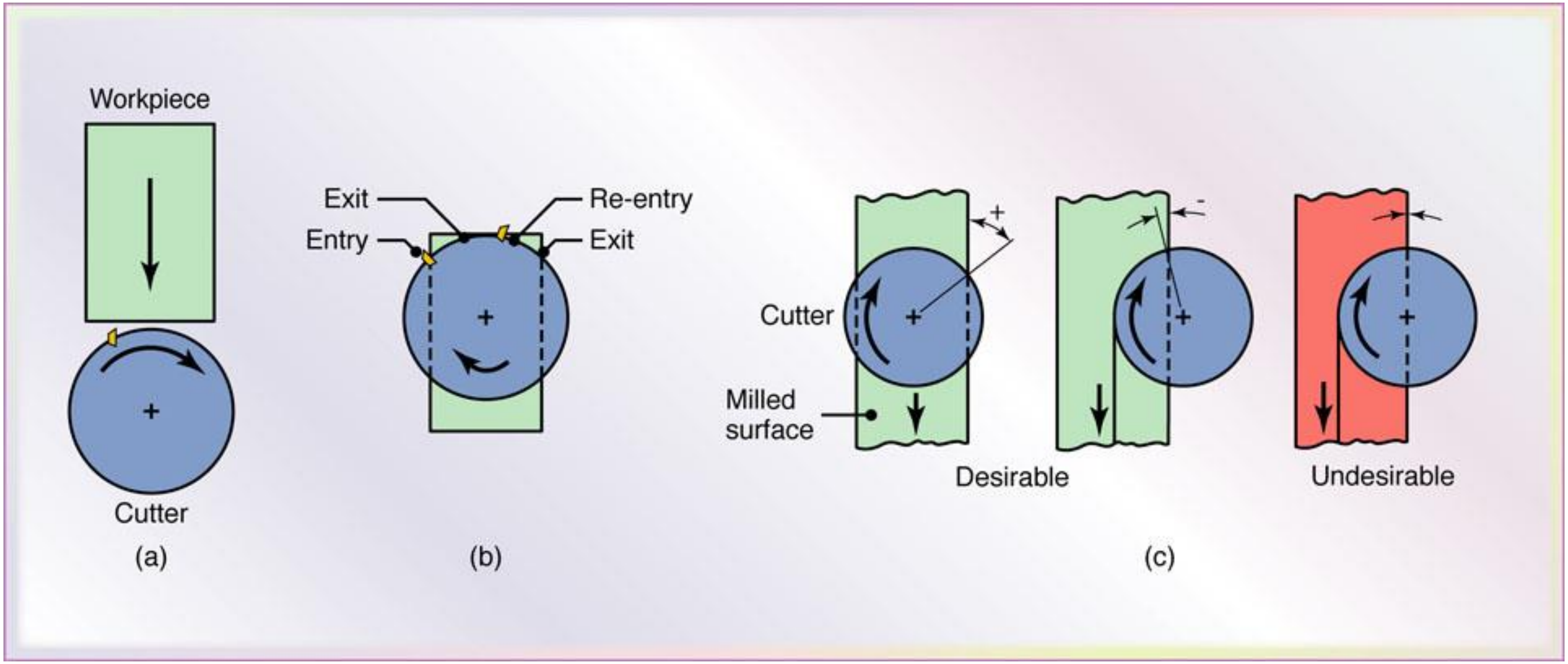


Figure 24.9 (a) Relative position of the cutter and insert as it first engages the workpiece in face milling. (b) Insert positions towards the end of cut. (c) Examples of exit angles of insert, showing desirable (positive or negative angle) and undesirable (zero angle) positions. In all figures, the cutter spindle is perpendicular to the page and rotates clockwise.

EXAMPLE 24.2 Material-removl Rate, Power Required, and Cutting Time in Face Milling

Milling and Milling Machines
Milling operations: End Milling

- The cutter usually rotates on an axis perpendicular to workpiece
- End mills are available with hemispherical ends (bull nose mills) for the production of sculptured surfaces, such on dies and molds.
- End milling can produce a variety of surfaces at any depth, such as curved, stepped, and pocketed.

Ball Nose End Mills

Figure 24.10 Ball nose end mills. These cutters are able to produce elaborate contours and are often used in the machining of dies and molds. (See also Fig. 24.2d.) *Source:* Courtesy of Dijet, Inc.

Cutters

a. Straddle: more cutters are used to machine two parallel surfaces on the workpiece
b. Form milling produces curved profiles using cutters that have specially shaped teeth
Slotting and slitting operations are performed with circular cutters. [T-slot cutters,

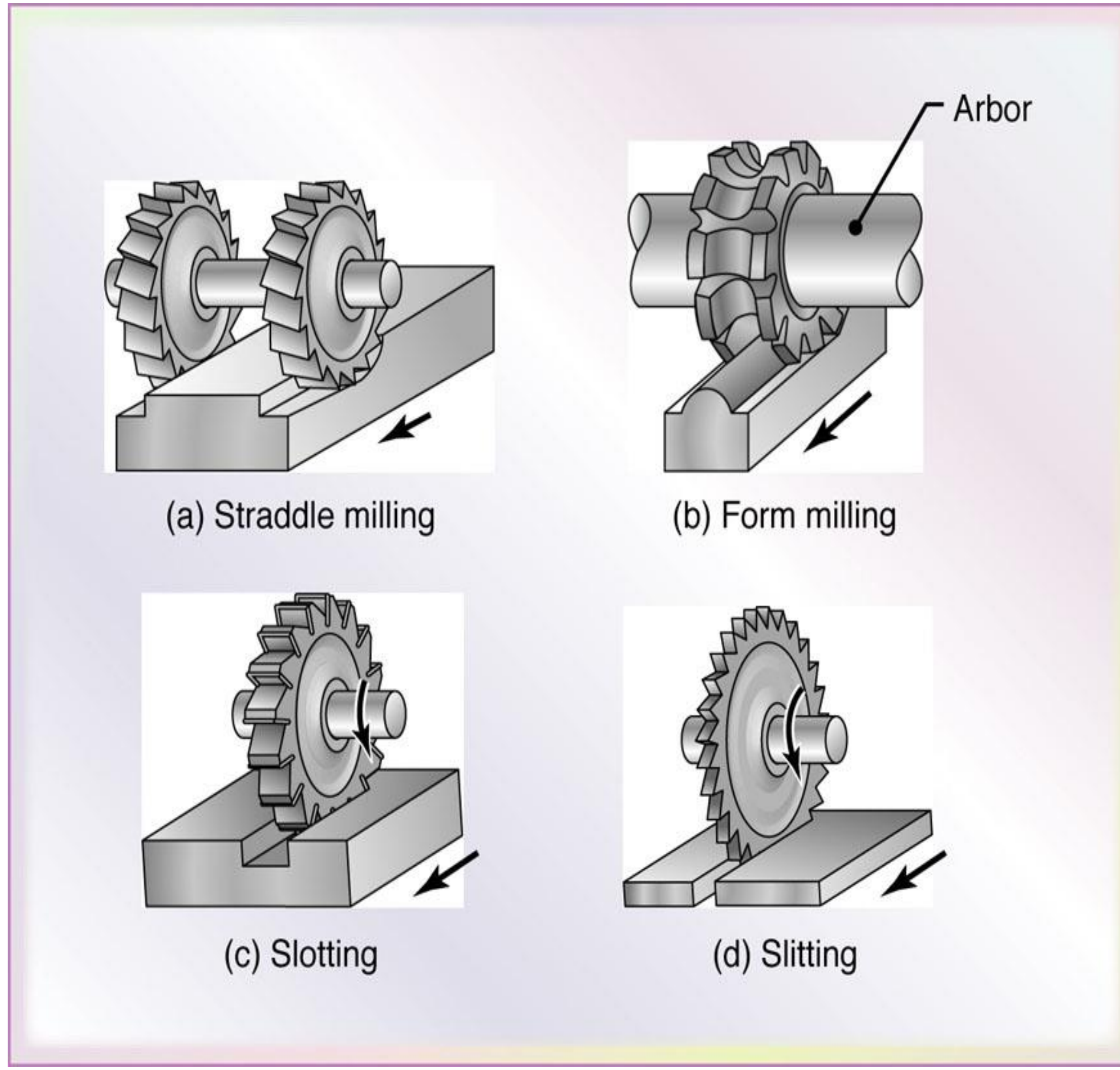


Figure 24.11 Cutters for (a) straddle milling, (b) form milling, (c) slotting, and (d) slitting with a milling cutter.

T-Slot Cutting and Shell Mill

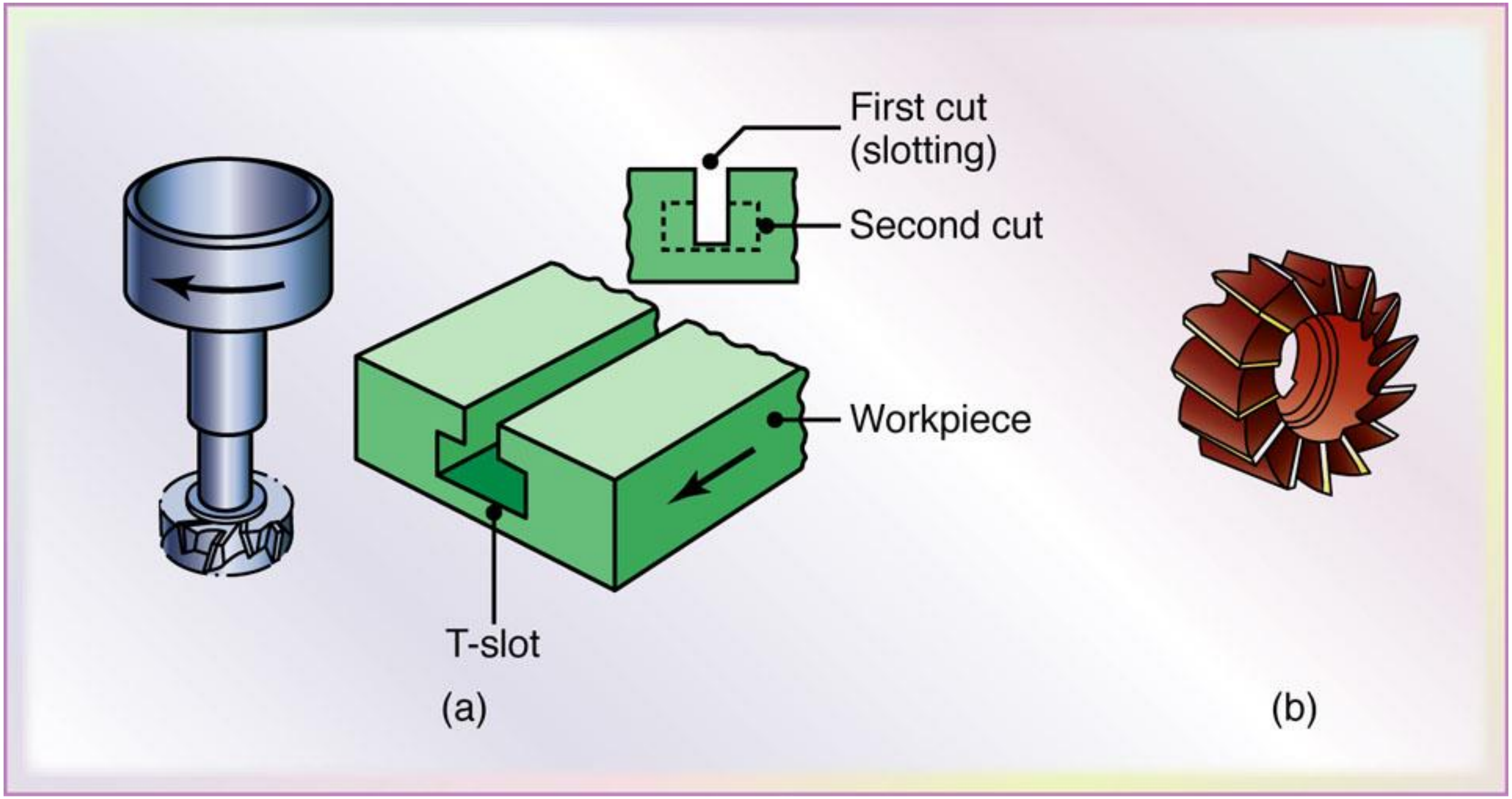


Figure 24.12 (a) T-slot cutting with a milling cutter. (b) A shell mill.

General Recommendations for Milling Operations

TABLE 24.2

General Recommendations for Milling Operations

		General-purpose starting conditions		Range of conditions	
Material	Cutting tool	Feed mm/tooth	Speed m/min	Feed mm/tooth	Speed m/min
Low-carbon and free-machining steels	Uncoated carbide, coated carbide, cermets	0.13–0.20	120–180	0.085–0.38	90–425
Alloy steels					
Soft	Uncoated, coated, cermets	0.10–0.18	90–170	0.08–0.30	60–370
Hard	Cermets, PcBN	0.10–0.15	180–210	0.08–0.25	75–460
Cast iron, gray					
Soft	Uncoated, coated, cermets, SiN	0.10–10.20	120–760	0.08–0.38	90–1370
Hard	Cermets, SiN, PcBN	0.10–0.20	120–210	0.08–0.38	90–460
Stainless steel, Austenitic	Uncoated, coated, cermets	0.13–0.18	120–370	0.08–0.38	90–500
High-temperature alloys Nickel based	Uncoated, coated, cermets, SiN, PcBN	0.10–0.18	30–370	0.08–0.38	30–550
Titanium alloys	Uncoated, coated, cermets	0.13–0.15	50–60	0.08–0.38	40–140
Aluminum alloys					
Free machining	Uncoated, coated, PCD	0.13–0.23	610–900	0.08–0.46	300–3000
High silicon	PCD	0.13	610	0.08–0.38	370–910
Copper alloys	Uncoated, coated, PCD	0.13–0.23	300–760	0.08–0.46	90–1070
Plastics	Uncoated, coated, PCD	0.13–0.23	270–460	0.08–0.46	90–1370

Troubleshooting Guide for Milling Operations

TABLE 24.3

General Troubleshooting Guide for Milling Operations

Problem	Probable causes
Tool breakage	Tool material lacks toughness, improper tool angles, machining parameters too high
Excessive tool wear	Machining parameters too high, improper tool material, improper tool angles, improper cutting fluid
Rough surface finish	Feed per tooth too high, too few teeth on cutter, tool chipped or worn, built-up edge, vibration and chatter
Tolerances too broad	Lack of spindle and workholding stiffness, excessive temperature rise, dull tool, chips clogging cutter
Workpiece surface burnished	Dull tool, depth-of-cut too low, radial relief angle too small
Back striking	Dull cutting tools, tilt in cutter spindle, negative tool angles
Chatter marks	Insufficient stiffness of system; external vibrations; feed, depth of cut, and width of cut too large
Burr formation	Dull cutting edges or too much honing, incorrect angle of entry or exit, feed and depth of cut too high, incorrect insert shape
Breakout	Lead angle too low, incorrect cutting edge geometry, incorrect angle of entry or exit, feed and depth of cut too high

Machined Surface Features in Face Milling

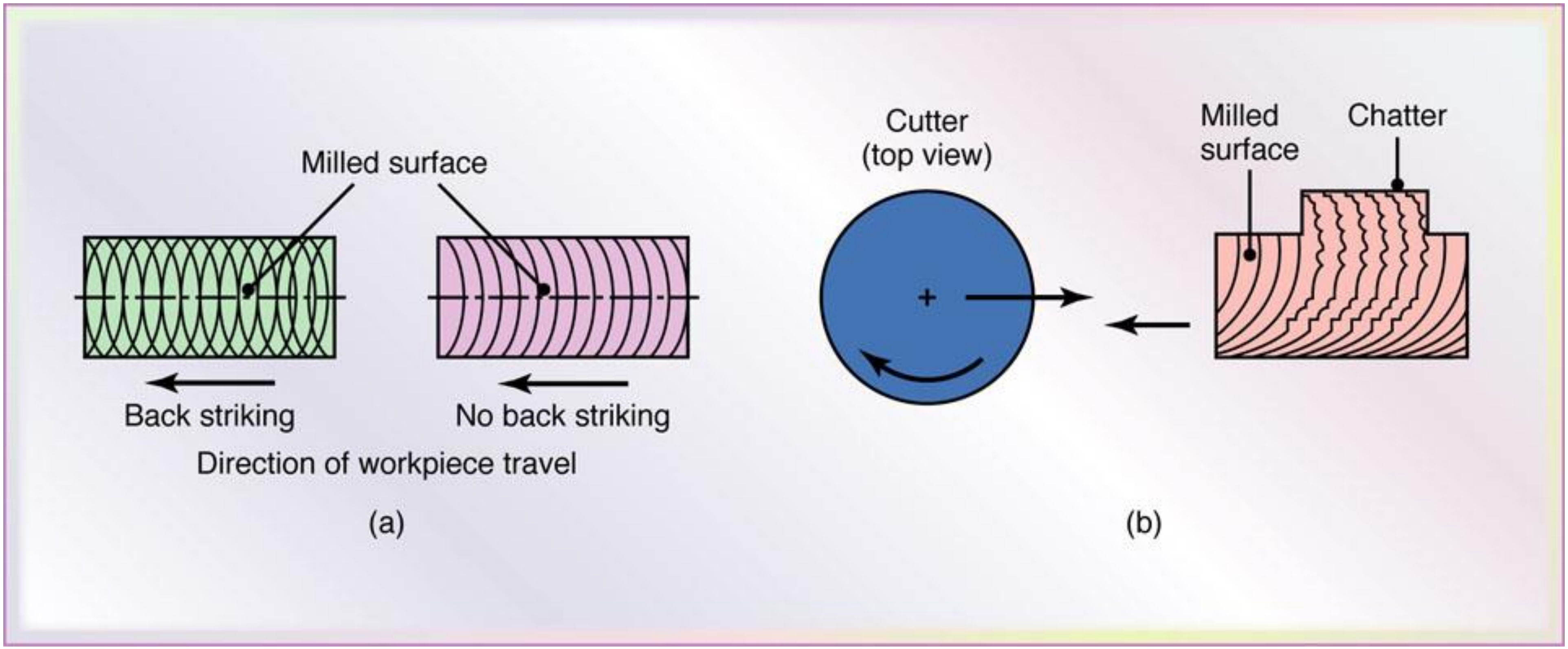


Figure 24.13 Machined surface features in face milling. See also Fig. 24.6.

Edge Defects in Face Milling

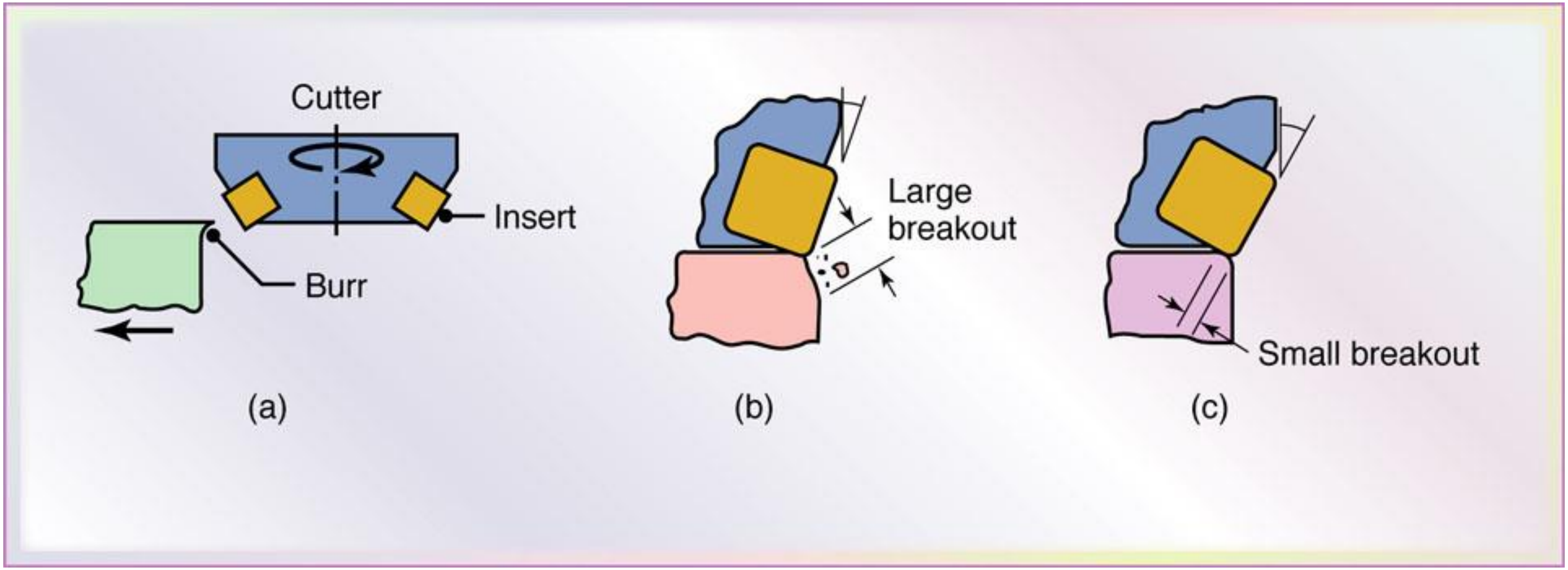


Figure 24.14 Edge defects in face milling: (a) burr formation along workpiece edge, (b) breakout along workpiece edge, and (c) how it can be avoided by increasing the lead angle (see also last row in Table 24.4).

Milling and Milling Machine
Design And Operating Guidelines

- Use standard milling cutters as much as possible
- Chamfers should be used instead of radii
- Avoid internal cavities and pockets with sharp corners
- Workpiece should be sufficiently rigid to minimize any deflections resulting from clamping and cutting forces

Milling and Milling Machine
Milling Machines

- **The basic components of these machines are as follows:**
- **Worktable:** on which the work-piece is clamped using T-slots. The table moves longitudinally relative to the saddle.
- **Saddle:** supports the table and can move in the transverse direction.
- **Knee:** supports the saddle and gives the table vertical movement so that the depth of cut can be adjusted and work-pieces with various heights can be accommodated.
- **Overearm:** used on horizontal machines; it is adjustable to accommodate different arbor lengths.
- **Head:** contains the spindle and cutter holders. In vertical machines, the head may be fixed or can be adjusted vertically, and it can be swiveled in a vertical plane on the column for cutting tapered surfaces.

Column-and-Knee Type Milling Machines

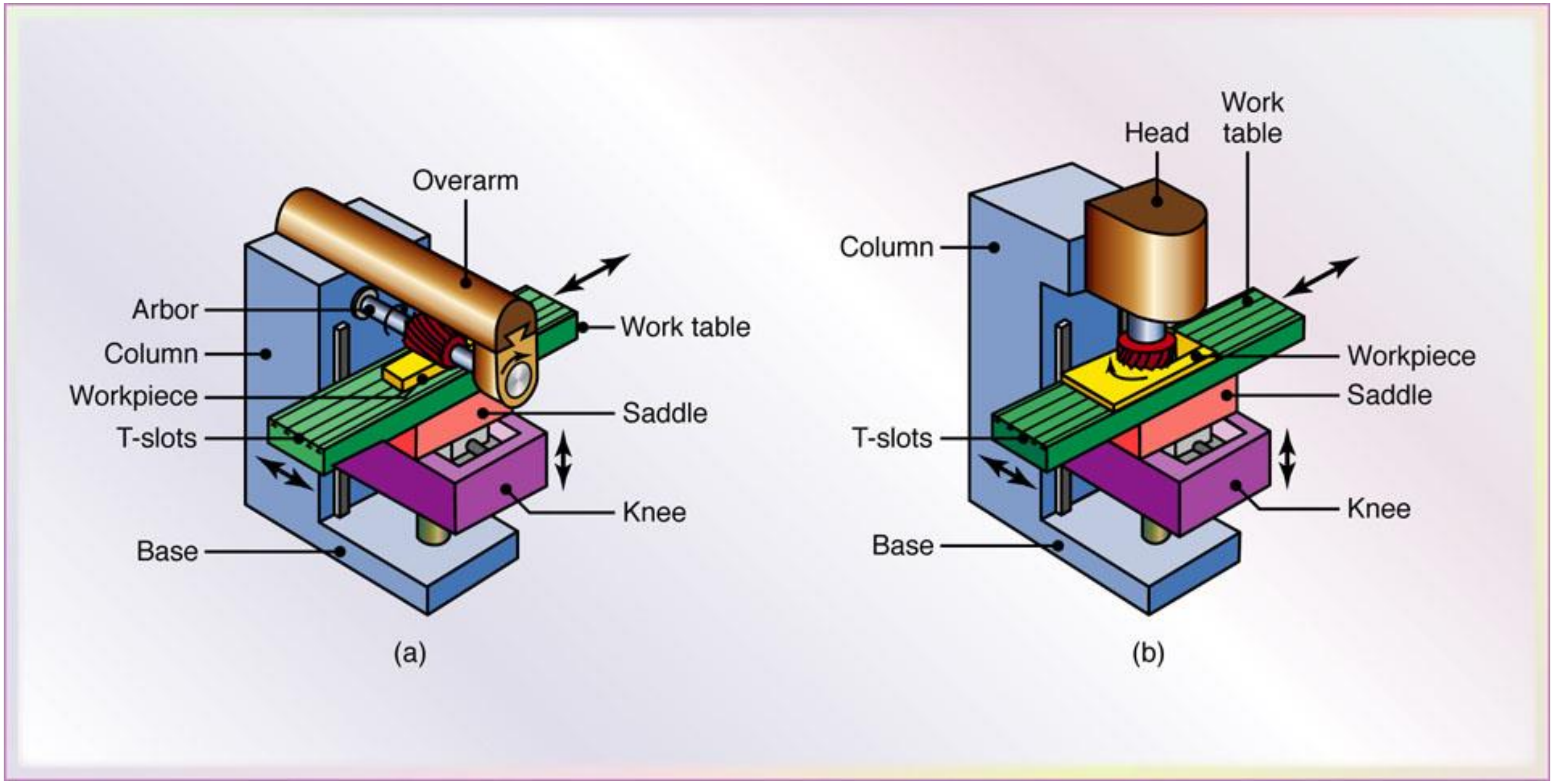


Figure 24.15 Schematic illustration of (a) a horizontal-spindle column-and-knee type milling machine and (b) vertical-spindle column-and-knee type milling machine. *Source*: After G. Boothroyd.

Bed-type Milling Machine

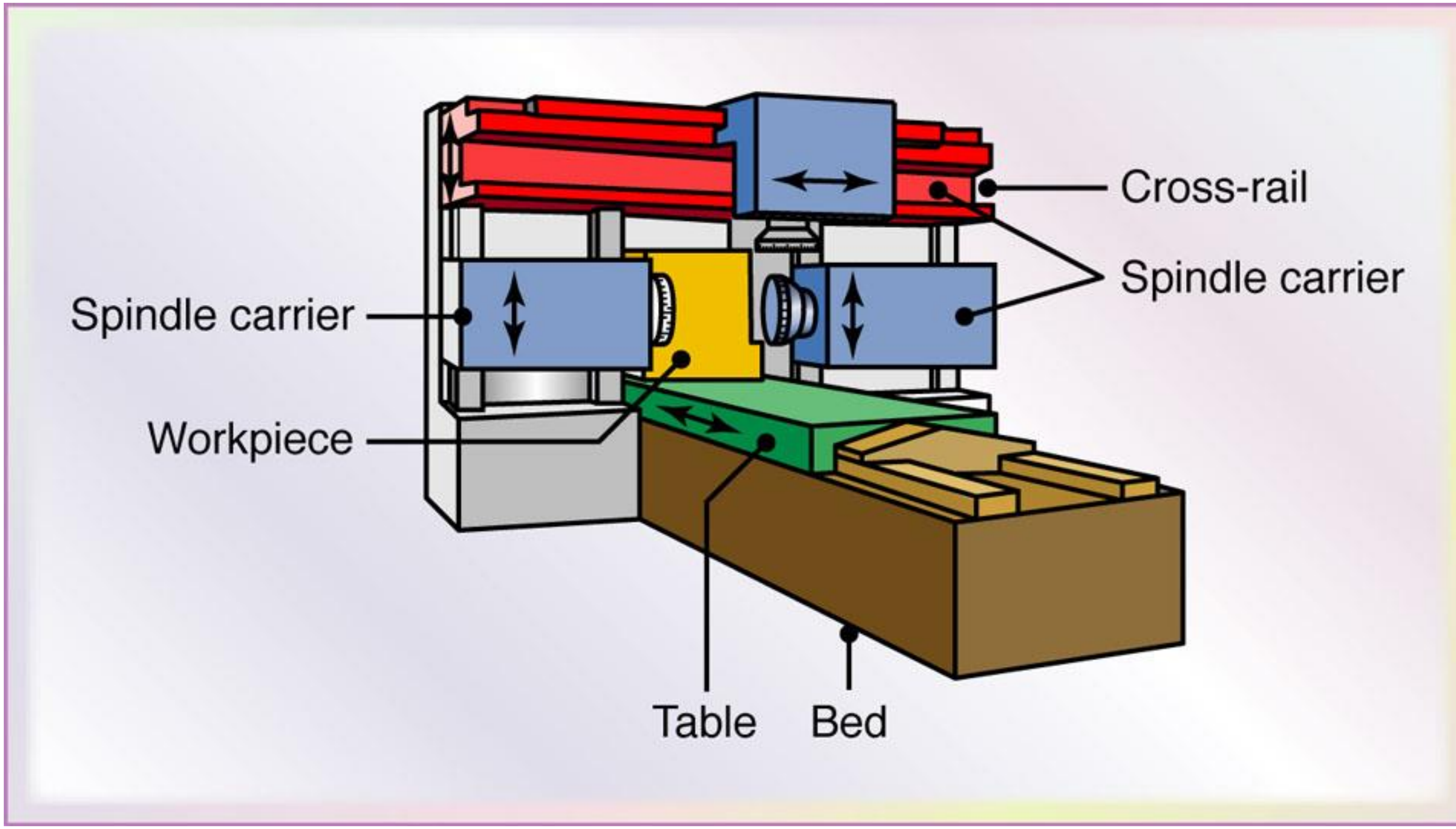


FIGURE 24.16 Schematic illustration of a bed-type milling machine.

CNC Vertical-Spindle Milling Machine

Figure 24.16 A computer numerical-control (CNC) vertical-spindle milling machine. This machine is one of the most versatile machine tools. The original vertical-spindle milling machine used in job shops is still referred to as a “Bridgeport”, after its manufacturer in Bridgeport, Connecticut. *Source*: Courtesy of Bridgeport Machines Dibision, Textron Inc.

Five-Axis Profile Milling Machine

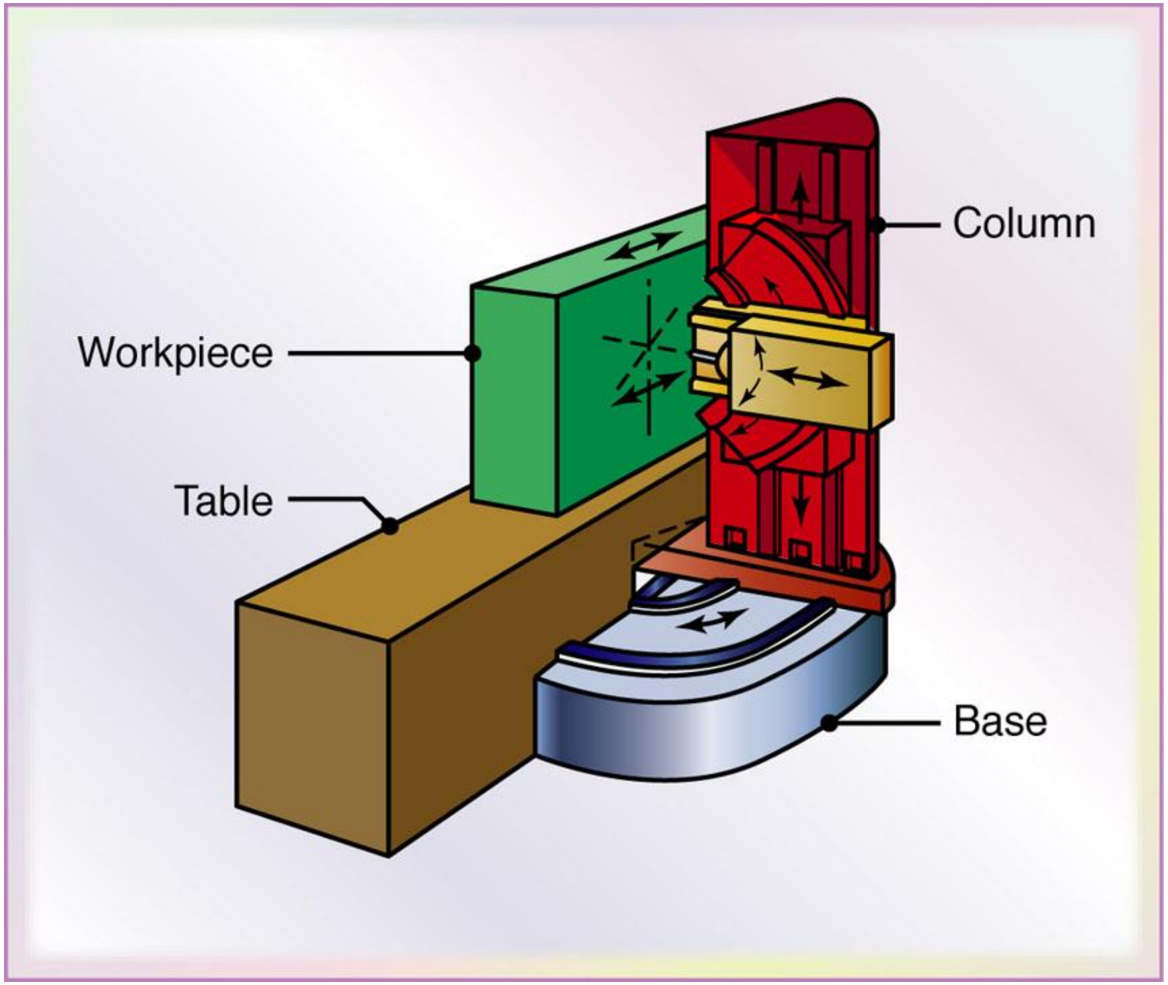


Figure 24.18 Schematic illustration of a five-axis profile milling machine. Note that there are three principal linear and two angular movements of machine components.

Why Machining is Important

- Variety of work materials can be machined
  - Most frequently applied to metals
- Variety of part shapes and special geometry features possible, such as:
  - Screw threads
  - Accurate round holes
  - Very straight edges and surfaces
- Good dimensional accuracy and surface finish

Disadvantages with Machining

- Wasteful of material
  - Chips generated in machining are wasted material, at least in the unit operation
- Time consuming
  - A machining operation generally takes more time to shape a given part than alternative shaping processes, such as casting, powder metallurgy, or forming

Machining in the Manufacturing Sequence

- Generally performed after other manufacturing processes, such as casting, forging, and bar drawing
  - Other processes create the general shape of the starting workpart
  - Machining provides the final shape, dimensions, finish, and special geometric details that other processes cannot create