# ME2300: Manufacturing Processes
# Jan-May 2020

# Shaping by mass change (removal: machining-introduction)

# Introduction

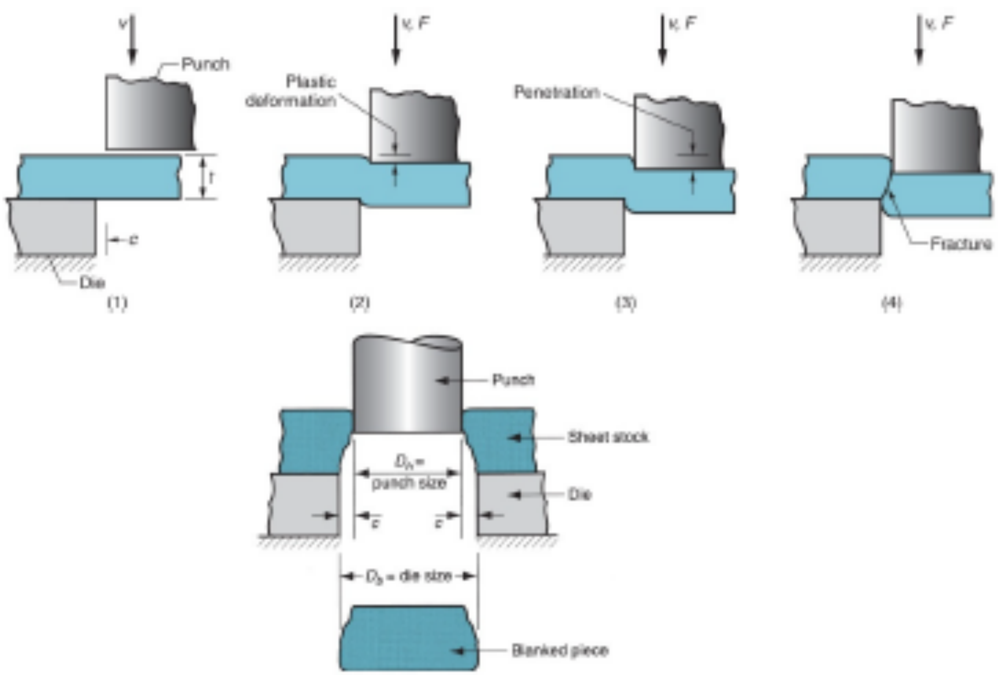
Five methods to achieve shape/properties

- Phase change: change raw material from solid to liquid (liquid-like) and back to solid
- Mass change: remove or add mass to raw material
- Joining: group together various raw material shapes
- Deformation: change shape in solid state by permanently distorting raw material
- Properties change: impart needed properties by changing structure of raw material

# Introduction

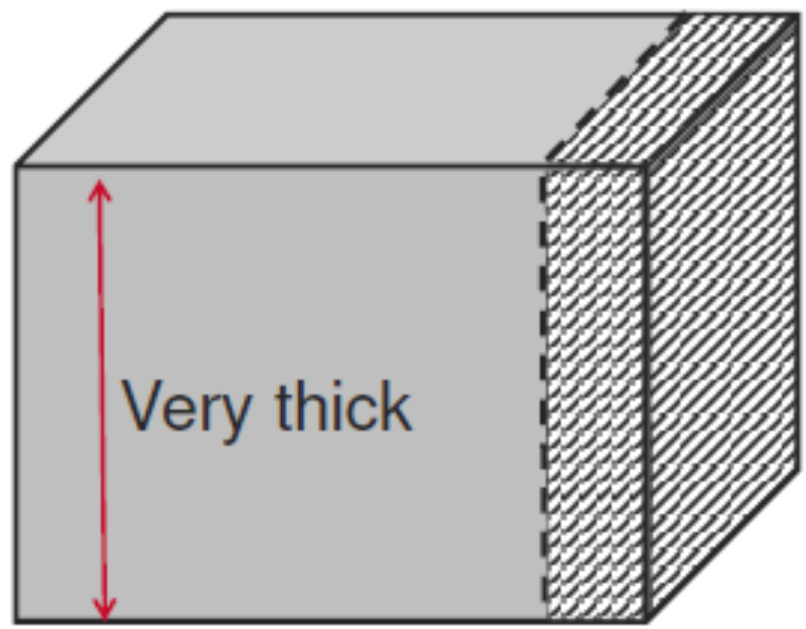
# Can we always shear, punch, blank to remove material?

You have already seen some material removal before in this course




What was the thickness 't' of this material?

Can this same technique be used for this starting raw material?




How can we cut this out?

# Mass removal – how to achieve?

- Shape raw material by mass removal (cut mass out)
- Requires energy – focused energy
- Many forms of energy
  - Moving mass (momentum); focused using a sharp edge (of many types: single point cutting tool, fixed abrasive, etc.)
  - Electric discharge: tiny sparks/arcs
  - Chemical energy
  - Light energy: laser beam
  - Electron beam, Ion beam, plasma etc.

Unconventional machining processes

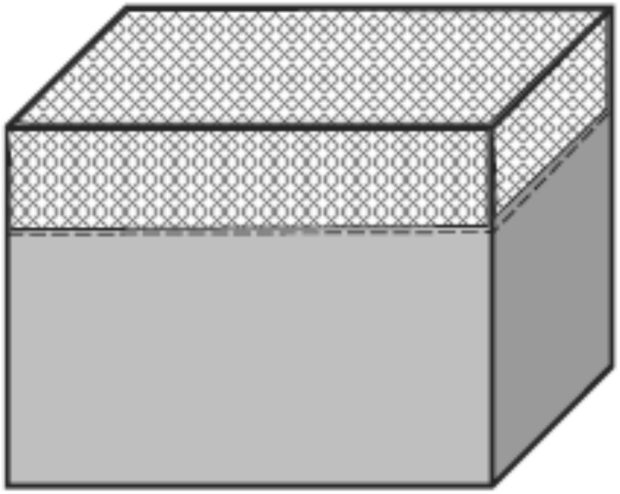
# Cutting using energy supplied by impact of a moving mass

- Commonly called machining or mechanical machining
- What impacts to provide the energy? – the raw material or tool relative to each other
- How to focus the energy?

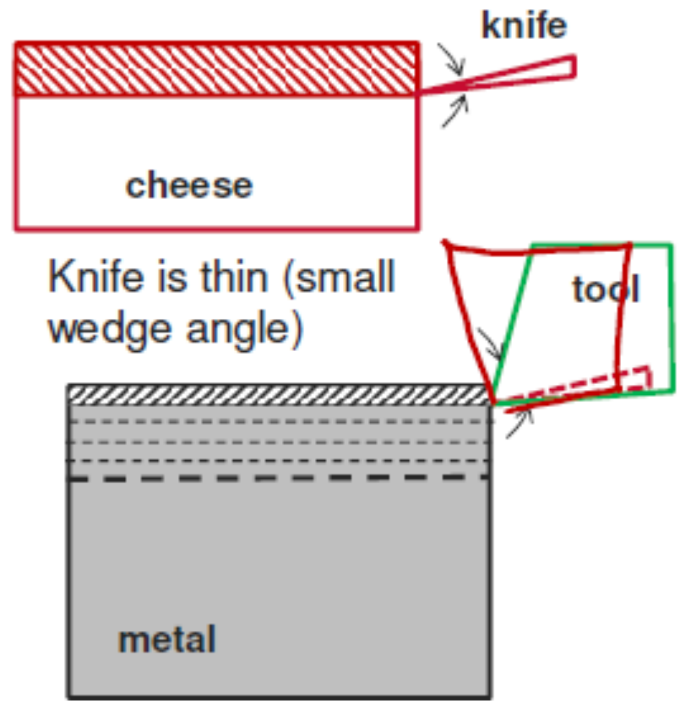
– Sharp edge is often provided to the cutting tool

- Need a rigid machine to hold both raw material and tool and to provide needed motion

# Cutting an engineering material

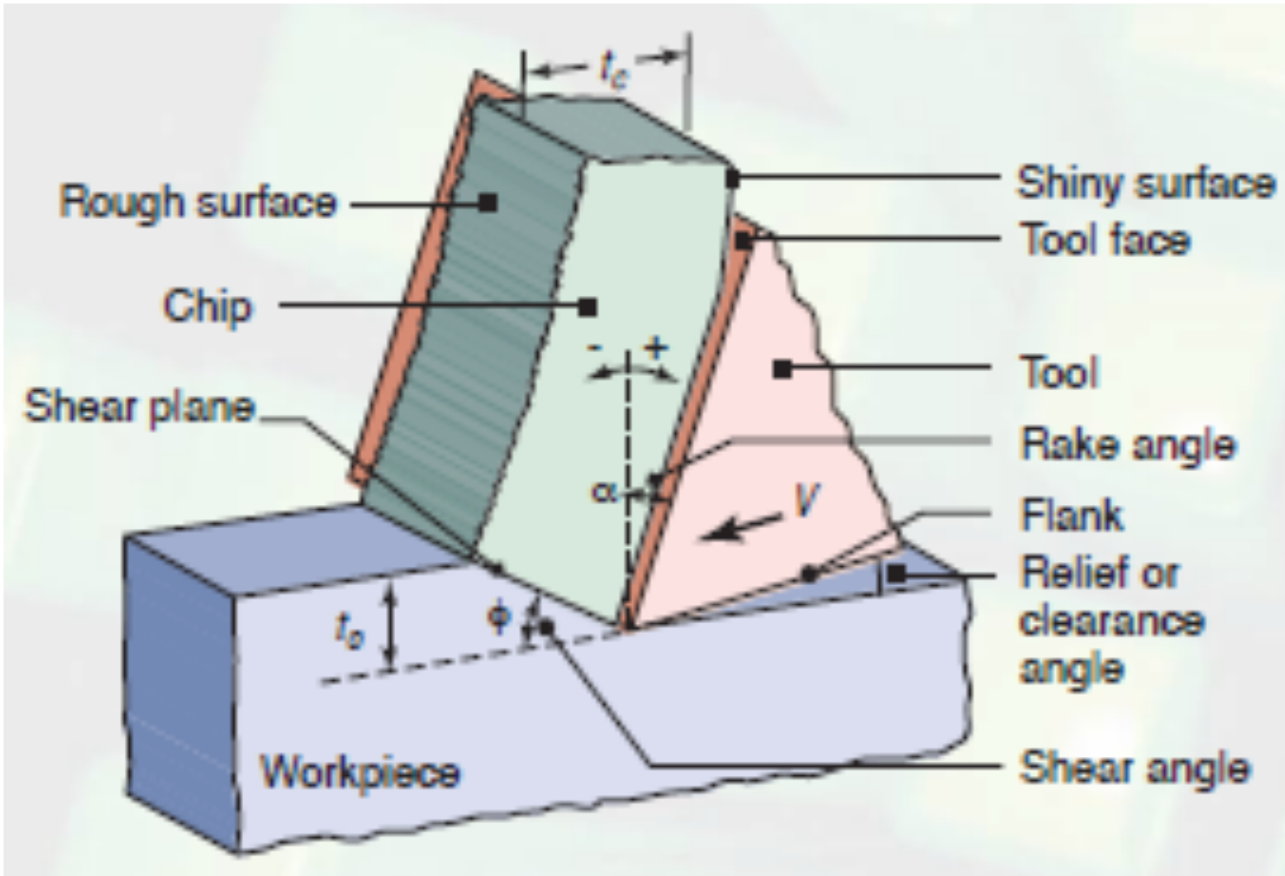


Can we use a knife and slice?

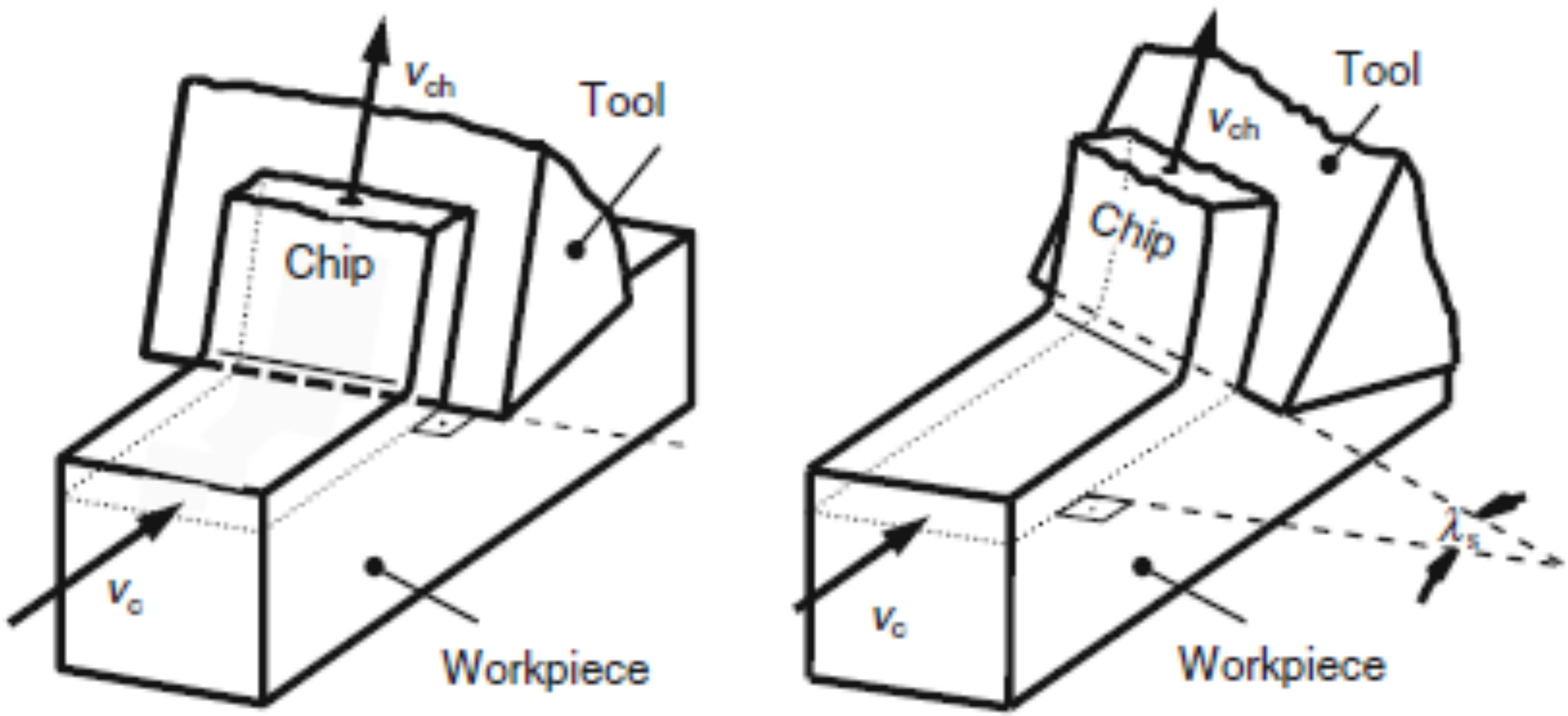



1. Tool has to be made stronger (larger wedge angle) to enable cutting
2. We cannot remove the entire material in one shot – we can only cut little by little

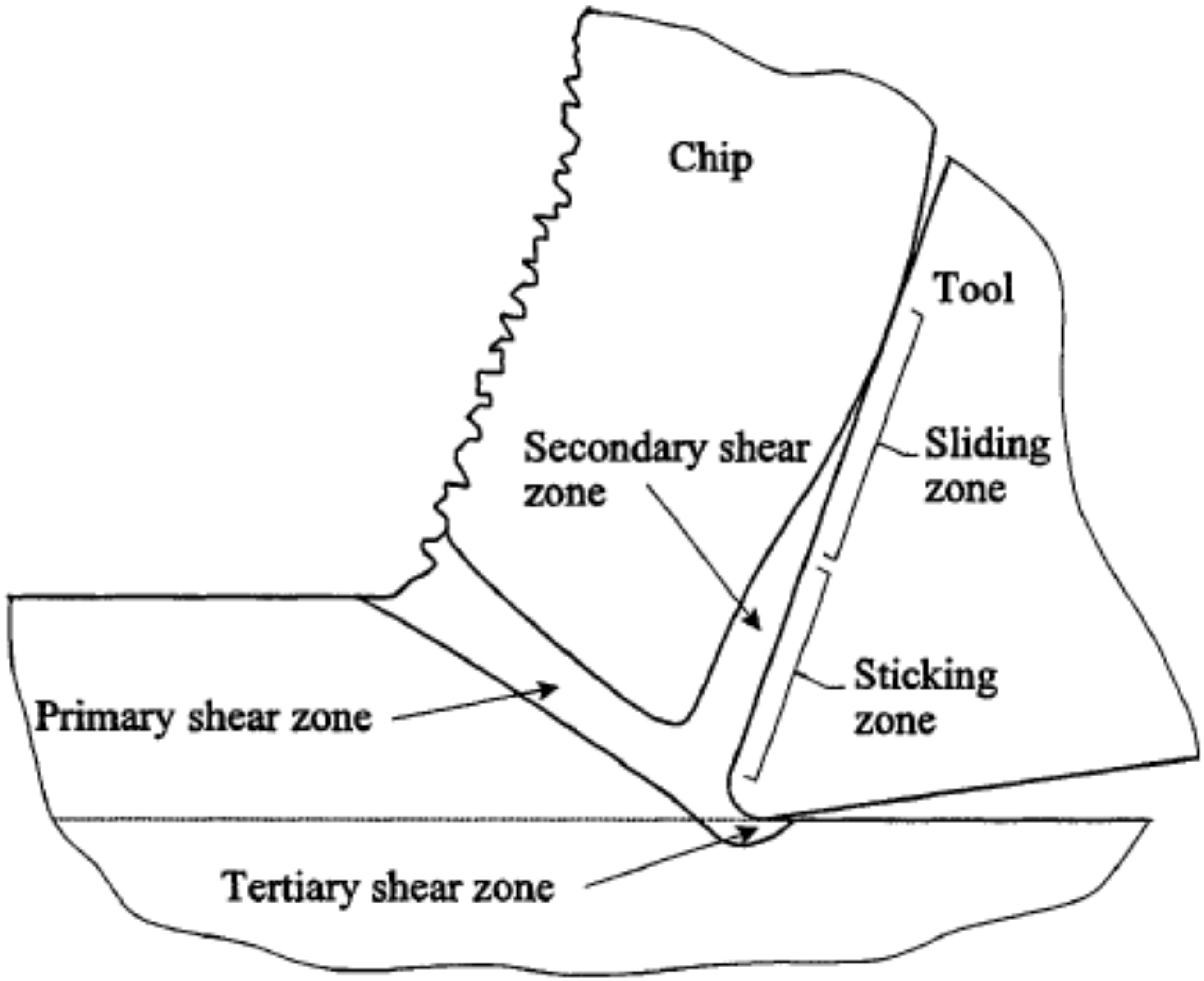
# Orthogonal cutting process



# Orthogonal and oblique cutting



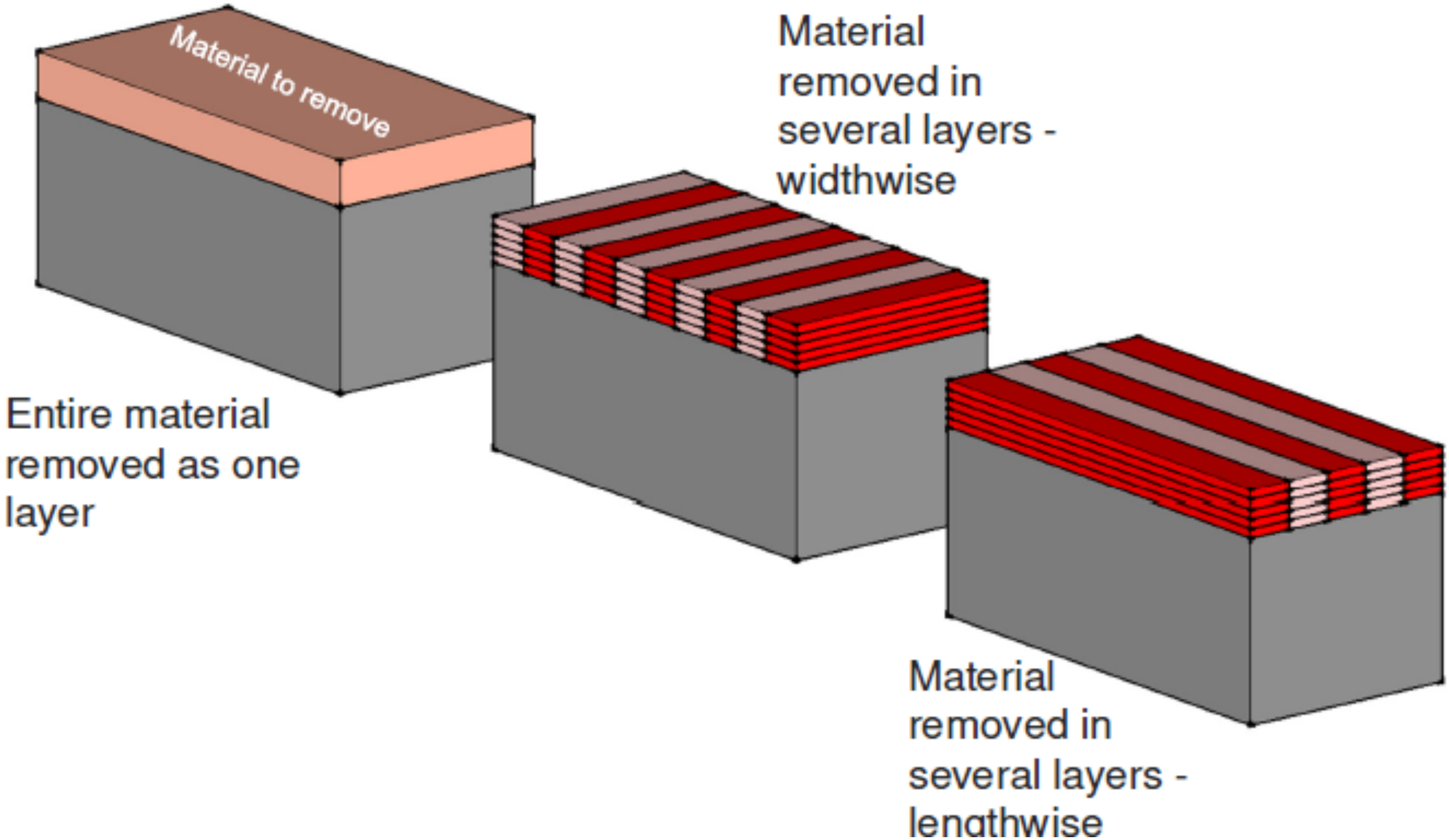
# Plastic deformation zone in the cutting process



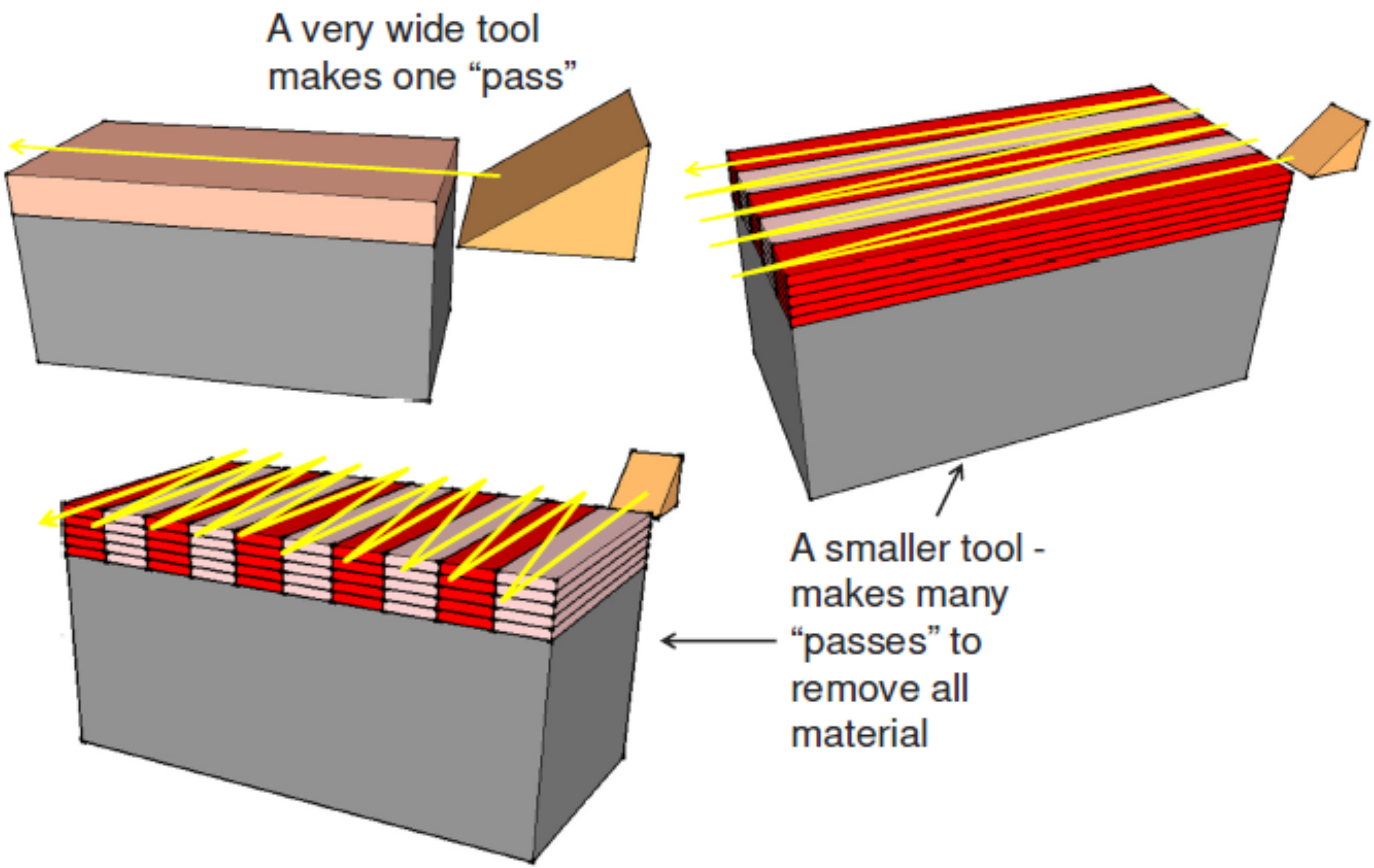
# How much material can we remove at a time?

- Cut engineering materials – we can only cut and remove a little bit at a time
- Why?
  – Work material is strong (unlike cheese!)
  – Cutting tool strength limitations
  – Requires high power; machine limitation
- So we have to cut a little at one place, then move over to another location to remove material, and so on over a large area so that a given shape can be created
- Hence, we need to partition the material and strategize on how we can cut each partition out

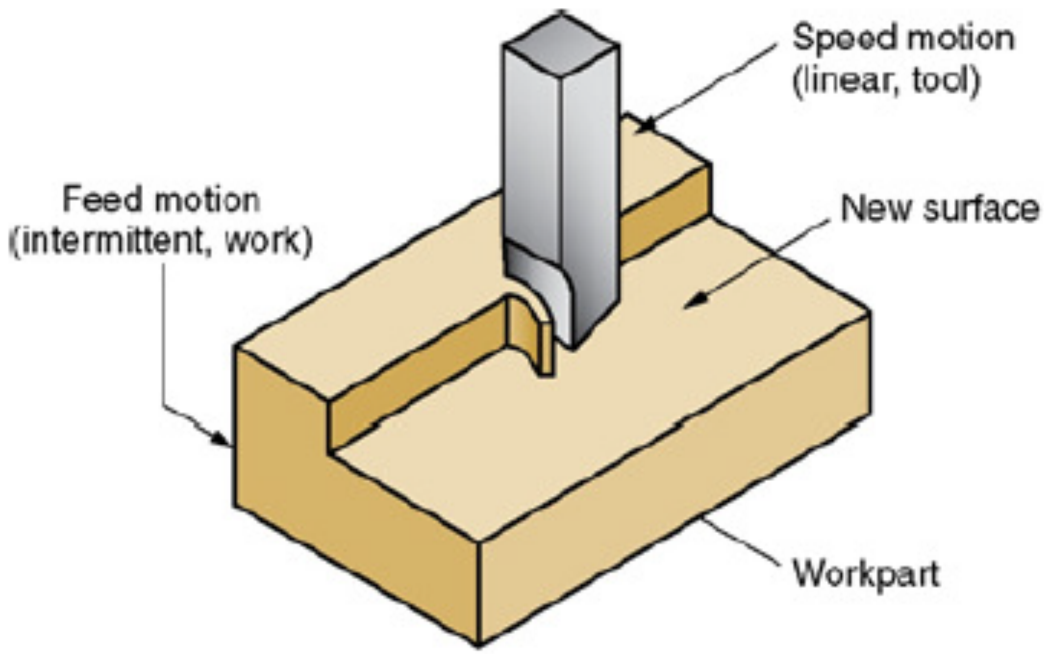
# Partitioning the material for removal



# Different ways to remove material



# Orthogonal cutting process

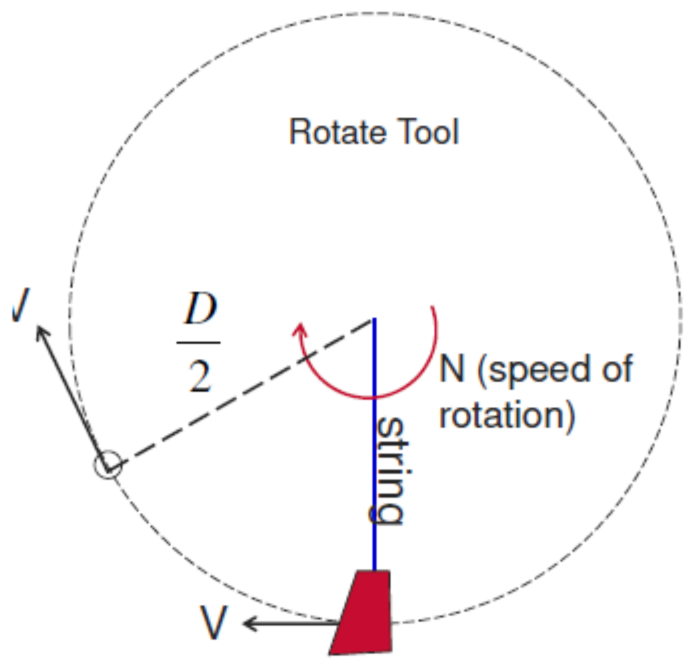



- A simple process to create large planar surfaces
- Tool moves linearly to remove material in layers
- Very seldom used nowadays – since process is very slow
- Limitation is from cutting speed achieved by linear motion – so speeds are very limited

# Circular cutting motion

- Very common to use circular motions in machining
- Such motion is provided to:
  - Tool: milling, drilling, boring
  - Work material: boring, turning

# Circular cutting motion

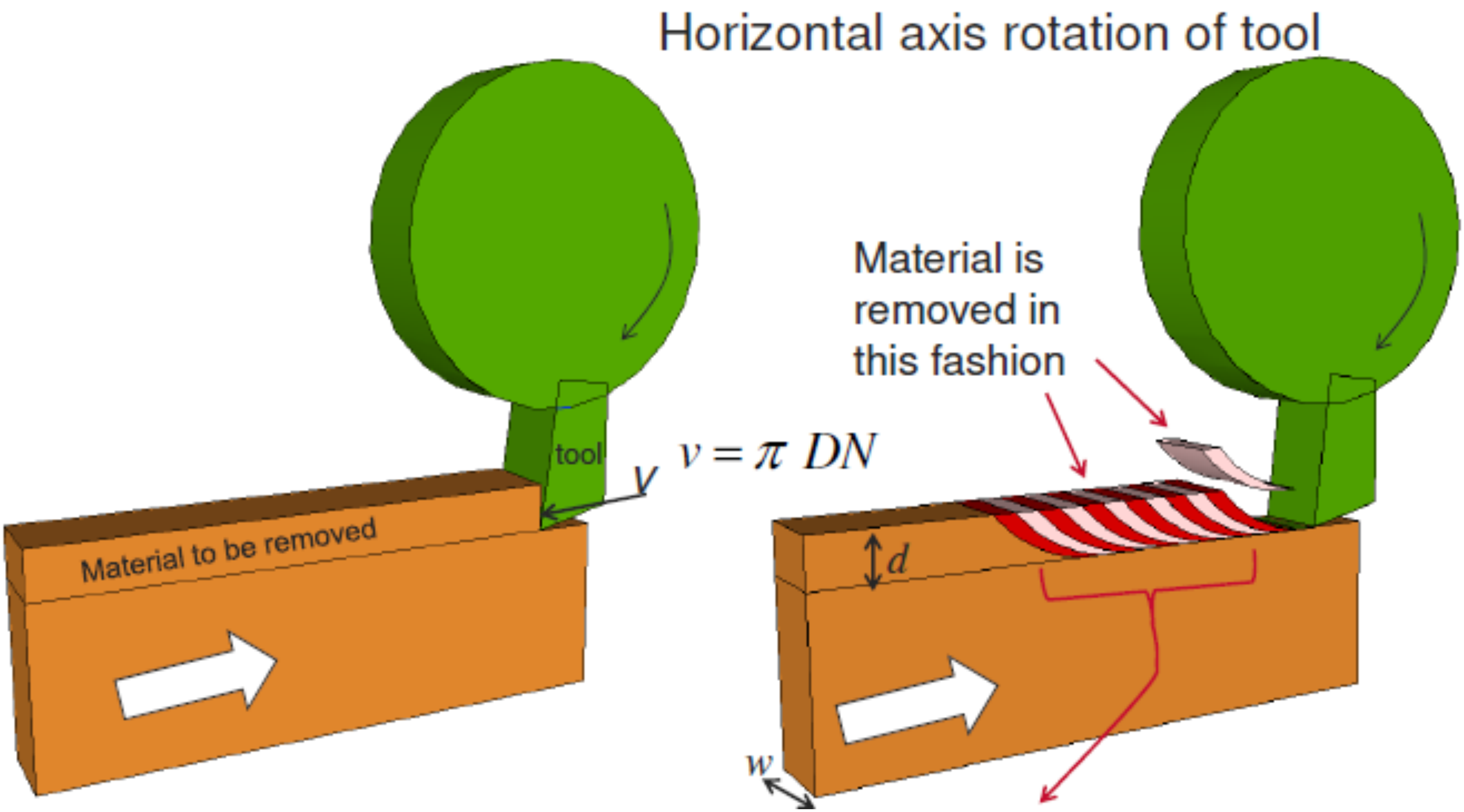



- Rotary motion – easier to get high speeds; plus the tool comes back too – convenient
  – Tangential speed is the cutting Speed

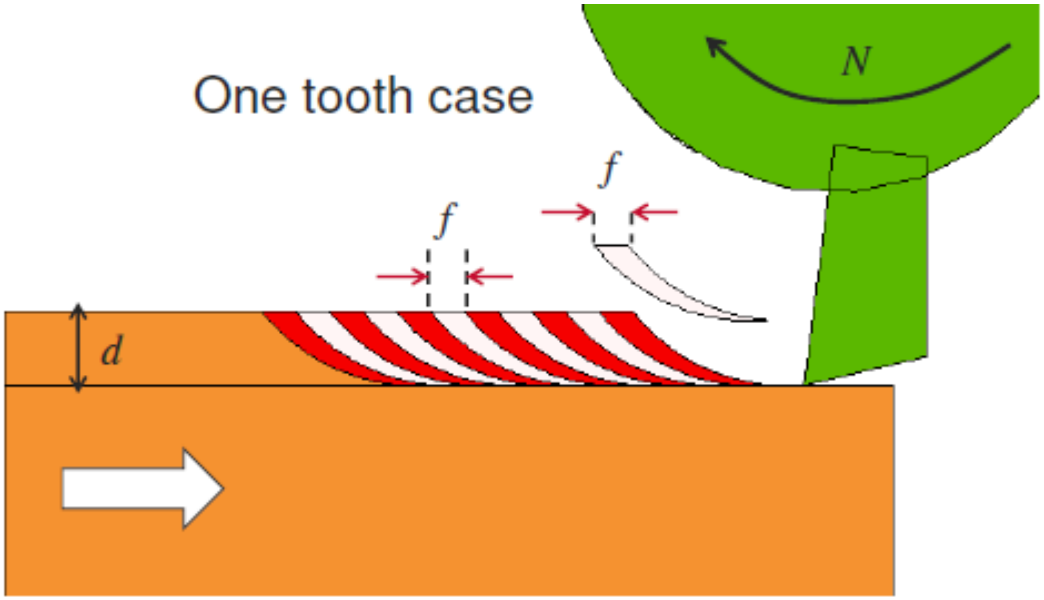
$$v = r\omega = \frac{D}{2}(2\pi N) = \pi DN$$

- We have two options:
  – A: Rotate tool
  – B: Rotate work material

# Option A: rotate the tool



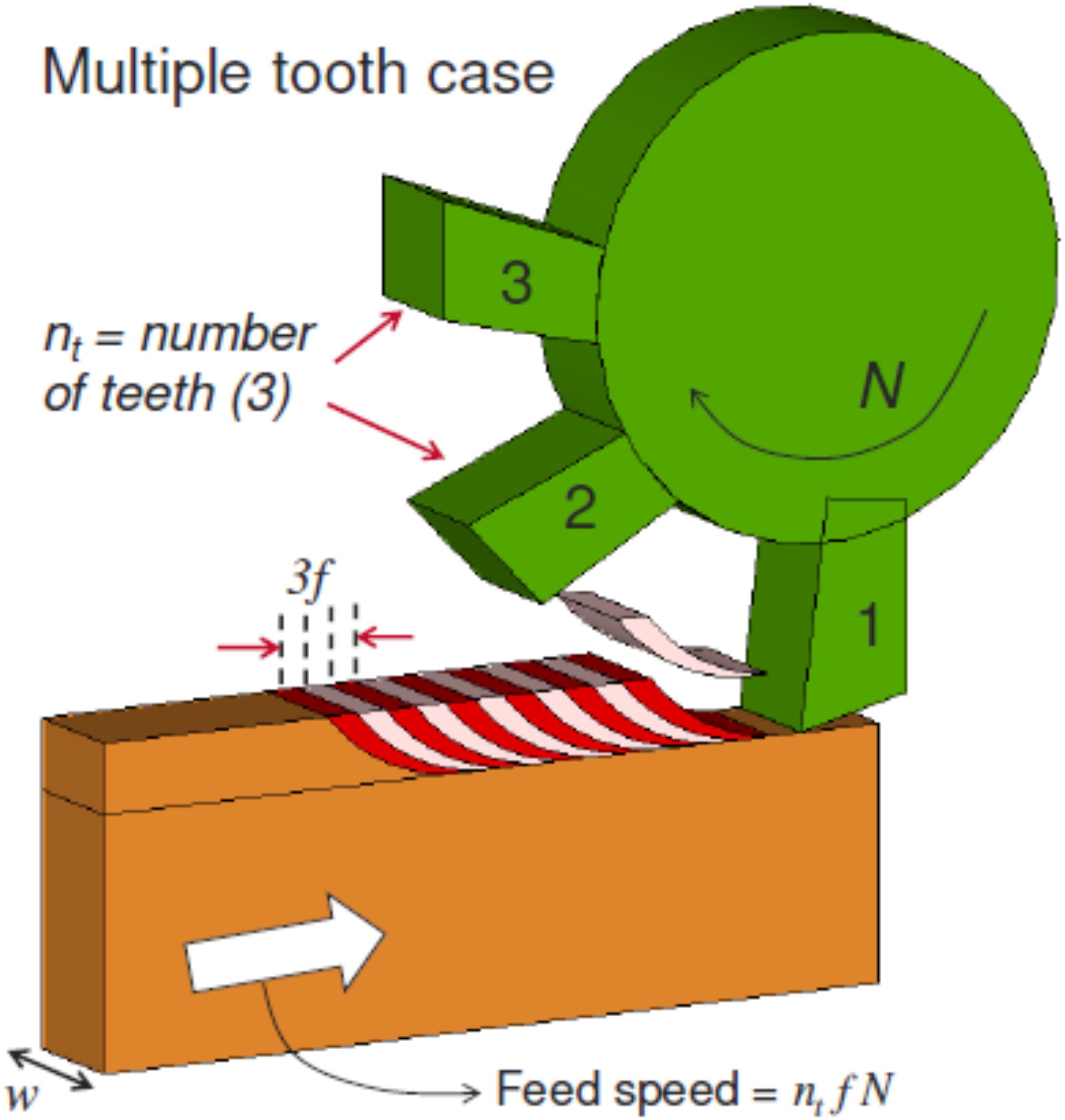
# Option A: rotate the tool




f = feed per tooth (chip load)

In one revolution, the tooth cuts ‘*f’ amount (horizontal thickness) of material.*
In *N revolutions per minute, (f N) amount of material is cut per minute. This is the*
rate at which work material has to be “fed in”.
So MRR = (*w d f N) ; w = width of cut; d = depth of cut*

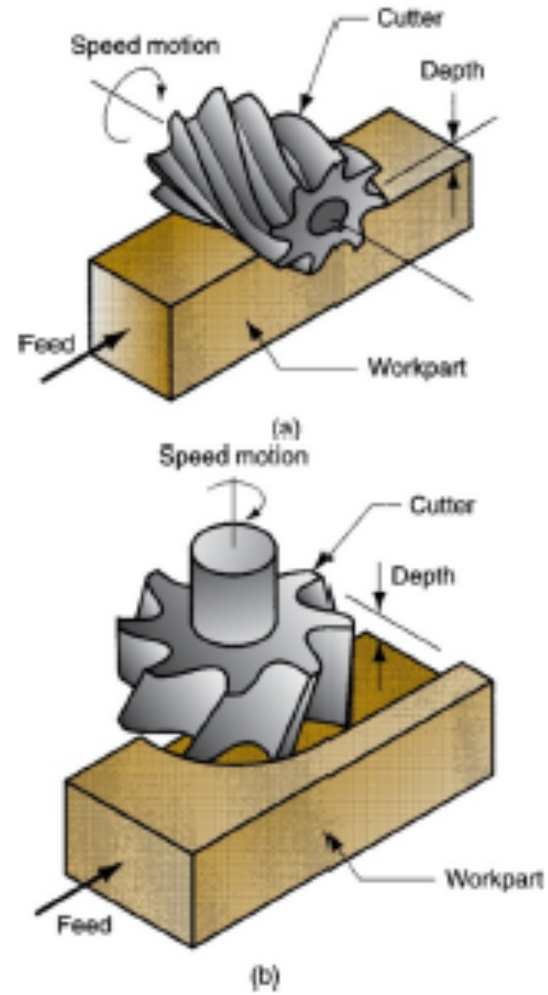
# Option A: rotate the tool



# Option A: rotate the tool

Another option:
Vertical axis rotation of tool

Peripheral milling



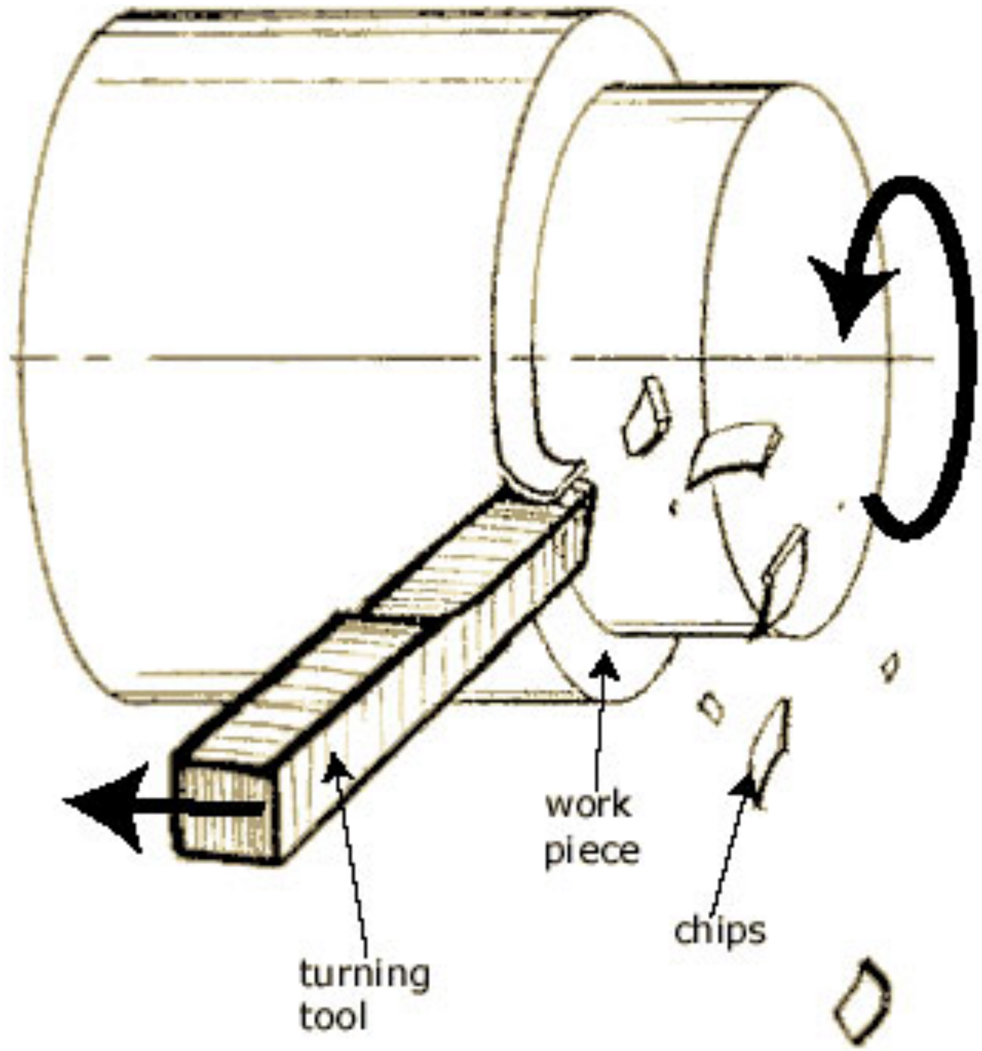

Face milling

# Circular cutting motion - turning

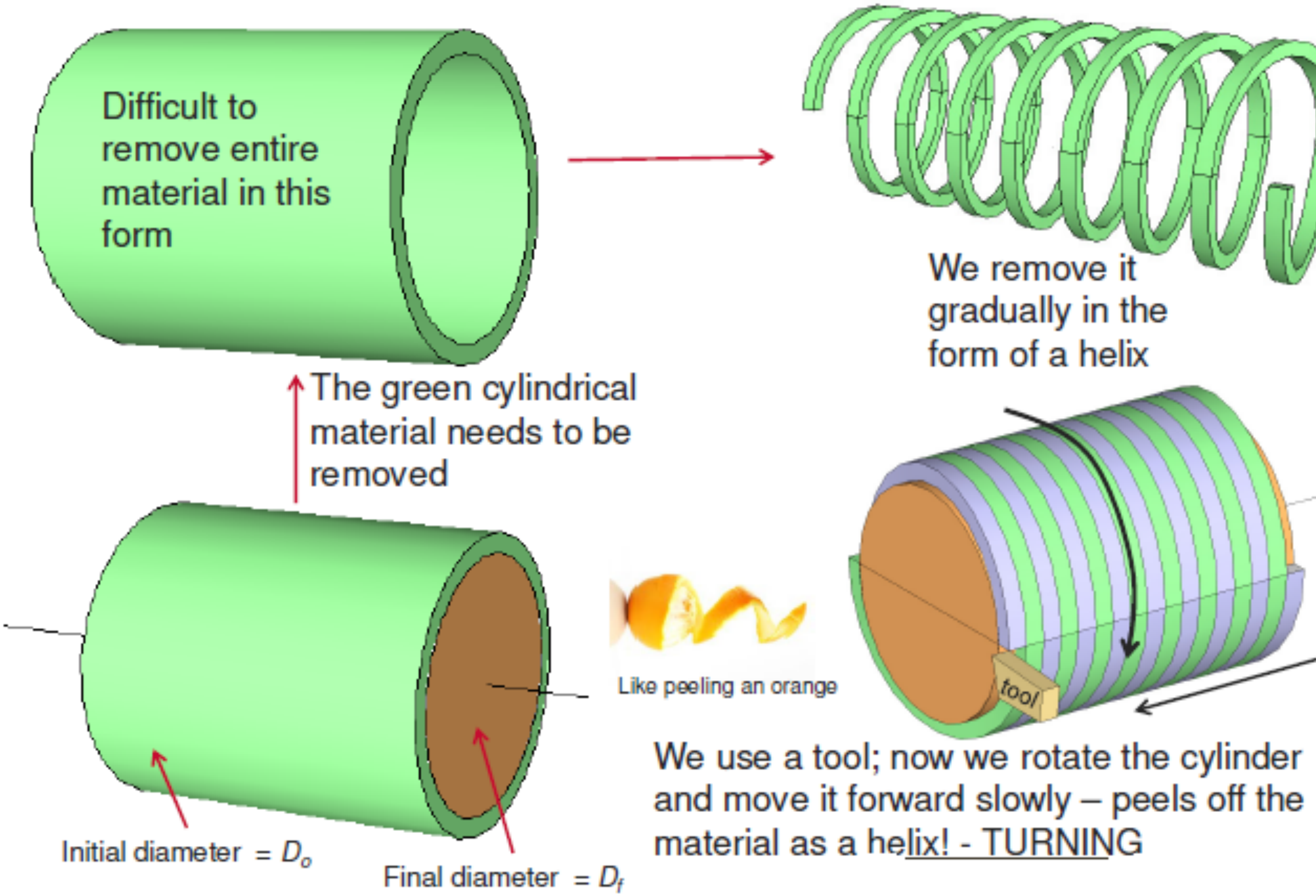
- Here we use option B:

– Rotate the work material instead of the tool

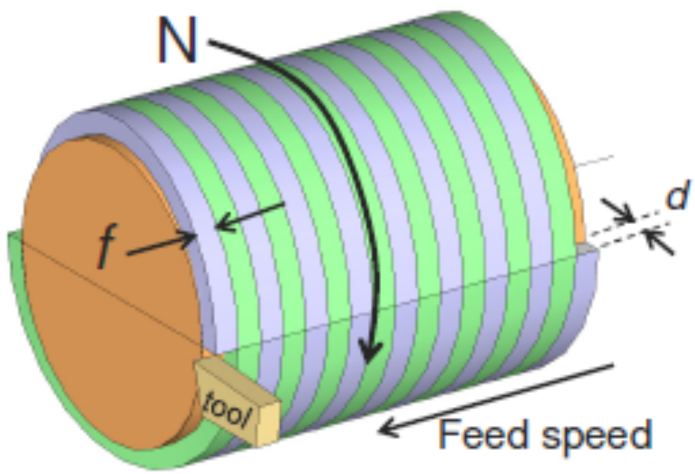
# Option B: rotate the workpiece (Turning)



# Option B: rotate the workpiece (Turning)



# Option B: rotate the workpiece (Turning)




Cutting speed is from circular rotation = tangential speed = $v = \pi D N$

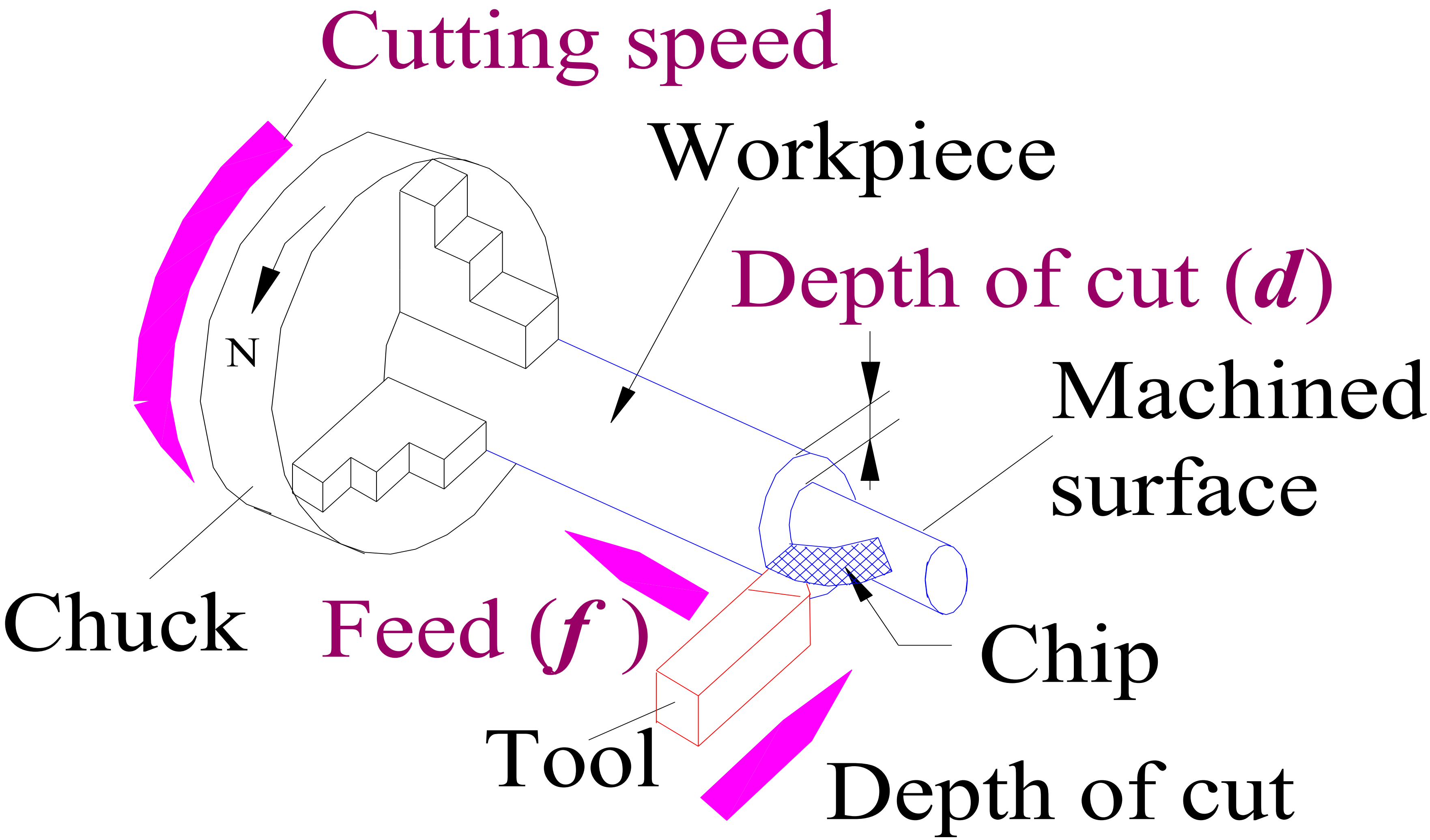
Feed speed = $f_r$ = depends on how wide ($f$) of a helix you want to take out = $f N$; in one revolution '$f$' is removed, so in N revolutions per minute, $f N$ is removed

Units of $f$ = *mm/rev*

Thickness of helix = depth of cut = $d$

Material removal rate??

# Option B: rotate the workpiece (Turning)



# MRR

Volume of material removed in one revolution $MRR = \pi D d f$ $mm^3$

- Job makes $N$ revolutions/min

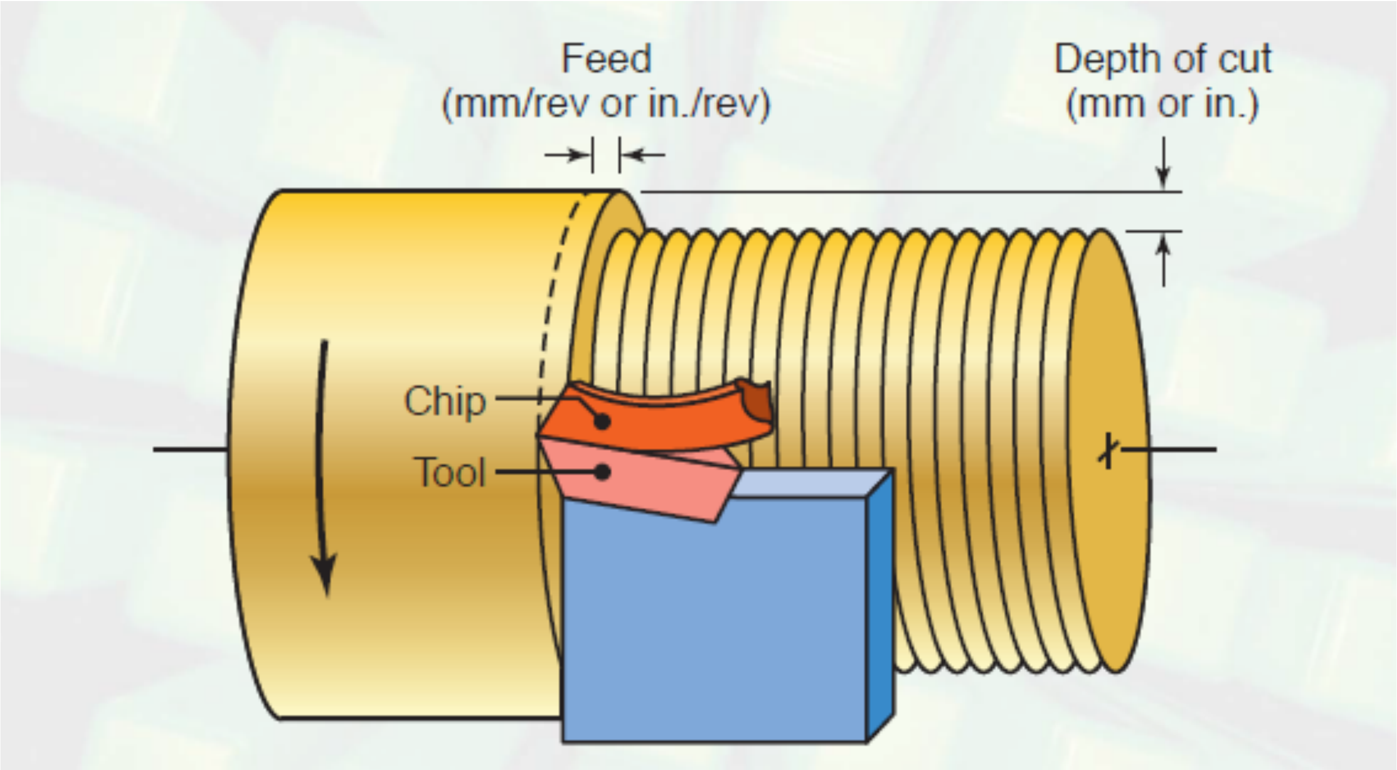
$$\mathbf{MRR} = \pi D d f N \quad (mm^3/min)$$

- In terms of $\boldsymbol{v}$ MRR is given by

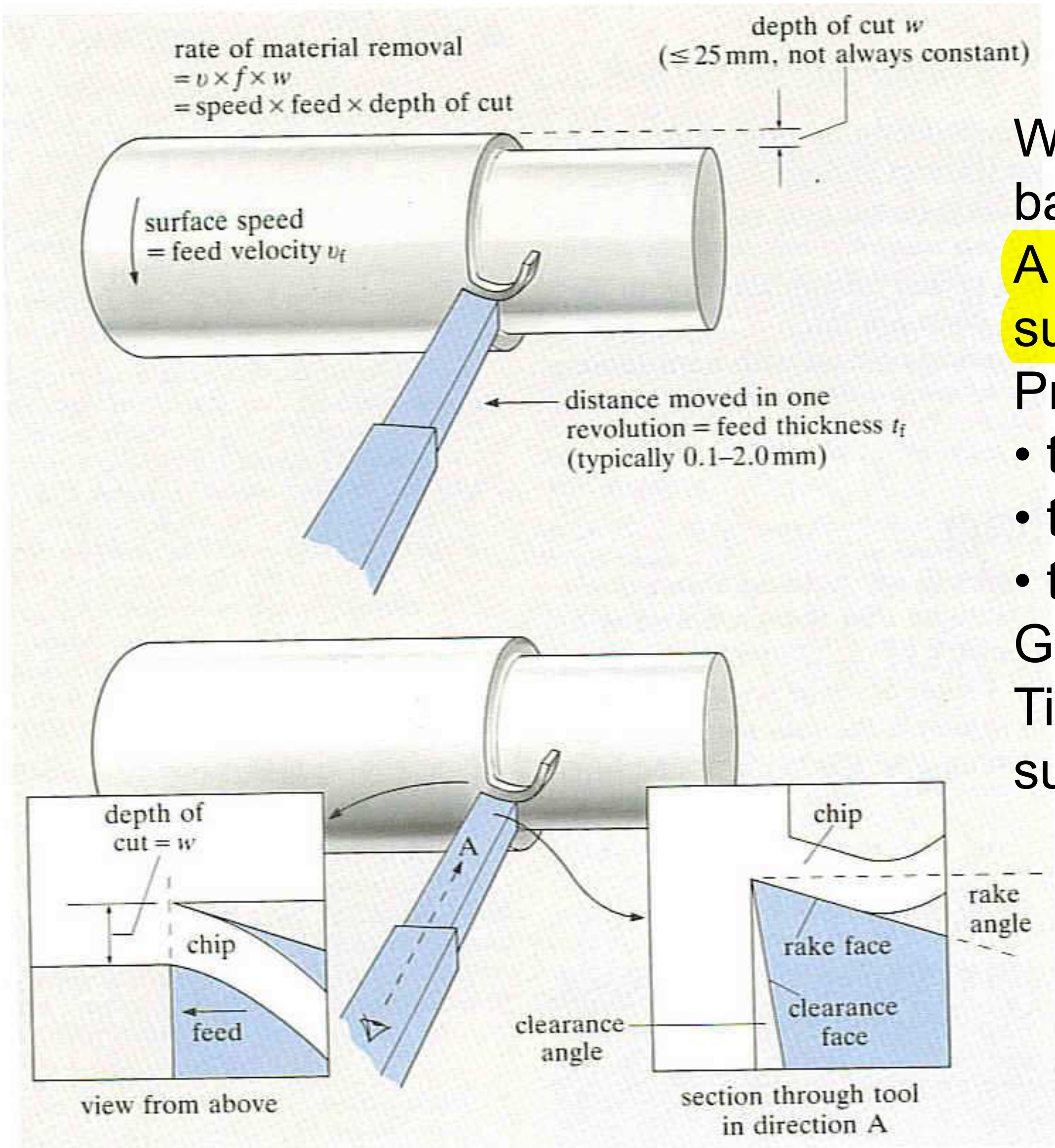
$$\mathbf{MRR} = 1000\, v\, d\, f \quad (mm^3/min)$$

# Mechanics of machining

# Terminology in Turning



# Turning




What happens during machining of a bar on a lathe?

A chip of material is removed from the surface of the workpiece.

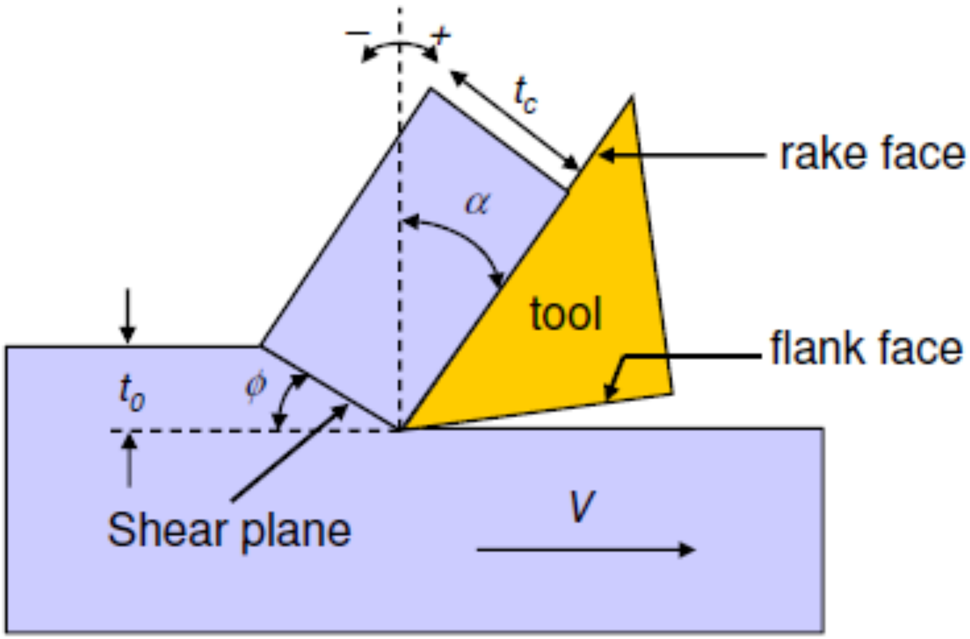
Principal parameters:

- the cutting speed, v
- the depth of cut, w or d
- the feed, f.

Geometry of single-point lathe turning

Time requires to turn a cylindrical surface of length Lw,

# Chip formation




$t_0$ : undeformed chip thickness

$t_c$ : deformed chip thickness

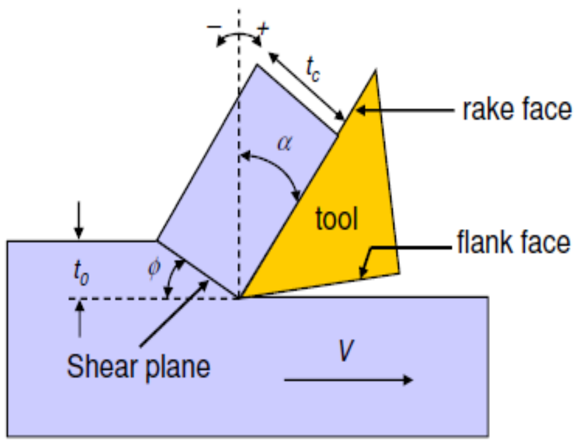
$\alpha$ : rake angle

$\phi$ : shear angle

$V$ : cutting speed

# Chip formation

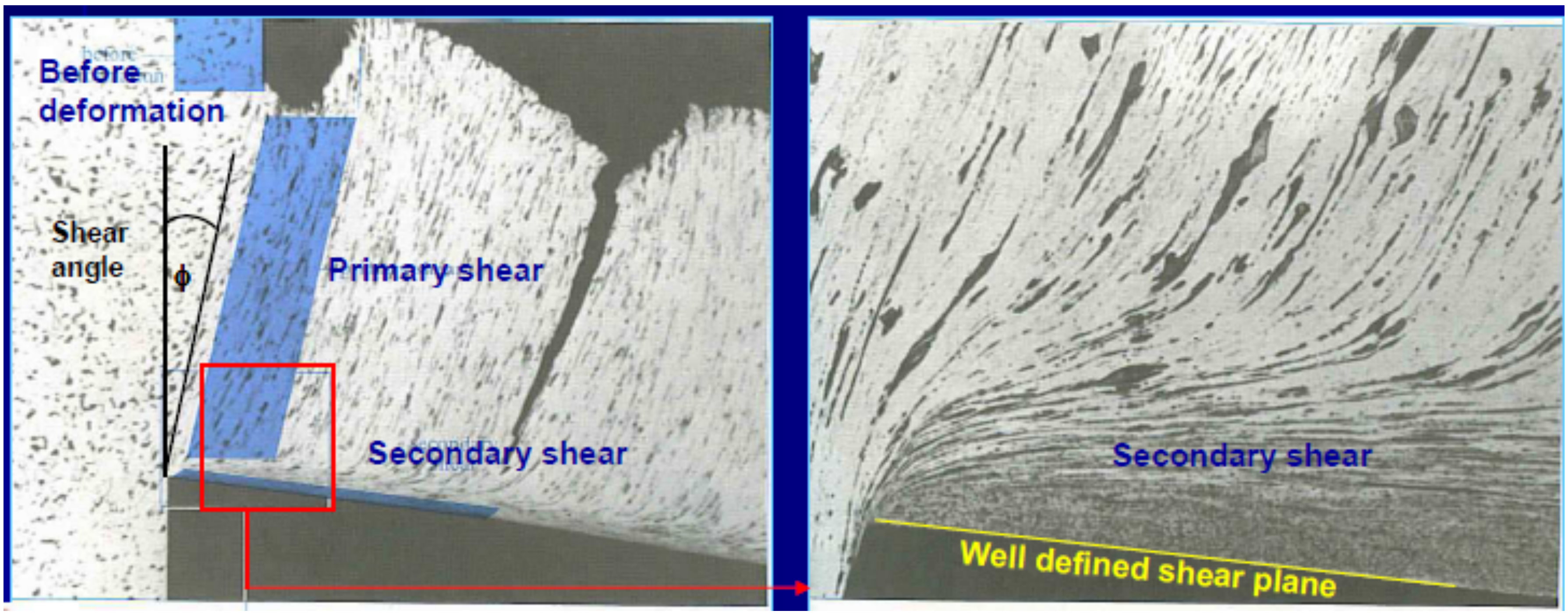
- The tool removes material near the surface of the workpiece by shearing it to form the chip.
- Material with thickness t is sheared and travels as a chip of thickness tc along the rake face of the tool.
- The chip compression ratio (cutting ratio) r = tc/to.



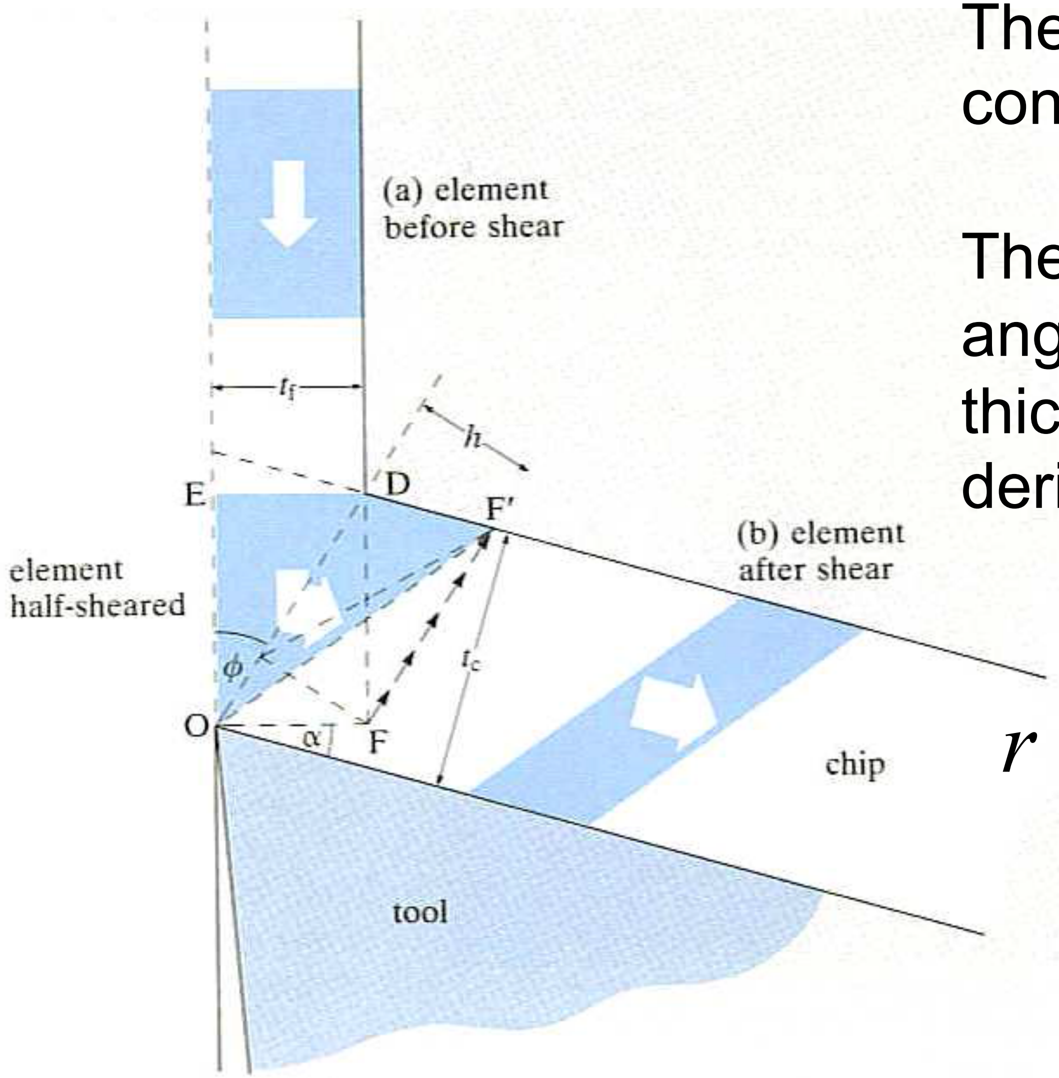
# Deformation zone

•The entire chip is deformed as it meets the tool, known as primary shear. Shear plane angle is φ.

•Localized region of intense shear occurring due to the friction at the rake face, known as secondary shear.



# Geometry of chip formation




The shear angle φ is controlled by the cutting ratio r.

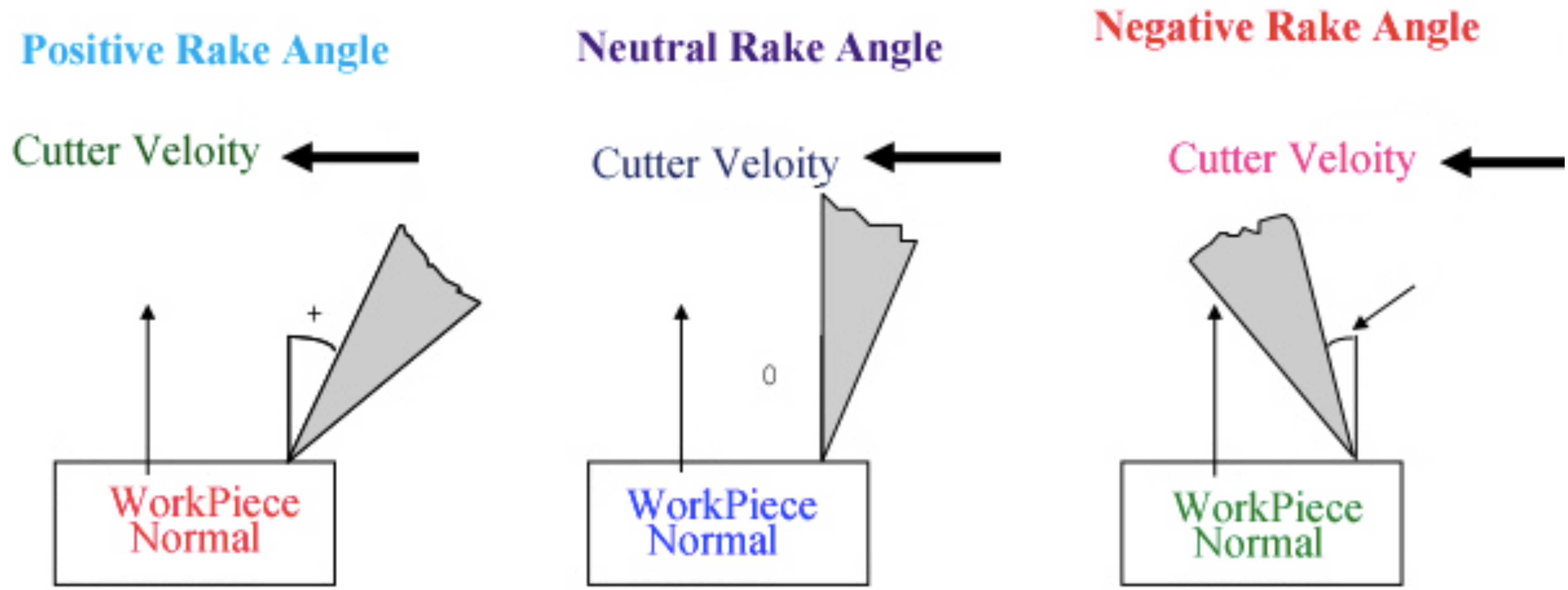
The relationship between rake angle, shear angle, and chip thickness ratio, r can be derived as follows

$$r = \frac{t}{t_c} = \frac{OD \sin\phi}{OD\cos(\phi - \alpha)}$$

# Shear angle and chip thickness ratio

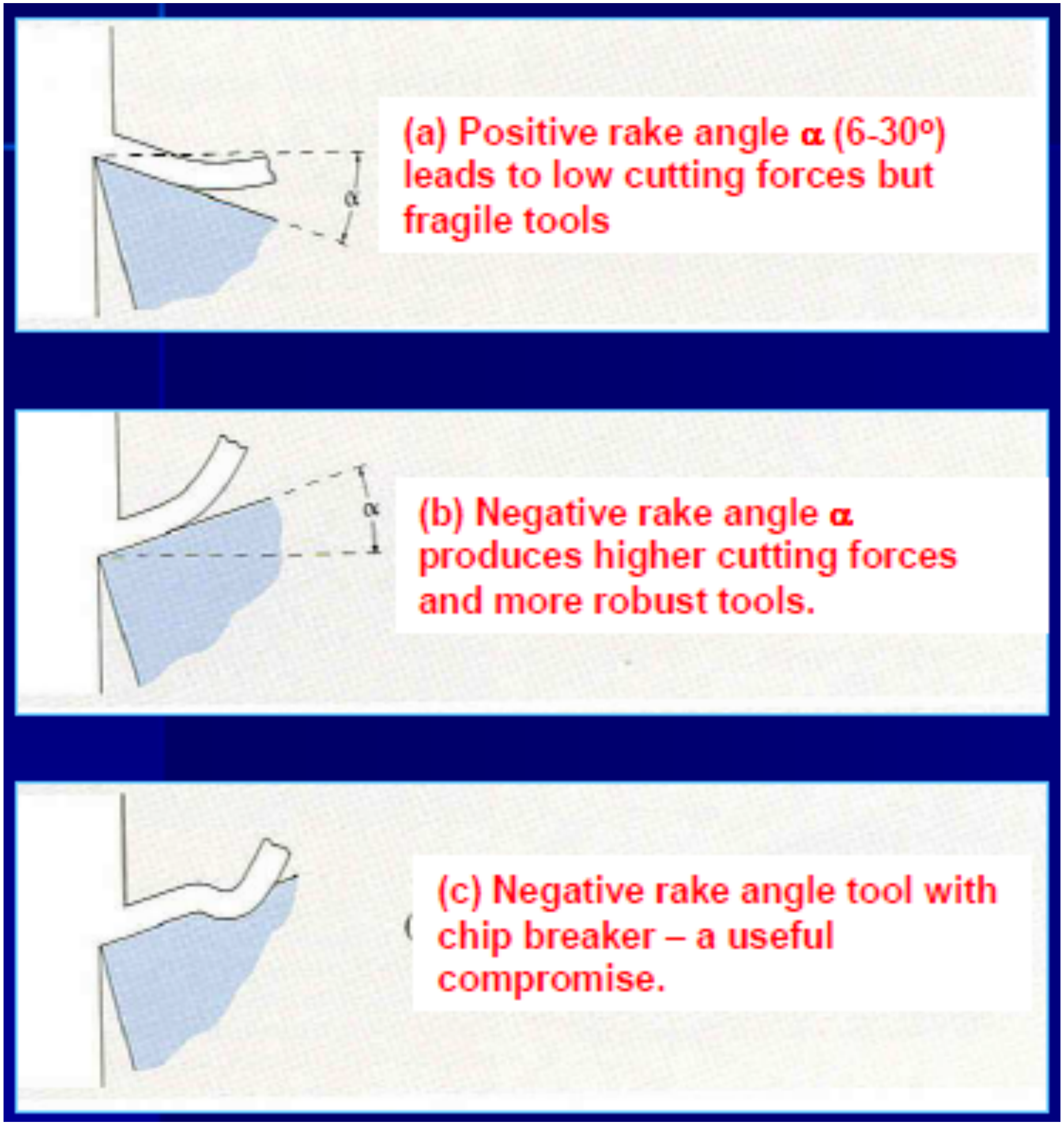
$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

# Rake angle

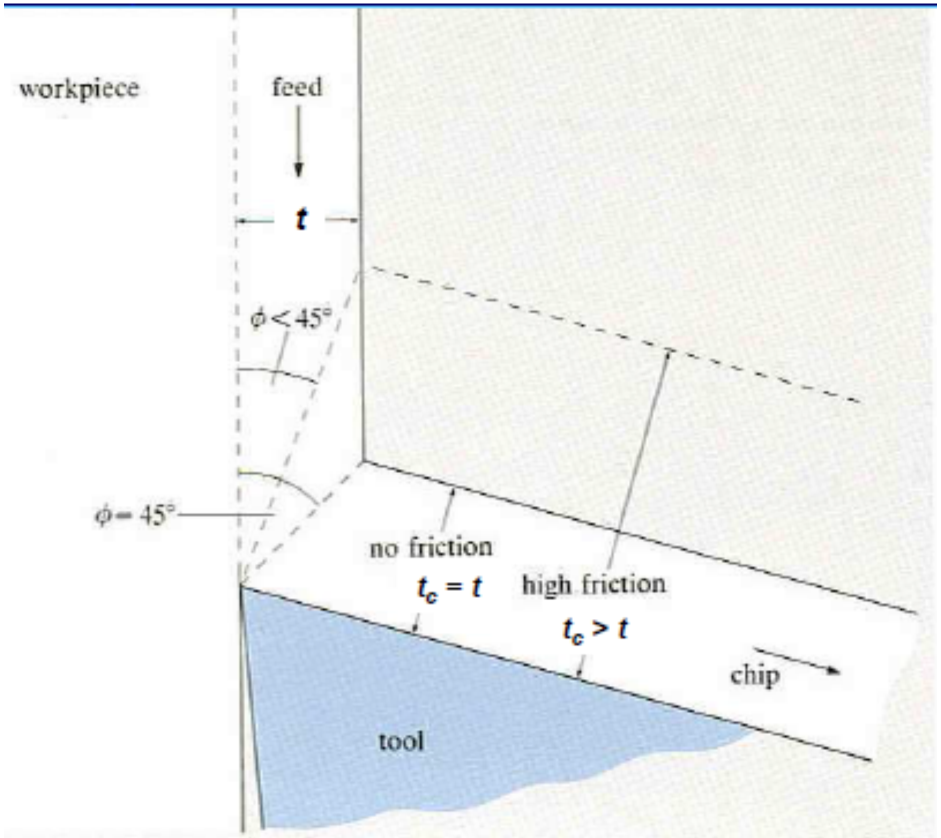



Various Types of Rake Angles

# Rake angle


(a) Positive rake angle α (6-30°) leads to low cutting forces but fragile tools
(b) Negative rake angle α produces higher cutting forces and more robust tools.
(c) Negative rake angle tool with chip breaker – a useful compromise.

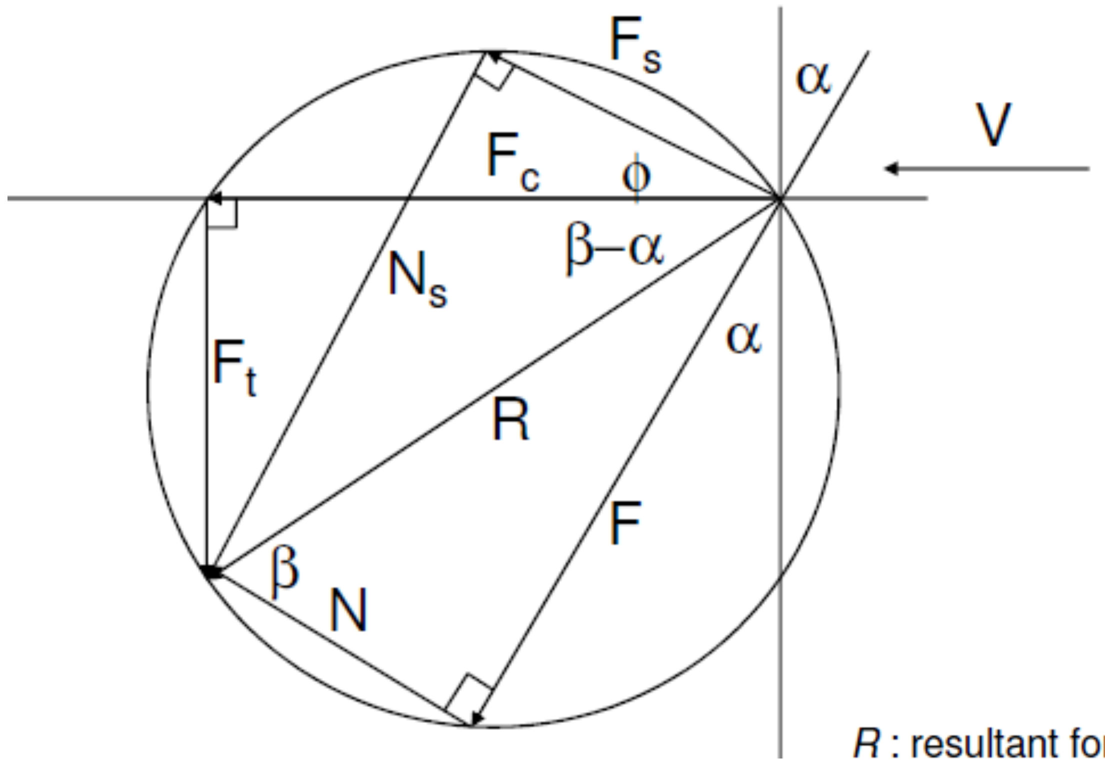
# Effect of rake face contact length




- The deformed chip is flowing over a static tool, leading to frictional force similar to friction hill.
- If μ is greater than 0.5, sticky friction will result and flow will occur only within the workpiece but not at the tool-workpiece interface.

Force to move chips ⇧ Chip thickness ⇧ Change in shear angle

# Merchant’s circle diagram




ıgene Merchant
1913 - 2006

$R$ : resultant force

$F_t$ : thrust force

$F_c$ : cutting force

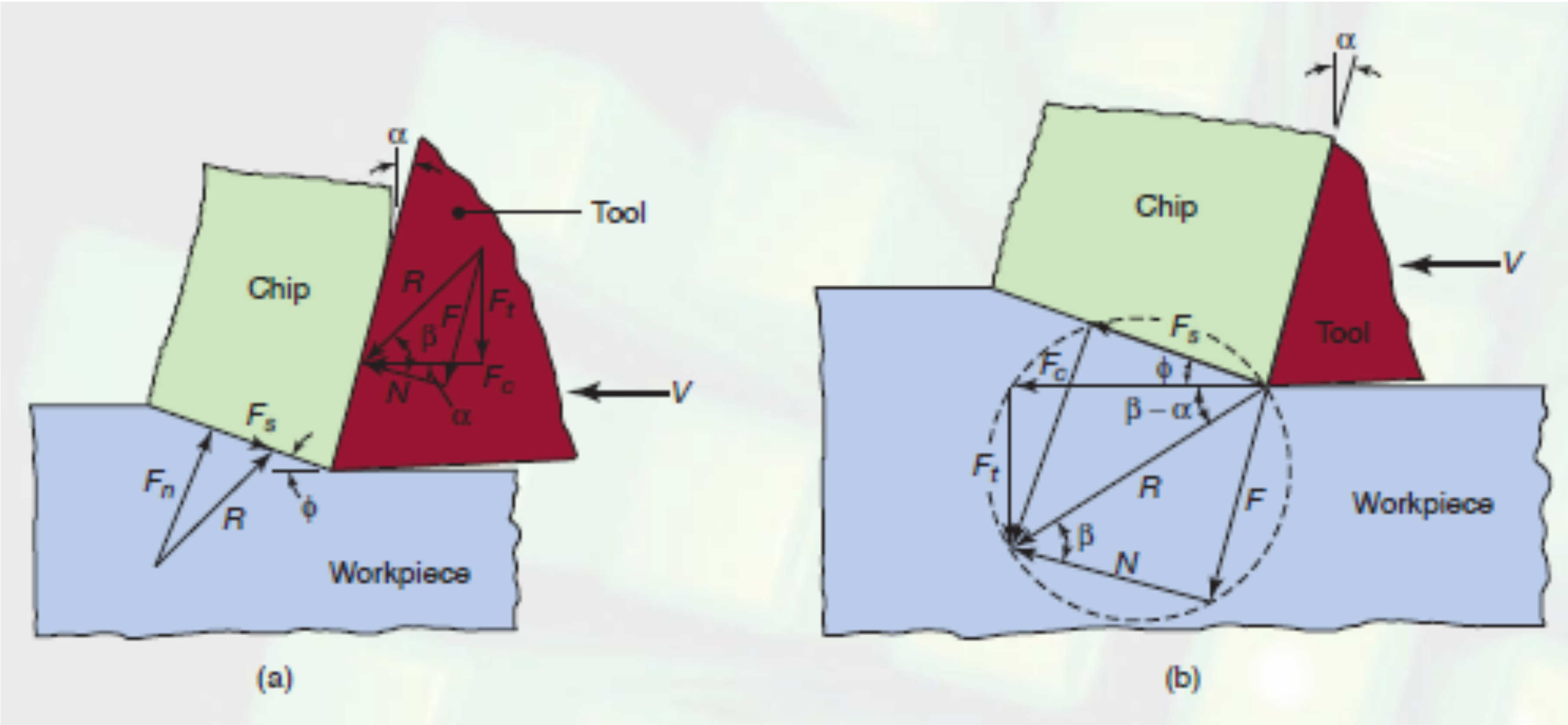
$F$ : friction force

$N$ : normal force

$F_s$ : shear force

$N_s$ : normal force on shear plane

# Cutting forces




(a) Forces acting on a cutting tool in two-dimensional cutting. Note that the resultant forces, *R, must be* collinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone. *Source: After M.E.* Merchant.

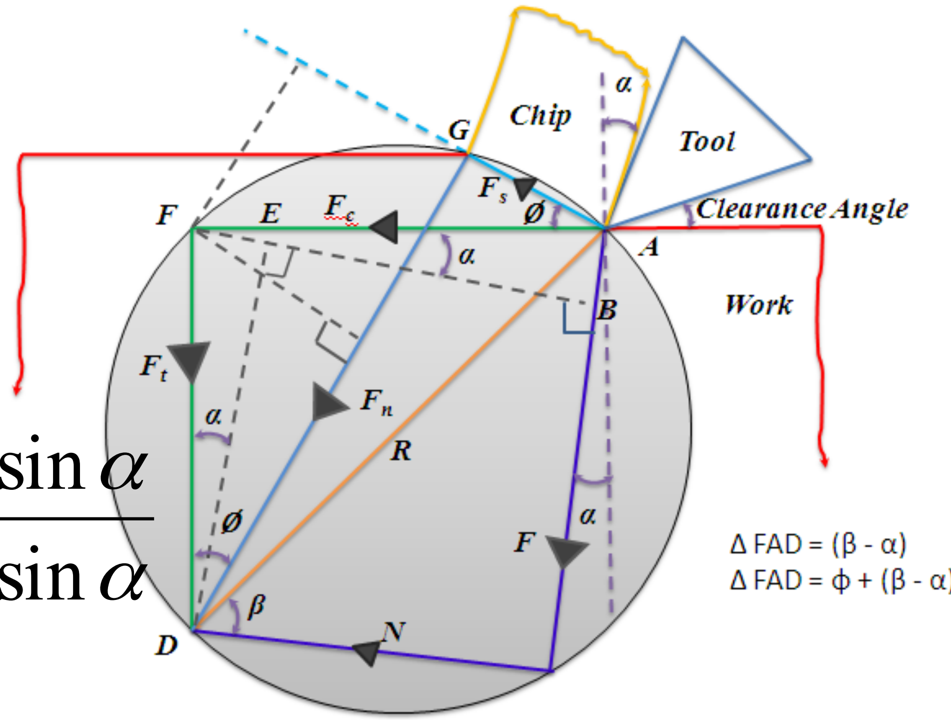
# Force analysis

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

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

Coefficient of friction μ

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




β = Friction angle

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

Also, $\beta = \tan^{-1}(\mu)$

# Force analysis

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

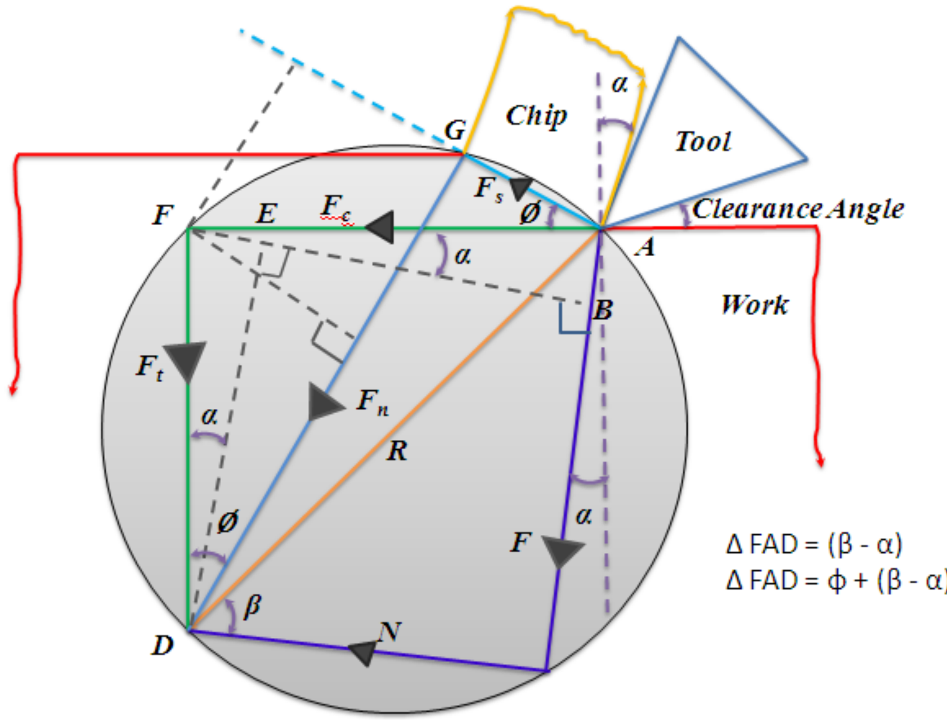
$$F_N = F_t \cos\phi + F_c \sin\phi$$

Also,

$$F_c = R\cos(\beta - \alpha)$$

$$F_s = R\cos(\phi + \beta - \alpha)$$

$$\therefore \frac{F_c}{F_s} = \frac{\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)}$$




Shear plane area, $A_s$ $= \dfrac{t_o \times w}{\sin\phi}$

# Force analysis

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

Shear strength of material

$$F_c = \left(\frac{t_o w \tau}{\sin\phi}\right)\left(\frac{\cos(\beta-\alpha)}{\cos(\phi+\beta-\alpha)}\right)$$

$$R = \left(\frac{t_o w \tau}{\sin\phi}\right)\left(\frac{1}{\cos(\phi+\beta-\alpha)}\right)$$

$$F_t = R\sin(\beta-\alpha) = \left(\frac{t_o w \tau}{\sin\phi}\right)\left(\frac{\sin(\beta-\alpha)}{\cos(\phi+\beta-\alpha)}\right)$$

$$\frac{F_t}{F_c} = \tan(\beta-\alpha)$$

# Force analysis

Mean shear stress on chip

$$\tau_{chip} = \frac{F_s}{A_s}$$

Mean normal stress on chip

$$\sigma_{chip} = \frac{F_N}{A_s}$$

# Shear Stress on Tool Face

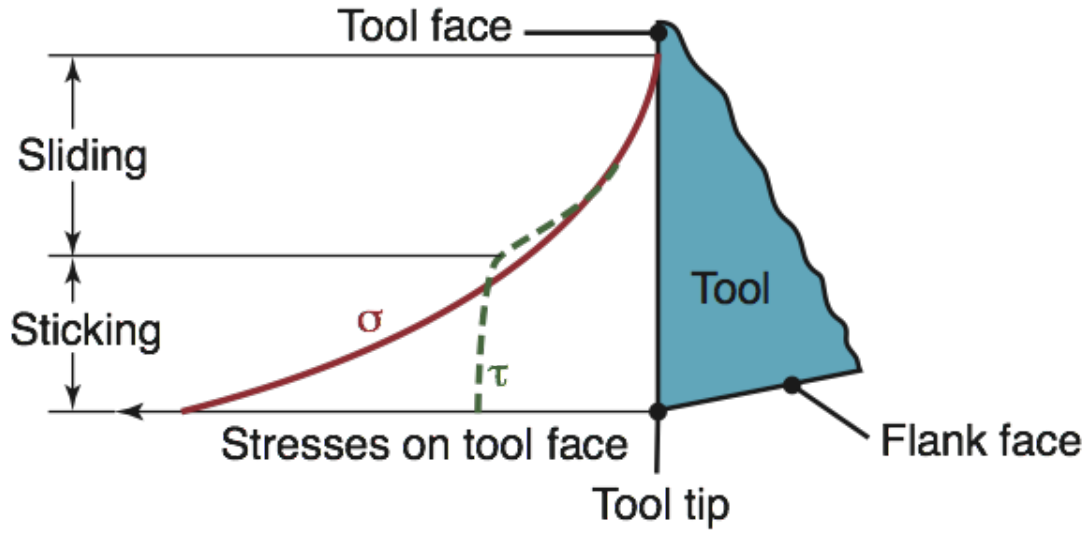


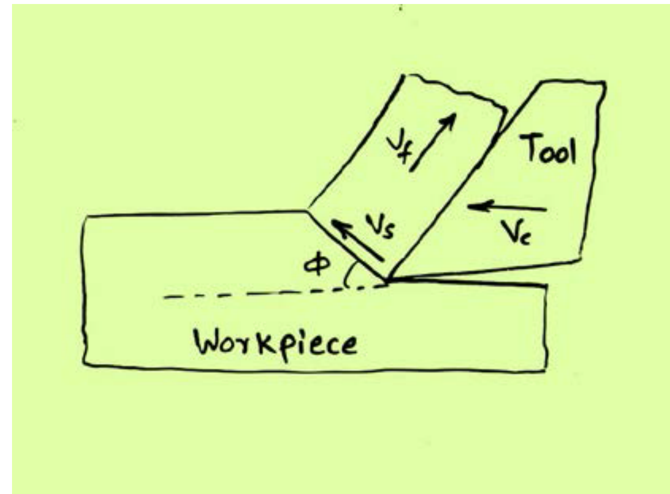

FIGURE 8.14 Schematic illustration of the distribution of normal and shear stresses at the tool-chip interface (rake face). Note that, whereas the normal stress increases continuously toward the tip of the tool, the shear stress reaches a maximum and remains at that value (a phenomenon known as *sticking*; see Section 4.4.1).

# Velocity analysis

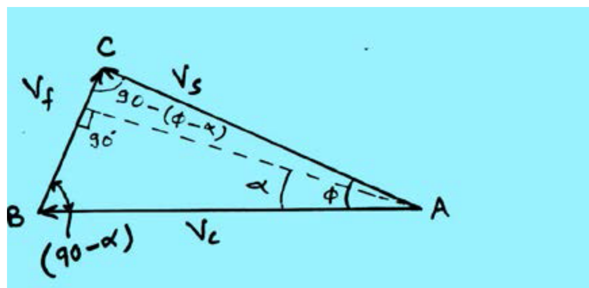
$V_c$: Cutting velocity

$V_f$: Chip flow velocity

$V_s$: Shear velocity




Using sine rule

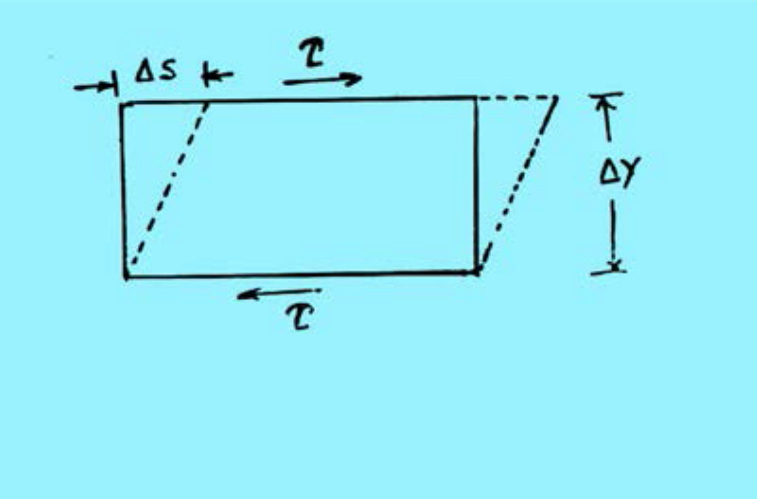


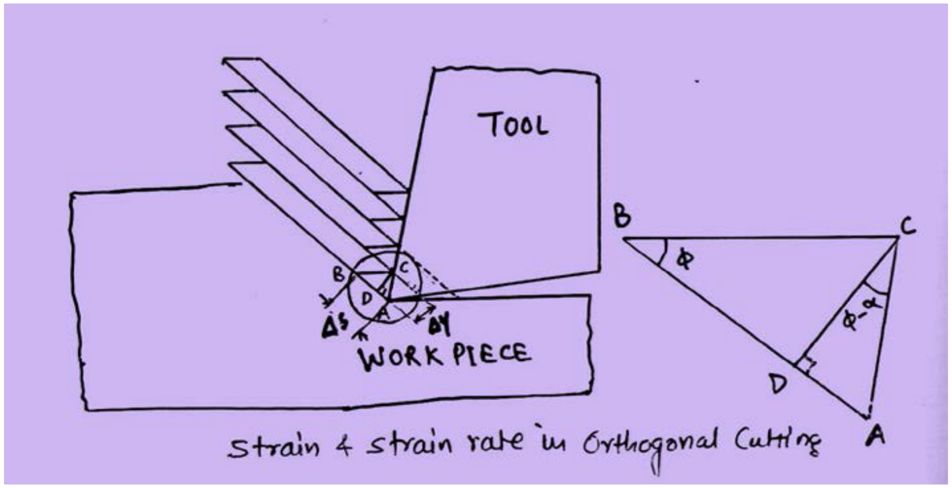

$$\frac{V_c}{\sin(90-(\phi-\alpha))}=\frac{V_f}{\sin\phi}=\frac{V_s}{\sin(90-\alpha)}$$

$$\frac{V_c}{\cos(\phi-\alpha)}=\frac{V_f}{\sin\phi}=\frac{V_s}{\cos\alpha} \qquad and \quad V_f=\frac{V_c\sin\phi}{\cos(\phi-\alpha)}=V_c\cdot r_c$$

$$\boxed{V_s=\frac{V_c\cos\alpha}{\cos(\phi-\alpha)}\Rightarrow\frac{V_s}{V_c}=\frac{\cos\alpha}{\cos(\phi-\alpha)}}$$

# Shear strain and strain rate




$$ShearStrain(\gamma) = \frac{deformation}{Length}$$

$$\gamma = \frac{\Delta s}{\Delta y} = \frac{AB}{CD} = \frac{AD}{CD} + \frac{DB}{CD} \qquad = \tan(\phi - \alpha) + \cot\phi$$

shear strain rate:

$\dot{\gamma} = \frac{V_s}{d}$, where $d$ is typically $10^{-2} \sim 10^{-3}$ mm

# Shear angle relationship

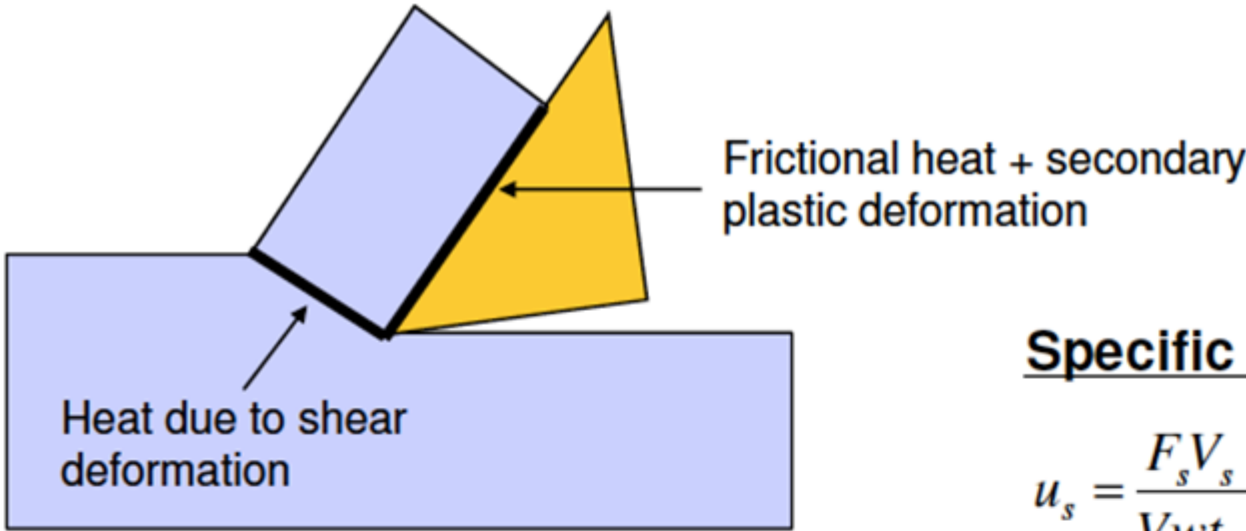
- Merchant's theory: shear angle $\phi$ assumes a value that minimizes the work done (or cutting force) in metal cutting
- Assuming that $\beta$ is independent of $\phi$ and shear yield stress of the work material is constant, we can show that

$$\frac{dF_c}{d\phi} = 0 \Rightarrow \phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha)$$

- General form of shear angle relationship

$$\phi = C_1 + C_2(\beta - \alpha)$$

# Energy in cutting




**Specific shear energy**

$$u_s = \frac{F_s V_s}{V w t_0} \quad (\mathrm{Jm^{-3}\ or\ Nm^{-2}})$$

**Specific cutting energy**

$$u_c = \frac{energy}{volume} = \frac{F_c V}{V w t_0} \quad (\mathrm{Jm^{-3}\ or\ Nm^{-2}})$$

**Specific friction energy**

$$u_f = \frac{F V_c}{V w t_0} \quad (\mathrm{Jm^{-3}\ or\ Nm^{-2}})$$

$$\boxed{u_c \approx u_s + u_f} \text{ OR } \boxed{P_c \approx P_s + P_f}$$

# Shear angle relationship

$P_c$ = cutting power = $F_c V = u_c(Vwt_0)$

$P_s$ = shear zone power = $F_s V_s = u_s(Vwt_0)$

$P_f$ = friction zone power = $FV_c = u_f(Vwt_0)$

- Typically, 60-70% of the energy in metal cutting is consumed in the shear zone
- Remaining 40-30% is consumed at the tool-chip interface (assuming a perfectly sharp tool)
- Momentum and surface creation energies are negligible

# Example

A orthogonal cutting process is being used to machine a 300 mm x 300 mm x 25 mm flat mild steel block. The sharp single point cutting tool has a rake angle $\alpha = 10°$. Other process parameters are as follows: cutting speed $V = 2$ m/s, undeformed chip thickness $t0 = 0.25$ mm, width of cut per pass $w = 2.5$ mm, deformed chip thickness $tc = 0.83$ mm. The cutting and thrust forces were measured during each pass with a cutting force dynamometer and found to be as follows: $Fc = 890$ N and $Ft = 667$ N. (Note: Planing is an orthogonal cutting process). Calculate the percentage of total power dissipated in the primary zone of deformation (shear zone).

# Types of Chips

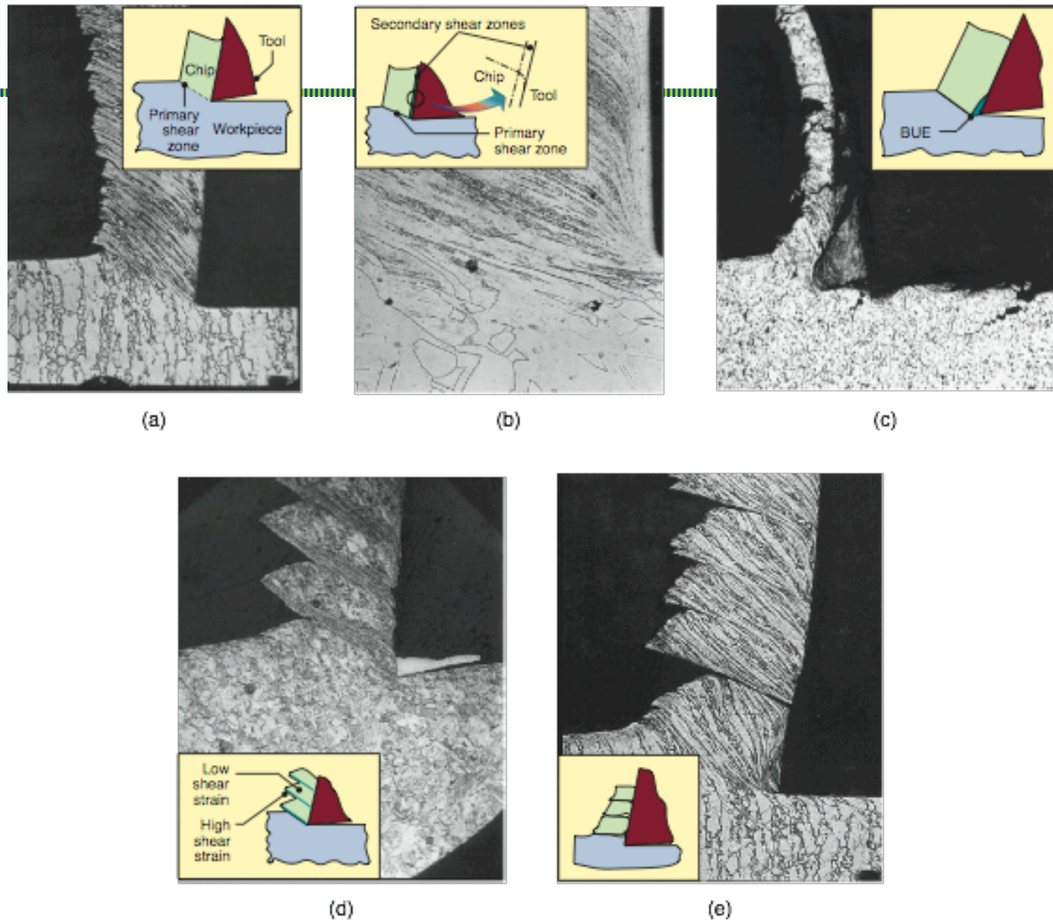



FIGURE 8.4 Basic types of chips produced in metal cutting and their micrographs: (a) continuous chip with narrow, straight primary shear zone; (b) secondary shear zone at the tool-chip interface; (c) continuous chip with built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip. *Source:* After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

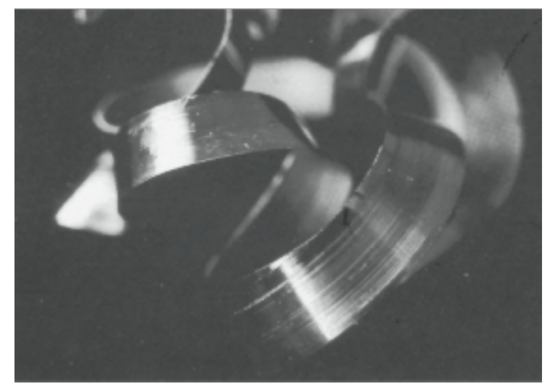
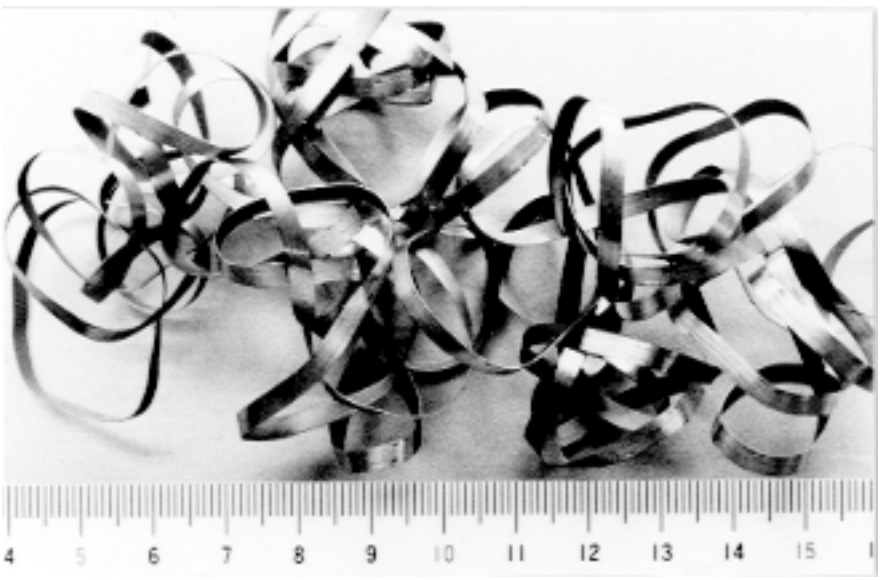


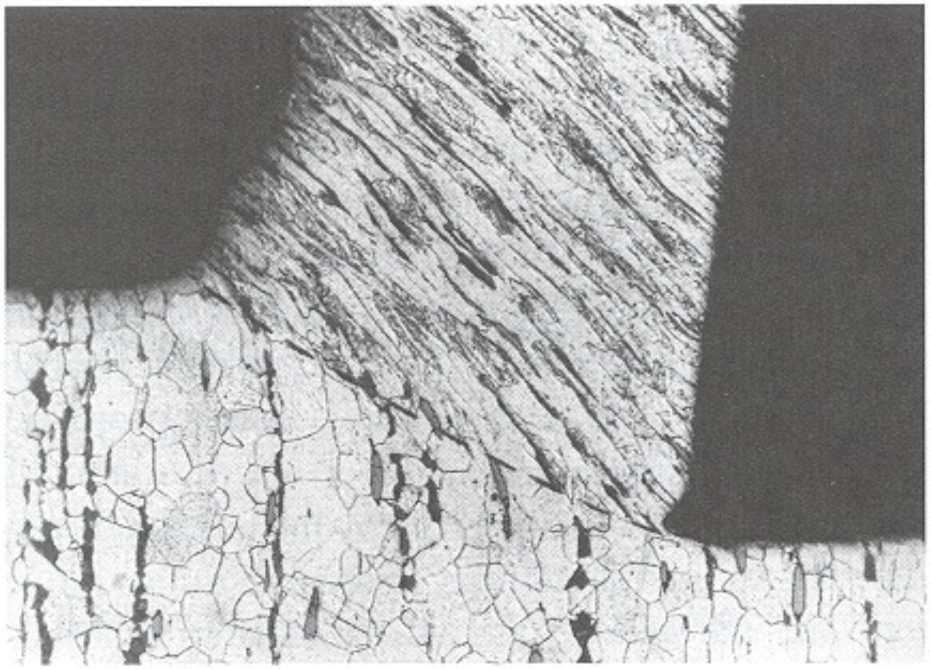
FIGURE 8.5 Shiny (burnished) surface on the tool side of a continuous chip produced in turning.

# Major chip types

Continuous chip is characteristic of cutting ductile materials under steady stage conditions. However, long continuous chips present handling and removal problems in practical operation.

- required chip-breaker.





# Chip Breakers

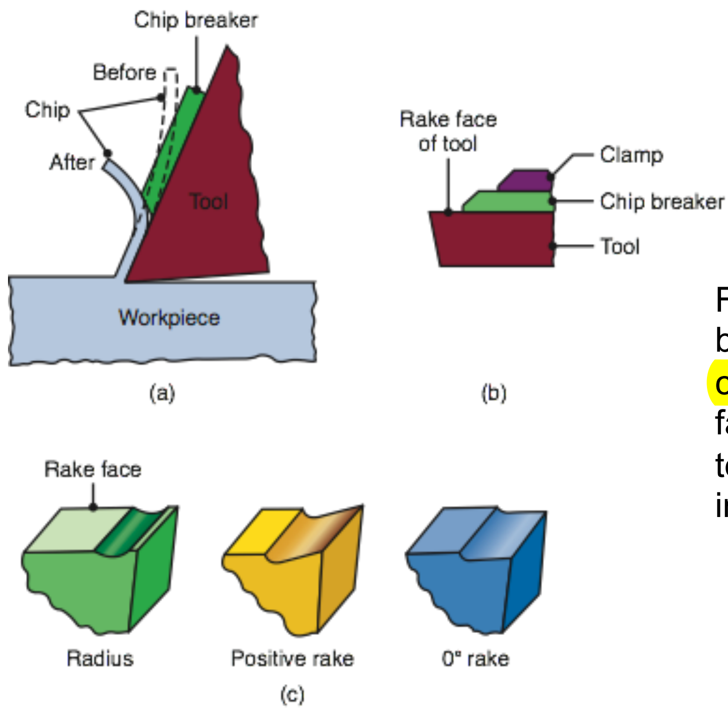
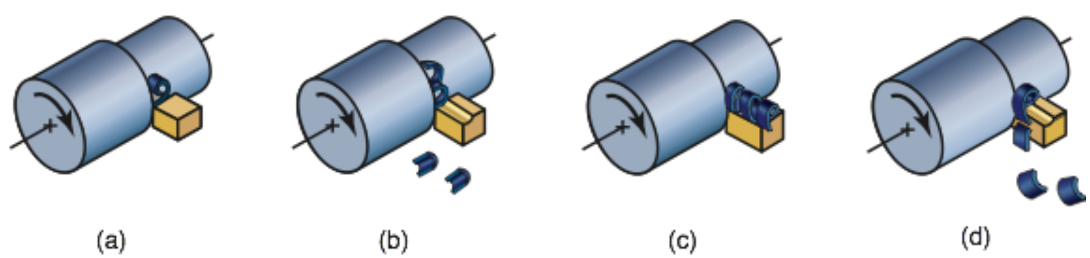



FIGURE 8.7 (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip. (b) Chip breaker clamped on the rake face of a cutting tool. (c) Grooves on the rake face of cutting tools, acting as chip breakers. Most cutting tools now are inserts with built-in chip-breaker features.

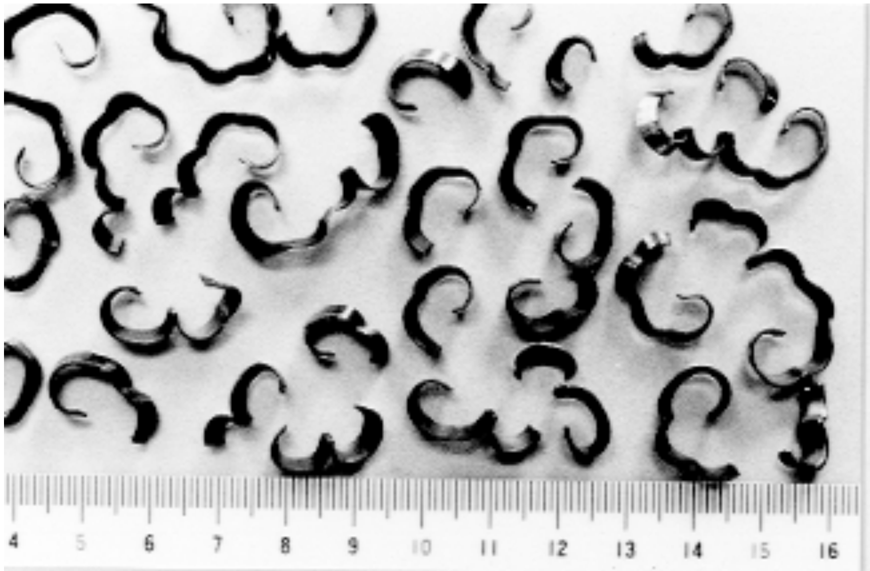
FIGURE 8.8 Various chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks; (c) continuous chip moving radially outward from workpiece; and (d) chip hits tool shank and breaks off. *Source:* After G. Boothroyd.



# Major chip types

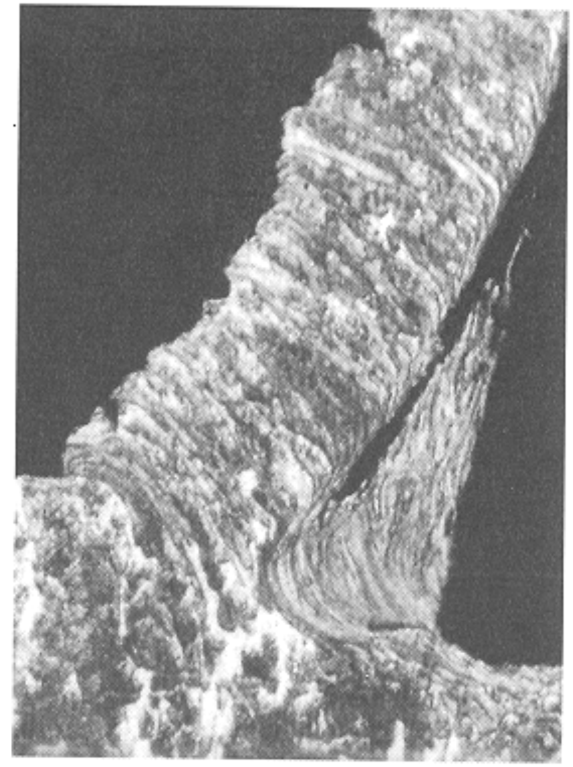
Discontinuous chip is formed in brittle materials which cannot withstand the high shear strains imposed during the machining process.

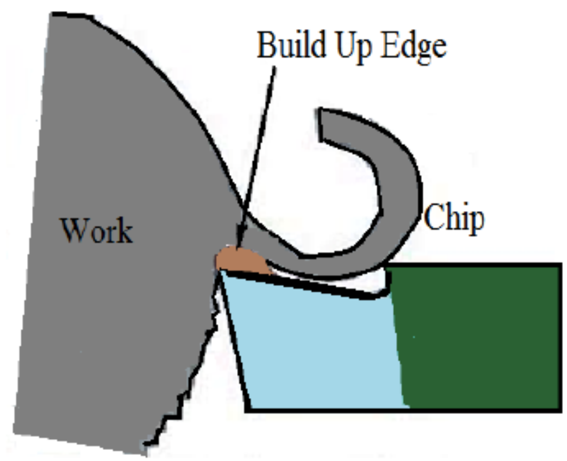
Ex: cast iron and cast brass, may occur in ductile materials machined at very low speeds and high feed.



# Major chip types

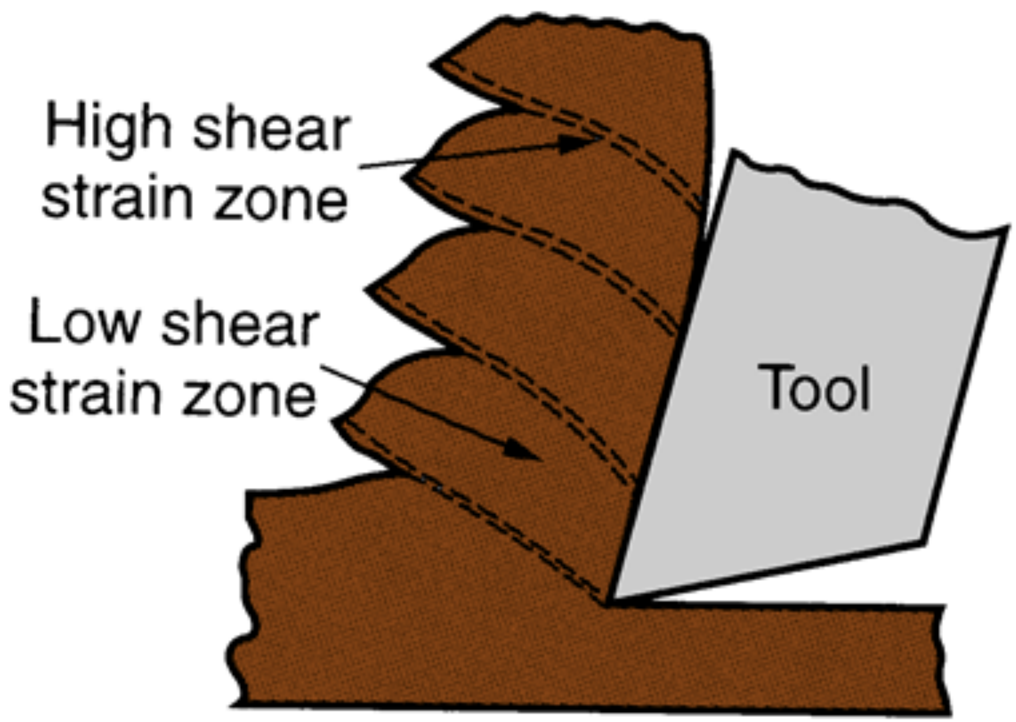
- Under conditions where the friction between the chip and the rake face of the tool is high, the chip may weld to the tool face.
- The accumulation of the chip material is known as a built-up edge (BUE).
- The formation of BUE is due to work hardening in the secondary shear zone at low speed (since heat is transferred to the tool).
- The BUE acts as a substitute cutting edge (blunt tool with a low rake angle).





# Major chip types

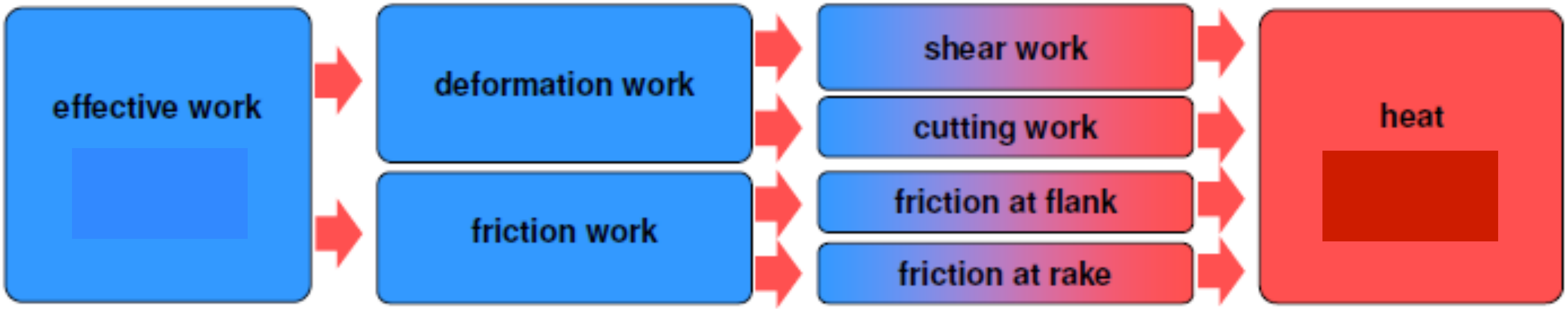
Segmented chips: low thermal diffusivity materials, very hard steels

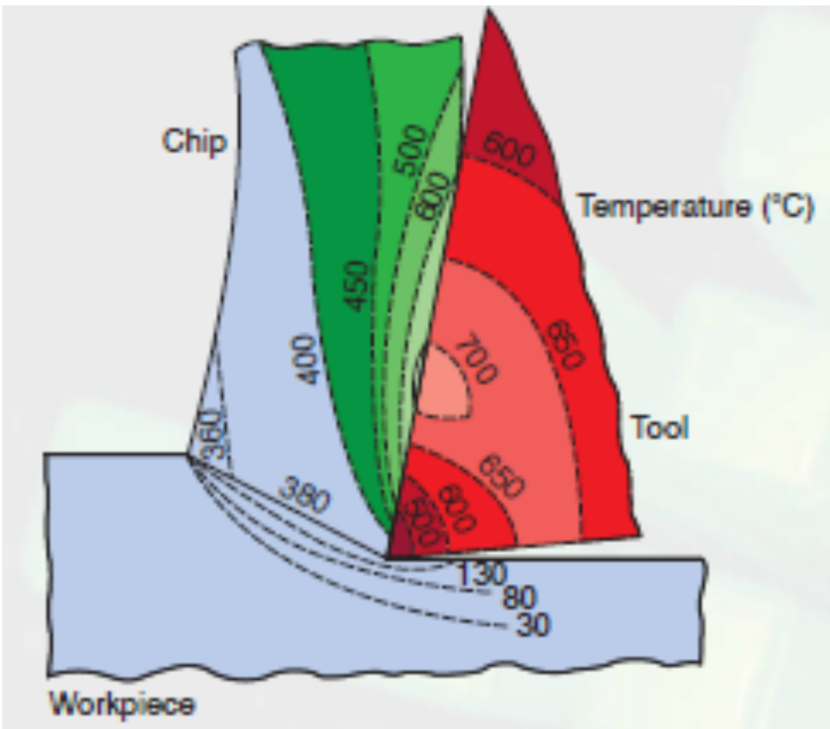


# Chip types

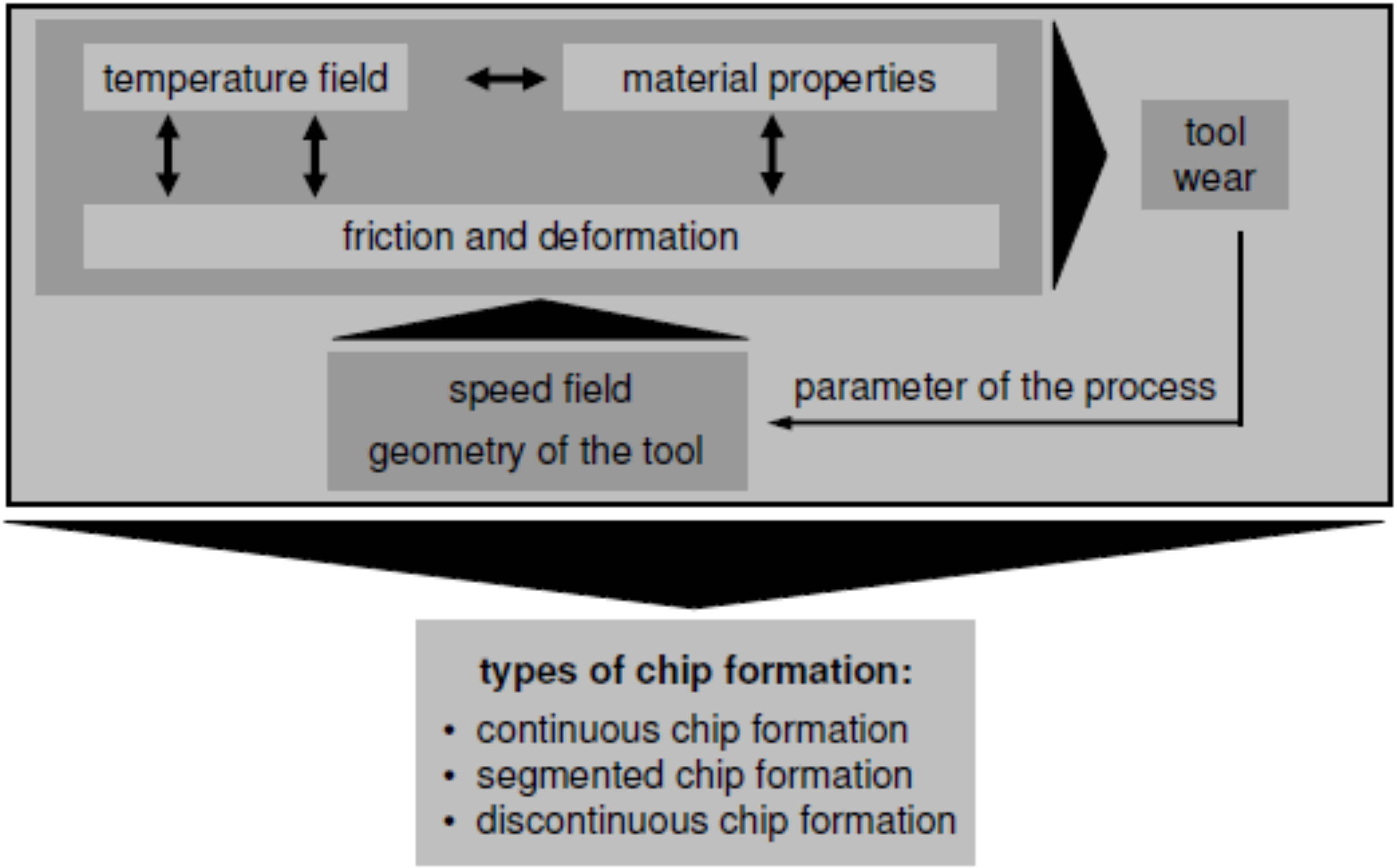
- (a) Continuous chip with narrow primary shear zone
  – ductile materials at high speed
  – bad for automation (use chip breakers)
- (b) Continuous chip with built up edge (BUE)
  – high plastic working
  – bad for automation
- (c) Continuous chip with large primary shear zone
  – soft metals at low speeds and low rake angles
  – poor surface finish and residual stresses
- (d) Segmented chip
  – low thermal conductivity materials
- (e) Discontinuous chip
  – low ductility materials and/or negative rake angles
  – good for automation

# Heat source and temperature in cutting



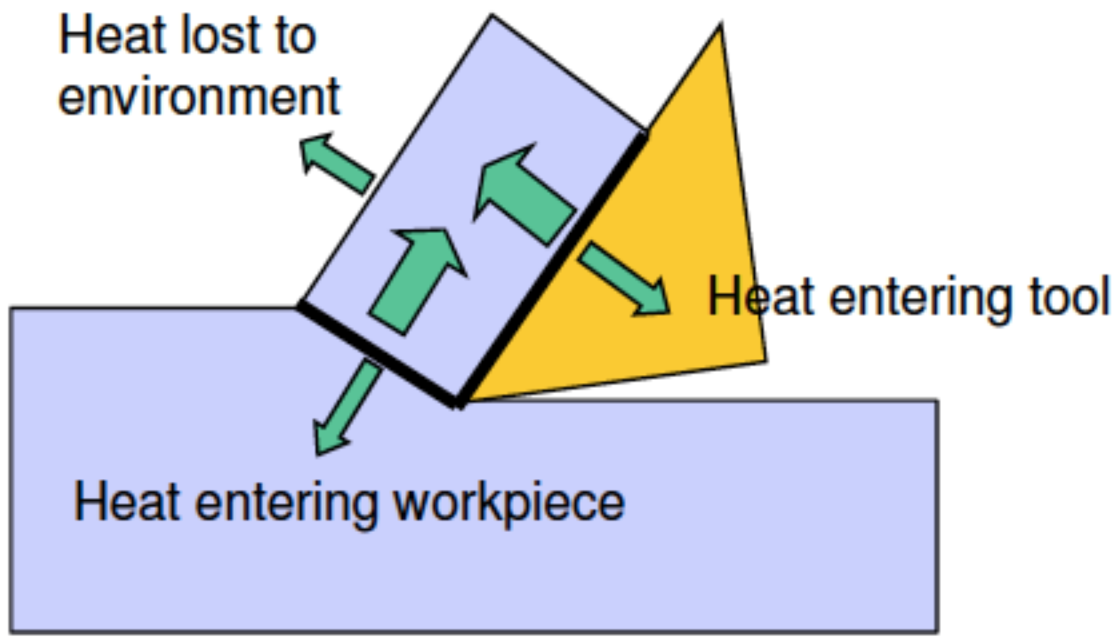



# Thermal and mechanical loads



# Temperature in metal cutting

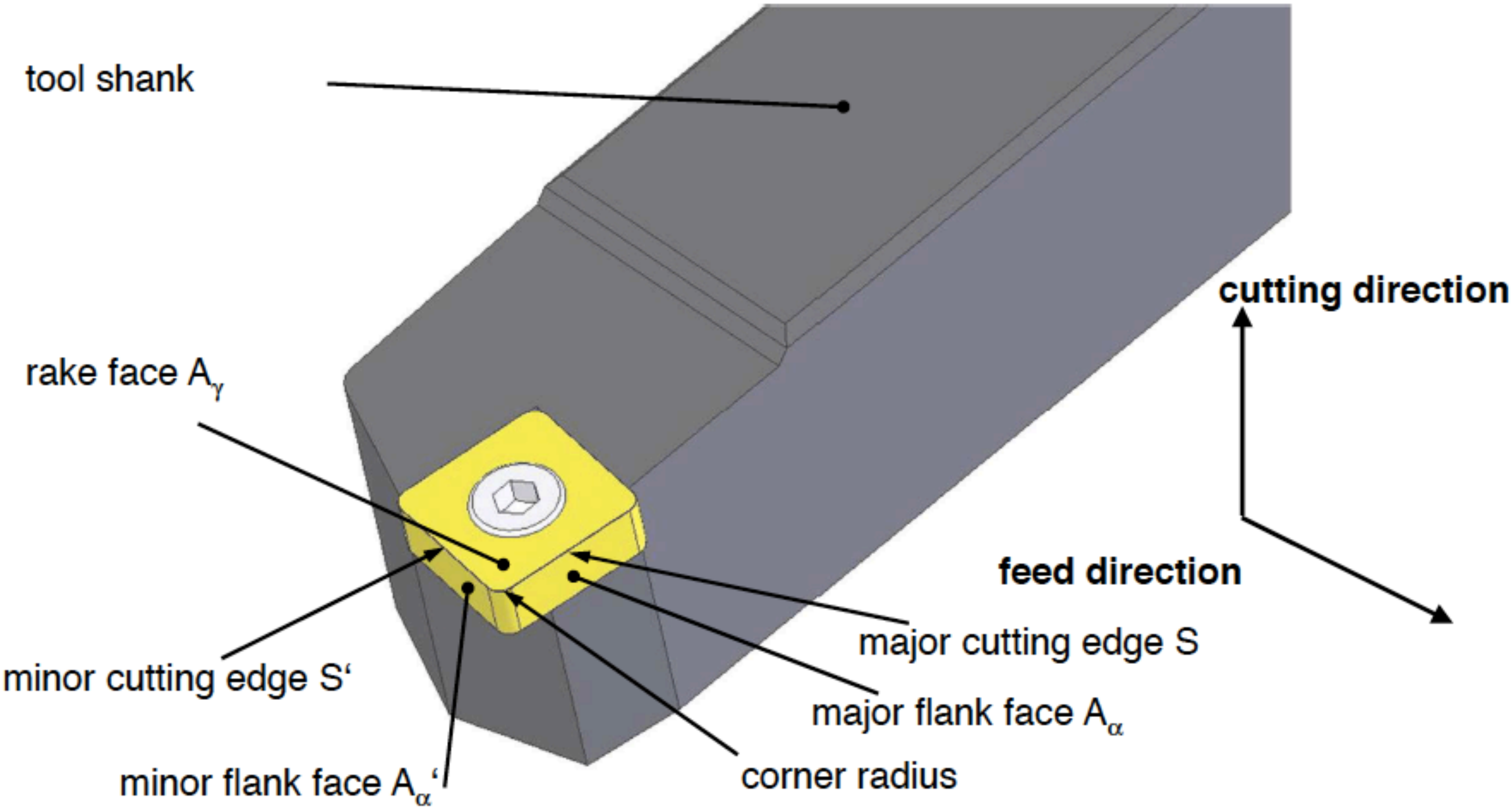
- Energy dissipated in cutting converted into heat in shear zone and tool-chip interface
- Heat transfer to environment is negligible



# Temperature in metal cutting

- Adverse effects of temperature rise in tool and workpiece
  - Increases tool wear
  - Harder to achieve part accuracy (due to thermal expansion of part)
  - Sub-surface damage (surface integrity)
- Desirable that most of the heat is carried away by chip

# Terms at the cutting edge



# Tool Angles

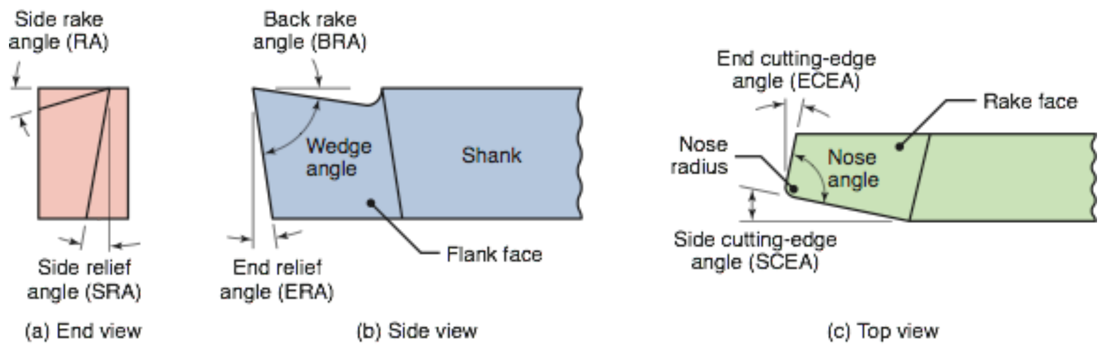



FIGURE 8.41 Designations and symbols for a right-hand cutting tool. The designation "right hand" means that the tool travels from right to left, as shown in Fig. 8.19.

TABLE 8.8 General recommendations for tool angles in turning.

| Material | High-speed steel | | | | | Carbide inserts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Back rake | Side rake | End relief | Side relief | Side and end cutting edge | Back rake | Side rake | End relief | Side relief | Side and end cutting edge |
| Aluminum and magnesium alloys | 20 | 15 | 12 | 10 | 5 | 0 | 5 | 5 | 5 | 15 |
| Copper alloys | 5 | 10 | 8 | 8 | 5 | 0 | 5 | 5 | 5 | 15 |
| Steels | 10 | 12 | 5 | 5 | 15 | -5 | -5 | 5 | 5 | 15 |
| Stainless steels | 5 | 8-10 | 5 | 5 | 15 | -5-0 | -5-5 | 5 | 5 | 15 |
| High-temperature alloys | 0 | 10 | 5 | 5 | 15 | 5 | 0 | 5 | 5 | 45 |
| Refractory alloys | 0 | 20 | 5 | 5 | 5 | 0 | 0 | 5 | 5 | 15 |
| Titanium alloys | 0 | 5 | 5 | 5 | 15 | -5 | -5 | 5 | 5 | 5 |
| Cast irons | 5 | 10 | 5 | 5 | 15 | -5 | -5 | 5 | 5 | 15 |
| Thermoplastics | 0 | 0 | 20-30 | 15-20 | 10 | 0 | 0 | 20-30 | 15-20 | 10 |
| Thermosets | 0 | 0 | 20-30 | 15-20 | 10 | 0 | 15 | 5 | 5 | 15 |

# Machinability

**machine tool**

- machine tool
- machine condition

**production conditions**

- production processes
- engagement parameter
- cooling

**machinability**

- tool life
- surface integrity
- total force
- chip form

**tool**

- tool type
- geometry of the cutting edge
- clamping

**workpiece**

- geometry
- surface integrity
- clamping

**cutting material**

- type of the material
- chemical configuration
- microstructure
- strength property
- surface treatment

**material**

- type of the material
- chemical configuration
- microstructure
- strength property
- heat treatment

# Tool wear

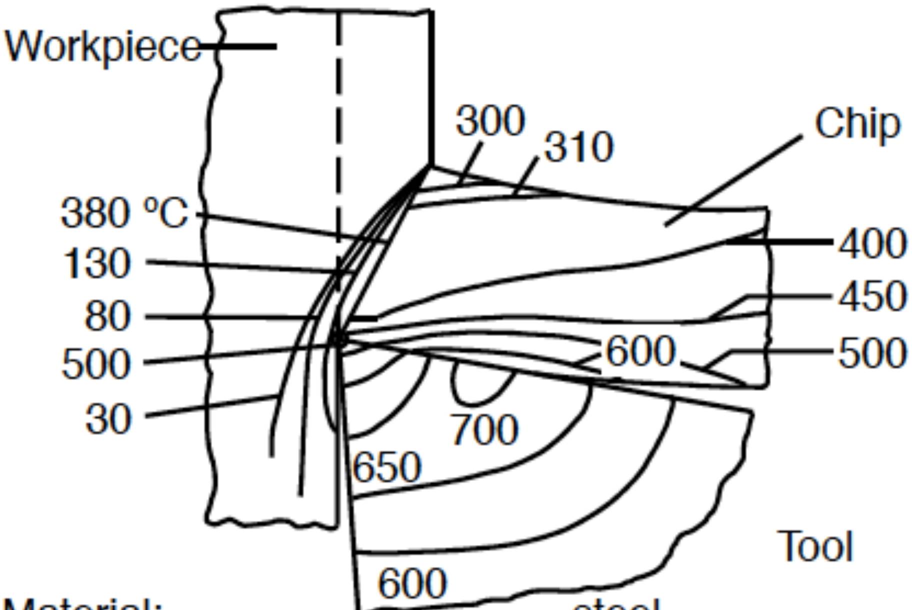
**Tool wear**
**is influenced by high contact stresses, high cutting temperatures and relative sliding velocities**

**These process values depend on:**

- tool and workpiece materials
- tool geometry
- interface conditions
- machining parameters

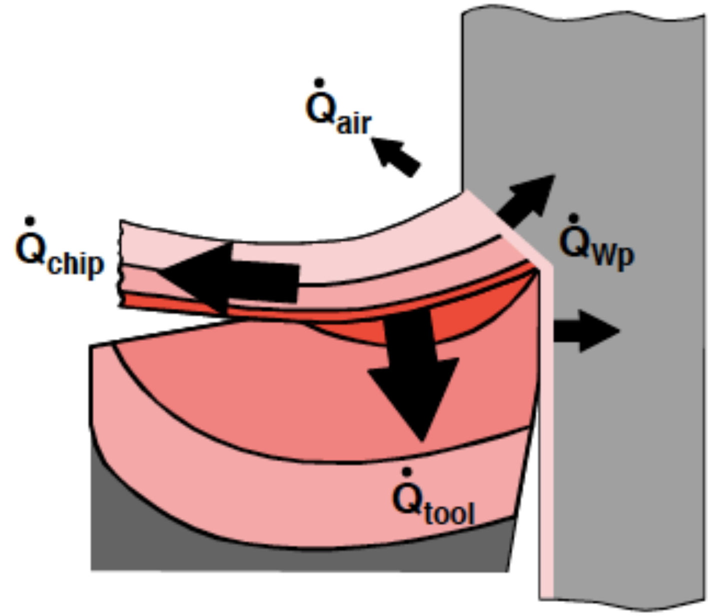
# Distribution of heat

## Allocation of heat in the machining zone




| | |
|---|---|
| Material: | steel |
| Yield stress: | $k_f = 850\ N/mm^2$ |
| Cutting material: | HW-P20 |
| Primary speed: | $v_c = 60$ m/min |
| Chip width: | h = 0,32 mm |
| Chip angle: | $\gamma_o = 10^o$ |

## Heat flows emerging from the machining zone




$Q_{air}$ = Heat flow to environment

$Q_{chip}$ = Heat flow to chip

$Q_{Wp}$ = Heat flow to workpiece

$Q_{tool}$ = Heat flow to tool

# Tool wear locations

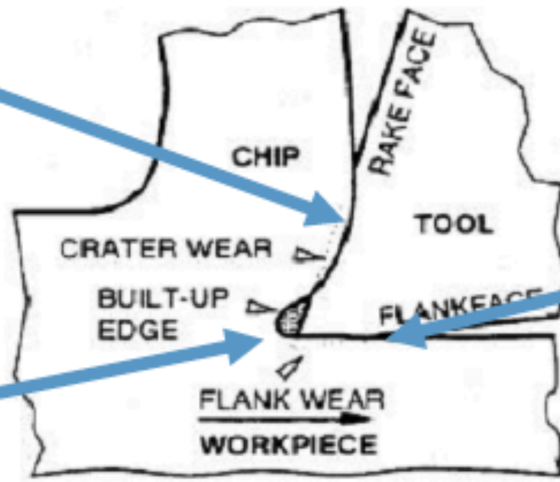
## Tool Wear appears at three locations at the cutting tool

**Crater Wear**

Area of high level of stress and temperature, i.e. of the order of 1200°C.

**Built-Up Edge**

Observable for ductile materials. Not stable, breaks off frequently

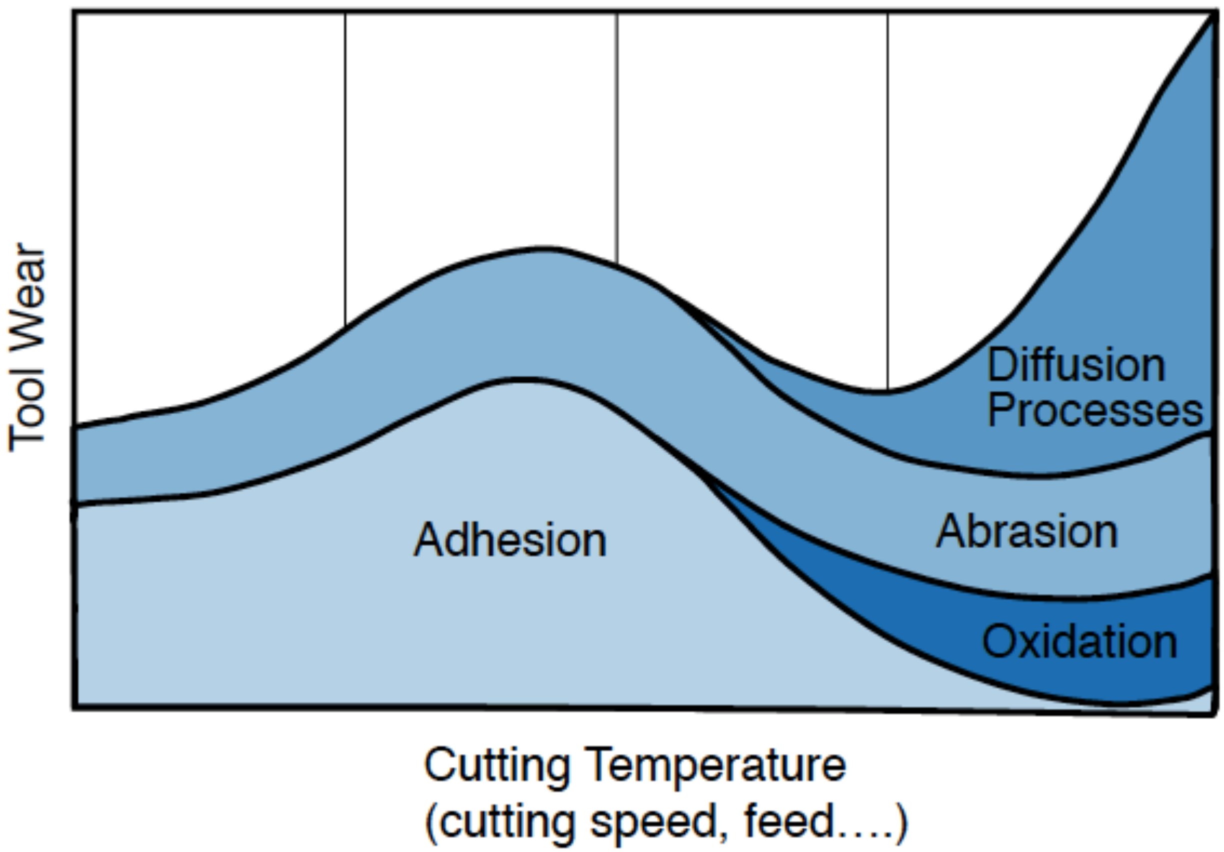



Tool Wear

**Flank Wear**

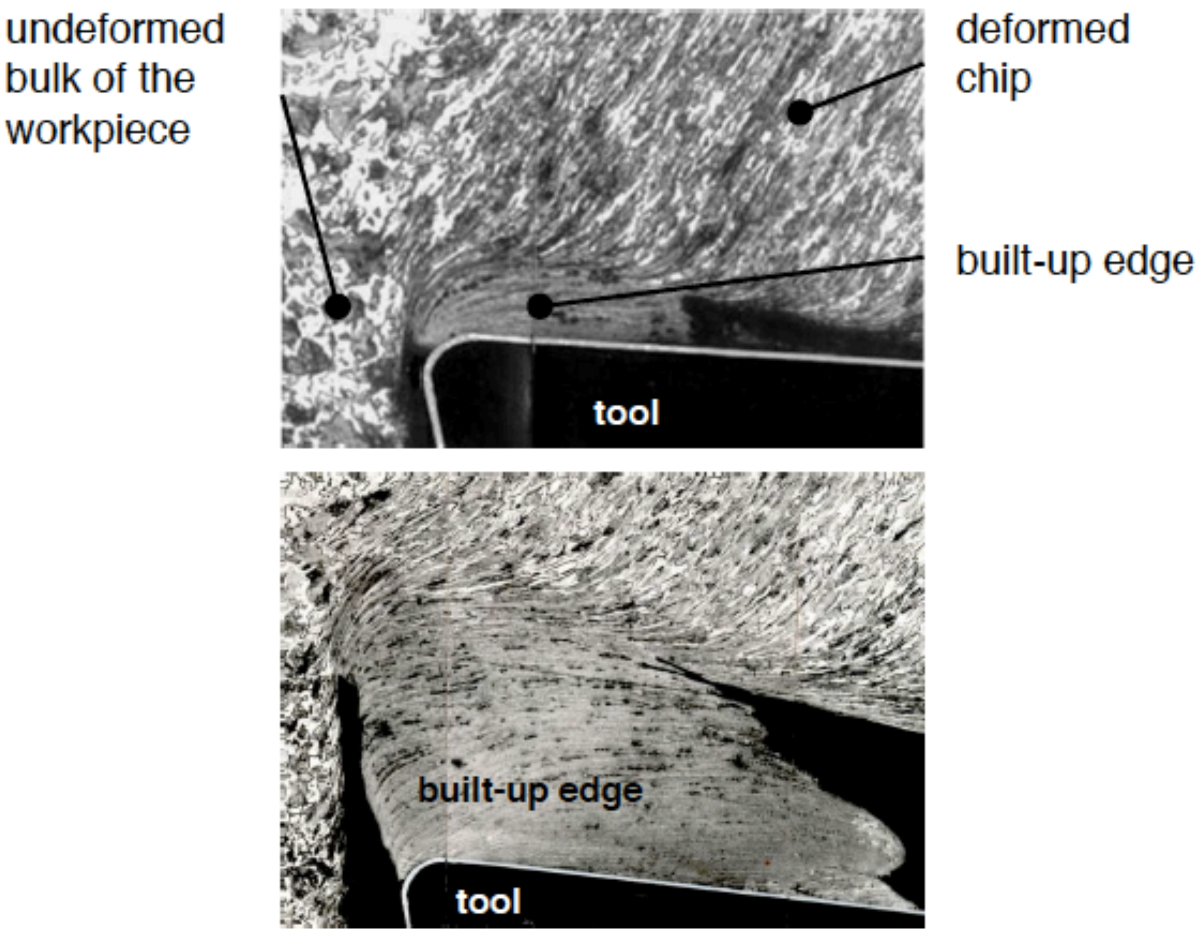
Mainly responsible for the resulting surface quality => used as failure criteria.

# Wear mechanisms



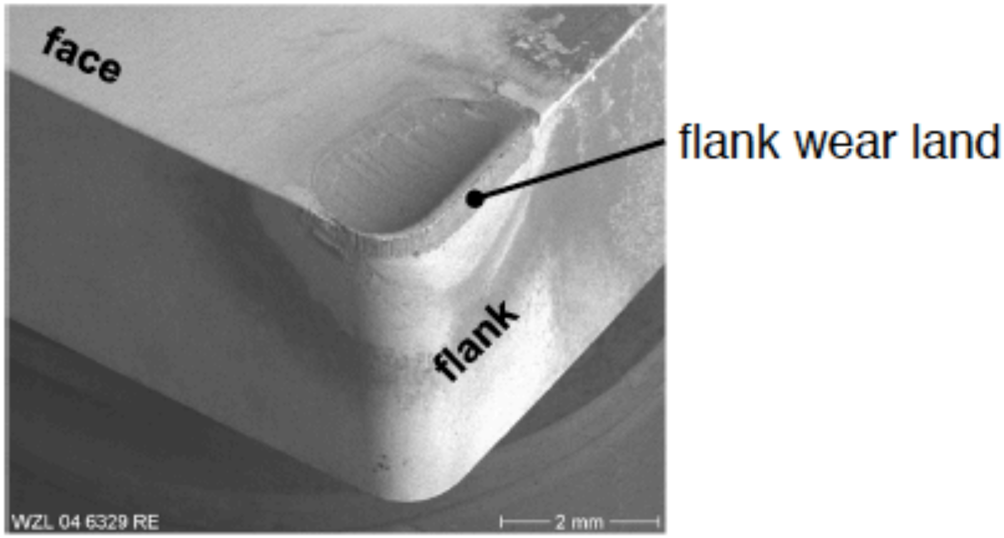

- The total wear at the wedge is a superposition of distinct wear mechanisms.
- During cutting all distinct wear mechanisms occur simultaneously.
- Diffusion and oxidation are dependent on the temperature level and occur mainly at high cutting speeds.

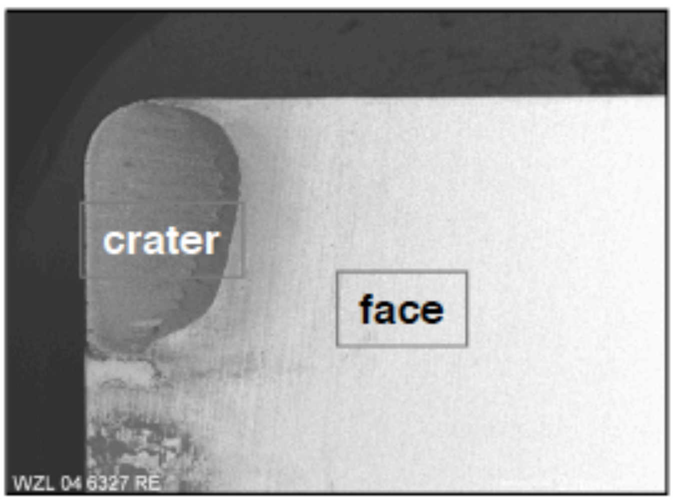
# Wear mechanism: Adhesion




- Low cutting speeds causes low contact temperatures between chip and tool. This goes along with high contact pressure.
- Low contact temperatures, high contact pressure and material affinity lead to adhesion.
- Adhesion at the wedge may cause built-up edges.
- Built-up edges are unstable. They peel away off the edge and slide over the flank and the face periodically.

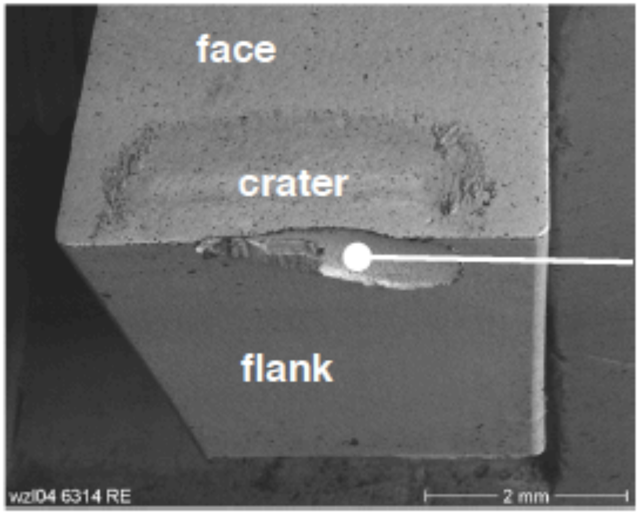
# Wear mechanism: Abrasion



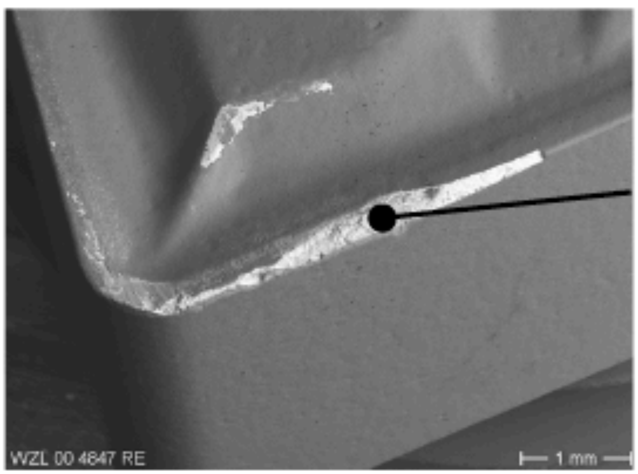




- Abrasion at the wedge is caused by hard particles in the chip, which penetrate into the tool material and slide and scratch over the face.
- As a result on the face a crater is generated.
- As a result on the flank a wear land is generated.

# Catastrophic failure of the wedge



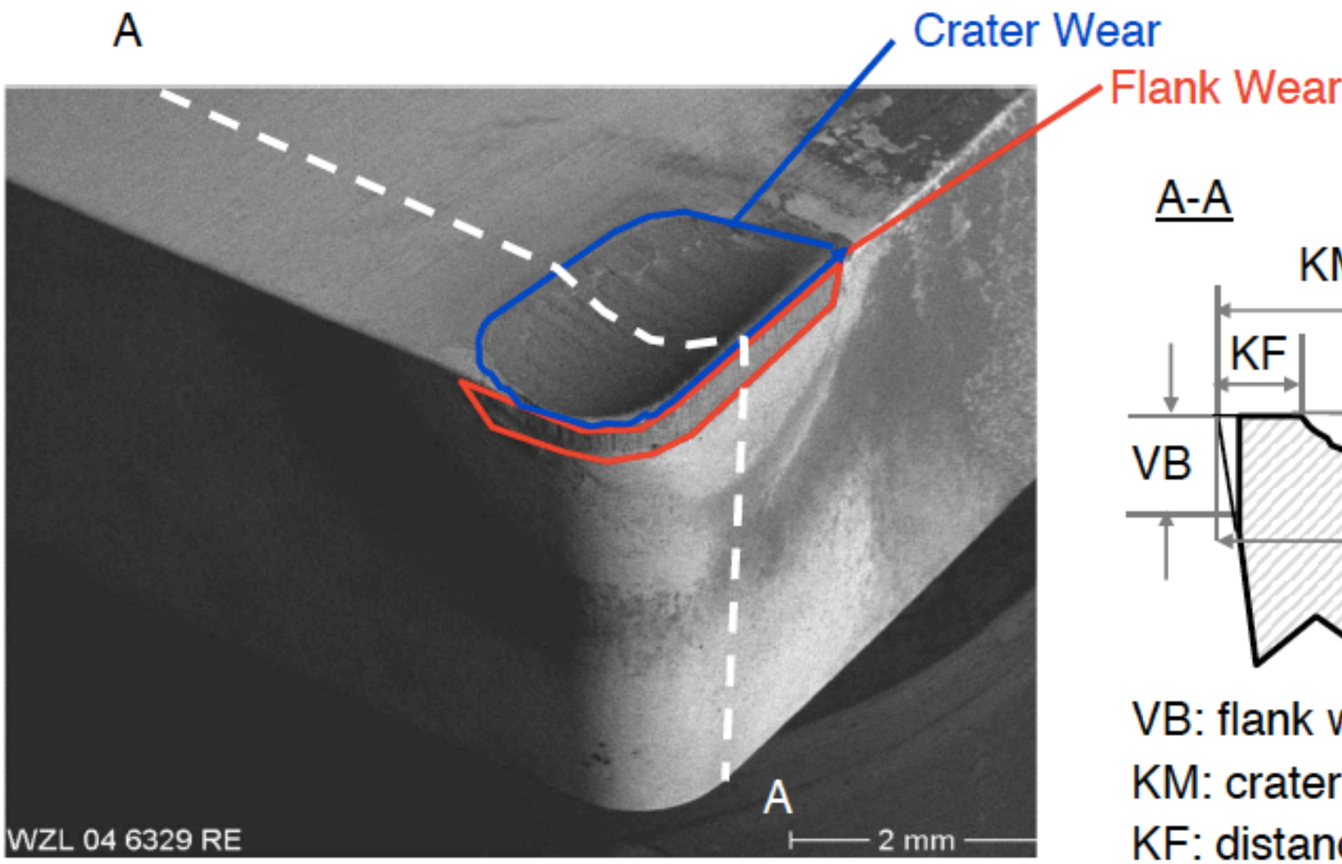

Chipping and break outs
at cutting edge

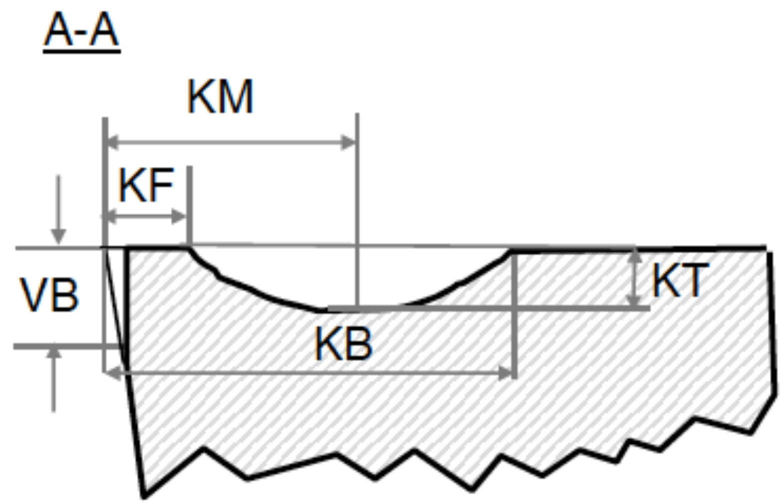



little disruptions
at the cutting edge

- If the mechanical load at the wedge surpasses the resistance of the cutting material, the cutting edge fails.

# Wear characterization




VB: flank wear width
KM: crater center distance
KF: distance from crater to edge
KB: crater width
KT: crater depth

# Tool Wear

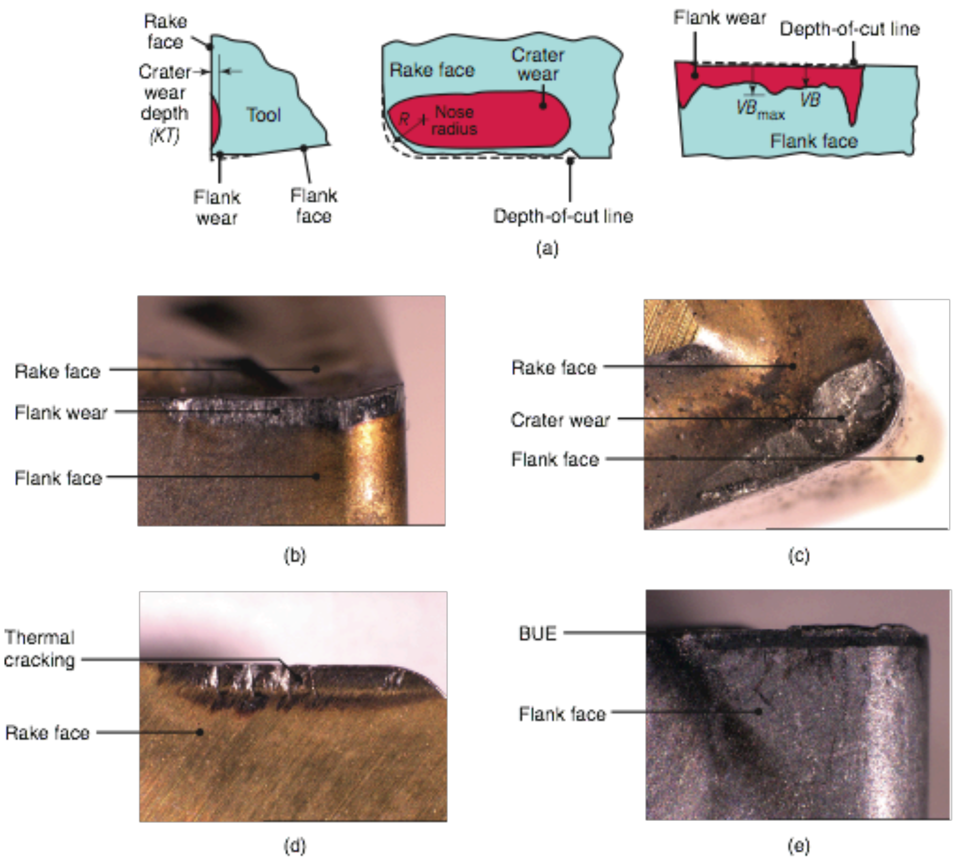



FIGURE 8.20 Examples of wear in cutting tools. (a) Flank wear; (b) crater wear; (c) chipped cutting edge; (d) thermal cracking on rake face; (e) flank wear and built-up edge. *Source:* Courtesy of Kennametal, Inc.

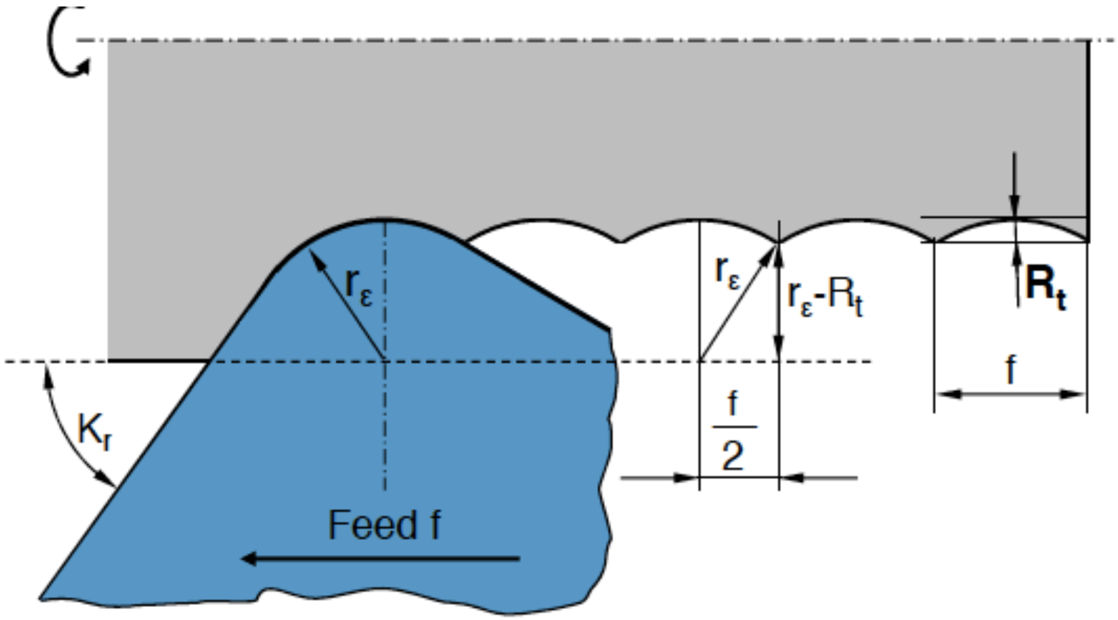
Taylor tool life equation:

$$VT^n = C$$

TABLE 8.4 Range of *n* values for various cutting tool

| | |
|---|---|
| High-speed steels | 0.08-0.2 |
| Cast alloys | 0.1-0.15 |
| Carbides | 0.2-0.5 |
| Ceramics | 0.5-0.7 |

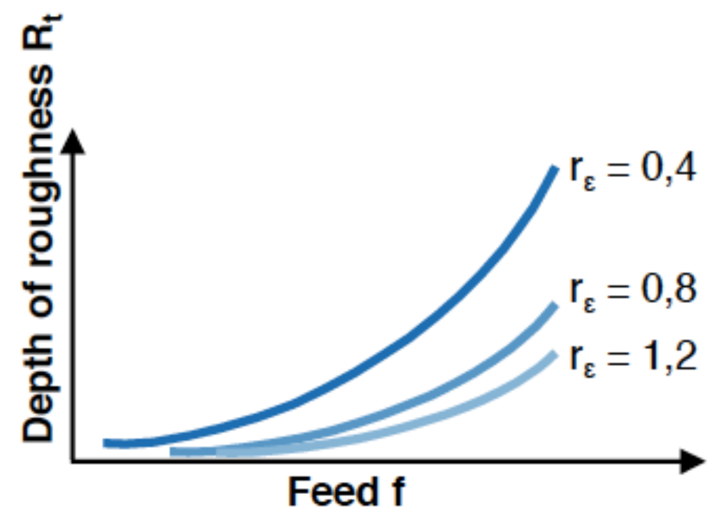
# Theoretical surface roughness




$$R_t = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f^2}{4}}$$

or :

$$R_t = \frac{f^2}{8 \cdot r_\varepsilon}$$

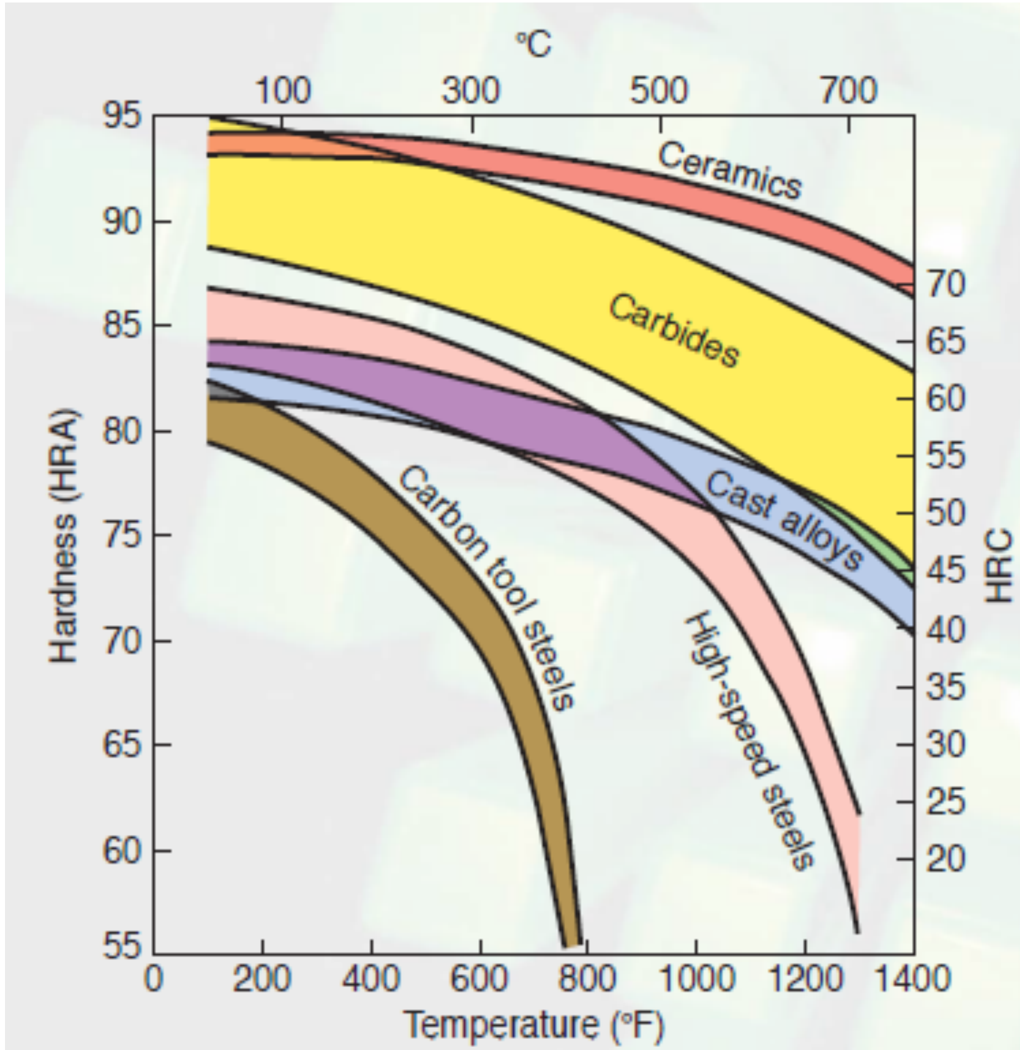



The theoretical depth of roughness $R_t$ can be derived from the geometrical engagement specifications and is a function of the feed and the corner radius $r_\varepsilon$

# Problem

If in turning of a steel rod by a given cutting tool (material and geometry) at a given machining condition (So and t) under a given environment (cutting fluid application), the tool life decreases from 80 min to 20 min. due to increase in cutting velocity, Vc from 60 m/min to 120 m/min., then at what cutting velocity the life of that tool under the same condition and environment will be 40 min.?

# Hardness of cutting tools



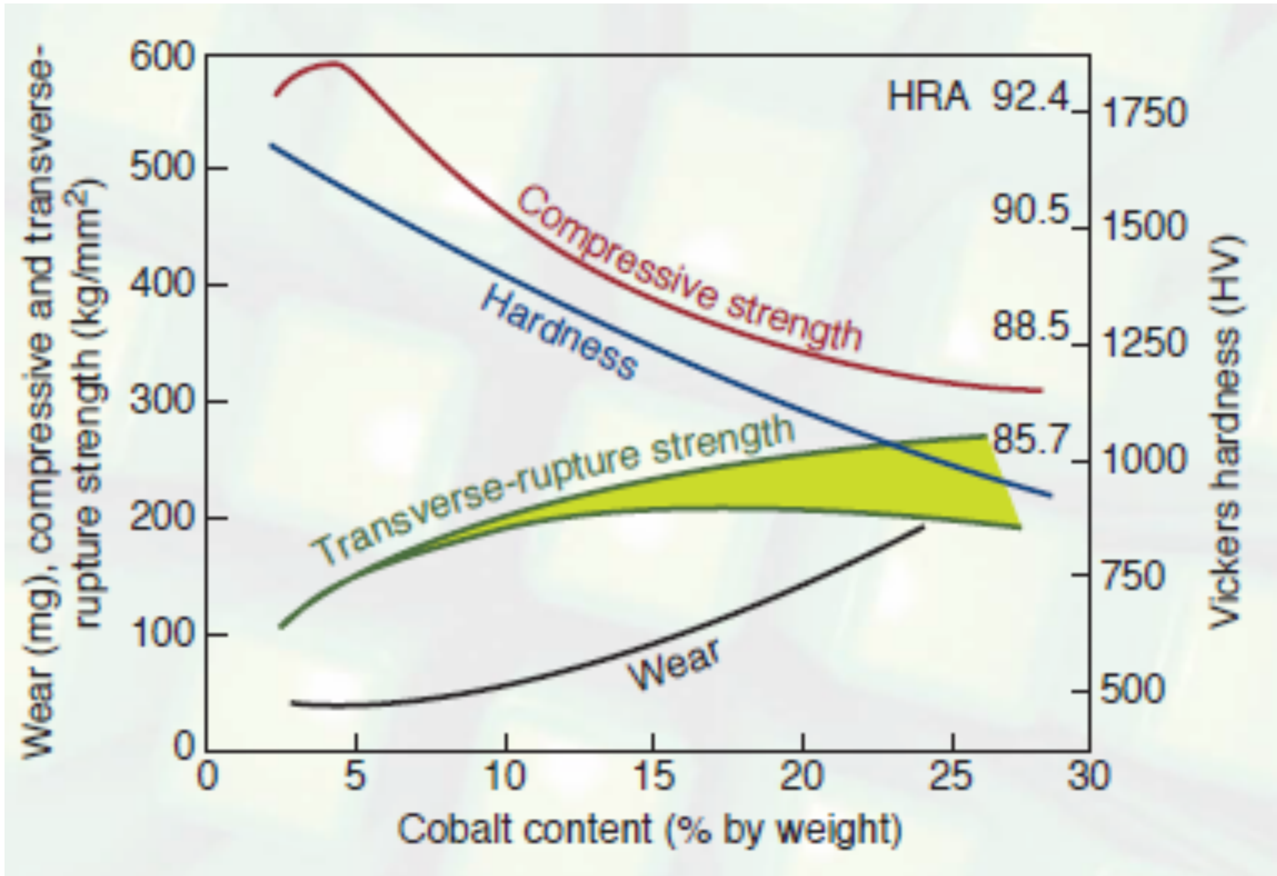

Hardness of various cutting-tool materials as a function of temperature (hot hardness).

# Tool materials

| Property | High-Speed Steel | Cast Alloys | Carbides WC | Carbides TiC | Ceramics | Cubic Boron Nitride | Single Crystal Diamond* |
|---|---|---|---|---|---|---|---|
| Hardness | 83-86 HRA | 82-84 HRA | 90-95 HRA | 91-93 HRA | 91-95 HRA | 4000-5000 HK | 7000-8000 HK |
| Compressive strength | | | | | | | |
| MPa | 4100-4500 | 1500-2300 | 4100-5850 | 3100-3850 | 2750-4500 | 6900 | 6900 |
| psi $\times 10^3$ | 600-650 | 220-335 | 600-850 | 450-560 | 400-650 | 1000 | 1000 |
| Transverse rupture strength | | | | | | | |
| MPa | 2400-4800 | 1380-2050 | 1050-2600 | 1380-1900 | 345-950 | 700 | 1350 |
| psi $\times 10^3$ | 350-700 | 200-300 | 150-375 | 200-275 | 50-135 | 105-200 | |
| Impact strength | | | | | | | |
| J | 1.35-8 | 0.34-1.25 | 0.34-1.35 | 0.79-1.24 | $< 0.1$ | $< 0.5$ | $< 0.2$ |
| in.-lb | 12-70 | 3-11 | 3-12 | 7-11 | $< 1$ | $< 5$ | $< 2$ |
| Modulus of elasticity | | | | | | | |
| GPa | 200 | — | 520-690 | 310-450 | 310-410 | 850 | 820-1050 |
| psi $\times 10^6$ | 30 | — | 75-100 | 45-65 | 45-60 | 125 | 120-150 |
| Density | | | | | | | |
| $kg/m^3$ | 8600 | 8000-8700 | 10,000-15,000 | 5500-5800 | 4000-4500 | 3500 | 3500 |
| $lb/in^3$ | 0.31 | 0.29-0.31 | 0.36-0.54 | 0.2-0.22 | 0.14-0.16 | 0.13 | 0.13 |
| Volume of hard phase (%) | 7-15 | 10-20 | 70-90 | — | 100 | 95 | 95 |
| Melting or decomposition temperature | | | | | | | |
| °C | 1300 | — | 1400 | 1400 | 2000 | 1300 | 700 |
| °F | 2370 | — | 2550 | 2550 | 3600 | 2400 | 1300 |
| Thermal conductivity, W/mK | 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 |

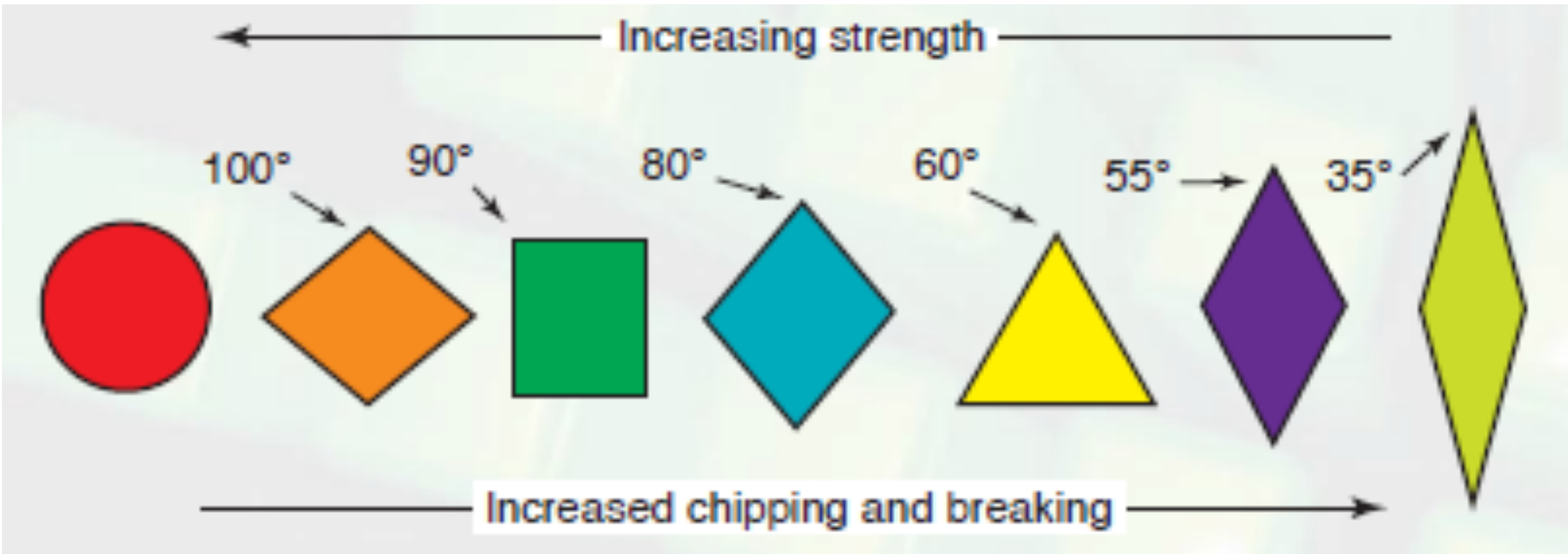
* The values for polycrystalline diamond are generally lower, except impact strength, which is higher.

# Properties of WC tools



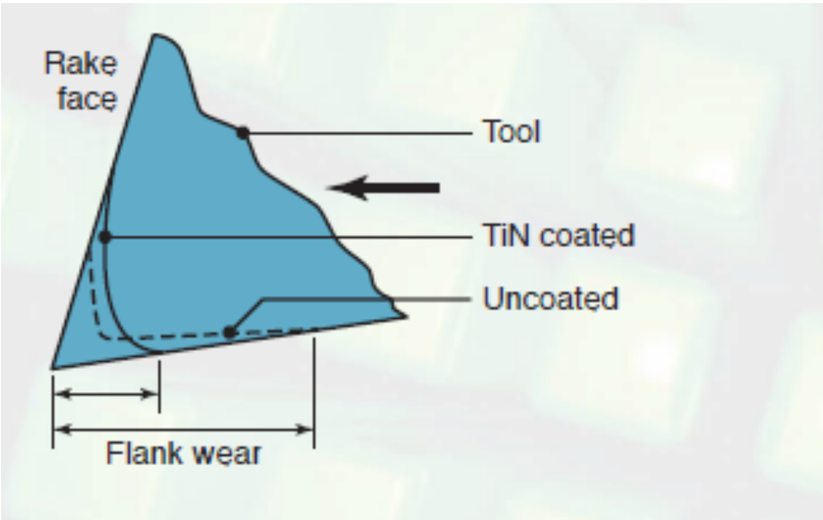

Effect of cobalt content in tungsten-carbide tools on mechanical properties. Note that hardness is directly related to compressive strength (see Section 2.6.8) and hence, inversely to wear

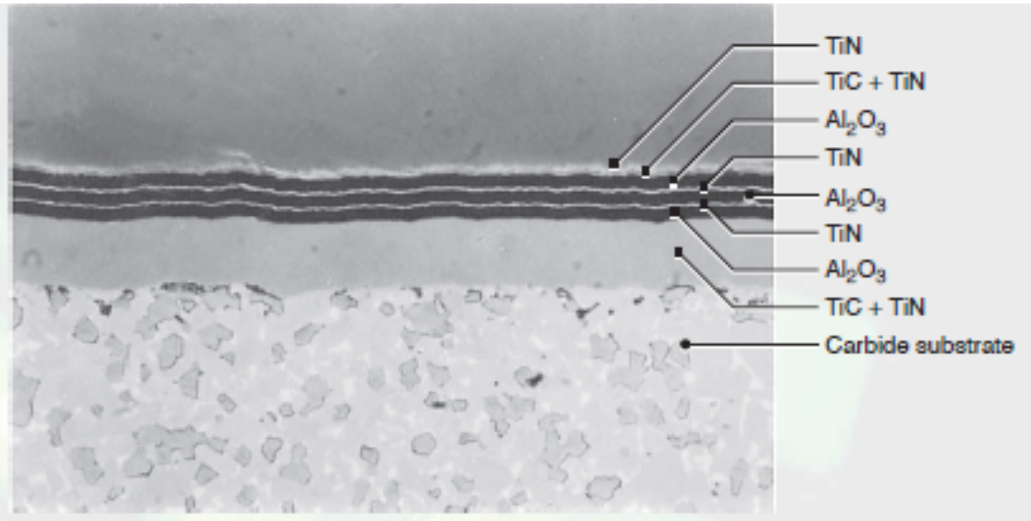
# Insert strength (Wedge angle)




Relative edge strength and tendency for chipping and breaking of inserts with various shapes. Strength refers to that of the cutting edge shown by the included angles. *Source: Courtesy of Kennametal, Inc.*

# Coated tools

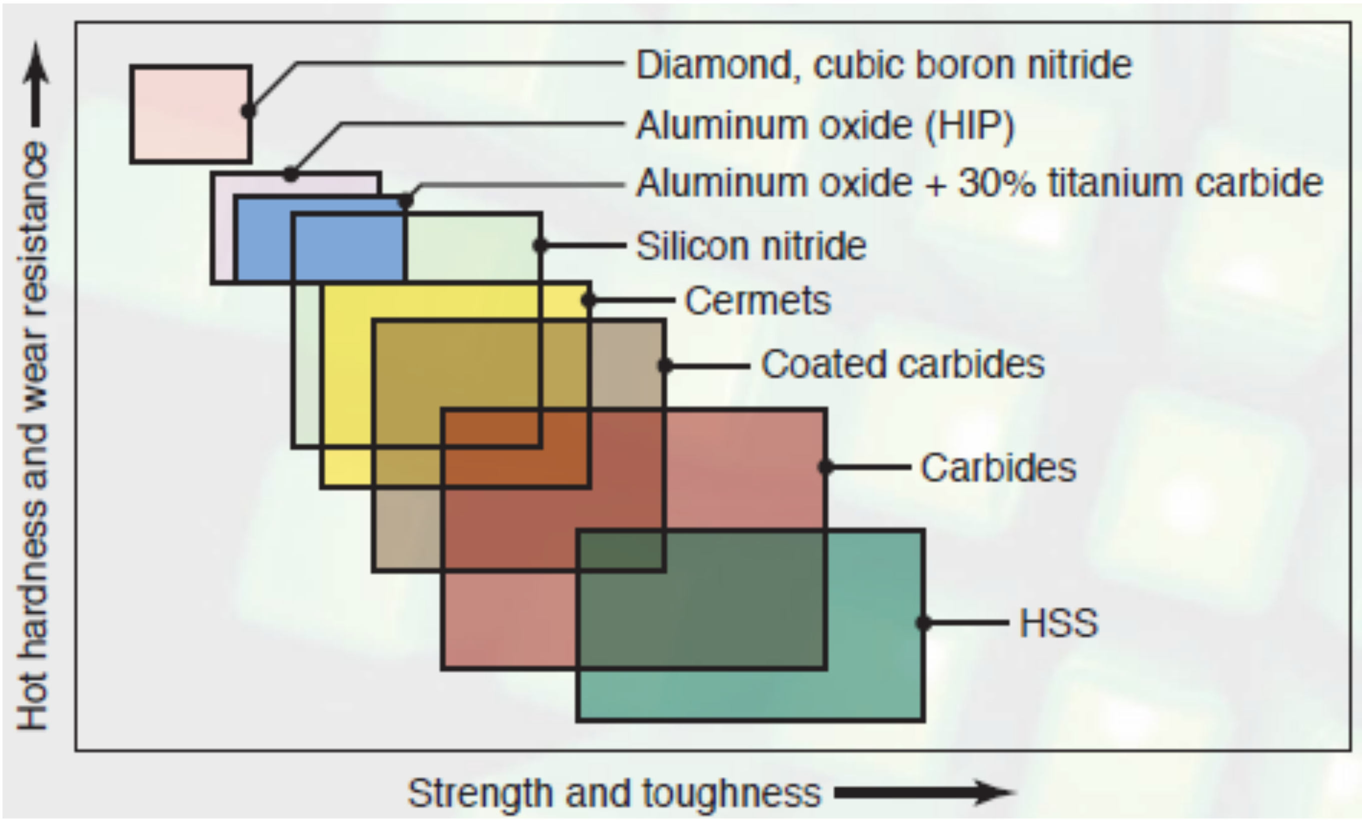


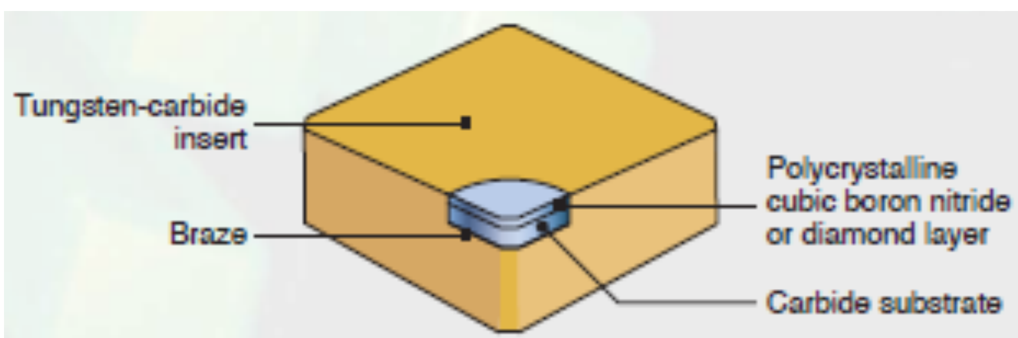




Wear patterns on high-speed-steel uncoated and titanium-nitride-coated cutting tools. Note that flank wear is lower for the coated tool.

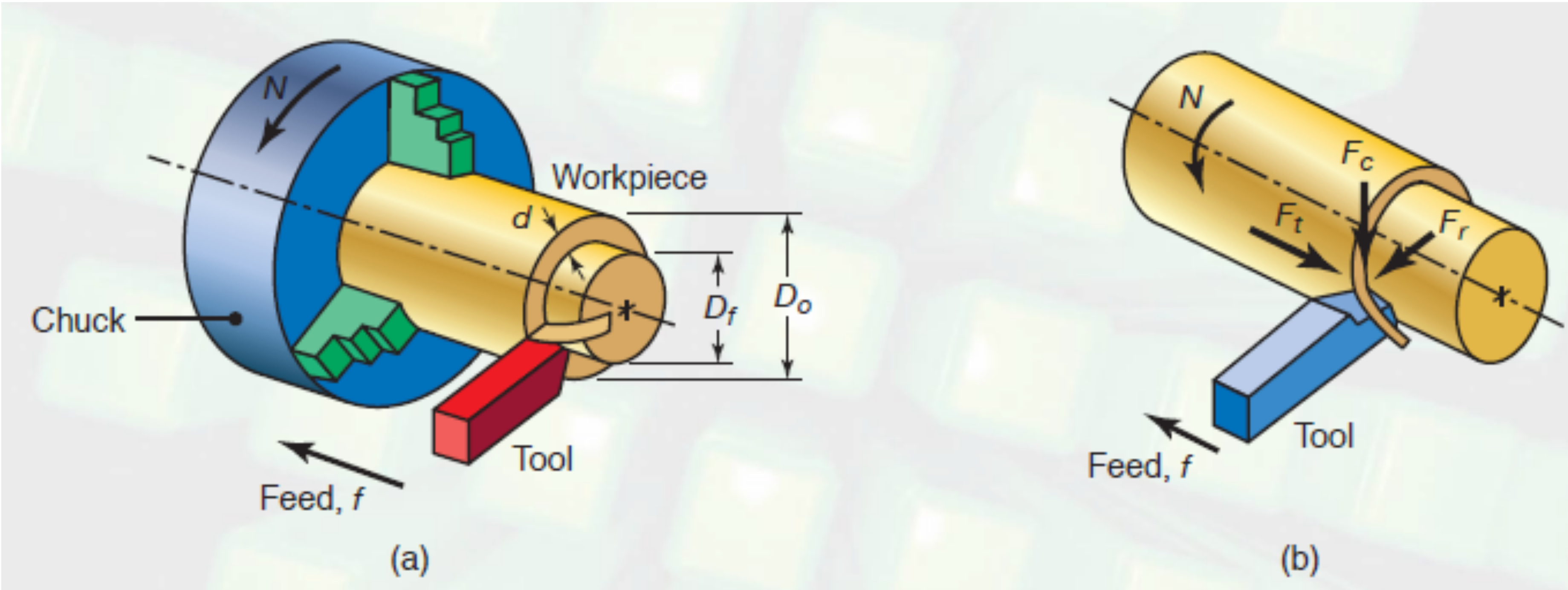
Multiphase coatings on a tungsten-carbide substrate. Three alternating layers of aluminum oxide are separated by very thin layers of titanium nitride. Inserts with as many as 13 layers of coatings have been made. Coating thicknesses are typically in the range of 2 to 10 μm. *Source:* Courtesy of Kennametal, Inc.

# Properties of cutting tool materials



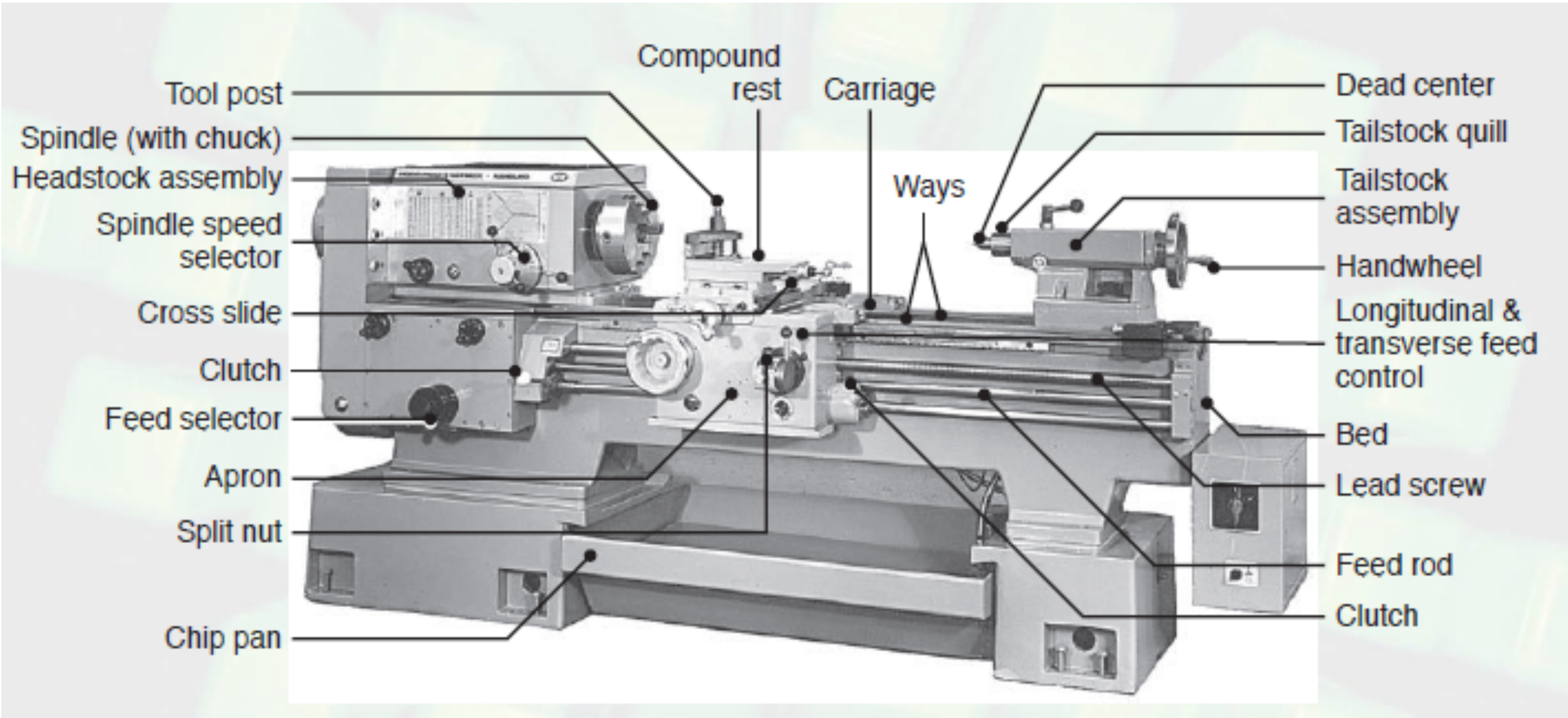



# Turning operations



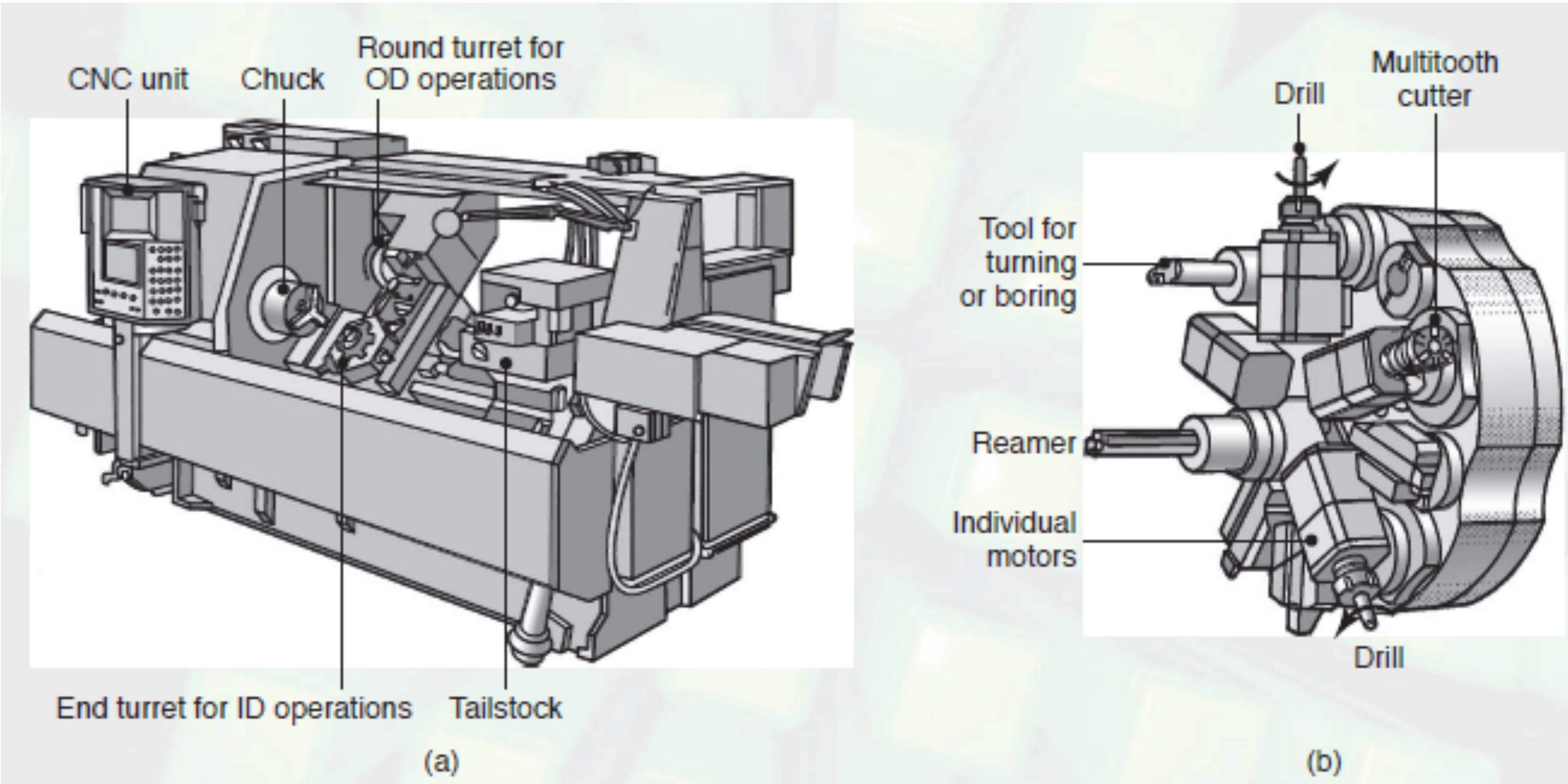

(a) Schematic illustration of a turning operation, showing depth of cut, *d, and feed, f. Cutting speed* is the surface speed of the workpiece at the tool tip. (b) Forces acting on a cutting tool in turning. *Fc is the* cutting force; *Ft is the thrust or feed force (in the direction of feed); and Fr is the radial force that tends to push* the tool away from the workpiece being machined.

# Lathe



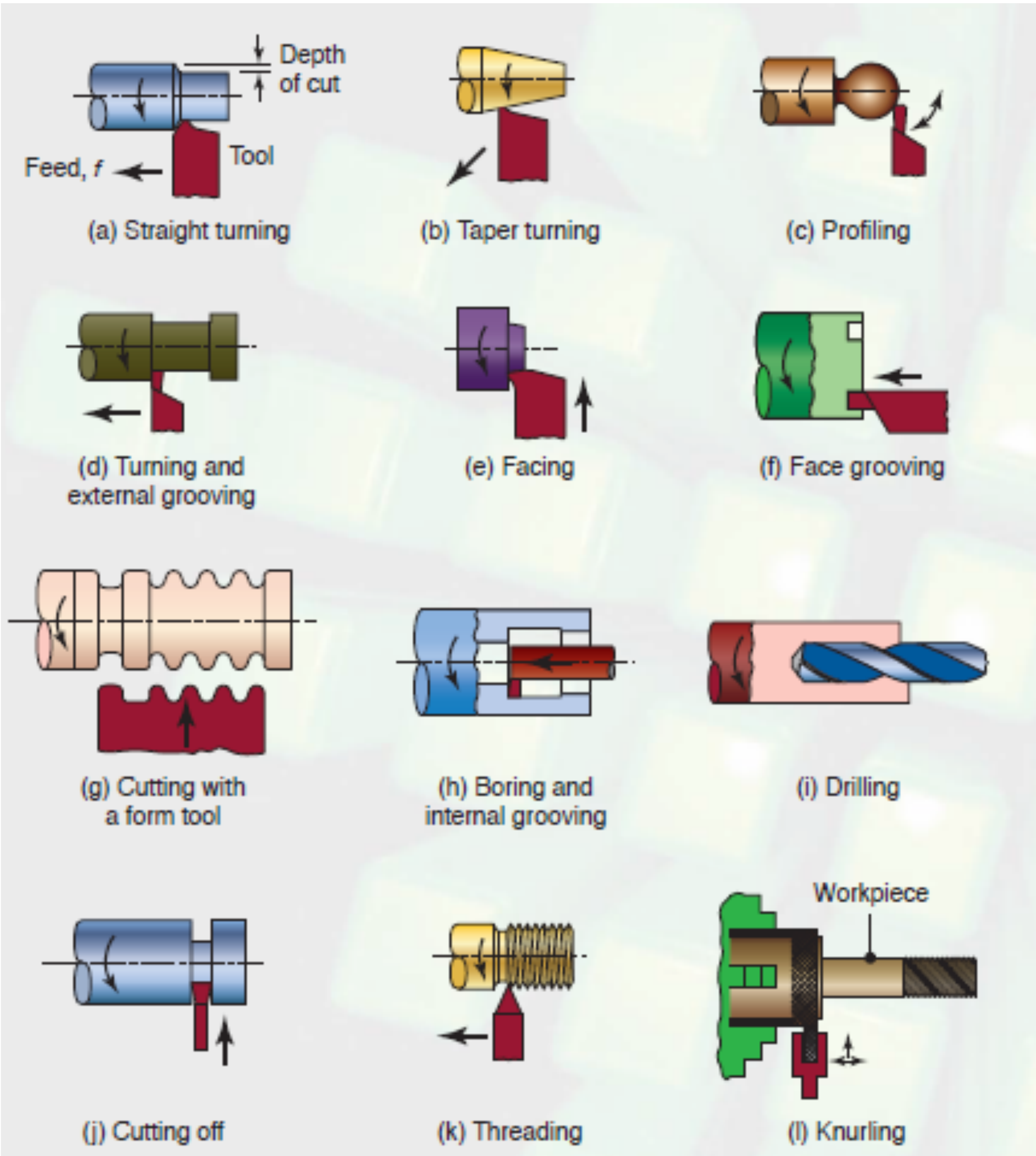

General view of a typical lathe, showing various major components. *Source: Courtesy of* Heidenreich & Harbeck.

# CNC lathe




(a) A computer-numerical-control lathe, with two turrets; these machines have higher power and spindle speed than other lathes in order to take advantage of advanced cutting tools with enhanced properties; (b) a typical turret equipped with ten cutting tools, some of which are powered.

# Lathe operations




Variety of machining operations that can be performed on a lathe.

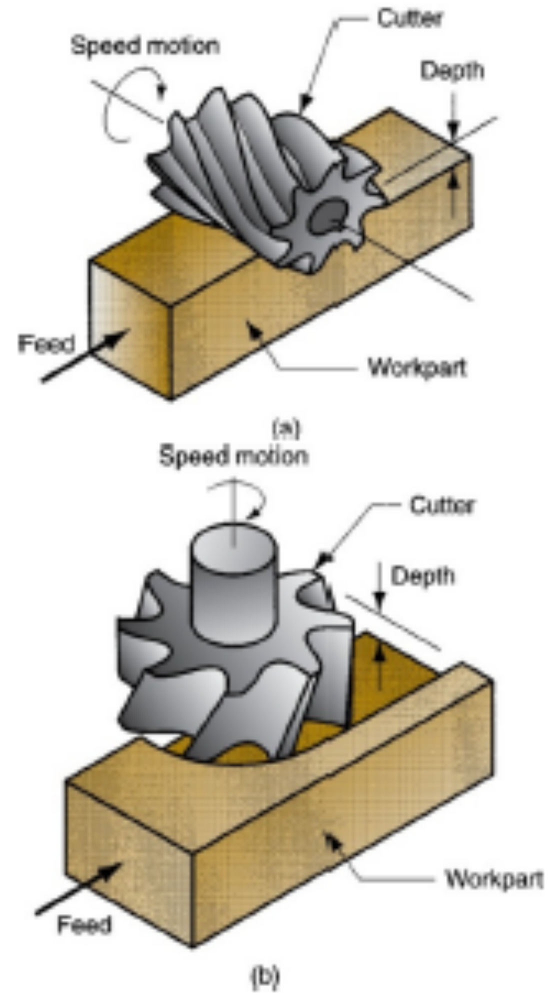
# Milling processes

- Slab/Face milling
- Circular milling
- Helical milling
- Hobbing
- Profile milling
- Form milling

# Option A: rotate the tool

Another option:
Vertical axis rotation of tool

Peripheral milling

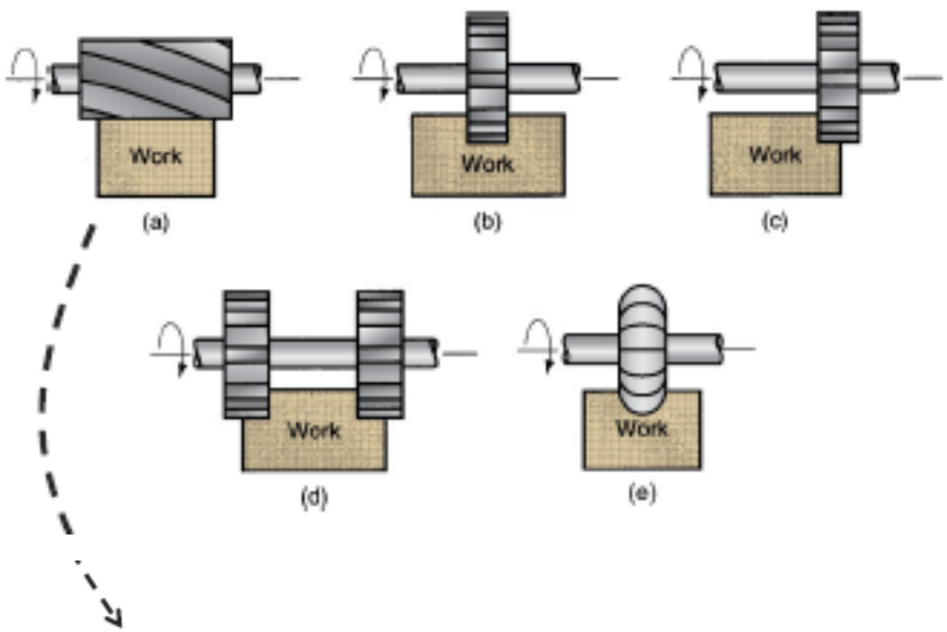


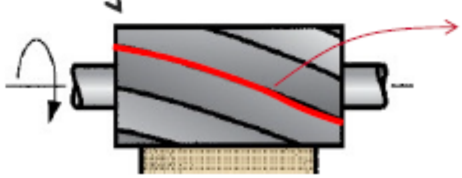

Face milling

# Option A: rotate the tool (Milling)

## Horizontal axis rotation

(a) Slab milling, (b) slotting, (c) side milling, (e) straddle milling, and (e) form milling



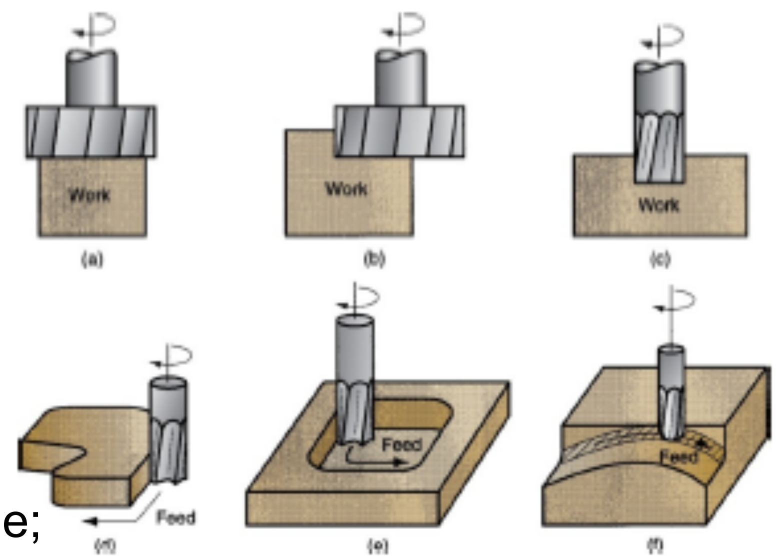



Note the curved cutting edge;
there is a helical angle to the edge
This helps in removing chip and also
allows gradual engagement of cut

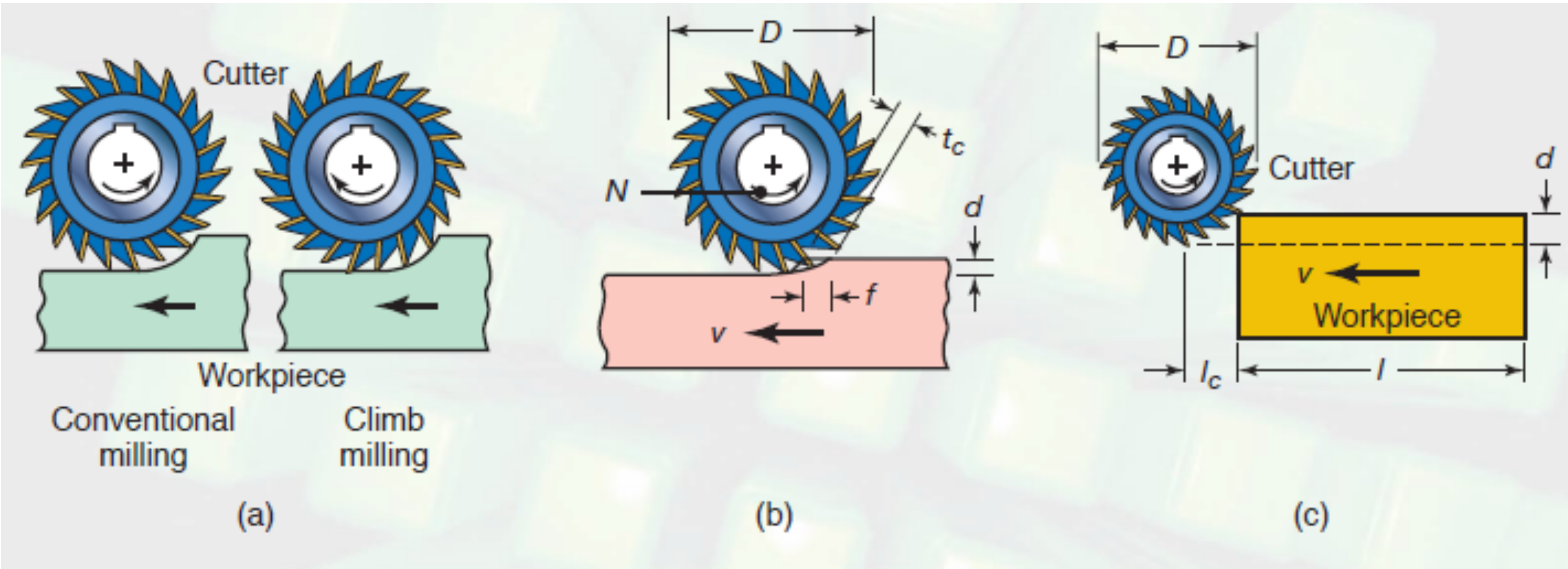
## Vertical axis rotation

(a) Conventional face milling, (b) partial face milling, and (c) end milling

(d) Profile milling, (e) pocket milling, and (f) surface contouring

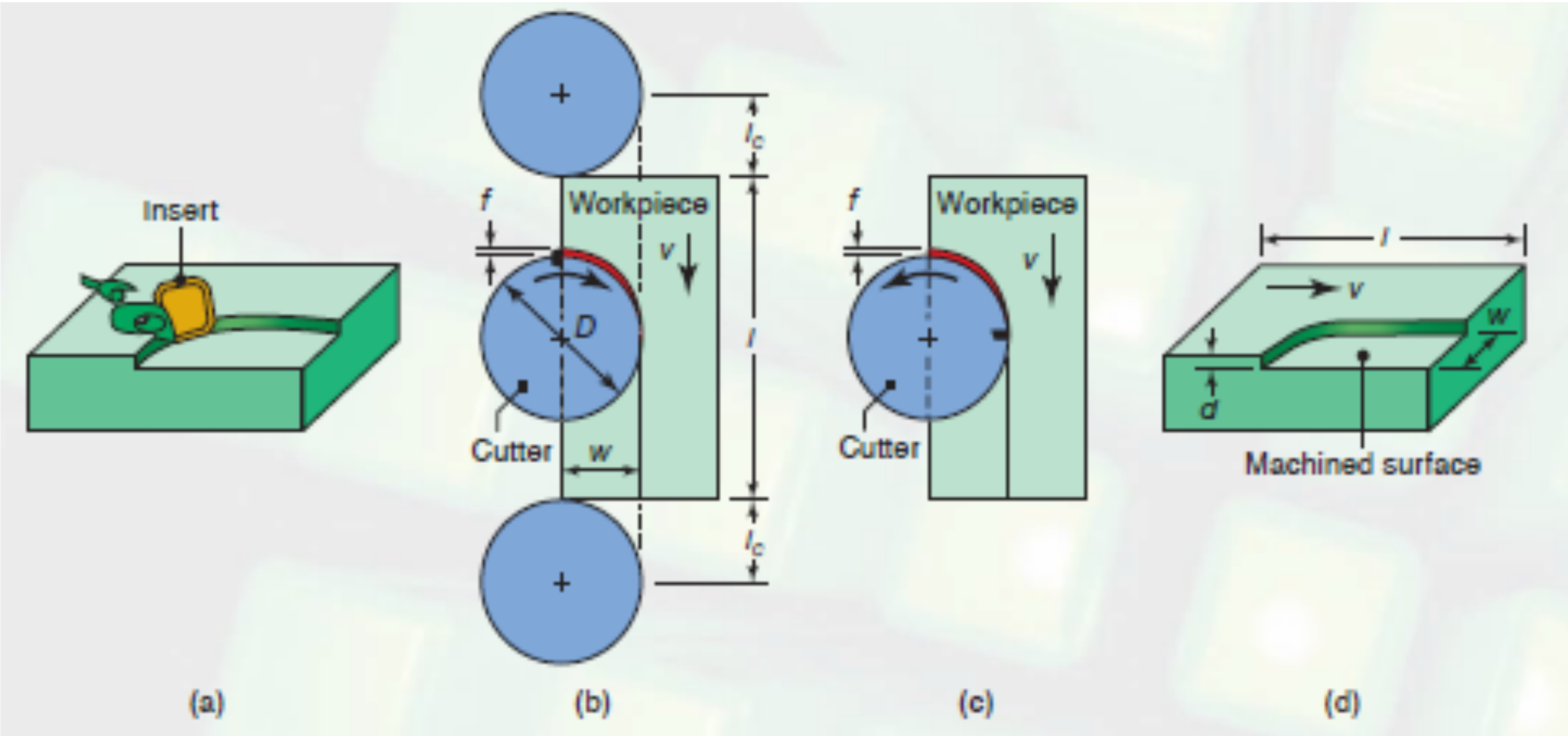


# Conventional and climb milling



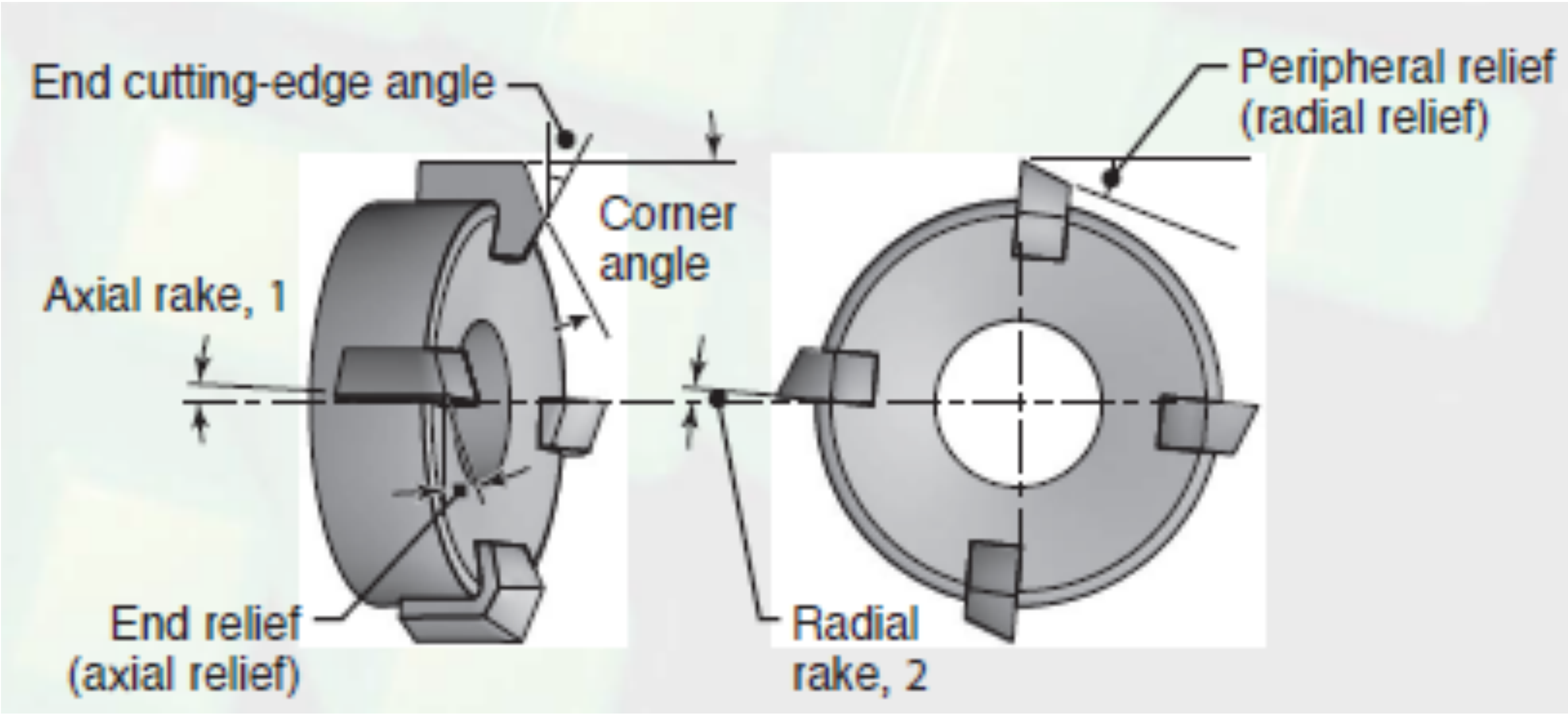

(a) Illustration showing the difference between conventional milling and climb milling. (b) Slab-milling operation, showing depth of cut, *d; feed per tooth, f; chip depth of* cut, *tc and workpiece speed, v. (c) Schematic illustration of cutter travel distance, lc, to reach* full depth of cut.

# Face milling



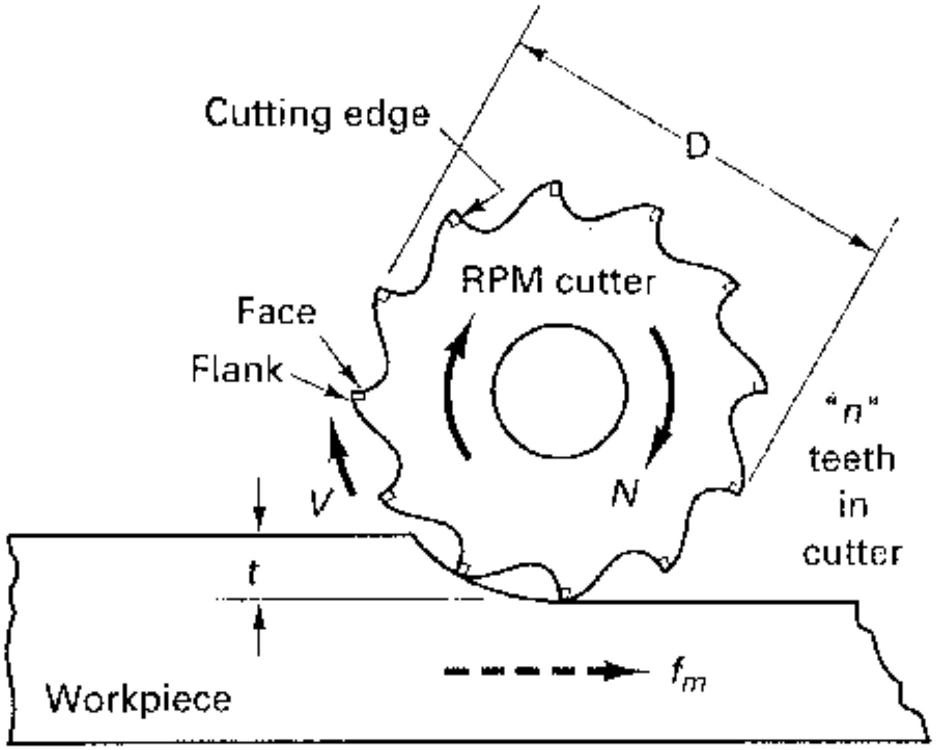

Face-milling operation showing (a) action of an insert in face milling; (b) climb milling; (c) conventional milling; (d) dimensions in face milling.

# Face milling cutter

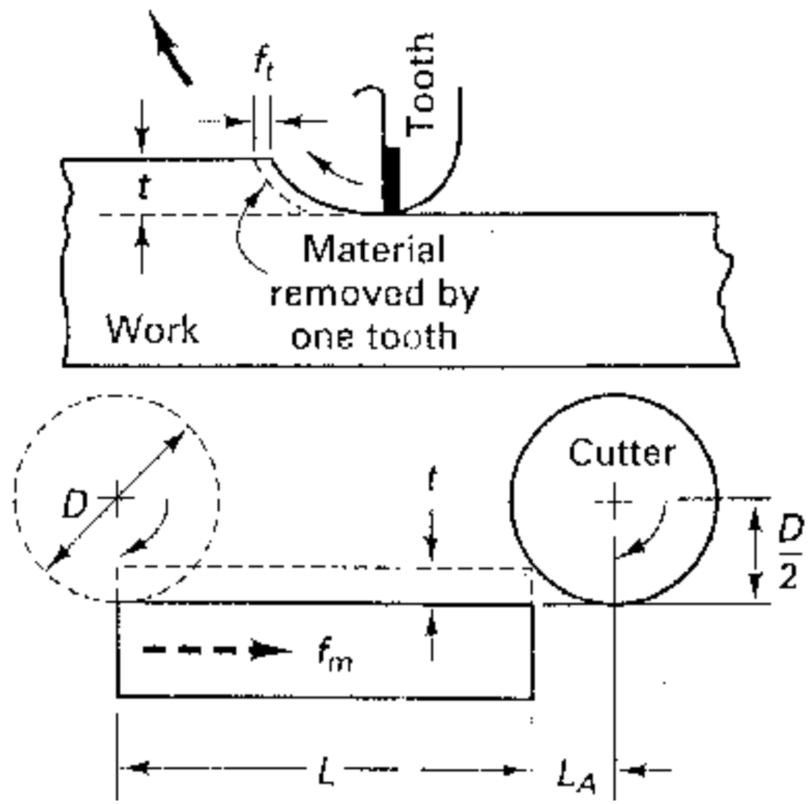



Terminology for a face milling cutter

# Milling operation




Slab milling – multiple tooth



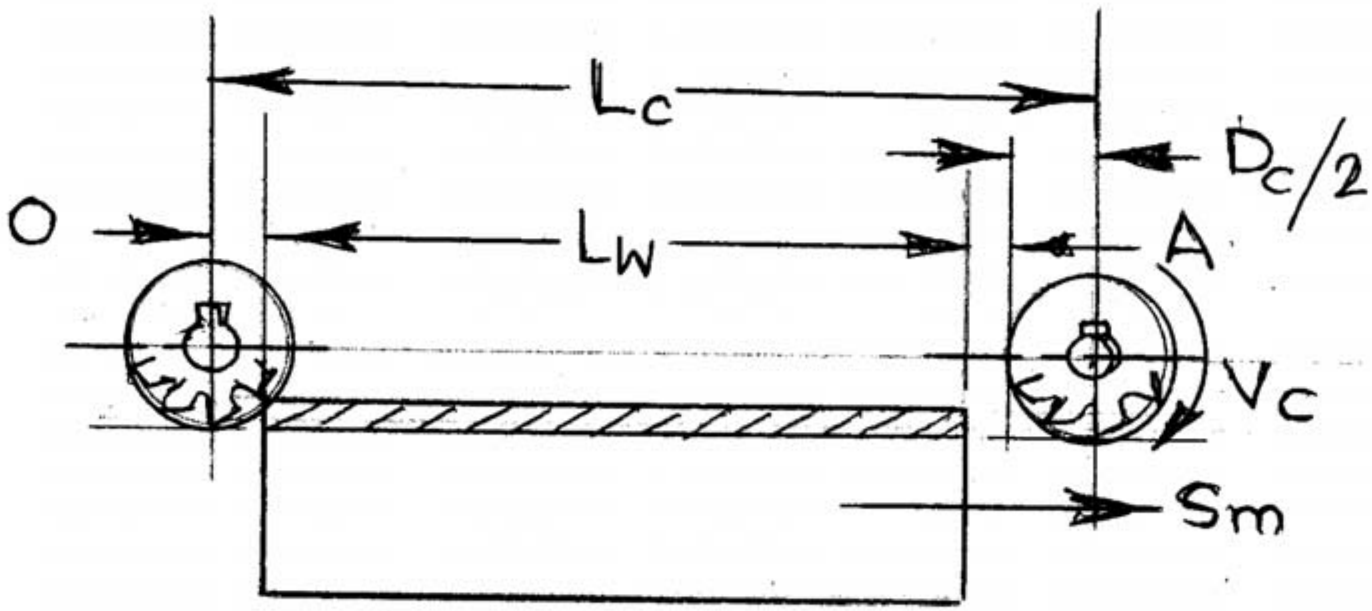

Terms Used:
N: RPM of Cutter
n: Number of Teeth on Cutter
W: Width of cut (may be full cutter or partial cutter)
t: depth of cut
V: cutting speed -- a Handbook value
L: Length of pass or cut
$f_m$: Table (machine) Feed
$f_t$: feed/tooth of cutter -- a Handbook value
D: Cutter Diameter

$$N = \frac{kV}{\pi D}$$

$$f_m = f_t * N * n$$

$$MRR = \frac{\text{Vol. Removed}}{CT} = \frac{L * W * t}{CT} = W * t * f_m$$

# Machining time in a milling operation



# Machining time in a milling operation

$T_C = L_C / s_m$ (for job width < cutter length)

Where, $L_C$ = total length of travel of the job

$= L_w + A + O + D_c/2$

$L_w$ = length of the workpiece

A, O = approach and over run (5 to 10 mm)

$D_C$= diameter of the cutter, mm

$S_m$= table feed, mm/min

$= s_o Z_C N$

where, $s_o$ = feed per tooth, mm/tooth

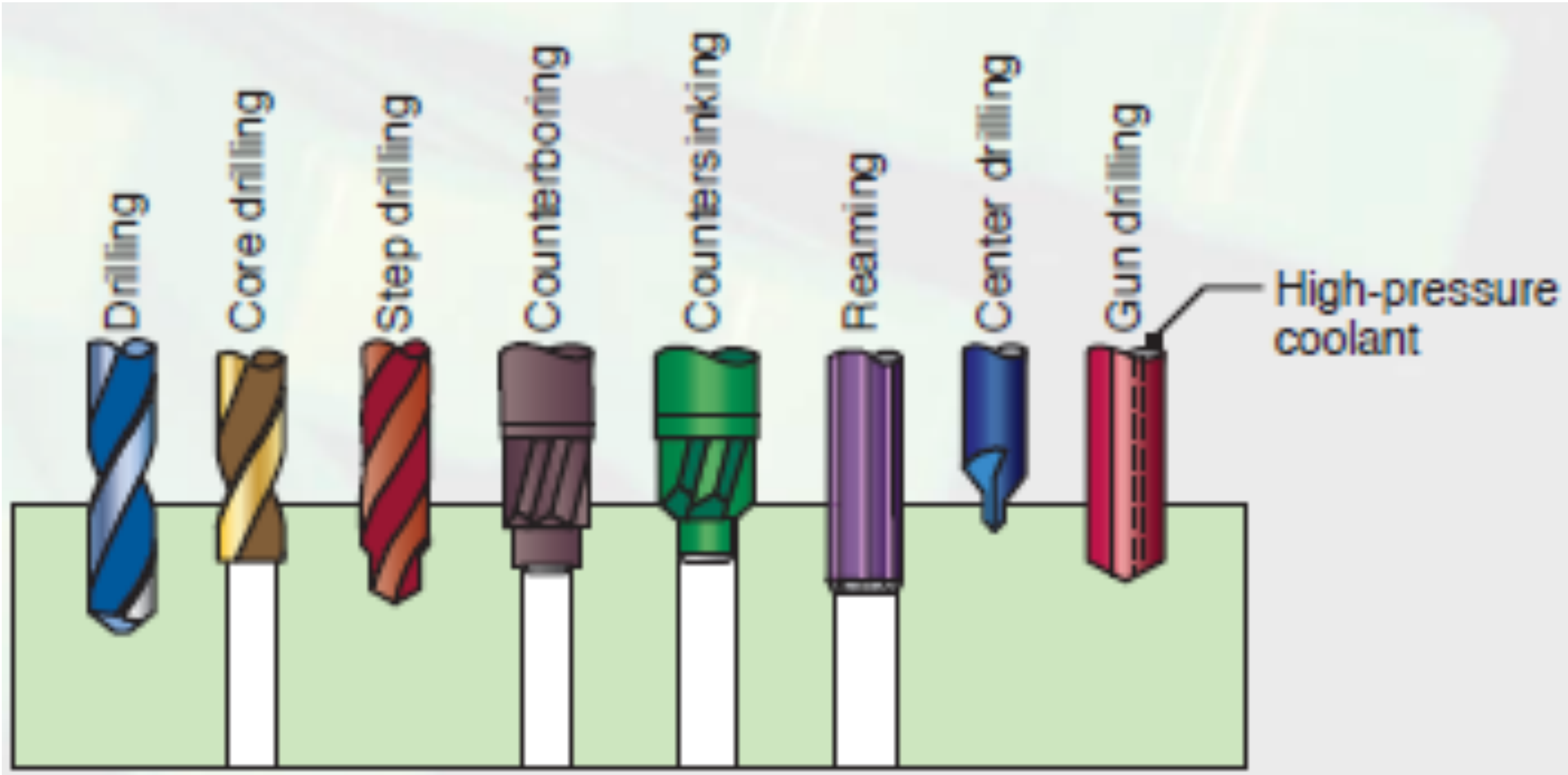
$Z_C$= number of teeth of the cutter

N = cutter speed, rpm.

Again, N has to be determined from $V_C$ as

$$V_C = \frac{\pi D_C N}{1000} \quad \text{m/min}$$

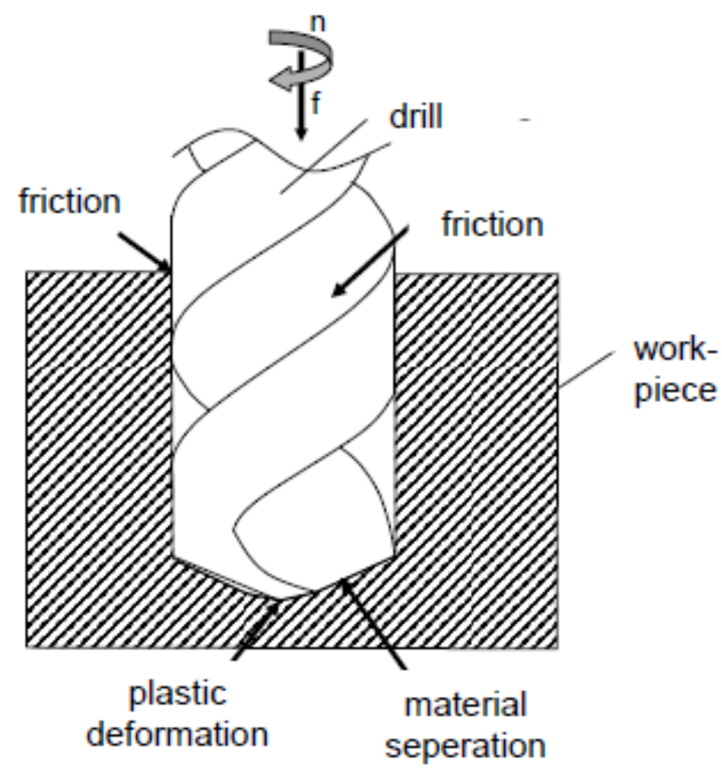
# Drilling operations



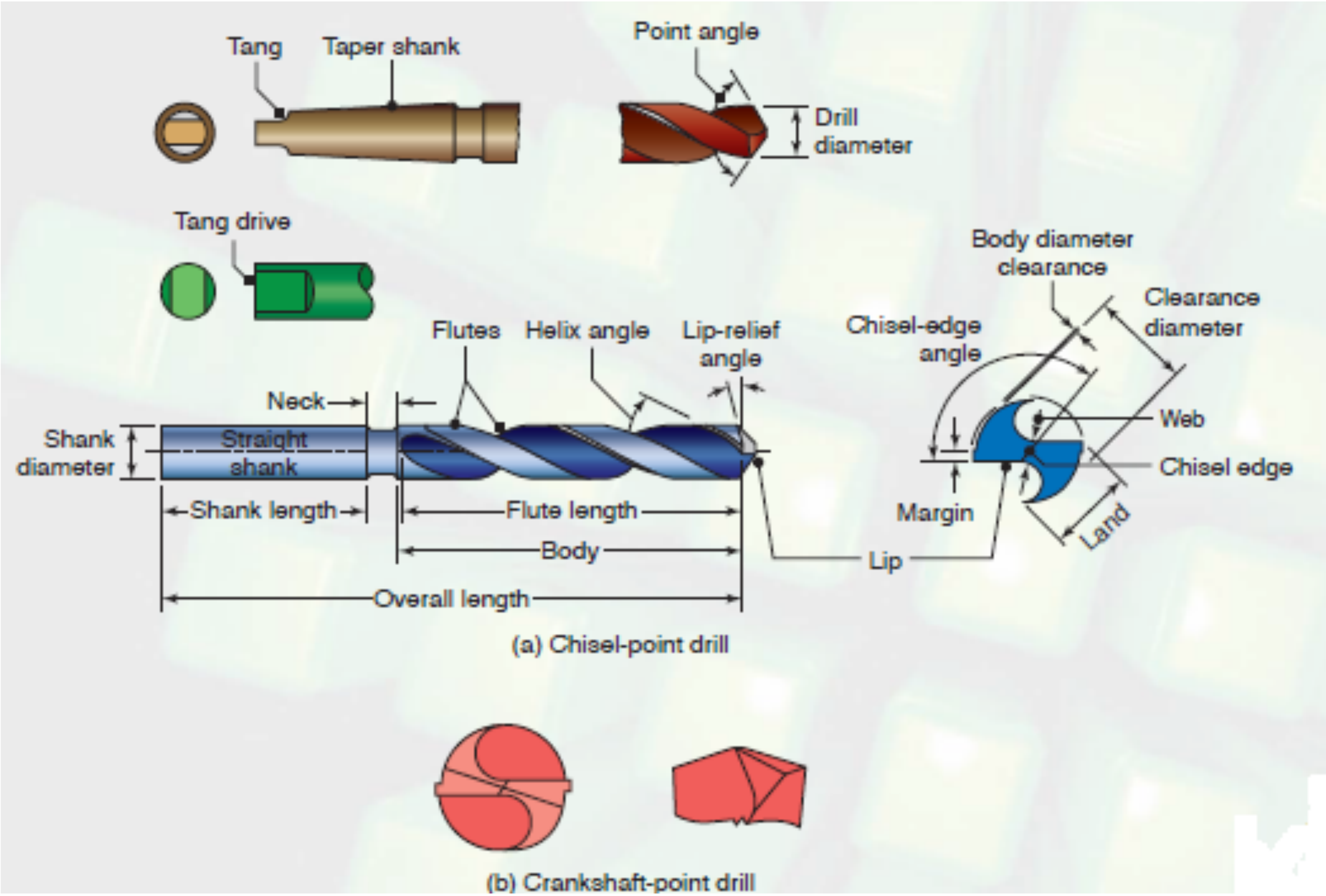

Various types of drills and drilling operations

# Criteria for drilling

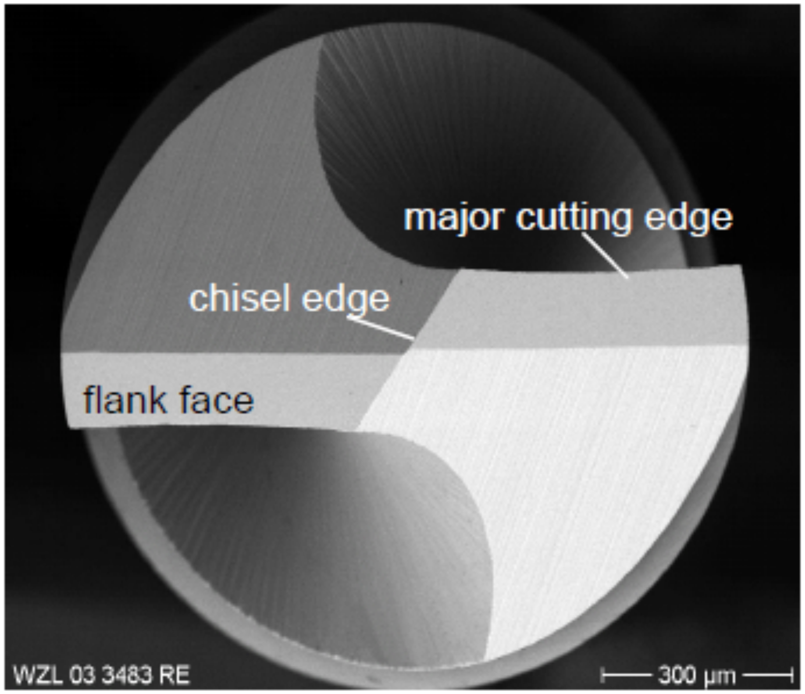
- Material separation and reaming at the major cutting edge
- Plastic deformation at the chisel edge
- Cutting speed drops down to zero in the centre of the drill
- Chips are difficult to remove
- Unfavourable heat distribution at the interface
- Increased wear at the sharp-edged corner
- Reaming between leading lands and drilling wall

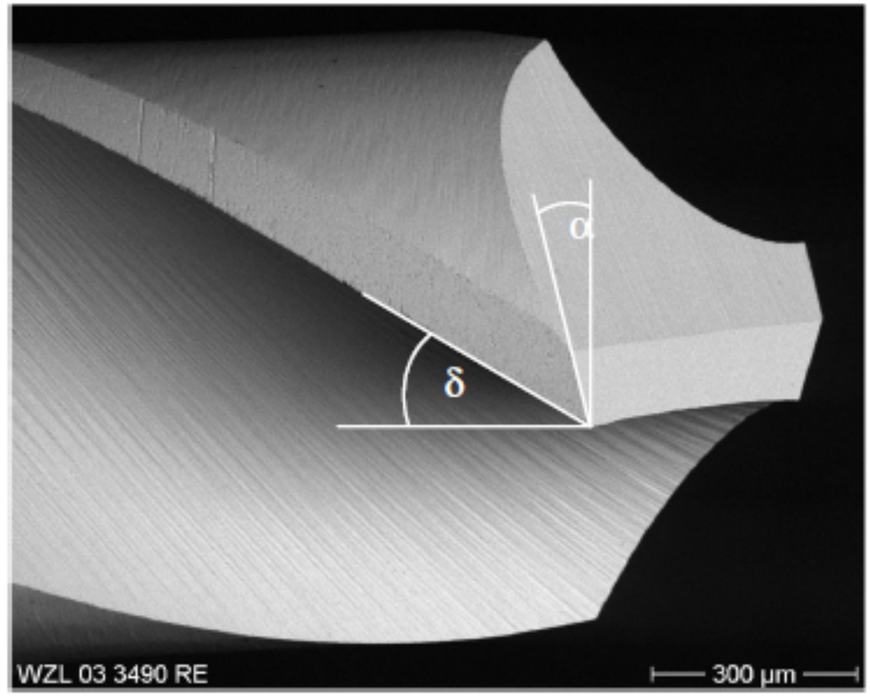


# Geometry of a twist drill



# Geometry of a twist drill



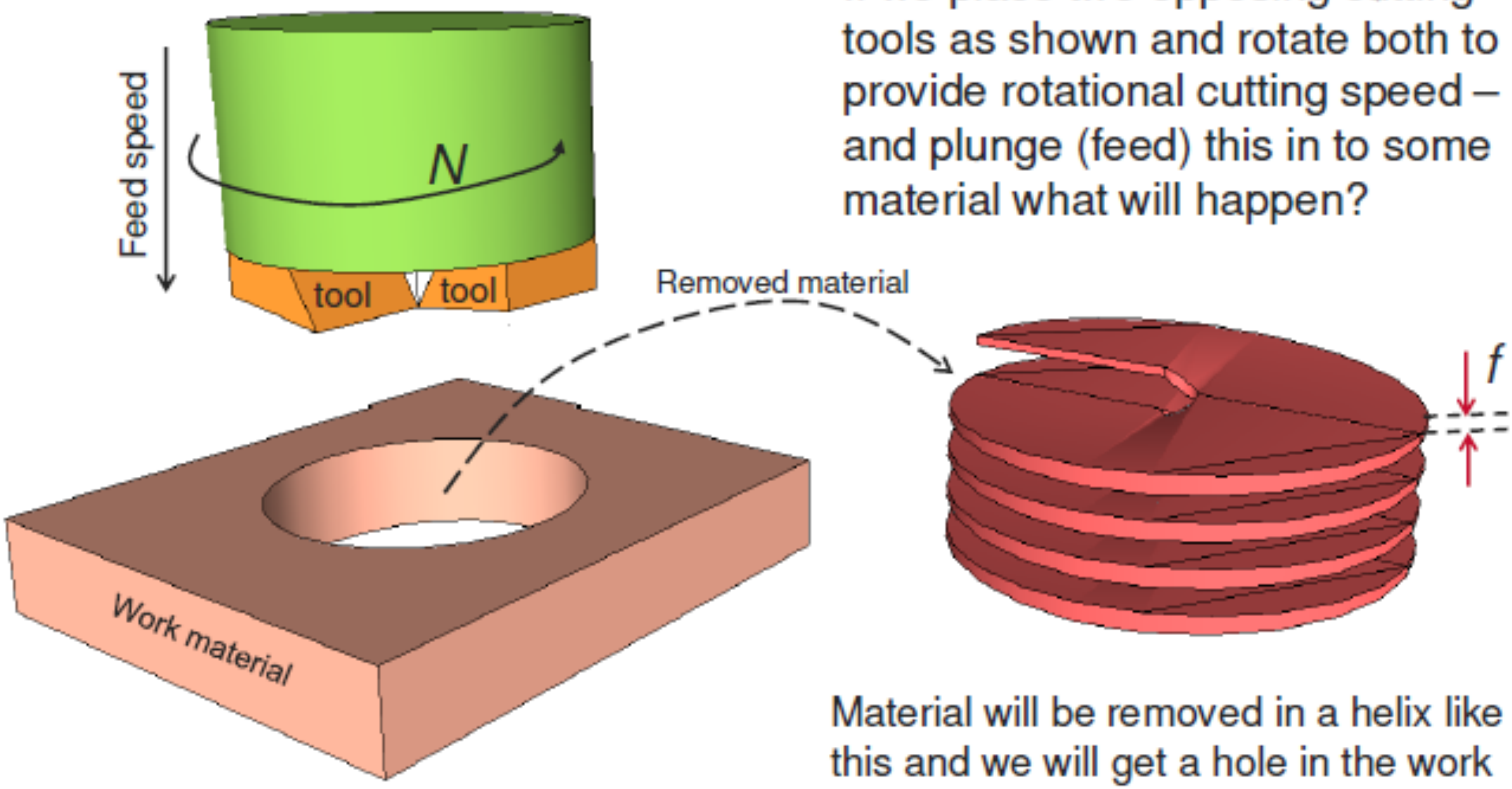




construction dimensions DIN 6539, Typ N
diameter d: 1 mm
drill-point angle $\sigma$: 118°

major clearance angle $\alpha$: 10°
angle of twist $\delta$: 35°
cutting material: HW-K20
grain size $D_K$: 0.5 - 0.7 µm

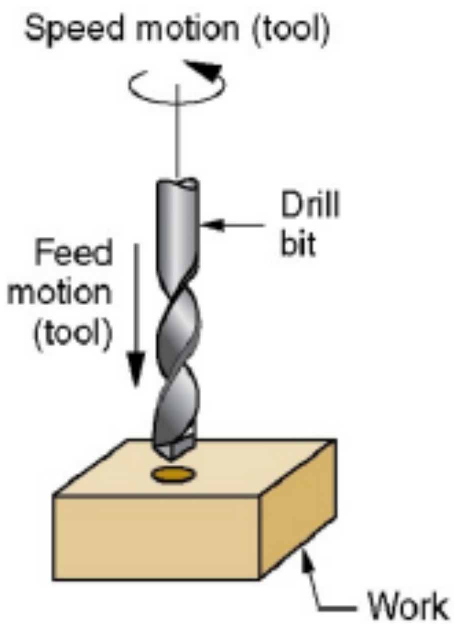
# Circular cutting motion: Drilling concept

If we place two opposing cutting tools as shown and rotate both to provide rotational cutting speed – and plunge (feed) this in to some material what will happen?

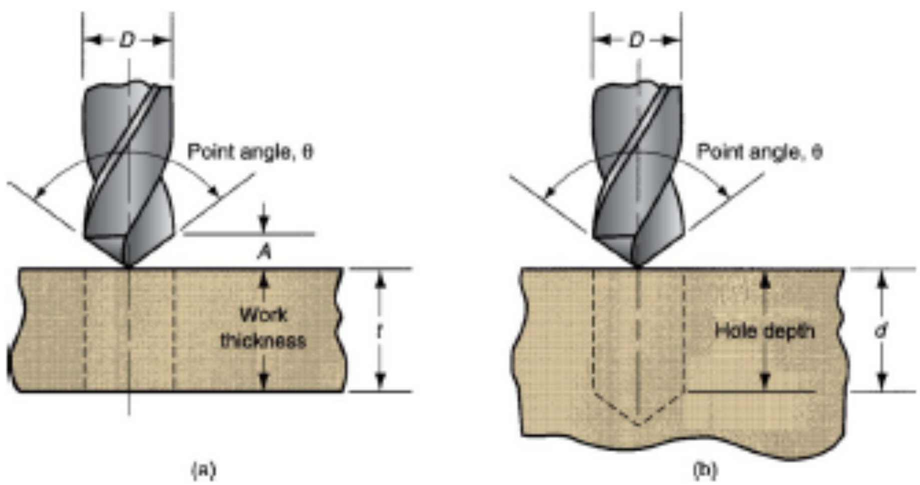



Material will be removed in a helix like this and we will get a hole in the work material! - DRILLING

# Circular cutting motion: Drilling concept

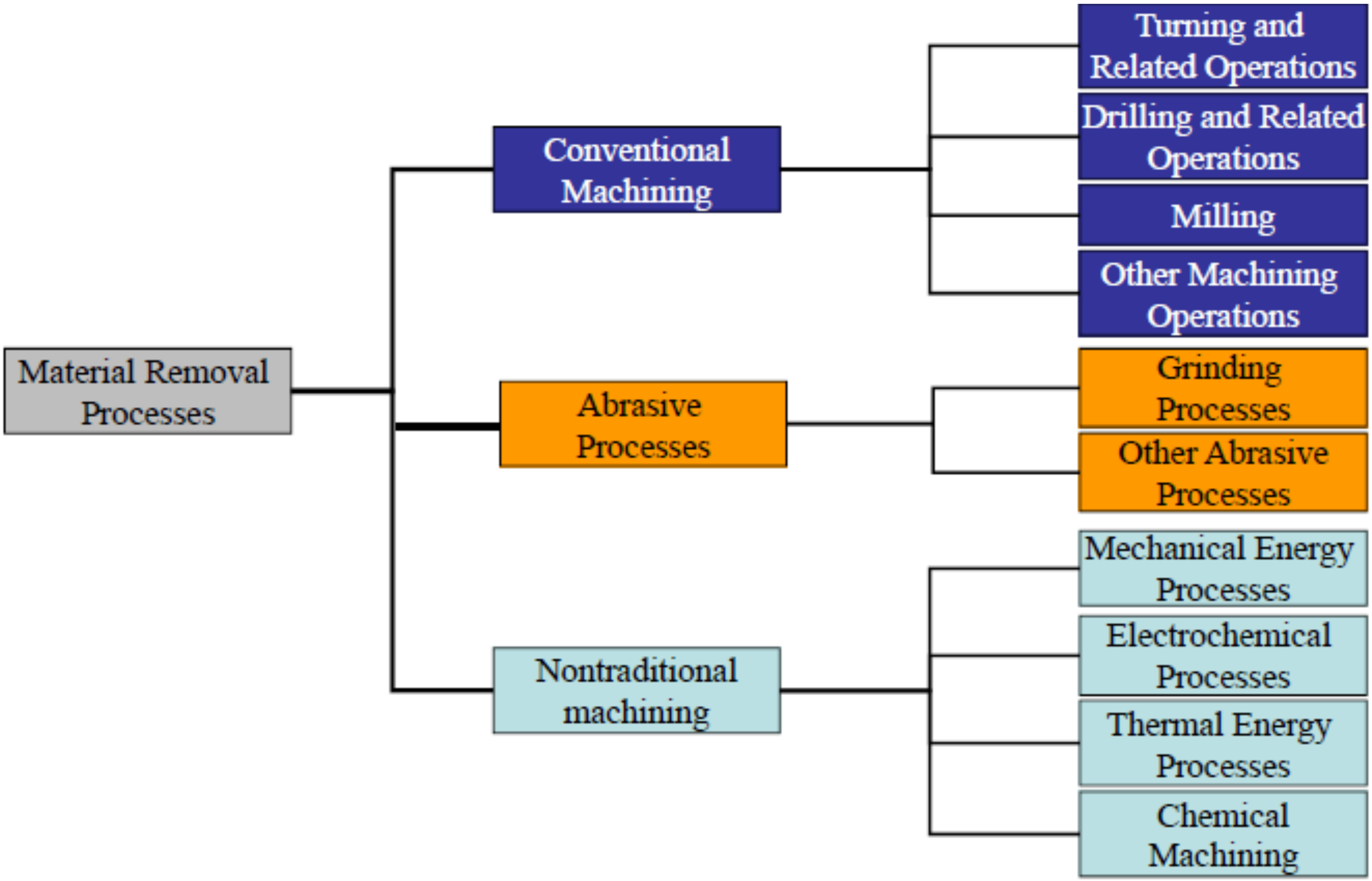



Material removal rate??
Cutting speed/RPM
Feed (mm/r) (mm/min)
D
Area*f*N (RPM)



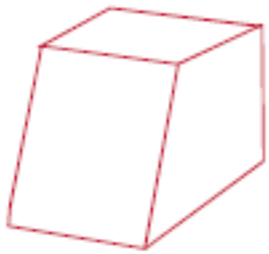
# Abrasive Machining and Finishing Operations

# Classification

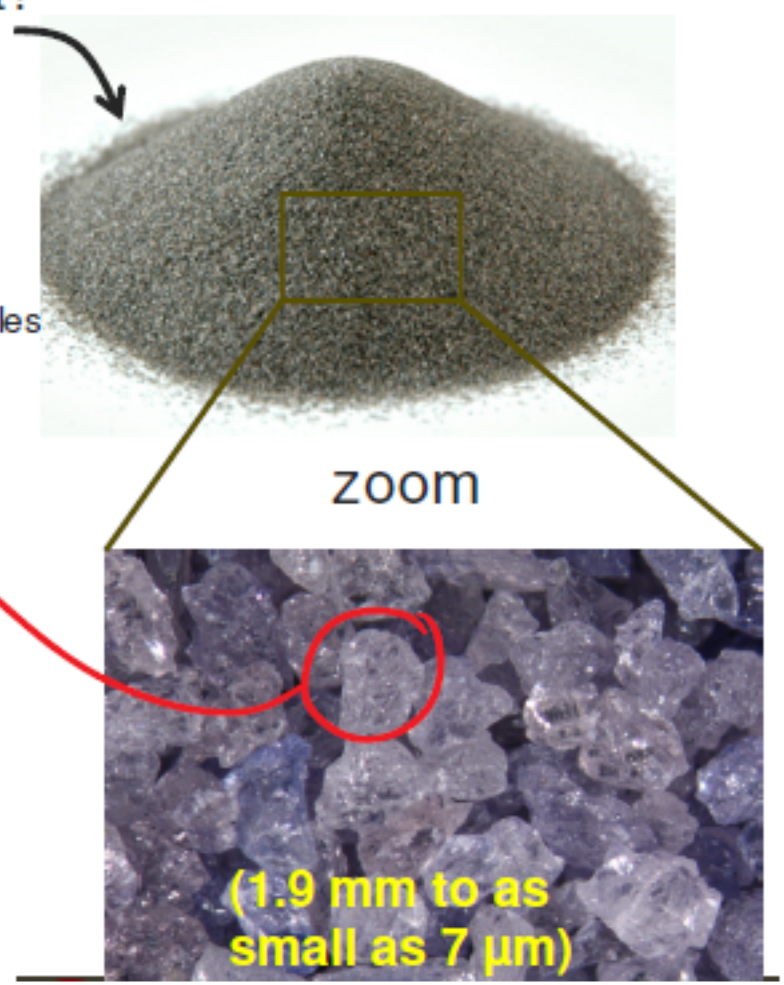


# Cutting using abrasive particles

This we know can cut



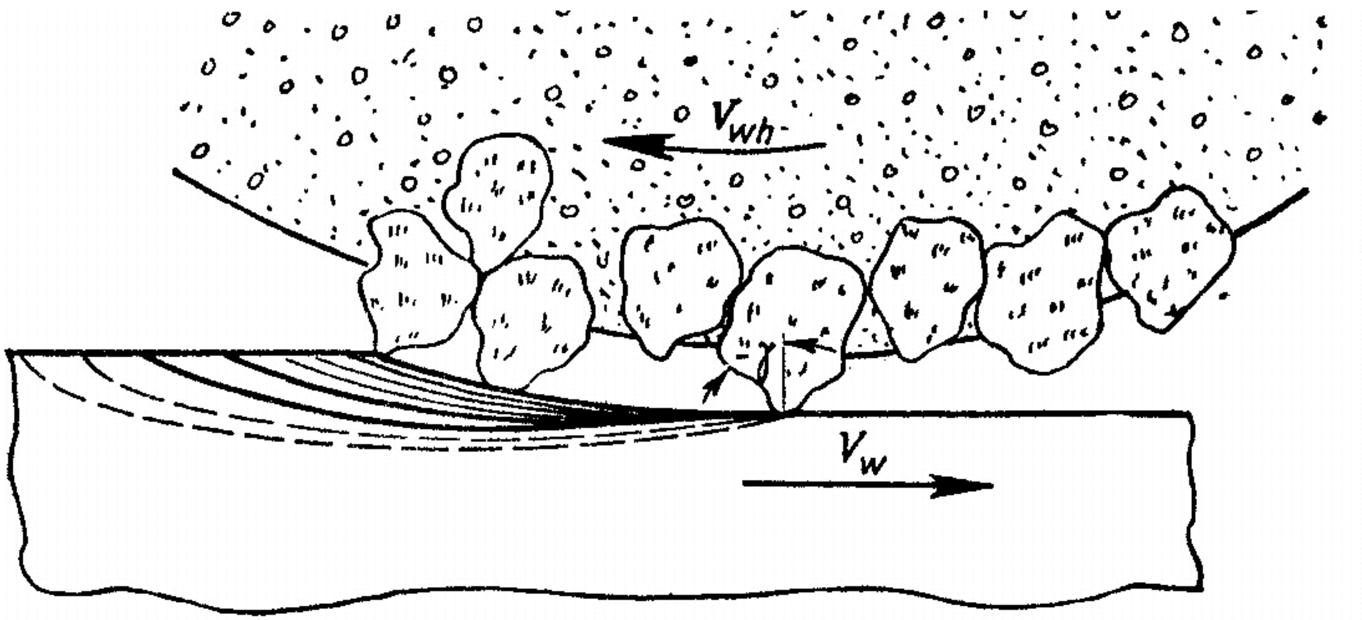
Can this cut?



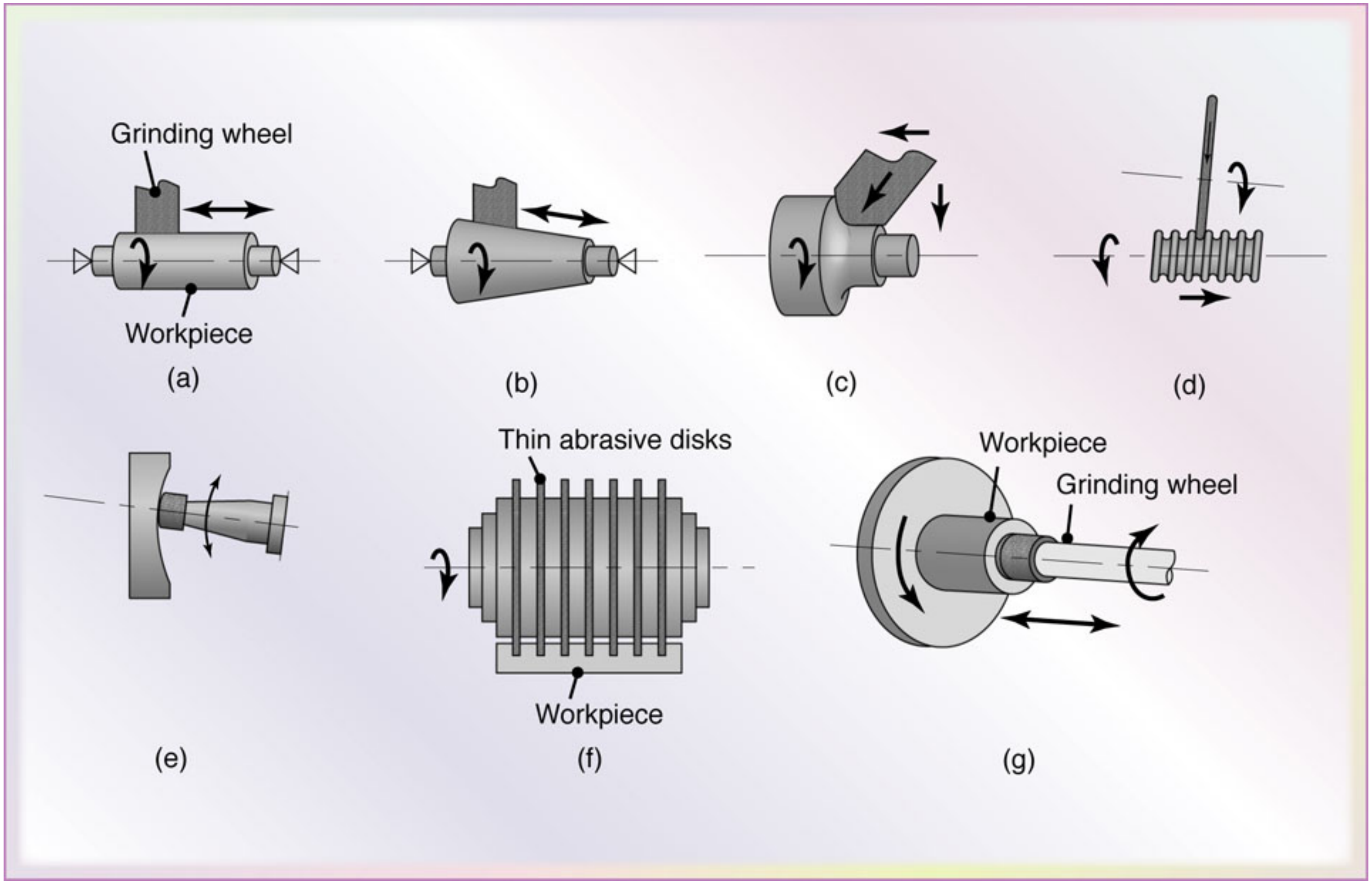

Irregularly shaped hard abrasive particles

# Grinding

Grinding is the most common form of abrasive machining. It is a material cutting process which engages an abrasive tool whose cutting elements are grains of abrasive material known as grit. These grits are characterized by sharp cutting points, high hot hardness, chemical stability and wear resistance. The grits are held together by a suitable bonding material to give shape of an abrasive tool.



# Workpieces and Operations Used in Grinding




The types of workpieces and operations typical of grinding: (a) cylindrical surfaces, (b) conical surfaces. (c) fillets on a shaft, (d) helical profiles, (e) concave shape, (f) cutting off or slotting with thin wheels, and (g) internal grinding.

# Grinding

**Advantage**

A grinding wheel requires two types of specification

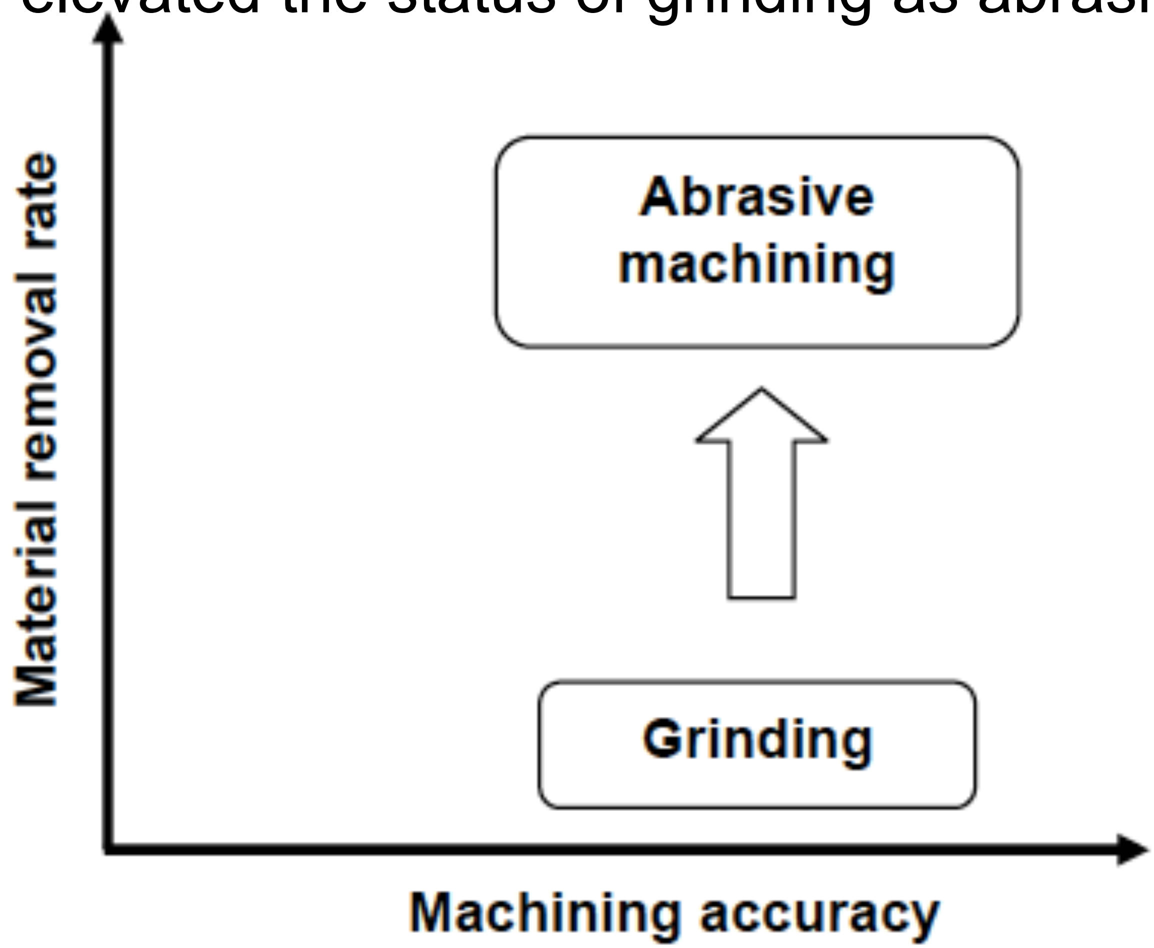
- dimensional accuracy and good surface finish
- good form and locational accuracy applicable to both hardened and unhardened material

**Applications**

- surface finishing
- slitting and parting
- descaling, deburring
- stock removal (abrasive milling)
- finishing of flat as well as cylindrical surface
- grinding of tools and cutters and re-sharpening of the same.

# Grinding

Conventionally grinding is characterized as low material removal process capable of providing both high accuracy and high finish. However, advent of advanced grinding machines and grinding wheels has elevated the status of grinding as abrasive machining

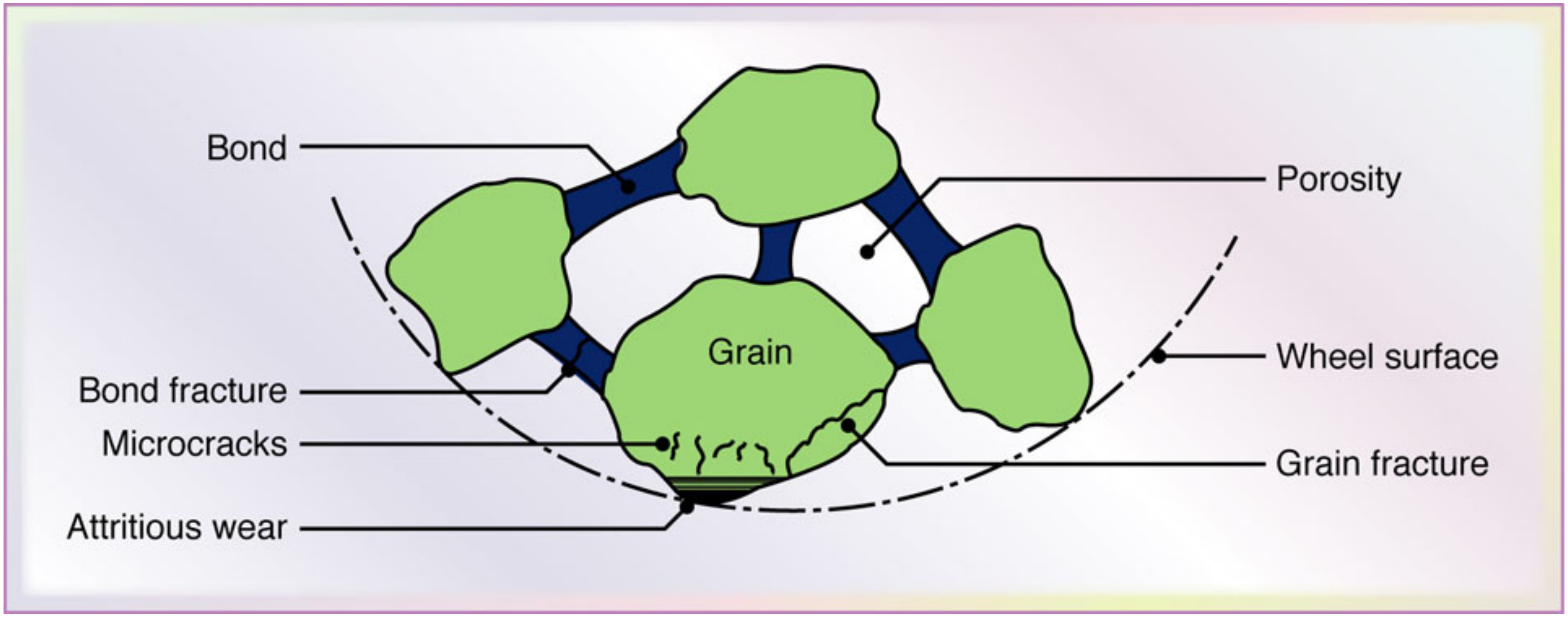


# Ranges of Knoop Hardness for Various Materials and Abrasives

**TABLE 26.1**

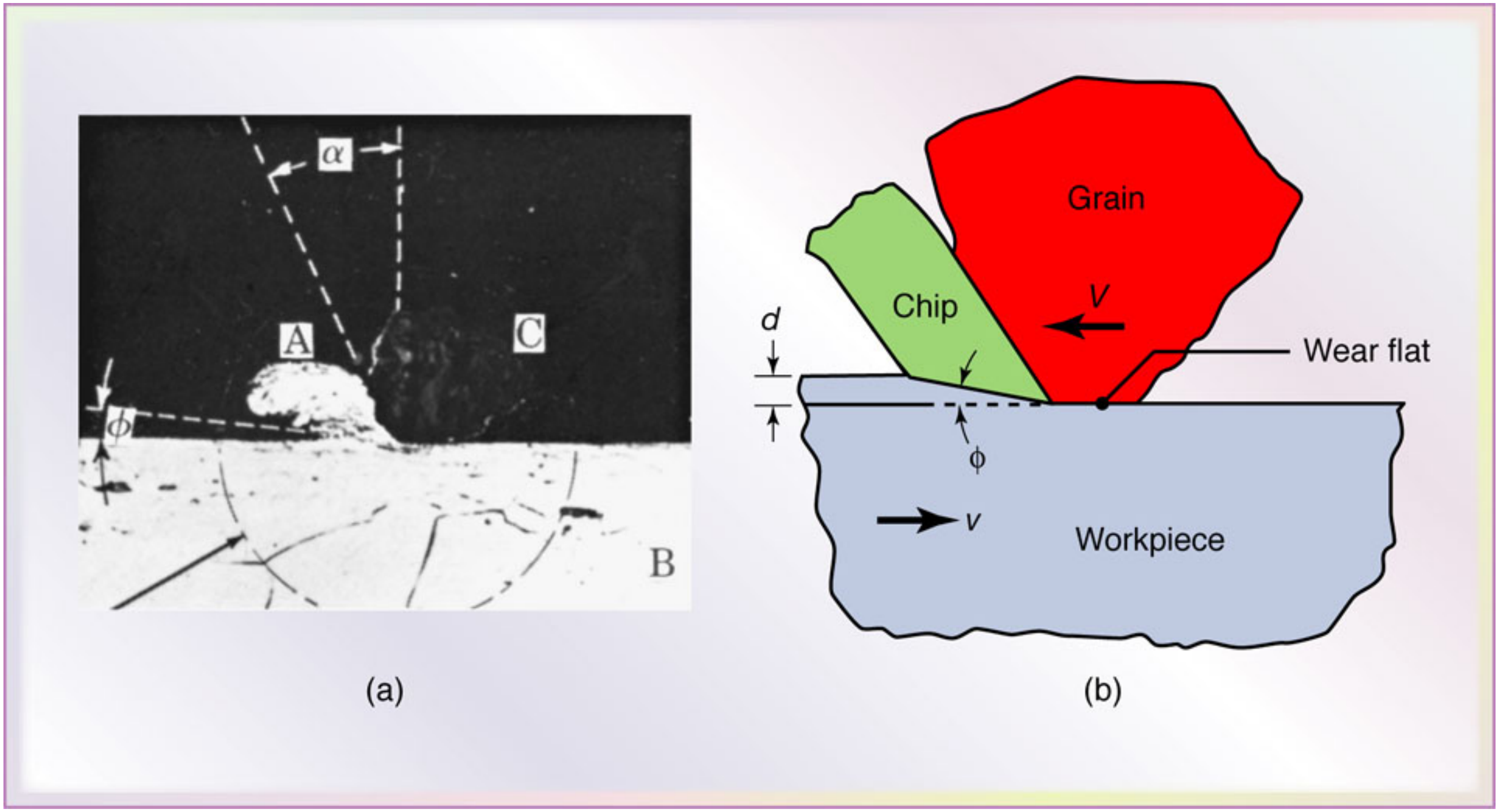
| Ranges of Knoop Hardness for Various Materials and Abrasives | | | |
|---|---|---|---|
| Common glass | 350–500 | Titanium nitride | 2000 |
| Flint, quartz | 800–1100 | Titanium carbide | 1800–3200 |
| Zirconium oxide | 1000 | Silicon carbide | 2100–3000 |
| Hardened steels | 700–1300 | Boron carbide | 2800 |
| Tungsten carbide | 1800–2400 | Cubic boron nitride | 4000–5000 |
| Aluminum oxide | 2000–3000 | Diamond | 7000–8000 |

# Grinding Wheel Model



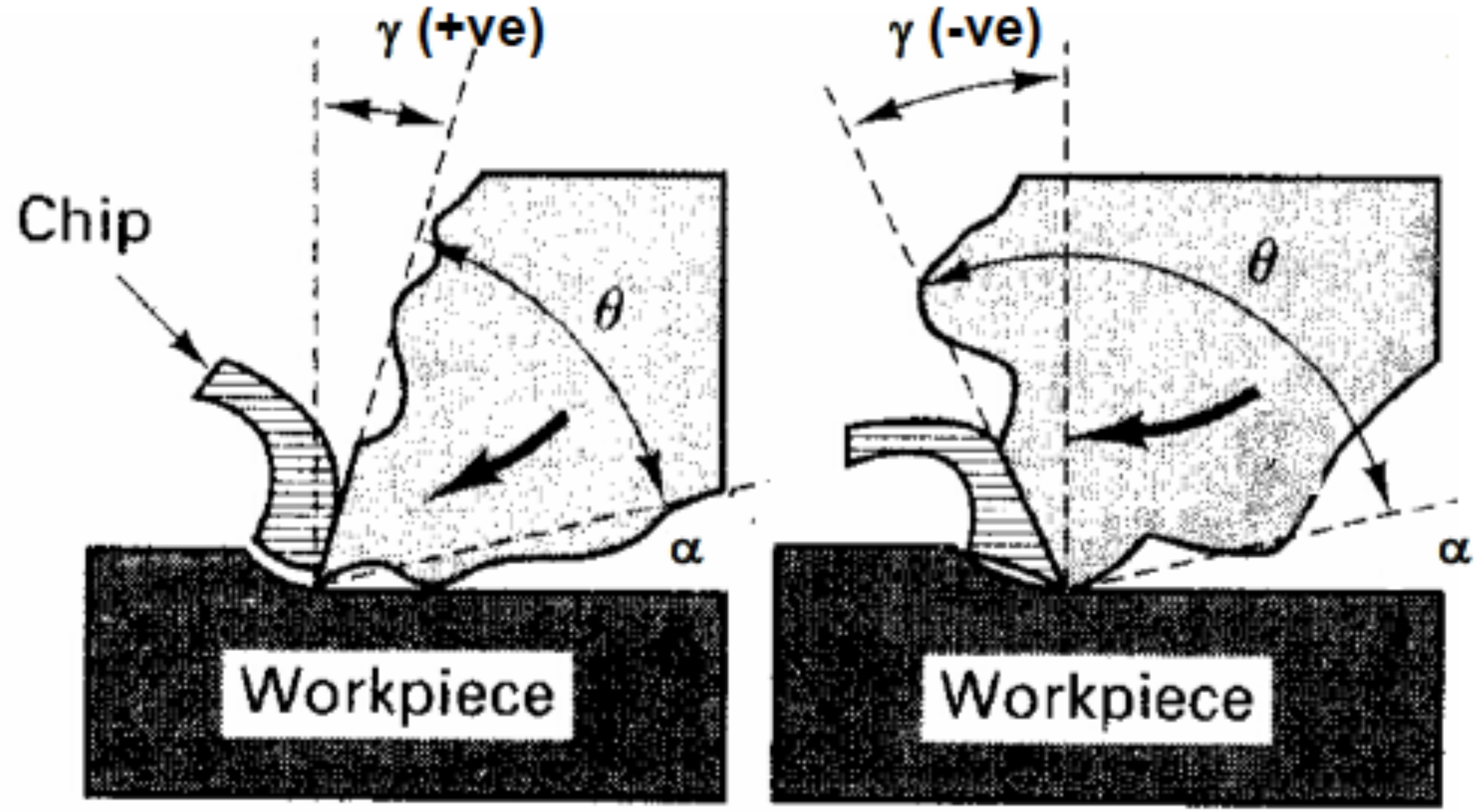

Schematic illustration of a physical model of a grinding wheel showing its structure and wear and fracture patterns.

# Chip Formation by Abrasive Grain

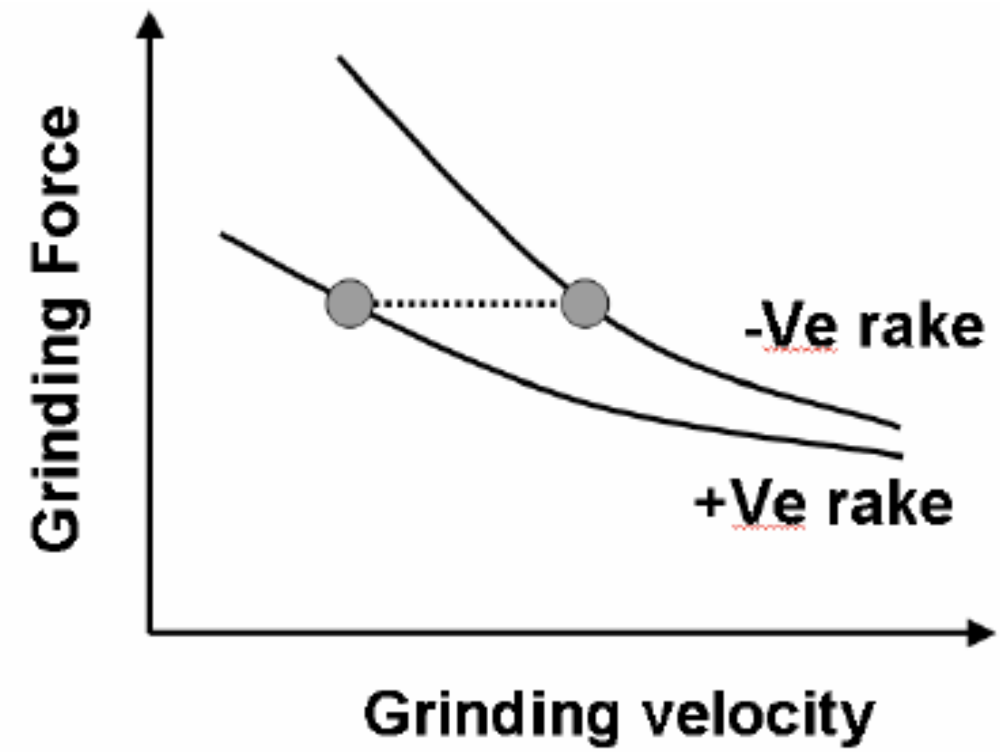


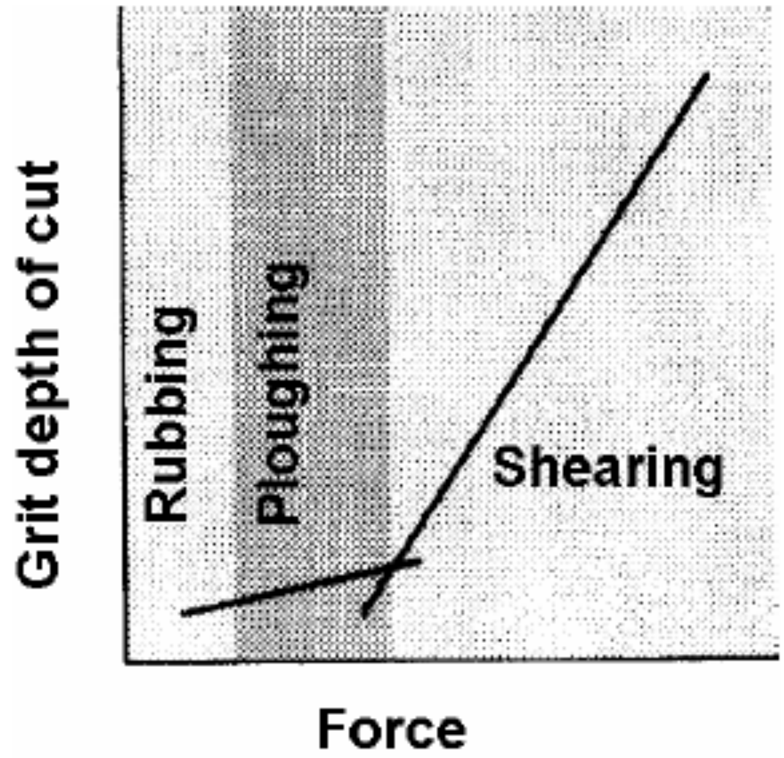

(a) Grinding chip being produced by a single abrasive grain: (A) chip, (B) workpiece, (C) abrasive grain. Note the large negative rake angle of the grain. The inscribed circle is 0.065 mm (0.0025 in.) in diameter. (b) Schematic illustration of chip formation by an abrasive grain with a wear flat. Note the negative rake angle of the grain and the small shear angle. *Source:* (a) After M.E. Merchant.

# Abrasive Grain Ploughing Workpiece Surface

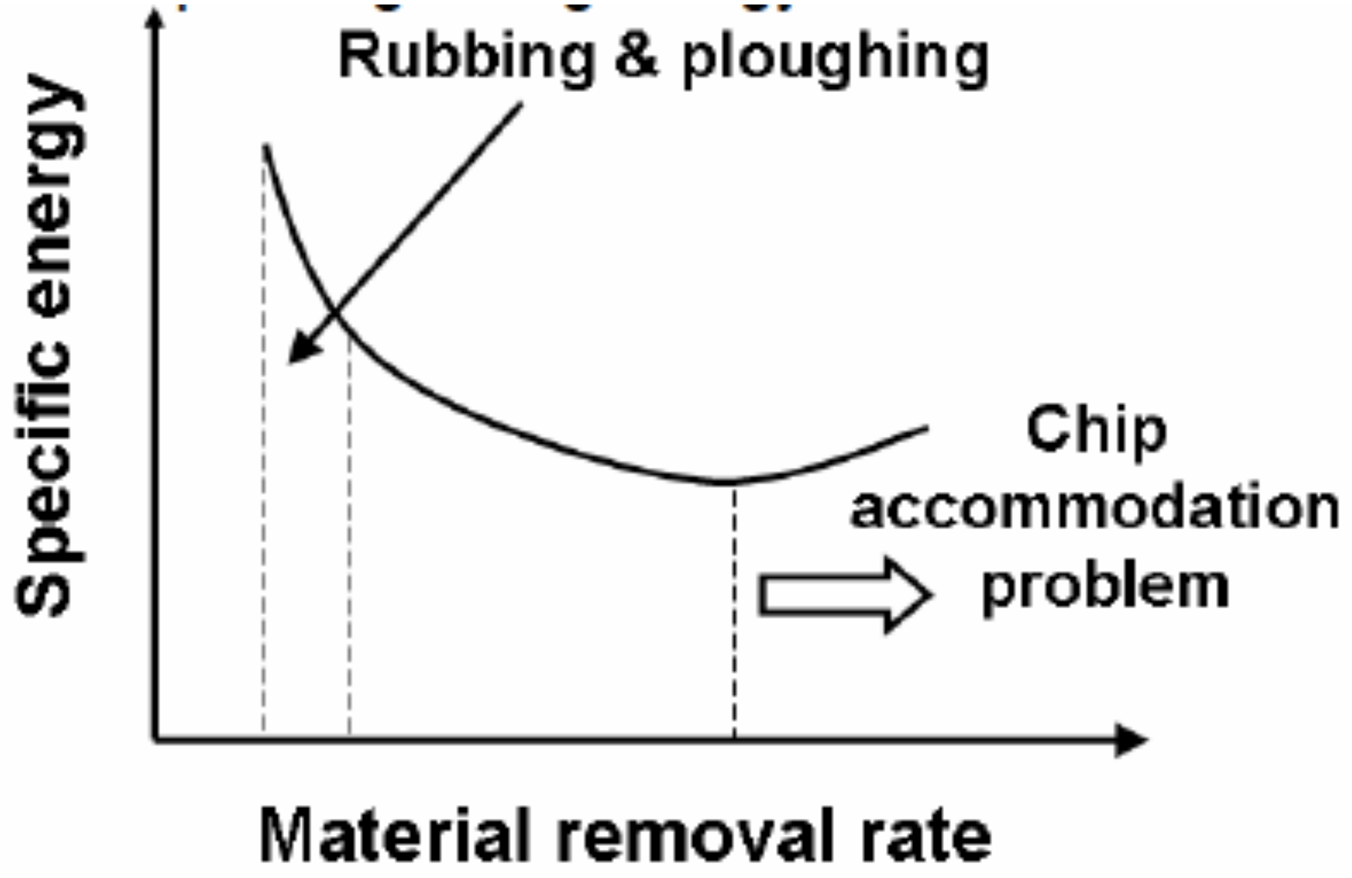


# Grinding velocity, Rake angle and Grit depth

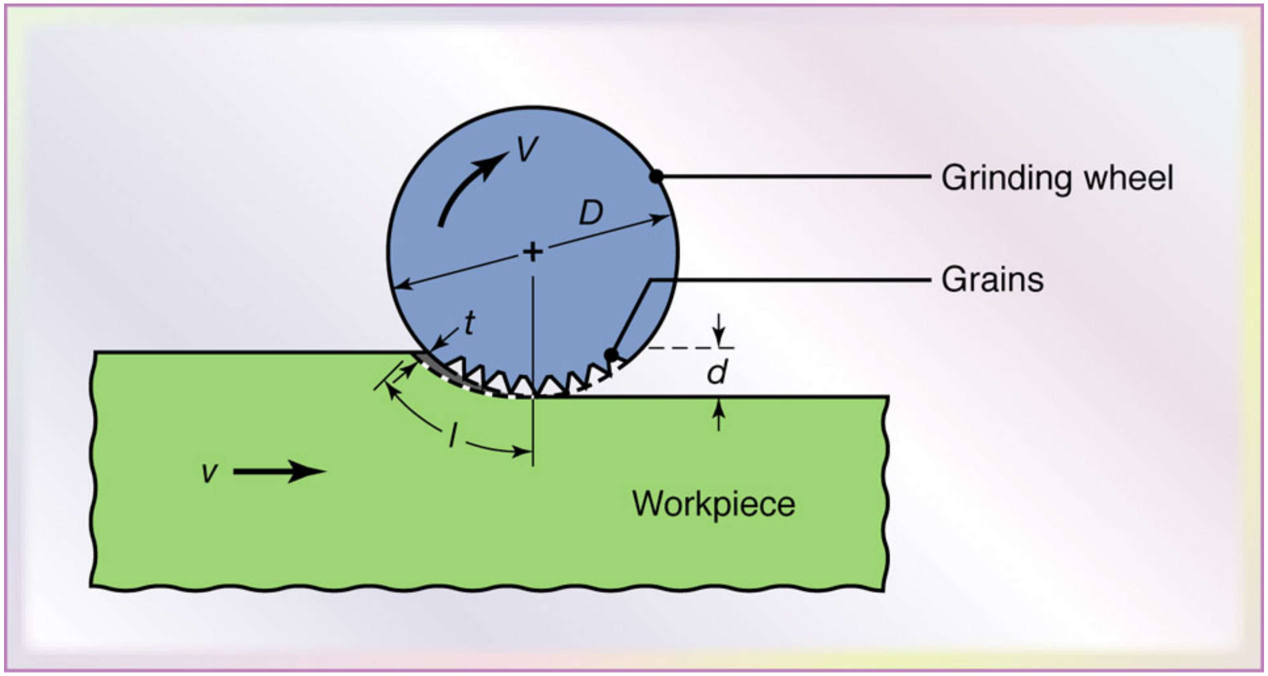


# Specific cutting energy



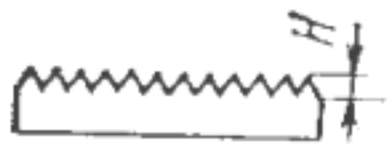
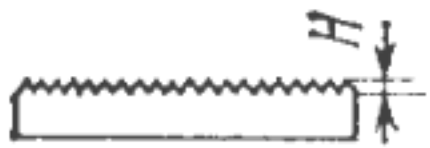
# Grinding ratio




$$\text{Grinding ratio, } G = \frac{\text{Volume of material removed}}{\text{Volume of wheel wear}}$$

# Superfinishing processes: Honing, Lapping and Superfinishing

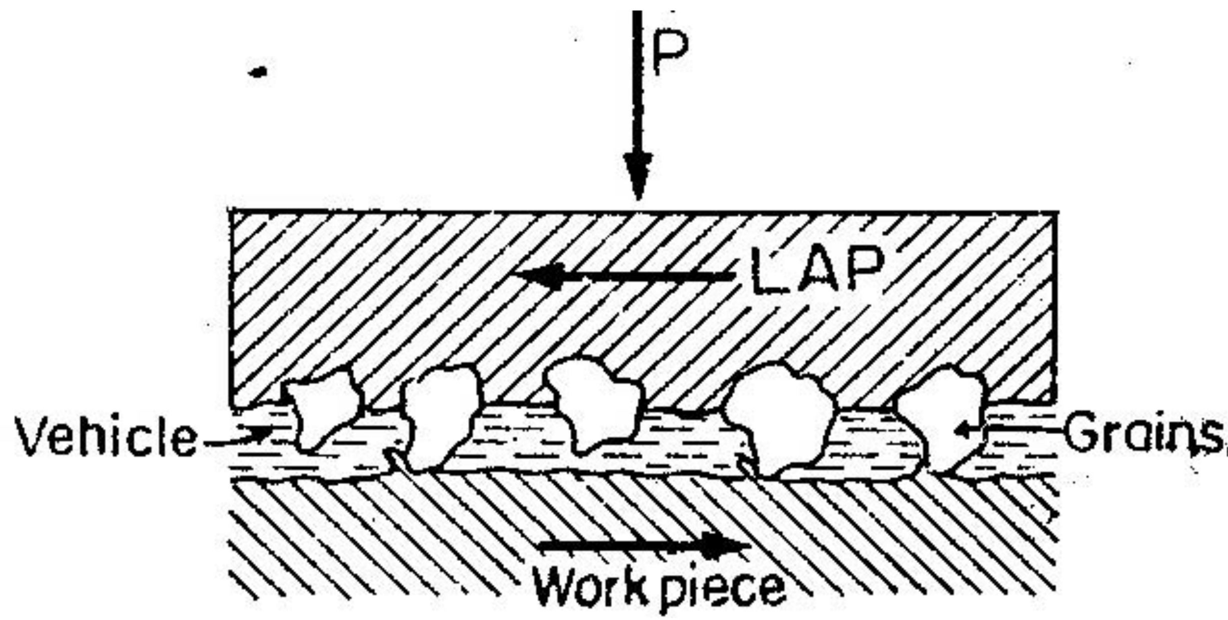
# Improvement of surface roughness

| Process | Diagram of resulting surface | Height of micro irregularity (μm) |
|---|---|---|
| Precision Turning |  | 1.25-12.50 |
| Grinding |  | 0.90-5.00 |
| Honing |  | 0.13-1.25 |
| Lapping |  | 0.08-0.25 |
| Super Finishing |  | 0.01-0.25 |

# Lapping process

**Characteristics of lapping process:**

- Use of loose abrasive between lap and the workpiece
- Usually lap and workpiece are not positively driven but are guided in contact with each other
- Relative motion between the lap and the work should change continuously so that path of the abrasive grains of the lap is not repeated on the workpiece.



# Lapping

**Abrasives of lapping:**

- $Al_2O_3$ and SiC, grain size 5~100μm
- $Cr_2O_3$, grain size 1~2 μm
- $B_4C_3$, grain size 5-60 μm
- Diamond

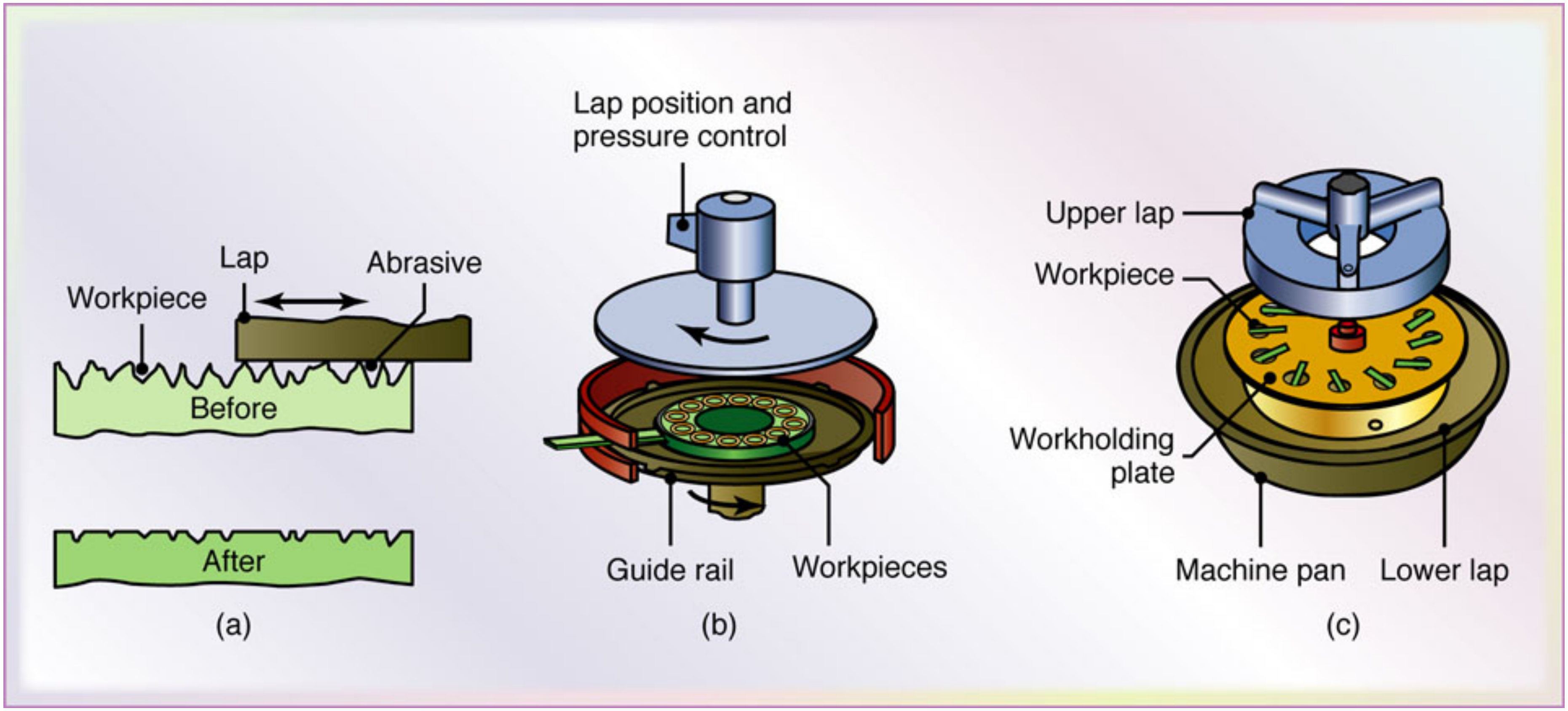
**Materials for lapping**

- Machine oil
- grease

**Technical parameters affecting lapping processes are:**

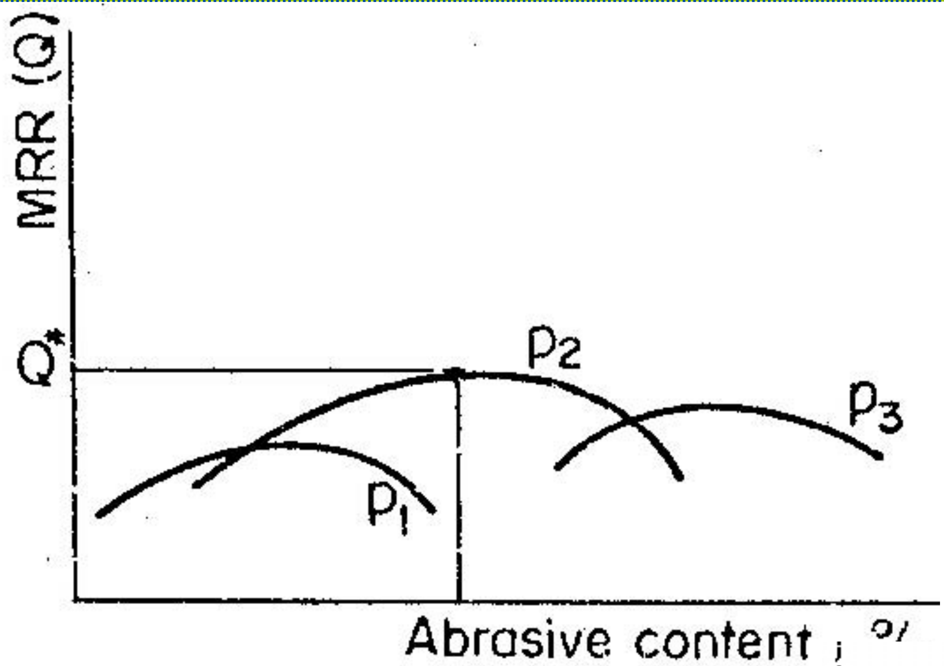
- unit pressure
- the grain size of abrasive
- concentration of abrasive particles
- lapping speed

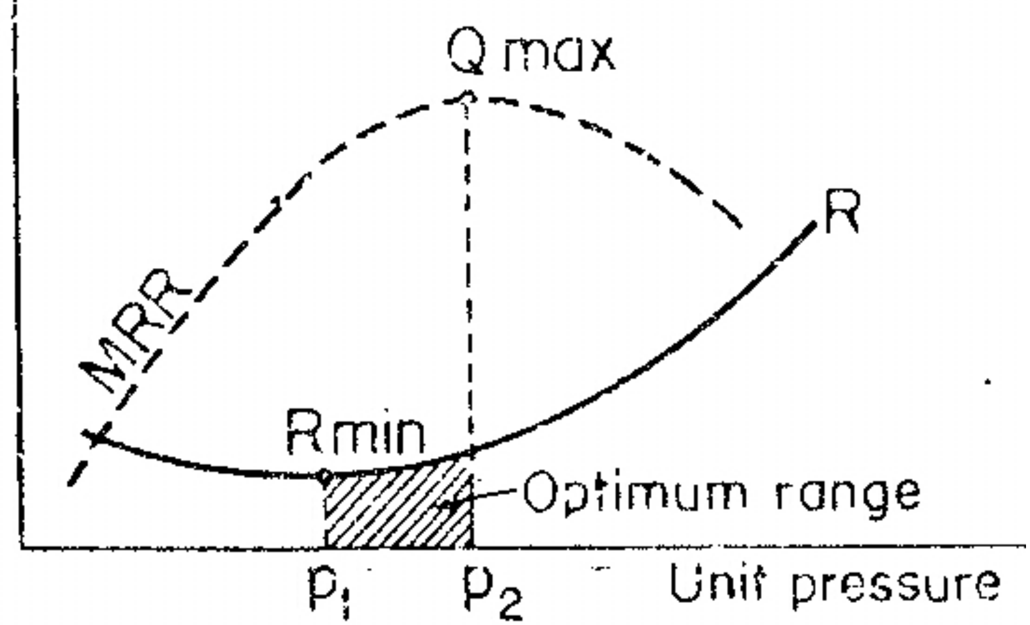
# Production Lapping




(a) Schematic illustration of the lapping process. (b) Production lapping on flat surfaces. (c) Production lapping on cylindrical surfaces.

# Production Lapping



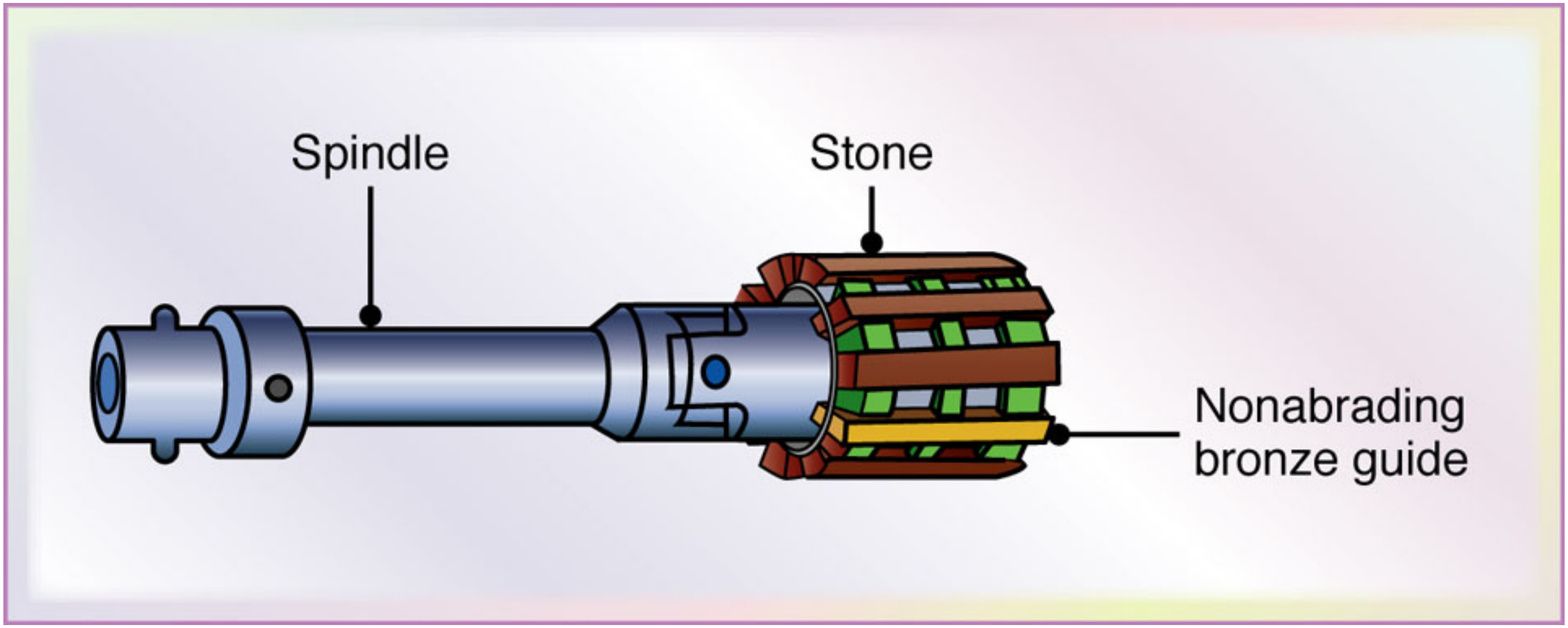



# Honing process

Honing is a finishing process, in which a tool called hone carries out a combined rotary and reciprocating motion while the workpiece does not perform any working motion. Most honing is done on internal cylindrical surface, such as automobile cylindrical walls. The honing stones are held against the workpiece with controlled light pressure. The honing head is not guided externally but, instead, floats in the hole, being guided by the work surface. It is desired that

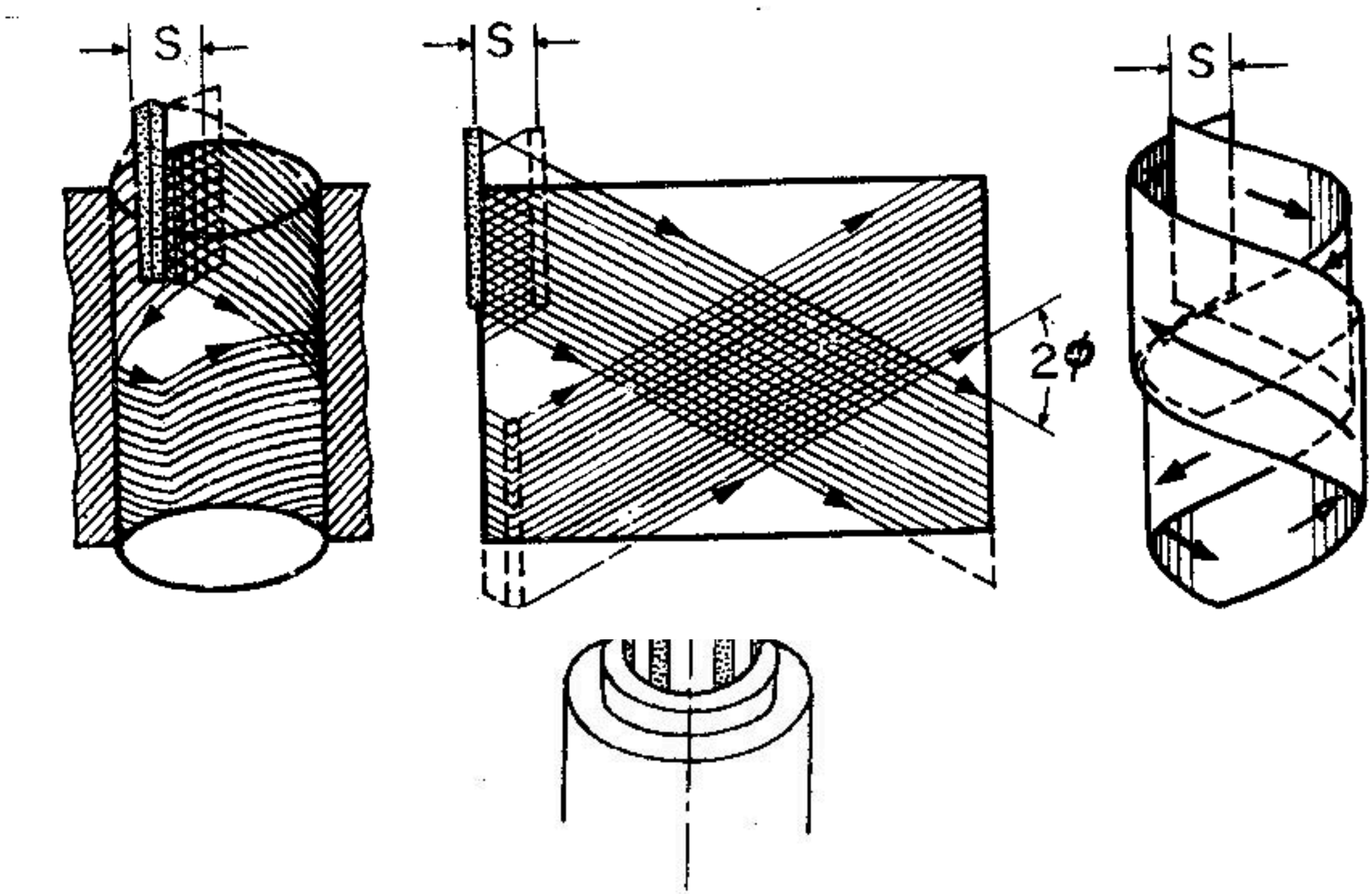
1. honing stones should not leave the work surface
2. stroke length must cover the entire work length.

# Honing Tool




Schematic illustration of a honing tool used to improve the surface finish of bored or ground holes.

# Honning process



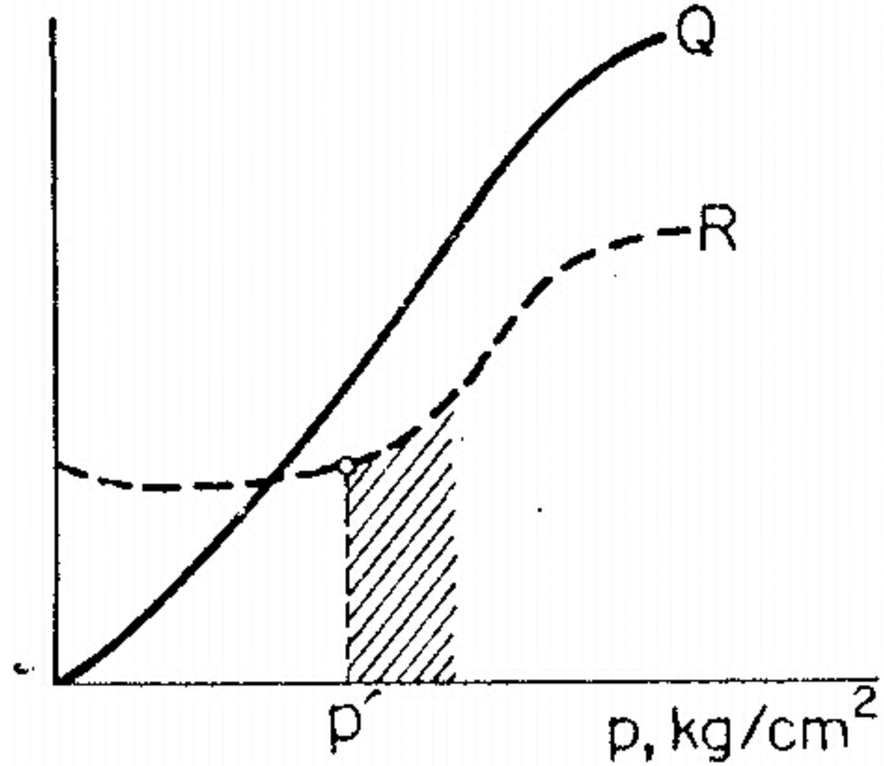
# Honing Tool

The important parameters that affect material removal rate (MRR) and surface roughness (R) are:

(i) unit pressure, p

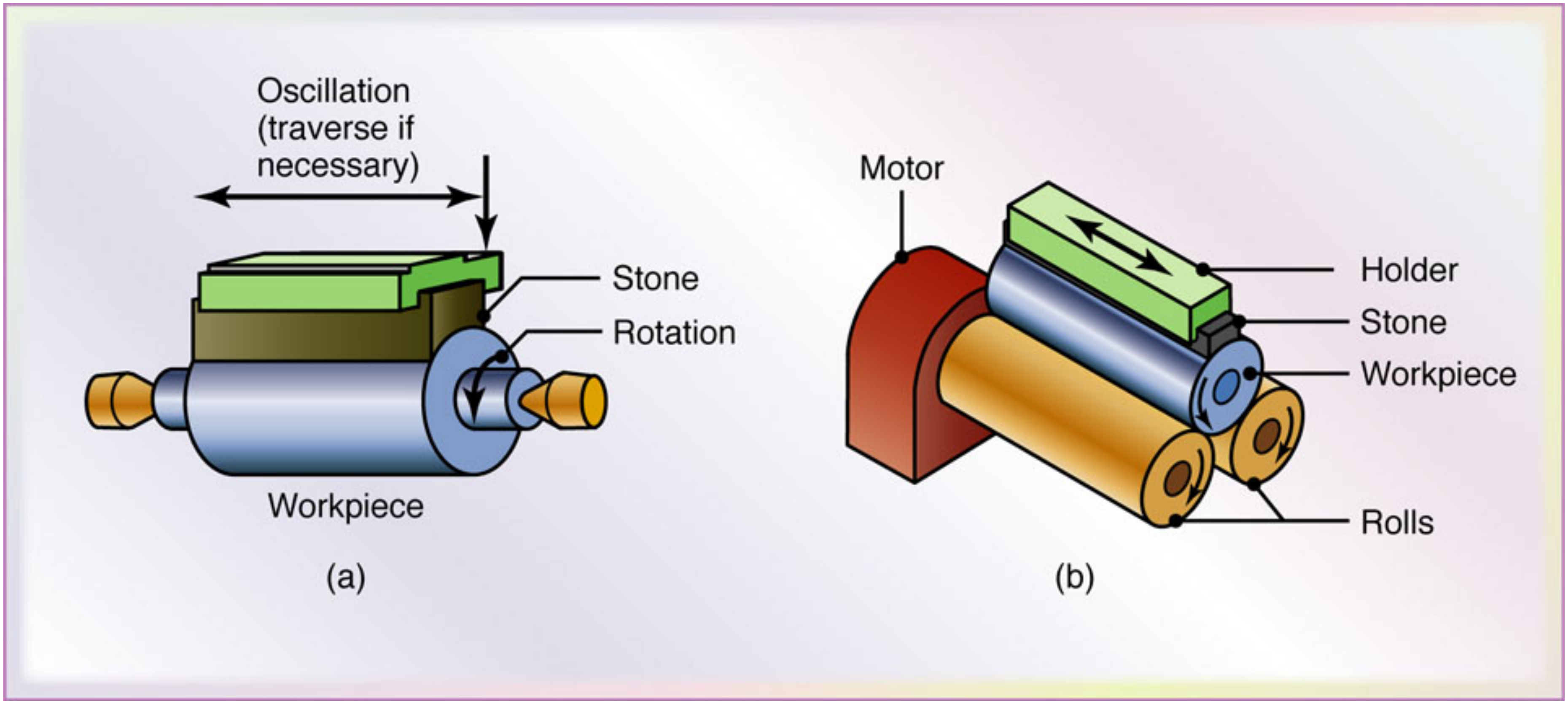
(ii) peripheral honing speed, Vc

(iii) honing time, T



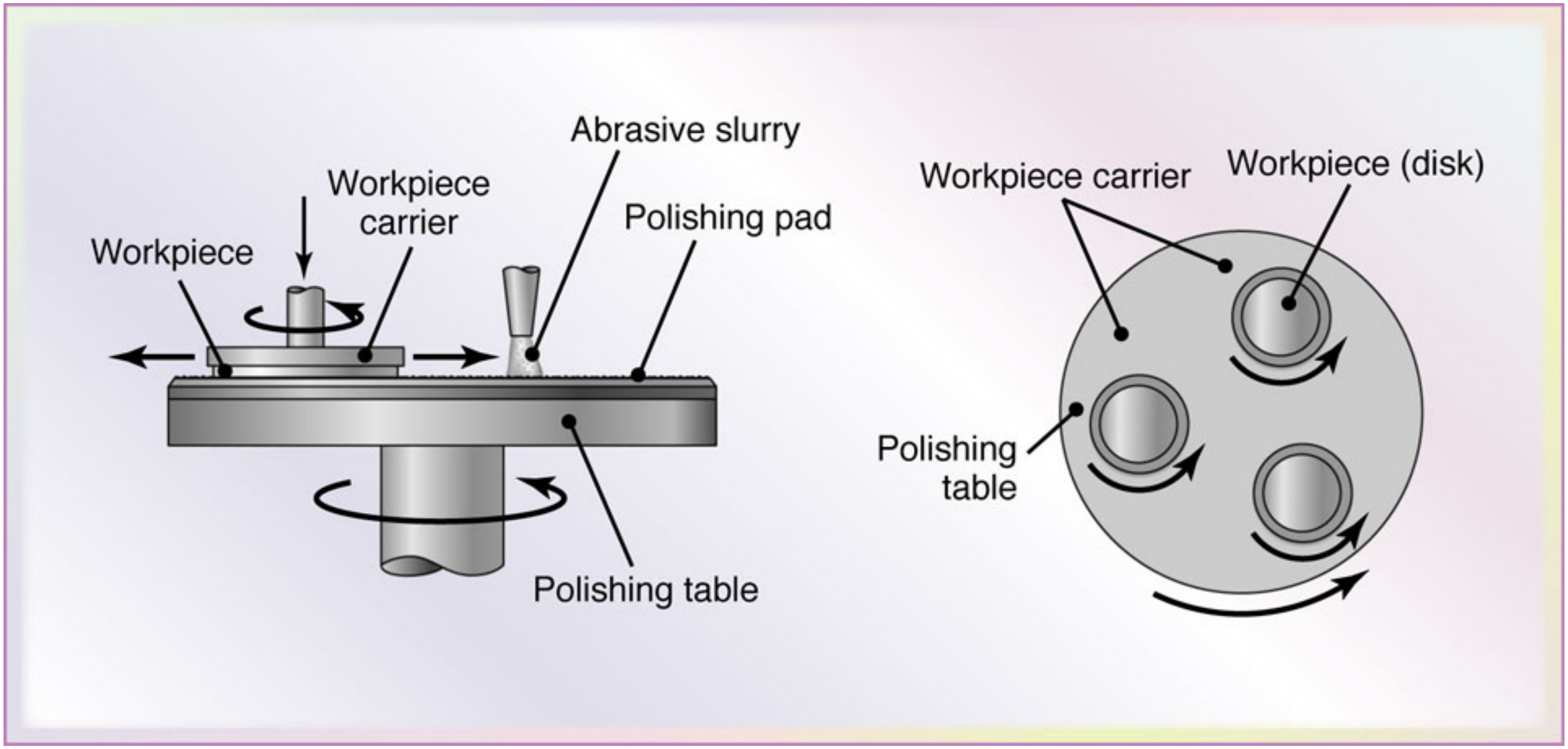

*Effect of honing pressure on MRR and surface finish*

# Super-finishing Process




Schematic illustration of the superfinishing process for a cylindrical part. (a) Cylindrical microhoning. (b) Centerless microhoning.

# CMP Process (Chemical-mechanical polishing)




(a) Schematic illustration of the chemical-mechanical polishing (CMP) process. This process is used widely in the manufacture of silicon wafers and integrated circuits and also is known as chemical-mechanical planarization. For other materials, more carriers and more disks per carrier are possible.