Lecture 6 - ‘Classical machining’ / material removal through mechanical means

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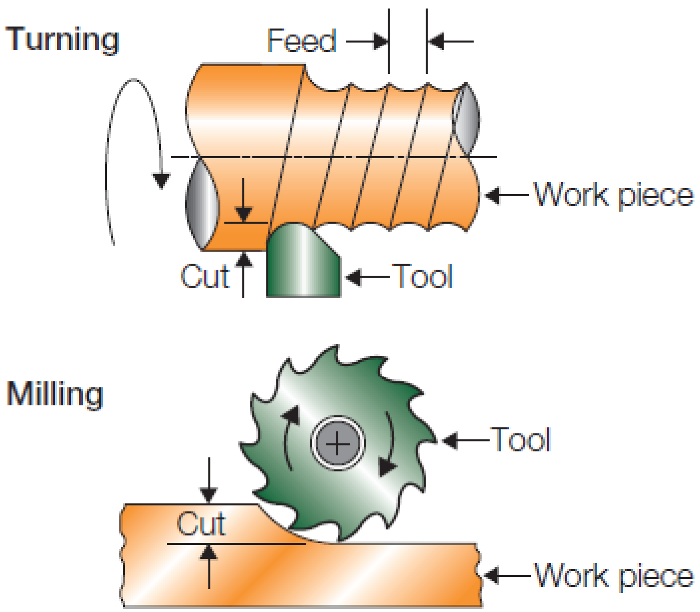
Learning objectives

1. Methods related to **material removal by mechanical means** involving cutting techniques (*'Enlévements de copeaux'*)
2. Differences between processes like

   1. **Cutting** (*'Découpe'*)
   2. **Milling** (*'Fraisage'*)
   3. **Drilling** (*'Perçage'*)
   4. **Turning** ('Tournage')

3. Modelling



(Illustration M. Ashby)

Machining through material removal processes

‘***Removal*** of material from a raw material so the remaining material has the desired, final shape’

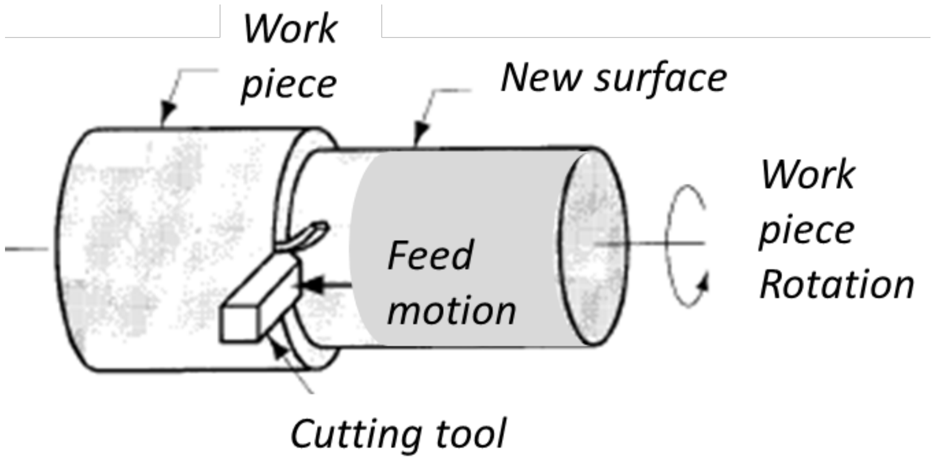
- *Machining* – material removal by a sharp cutting too (turning, milling, drilling)
- *Abrasion* – material removal by hard, abrasive particles (grinding, lapping, polishing)
- *Unconventional – lasers, EDM, water-jet etc.*

Why Machining is Important...

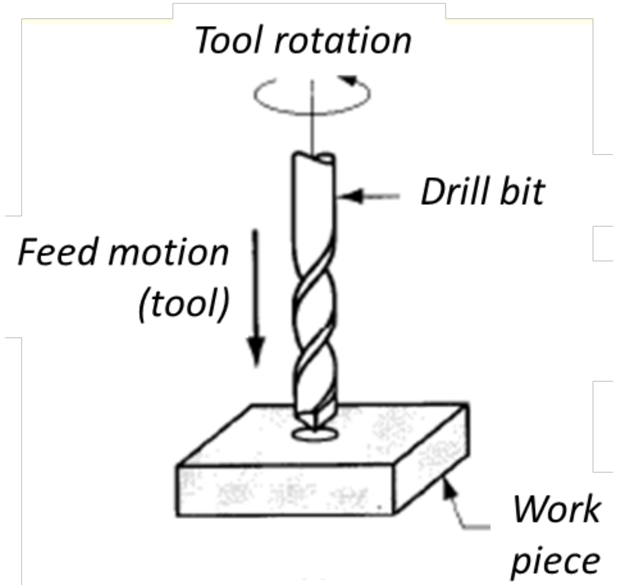
- **Variety of work materials** can be machined
  - Most frequently applied to metals (but not only!)
- **Variety of part shapes and special geometry features**:
  - Threads (screw)
  - Accurate round holes
  - Straight edges and surfaces
- 0.01 mm to micron dimensional accuracy and surface finish (down to optical quality – in the case of diamond turning)

Metal cutting operations

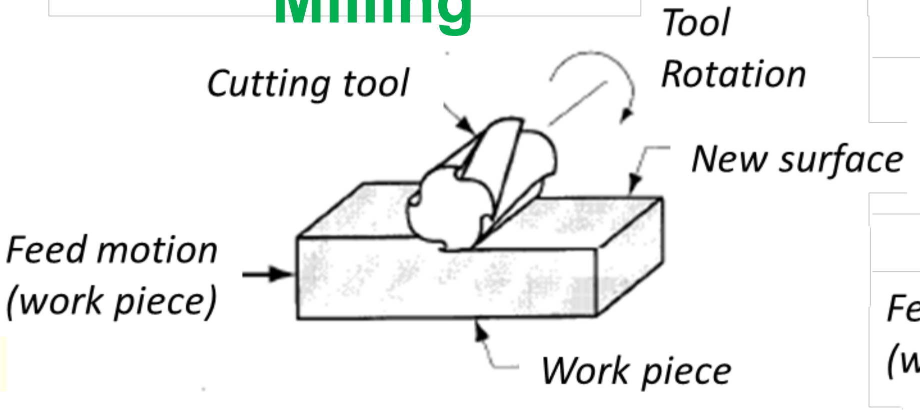
Turning



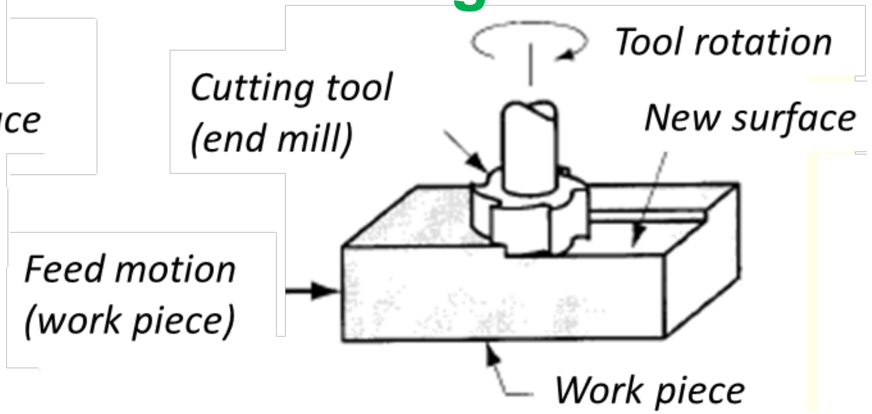
Drilling



Milling



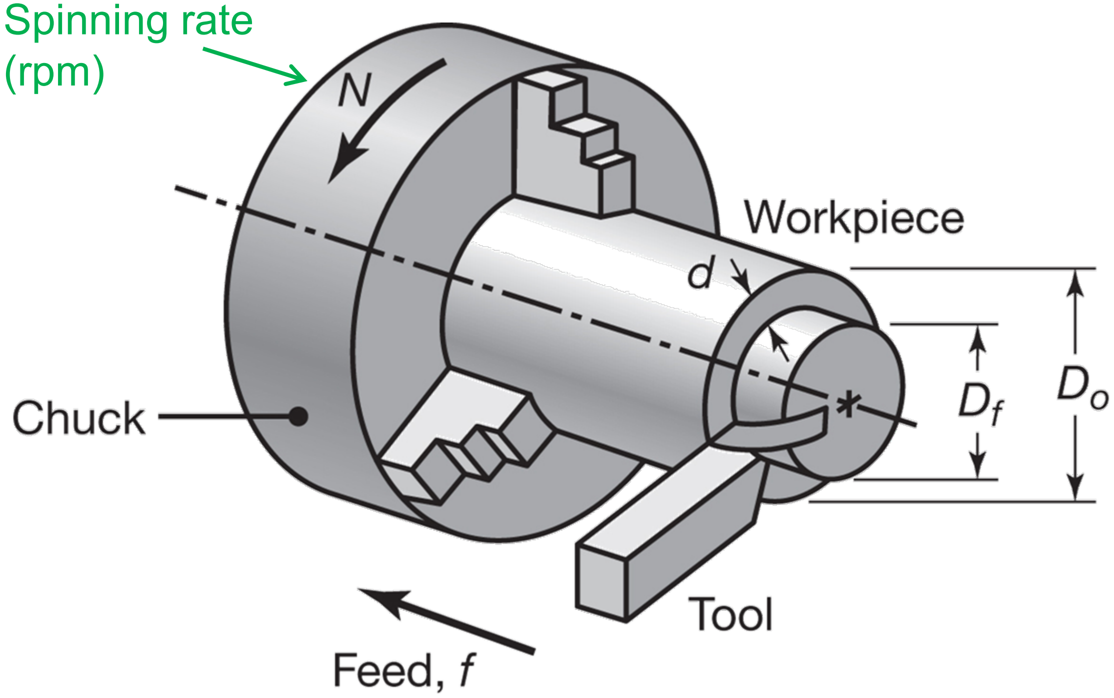
Milling



Metal cutting operations: turning

Key process control parameters

Spinning rate (rpm)

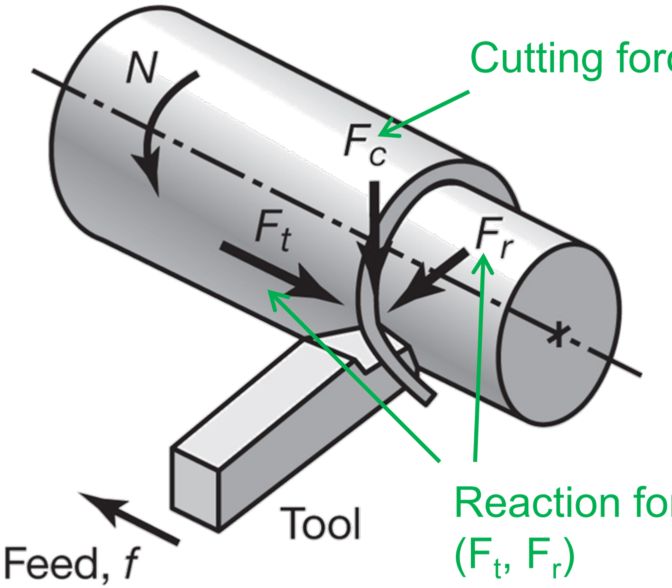


Feed rate (m/s)
'tool progression'

'Avance de l'outil'

Force acting on a cutting tool during operation

Cutting force



Reaction forces (F_t, F_r)

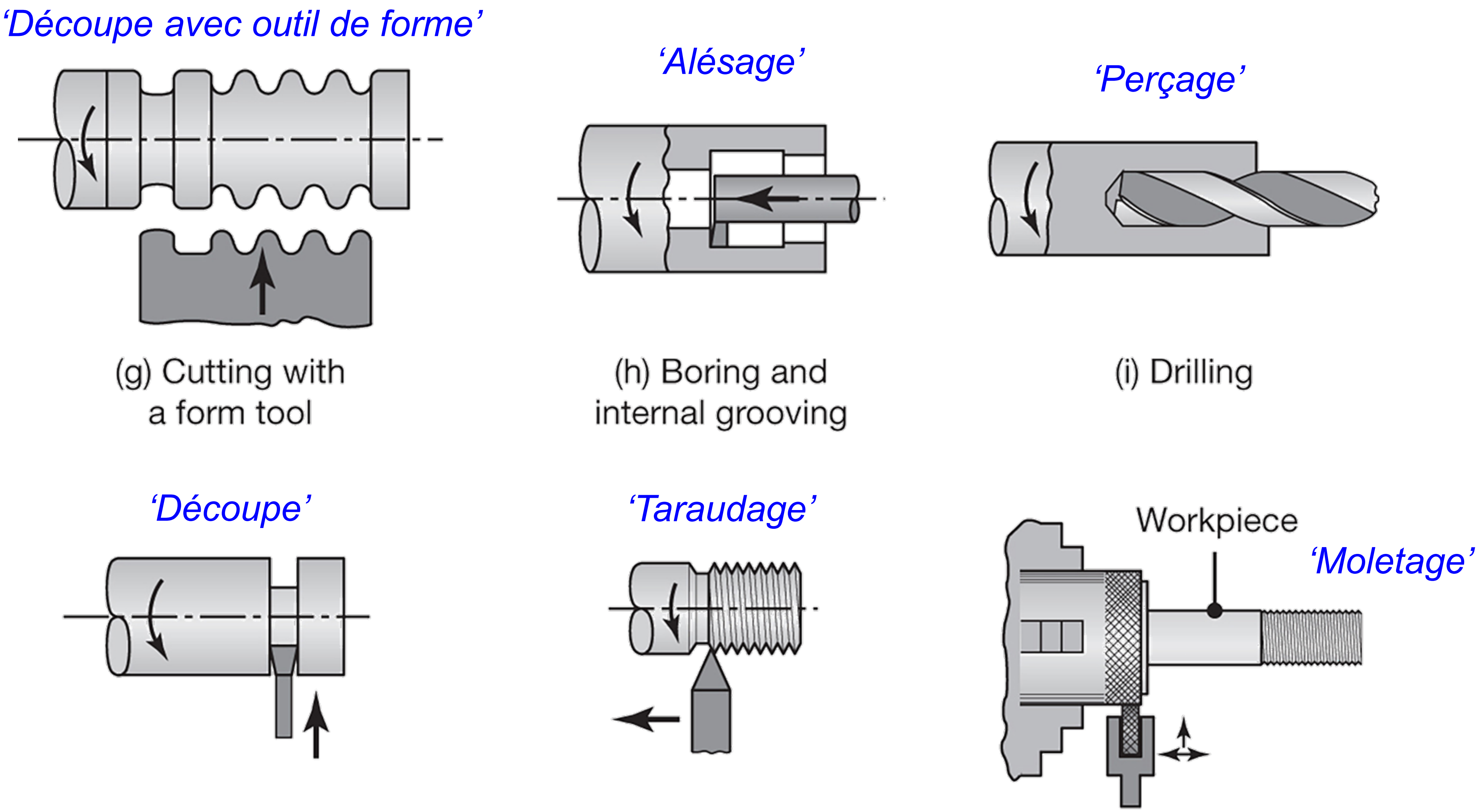
Key process control parameters:

- ***Feed rate:*** *speed at which the tools move into the specimen*
- ***Spinning rate (N):*** *rotational speed of the tool*

Illustrative video

https://youtu.be/8EsAxOnzEms

Turning terminology



(g) Cutting with a form tool

(h) Boring and internal grooving

(i) Drilling

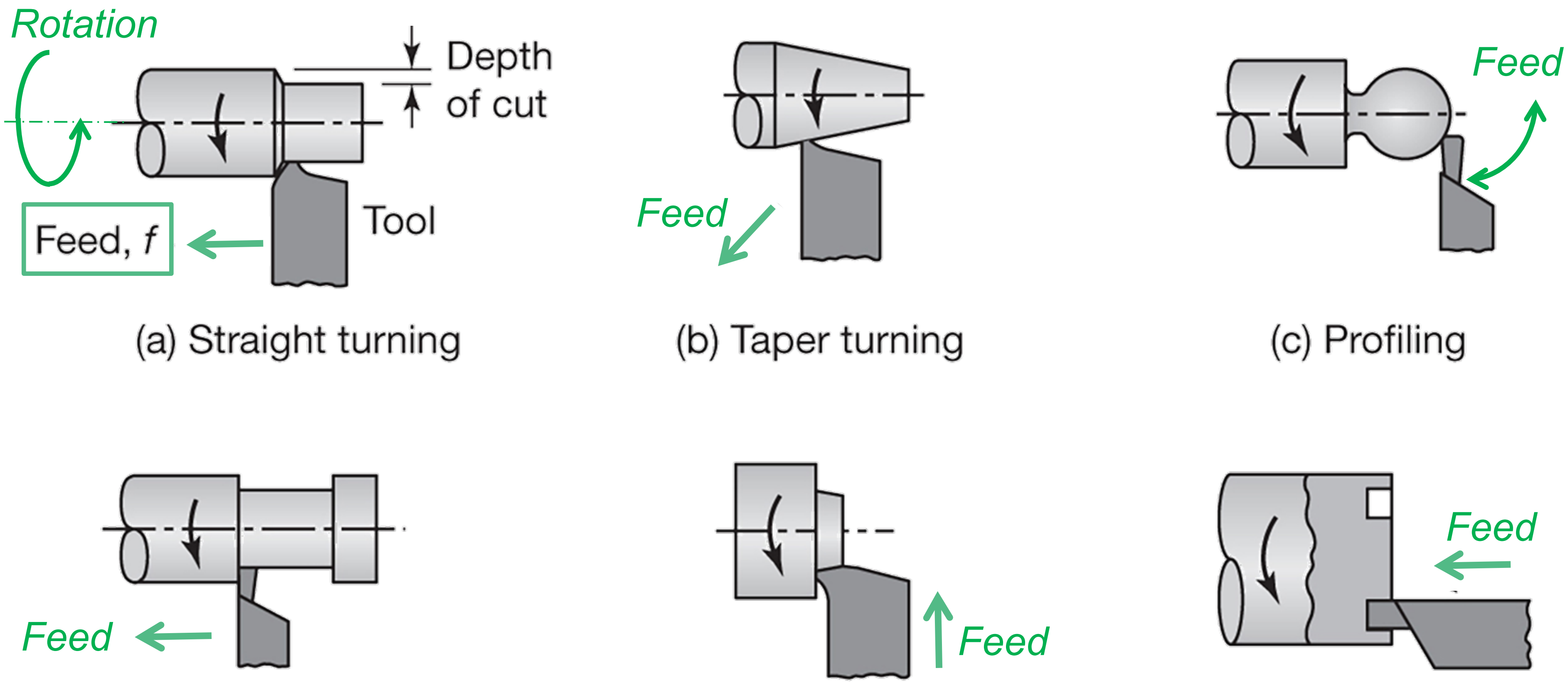
(j) Cutting off

(k) Threading

(l) Knurling

Turning

Different shape are obtained by proper choice of the tool and coordinated motion of the tool.



(a) Straight turning

(b) Taper turning

(c) Profiling

(d) Turning and external grooving

(e) Facing

(f) Face grooving

Illustration of the diversity of tools in watch making

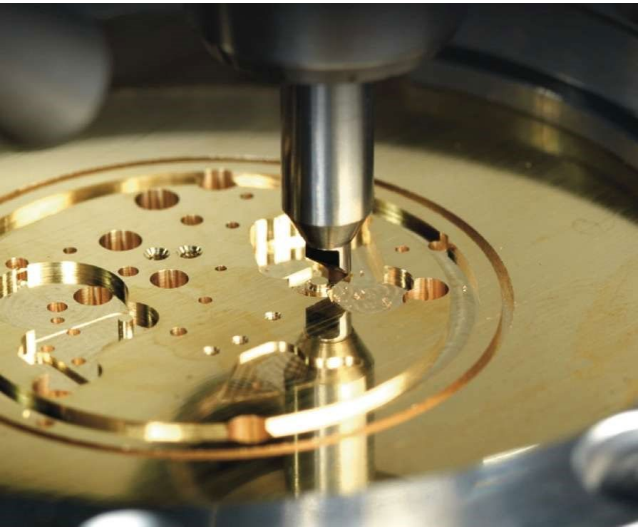


Illustration Polymedia.ch

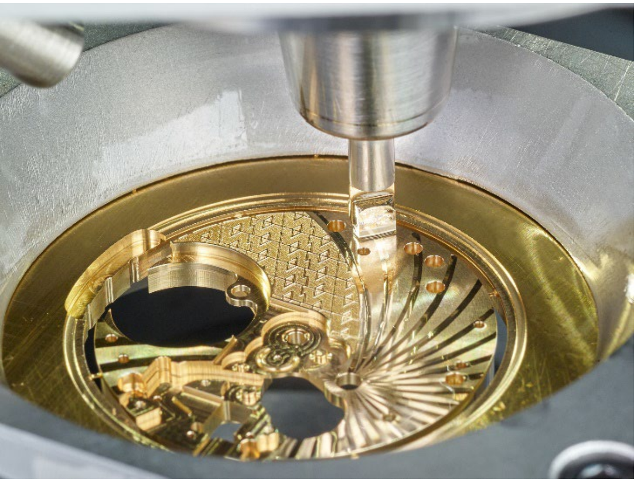
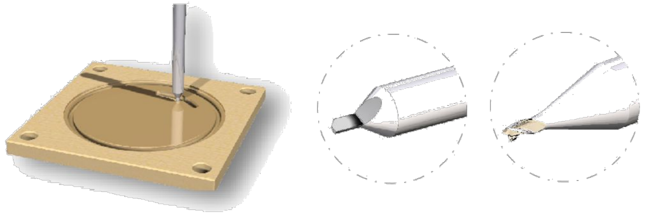


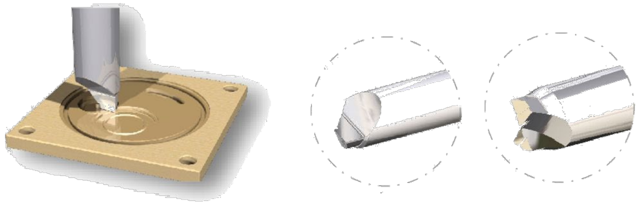
Illustration Willemin-Macodel

‘Surfaçage’

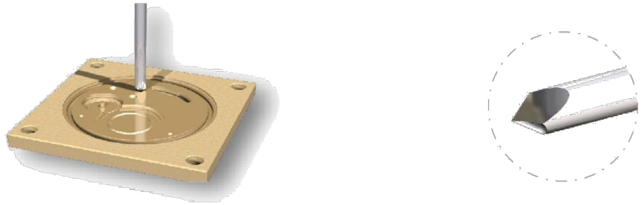
‘Rainurage extérieur’



‘Uninage de poche par fraisage’



‘Creusures’



‘Pointage’

‘Perçage’

‘Tourbillonnage de filet’

‘Gravage’

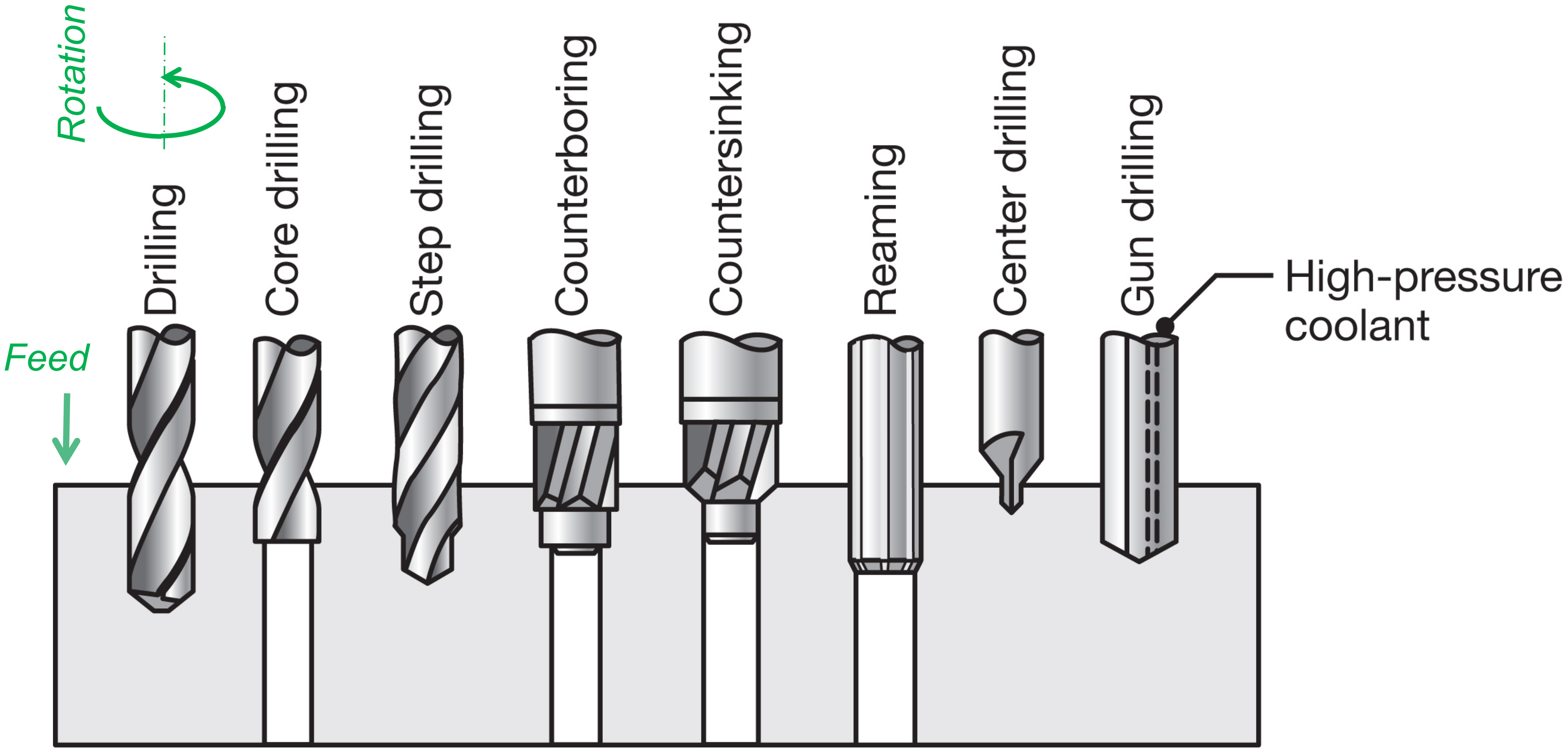
(Source: Louis Bélet, Swiss cutting tool)

Precision Turning *('Decolletage')*

(source Snaem)

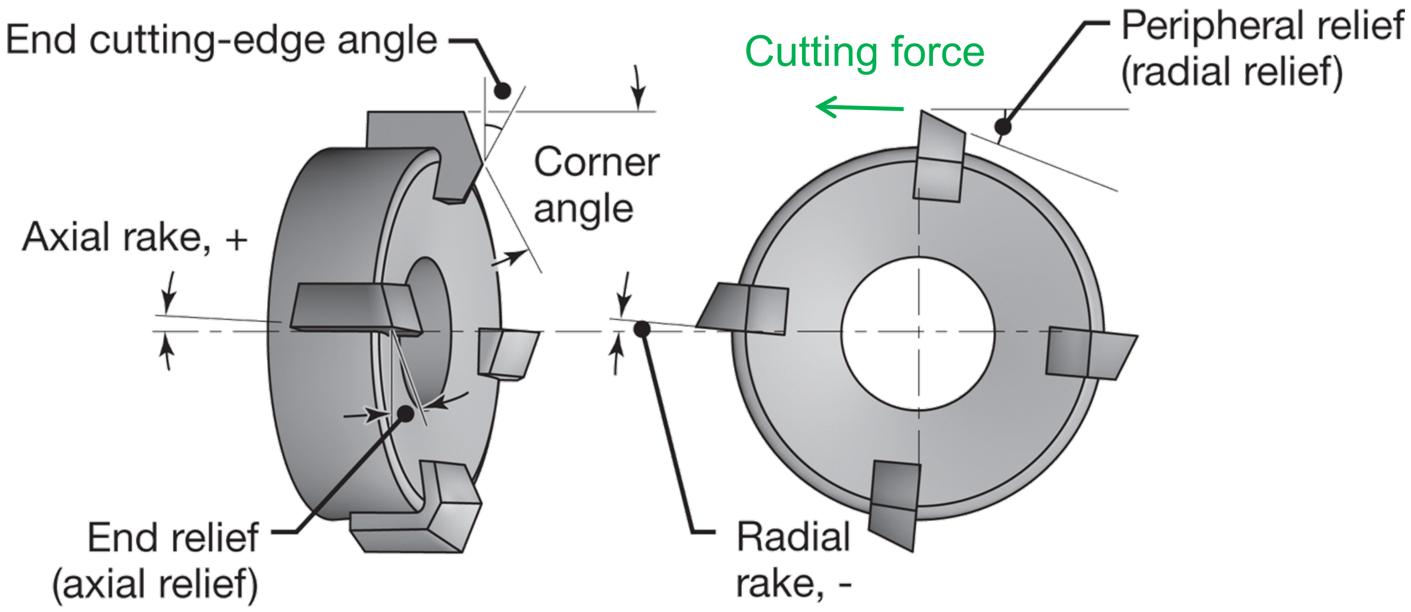
(source: 3D Décolletage)

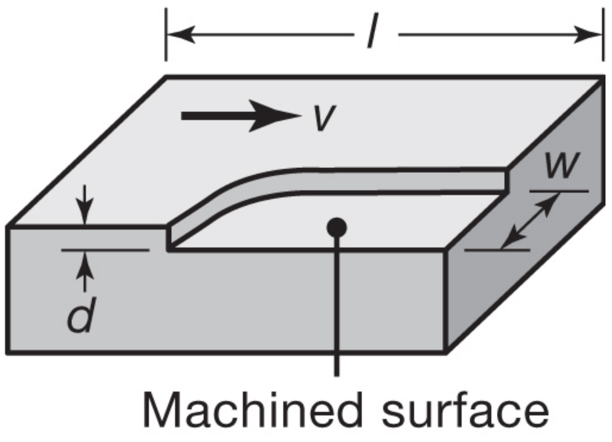
Drilling operations

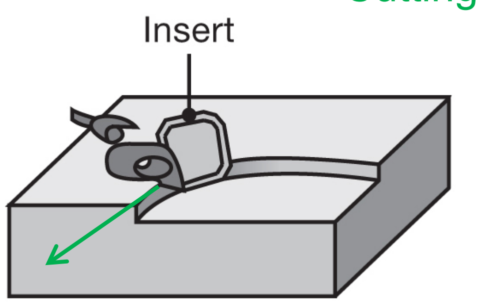


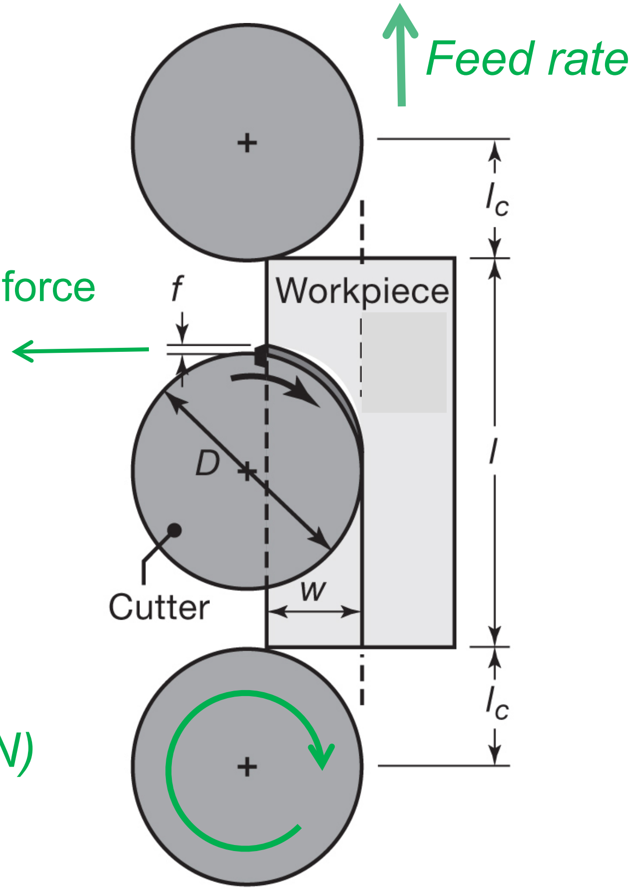
Face milling

'Fraisage'









Typical manufacturing Sequence

1. Raw material is prepared by **forming processes**, such as casting, forging, rolling and bar drawing

2. **Machining provides the final shape**, dimensions, finish, and special geometric details that other processes cannot create

3. May be followed by **additional finishing steps** (for instance anodizing and other surface treatments)

Machine Tools

(ex. Rollomatic)

- Modern machine centers are complex machines (= robots)
- Functions:
  - Holds the work piece
  - Positions tool relative to work
  - Provides power at speed, feed, and depth that have been set (CNC controlled)

Illustrative videos:
https://youtu.be/CqePrbeAQoM

Some more videos resources... (for after-class viewing)

- Interesting video showing the variety of machining types:
  - https://youtu.be/8H-0lI7kxbg
- ‘Miniature’ metal cutting: (Delta robot)
  - https://youtu.be/As4Qc6Q7H88
- Machining center (5 axis) (example)
  - https://youtu.be/7frY_qc3-cg
- One more thing… https://youtu.be/sxbiIpXZfG8
- Illustration of machining (watchmakers)
  - https://www.youtube.com/watch?v=UvCp6DdA1lI
- Optics and diamond turning
  - https://youtu.be/rJ8U5kwCZDk

Advantages

- **High flexibility / 3D**
  - The same machine can make diverse parts with complex features such as threads.
  - Thanks to the progress made in robotics and machine centers, true 3D parts can be made

- **Variety of materials**
  - A broad variety of metals
  - Some polymers (POM for instance)
  - Some brittle materials

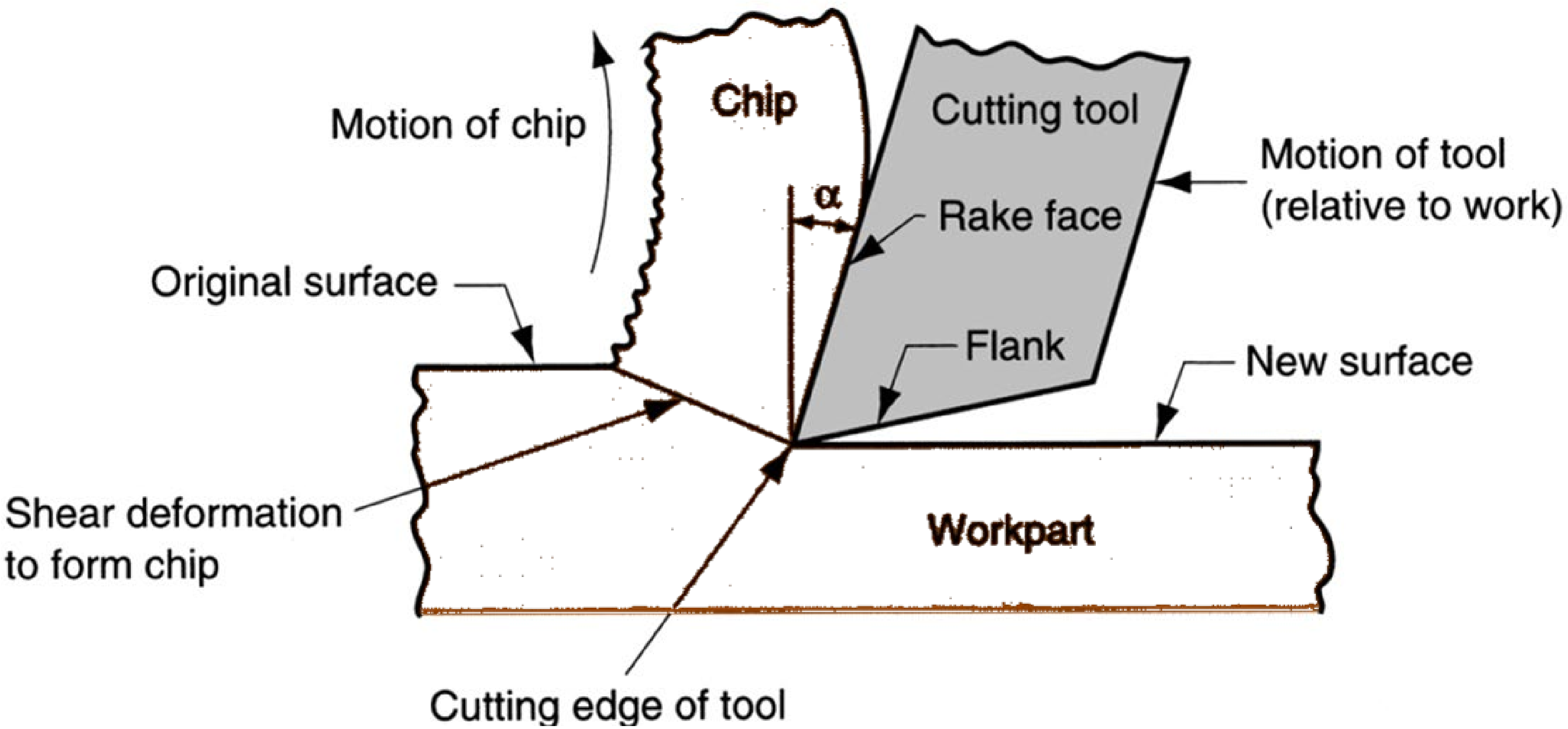
Disadvantages

- **Waste of material / Tooling**
  - Chips generated in machining are wasted material (There are some ongoing attempts to valorize this wasted material, but it cannot be reused for processing)
  - Requires some tooling and cutting fluids for cooling.

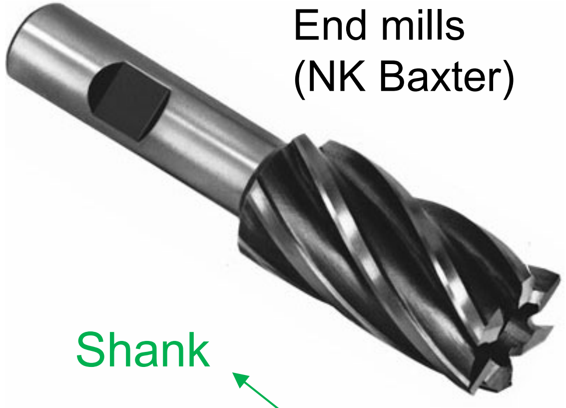
- **Time consuming**
  - A machining operation generally takes more time to shape a given part than alternative shaping processes, such as casting, powder metallurgy, or forming
  - Serial operation

Fundamental working principle

Cutting action involves **shear deformation** of layer of the work material.
As chip is removed, a new surface is exposed.

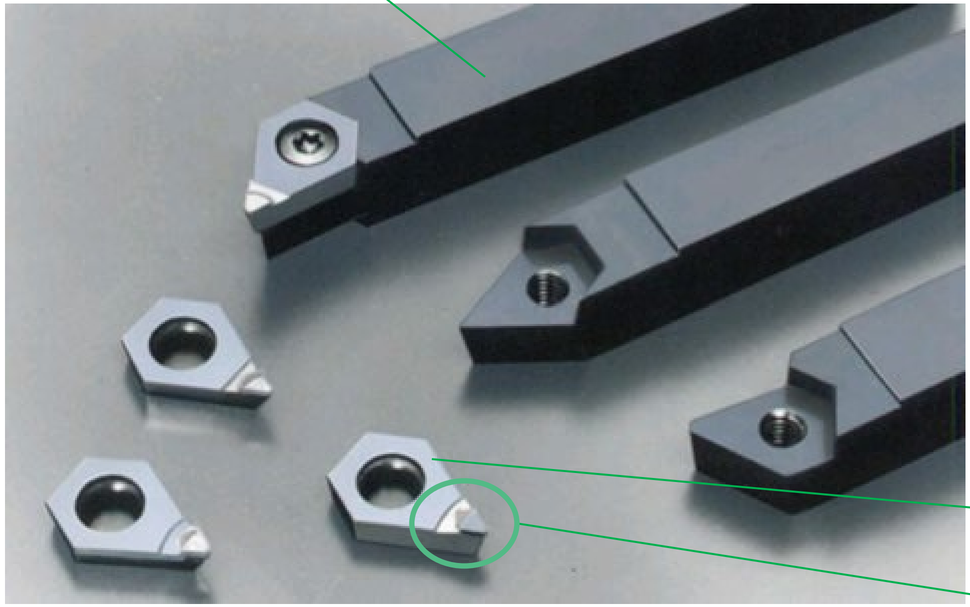


Cutting tools in real life...



End mills
(NK Baxter)

Shank



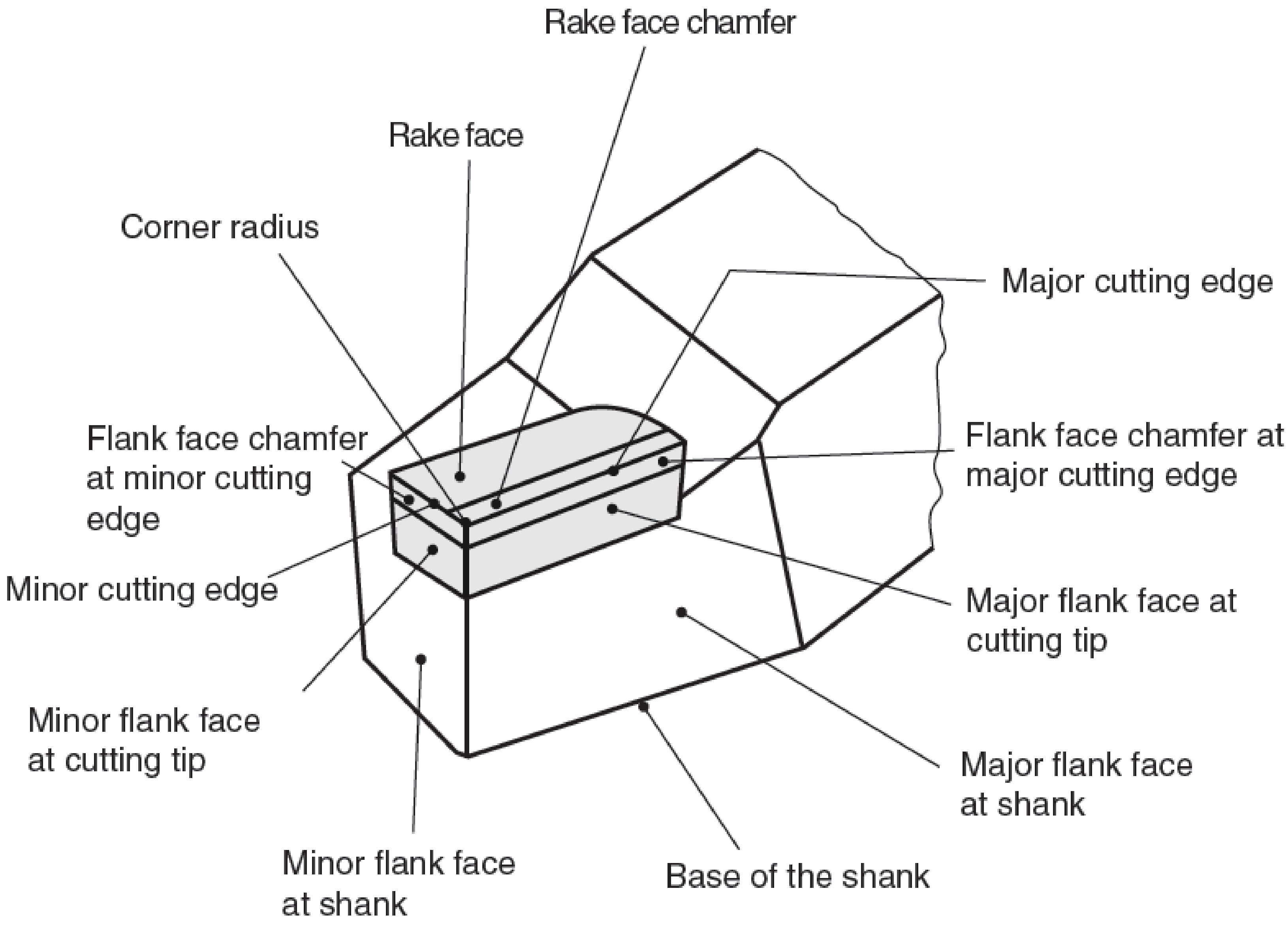
Diamond cutting tools
(Allied Materials)

Insert

Active cutting tool

Various cutting tools
(Engineering blogspot)

Standardized form of a cutting tool

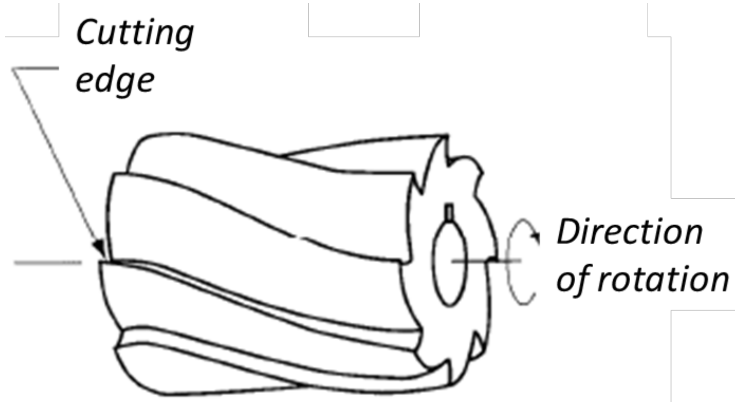


Cutting Tool Classification

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

(Source: CNC Blogspot)

(Source: Louis Bélet SA)



Mechanical analysis of the cutting process: **Why** and **Goals**

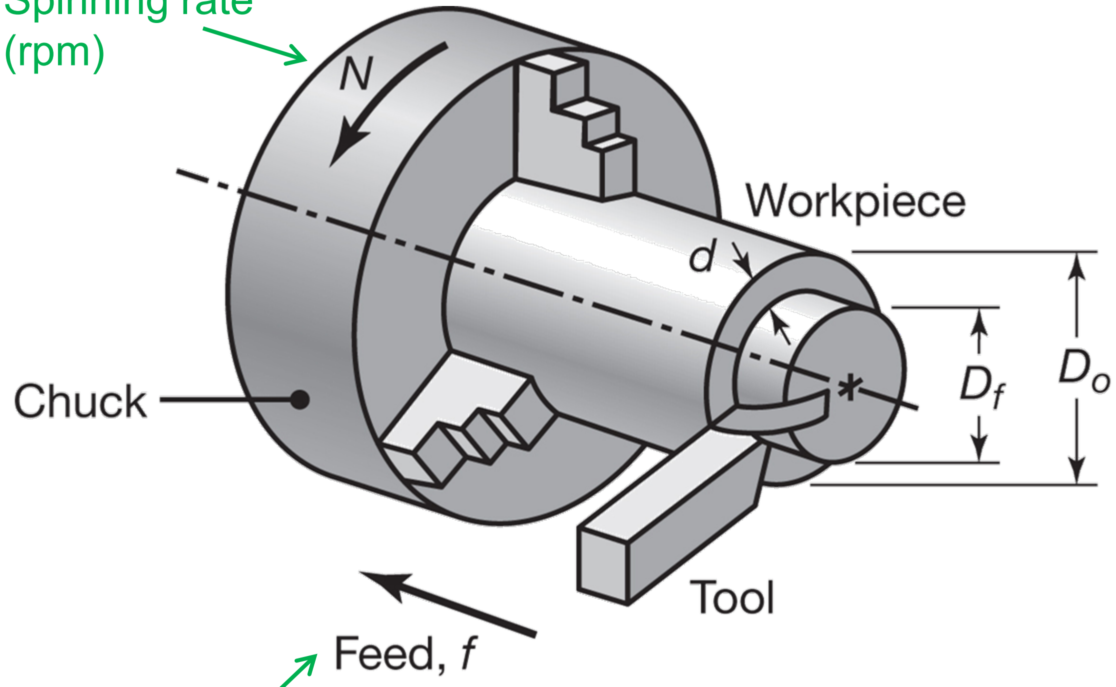
- **Why?**
  - Optimize the cutting process in term of tool wear vs material removal rate / increase productivity

- **Goals**
  - Established the force required
  - The power consumption
  - Heat transfer process

Metal cutting operations: turning

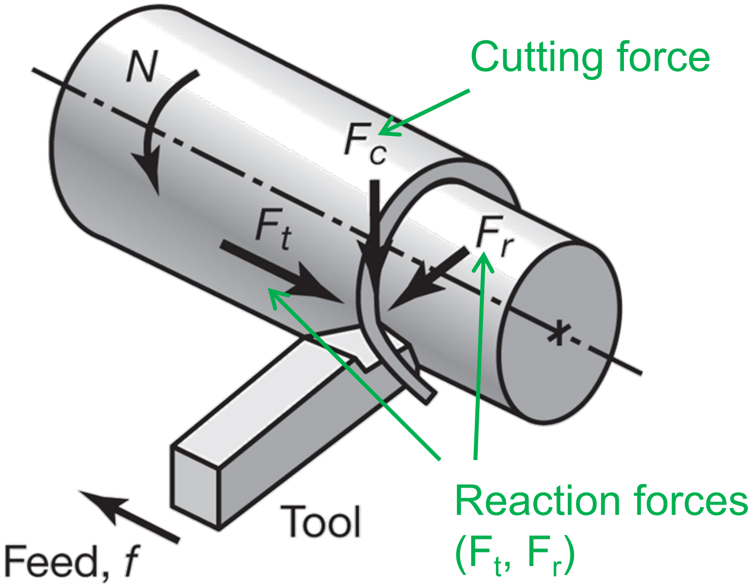
Key process control parameters

Spinning rate (rpm)



Feed rate (m/s or mm/rev) 'tool progression'

Force acting on a cutting tool during operation



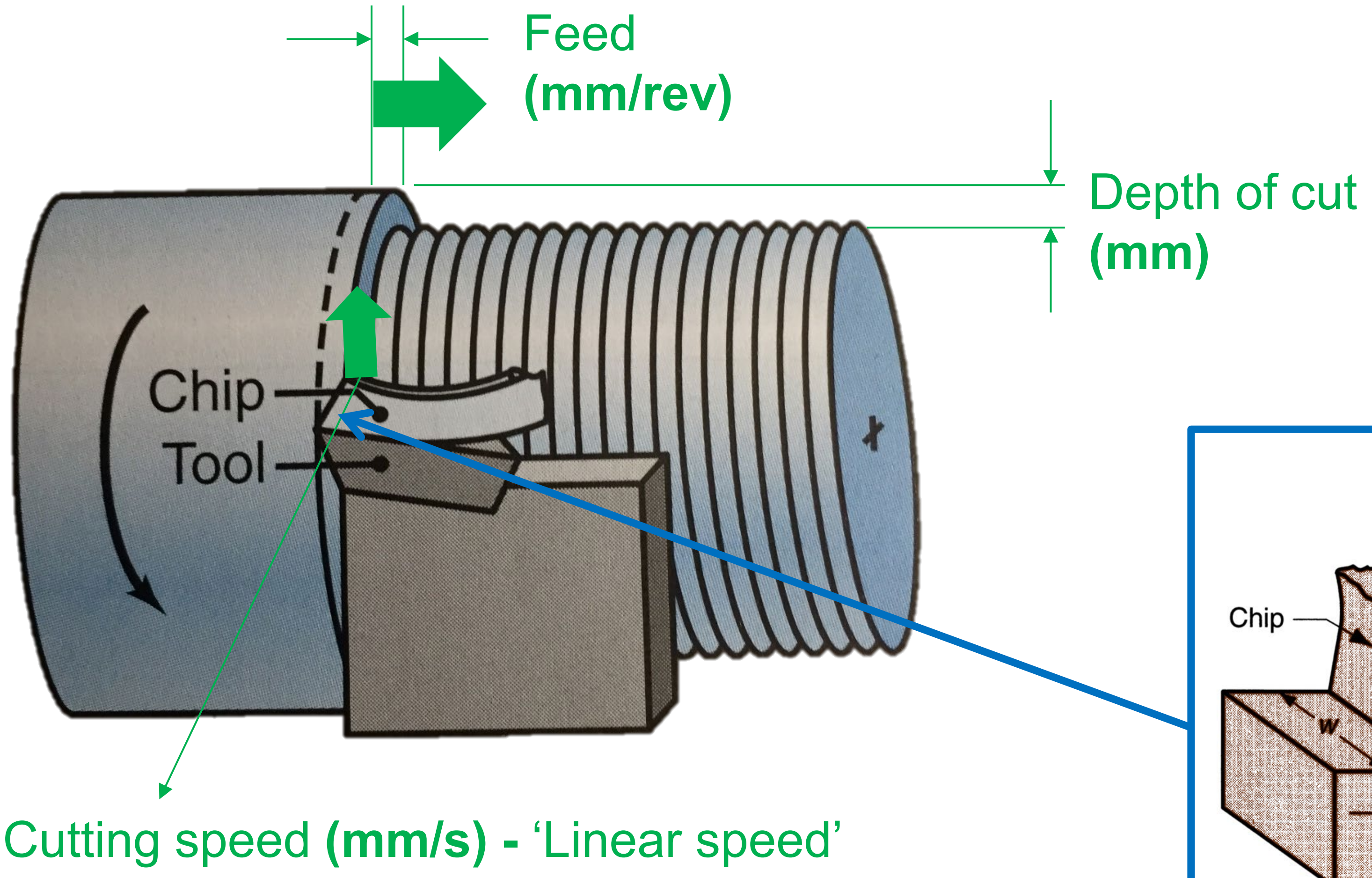
Key process control parameters:

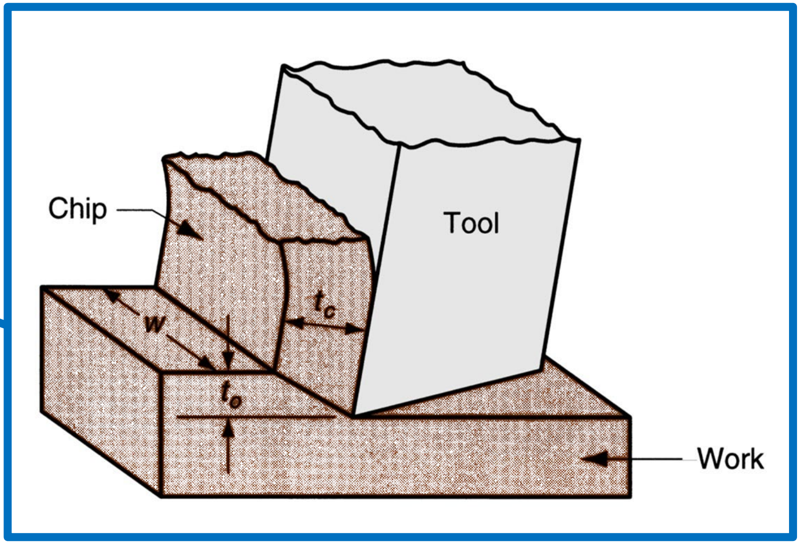
- ***Feed rate:*** *speed at which the tools move into the specimen*
- ***Spinning rate (N):*** *rotational speed of the tool*

Some general and tool design parameters influencing machining...

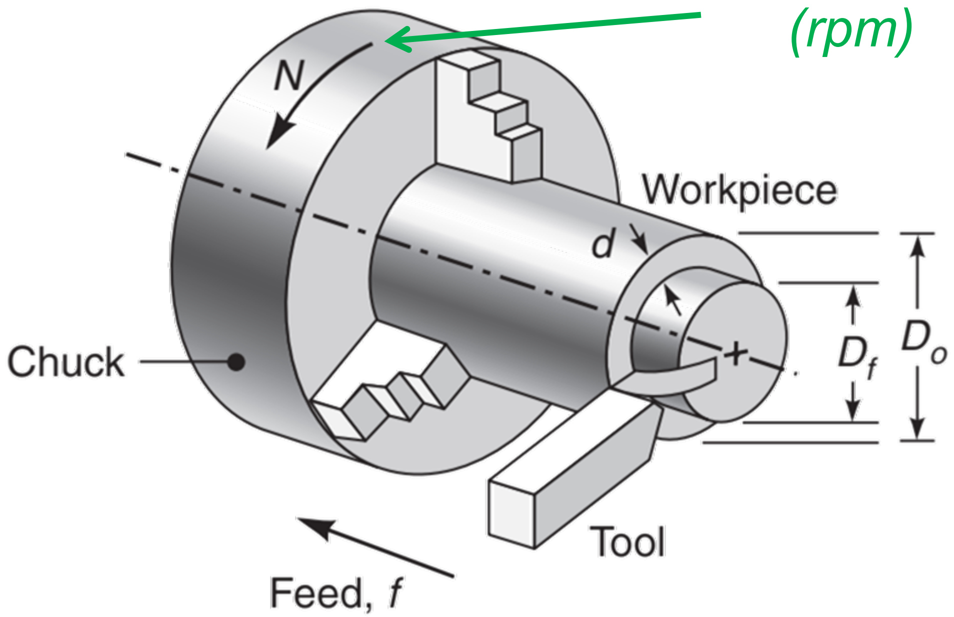
- **Cutting speed, depth of cut, feed, cutting fluids**
  - *Forces, power, temperature rise, tool life, type of chip, surface finish...*
- **Tool angles**
  - *Efficiency, tool resistance*
- **Continuous chip**
  - *Surface finish (but may be undesirable in automated machinery / use of 'chip cutter')*
- **Discontinuous chip**
  - *Fluctuating cutting force, poor surface finish / vibration...*
- **Too wear**
  - *Surface finish, temperature rise, accuracy*

Cutting terms





Material Removal Rate (MRR)



- Average removal rate per revolution:

Penetration thickness of the tool (mm) — *Feed rate mm/rev*

$$Mat_{/rev} = d\left[\pi\left(\frac{D_f + D_0}{2}\right)\right]f$$

Average circumference

- Material removal rate (turning operation)

$$MRR_{turning} = Mat_{/rev} \times N$$ and

Average tangential speed (mm/min) — *Spindle speed (rpm)*

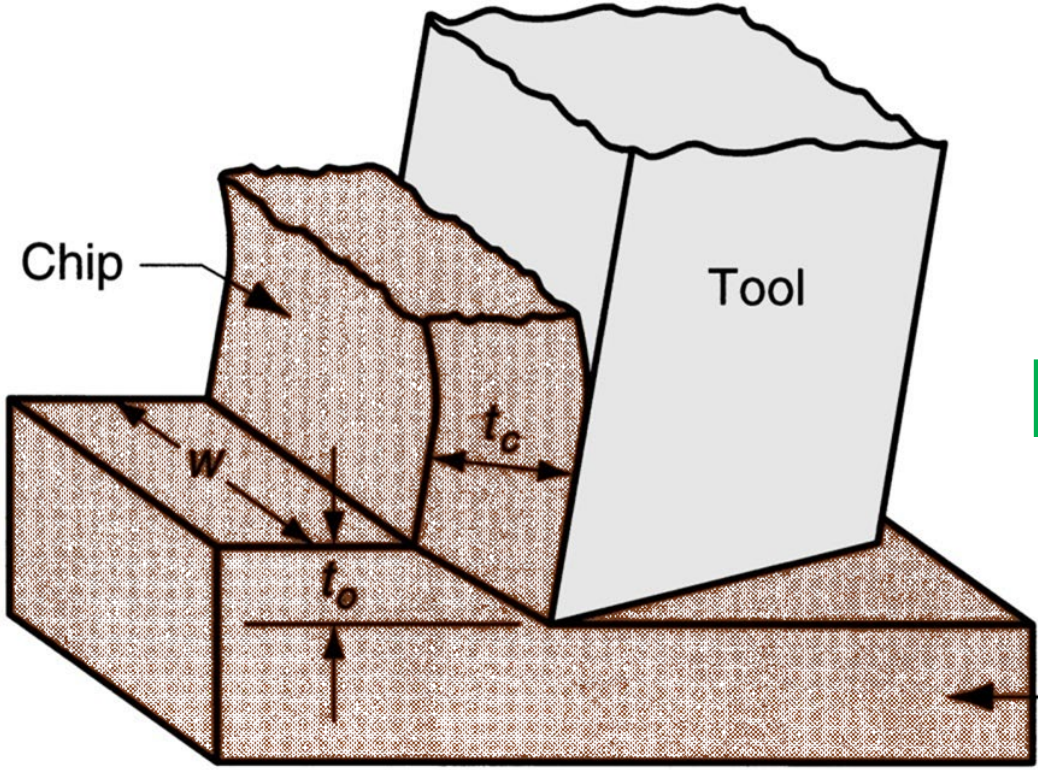
$$V_{cutting} = \pi\left(\frac{D_f + D_0}{2}\right)N$$

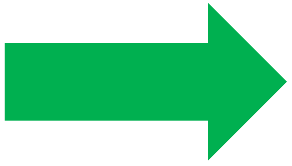
mm^3/min →

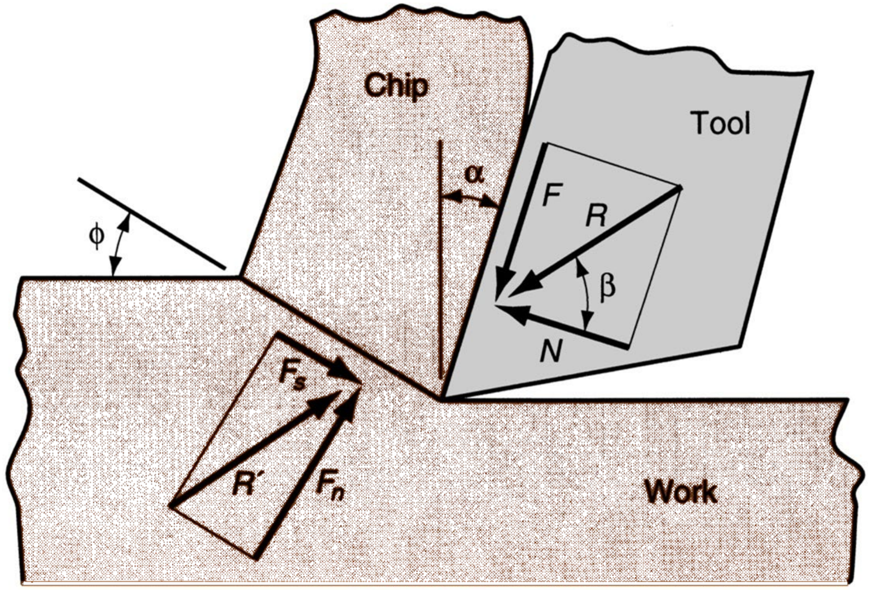
$$MRR_{turning} = f \times d \times V_{cutting}$$

Modelling... From 3D to 2D (model reduction)

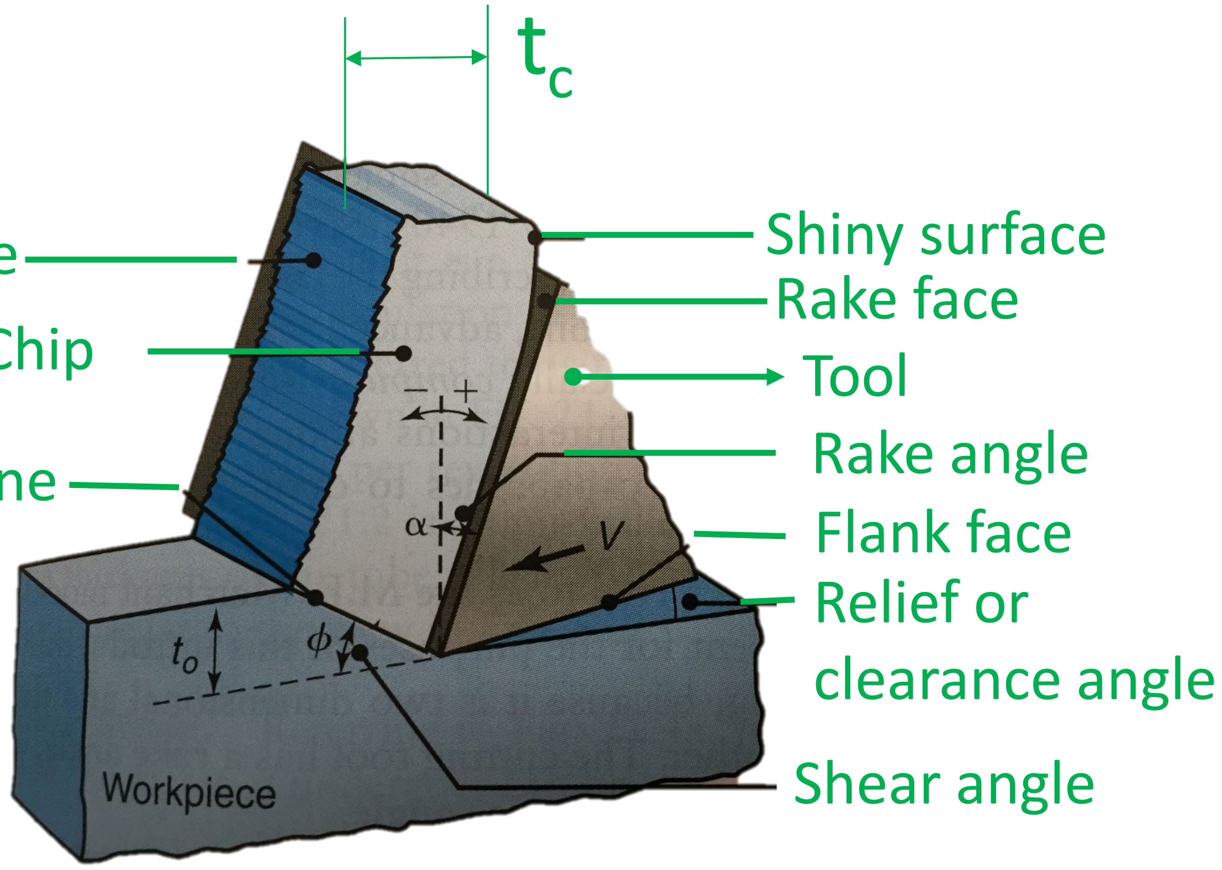
A simplified 2-D model of machining that describes the mechanics of machining with a fair accuracy.







Key parameters: chip thickness ratio

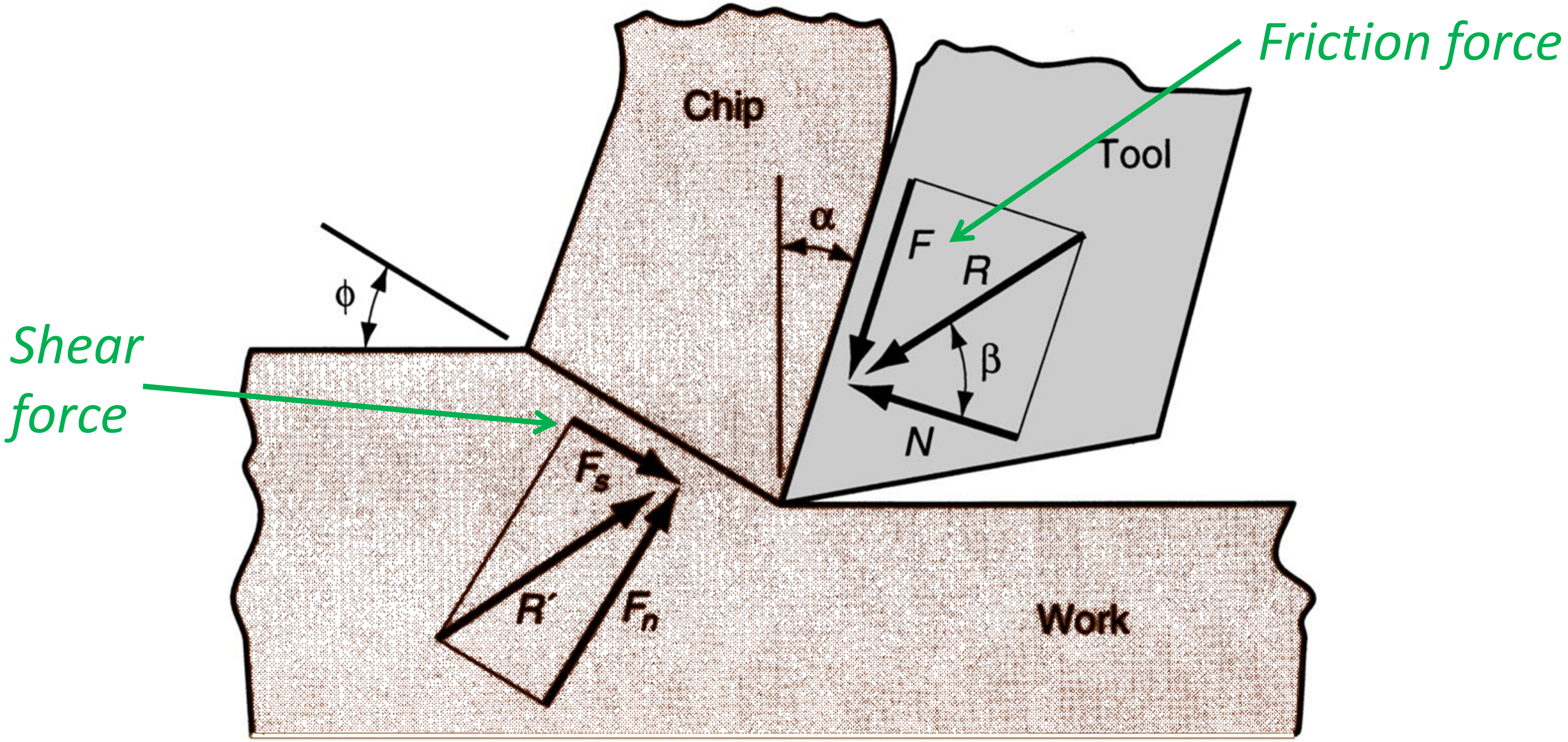


$$r = \frac{t_o}{t_c}$$

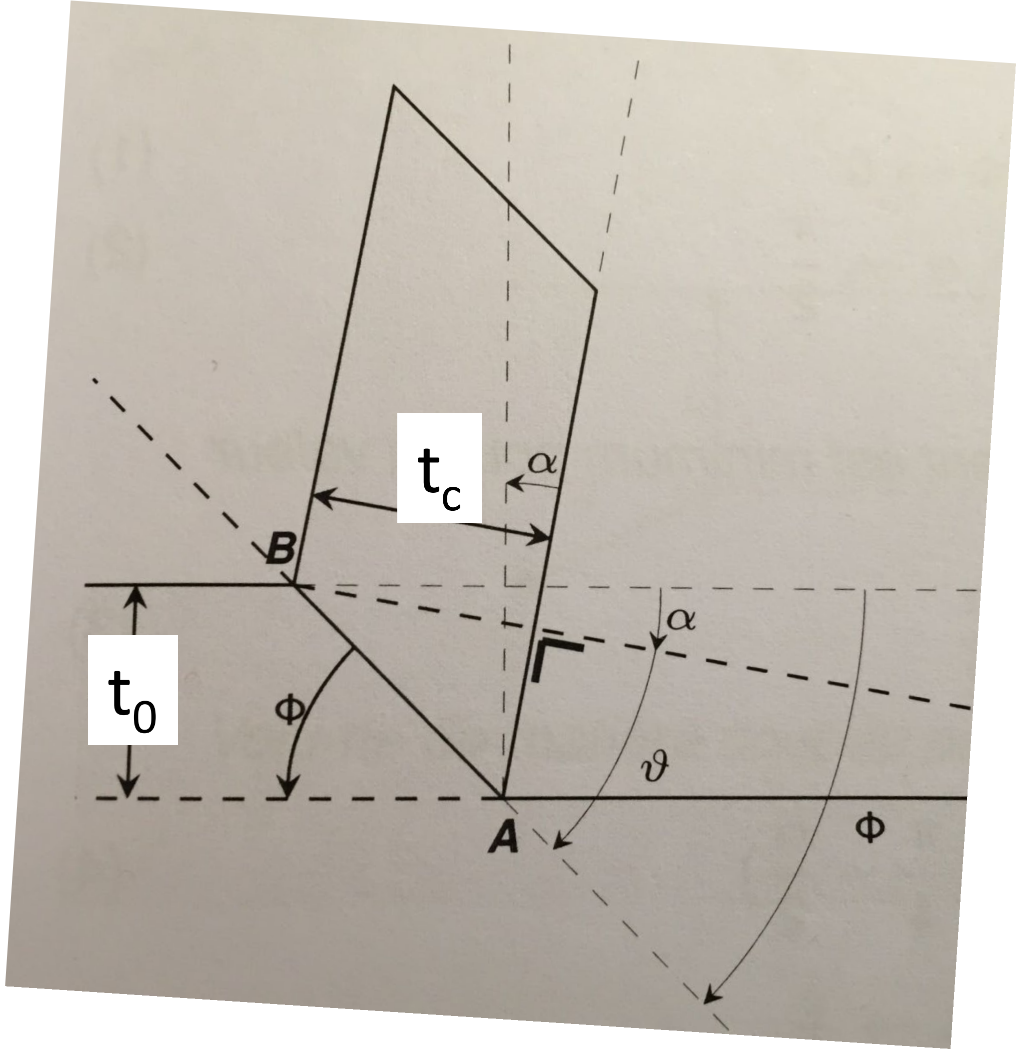
- Chip thickness after cut is always greater than before, r < 1.0

Forces acting during machining

- ***Friction force*** *F* and *Normal force to friction N*
- ***Shear force*** F_s and *Normal force to shear* F_n



Chip thickness ratio vs definition angles



(Dessin E. Boillat)

$$t_0 = \|\mathbf{AB}\| \sin\phi$$

$$t_c = \|\mathbf{AB}\| \cos\upsilon$$

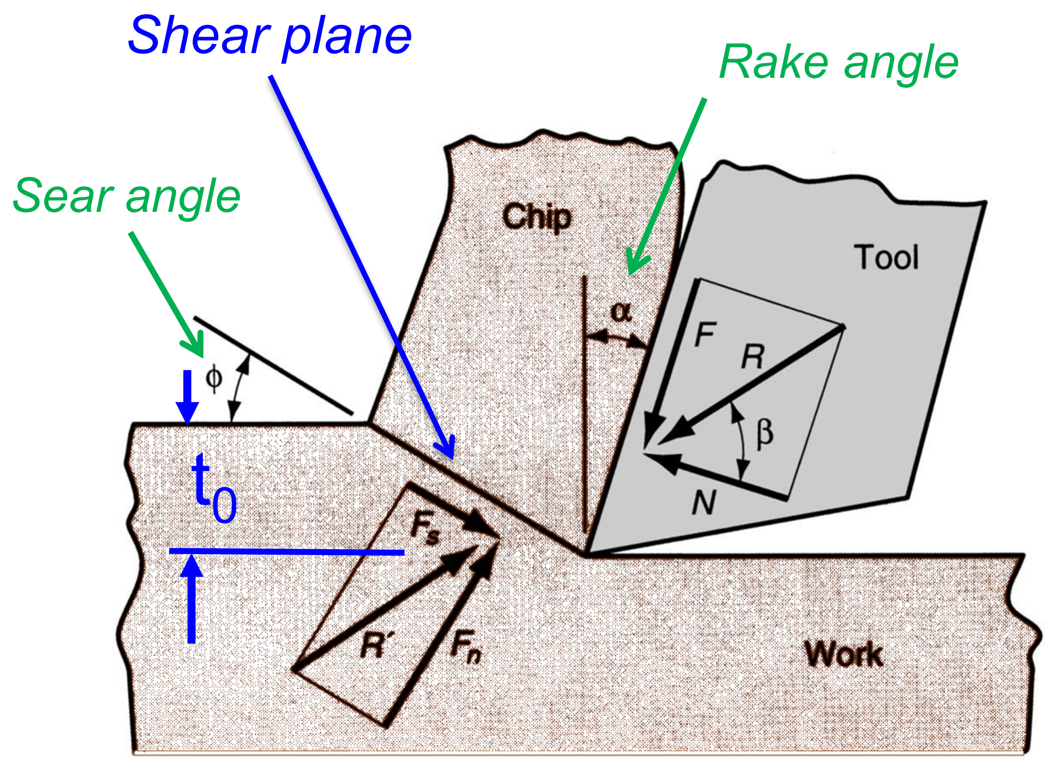
$$\frac{t_0}{t_c} = \frac{\sin\phi}{\cos\upsilon} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

Shear plane approximation

Shear stress acting along the shear plane: $\tau = \frac{F_s}{A_s}$

Shear force

Sheared surface



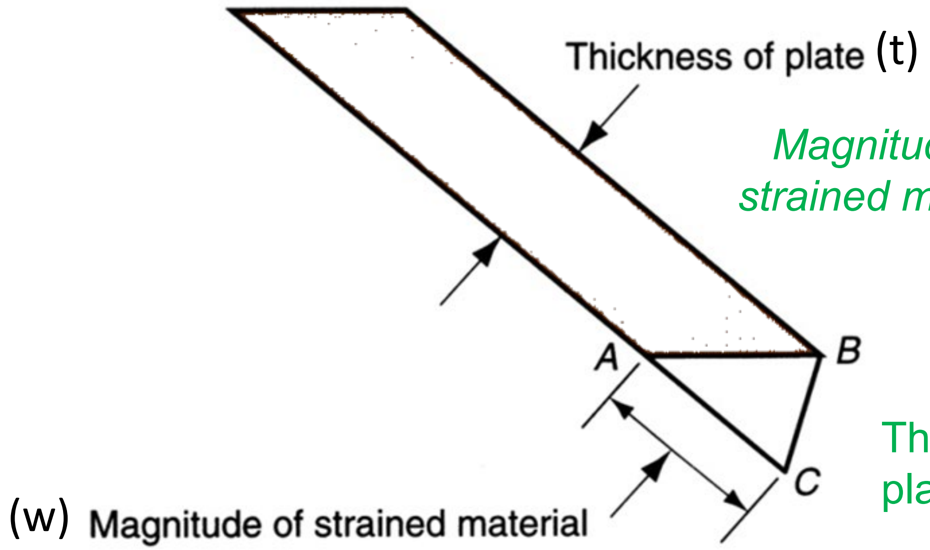
Cut depth

Tool width

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

$$\tau = \frac{F_s}{\left(\frac{t_0 w}{\sin\phi}\right)}$$

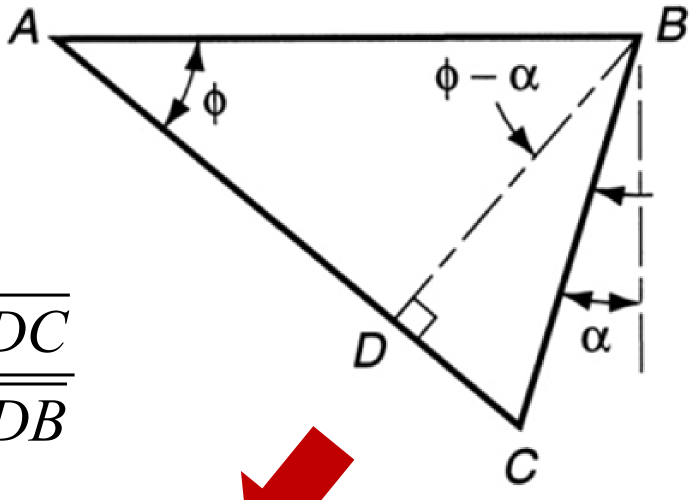
Pure shear strain model (approximation)



Magnitude of strained material

$$\gamma = \frac{w}{t} = \frac{\overline{AC}}{\overline{DB}} = \frac{\overline{AD}}{\overline{DB}} + \frac{\overline{DC}}{\overline{DB}}$$

Thickness of plate

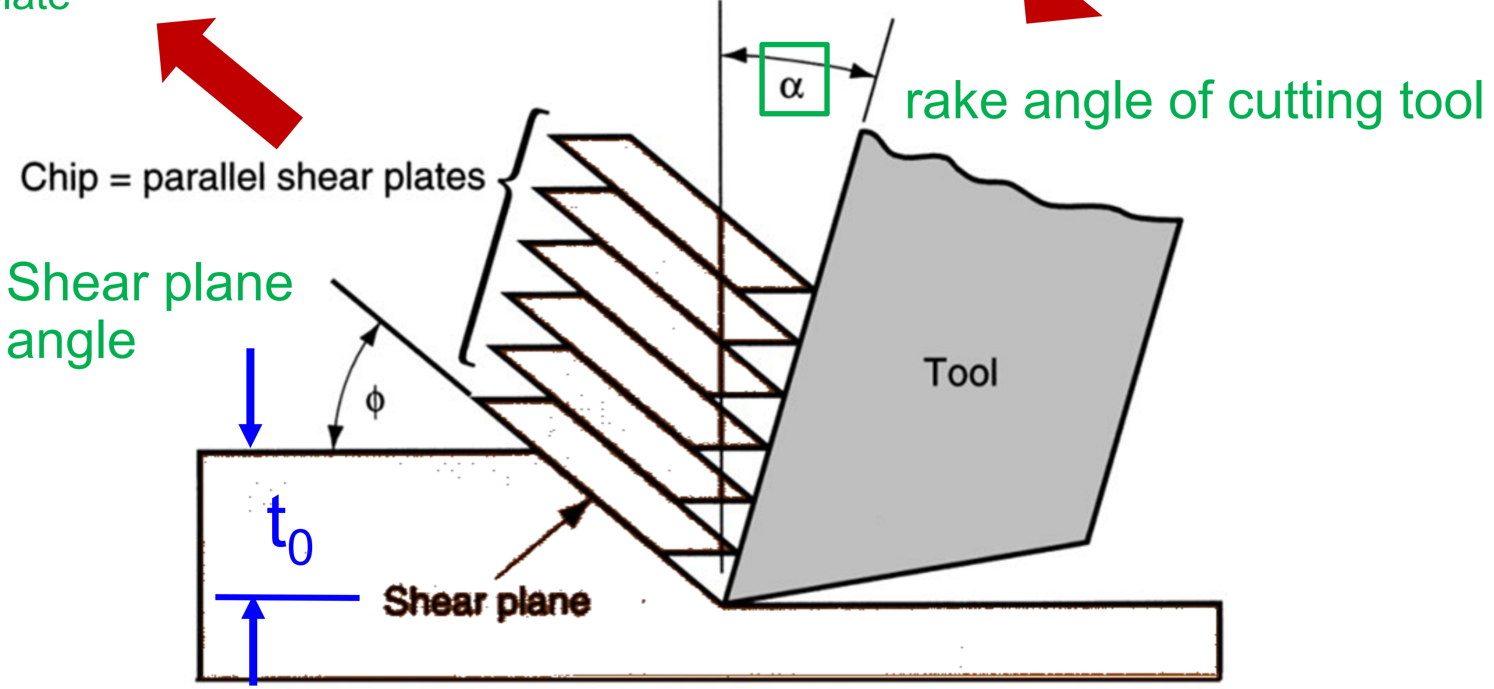


Shear strain

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

Shear plane angle

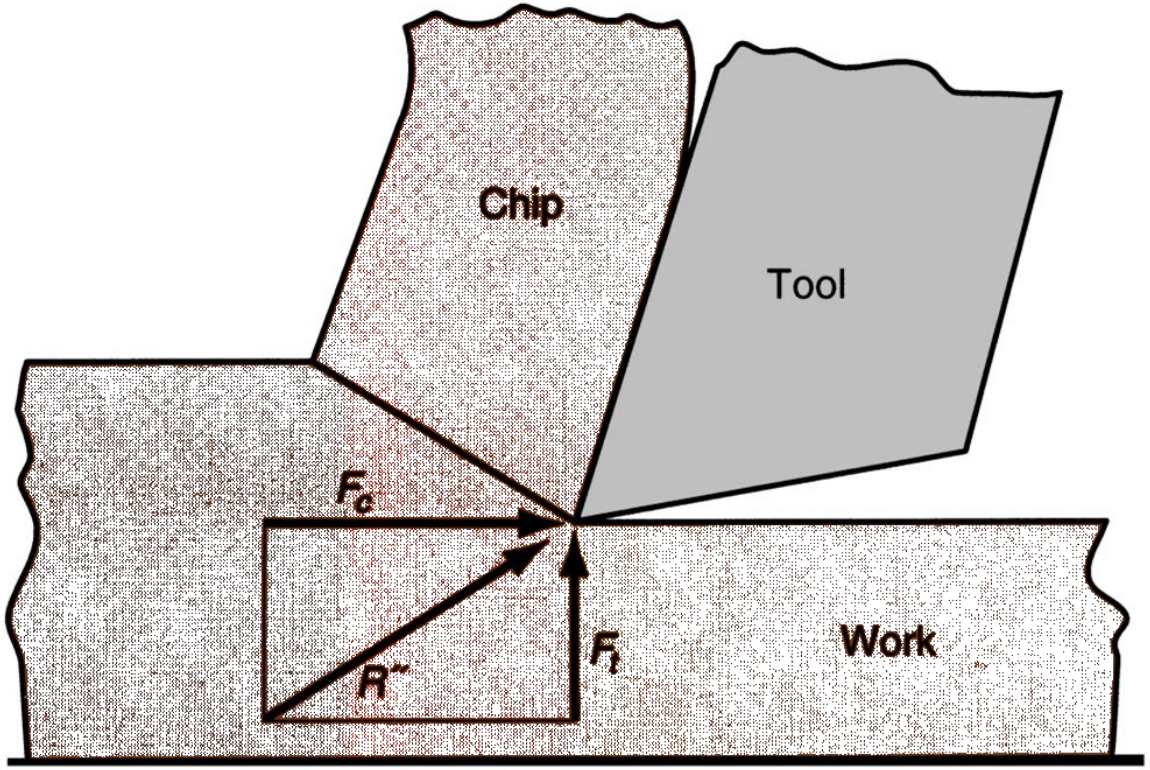
Rake angle (cutting tool)



ϕ = shear plane angle
α = rake angle of cutting tool

Measurable forces during machining

- Forces F, N, F_s, and F_n cannot be directly measured
- Forces acting on the tool that can be measured: *Cutting force* $\boldsymbol{F_c}$ and *Thrust force* $\boldsymbol{F_t}$



Forces in Metal Cutting derived from measureable forces

Normal to the tool → N | *Rake angle* → α

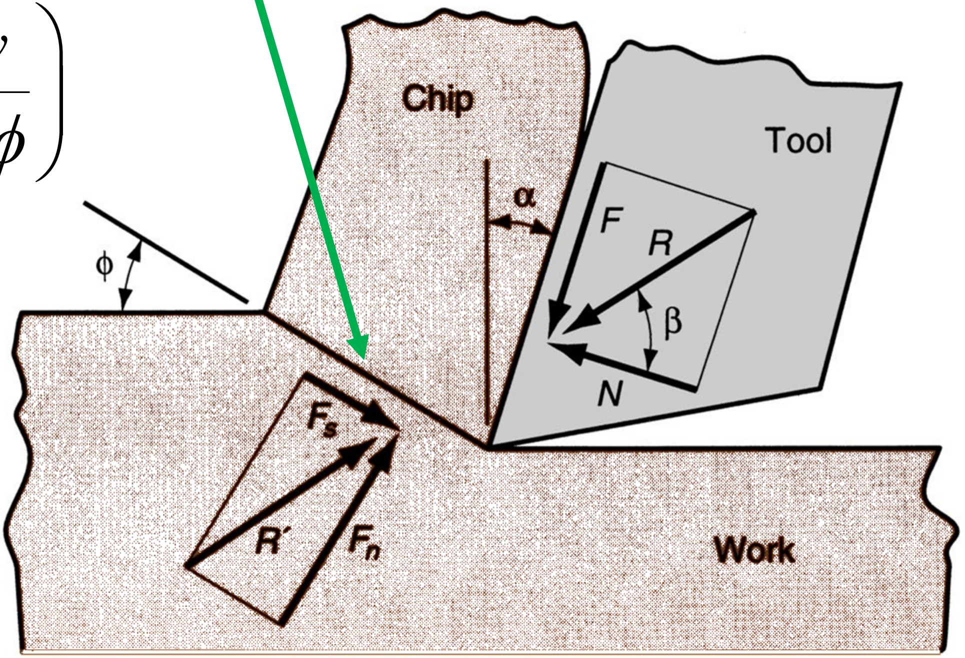
Friction force $\quad F = F_c \sin\alpha + F_t \cos\alpha \quad / \quad N = F_c \cos\alpha - F_t \sin\alpha$

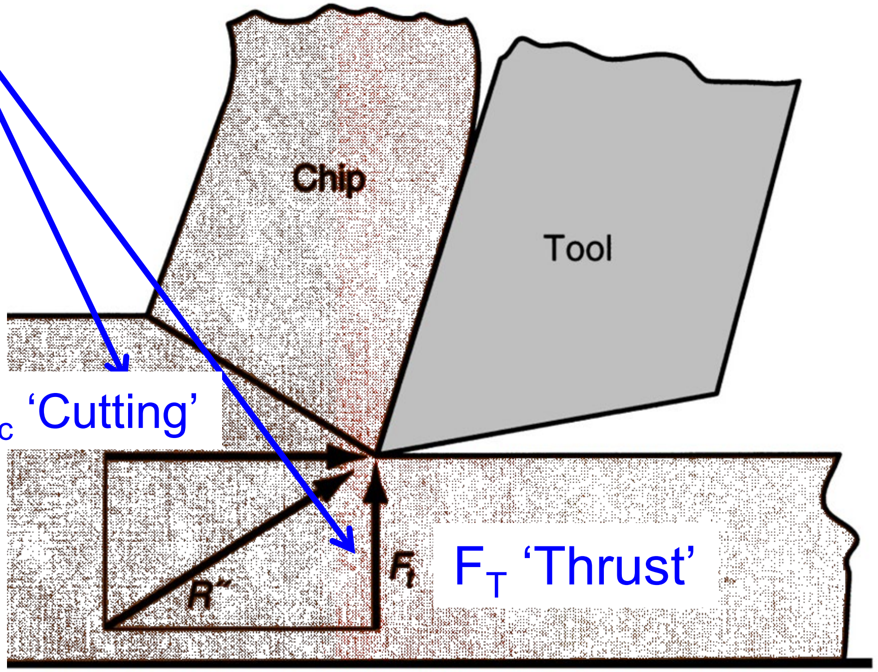
Shear force $\quad F_s = F_c \cos\phi - F_t \sin\phi \quad / \quad F_n = F_c \sin\phi + F_t \cos\phi$

Shear angle → ϕ | *Normal to the shear plane* → F_n

Are measurable ! → F_c, F_t

$$\tau = \frac{F_s}{\left(\frac{t_0 w}{\sin\phi}\right)}$$



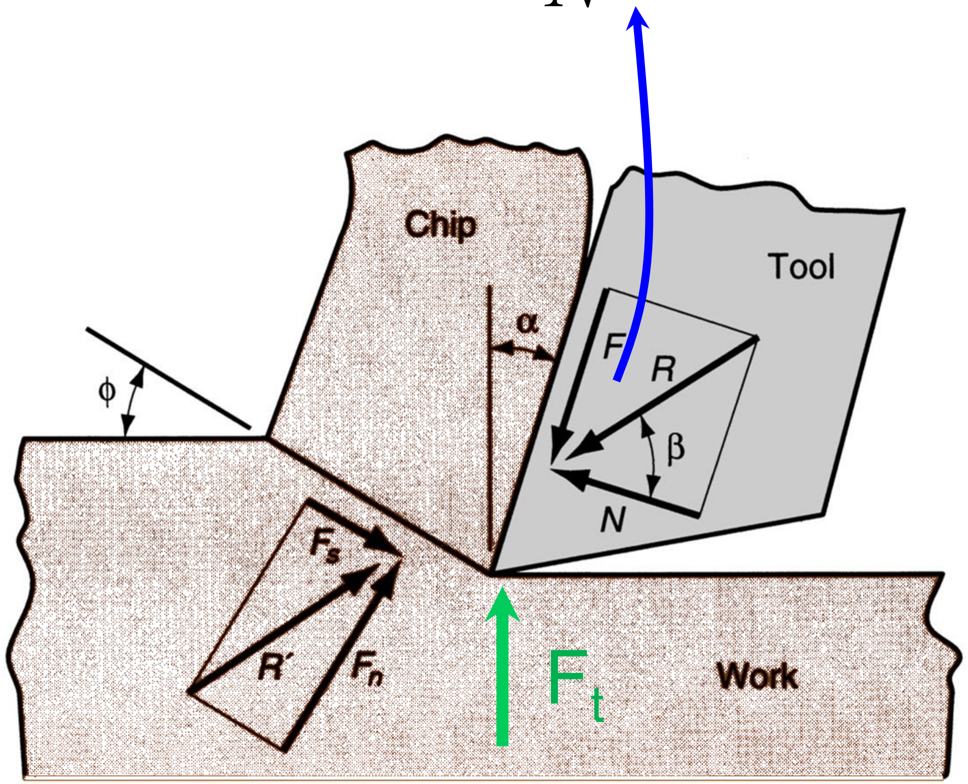


Expressing the Thrust (F_t) as a function of friction

Coefficient of friction between tool and chip:

$$\mu = \frac{F}{N}$$ with $$\mu = \tan\beta$$ $$(\beta = \arctan\mu)$$

'Friction angle'



We have: $$F_t = \|\mathbf{R}\|\cos(\alpha-\beta)$$

Exists if $$F_t > 0 \Leftrightarrow (\alpha-\beta) < \frac{\pi}{2}$$

F_s and F_t as a function of shear strength only…

$$F_s = \tau A_s$$

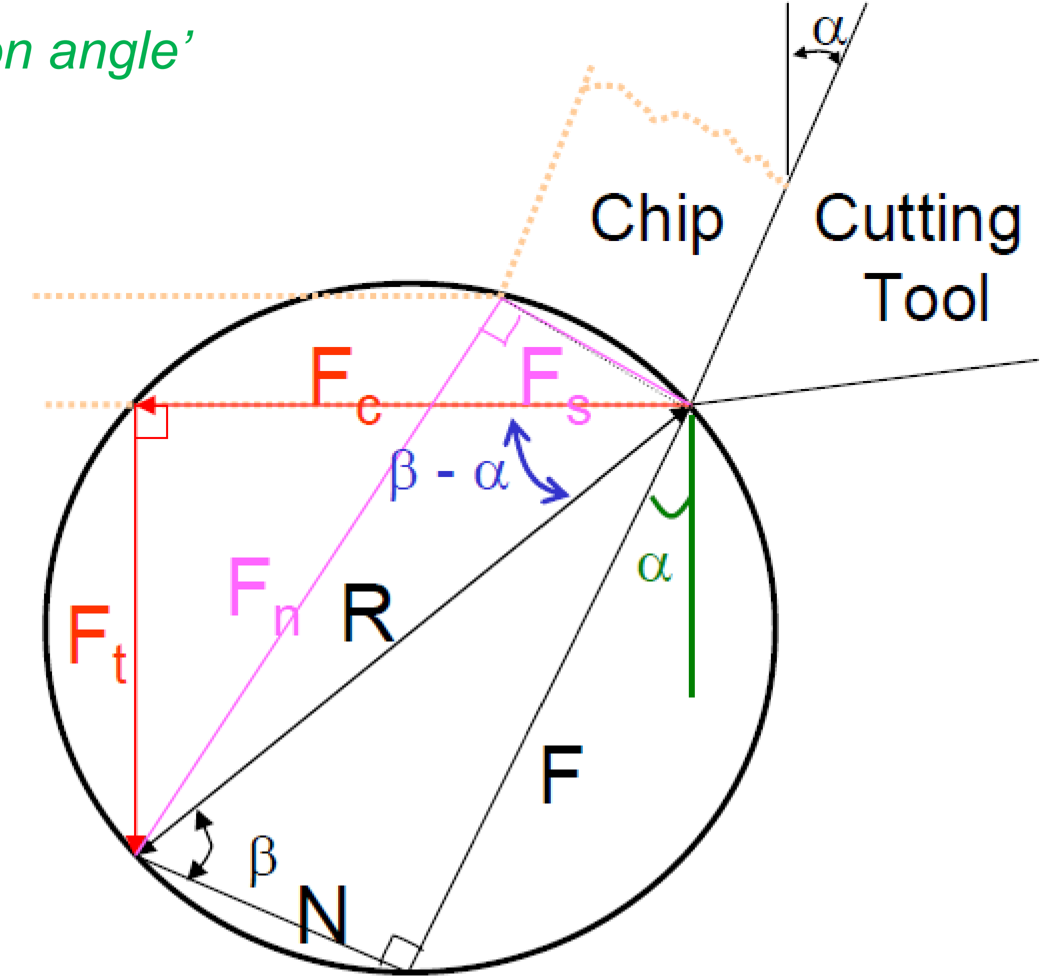
$$F_c = F_s \cos(\beta - \alpha)/[\cos(\phi + \beta - \alpha)]$$

$$F_t = F_s \sin(\beta - \alpha)/[\cos(\phi + \beta - \alpha)]$$

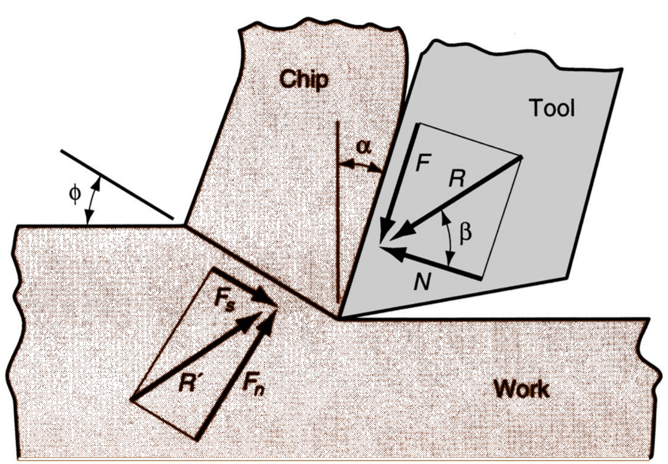
'Friction angle'

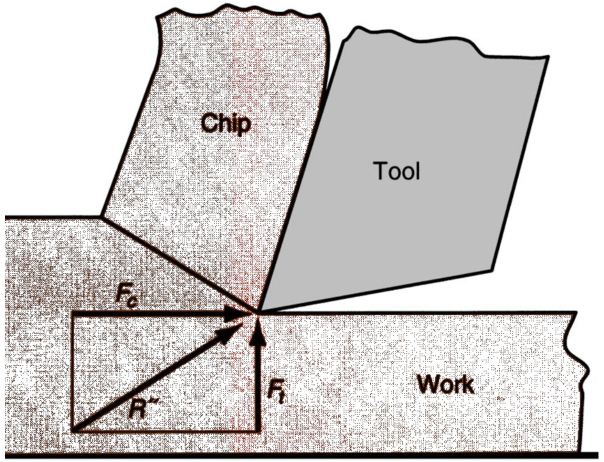
'Shear angle'

'Rake angle'



We use the equations from slide 36, and express F_c and F_t only as a function of the shear force and the shear strength and the friction angle. It is essentially a geometrical problem that can be solve by reporting all the forces on the same diagram (left).





The Merchant condition

Merchant Equation:
(combining slide 33
and slide 36)

$$\tau = \frac{F_c \cos\phi - F_t \sin\phi}{\left(\frac{t_0 w}{\sin\phi}\right)}$$

- Minimizing shear stress
- Using F_c and F_t as a function of the shear strength (previous slide)
- The shear plane angle ϕ minimizes the energy when:

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

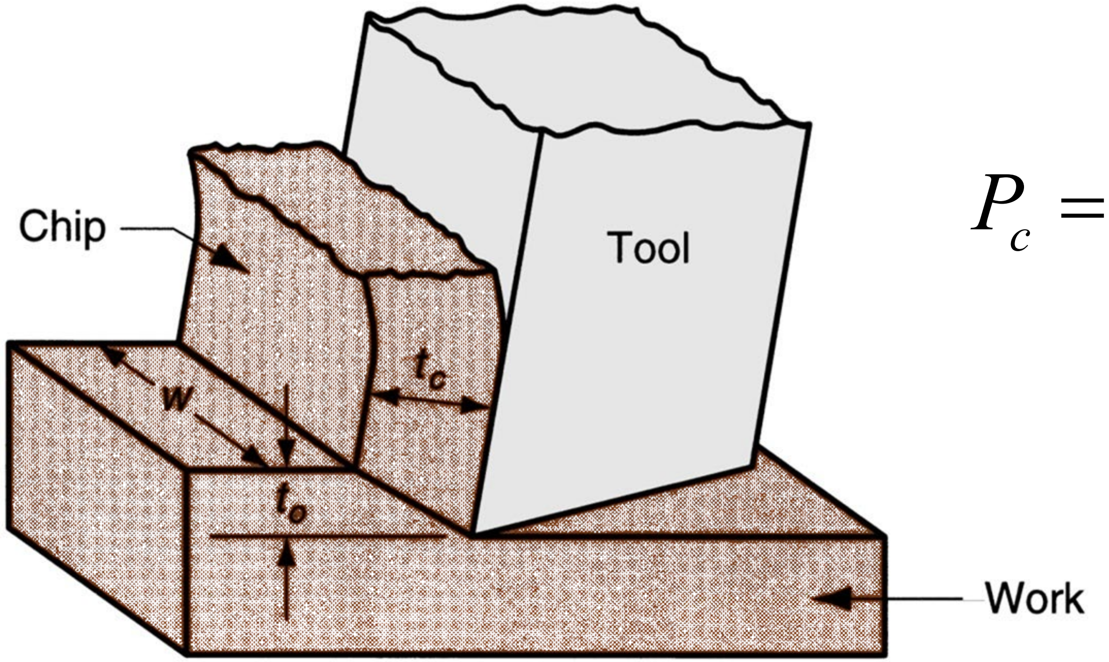
→ β= arctg (μ)

- *Hypothesis: **'The shear angle adjusts itself to minimize the cutting force' ⇔ 'The shear plane is a plane of maximum shear stress'***

Conclusion: Knowing the friction coefficient, one can apply the optimal rake angle (α)

Energy considerations

- Power of a force: P = F v (unit W)
- Here, the power to perform machining is: $P_c = F_c\, v$



$$P_c = vF_c = 2\tau\left[\frac{\cos(\alpha-\beta)}{1+\sin(\alpha-\beta)}\right](t_0 w)v$$

(for Merchant's conditions)

Specific cutting energy

- We define the cutting rate as:

$$\dot{V}_c = v(t_0 w)$$

Cutting rate [mm³/s] — $\dot{V}_c$

Chip section — $t_0 w$

Feed rate — v

in (mm³/s)

$$\mu = \tan\beta$$

$$(\beta = \arctan\mu)$$

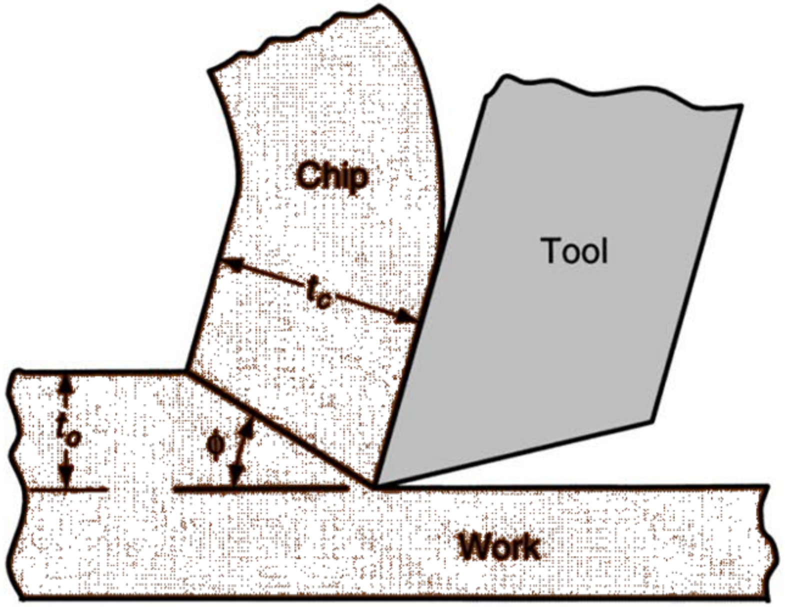
$$P_c = vF_c = 2\tau\left[\frac{\cos(\alpha-\beta)}{1+\sin(\alpha-\beta)}\right]\dot{V}_c$$

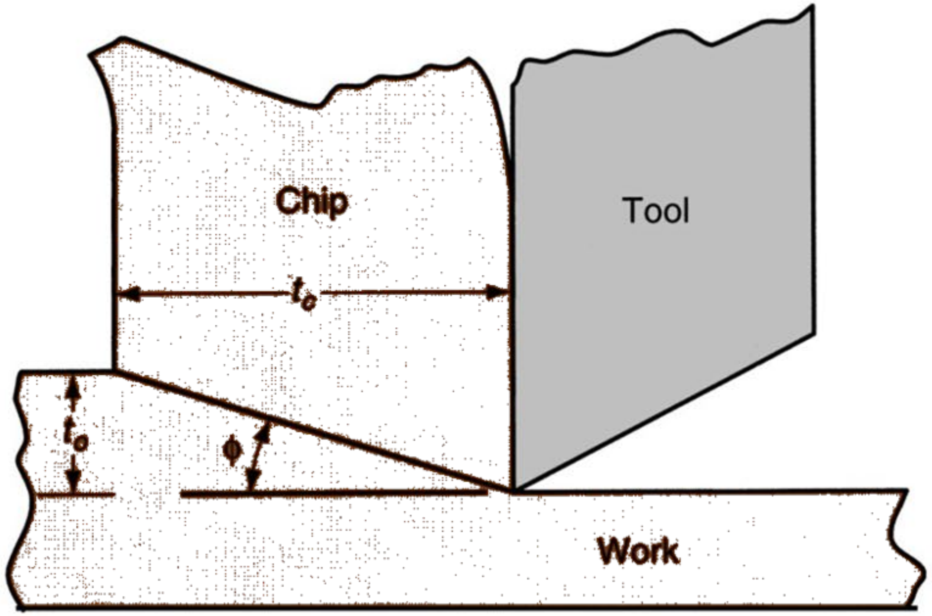
Specific cutting energy (e_c) [J/mm³] — $2\tau\left[\frac{\cos(\alpha-\beta)}{1+\sin(\alpha-\beta)}\right]$

Cutting rate [mm³/s] — $\dot{V}_c$

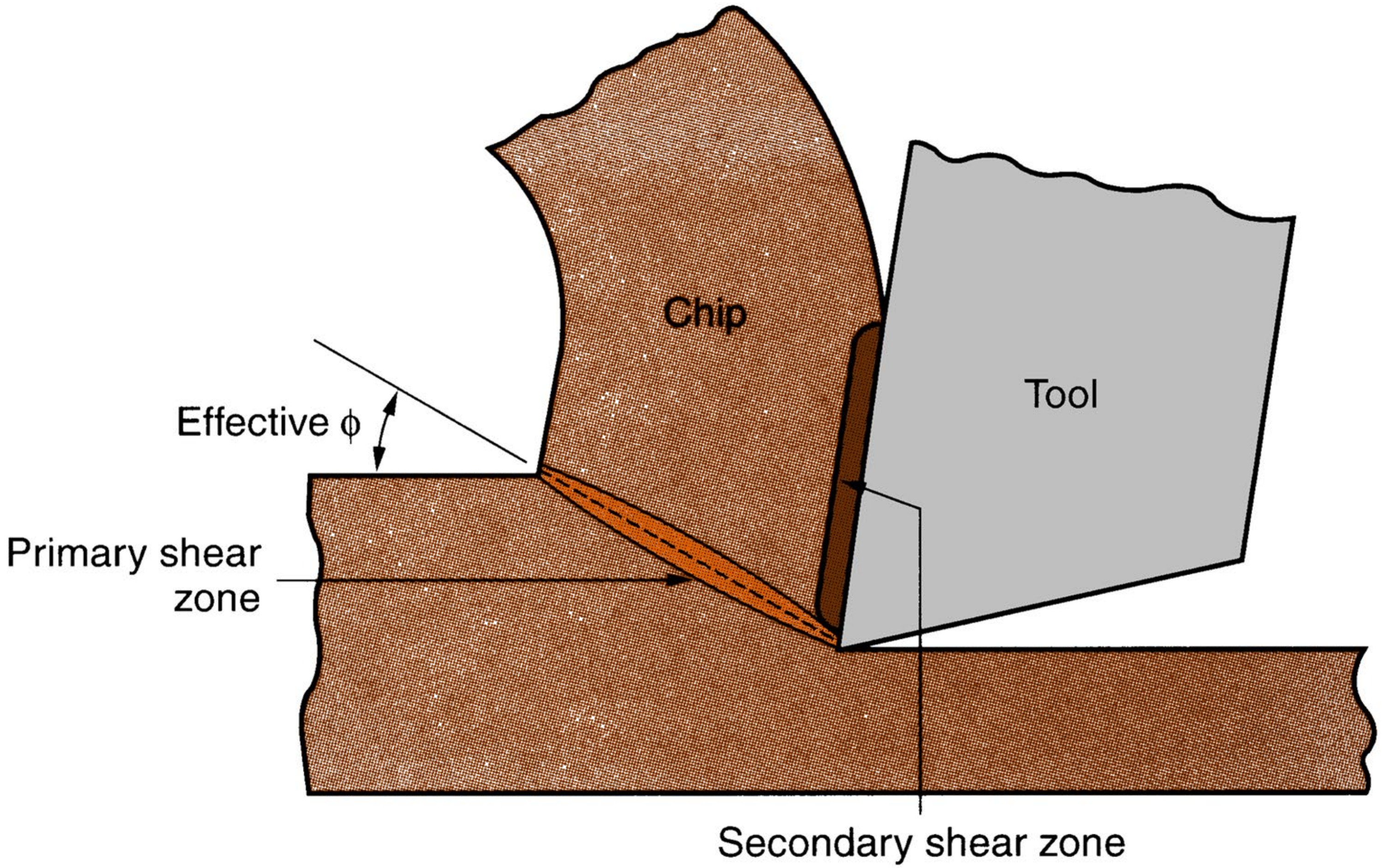
Discussion / existence of an **optimal** tool-cutting angle

- Increase in friction angle ⇔ decreases of shear angle
- Higher shear plane angle ⇔ smaller shear plane ⇔ lower shear force
- Consequences: lower cutting forces, power, temperature, ... => easier machining, but tool angle needs to satisfy the Merchant condition



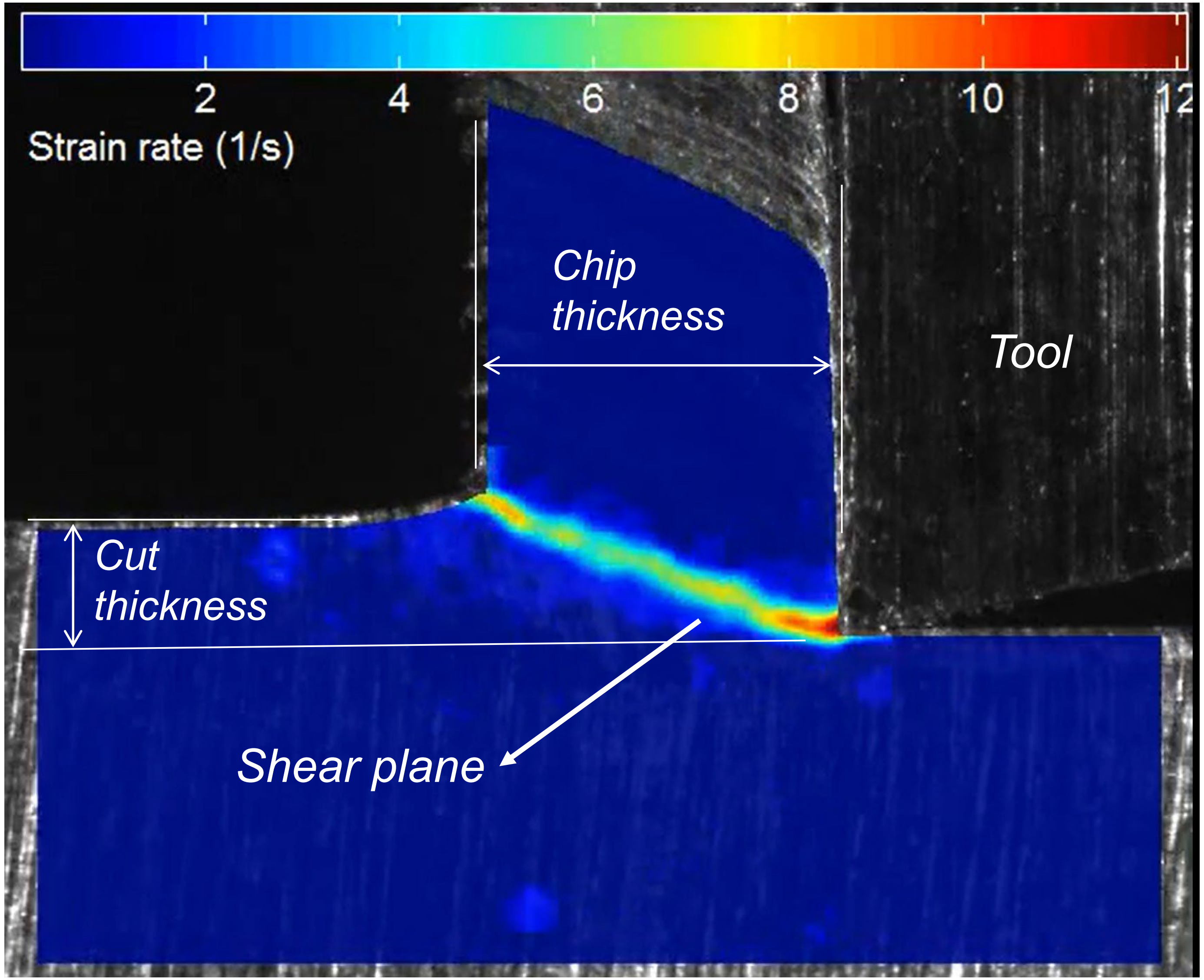


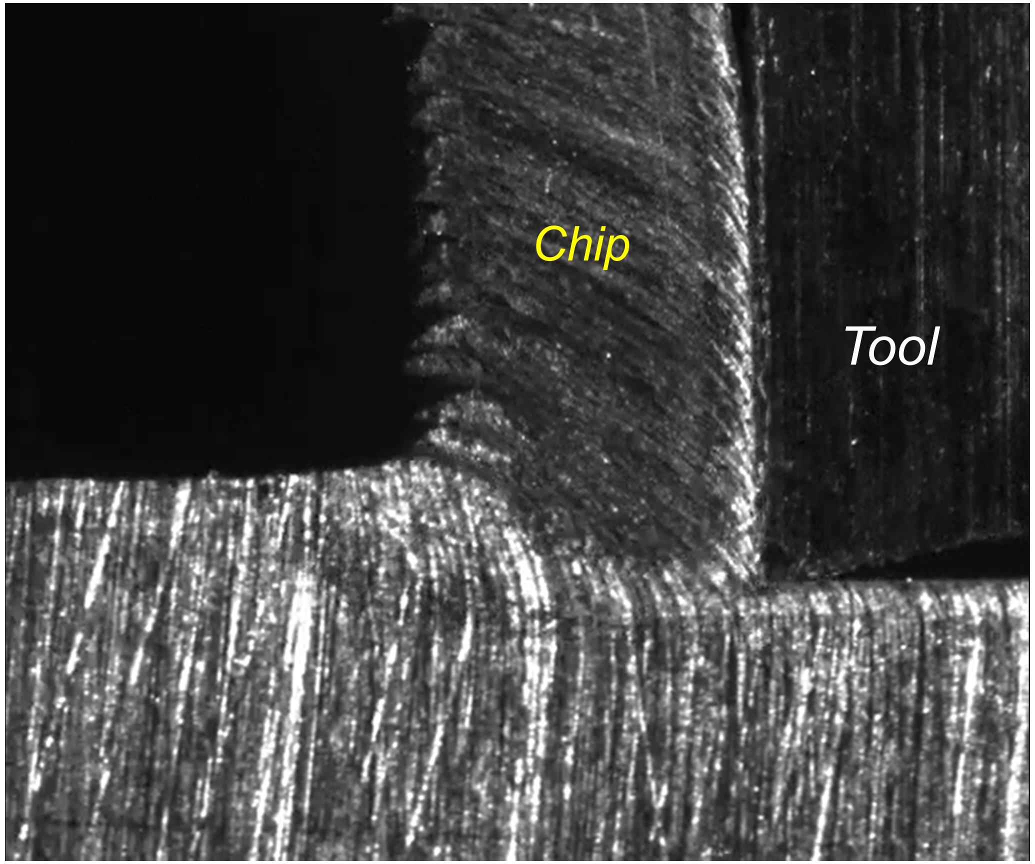
A more realistic description...



Presence of a secondary shear zone

Continuous chip formation (real case illustration)





https://youtu.be/xmOyaYEWbT4?si=k2xh0T6BpCO05E3L

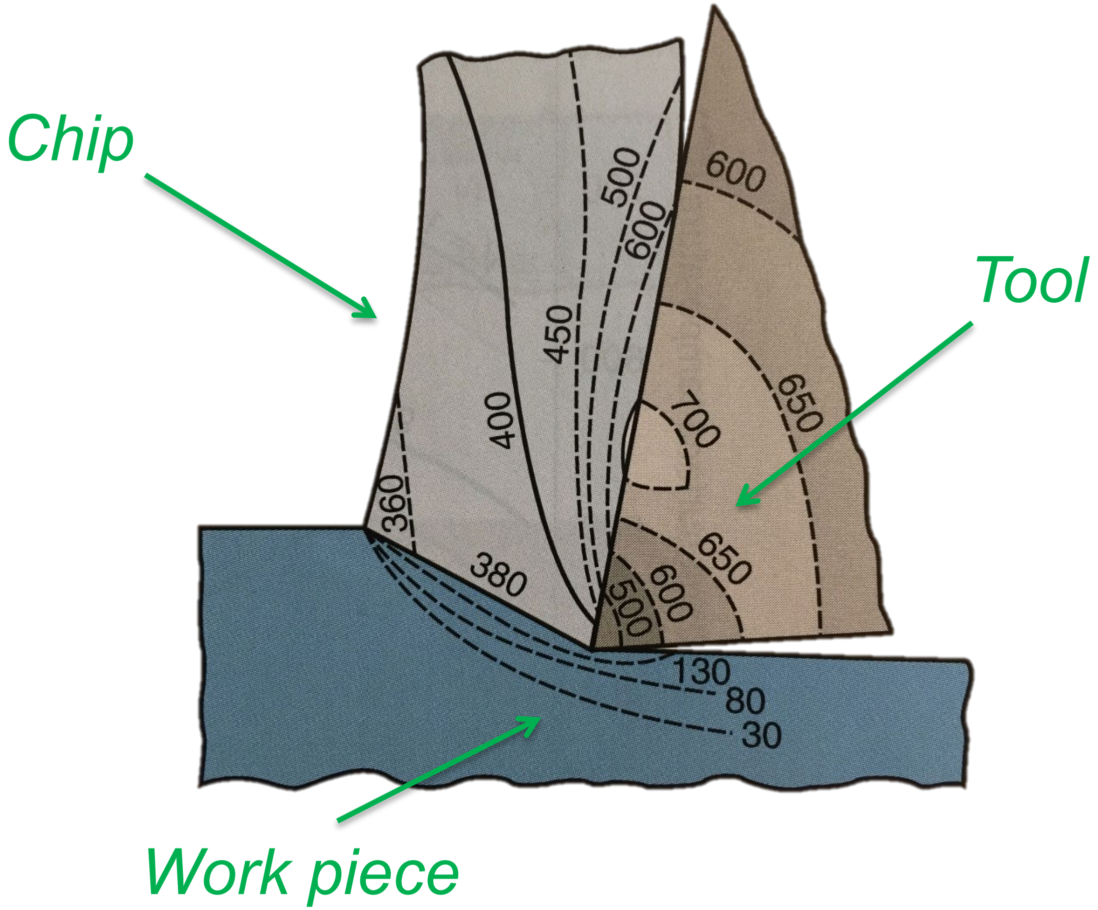
Specific cutting energy: typical order of magnitude

Material	Specific energy*	
	W-s/mm^3	hp-min/in^3
Aluminum alloys	0.4–1.1	0.15–0.4
Cast irons	1.6–5.5	0.6–2.0
Copper alloys	1.4–3.3	0.5–1.2
High-temperature alloys	3.3–8.5	1.2–3.1
Magnesium alloys	0.4–0.6	0.15–0.2
Nickel alloys	4.9–6.8	1.8–2.5
Refractory alloys	3.8–9.6	1.1–3.5
Stainless steels	3.0–5.2	1.1–1.9
Steels	2.7–9.3	1.0–3.4
Titanium alloys	3.0–4.1	1.1–1.5

*At drive motor, corrected for 80% efficiency; multiply the energy by 1.25 for dull tools.

Temperature / Heat transfer

- About **98%** of the energy in machining is converted into heat...
- Most of the energy goes in the tool and in the chip
- Temperatures can be very high at the tool-chip
- The remaining energy (about **2%**) is retained as elastic energy in the chip
- **Consequences:** requires coolant during operation ...



Cutting Temperature

- Experimental methods can be used to measure temperatures in machining (tool-chip thermocouples, IR camera, etc.)
- K. Trigger's empirical law: determined the speed-temperature relationship to be of the form:

$$T = Kv^m$$

Empirical factor (m)

Temperature

Cutting speed

Thermal conductivity of the work material

Cutting Temperature: other models...

- Several analytical methods to calculate cutting temperature
- Example. N. Cook derived from dimensional analysis using experimental data for various work materials

$$T = 0.4\left(\frac{e_c}{\rho C_p}\right)\left(\frac{v t_o}{K}\right)^{1/3}$$

Cutting speed

Cutting thickness

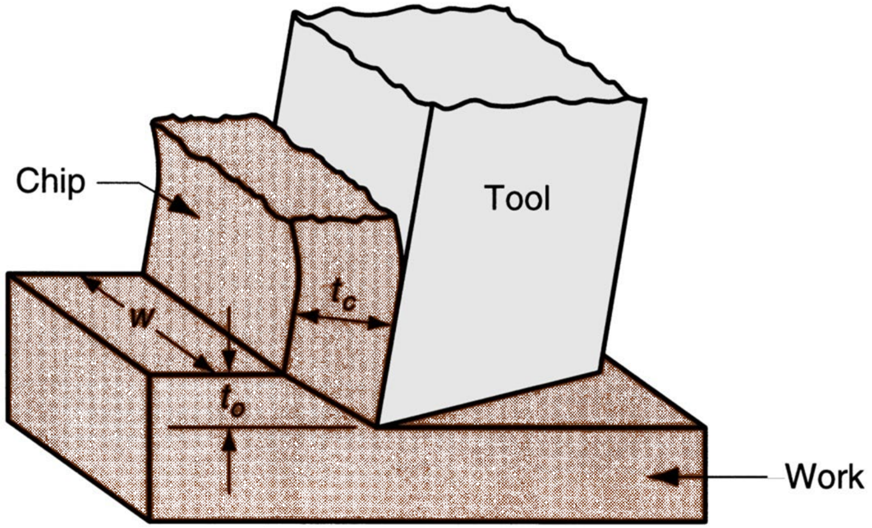
Thermal conductivity of the material

Calorific capacity

Material density

$$e_c = 2\tau\left[\frac{\cos(\alpha - \beta)}{1 + \sin(\alpha - \beta)}\right]$$

Cutting tools wear: empirical model (Taylor)



Material	n
High-speed steels	0.08 – 0.2
Carbides	0.2 – 0.5
Ceramics	0.5 – 0.7

$$LT = \left(\frac{C}{w^x t_0^{\,y} v} \right)^{\frac{1}{n}}$$

Constant

Life time (LT)

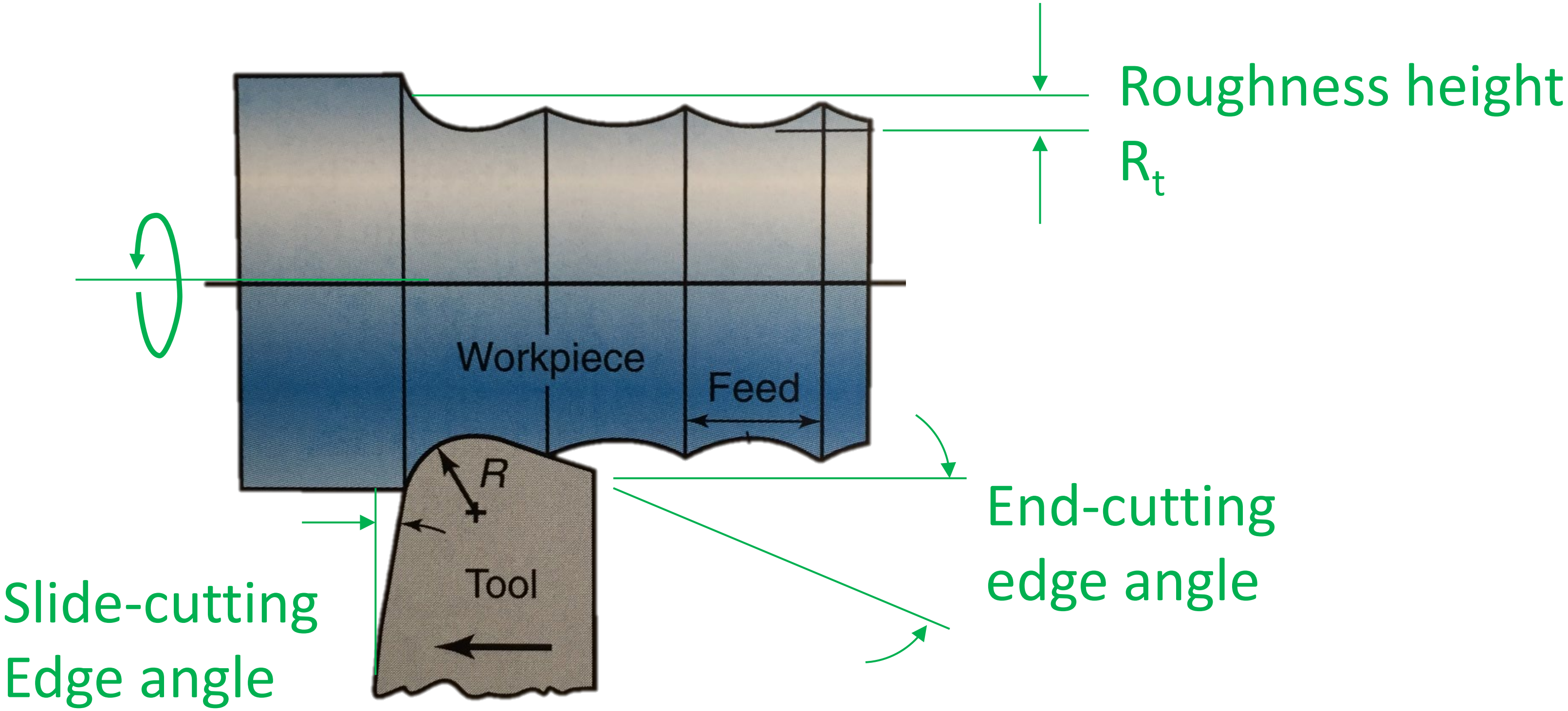
Tool width

Penetration depth

Cutting speed

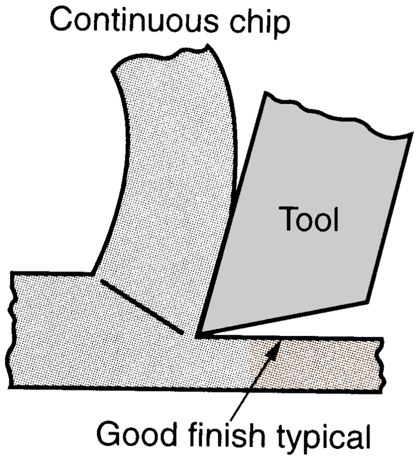
n, x, y : experimental parameters

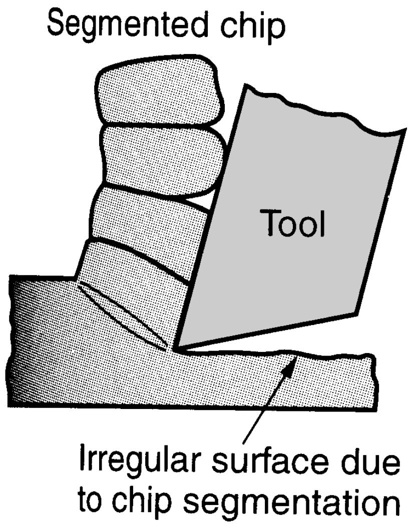
Effect of tool wear on surface finish…

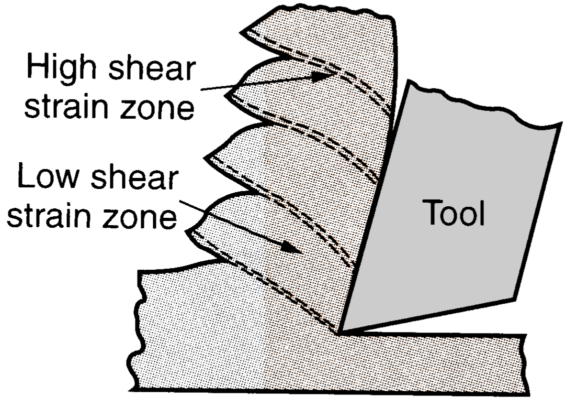


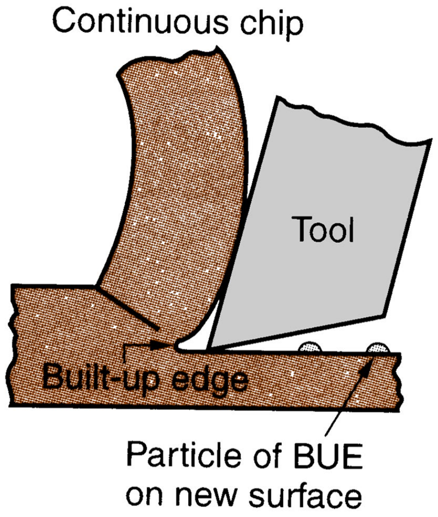
The produced chip tells about machining parameters...

1. Continuous chip
2. Segmented chip
3. Continuous chip with Built-up Edge (BUE)
4. Saw-tooth appearance





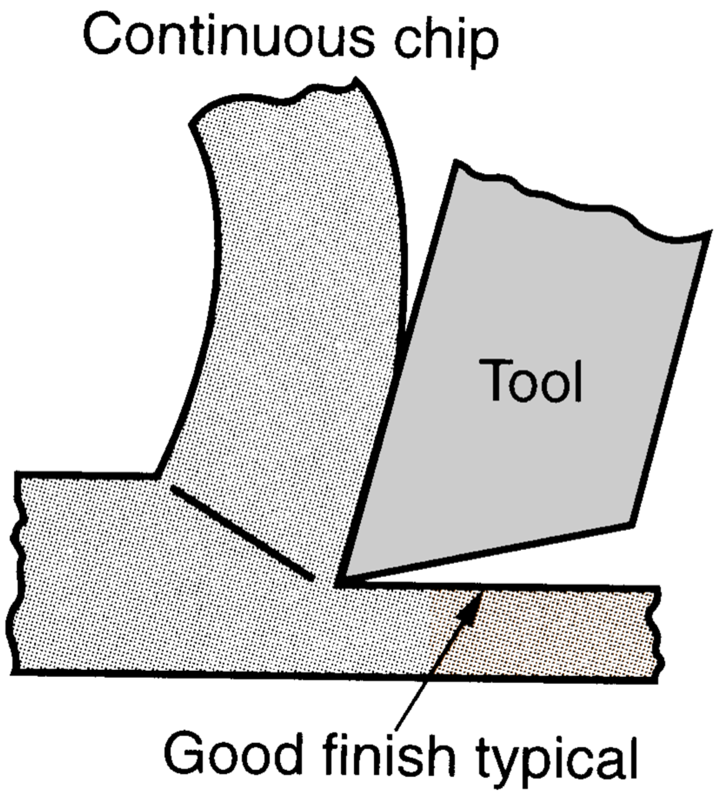




Check illustrative videos on the Moodle!

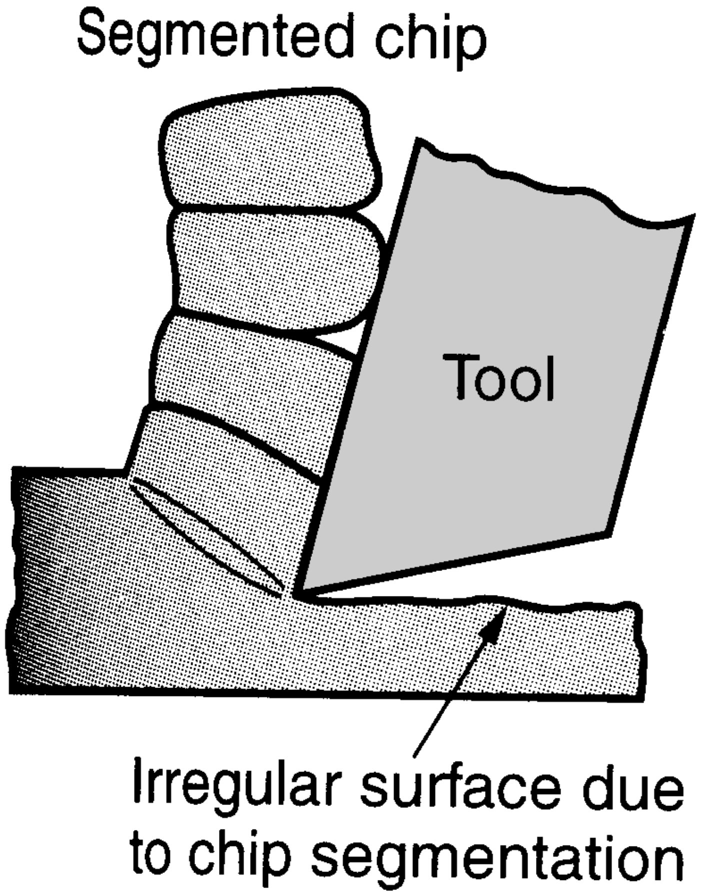
Ideal case: continuous chip formation

- **Ductile work materials** (e.g., low carbon steel)
- High cutting speeds
- Small feeds and depths
- Sharp cutting edge on the tool
- Low tool-chip friction



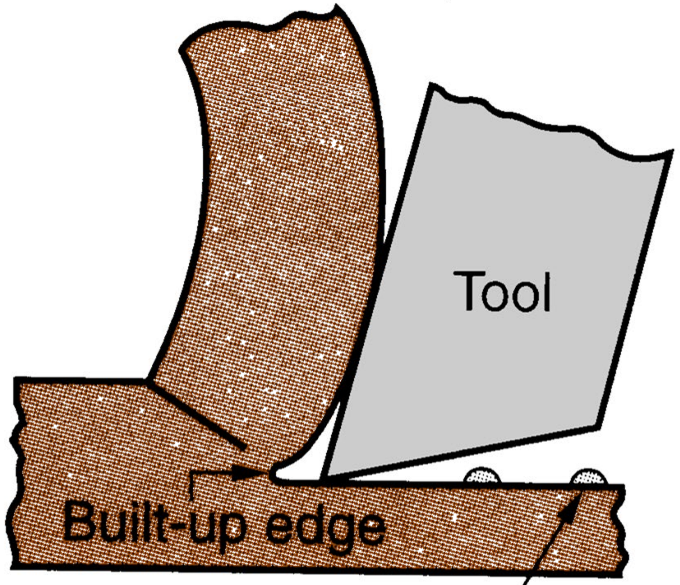
Segmented chip...

- **Brittle work materials** (e.g., cast irons)
- Low cutting speeds
- Large feed and depth of cut
- High tool-chip friction



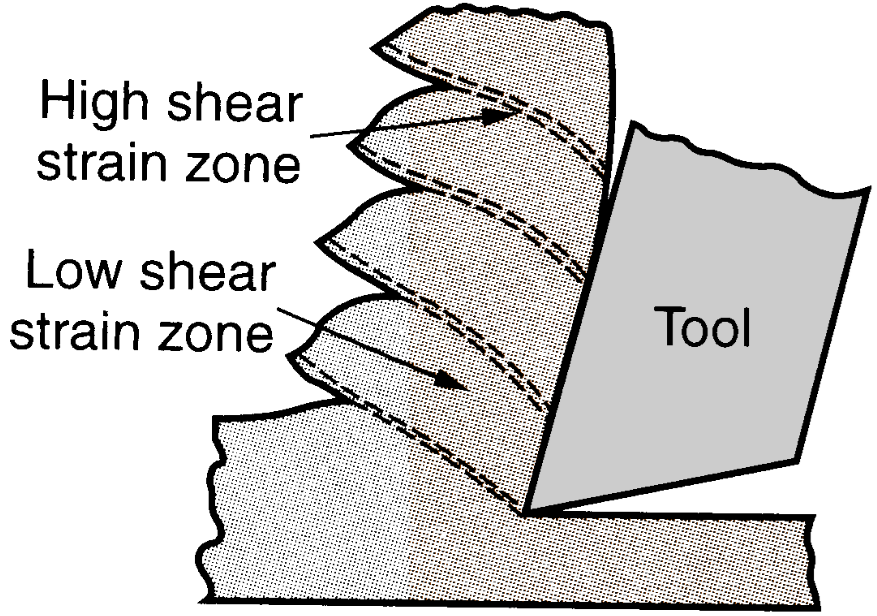
Continuous chip with built-up edge (BUE)

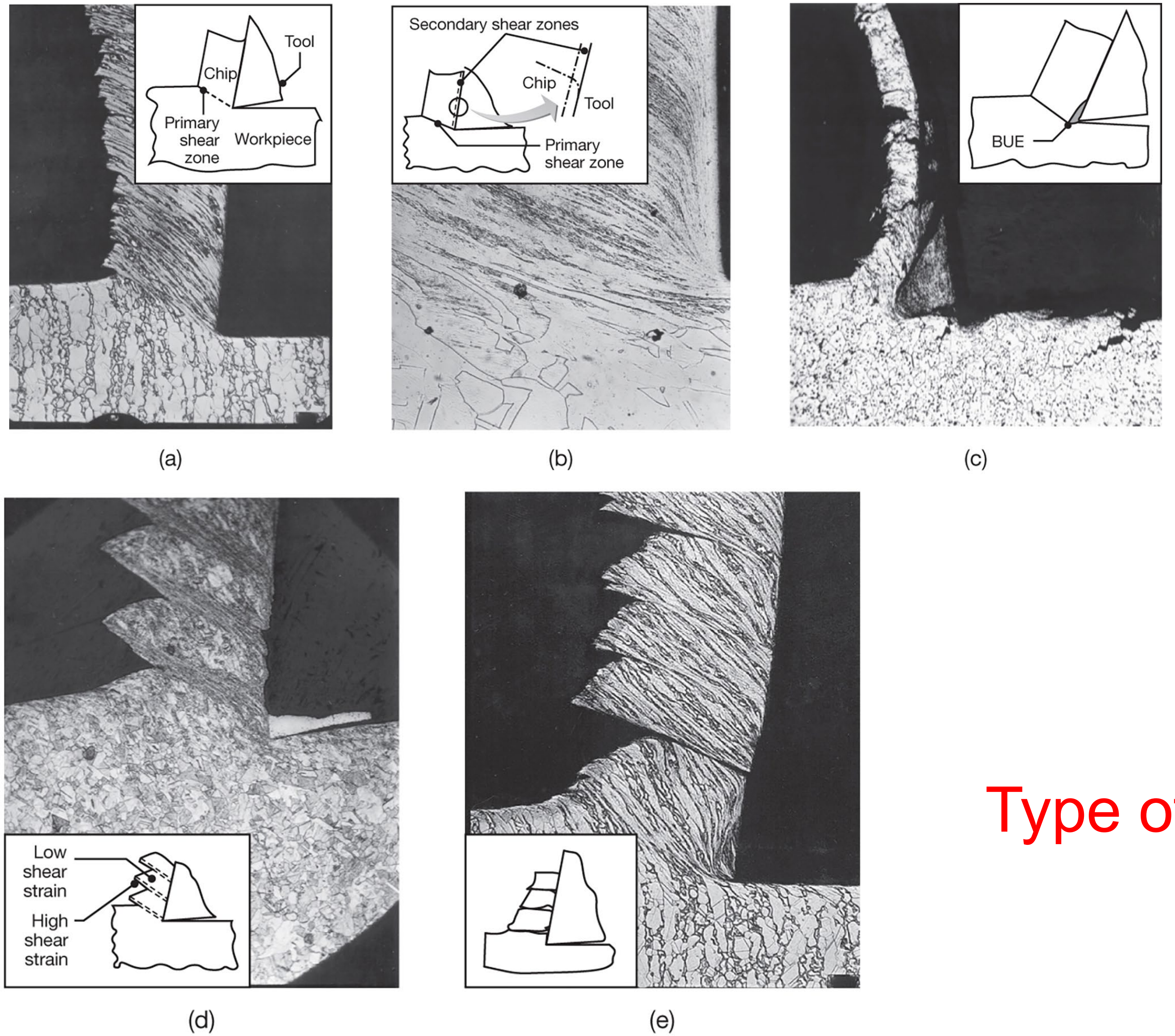
- **Ductile materials**
- Low-to-medium cutting speeds
- Tool-chip friction causes portions of chip to adhere to rake face
- BUE formation is cyclical; it forms, then breaks off



Saw-tooth appearance

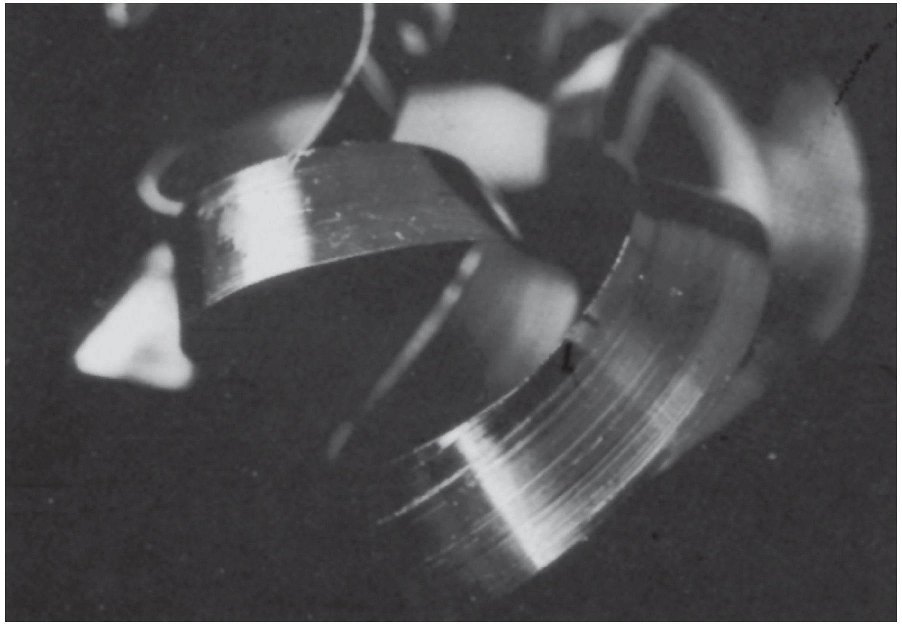
- Semi-continuous - saw-tooth appearance
- Cyclical chip formation of alternating high shear strain then low shear strain
- Associated with difficult-to-machine metals at high cutting speeds

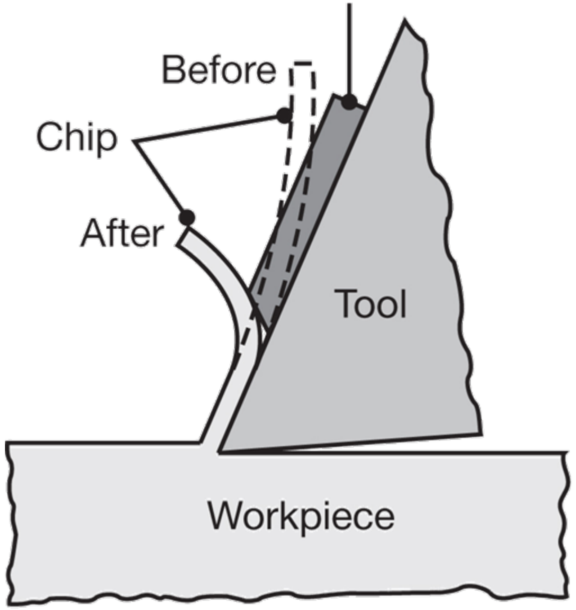




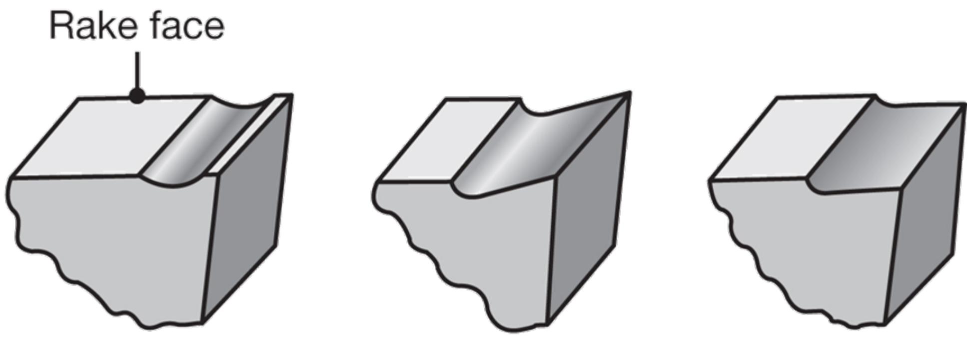
Type of chips...

Some technological aspects...
(chip breaker)





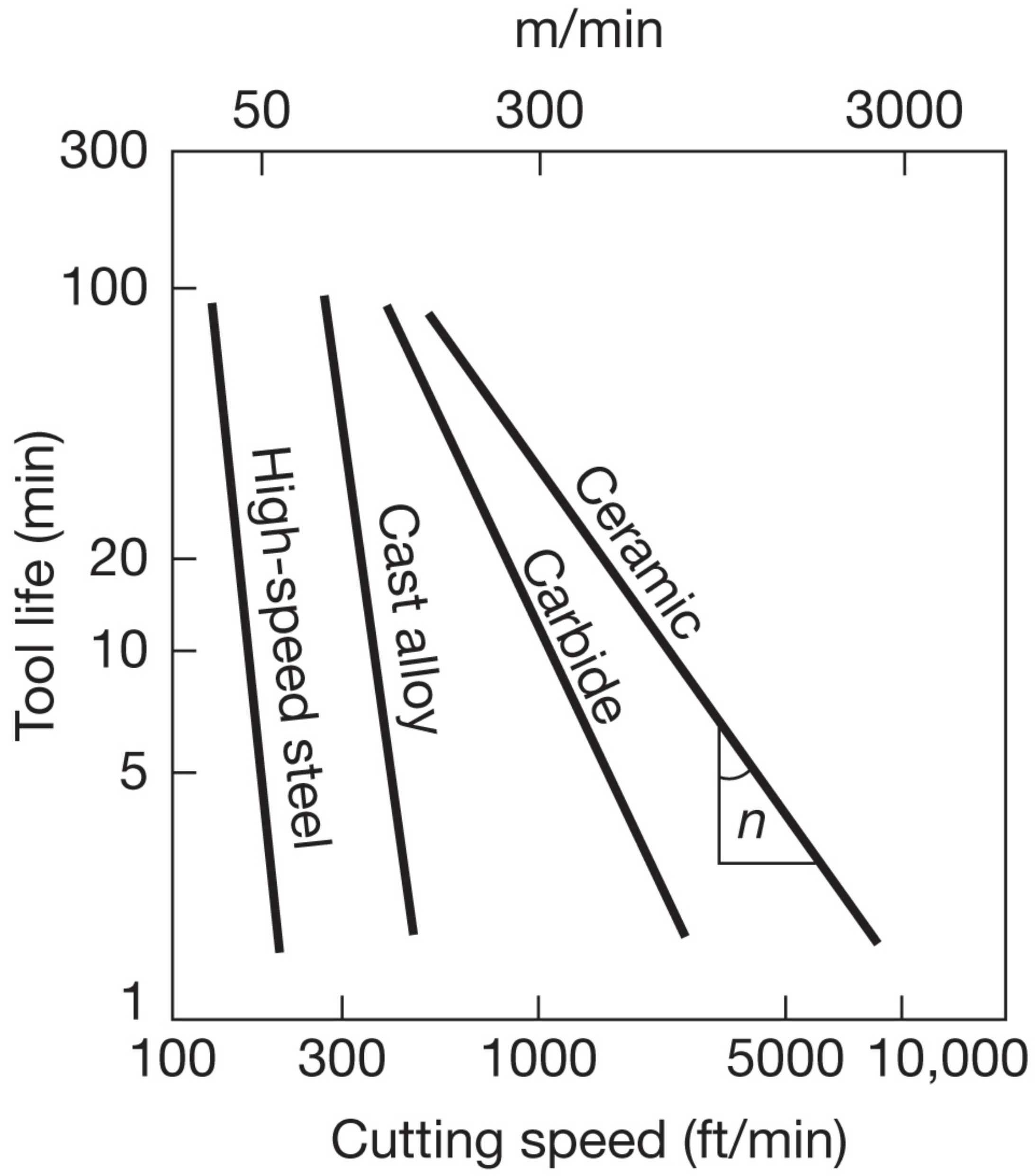
(a)



(b)

Importance of tool coatings and materials

- High hardness at elevated temperature → *Resist wear*
- Chemical stability and inertness to the workshop material → *Reduce wear*
- Low thermal conductivity → *Limit temperature rise of the substrate*
- Compatibility and good bonding → *Prevent flaking, spalling*
- Little or no porosity → *Strength and integrity*



Example of tool-life curves for selected cutting tool materials as a function of the cutting-speed

Progress made in cutting speed thanks to the tooling…

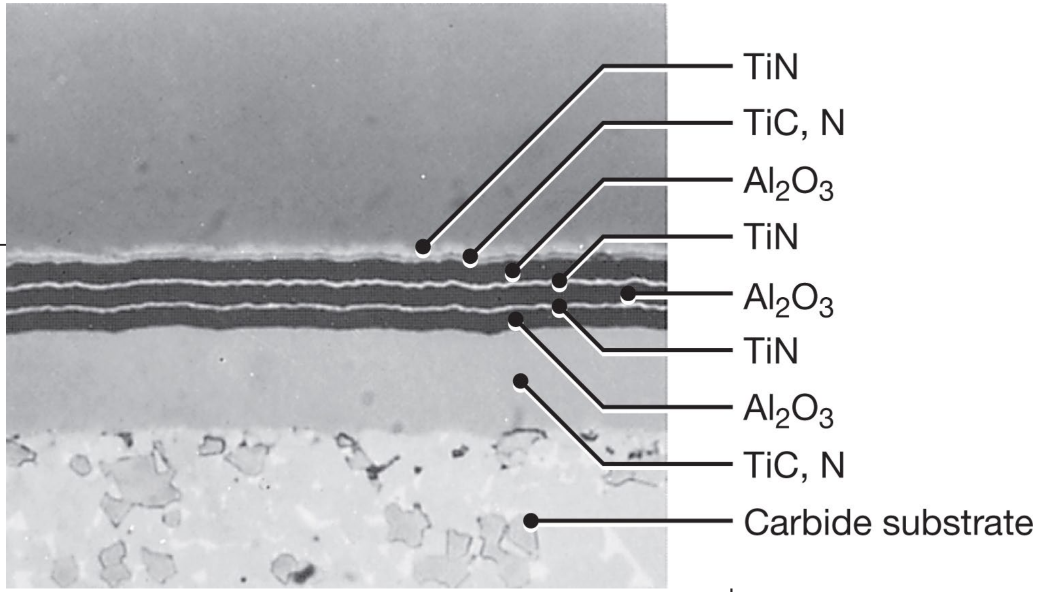
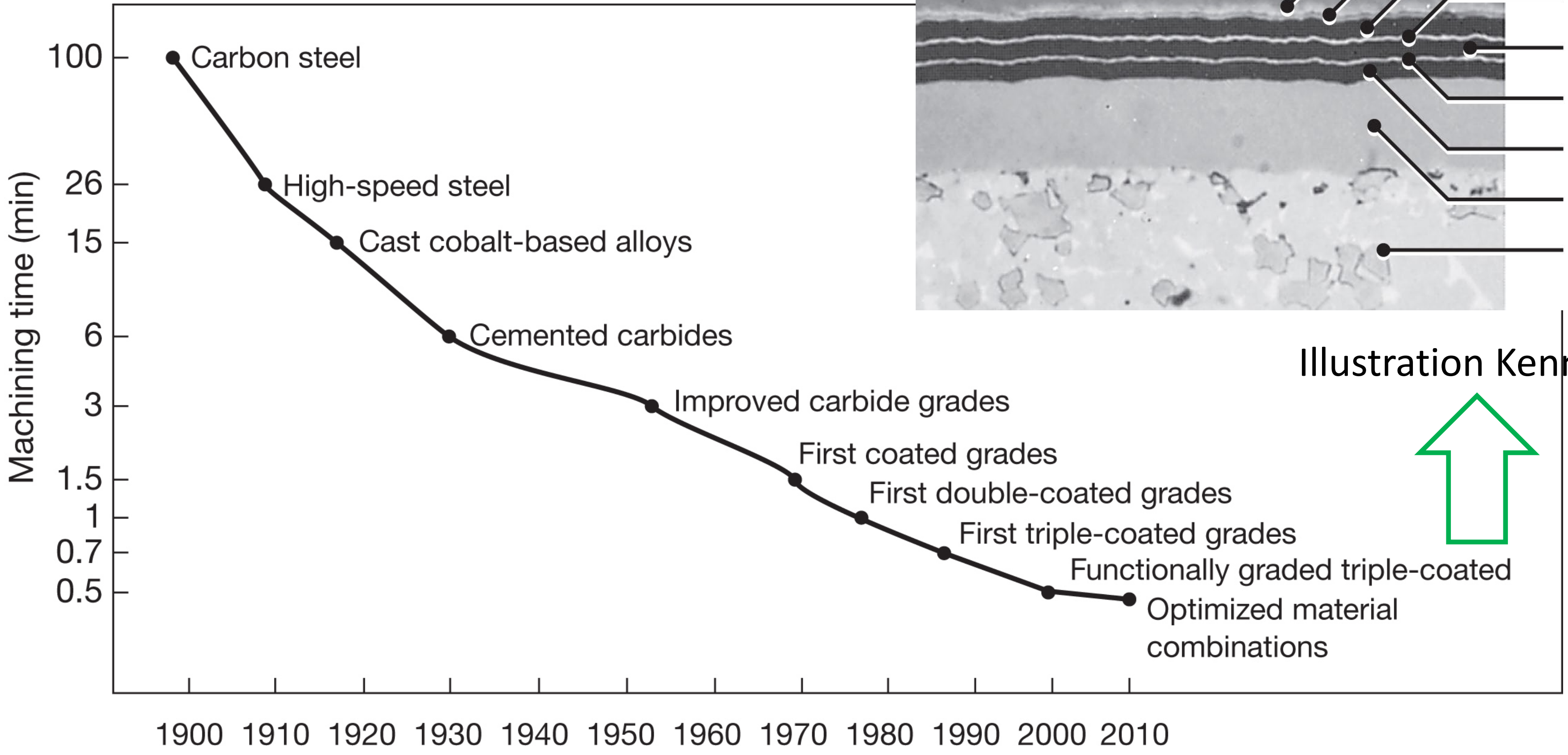
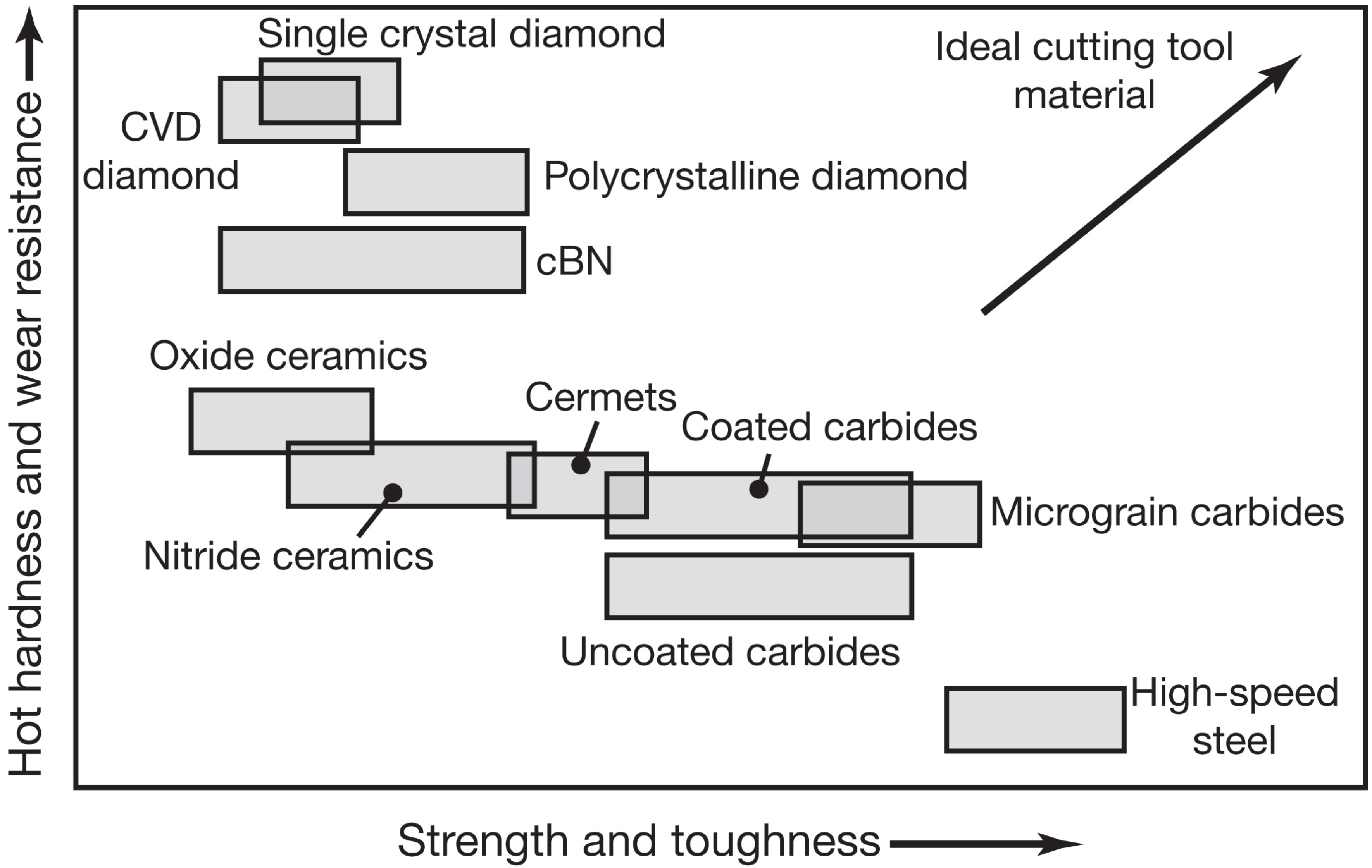


Illustration Kennametal, Inc.

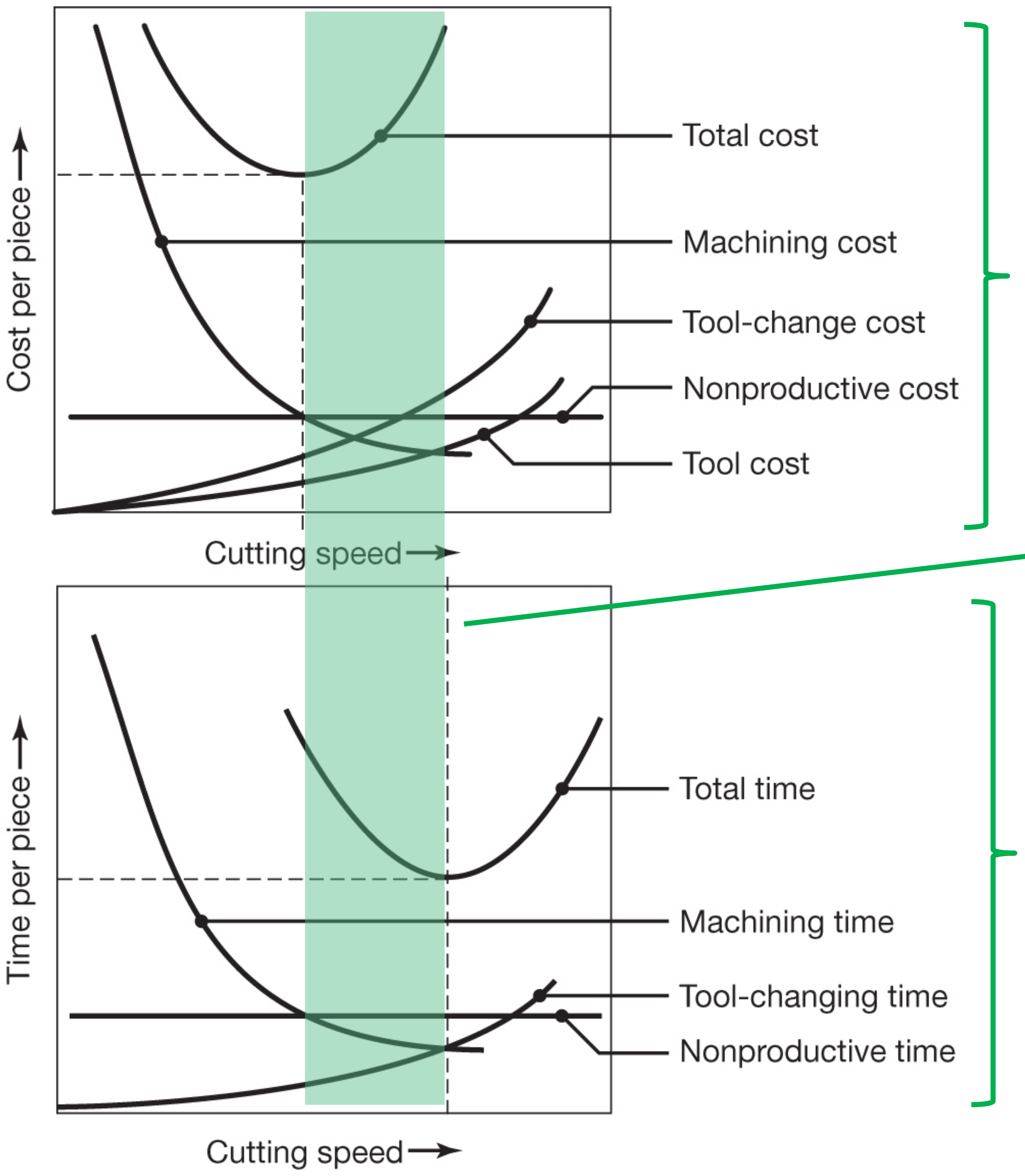


(source Sandvik Coromant)

Range of properties for cutting tools



Economics



Production cost

Optimal zone
(High efficiency machining at optimal cost)

Production time

Roughing vs. Finishing

- Production is usually done in multiple steps... First **roughing**, then **finishing**.

- ***Roughing*** - removes large amounts of material from the initial workpiece
  - Creates shape approaching the desired geometry, but leaves some material for finish cutting
  - Done at high feeds and depths, low speeds

- ***Finishing*** – Final part geometry
  - Achieves final dimensions, tolerances, and finish
  - Done at Low feeds rate and depths, high cutting speeds

Key points to remember

- A general view of conventional machining methods
- The physical principles behind material removal by mechanical cutting and to calculate the key parameters
- Basic equations to estimate material removal rates (MRR)
- Importance of tooling
- Economical aspects: the optimization between tool costs and machining speed.

'Lexique manufacturing'

English (UK) > French

- Machining by material removal: *Usinage par enlévement de matières*
- Cutting: *Découpage /* Cuttting-tool: *Outil de coupe*
- Milling: *Fraisage /* End-mill: *Fraise*
- Drilling: *Preçage /* Drill: *Foret*
- Turning: *Tournage*
- Threading: *Taraudage*
- Chip: *Copeau*
- Rake: *Copeau*
- Reaming: *Alésage*
- Knurling: *Moletage*
- Roughing: *Usinage grossier*
- Finishing: *Usinage de finission*
- Saw-tooth: *Dent de scie*
- Feed rate: *Vitesse d'avance de l'outil*
- Rake: *'rateau'*
- Flank face: *Flanc de l'outil*

Credits (sketches & Illustrations)

Unless stated otherwise: illustrations are adapted from: Manufacturing Engineering & Technology, M.C. Shaw, P.K. Wright, S. Kalpakjian, Pearson.