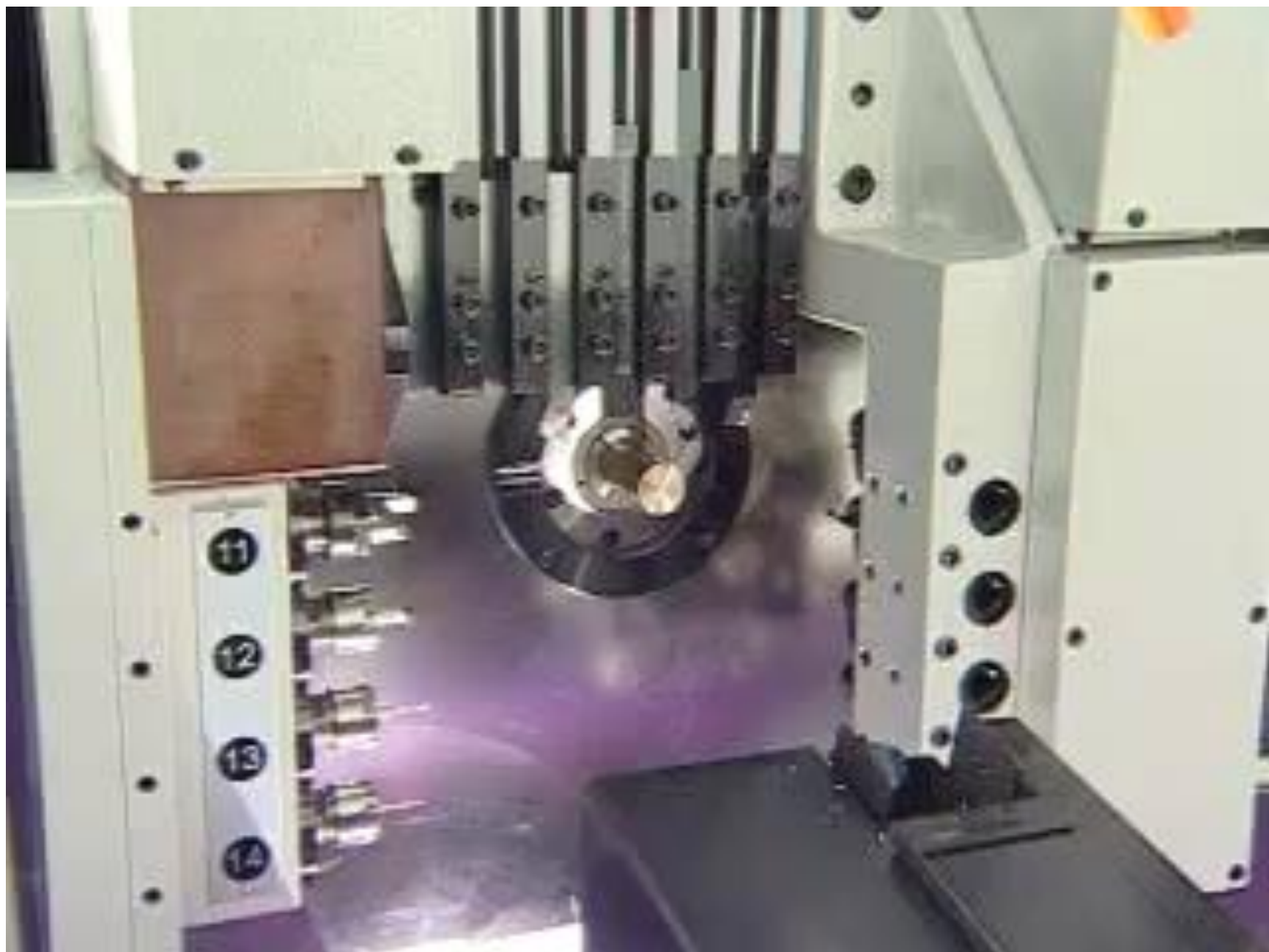
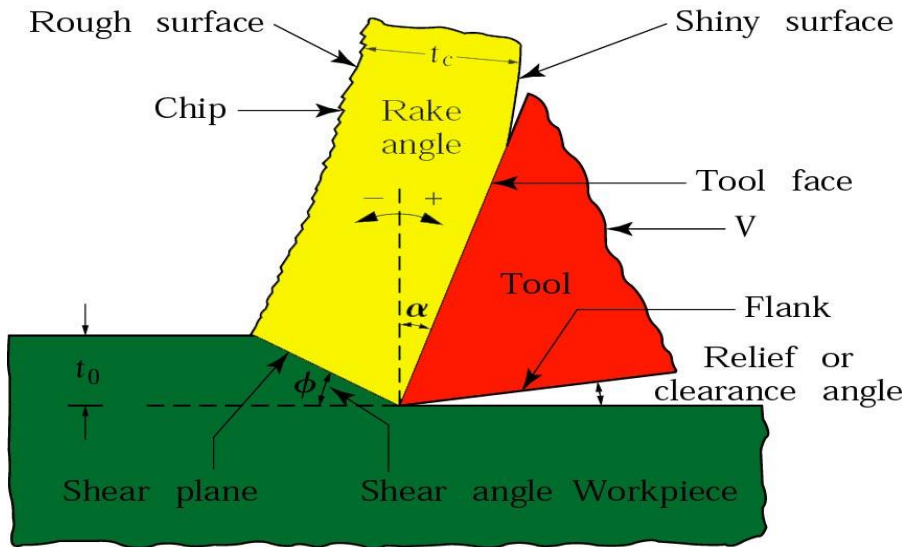
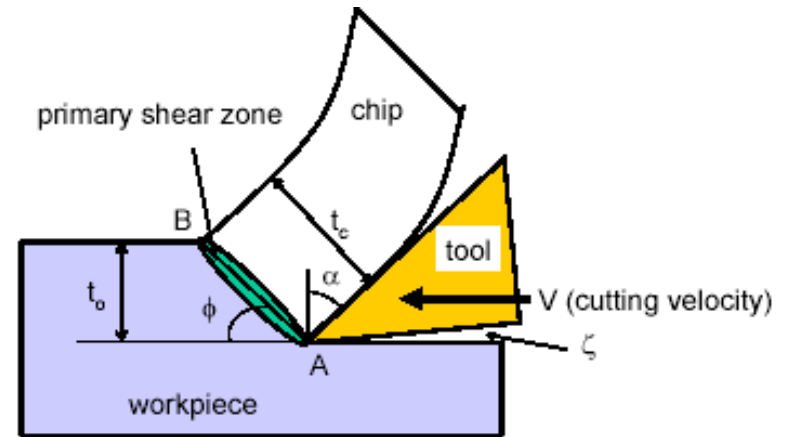


Mechanics of chip formation

Chapter 8



Chip formation



t_0 = depth of cut (d) = undeformed chip thickness

t_c = chip thickness

α = rake angle

ϕ = shear angle

ζ = clearance angle

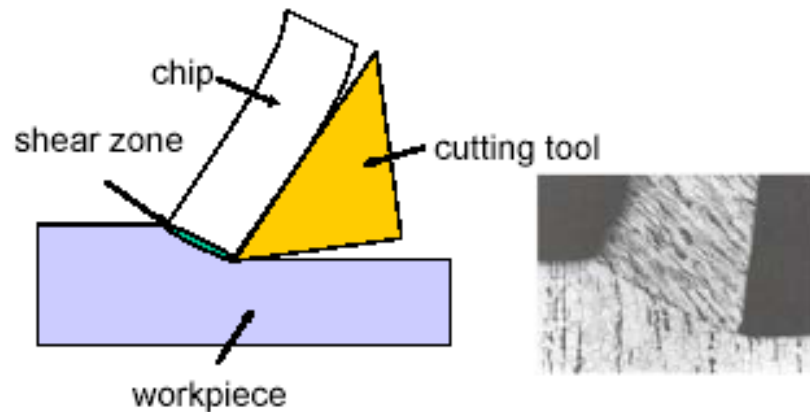
- Independent variables

t_0, α, ζ, V

- Dependent variables

ϕ, t_c

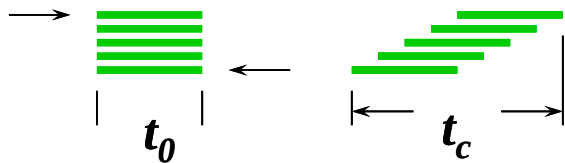
Orthogonal cutting hypotheses



- The process adequately represented by a two-dimensional geometry
- The tool is perfectly sharp
- The tool only contacts the workpiece on its front (rake) face
- Primary deformation occurs in a very thin zone adjacent to the shear plane
- The cutting edge is perpendicular to the cutting direction
- The chip does not flow to the side

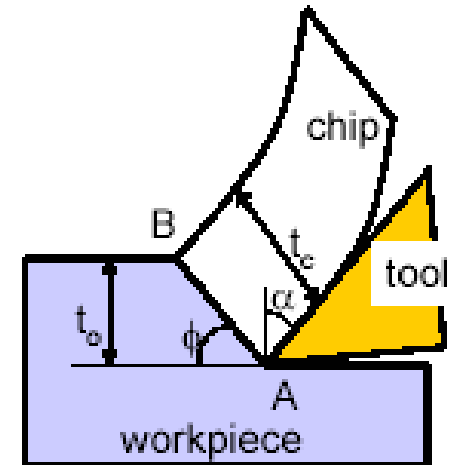
Cutting ratio r

$$r = t_o/t_c$$



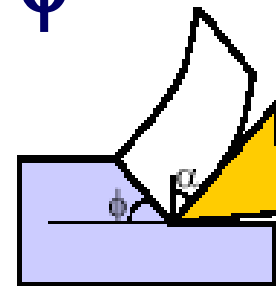
$$t_o \neq t_c$$

$$r = \frac{t_o}{t_c} = \frac{\overline{AB} \cdot \sin \phi}{\overline{AB} \cdot \cos(\phi - \alpha)}$$



Shear angle ϕ

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



where:

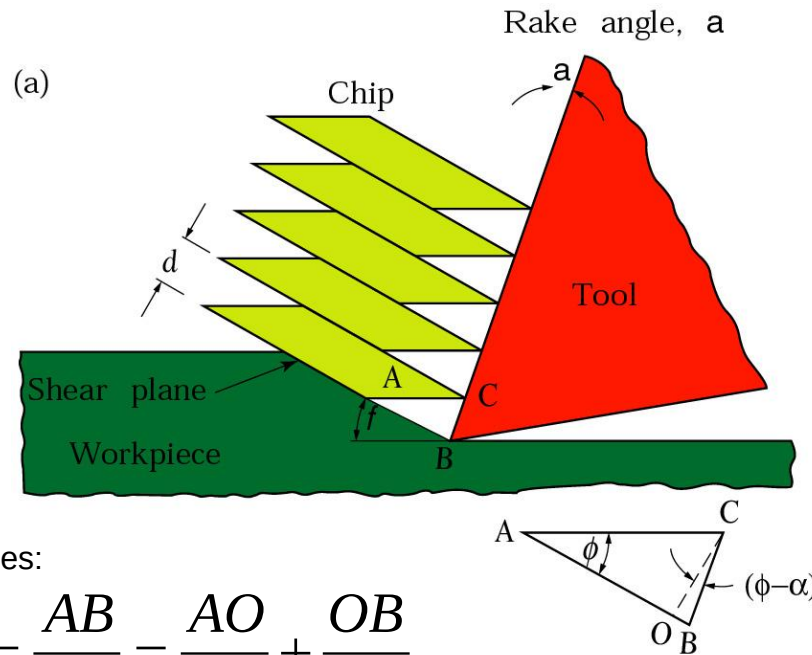
input

→ t_o and rake angle, α , are controlled by the machinist.

output

→ t_c and shear angle, ϕ , are the result

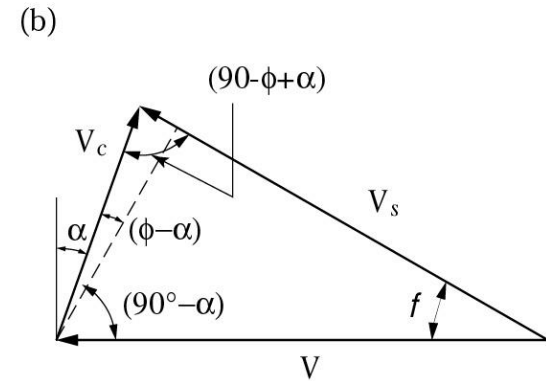
Shear strain γ



For small angles:

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

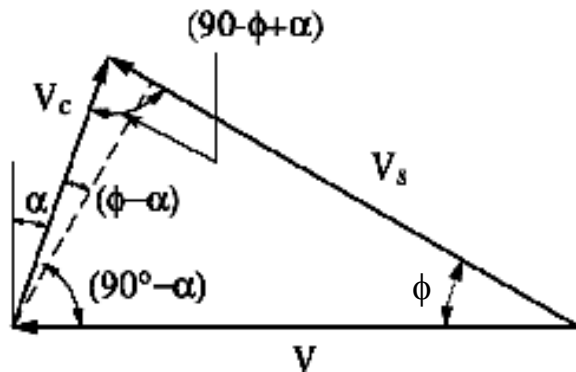
→ $\gamma = \cot(\phi) + \tan(\phi - \alpha)$



for $\alpha = 0$

ϕ	γ
10	5.84
20	3.12
30	2.3

Cutting velocities



Note: Mass continuity
has to be maintained

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

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

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

- Cutting Speed (V)
– tool relative to workpiece
- Shear Velocity (V_s)
– chip relative to workpiece
- Chip Velocity (V_c)
– chip relative to tool

Shear strain rate

$$\dot{\gamma} = \frac{d\gamma}{dt} \quad \longrightarrow \quad \dot{\gamma} = \frac{V_s}{d}$$

For a shear zone thickness = 25 μm
 $V_s = 2.54 \text{ m/s}$



$$\dot{\gamma} = 10^5 \text{ s}^{-1}$$

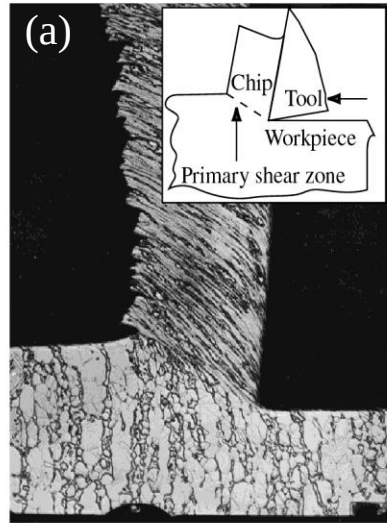
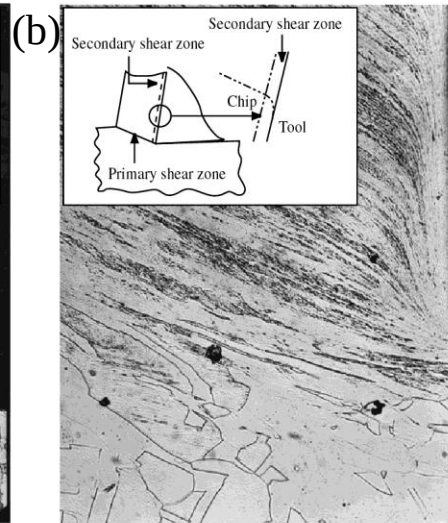
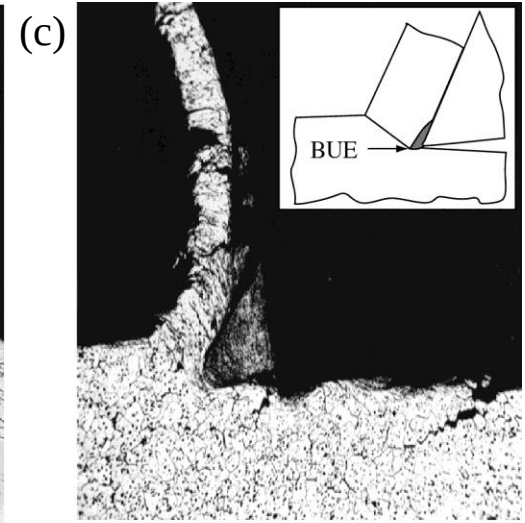
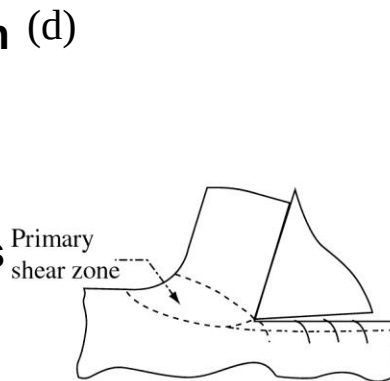
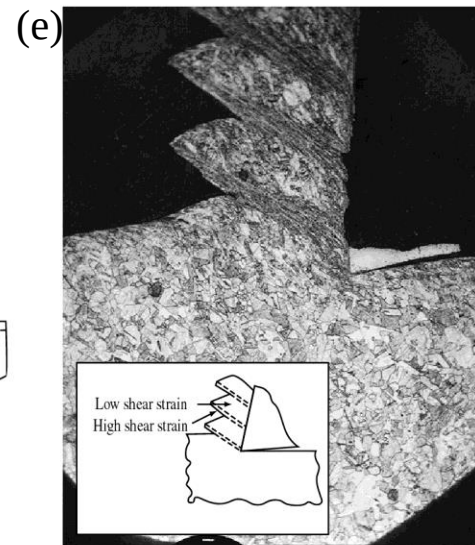
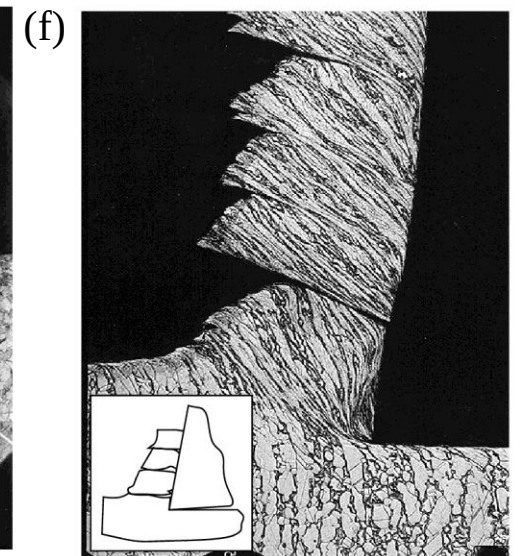
- $1 < \gamma < 6$
- $2 < \gamma < 4$: typical
- $10^4/\text{s} < \dot{\gamma} < 10^6/\text{s}$: typical



No tests available to determine
the material behaviour under
these extreme conditions

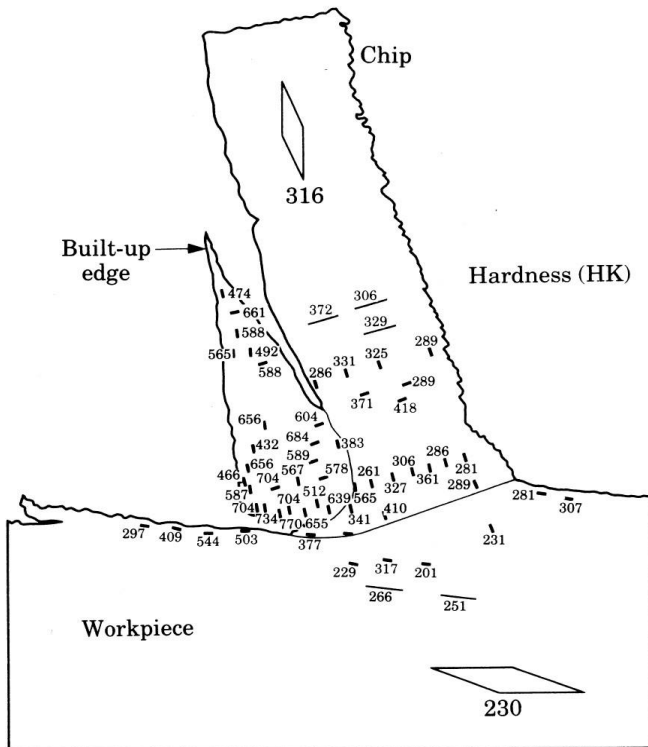
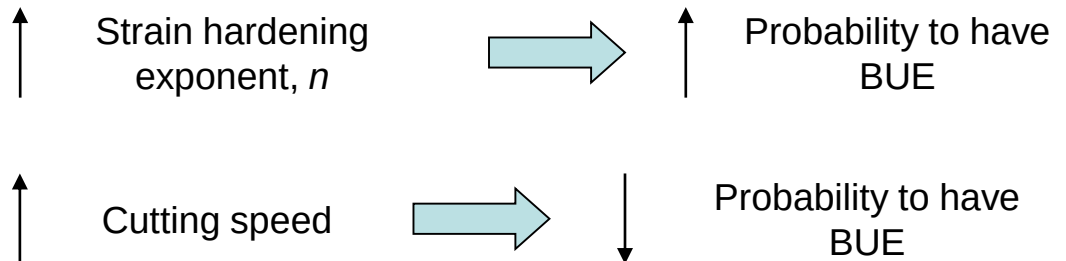
Chip morphology

Basic types of chips and their photomicrographs produced in metal cutting: (a) **continuous chip** with narrow, straight primary shear zone; (b) secondary shear zone at the chip-tool interface; (c) **continuous chip with built-up edge**; (d) continuous chip with large primary shear zone; (e) **segmented or nonhomogeneous chip** and (f) **discontinuous chip**.



Built-up edge

1. Adhesion of the workpiece material to the rake face of the tool
2. Growth of the adhered metal layers



To decrease BUE:

- decrease the depth of cut
- increase the rake angle
- use a tool with a small tip radius
- use an effective cutting fluid



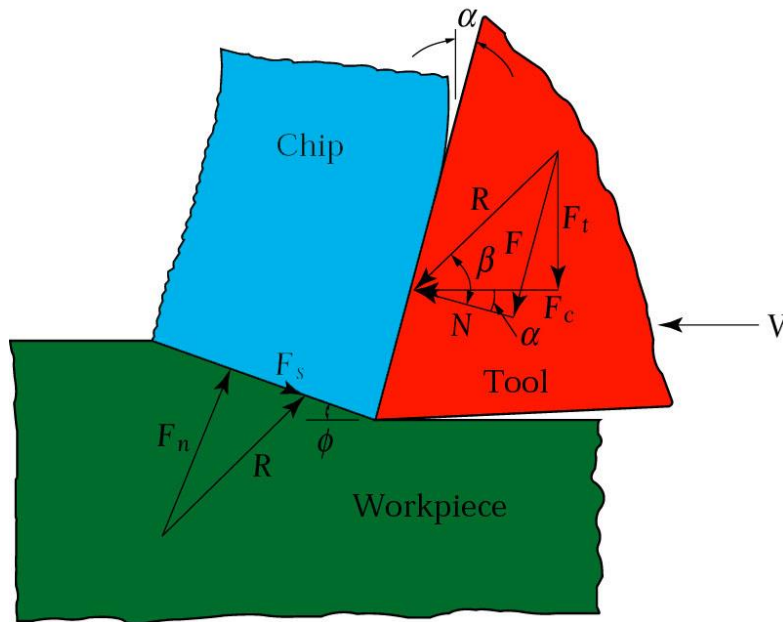
Segmented chip

- Zones characterised by low and high shear strain
- Metals with low thermal conductivity and strength that decreases sharply with temperature (like titanium alloys)

Discontinuous chip

- Brittle materials
- Materials containing hard inclusions and impurities
- When the cutting speed is too high or too low
- When the depth of cut is very large
- Without a proper cutting fluid
- When the machine is not sufficiently stiff

Forces in orthogonal cutting



- Cutting (power) force: F_c
 - does the work of cutting ($P = F_c \times V$)
- Thrust force: F_t
 - perpendicular to cutting velocity
 - pushes tool and work piece apart
- F_t = thrust force ($\perp$ to cutting velocity)
- F_c = cutting force ($\parallel$ to cutting velocity)
- N, F = Normal, tangent friction force of tool on chip
- N_s, F_s = Normal, tangent shear force of workpiece on chip
- α = rake angle
- ϕ = shear angle
- β = friction angle
- b = width of chip (into board)

Cutting specific energy

- **Power** = $F_c V$

- where F_c is the cutting force and V is the tool velocity

- **Specific Energy** = power/volume in time unit
= shearing energy + friction energy

- where t_0 is the depth of cut, w is the width of cut

$$u_t = \frac{F_c V}{w t_0 V} = \frac{F_c}{w t_0}$$

$$u_t = u_f + u_s$$

$$u_f = \frac{F V_c}{w t_0 V} = \frac{F r}{w t_0}$$

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

u is composed of:

- u_s , the shear energy per unit volume
- u_f , frictional energy per unit volume
- chip curl energy, chip acceleration kinetic energy, surface energy of the new surfaces, energy associated with the momentum change (all negligible)

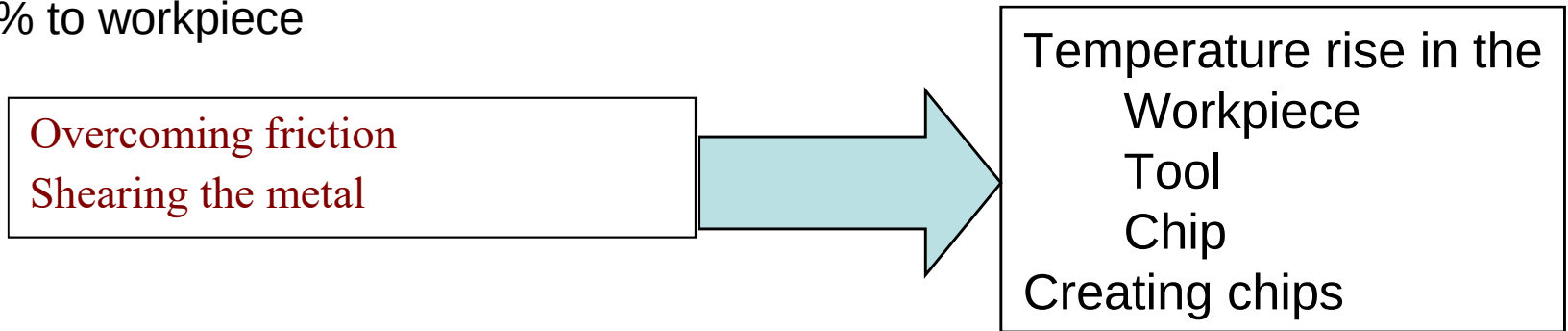
Cutting specific energy

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.

Where energy goes..

- 90% to chip
- 5% to tool
- 5% to workpiece

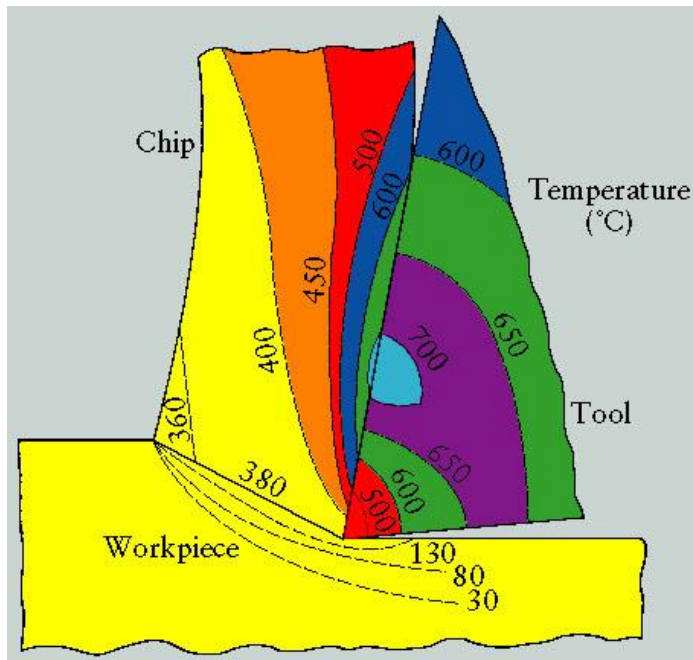
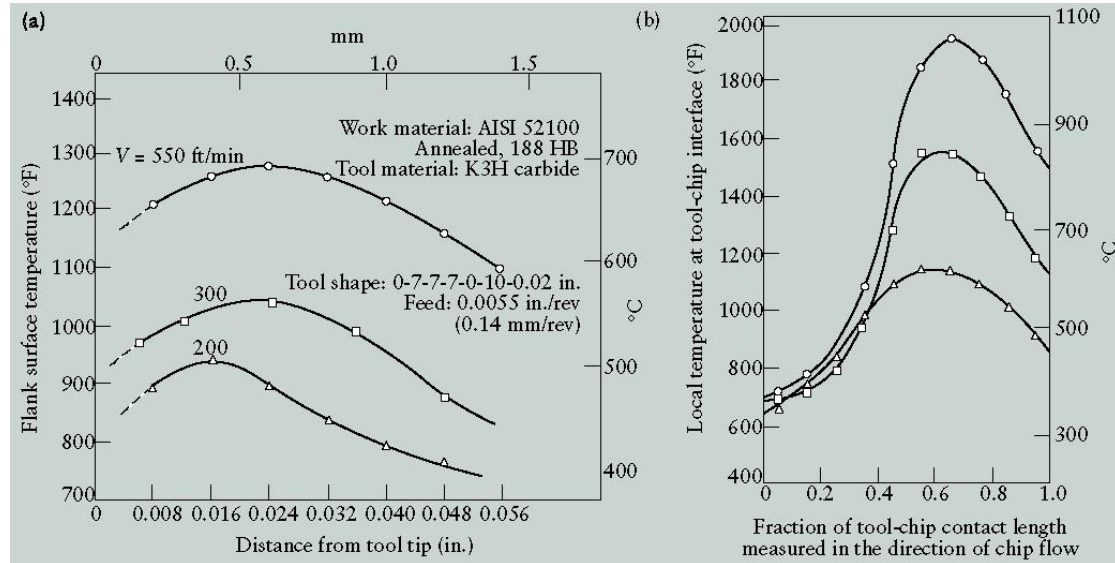


Higher temperatures:

- Cause dimensional changes in the workpiece
- Induce thermal damage in the machined surface
- Affect strength, hardness and wear resistance of the cutting tool
- Eventually distort the machine tool itself

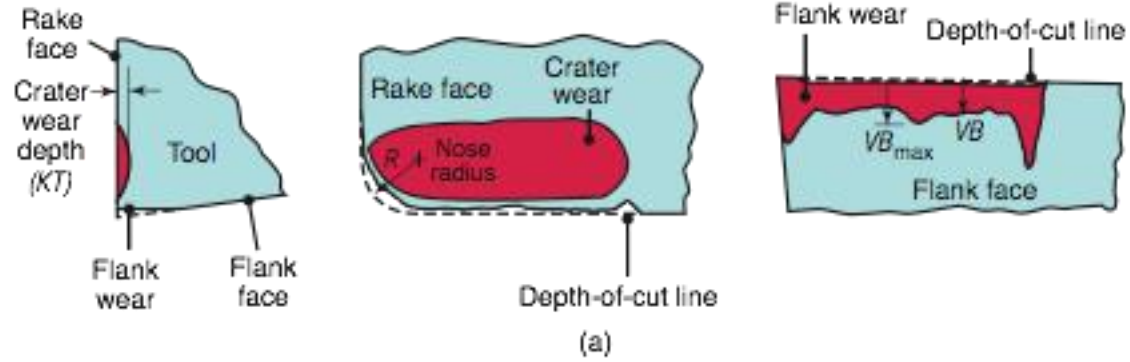
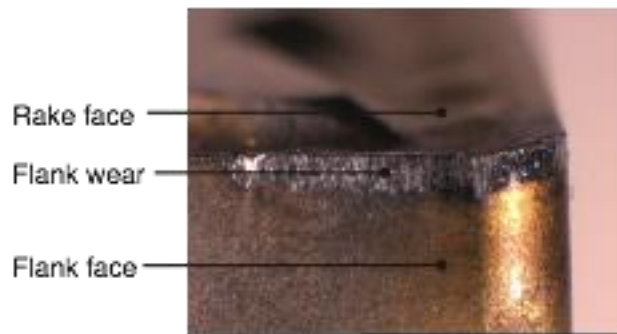
Dull tools also generate heat through rubbing of the workpiece surface

Temperature field

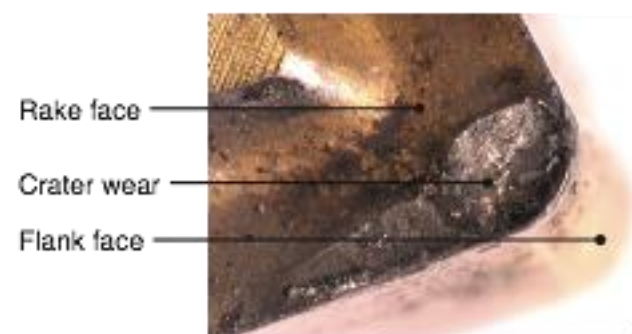


Temperature distribution in turning: (a) flank temperature; (b) temperature of the tool-chip interface. Note that the rake face temperature is higher than that at the flank surface.

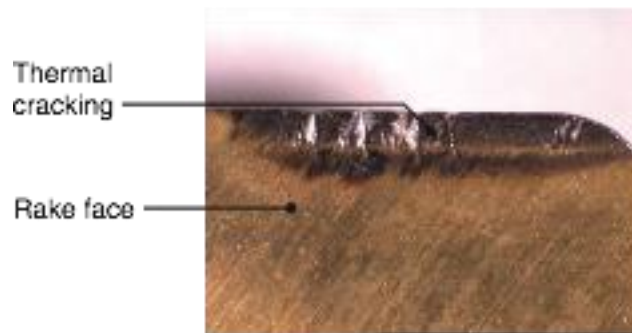
Tool wear



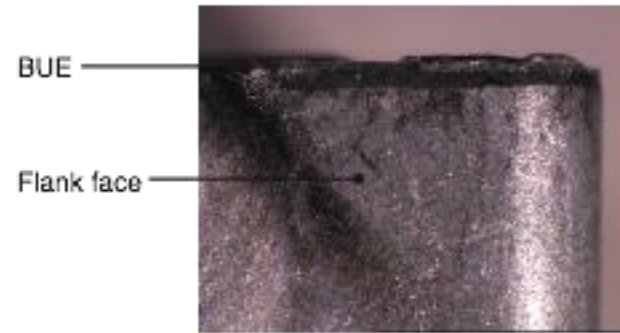
(b)



(c)



(d)



(e)

Flank wear

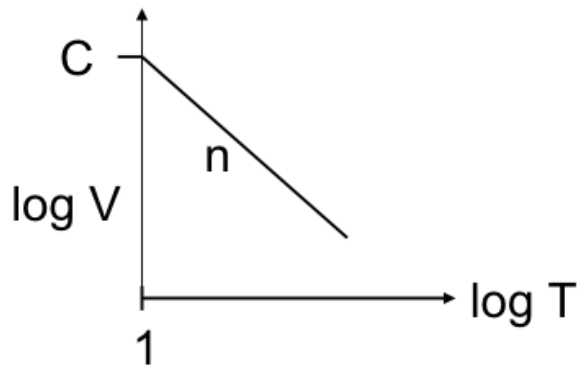
Taylor's Equation

$$VT^n = C$$

V = cutting speed

T = tool life

n, C = Taylor constants (empirical)



Note: C is the cutting speed at a tool life equal to 1 minute



F.W. Taylor

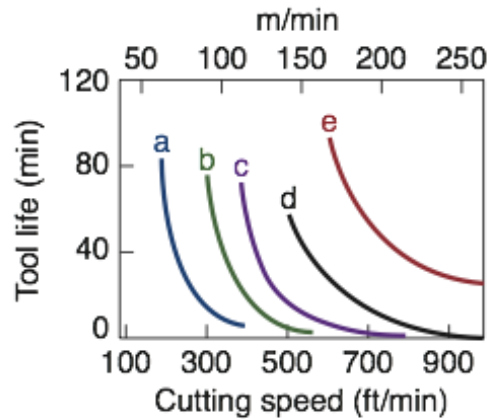
Causes:

- Sliding of the tool along the machined surface
- Temperature rise

Range of n values for various cutting tools

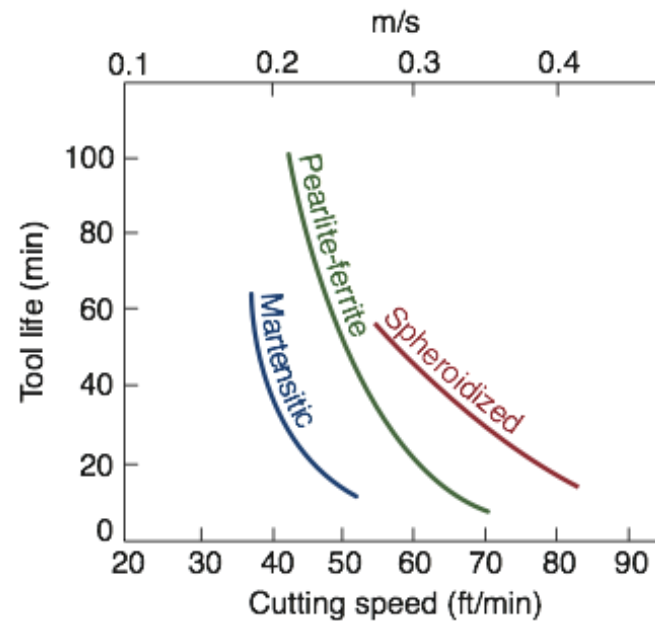
High-speed steels	0.08-0.2
Cast alloys	0.1-0.15
Carbides	0.2-0.5
Ceramics	0.5-0.7

Tool life curves



	Hardness (HB)	Ferrite	Pearlite
a. As cast	265	20%	80%
b. As cast	215	40	60
c. As cast	207	60	40
d. Annealed	183	97	3
e. Annealed	170	100	—

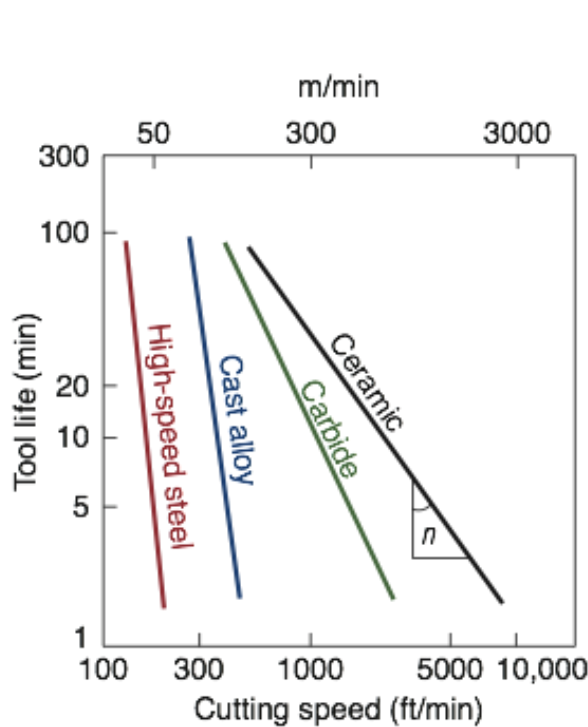
(a)



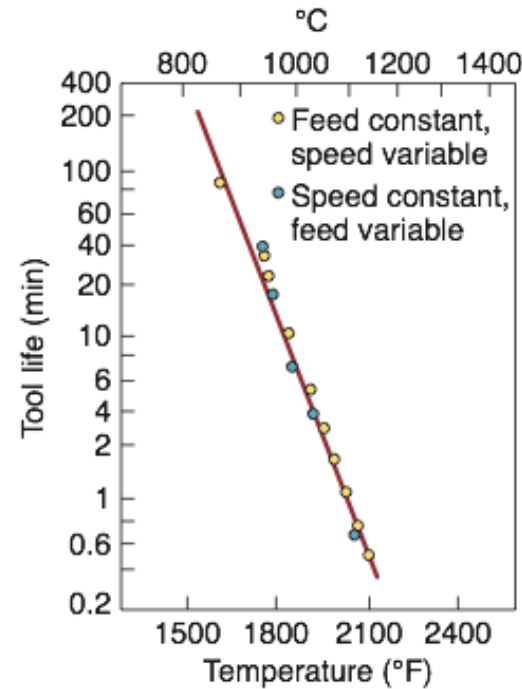
(b)

Effect of workpiece microstructure on tool life in turning. **Tool life is given in terms of the time (in minutes) required to reach a flank wear land of a specified dimension.** (a) Ductile cast iron; (b) steels, with identical hardness. Note in both figures the rapid decrease in tool life as the cutting speed increases.

Tool life curves



(a)



Work material: Heat-resistant alloy
 Tool material: Tungsten carbide
 Tool life criterion: 0.024 in. (0.6 mm) flank wear

(b)

(a) Tool-life curves for a variety of cutting-tool materials. The negative inverse of the slope of these curves is the exponent n in tool-life equations. (b) Relationship between measured temperature during cutting and tool life (flank wear). Note that high cutting temperatures severely reduce tool life.

Extended Taylor's equation

$$V \cdot T^n \cdot d^x \cdot f^y = C$$

Where:

d is the depth of cut

f is the feed rate

OPERATION	ALLOWABLE WEAR LAND (mm)	
	HIGH-SPEED STEELS	CARBIDES
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

Allowable average *wear land* for cutting tools for various operations.

Crater wear

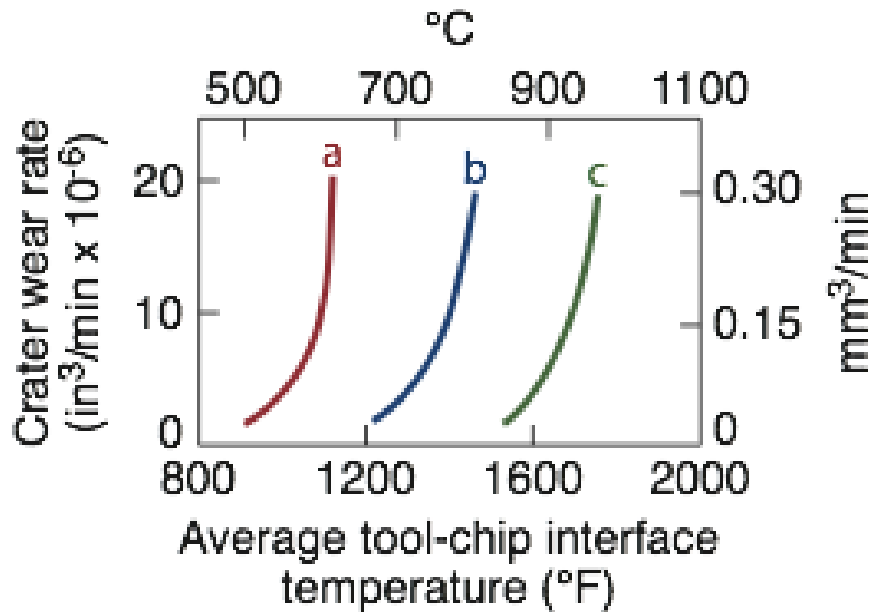
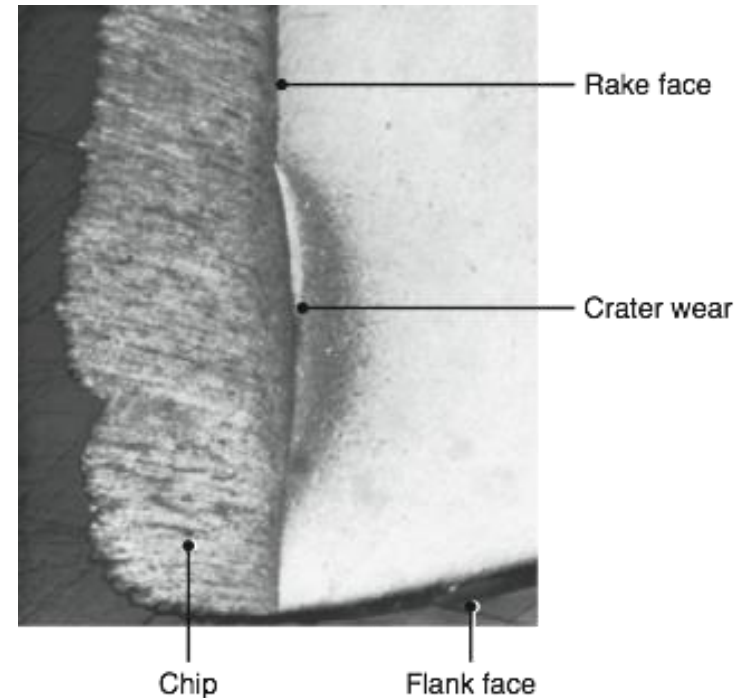
Causes:

- Chemical affinity between tool and workpiece
- Temperature rise

Maximum temperature



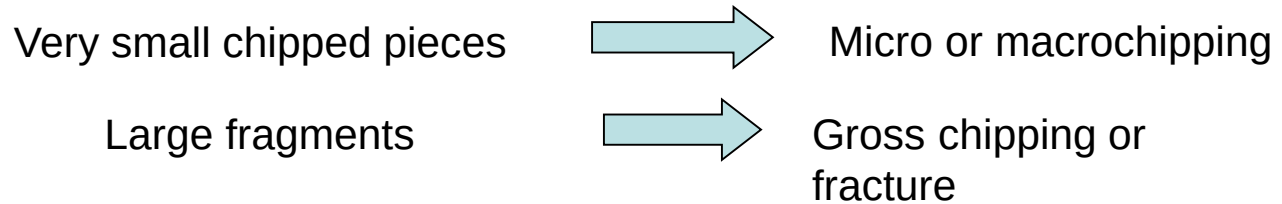
Maximum depth of crater wear



Relationship between crater-wear rate and average tool-chip interface temperature in turning: (a) C-1 Carbide; (c) C-5 carbide. Note that crater wear increases rapidly within a narrow range of temperature.

Tool chipping

Breaking away of a piece from the cutting edge of the tool



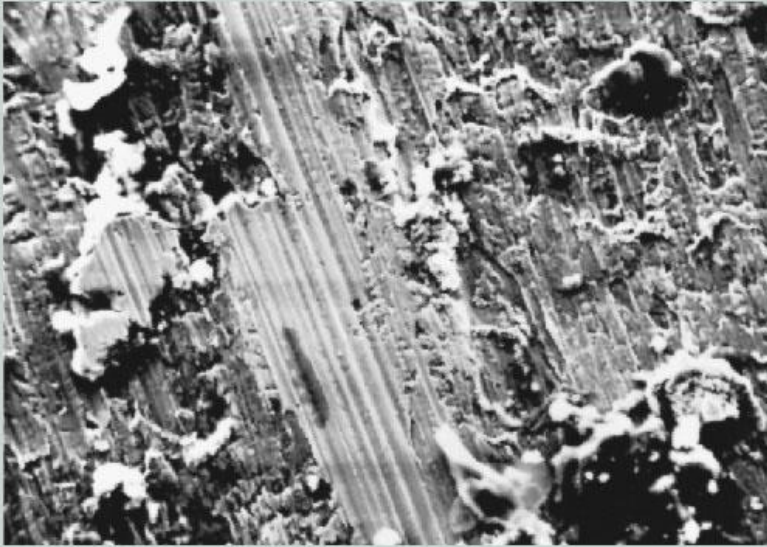
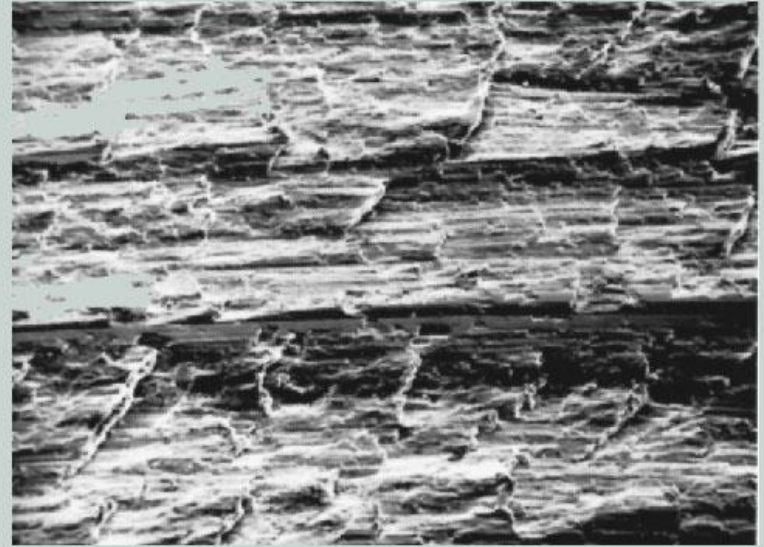
Causes:

- Mechanical shock
- Thermal fatigue

Application

Cutting time(min)	1	3	5	7	9	11	13	15	20	25
Flank wear (mm) v=125 m/min	0.12	0.20	0.27	0.33	0.40	0.45	0.50	0.58	0.73	0.97
Flank wear (mm) v=165 m/min	0.22	0.35	0.47	0.57	0.70	0.80	0.99			

Machined surfaces

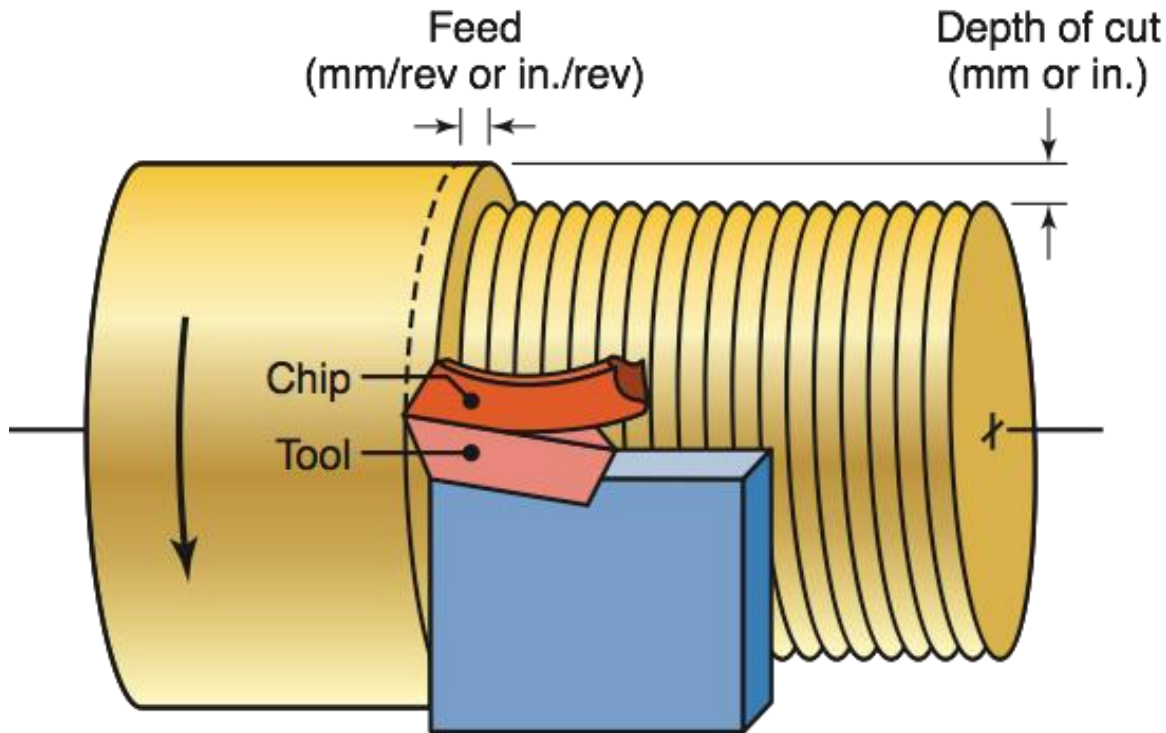


Surfaces produced on steel by cutting, as observed with a scanning electron microscope: (a) turned surface and (b) surface produced by shaping.

SURFACE FINISH: geometric features of the surface

SURFACE INTEGRITY: pertains to properties as fatigue life and corrosion resistance

Turning terminology



Terminology used in a turning operation on a lathe, where f is the feed (mm/rev) and d is the depth of cut. Note that **feed in turning is equivalent to the depth of cut in orthogonal cutting**, and the **depth of cut in turning is equivalent to the width of cut in orthogonal cutting**.

Turning terminology

CUTTING SPEED v_t : relative speed between the tool and the workpiece [m/min]

FEED RATE v_a : speed at which the tool travels along the feed direction [mm/min]

FEED f : distance travelled by the tool on the feed direction for each turn of the workpiece [mm/rev]

DEPTH OF CUT d : amount of metal to be removed, measured perpendicularly to the feed direction [mm]

N [rev/min]

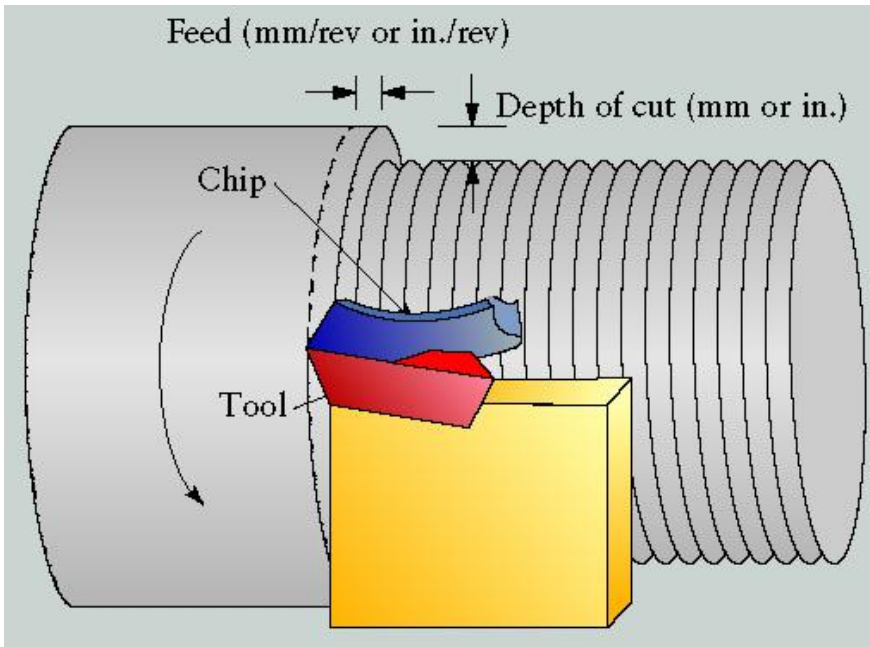
D [mm]

$$v_t = \frac{\pi DN}{10^3}$$

$$d = \frac{D_0 - D_f}{2}$$

$$v_a = Nf$$

Feed marks



Peak-to-valley roughness:

$$R_t = \frac{f^2}{8R}$$

Where:

R is the nose radius

f is the feed rate

Machinability

- Force and power requirements
- Tool life obtained
- Surface finish and integrity of the machined part
- Chip control

*Machinability
Rating* $I = \frac{v_{t60} \text{ tested_materiale}}{v_{t60} \text{ reference_material}}$

$I < 1$ Machinability less than AISI 1112

$I > 1$ More machinable material

Tool materials

Cutting Tools

- 19th Century

- Plain carbon steels (HB $\approx$ 700 kg/mm²)

- Poor cutting properties

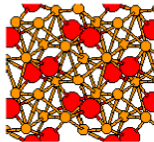
- begin to lose strength 200-300°C

- used in taps, cheap drills

- 1850's

- Discovery of Fe₃C (cementite)

- Hardening of steel



- 1890's: Moisson

- Used electrical arc furnace

- Tried to make diamonds

- Made lots of carbides



- 1900: Development of high-speed steel by Taylor, et al.

- add W, Mo, Cr, V to steel $\Rightarrow$ Fe_xM_yC

- not much harder (HB $\approx$ 800 kg/mm²)

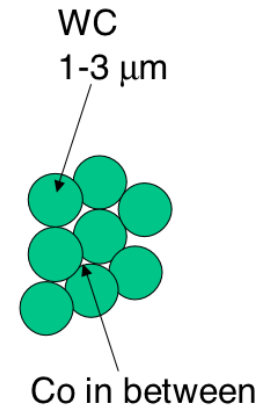
- stable at high temperatures

- 20-30% by volume carbides

- can be used at twice the speed of tool steels

Tool materials

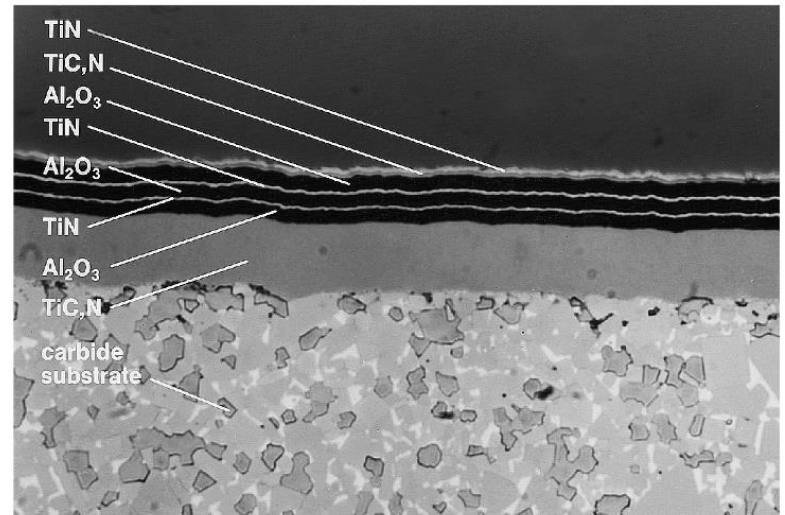
- Tungsten carbide (WC)
 - HB $\approx 2,000$ kg/mm²
 - Too brittle for cutting
- 1923: Schroter
 - WC + Co
 - Co wets WC and binds together
Cemented carbide structure
vice the speed of WC
ot as tough as HSS
fine grain structure helps
 - Machine vibration is problem
 - rigid machines help
 - Solubility of WC in Fe $\approx 5\%$



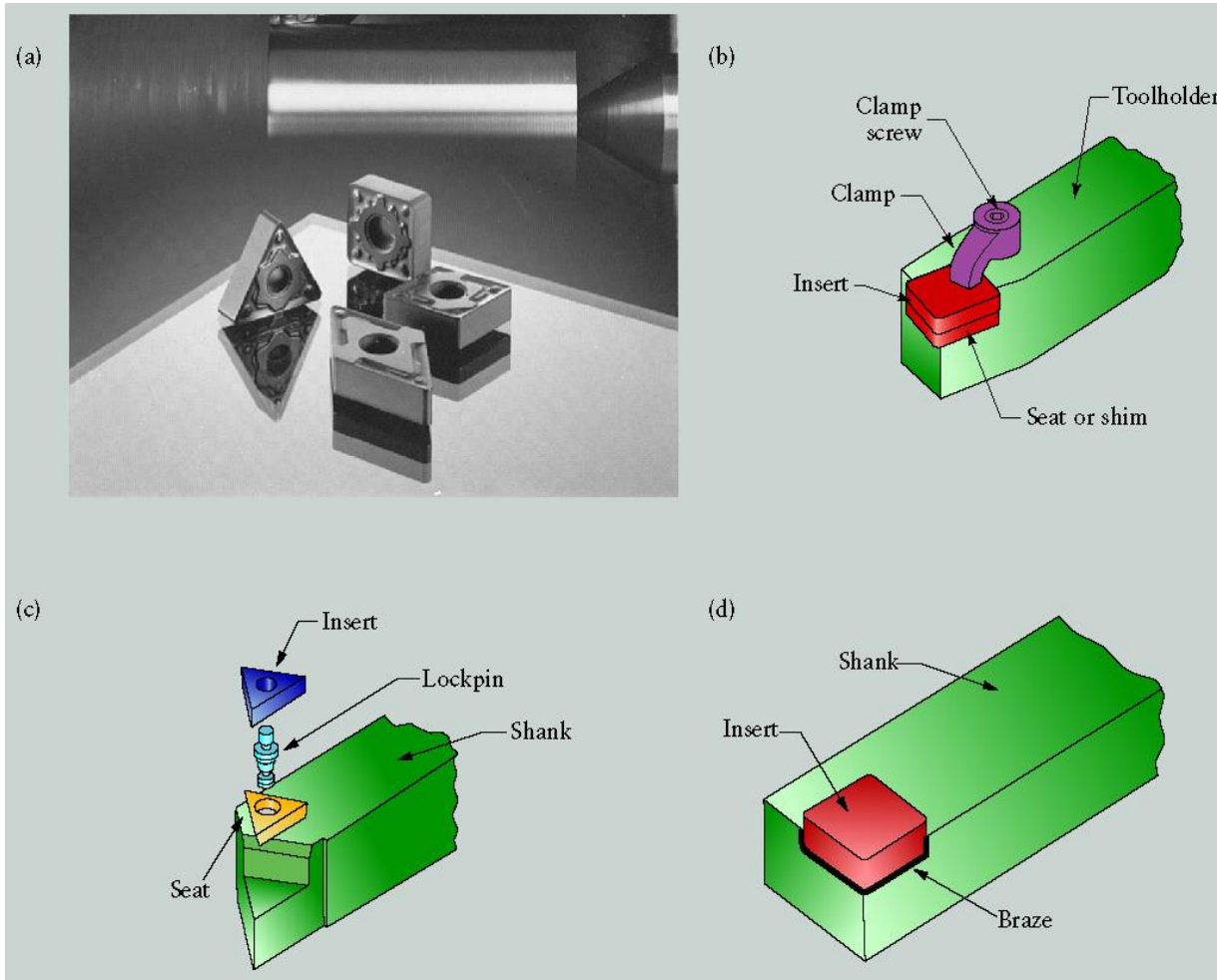
- 1931: Complex carbides developed
 - TiC added to increase chemical stability
 - 2x the cutting speed of WC + Co
 - lower strength
 - increased wear resistance

Tool materials

- 1960's: Increased cutting speeds
- Powder metallurgy
 - production of carbide inserts
 - disposable inserts, no resharpener
 - coatings feasible: TiC , TiN , Al_2O_3
 - $\approx 5 \mu\text{m}$ layer to minimize strain
 - very wear resistant
 - 50-70% of tool life expended before coating penetrated



Inserts

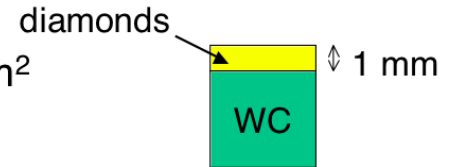


(a) Typical carbide inserts with various shapes and chip-breaker features. Round inserts are also available. The holes in the inserts are standardized for interchangeability.

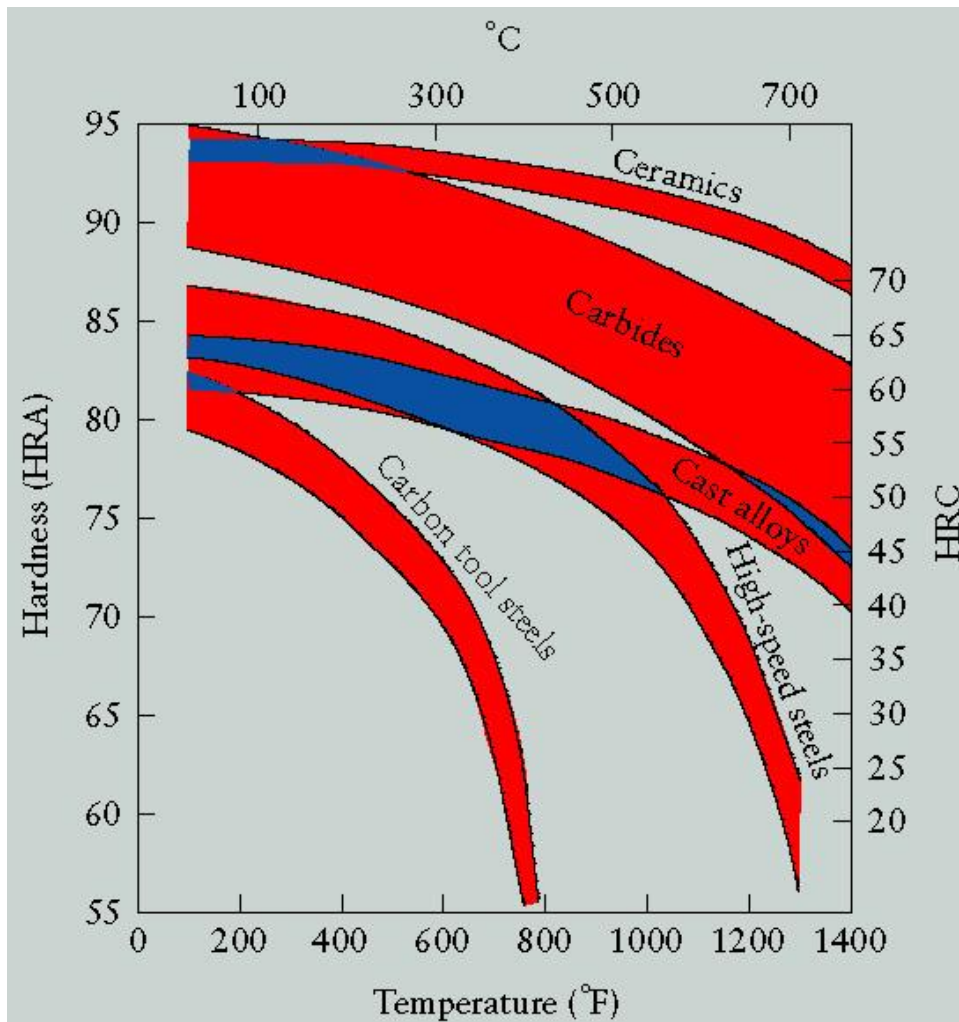
Source: Courtesy of Kyocera Engineered Ceramics, Inc., and *Manufacturing Engineering*, Society of Manufacturing Engineers. (b) Methods of attaching inserts to a tool shank by clamping, (c) with wing lockpins, and (d) with a brazed insert on a shank.

Tool materials

- Aluminum oxide (Al_2O_3)
 - wear resistant, but low strength
- $\text{Al}_2\text{O}_3 + 30\% \text{ TiC}$: hot-pressed
 - increased strength 15-30%
 - higher speeds - 3-5x of carbides
- Cubic Boron Nitride (CBN)
 - more stable with respect to steel and Ni
 - $\text{HB} \approx 4,500 \text{ kg/mm}^2$
 - cuts very hard steels (10x carbide)
 - cuts Ni-based super alloys (10x carbide)
 - wears quickly at low speeds, only good at high speeds
- Si_3N_4
 - high toughness in bulk form
 - low thermal expansion
 - not for steel, dissolves - fast wear
- $\text{Al}_2\text{O}_3 + \text{Si}_3\text{N}_4$ (SiAlON)
 - cuts Ni superalloys and steels
- Diamond (C)
 - $\text{HB} \approx 10,000 \text{ kg/mm}^2$
 - soluble in steel
 - good for aluminum
 - good for Si-Al alloys
 - 10-40 μm particles are sintered onto a WC substrate $\Rightarrow$ polycrystalline tool

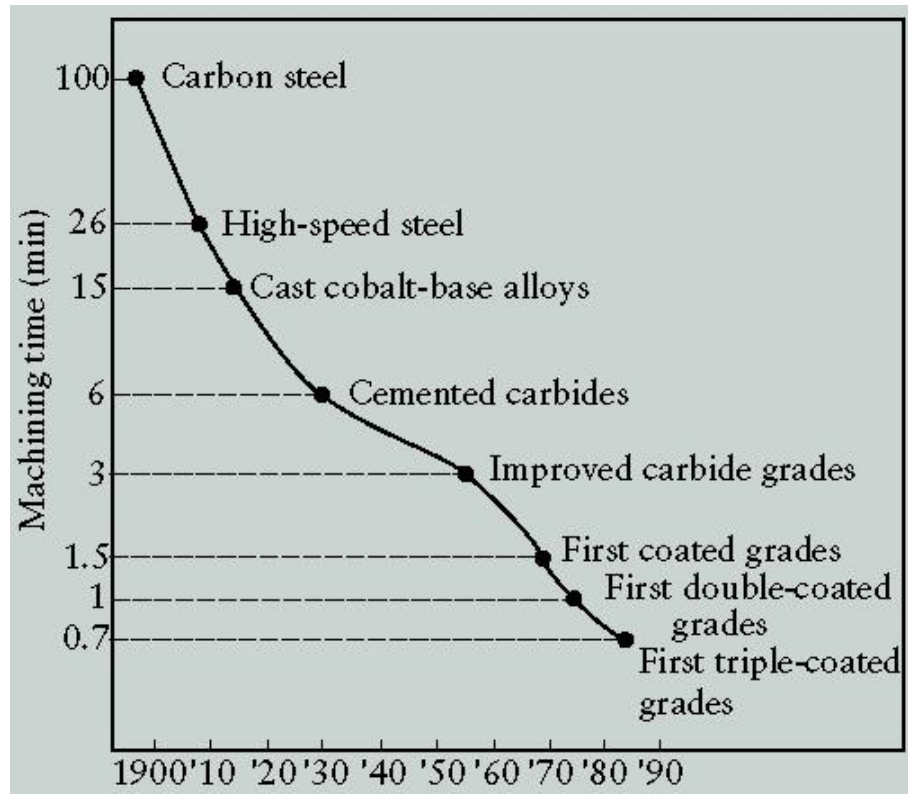


Hardness vs. temperature



Hardness of various cutting-tool materials as a function of temperature (**hot hardness**). The wide range in each group of materials results from the variety of tool compositions and treatments available for that group.

Relative cutting time



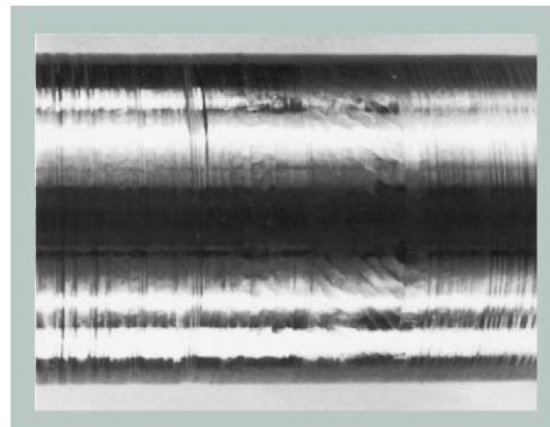
Relative time required to machine with various cutting-tool materials, with indication of the year the tool materials were introduced

Cutting fluids

- Reduce friction and wear
 - improve tool life, surface finish
 - Cool cutting zone
 - reduce temperature and distortion
 - Wash chips away
 - Prevent corrosion
 - Reduces forces and energy consumption
- | | |
|--|--|
| <ul style="list-style-type: none">• Water based<ul style="list-style-type: none">– contain salts or soluble oils• Mineral-oil based• Synthetic | <ul style="list-style-type: none">• Bio-degradable• Bio-resistant• Soaps• Defoamers• Sulphur• Chlorinated |
|--|--|
- Brush
 - manual
 - Mist
 - mostly water based coolants
 - Flood

Vibrations

- Forced
 - periodic applied force
 - from a motor or gear drive
- Self-excited
 - interaction of dynamics of chip removal process and structural dynamics of machine tool
 - Results from vibration
 - Tool bounces in and out of the workpiece



How to eliminate vibrations

- Stiffer machines
- Tuned dampers
- Active control
- Support workpiece rigidly
- Minimize cutter overhang
- Modify tool and cutter geometry
- Change process parameters
 - speed, feed, depth of cut, cutting fluid

