# Conventional Machining - 2

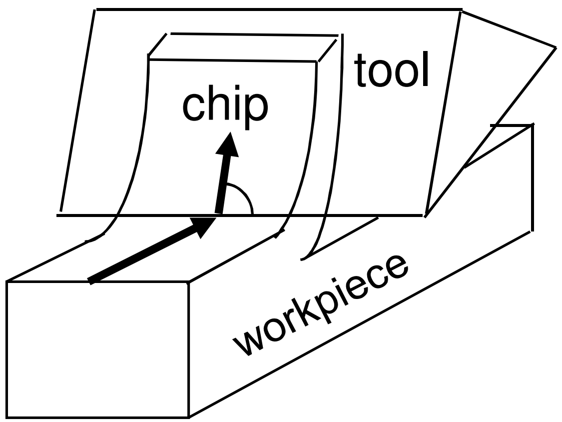
ME 338: Manufacturing Processes II
Instructor: Ramesh Singh; Notes: Profs. Singh/Melkote/Colton

# Outline

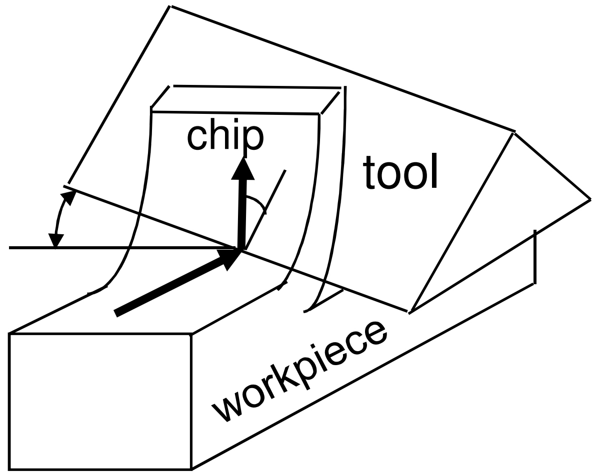
- Machining basics
- Mechanics of chip formation
- Tool wear and tool life
- Surface finish and integrity

# Machining Basics

- Conventional machining: removal of material from a workpiece in the form of a chip via brute force of a sharp cutting tool




**Orthogonal Cutting**




**Oblique Cutting**

# Classification of Conventional Machining

- Cutting processes
  - Single point: e.g. shaping, planing, turning, boring, etc.
  - Multiple point: e.g. milling, drilling, etc.
- Abrasive processes
  - Grinding, honing, etc.

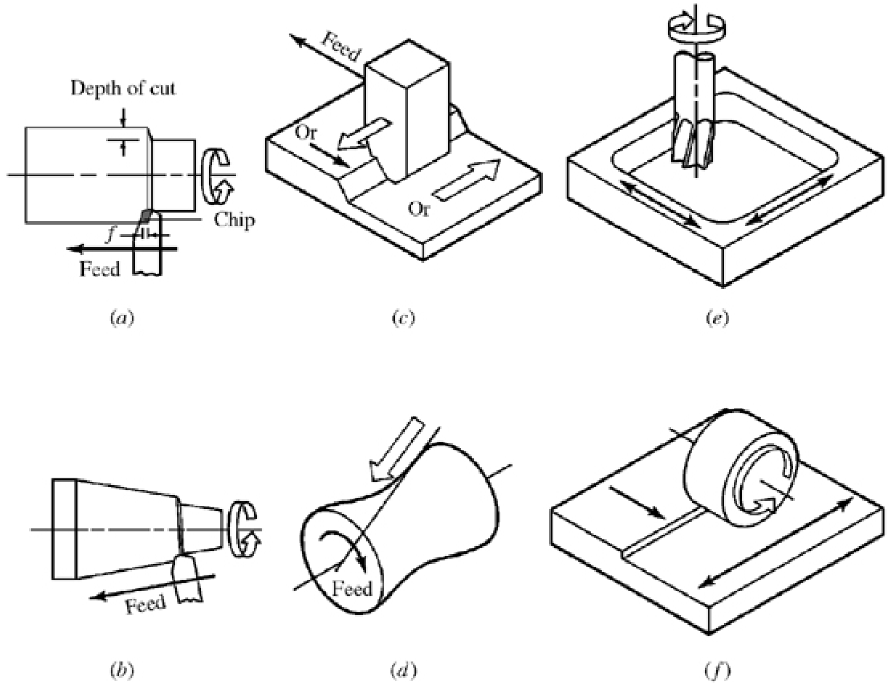


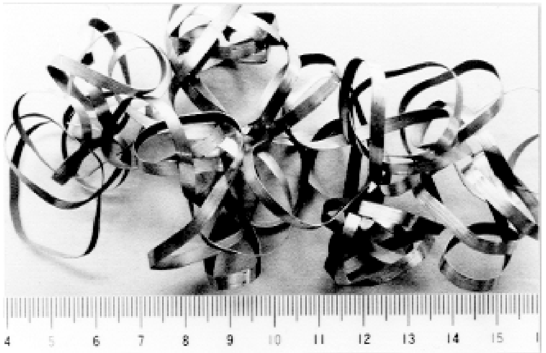

figure 16.25

# Major Process Variables

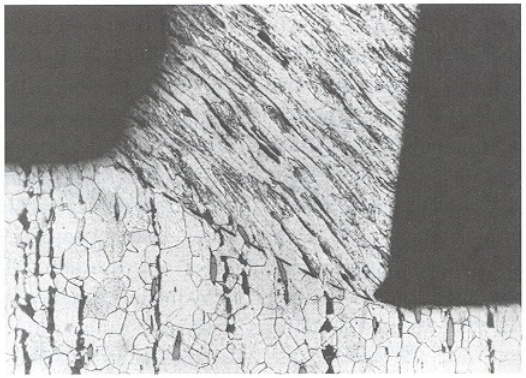
- Independent variables
  - Cutting conditions e.g. feed, speed, depth of cut
  - Tool and workpiece materials
  - Tool geometry
  - Machine tool
  - Workholding devices
  - Cutting fluids
- Dependent variables
  - Chip type
  - Cutting forces and energy dissipation
  - Temperature rise
  - Tool wear
  - Surface finish/integrity

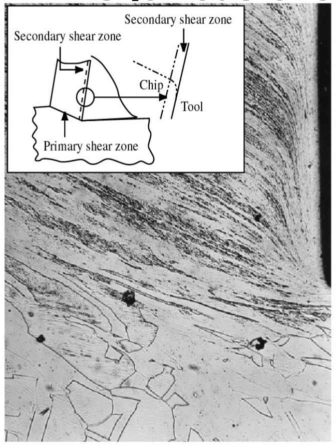
# Major Chip Types

- Continuous: ductile metals, thermoplastics



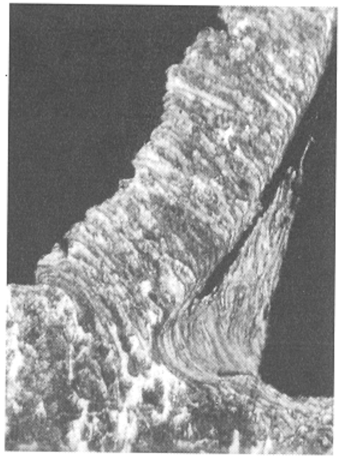






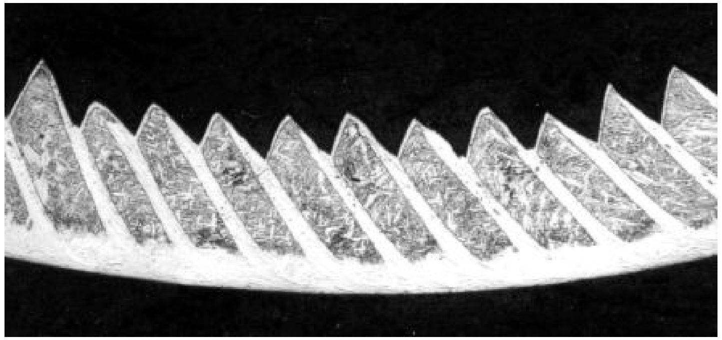


- Continuous with built-up edge (BUE): at low cutting speeds



# Major Chip Types

- Segmented: low thermal diffusivity materials, very hard steels



- Discontinuous: brittle materials

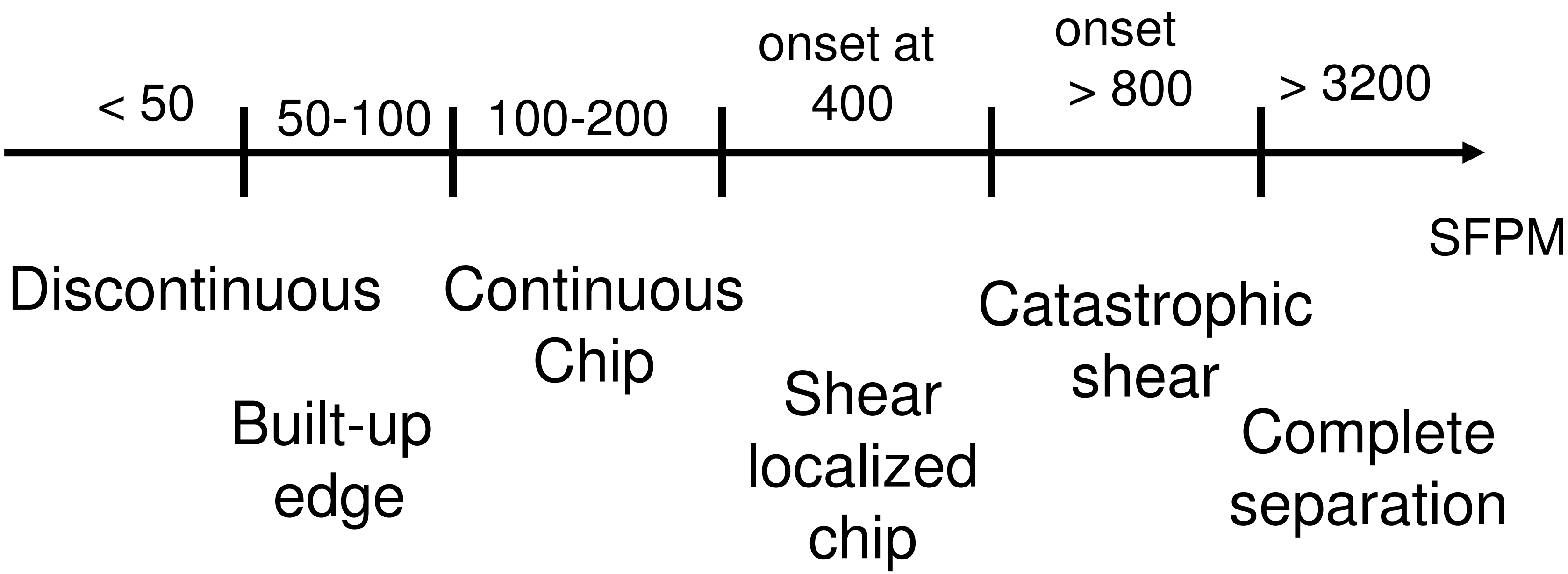
# Chip Types-Characteristics

- (a) Continuous chip with narrow primary shear zone
  - ductile materials at high speed
  - bad for automation (use chip breakers)
- (b) Secondary shear zone at chip-tool interface
  - increased energy dissipation
- (c) Continuous chip with built up edge (BUE)
  - high plastic working
  - bad for automation

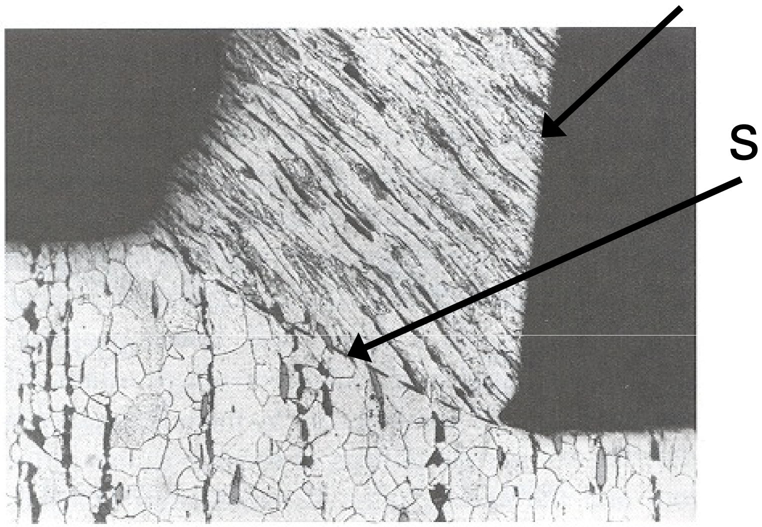
# Chip Types

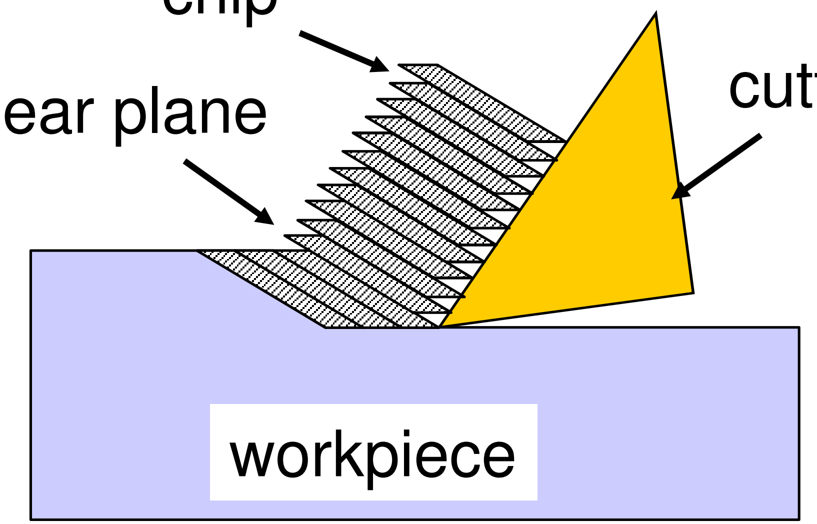
- (d) Continuous chip with large primary shear zone
  - soft metals at low speeds and low rake angles
  - poor surface finish
  - residual stresses
- (e) Segmented chip
  - low thermal conductivity materials
- (f) Discontinuous chip
  - low ductility materials and/or negative rake angles
  - good for automation

# Chip Formation - AISI 4340

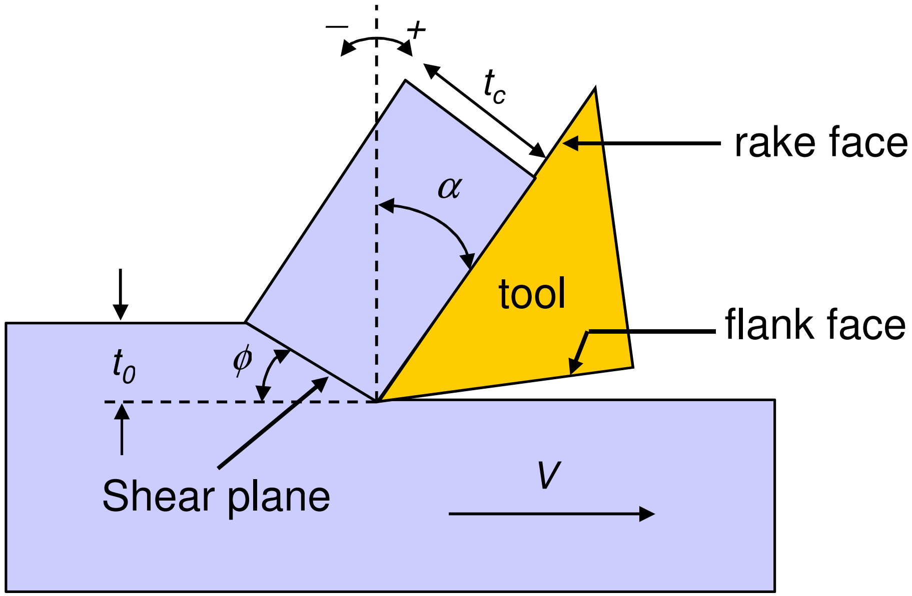


# Piispanen's Card Model of Continuous Chip Formation



# Major Variables in Orthogonal Cutting




$t_0$ : undeformed chip thickness

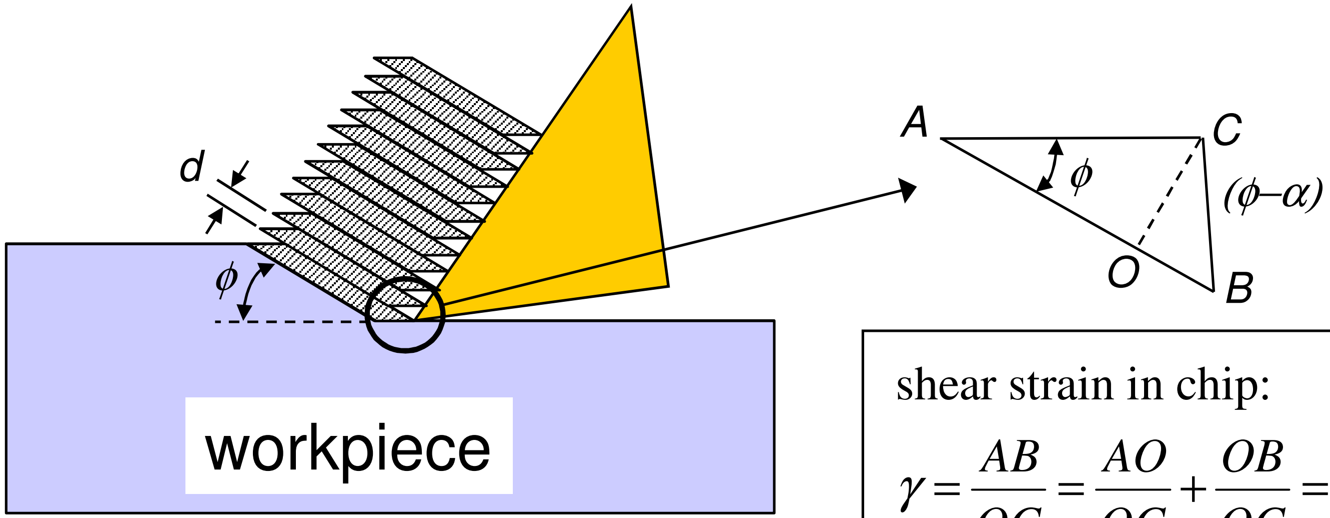
$t_c$ : deformed chip thickness

$\alpha$ : rake angle

$\phi$ : shear angle

$V$ : cutting speed

# Kinematics of Orthogonal Cutting




shear strain in chip:

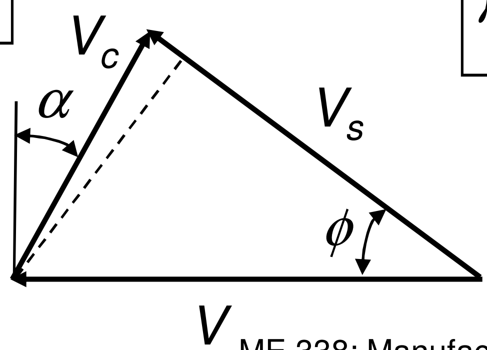
$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC} = \cot\phi + \tan(\phi - \alpha)$$

cutting ratio:

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

shear strain rate:

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




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

# Kinematics of Orthogonal Cutting

$V_s$ = shear velocity (along shear plane)
$V_c$ = chip velocity

- Typical strains, $\gamma = 2 \sim 5$
- Typical strain rates, $\dot{\gamma} = 10^4 \sim 10^6 \text{ s}^{-1}$
- Deformed chip thickness, $t_c$ > undeformed chip thickness, $t_0 \rightarrow r < 1$

# Forces in Orthogonal Cutting

Knowledge of cutting forces needed for:

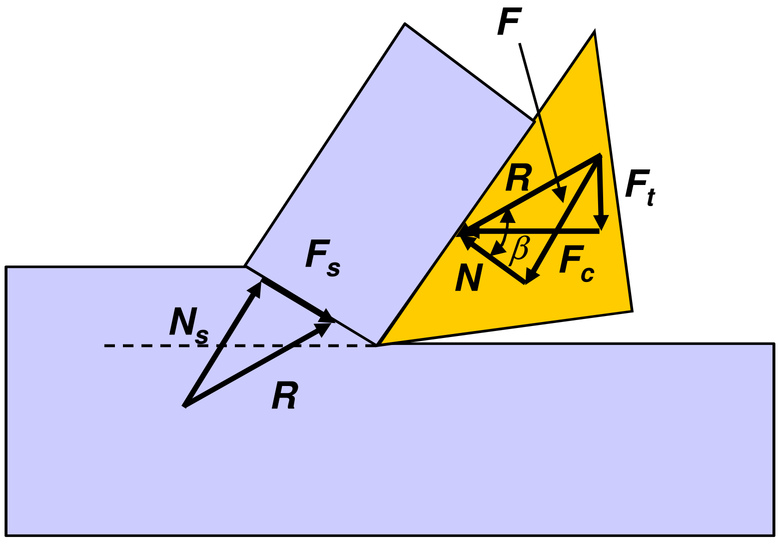
- Estimation of power requirements
- Machine tool design e.g. static/dynamic stiffness
- Part accuracy e.g. tool-workpiece deflections

# Forces in Orthogonal Cutting

Assumptions

- 2-d cutting process → plane strain process → 2-d force system
- $t_0 << w$ (width of cut)
- Infinitely sharp cutting edge
- Continuous chip with no BUE
- No chip curl
- No tool wear
- Uniform shear and normal stresses along shear plane and tool-chip interface

# Forces in Orthogonal Cutting




$R$ : 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

Shear plane decomposition of resultant force:

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

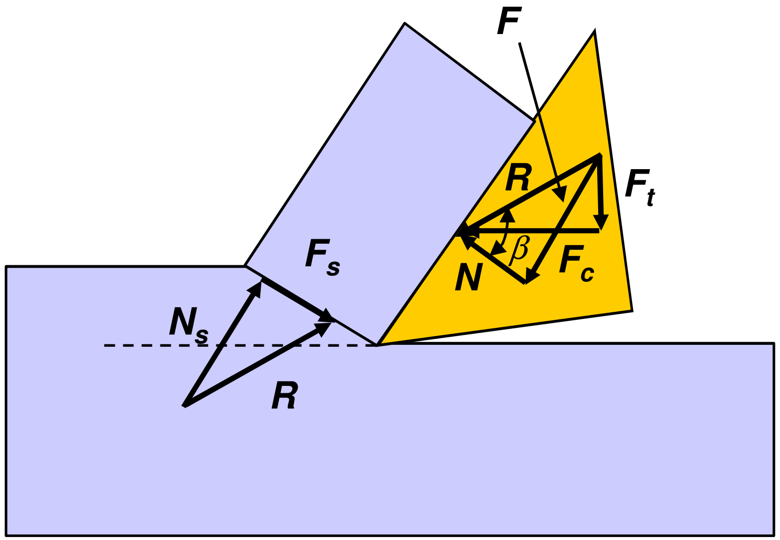
$$N_s = F_t \cos\phi + F_c \sin\phi = F_s \tan(\phi + \beta - \alpha)$$

Tool-chip interface decomposition of resultant force:

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

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

# Forces in Orthogonal Cutting




Tool-chip interface mean friction:

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

Forces:

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

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

$$F_c = \frac{\tau w t_0 \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$

$$F_t = \frac{\tau w t_0 \sin(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$

$$F_c \propto w t_0$$

$$F_t \propto w t_0$$

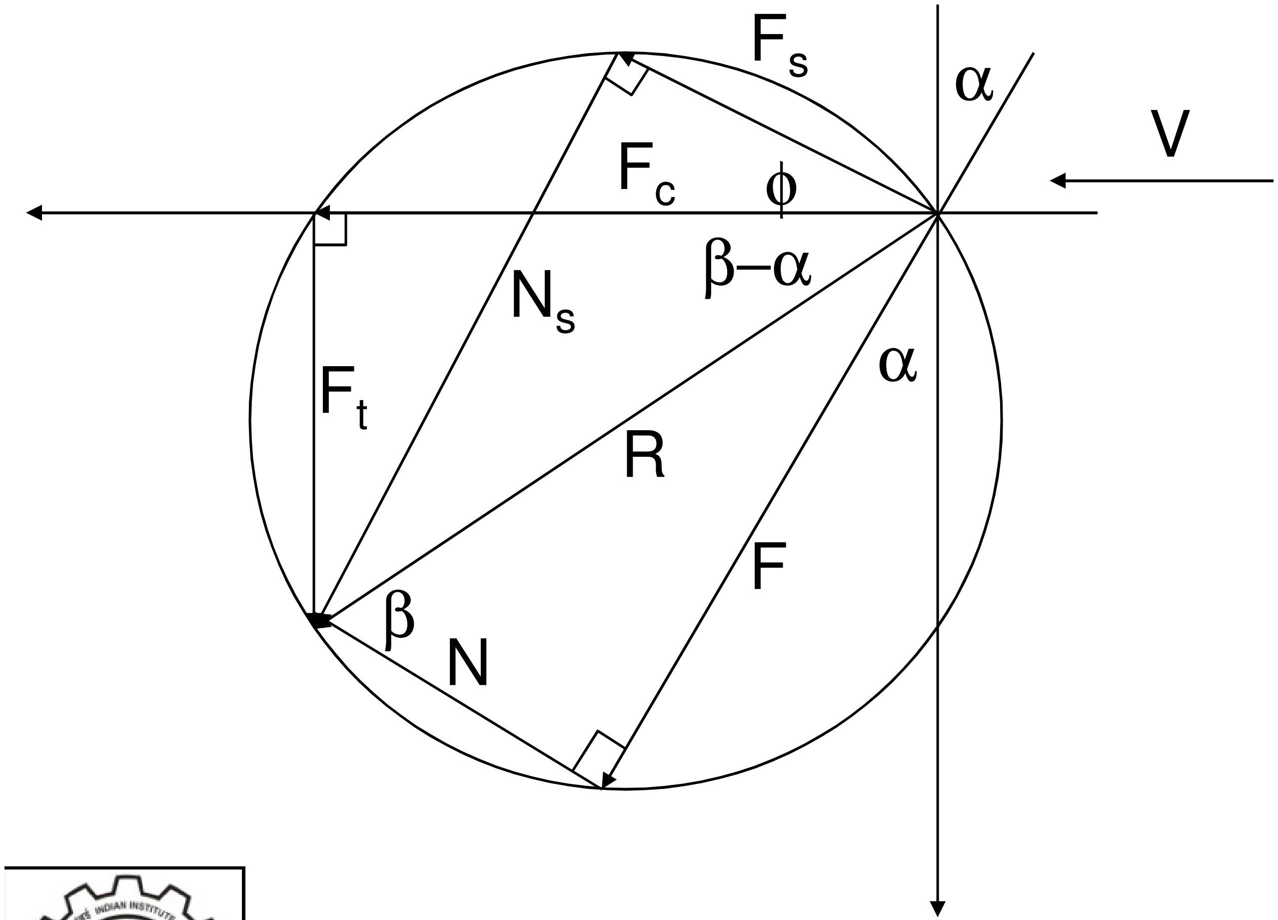
Shear plane stresses:

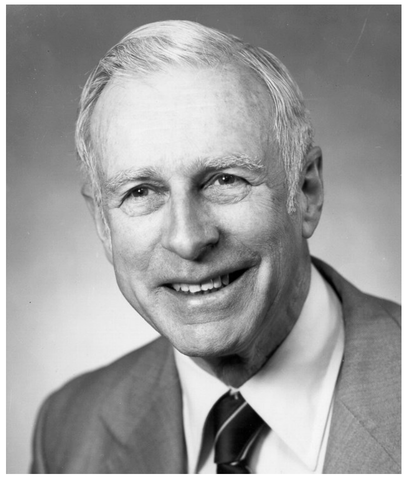
$$\tau = \frac{F_s}{A_s} \rightarrow F_s = \tau A_s$$

$$A_s = \frac{w t_0}{\sin\phi}$$

$$\sigma = \frac{N_s}{A_s} = \frac{(F_c \sin\phi + F_t \cos\phi)\sin\phi}{w t_0}$$

# Merchant's Force Circle



M. Eugene Merchant
1913 - 2006

# Cutting With an Oblique Tool

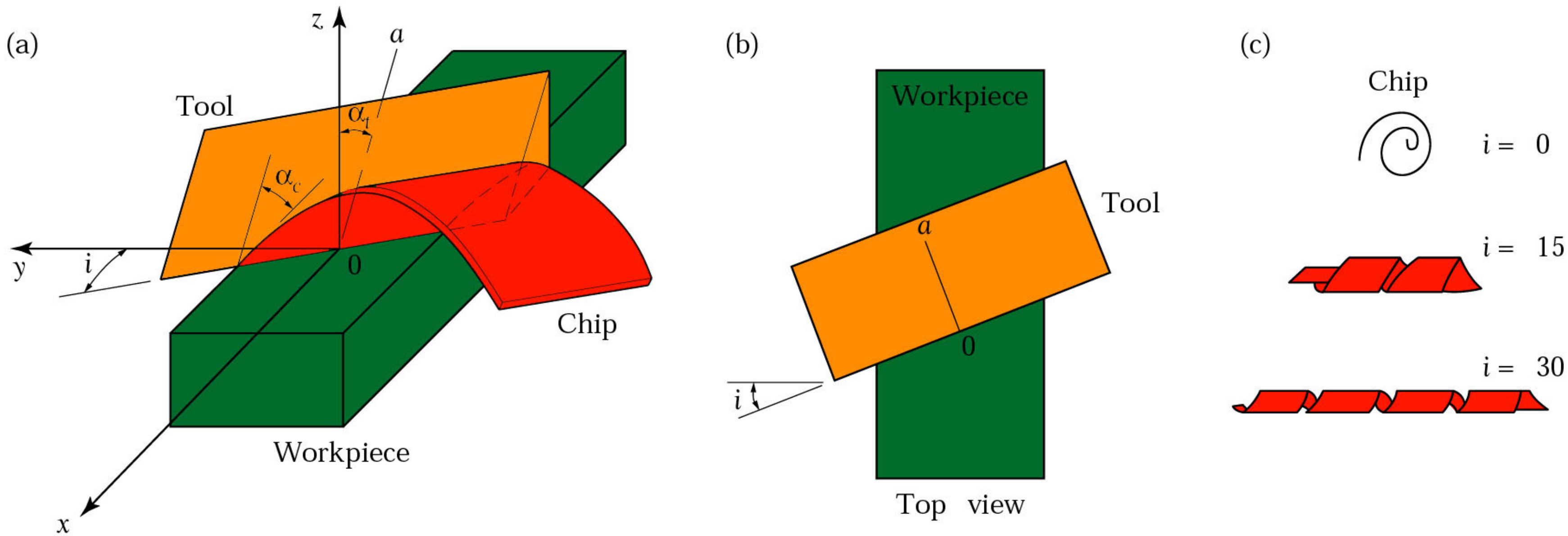



Figure 20.9 (a) Schematic illustration of cutting with an oblique tool. (b) Top view showing the inclination angle, *i*. (c) Types of chips produced with different inclination.

$$\alpha_e = \sin^{-1}\left(\sin^2 i + \cos^2 i \sin \alpha_n\right)$$

# Merchant's 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

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

- OK for plastic but does not hold very well for most metals
- General form of shear angle relationship

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

# Mathematica Solution

$$F_c = \frac{\tau\, A_c \,\mathrm{Cos}[\beta - \alpha]}{\mathrm{Sin}[\phi]\,\mathrm{Cos}[\phi + \beta - \alpha]}$$

Differentiation of $F_c$ with respect to $\phi$

$$D[F_c,\ \phi]$$

$$-\tau\,\mathrm{Cos}[\alpha-\beta]\,\mathrm{Cot}[\phi]\,\mathrm{Csc}[\phi]\,\mathrm{Sec}[\alpha-\beta-\phi]\,A_c - \tau\,\mathrm{Cos}[\alpha-\beta]\,\mathrm{Csc}[\phi]\,\mathrm{Sec}[\alpha-\beta-\phi]\,A_c\,\mathrm{Tan}[\alpha-\beta-\phi]$$

$$\mathrm{FullSimplify}[-\tau\,\mathrm{Cos}[\alpha-\beta]\,\mathrm{Cot}[\phi]\,\mathrm{Csc}[\phi]\,\mathrm{Sec}[\alpha-\beta-\phi]\,A_c - \tau\,\mathrm{Cos}[\alpha-\beta]\,\mathrm{Csc}[\phi]\,\mathrm{Sec}[\alpha-\beta-\phi]\,A_c\,\mathrm{Tan}[\alpha-\beta-\phi]]$$

$$\tau\left(-\mathrm{Csc}[\phi]^2 + \mathrm{Sec}[\alpha-\beta-\phi]^2\right) A_c$$

Actual differentiation:

$$\frac{Sin(\phi+\beta-\alpha)}{Sin(\phi)Cos^2(\phi+\beta-\alpha)}-\frac{Cos(\phi)}{Sin^2(\phi)Cos(\phi+\beta-\alpha)}=0$$

$$Cos(2\phi+\beta-\alpha)=0$$

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

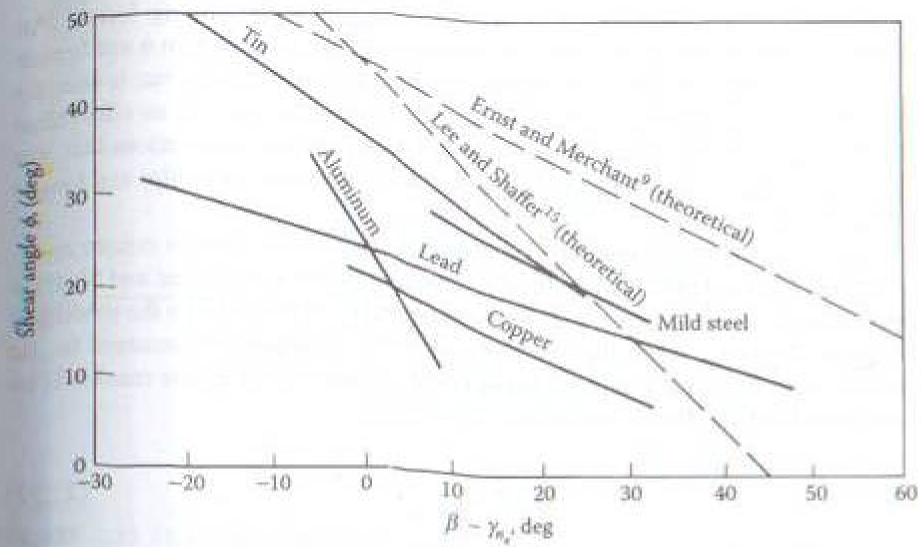
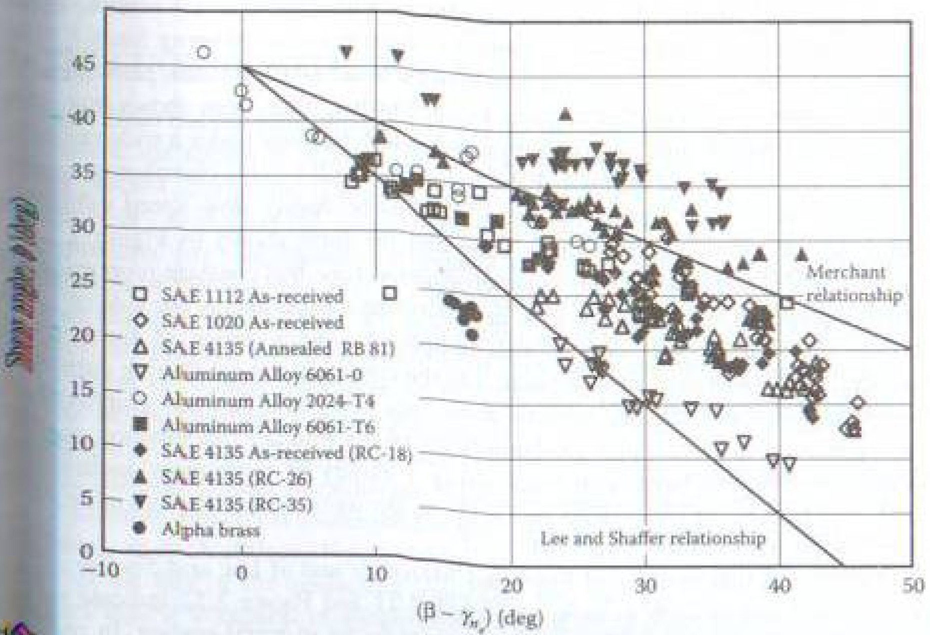


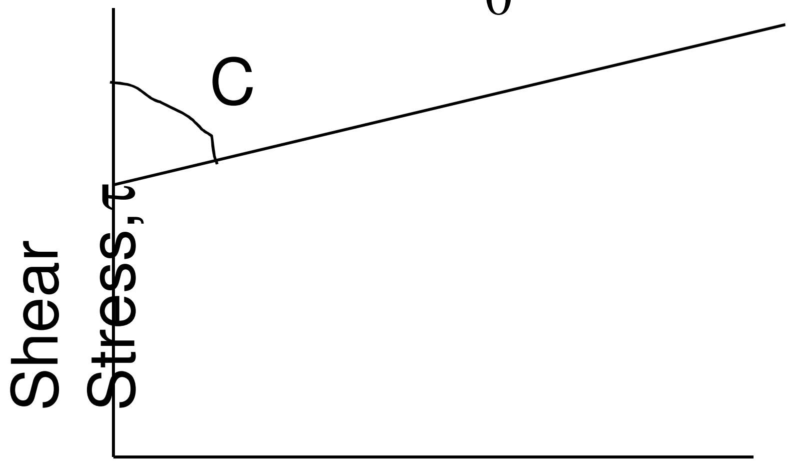

**FIGURE 2.21** Comparison of theoretical and experimental shear-angle relationships for orthogonal metal cutting, where $\phi$ = shear angle, $\gamma_{ne}$ = working normal rake, and $\beta$ = mean friction angle on tool face. (After Pugh., H.D., Proc. Inst. Mech. Eng. Conf. Technol. Eng. Manuf., London, 1958, 235.)




URE 2.22 Experimental shear angle results; top line represents Merchant's relation- and the bottom line represents Lee and Shaffer's relationship. (Adapted from Koba- ni, S., et al., *Trans. ASME, J. Eng. Ind.*, Vol.82B/4, 333–347, 1960.)

# Modified Merchant Relationship

$$\tau = \tau_0 + k\sigma$$



# Modified Merchant’s Rel. (Contd.)

- From Force Circle,

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

$$N_s = R\sin(\phi + \beta - \alpha)$$

$$\tau = \frac{R\sin\phi\cos(\phi + \beta - \alpha)}{A_c}$$

$$\sigma = \frac{R\sin\phi\sin(\phi + \beta - \alpha)}{A_c}$$

$$\tau = \tau_0 + k\sigma$$

$$\frac{R\sin\phi\cos(\phi + \beta - \alpha)}{A_c} = \tau_0 + k\frac{R\sin\phi\sin(\phi + \beta - \alpha)}{A_c}$$

$$R = \frac{\tau_0 A_c}{\sin\phi\left(\cos(\phi + \beta - \alpha) - k\sin(\phi + \beta - \alpha)\right)}$$

# Modified Merchant's Rel. (Contd.)

$$R = \frac{\tau_0 A_c}{\sin\phi\left(\cos(\phi+\beta-\alpha) - k\sin(\phi+\beta-\alpha)\right)}$$

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

$$F_c = \frac{\tau_0 A_c \cos(\beta-\alpha)}{\sin\phi\left(\cos(\phi+\beta-\alpha) - k\sin(\phi+\beta-\alpha)\right)}$$

# Mathematica Solution

In[1]:= $$F_c = \frac{\tau A_c \text{Cos}[\beta - \alpha]}{\text{Sin}[\phi]\ (\text{Cos}[\phi + \beta - \alpha] - k\ \text{Sin}[\phi + \beta - \alpha])}$$

Out[1]= $$\frac{\tau \text{Cos}[\alpha - \beta]\ \text{Csc}[\phi]\ A_c}{\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi]}$$

In[2]:= $D[F_c,\ \phi]$

Out[2]= $$-\frac{\tau \text{Cos}[\alpha - \beta]\ \text{Csc}[\phi]\ (-k\ \text{Cos}[\alpha - \beta - \phi] + \text{Sin}[\alpha - \beta - \phi])\ A_c}{(\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi])^2} - \frac{\tau \text{Cos}[\alpha - \beta]\ \text{Cot}[\phi]\ \text{Csc}[\phi]\ A_c}{\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi]}$$

In[5]:= $$\text{FullSimplify}\left[-\frac{\tau \text{Cos}[\alpha - \beta]\ \text{Csc}[\phi]\ (-k\ \text{Cos}[\alpha - \beta - \phi] + \text{Sin}[\alpha - \beta - \phi])\ A_c}{(\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi])^2} - \frac{\tau \text{Cos}[\alpha - \beta]\ \text{Cot}[\phi]\ \text{Csc}[\phi]\ A_c}{\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi]}\right]$$

Out[5]= $$-\frac{\tau \text{Cos}[\alpha - \beta]\ \text{Csc}[\phi]^2\ (\text{Cos}[\alpha - \beta - 2\phi] + k\ \text{Sin}[\alpha - \beta - 2\phi])\ A_c}{(\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi])^2}$$

In[6]:= $$\text{Solve}\left[\frac{\tau \text{Cos}[\alpha - \beta]\ \text{Csc}[\phi]^2\ (\text{Cos}[\alpha - \beta - 2\phi] + k\ \text{Sin}[\alpha - \beta - 2\phi])\ A_c}{(\text{Cos}[\alpha - \beta - \phi] + k\ \text{Sin}[\alpha - \beta - \phi])^2} == 0,\ \phi\right]$$

# Modified Merchant's Relationship

- From Mathematica;

$$Cos(-(2\phi+\beta-\alpha)) - kSin((2\phi+\beta-\alpha)) = 0$$

$$Cos(2\phi+\beta-\alpha) = kSin(2\phi+\beta-\alpha)$$

$$(2\phi+\beta-\alpha) = Cot^{-1}(k)$$

$$2\phi+\beta-\alpha = C$$

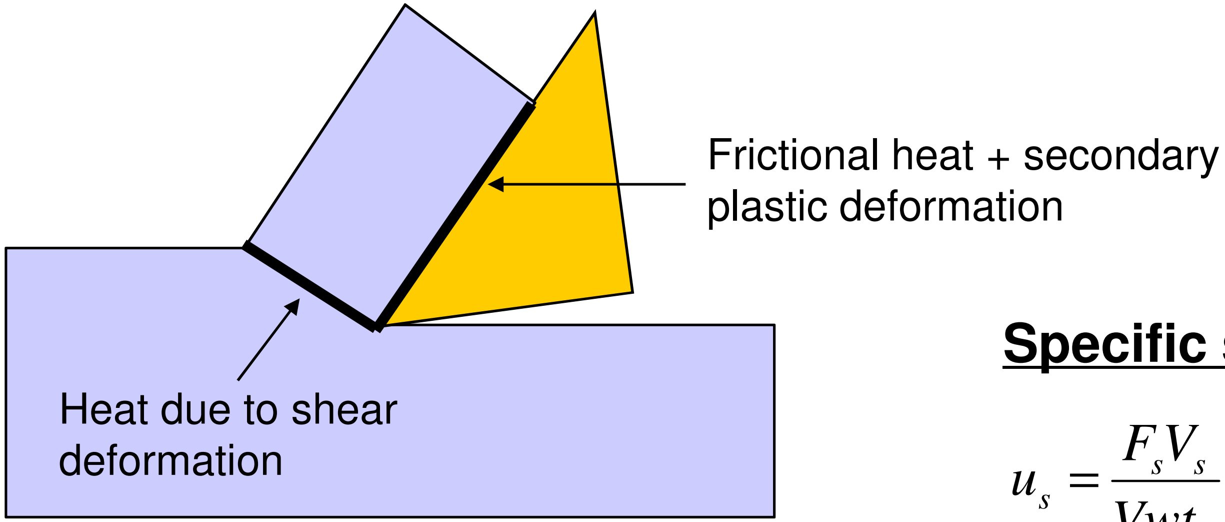
TABLE 7.1

Values of machining constant, $C$

| Type of work material (Hot-rolled steels) | Machining constant $C$ in degrees |
|---|---|
| AISI–1010 | 69·8 |
| AISI–1020 | 69·6 |
| AISI–1045 | 78·0 |
| AISI–2340 | 76·2 |
| AISI–3140 | 70·6 |
| AISI–4340 | 74·5 |
| Stainless–303 | 92·0 |
| Stainless–304 | 82·0 |

According to Merchant, $C$ is a property of work material u conditions but micro-structure and grain size have affect on $C$. Col increases its machining constant.

# Energy Dissipation in Cutting




## Specific shear energy

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

## Specific cutting energy

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

## Specific friction energy

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

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

# Energy Dissipation in Cutting

$P_c$ = 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 1

A planing process is being used to machine a 300 mm x 300 mm x 25 mm flat mild steel block as shown in the figure. 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 $t_0$ = 0.25 mm, width of cut per pass $w$ = 2.5 mm, deformed chip thickness $t_c$ = 0.83 mm. The cutting and thrust forces were measured during each pass with a cutting force dynamometer and found to be as follows: $F_c$ = 890 N and $F_t$ = 667 N. (Note: Planing is an orthogonal cutting process). Calculate the percentage of total power dissipated in the primary zone of deformation (shear zone).

# Example 1 (contd)

Solution:

$P_c = F_c V = (890)(2) = 1780$ W

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

R = $\sqrt{F_c^2 + F_t^2} = 1112.2N$

$$\tan\varphi = \frac{r\cos\alpha}{1 - r\sin\alpha} = \frac{(0.25/0.83)*\cos(10)}{1-(0.25/0.83)*\sin(10)} \Rightarrow \varphi = 17.3\deg$$

$$\beta = \tan^{-1}\left(\frac{F_t + F_c\tan\alpha}{F_c - F_t\tan\alpha}\right) = 46.85\deg$$

Atlernatively,
$\beta-\alpha=\tan^{-1}(F_t/F_c)$

# Example 1 (contd)

$$V_s = \frac{V \cos\alpha}{\cos(\varphi - \alpha)} = 1.986 m/s$$

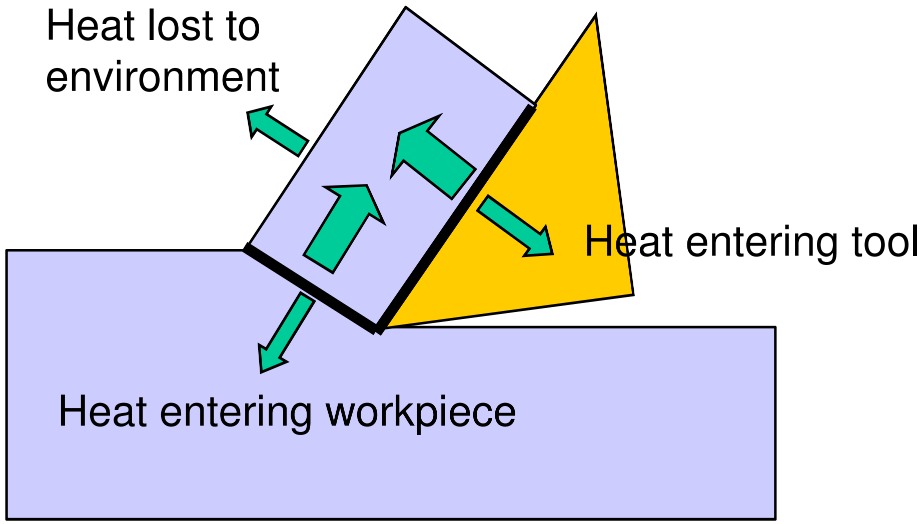
$P_s = F_s V_s = 1293.63$ W

% of total power dissipated in shear zone =

$$\frac{P_s}{P_c} \times 100 = 72.6\%$$

# Cutting Temperatures

- Energy dissipated in cutting → converted into heat in shear zone and tool-chip interface




- Heat transfer to environment is negligible

# Cutting Temperatures

- 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

# Cutting Temperatures

- Mean temperature rise of material passing through shear zone

$$\overline{\theta}_s = \frac{(1-\Gamma)P_s}{\rho c V w t_0}$$

Where $\Gamma$ = fraction of shear zone heat conducted into workpiece

$\rho$ = density of workpiece material

$c$ = specific heat of work material

- Mean temperature rise of the chip due to frictional heat from the tool-chip interface

$$\overline{\theta}_f = \frac{P_f}{\rho c V w t_0}$$

# Example 2

For the problem in Example 1 calculate the mean temperature rise in the chip if it is given that the power dissipated into the workpiece per pass of the tool is 200 W. Assume the density of mild steel is 7200 $kgm^{-3}$ and specific heat is 502 $Jkg^{-1}K^{-1}$. Also assume that the cutting tool is insulated and no heat is lost to the environment.

Solution:

Total cutting power, $P_c = P_s + P_f$

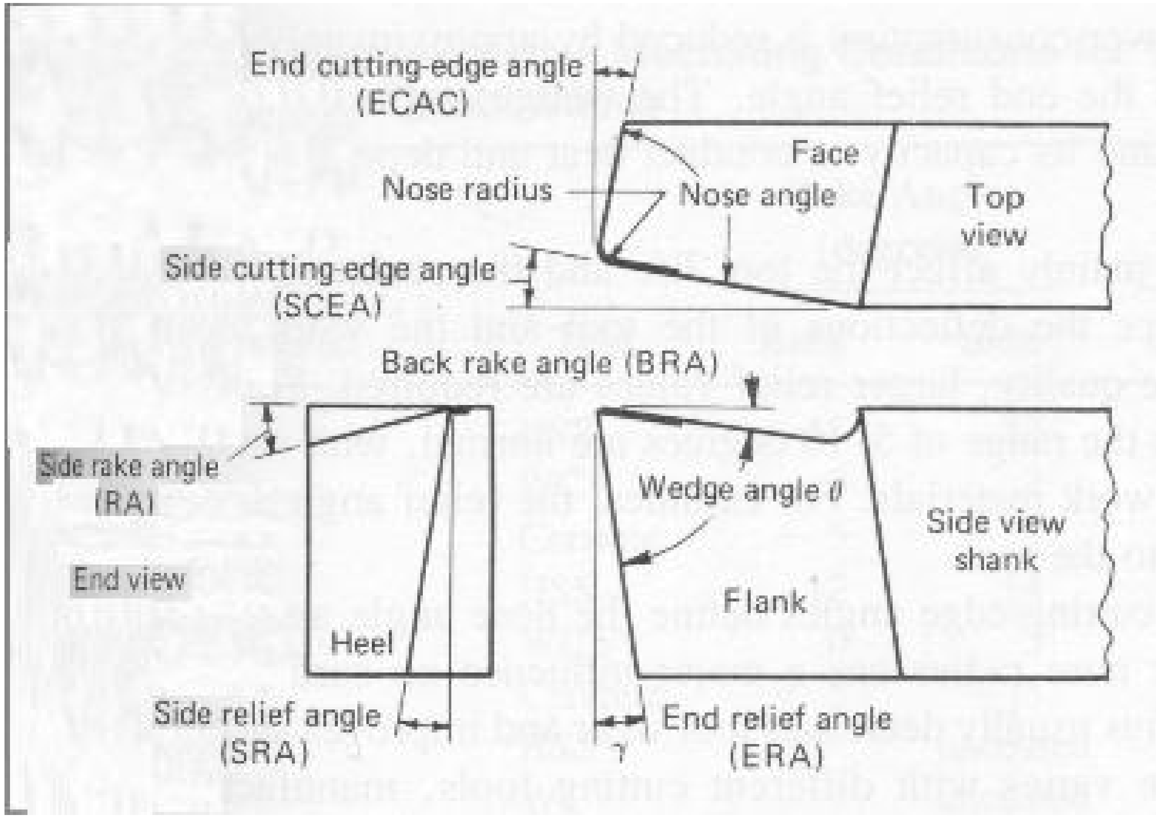
Insulated tool → no heat goes into tool

Total heat dissipated in the chip = $P_c$ – 200 = 1780 – 200 = 1580 W

Mean temperature rise in chip,

$$\Delta T = \frac{1580}{\rho c V w t_0} = 349.71 \text{ K}$$

# Tool Geometry for Single Point Tool



# Wear

- Wear: loss of material from a surface
- Mechanisms
  - Adhesive wear
  - Abrasive wear
  - Corrosive wear
  - Fatigue wear

# Adhesive Wear

- Mechanical wear process; wear particles generated from the softer of two contacting surfaces; characterized by metal transfer from softer to harder body

- Archard's wear equation:

$$V = K\frac{LN}{3H}$$

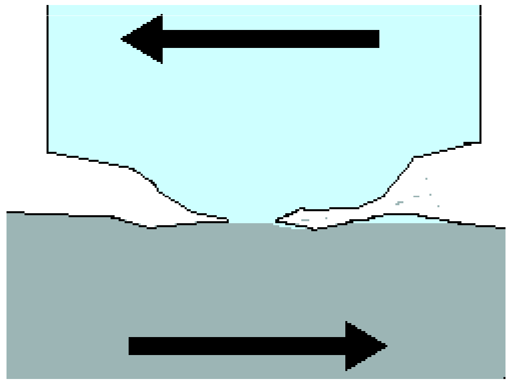
*K: wear coefficient*

*V: volume of wear*

*L: sliding distance*

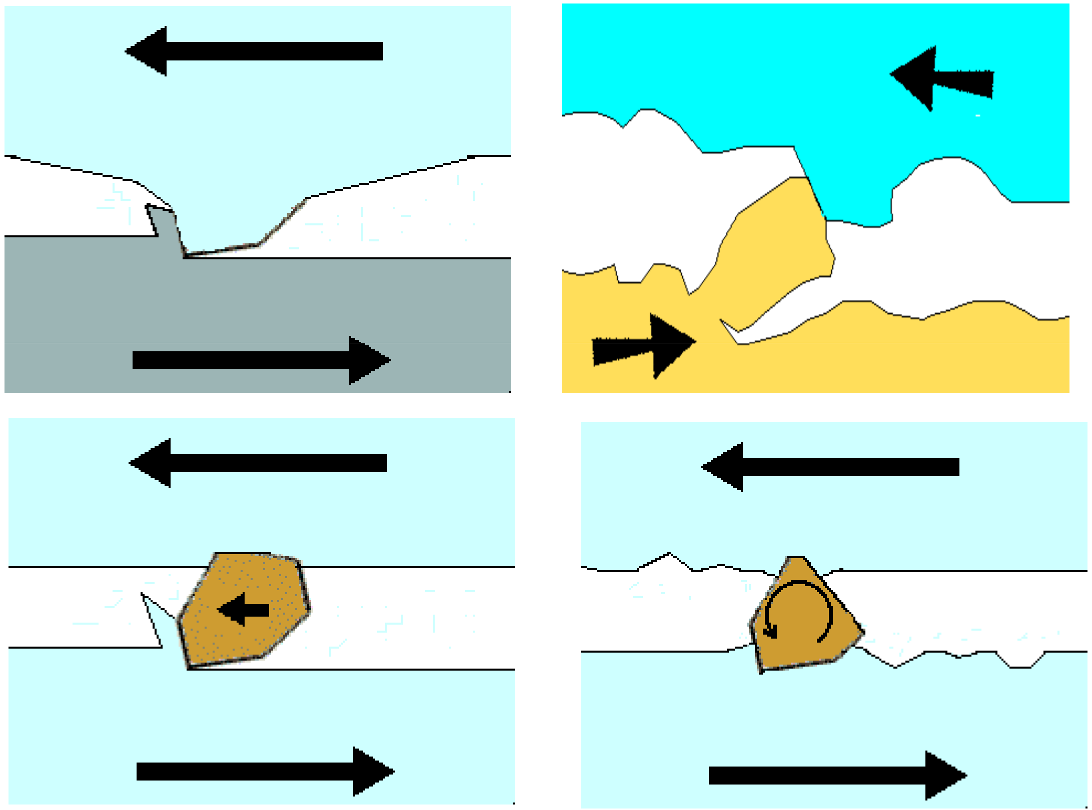
*N: normal load*

*H: hardness of softer surface*



# Abrasive Wear

- Mechanical wear process; loss of material by micro-cutting action



2-body wear

3-body wear

- Abrasive wear resistance ∝ hardness

# Corrosive Wear

- Chemical wear process; due to chemical reactions between the surface and environment (water, oxygen, acids, etc.)

- Example: solution wear of cemented carbide cutting tool materials when cutting ferrous metals at high speeds

# Fatigue Wear

- Loss of material from a surface due to fracture under cyclic loading conditions
  - Mechanical fatigue wear: fracture due to cyclic mechanical loads e.g. spalling in roller bearing races

  - Thermal fatigue wear: fracture due to thermal cycling, e.g. hot forging with cool dies

# Tool Wear and Tool Life

- Problem of economic importance
- Factors affecting tool wear
  - Tool material
  - Workpiece material
  - Cutting conditions
  - Tool geometry

- End of tool life can occur by
  - Progressive wear of flank and/or rake face of tool
  - Catastrophic failure

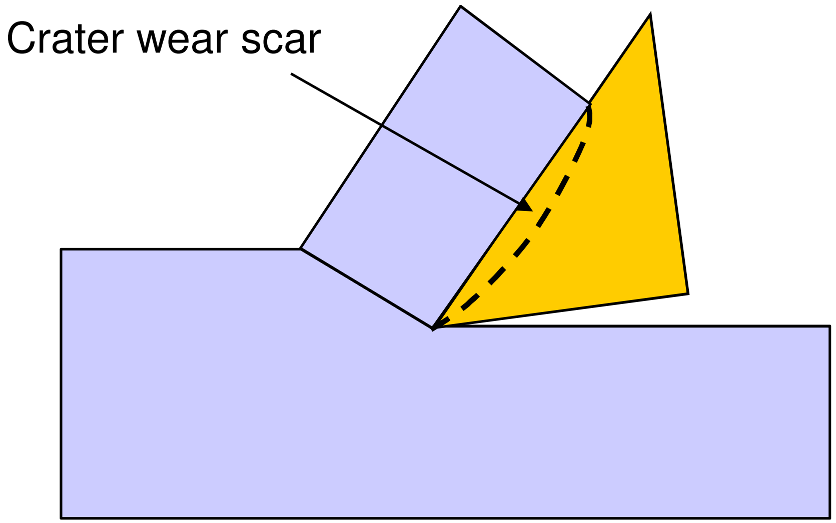
# Cutting Tool Failure-I

- Progressive wear and catastrophic failure
- Tool Life Criterion determines life of tool
  – Flank wear width
  – Crater depth
  – Catastrophic failure

Whichever occurs first

# Progressive Tool Wear

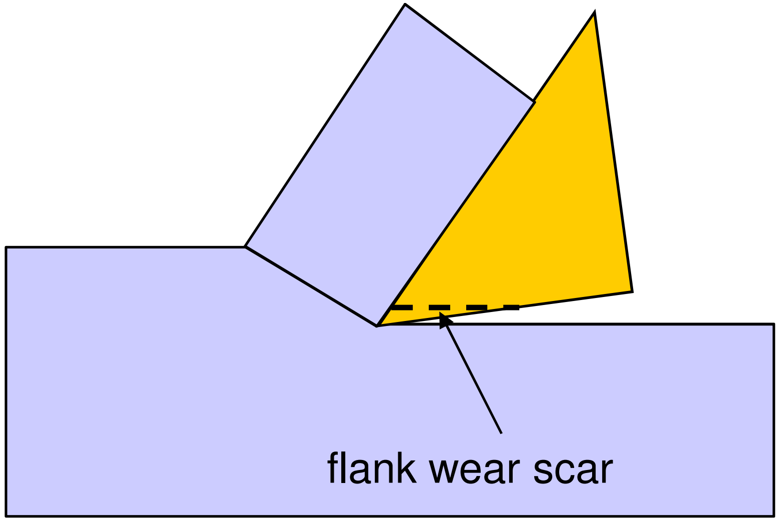
- Crater wear: wear scar on rake face of tool



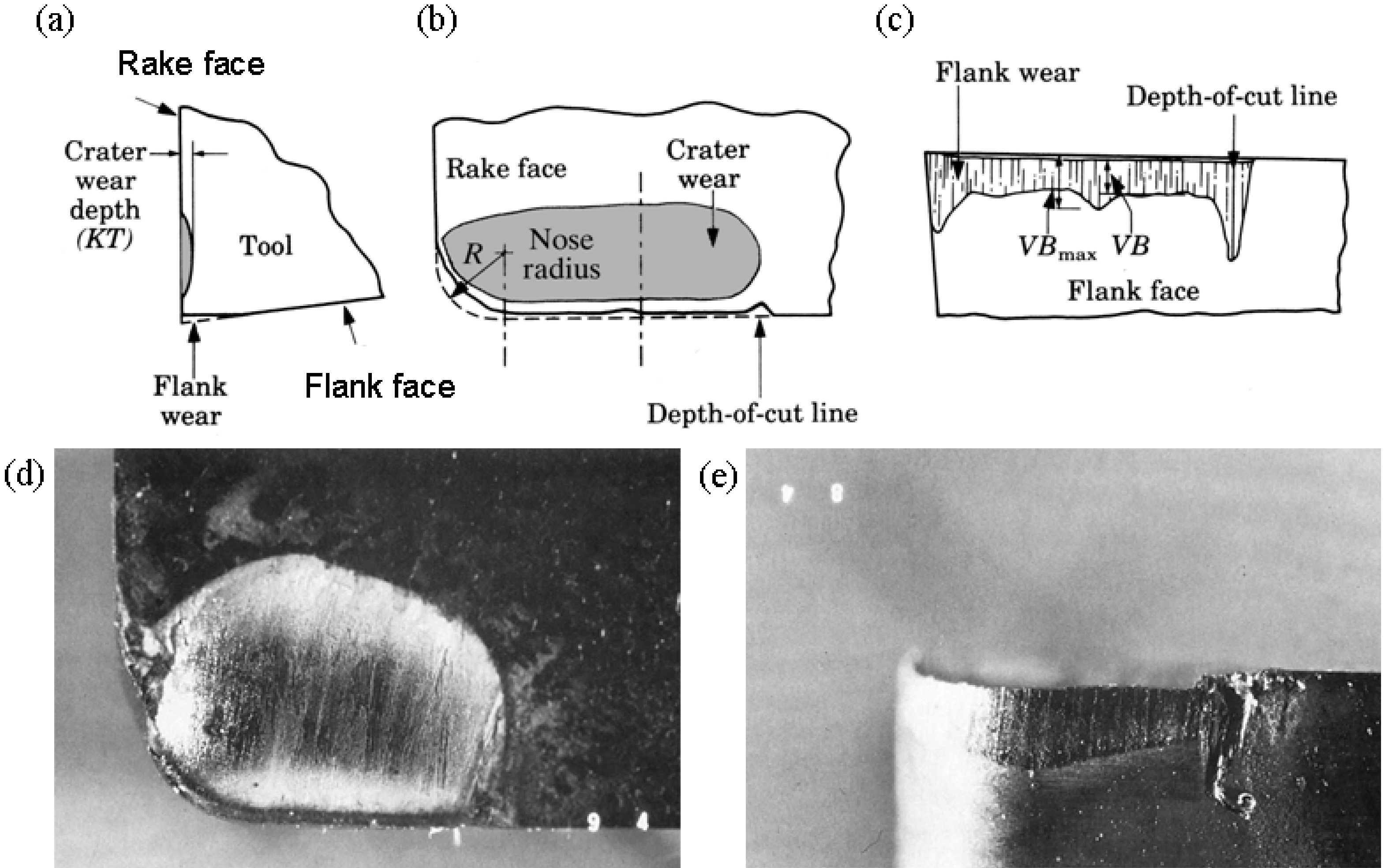

- Possible mechanisms: adhesion, abrasion, diffusion (at high cutting speeds)

# Progressive Tool Wear

- Flank wear: wear scar on flank face of tool




- Possible mechanisms: adhesion, abrasion (due to rubbing of flank face against cut surface)

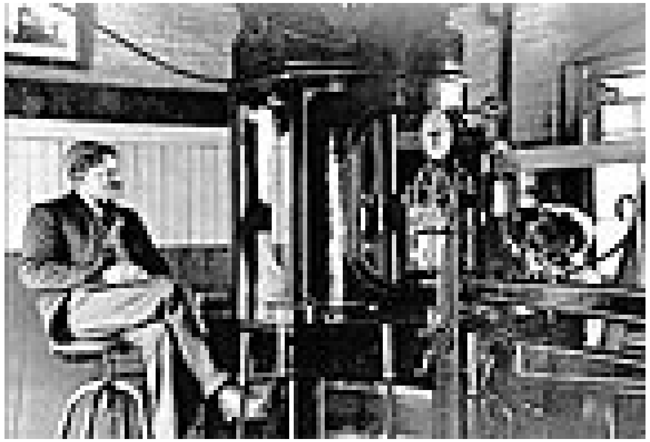

(a)
Rake face
Crater wear depth (KT)
Tool
Flank wear
Flank face
(b)
Rake face
Crater wear
R
Nose radius
Depth-of-cut line
(c)
Flank wear
Depth-of-cut line
VB max
VB
Flank face
(d)
(e)

# Cutting Tool Failure - III

- ISO Criterion for HSS, WC, Ceramic
  - VB = 0.3 for regular
  - VBmax = 0.6 for irregular
  - Catastrophic
  - KT = 0.06 + 0.3f, f = feed; for carbide tool

# F.W. Taylor's Contributions

- Metal cutting
- Time / motion studies
  - Led to Congressional inquiry and banning of stop watch use by civil servants (1921-1949)
- Design of shovels
- Scientific management



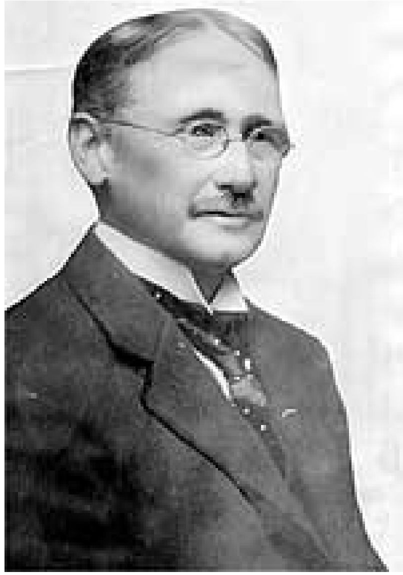
# Taylor's Equation

$$VT^n = C$$

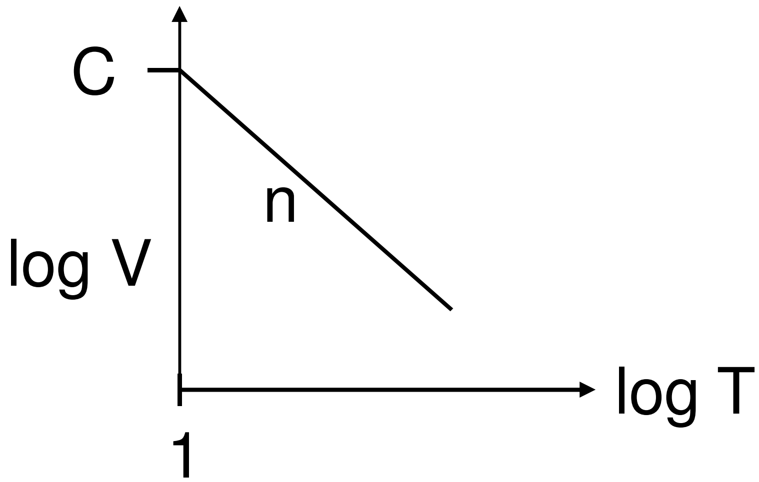
V = cutting speed

T = tool life

n, C = Taylor constants (empirical)



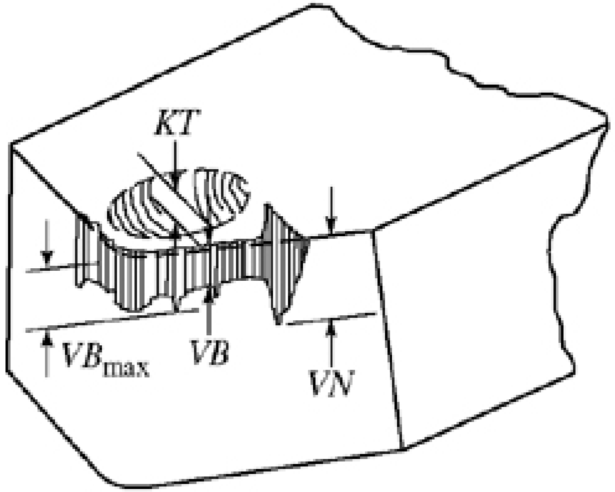
F.W. Taylor



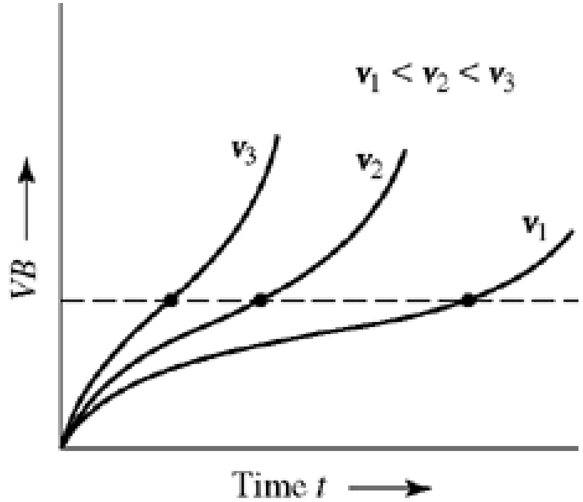

n For HSS – 0.1; WC-0.2; Ceramics-0.4

# Progressive Tool Wear-Flank

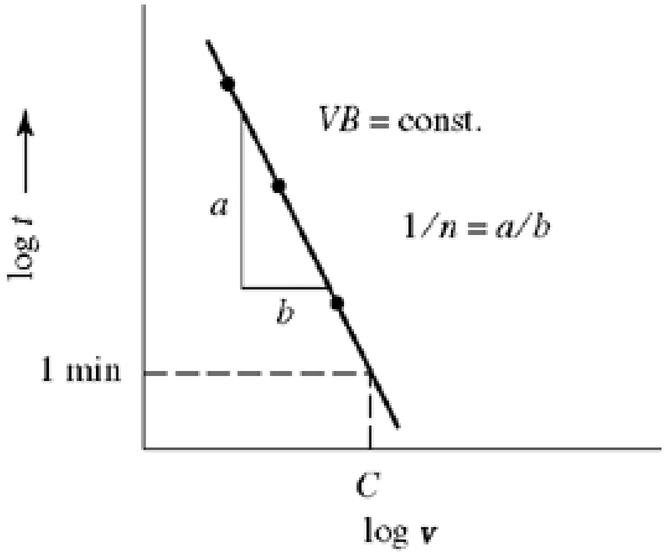
- Taylor's tool life curve $VT^n = C$



(a)



(b)



# Extended Taylor's Equation

$$VT^nf^m=C'$$

f = feed rate

- For high speed steels:

$$V\ T^{0.24}\ f^{0.45} = 23$$

$$T= C'\ V^{-4.2}\ f^{-1.9}$$

# Taylor's Equation

Derive Taylor's equation from data

| speed (V) (sfpm) [m/s] | tool life (T) (min) |
|---|---|
| 600 [3.1] | 19.95 |
| 700 [3.6] | 12.20 |

# Taylor's Equation

- $VT^n$@(600 sfpm) = $VT^n$@(700 sfpm)
- $700(12.2)^n = 600(19.95)^n$
- $700/600 = 1.167 = (19.95/12.2)^n$
- $n \approx 0.31$
- $C = 600 \times 19.95^{0.31} \approx 1520$
- $VT^{0.31} = 1520$

# Tool Failure-Crater Wear

- Severe than flank face (Temp, Pressure, wear rate)
- KT can be used as measure
- Taylor like equation can be used
- Tool life due to crater and wearland or flank are about same

# Groove Formation

- Deep grooves occur with high temperature alloys, soft steels (strain hardening)
- Large groove at free edge
- Temperature-Experimental measurement
- Other reasons
  - Work hardened layer on previously cut material
  - Stress concentration due to stress gradient at free surface
  - Burr at edge
  - Abrasive oxide layer
  - Fatigue at edge

# Tool Failure-Gross Fracture

– Gross Fracture and Edge Chipping are two failure modes
– Interrupted cutting has severe fracture
– More likely at tool leaving then engaging
  - Overshoots the equilibrium unloaded condition
  - Shear plane rotates assuming negative value results in rapid unloading
  - Rate of unloading increase with speed

# Tool Failure-Plastic Deformation

- Occurs at High Temperature
- W/P material with poor conductivity
  - Temperature accumulation
  - Tool tip melting
  - Occurs in Titanium

# Tool Wear Cycle

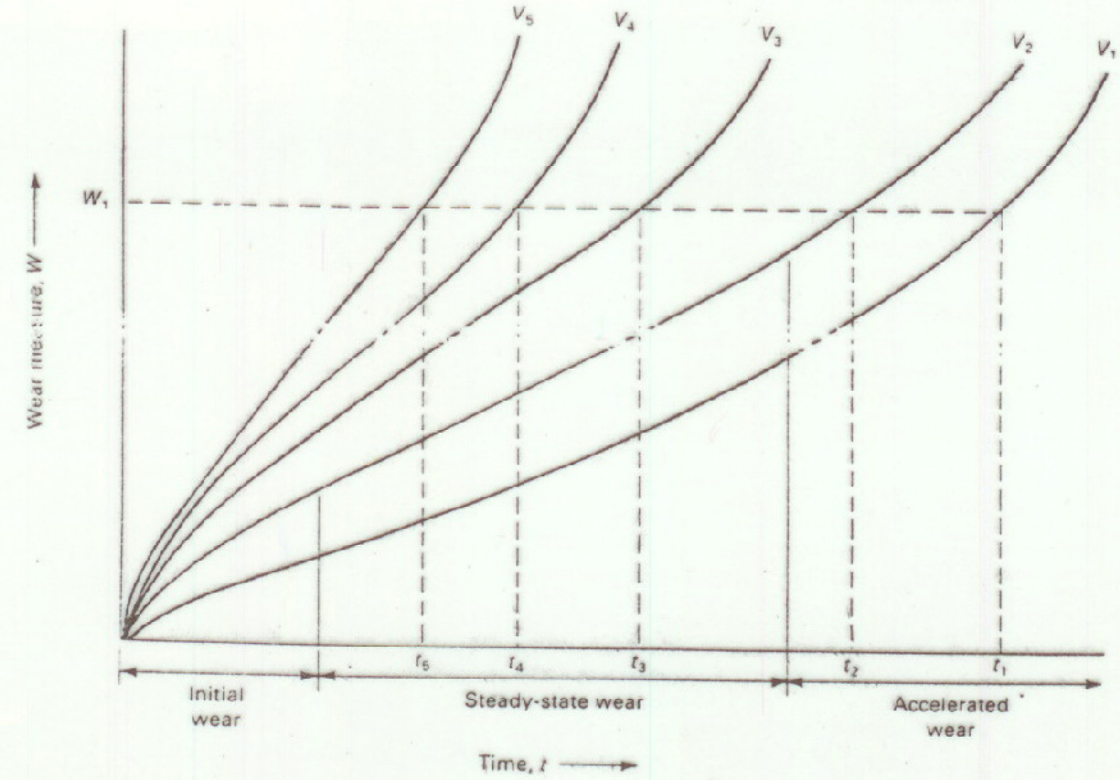



**Fig. 9** Tool wear curves for different cutting velocities

# Tool Wear Cycle and Maps

- Initial Wear Mechanisms
  - Initial contact between two surfaces
  - Stresses/heat are intensified at contact with fracture and melting of asperities
  - Surface contact increases and visible wear marks

# Wear cycle

- Steady State Wear
  - Velocity and normal stress remain stable
  - Crater wear due to diffusion due to transfer of atoms
  - BUE formed in some cases; fracture causes attritious/adhesive wear
  - Chipping in case of discontinuous chips
  - Crack initiation and propagation due to cyclic loading
  - Stable abrasion

# Wear Cycle

- Tertiary Wear
  - Wear surfaces enlarges to critical size and wear accelerates
  - Wear resistant coatings separate causing accelerated wear
  - Rapid diffusion/local seizure and melting

# Tool Wear Maps

- Mechanisms under different velocities, contact pressures and feed rate
- At low velocities BUE and adhesion
- Very high velocity diffusion/oxidation
- At low velocity and high normal pressure seizure takes place
- Safe limits for cratering and fracture can be determined for a combination of tool and W/P.

# Tool Wear Mechanisms

| Low speed | High speed | Very high speed |
| --- | --- | --- |
| Mechanical properties | Chemical diffusion and convection | Chemical diffusion |

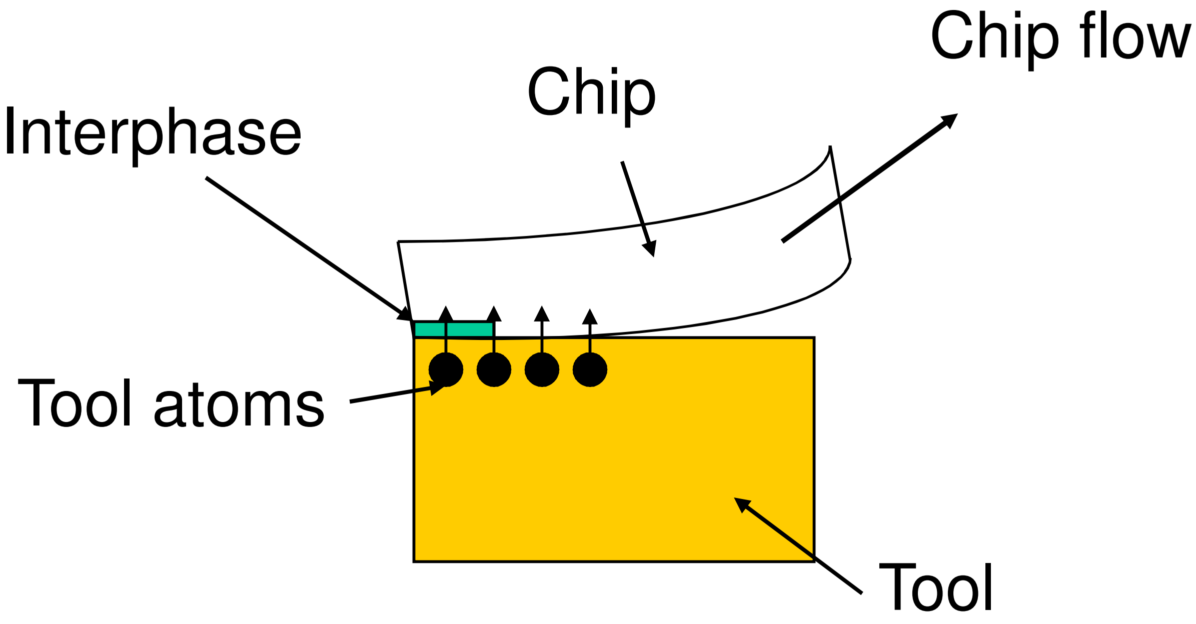
# Wear at Low Speeds

Mechanical Properties

- flow induced crack nucleation and growth
- micro fracture
- fatigue
- abrasion

- $Al_2O_3$ at all speeds
  - cutting steel and Ni

# Wear at High Speeds - Chemical Diffusion and Convection



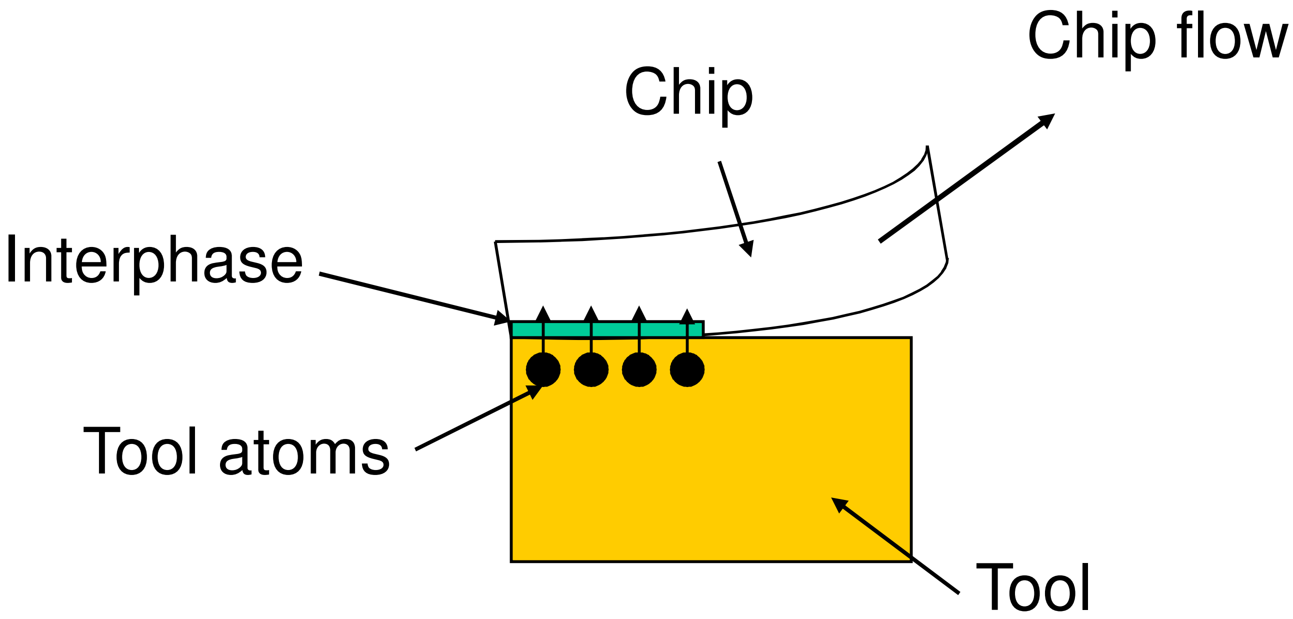
# Chemical Diffusion and Convection

- Tool dissolves directly into chip
- Convection - chip sliding on surface
  – transition between sliding and sticking begins
  – maximum heat generation point moves away from tool tip
- Net flow of material away from interface

# Wear at High Speeds

- Carbides - super alloys, hard steels
- $Al_2O_3$ - Ti
- Carbides, nitrides - steels
- CBN - steels

# Wear at Very High Speeds -Chemical Diffusion



# Chemical Diffusion

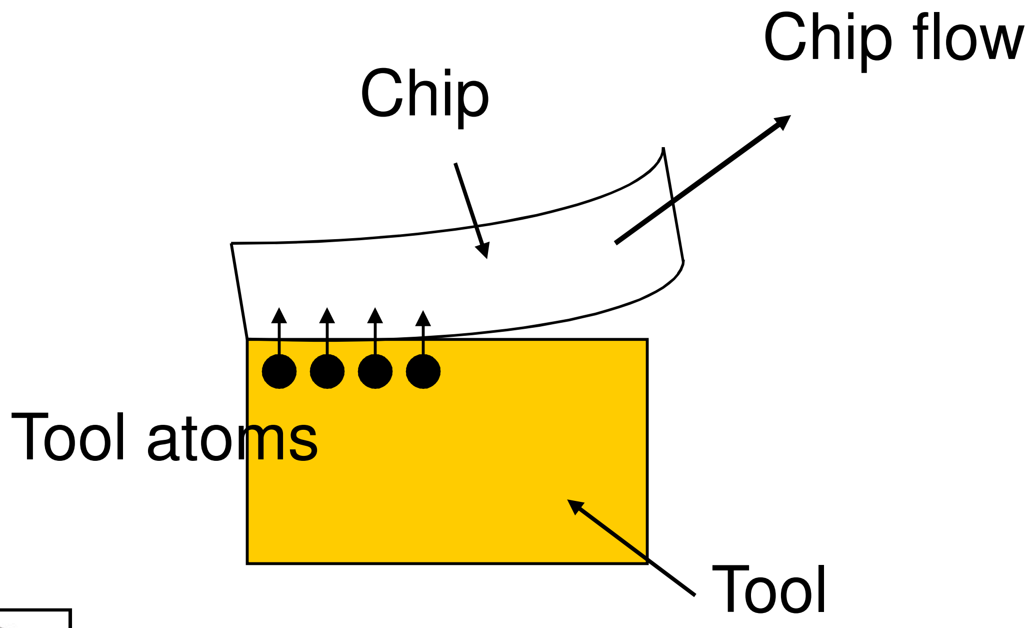
- Transition from sliding to sticking moves from the nose
  - finally sticking occurs everywhere
- Boundary layer builds up
  - no convection directly from tool to chip
  - only chemical diffusion through boundary layer of chip material

# Wear at Very High Speeds

- Carbide, diamond - Ti at all speeds
- CBN - super alloys, hard steels

# Dissolution Controls Wear

- Tool atoms diffuse up and are swept away by the chip at high temps.



# Wear Velocity ($v_{wear}$)

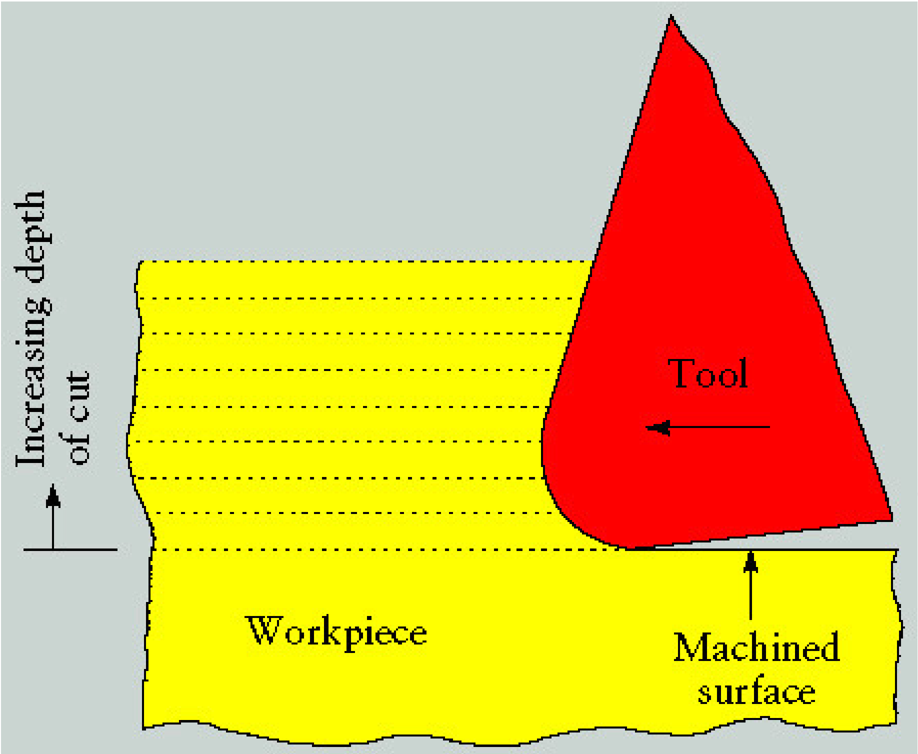
$$v_{wear} = kcv_y - kD\frac{\partial c}{\partial y}$$

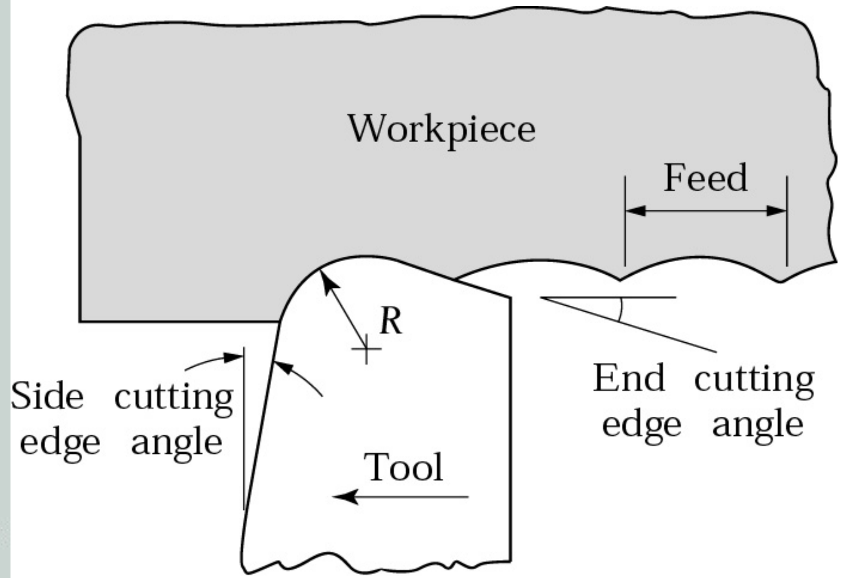
- k = $\dfrac{\text{Molar volume of tool material } (V_{tool})}{\text{Molar volume of chip material } (V_{chip})}$
- c = equilibrium solubility
- $v_y$ = $\perp$ bulk velocity of chip at chip-tool interface
- D = chemical diffusivity
- $\dfrac{\partial c}{\partial y}$ = concentration gradient

# Choosing Machining Conditions

- Pick maximum possible depth of cut
- Take maximum feed rate subject to:
  - surface finish (see next slides)
  - power limitations of machine
    - If you're power limited, are chips breaking?
    - Chips break at f > 0.005"/min (0.13 mm/min)
- Pick cost optimum speed (from Taylor's Eqn)

# Tool Marks

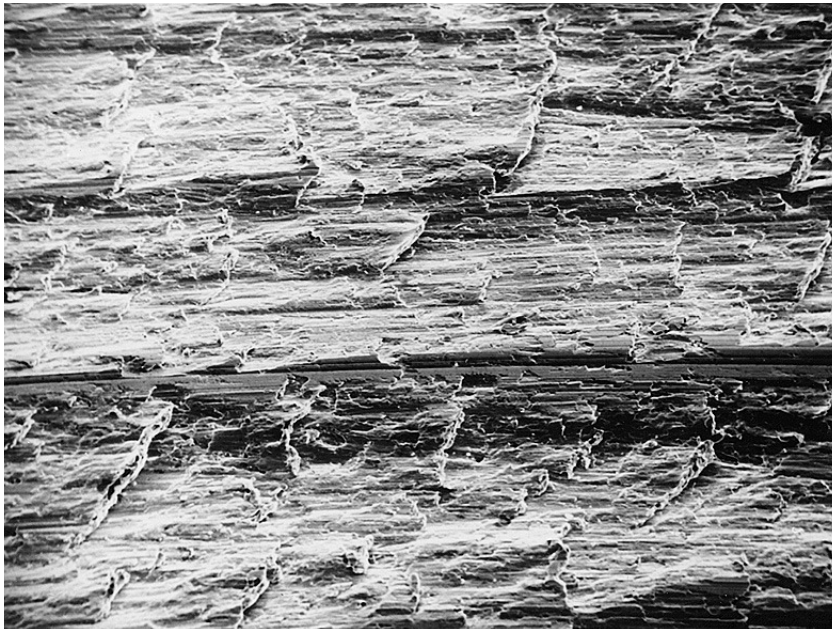

Increasing depth of cut
Tool
Workpiece
Machined surface


Workpiece
Feed
R
Side cutting edge angle
Tool
End cutting edge angle

# Surface Marks

(a)

(b)



Surfaces produced on steel by cutting, as observed with a scanning electron microscope: (a) turned surface and (b) surface produced by shaping. *Source*: J. T. Black and S. Ramalingam.

# Roughness

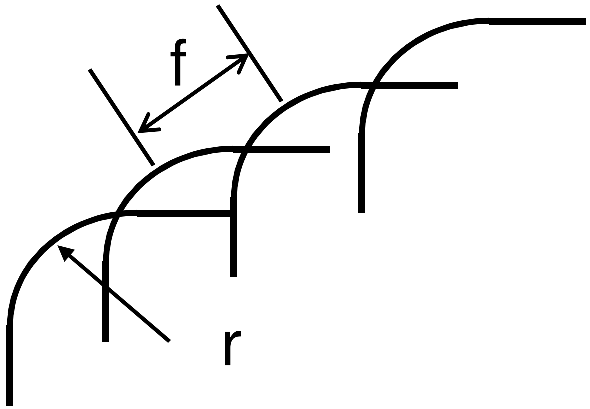
$$Roughness_{AA} \approx \frac{f^2}{18\sqrt{3}\,r} \qquad Roughness_t \approx \frac{f^2}{8r}$$

f = feed

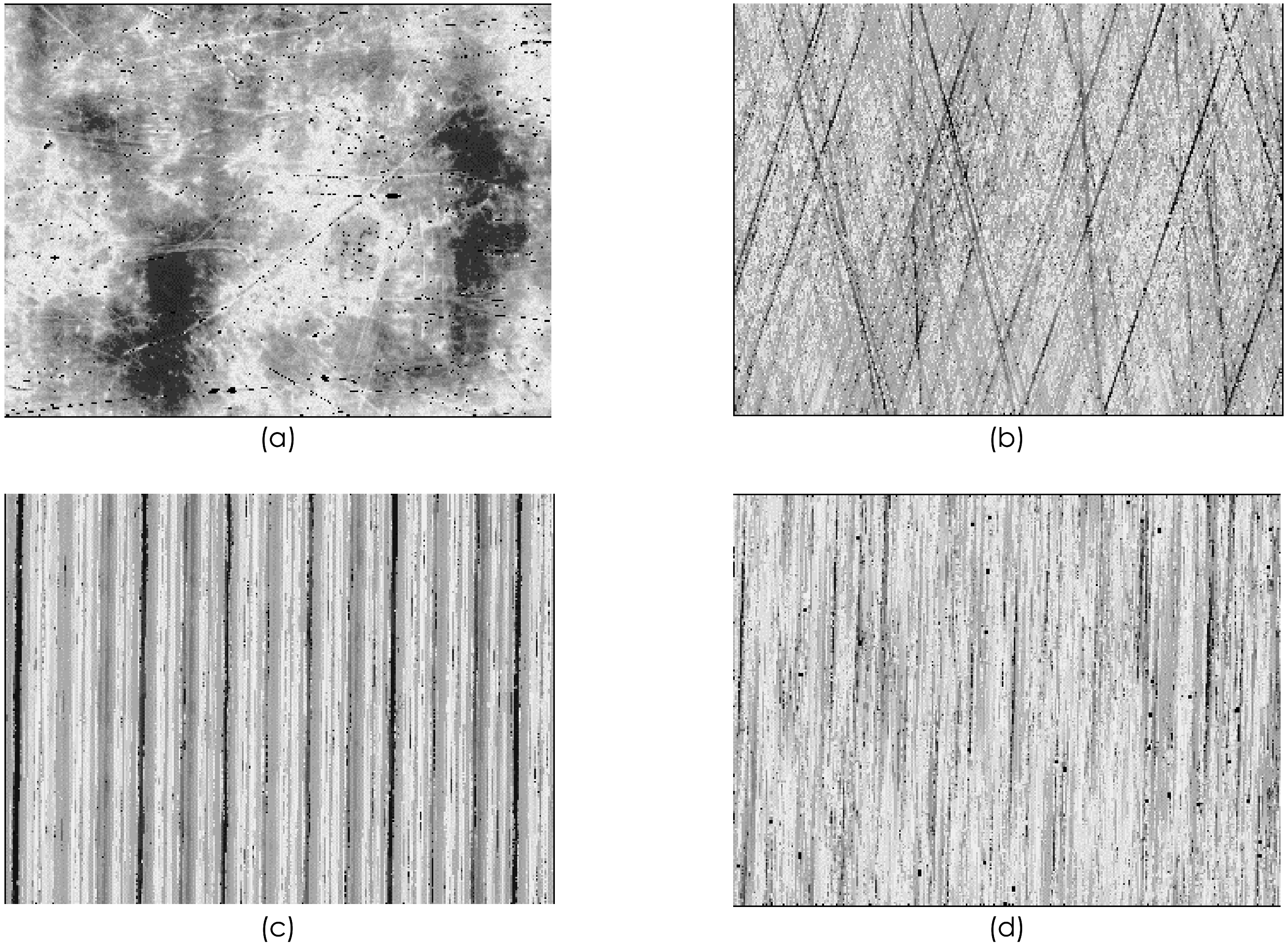
r = nose radius

AA = arithmetic average

t = peak-to-valley



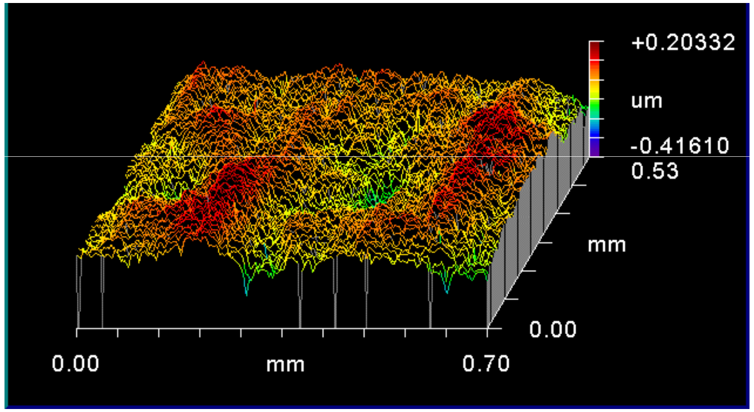
# Surface Texture



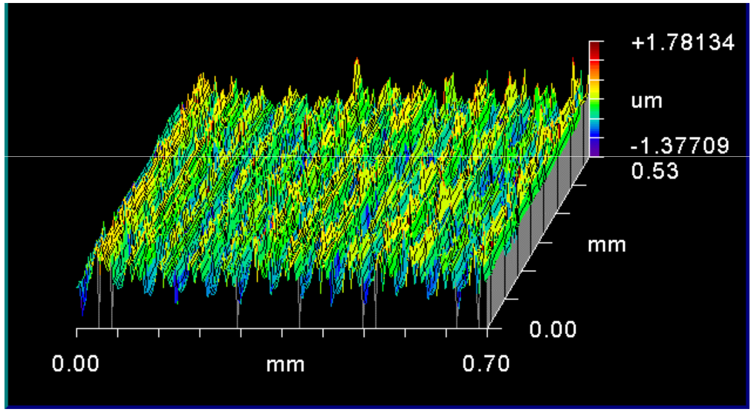

Gray Scale Images of (a) Isotropic finished, (b) Honed, (c) Turned and (d) Ground surfaces

# Surface Texture

- Definition: Periodic and/or random deviations of a real surface from the nominal surface.




Isotropic Surface: random



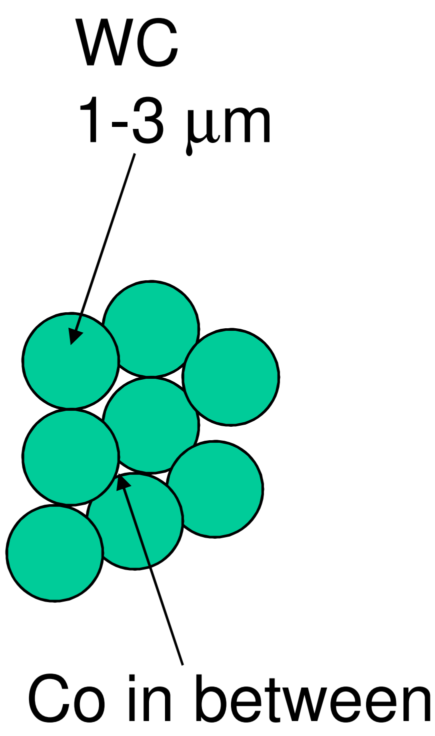

Turned Surface: Periodic

# Tool Material Properties

- Main requirements
  - Elevated temperature hardness ("hot hardness")
  - Toughness
  - High wear resistance

# Cutting Tools

- 1923: Schroter
  - WC + Co
    - Co wets WC and binds together
    - Cemented carbide structure
  - Twice the speed of WC
  - Not as tough as HSS
    - fine grain structure helps
  - Machine vibration is problem
    - rigid machines help
  - Solubility of WC in Fe ≈ 5%



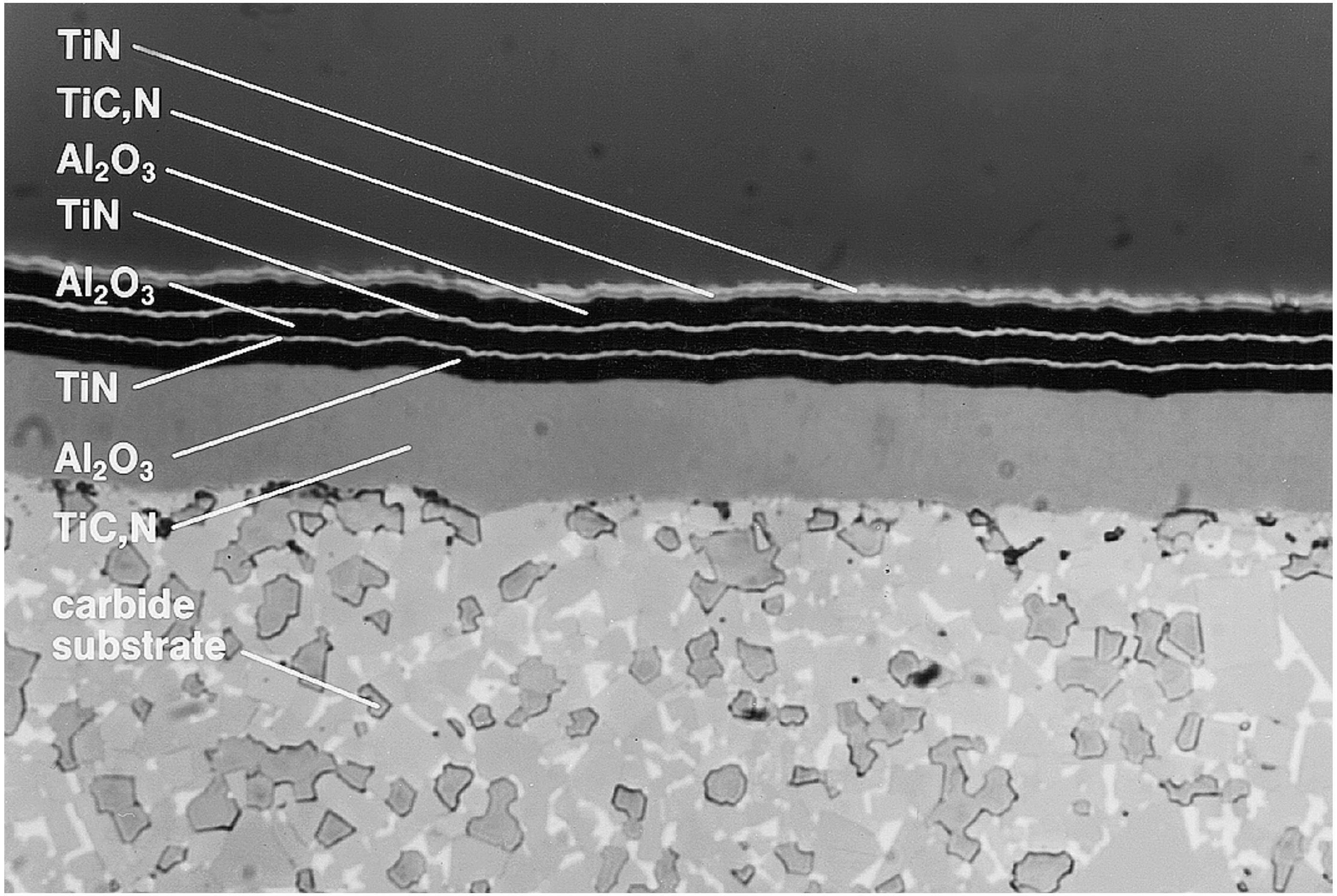
# Cutting Tools

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

# Cutting Tools

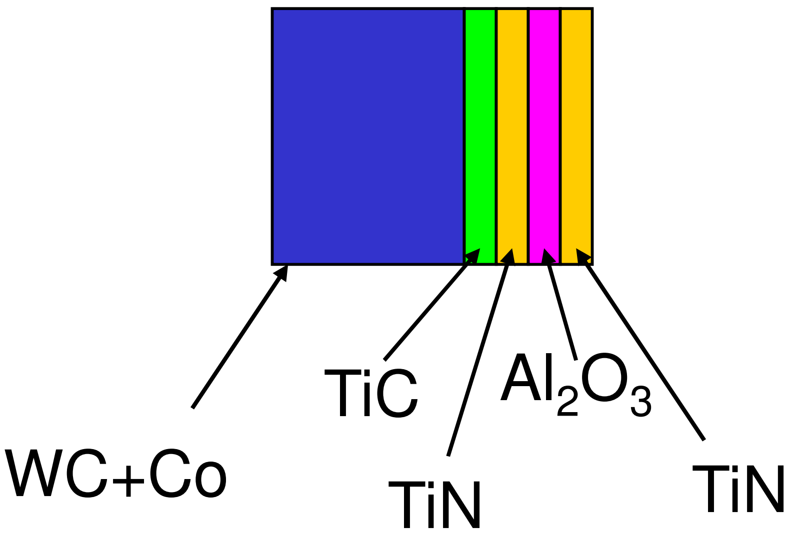
- 1960's: Increased cutting speeds
- Powder metallurgy
  - production of carbide inserts
  - disposable inserts, no resharpening
  - coatings feasible: TiC, TiN, $Al_2O_3$
    - ≈ 5 μm layer to minimize strain
    - very wear resistant
    - 50-70% of tool life expended before coating penetrated

# Tool Coatings



# Cutting Tools

- Optimization of bonding between coating and substrate



# Cutting Tools

- Aluminum oxide ($Al_2O_3$)
  - wear resistant, but low strength
- $Al_2O_3$ + 30% TiC: hot-pressed
  - increased strength 15-30%
  - higher speeds - 3-5x of carbides

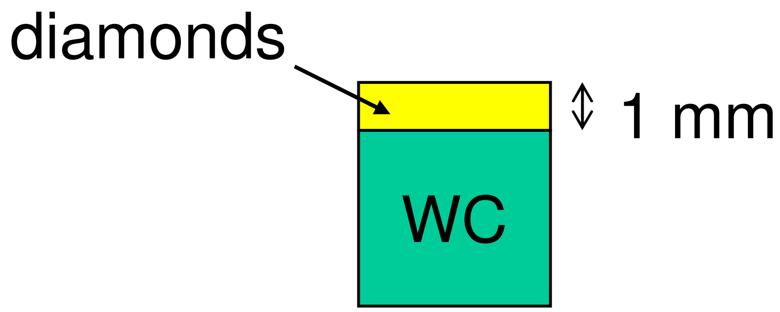
# Cutting Tools

- $Si_3N_4$
  - high toughness in bulk form
  - low thermal expansion
  - not for steel, dissolves - fast wear

- $Al_2O_3$ + $Si_3N_4$ (SiAlON)
  - cuts Ni superalloys and steels

# Cutting Tools

- Diamond (C)
  - HB ≈10,000 kg/mm$^2$
  - soluble in steel
  - good for aluminum
  - good for Si-Al alloys
  - 10-40 μm particles are sintered onto a WC substrate ⇒ polycrystalline tool



# Cutting Tools

- Cubic Boron Nitride (CBN)
  - more stable with respect to steel and Ni
  - HB ≈ 4,500 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

# Tool Materials

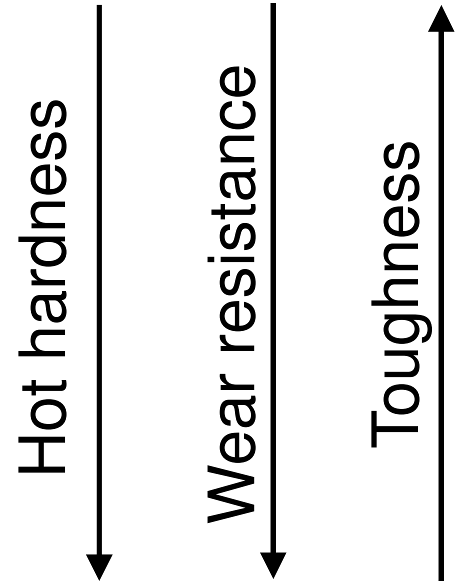
1. High Speed Steel (HSS)

2. Carbide (WC)

3. Ceramics ($Al_2O_3$)

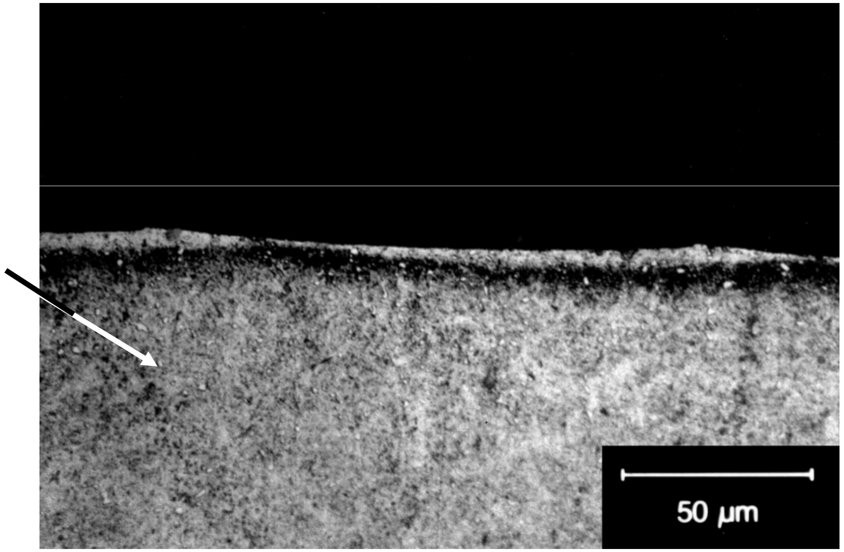
4. Polycrystalline Diamond (PCD)/ Cubic Boron Nitride (CBN)

5. Single Crystal Diamond (SCD)



# Surface Finish/Surface Integrity

- Surface finish a function of tool geometry and cutting conditions
- Surface roughness in machining a function of tool nose radius and feed
- Surface integrity
  - Sub-surface damage
  - Strain hardened layer
  - Residual stresses



# Summary

- Shaping & planing
- Turning
- Milling
- Orthogonal vs. oblique cutting
- Chip formation
- Kinematics and mechanics of orthogonal cutting
- Temperature analysis
- Tool wear and tool life
- Surface integrity