2.008 Design & Manufacturing II

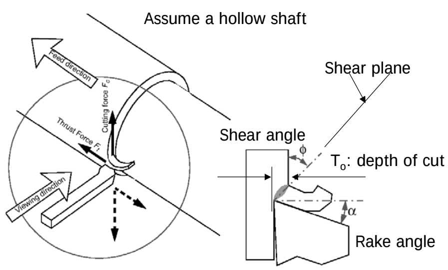
Spring 2004

Metal Cutting II

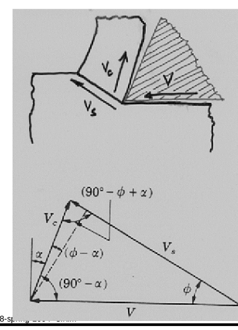
Cutting processes

- Objectives
  - Product quality: surface, tolerance
  - Productivity: MRR↑, Tool wear↓
- Physics of cutting
  - Mechanics
  - Force, power
- Tool materials
- Design for manufacturing

Orthogonal cutting in a lathe



Velocity diagram in cutting zone



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

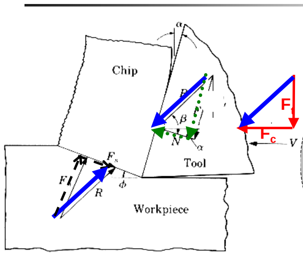
$$\frac{V_c}{V}=\frac{t_o}{t_c}=r=\frac{\sin(\varphi)}{\cos(\varphi-\alpha)}$$

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

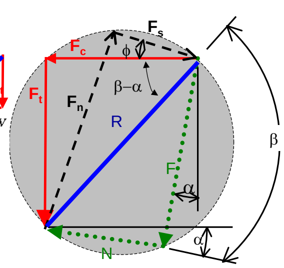
$$\frac{V_c}{V}=\frac{t_o}{t_c}=r=\frac{\sin(\varphi)}{\cos(\varphi-\alpha)}$$

Cutting ratio: $r<1$

E. Merchant's cutting diagram



Source: Kalpajkian



FBD of Forces

β = Friction Angle

$\mu=\tan(\beta)$

$F=R\cdot\sin(\beta)$

$N=R\cdot\cos(\beta)$

$Ft=R\cdot\sin(\beta-\alpha)$

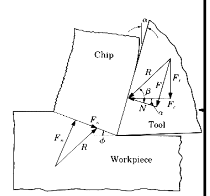
$Fc=R\cdot\cos(\beta-\alpha)$

$$F_s=F_c\cdot\cos(\varphi)-F_t\cdot\sin(\varphi)=R\cos(\varphi+\beta-\alpha)$$

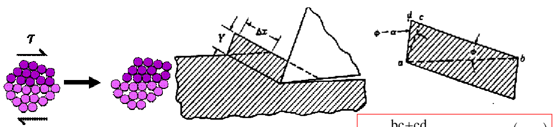
$$F_n=F_c\cdot\sin(\varphi)+F_t\cdot\cos(\varphi)$$

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

Typcially: $0.5<\mu<2$



Analysis of shear strain



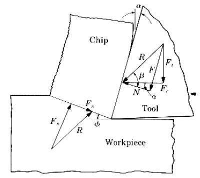
$$\gamma = \frac{bc+cd}{ac} = \cot\varphi + \tan(\varphi-\alpha)$$

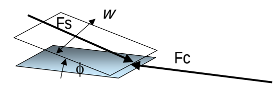
- What does this mean:
  - Low shear angle = large shear strain
- Merchant's assumption: Shear angle adjusts to minimize cutting force or max. shear stress
- Can derive:

$$\varphi = 45^o + \frac{\alpha}{2} - \frac{\beta}{2}$$

Shear Angle

$$\varphi = 45^o + \frac{\alpha}{2} - \frac{\beta}{2}$$





Maximize shear stress $\tau = \frac{Fs}{As} = \frac{Fs}{\frac{A}{\sin\varphi}}$

$$\frac{d\tau}{d\varphi} = 0$$

Minimize Fc

$Fs = As \cdot \sigma s$

$$F_s = F_c \cdot \cos(\varphi) - F_t \cdot \sin(\varphi) = R\cos(\varphi + \beta - \alpha)$$

$$Fc = R \cdot \cos(\beta - \alpha) \qquad \frac{dFc}{d\varphi} = 0$$

Power

Power input : $F_c \cdot V$ => shearing + friction

MRR (Material Removal Rate) = $w.t_o.V$

Power for shearing : $F_s \cdot V_s$

Specific energy for shearing : $u_s = \frac{F_s \cdot V_s}{w \cdot t_o \cdot V}$ ← MRR

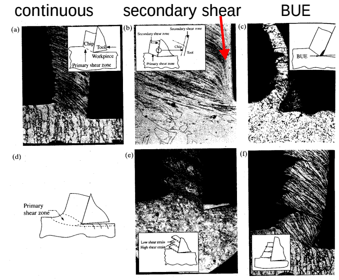
Power dissipated via friction : $F \cdot V_c$

Specific energy for friction : $u_f = \frac{F \cdot V_c}{w \cdot t_o \cdot V}$

Total specific energy : $u_s + u_f = \frac{F \cdot V_c}{w \cdot t_o \cdot V} + \frac{F_s \cdot V_s}{w \cdot t_o \cdot V}$

Experimantal data

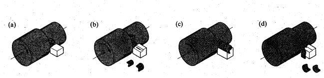
Cutting zone pictures

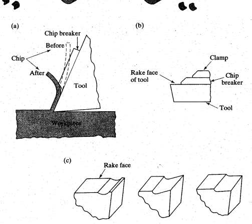


Kalpakjian

Chip breaker

Continuous chip: bad for automation

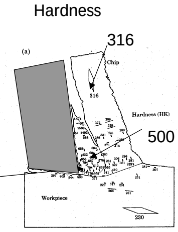




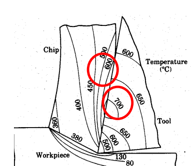
- Stop and go
- milling

Cutting zone distribution

Hardness



Temperature



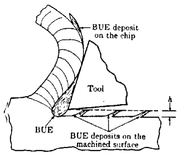
Mean temperature: CV^af^b

HSS: a=0.5, b=0.375

Built up edge

- What is it?
- Why can it be a good thing?
- Why is it a bad thing?
  - Thin BUE
- How to avoid it…

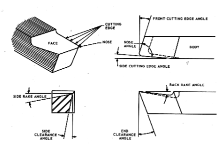
•Increasing cutting speed
•Decreasing feed rate
•Increasing rake angle
•Reducing friction (by applying cutting fluid)



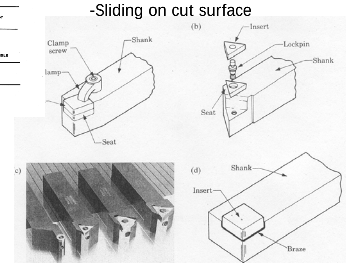
Tools

HSS (1-2 hours)

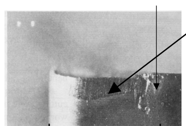
-High T
-High σ
-Friction
-Sliding on cut surface

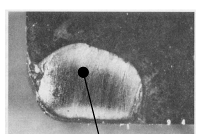


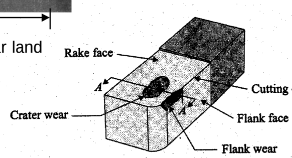
Inserts



Tool wear up close





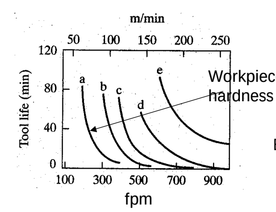


Taylor's tool wear relationship (flank wear)

F. W. Taylor, 1907

$$V \cdot T^n = C$$

T = time to failure (min)
V = cutting velocity (fpm)



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

d = depth of cut
f = feed rate

Ex. $T = C^7 \cdot V^{-7} \cdot d^{-1} \cdot f^{-4}$

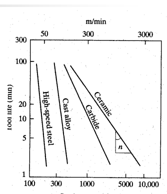
Optimum for max MRR?

Taylor's tool life curves (Experimental)

- Coefficient *n* varies from:

Steels	Ceramics
0.1	0.7

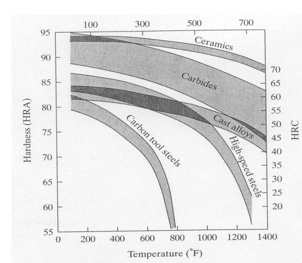
- As *n* increases, cutting speed can be increased with less wear.
- Given that, *n*=0.5, C=400, if the V reduced 50%, calculate the increase of tool life?



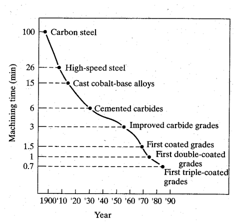
Log scale

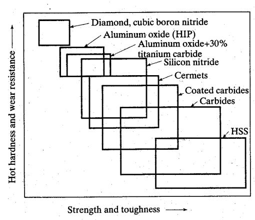
What are good tool materials?

- Hardness
  - wear
  - temperature
- Toughness
  - fracture



History of tool materials





Trade off: Hardness vs Toughness
wear vs chipping

Sandvik Coromant, Kalpakjian

HSS

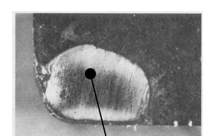
- High-speed steel, early 1900
- Good wear resistance, fracture resistance, not so expensive
- Suitable for low K machines with vibration and chatter, why?
- M-series (Molybdenum)
  - Mb (about 10%), Cr, Vd, W, Co
  - Less expensive than T-series
  - Higher abrasion resistance
- T-series (Tungsten 12-18%)
- Most common tool material but not good hot hardness

Carbides

- Hot hardness, high modulus, thermal stability
- Inserts
- Tungsten Carbide (WC)
  - (WC + Co) particles (1-5 μ) sintered
  - WC for strength, hardness, wear resistance
  - Co for toughness
- Titanium Carbide (TiC)
  - Higher wear resistance, less toughness
  - For hard materials
- Uncoated or coated for high-speed machining
  - TiN, TiC, TiCN, Al2O3
  - Diamond like coating
  - CrC, ZrN, HfN

Crater wear

- Diffusion is dominant for crater wear
- A strong function of temperature
- Chemical affinity between tool and workpiece
- Coating?



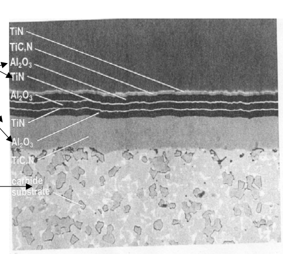
Crater wear

Multi-phase coating

Custom designed coating for heavy duty, high speed, interrupted, etc.

TiN low friction
Al2O3 thermal stability
TiCN wear resistance

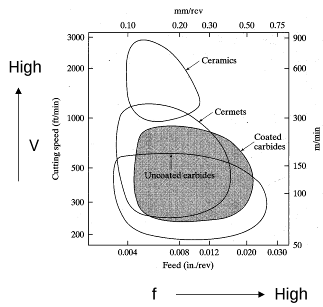
Carbide substrate
hardness and
rigidity



Ceramics and CBN

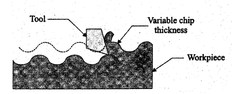
- Aluminum oxide, hardness, high abrasion resistance, hot hardness, low BUE
- Lacking toughness (add ZrO2, TiC), thermal shock
- Cold pressed and hot sintered
- Cermets (ceramic + metal)
  - Al2O3 70%, TiC 30%, brittleness, $$$
- Cubic Boron Nitride (CBN)
  - 2nd hardest material
  - brittle
- Polycrystalline Diamond

Range of applications



Chatter

- Severe vibration between tool and the workpiece, noisy.
- In general, self-excited vibration (regenerative)
- Acoustic detection or force measurements
- Cutting parameter control, active control



Turning parameters

- MRR = π Davg. N. *d . f*
  - N: rotational speed (rpm), f: feed (in/rev), d: depth of cut (in)
  - l; length of cut (in)
- Cutting time, *t = l / f* N
- Torque = Fc (Davg/2)
- Power = Torque. Ω
- 1 hp=396000 in.lbf/min = 550 ft.lbf/sec

Example

- 6 inch long and 0.5 in diameter stainless steel is turned to 0.48 in diameter. N=400 rpm, tool in traveling 8 in/min, specific energy=4 w.s/mm^2=1.47 hp.min/in^3
- Find cutting speed, MRR, cutting time, power, cutting force.

Sol.

- Davg=(0.5+0.48)/2= 0.49 in
- V=π. 0.49.400 = 615 in/min
- d=(0.5-0.48)/2=0.01 in
- F=8/400=0.02 in/rev
- MRR=V.f.d=0.123 in^3/min
- Time to cut=6/8=0.75 min

P=1.47 x 0.123 = 0.181 hp=Torque x ω
1hp=396000 in-lb/min
T=P/ω=Fc. (Davg/2)
Then, Fc=118 lbs

Drilling parameters

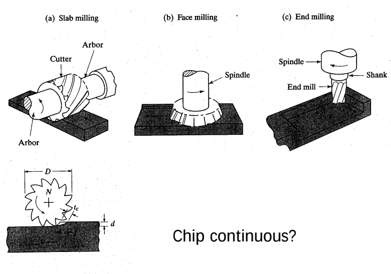
- MRR: $MRR = \left(\frac{\pi D^2}{4}\right) f \cdot N$
- Power: specific energy x MRR
- Torque: Power/ω

- A hole in a block of magnesium alloy, 10 mm drill bit, feed 0.2 mm/rev, N=800 rpm
- Specific power 0.5 W.s/mm^2
- MRR
- Torque

Sol

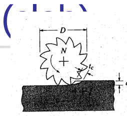
- MRR=π (10x10/4) . 0.2 . 800 =210 mm^3/s
- Power= 0.5 W.s/mm^2 . 210 mm^3/s
  =105 W = 105 N.m/s
  = T.ω
  =T 2π. 800/60
  =1.25 N.m

Milling



Chip continuous?

Milling parameters (



- Parameters:
  - Cutting speed, $V=\pi DN$
  - tc, chip depth of cut
  - d; depth of cut
  - f; feed per tooth
  - v; linear speed of the workpiece
  - n; number of teeth
  - t; cutting time,
  - w; width of cut
- Torque: Power/ω
- Power: sp. Energy x MRR

$$t_c = \frac{2\,fd}{D} \quad \leftarrow \text{approximation}$$

$$f = \frac{v}{Nn}$$

$$t = \frac{l + l_c}{v}$$

$$\text{MRR} = \frac{lwd}{t} = wdv$$

DFM for machining

- Geometric compatibility
- Dimensional compatibility
  - Availability of tools
  - Drill dimensions, aspect ratio
- Constraints
  - Process physics
  - Deep pocket
  - Machining on inclined faces
- Set up and fixturing
  - Tolerancing is $$$
  - Minimize setups