MATERIAL REMOVAL PROCESSES

Theory of Metal Machining

1. Overview
2. Theory of Chip Formation
3. Force Relationships
4. Power and Energy Relationship
5. Cutting Temperature

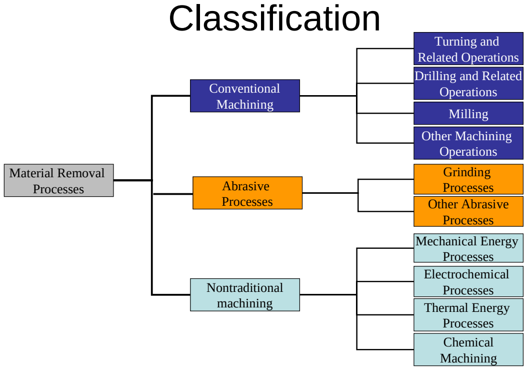
1

Introduction

- Everyday Experience: Scraping the ice from your windshield
  - Edge angle of the ice scraper
  - Force required depending on the characteristics of ice
- Incentives: Making a ceramic vase out of clay
  - Shaping
  - Removal of excess materials - ‘machining’
- Powder Metal or Cast
  - Exact dimension
  - Tolerance & Surface Finish

2

Classification



3

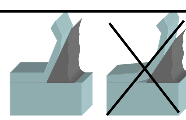
Material Removal Processes

A family of shaping operations through which undesired excess material is removed from a starting workpart so the remaining part become closer to the desired shape

- Categories:
  - *Machining* – material removal by a sharp cutting tool, e.g., turning, milling, drilling
  - *Abrasive processes* – material removal by hard, abrasive particles, e.g., grinding
  - *Nontraditional processes* - various energy forms other than sharp cutting tool to remove material

4

Machining

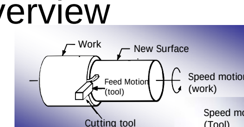


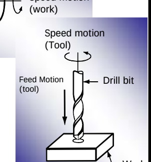
- A *shearing* process in which excess materials is removed by cutting tools.
  - A variety of work materials
  - ‘Repeatable’ regular geometries
  - Close tolerance (<0.025mm)
  - Smooth surface finish (0.4mm)
  - Waste, Expensive: Cost and Time
  - Other processes such as casting, forging, and bar drawing create the general shape
  - Machining provides the final shape, dimensions, finish, and special geometric details

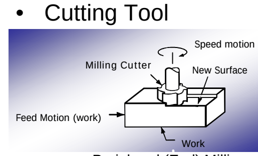
5

1. Overview

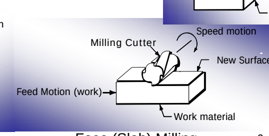
- Types
  - Turning - Lathe
  - Drilling – Drill press
  - Milling – Milling Machine
    - Peripheral
    - Face
- Cutting Tool







Peripheral (End) Milling



Face (Slab) Milling

6

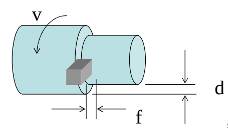
Cutting condition

- Relative motion between tool and work
- Cutting conditions
  - Cutting speed, v (m/s) – Surface speed
  - Feed f (m): the lateral distance traveled by the tool during one revolution.
  - Depth of cut d (m)
- Material Removal Rate: $MRR = v\ f\ d$
  - Roughing - removes large amounts of material, at high feeds and depths, low speeds
  - Finishing - Achieves final dimensions, tolerances, and finish, Low feeds and depths, high cutting speeds

7

Machine Tools

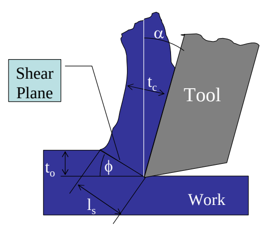
- A power-driven machine that performs a machining operation
  - Holds workpart
  - Positions tool relative to work
  - Provides power and controls speed, feed, and depth.
  - Pumps a Cutting fluid



8

2. Theory of Chip Formation

- Orthogonal Cutting Model



Rake angle: α

Shear angle: ϕ

Chip thickness ratio:

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

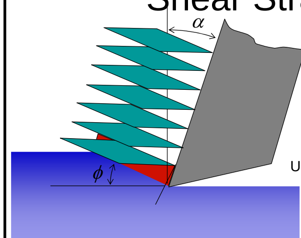
By rearranging

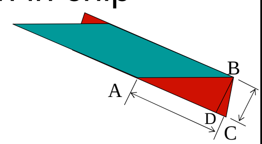
$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

r is always less than 1.0.

9

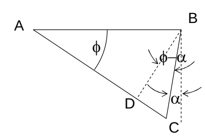
Shear Strain in chip





Using $\sin(\alpha\pm\beta) = \sin\alpha\cos\beta \pm \cos\alpha\sin\beta$

$\cos(\alpha\pm\beta) = \cos\alpha\cos\beta \mp \sin\alpha\sin\beta$



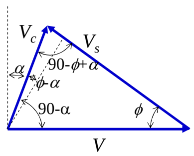
$$\gamma = \frac{AC}{BD} = \frac{DC+AD}{BD} = \tan(\phi-\alpha) + \cot\phi$$

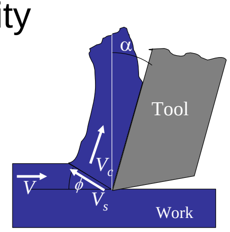
$$= \frac{\sin(\phi-\alpha)}{\cos(\phi-\alpha)} + \frac{\cos\phi}{\sin\phi} = \frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)}$$

As ϕ (from 10° to 35°) increase, γ (from 5 to 2) decreases.

10

Velocity





$$\frac{V}{\sin\left(\frac{\pi}{2}-\phi+\alpha\right)} = \frac{V_s}{\sin\left(\frac{\pi}{2}-\alpha\right)} = \frac{V_c}{\sin\phi}$$

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

$$\dot{\gamma} = \frac{V_s}{\Delta y} = \frac{\cos\alpha}{\cos(\phi-\alpha)}\frac{V}{\Delta y}$$

where Δy is the finite thickness of the shear plane, typically 0.03mm.

Shear Strain rate is around 10^3-10^5sec^{-1}

11

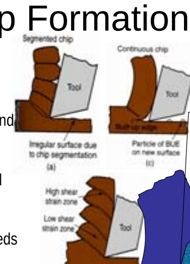
Actual Chip Formation

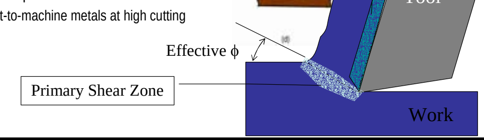
(a) Discontinuous chip
- Brittle materials at low cutting speed
- High tool-chip friction and large feed and depth

(b) Continuous chip
- Ductile materials with high speeds and small feed and depth of cut

(c) Continuous chip with built-up edge
- Ductile material at low to medium speeds

(d) Serrated chip
- Difficult-to-machine metals at high cutting speeds

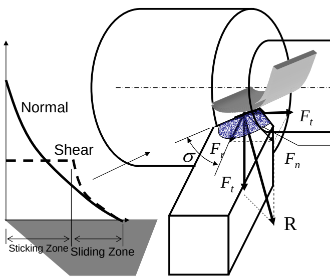




12

The 'Real' Cutting Force

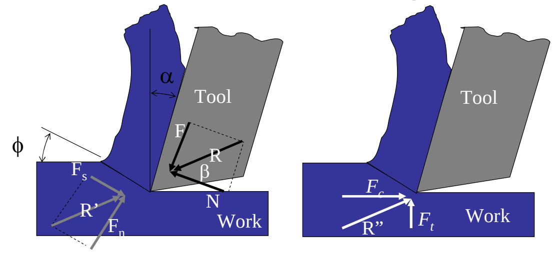
Cutting Forces are measured with Dynamometer.



- Area: A=bh
  where b=chip width
  h=chip thickness
- Temperature (500-1000^oC)
- Pressure (1000-3000 MPa)

13

3. Force Relationships



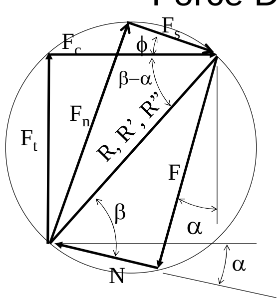
F: Friction Force
N: Normal Force

F_s: Shear Force
F_n: Normal Force

F_c: Cutting Force
F_t: Thrust Force

14

Force Diagram



$$F = F_c \sin\alpha + F_t \cos\alpha$$
$$N = F_c \cos\alpha - F_t \sin\alpha$$
$$F_s = F_c \cos\phi - F_t \sin\phi$$
$$F_n = F_c \sin\phi + F_t \cos\phi$$

$$R = \frac{F_s}{\sin\phi\cos(\phi+\beta-\alpha)} = \frac{\tau_s t_o w}{\sin\phi\cos(\phi+\beta-\alpha)}$$

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

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

15

Cutting Force

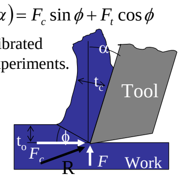
- Cutting Force: $F_c = bh\tau_s\left[\frac{\cos(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)}\right] = K_c bh \quad K_c\left[N/mm^2\right]$
- Thrust Force: $F_t = bh\tau_s\left[\sin\frac{\cos(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)}\right] = K_t bh$

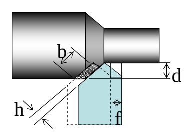
$$F_s = R\cos(\phi+\beta-\alpha) = F_c\cos\phi - F_t\sin\phi = \frac{\tau_s bh}{\sin\phi}$$

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

$$F_n = R\sin(\phi+\beta-\alpha) = F_c\sin\phi + F_t\cos\phi$$

K_c and K_t must be calibrated through machining experiments.





Top View

16

The Merchant Equation

- Shear stress: $\tau = \frac{F_s}{A_s}$
- Shear Plane Area: $A_s = \frac{t_o w}{\sin\phi}$
- Shear stress: $\tau = \frac{F_c\cos\phi - F_t\sin\phi}{t_o w/\sin\phi}$
- Merchant's Assumption: Shear plane angle will form to minimize energy
- After differentiating τ w.r.t ϕ, Merchant's Equation:

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

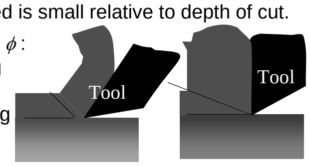
17

Implication of Merchant's Eq.

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

- An increase in rake angle causes the shear plane angle to increase.
- A decrease in friction angle cause the shear plane angle to increase.
- The analysis from orthogonal cutting can be used in a typical turning if the feed is small relative to depth of cut.

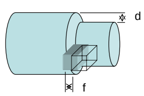
Effect of shear plane angle ϕ:
(a) higher ϕ with a resulting lower shear plane area;
(a) smaller ϕ with a resulting larger shear plane area.

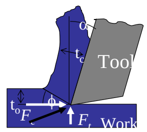


18

Turning vs. Orthogonal

Turning	Orthogonal
Feed f	Uncut Chip thickness t_o
Depth d	Width of cut w
Cutting speed v	Cutting speed v
Cutting force F_c	Cutting force F_c
Feed force F_f	Thrust force F_t





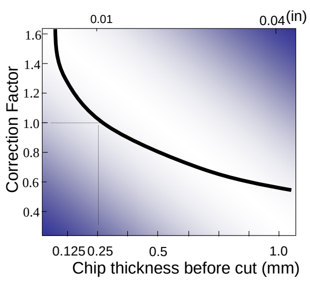
19

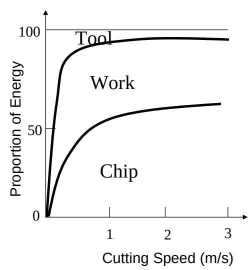
4. Power & Energy Relation

- Power (energy per unit time) $P_c = F_c V$
  $$HP_c = \frac{F_c V}{33{,}000}$$
  $$hp_c = \frac{P}{33{,}000} \quad P \text{ in ft-lb/min}$$
- Horse power $P_g = \frac{P_c}{E}$ or $hp_g = \frac{hp_c}{E}$ with mechanical efficiency E=90%
- Unit Power $P_u = \frac{P_c}{MRR}$
- Specific energy $U = P_u = \frac{P_c}{MRR} = \frac{F_c v}{v t_o w} = \frac{F_c}{t_o w}$

20

Size Effect & Energy Distribution





21

Specific Energy for various work materials (t_o=0.25mm)

Materials	Brinell Hardness	Specific Energy (U) N·m/mm³	In-lb/in³	Hp/in³/min
Carbon Steel	150-200	1.6	240,000	0.6
	200-250	2.2	320,000	0.8
	251-300	2.8	400,000	1.0
Alloy Steels	200-250	2.2	320,000	0.8
	251-300	2.8	400,000	1.0
	301-350	3.6	520,000	1.3
	351-400	4.2	640,000	1.6
Cast iron	125-175	1.1	160,000	0.4
	175-250	1.6	240,000	0.6
Stainless steel	150-200	2.8	400,000	1.0
Aluminum	50-100	0.7	100,000	0.25
Aluminum Alloys	100-150	0.8	120,000	0.3
Magnesium Alloys	50-100	0.4	60,000	0.15

22

Problem 21.30

A lathe performs a turning operation on a work piece of 6in diameter. The shear strength of the work=40,000lb/in2. The rake angle of the tool =10º. The machine settings are: rotational speed=500rev/min, feed=0.0075in/rev. and depth=0.075in. The chip thickness after the cut is 0.015in. Determine: (a) the horsepower required (b) the unit horsepower for this material, (c) the unit horsepower with the correction factor (1 for t_o=0.01in.) Use the orthogonal model.

(a) To get HP, F_c and v are needed

$$r = \frac{t_o}{t} = \frac{0.0075}{0.015} = 0.5$$

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}; \qquad \phi = \arctan\left(\frac{0.5\cos 10}{1 - 0.5\sin 10}\right) = 28.3^\circ$$

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}; \quad \beta = 2\left(45 + \frac{10}{2} - 28.3\right) = 43.4^\circ$$

$$A_s = \frac{t_o w}{\sin\phi} = \frac{0.0075 \cdot 0.075}{\sin 28.3} = 0.00119\text{in}^2$$

$$F_s = SA_s = 40{,}000(0.00119) = 47.5\text{lb}$$

$$F_c = \frac{F_s\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} = \frac{47.5\cos(43.3 - 10)}{\cos(28.3 + 43.4 - 10)} = 83.6\text{lb}$$

$$v = \omega r = 500\text{rev/min}(\pi 6/12)\text{ft/rev} = 785\text{ft/min}$$

$$HP = \frac{F_c v}{33{,}000} = \frac{83.6(785)}{33{,}000} = 2\text{hp}$$

(b) HP_u

$$MRR = vfd = 785(0.0075)(0.075) = 5.3\text{in}^3/\text{min}$$

$$HP_u = \frac{HP}{MRR} = \frac{2}{5.3} = 0.375\text{hp/(in}^3\text{/min)}$$

(c) HP_u with the correction factor Fig. 21.14

$$HP_u = \frac{HP_u}{f} = \frac{0.375}{1.15} = 0.326\text{hp/(in}^3\text{/min)}$$

23

5. Cutting Temperature

- Cook's dimensional analysis
  $$\boxed{T = 0.4\frac{U}{\rho C}\left(\frac{v t_o}{K}\right)^{0.333}}$$
- Experimental Measurement
  - Tool-chip thermocouple
  - Trigger's results $T = Kv^m$
    - RC-130B Ti ($T=479v^{0.162}$)
    - 18-8 Stainless steel ($T=135v^{0.361}$)
    - B113 Free machining steel ($T=86.2v^{0.348}$)

24

Chatter Analysis

- Mechanical vibration

Free Vibration: $m\ddot{x}+c\dot{x}+kx=0$

Forced Vibration: $m\ddot{x}+c\dot{x}+kx=F_o\sin\omega t$

Assume $x(t)=X\sin(wt+\phi)$

Or using complex harmonic functions

$$m\ddot{x}+c\dot{x}+kx=F_o e^{j\alpha}e^{j\omega t}$$

$$\text{Assume } x(t)=Xe^{j(\omega t+\phi)}$$

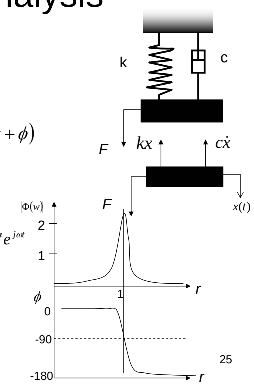
$$\left(k-\omega^2 m+j\omega c\right)Xe^{j\phi}e^{j\omega t}=F(t)=F_o e^{j\alpha}e^{j\omega t}$$

Magnitude ratio: $|\Phi(w)|=\left|\frac{X}{F_o}\right|=\frac{1}{k}\frac{1}{\sqrt{\left(1-r^2\right)^2+\left(2\zeta r\right)^2}}$

Phase: $\phi=\tan^{-1}\frac{-2\zeta r}{1-r^2}+\alpha$

where $r=\omega/\omega_n$ $\zeta=c/2\sqrt{km}$

and $\omega_n=\sqrt{\frac{k}{m}}$



25