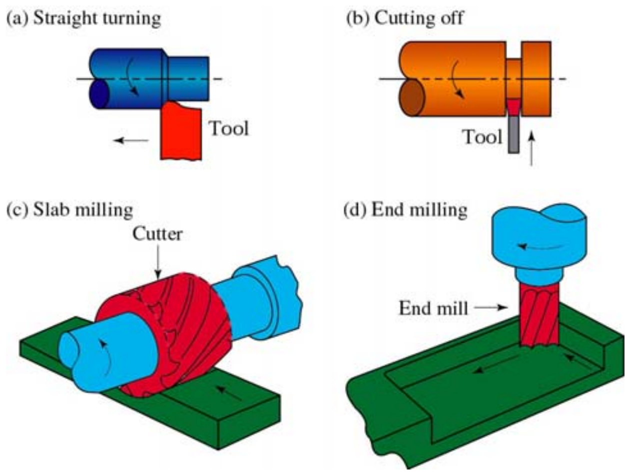
Outline

- Introduction
  - *Cutting terminology*
  - *Cutting principles*
- Cutting Geometry
- Machining Parameters
- Machining forces and power
- Cutting Model

Machining Types

- Turning
- Drilling
- Milling
- Boring
- Shaping
- Planing
- Broaching
- Filing
- Sawing
- Grinding
- Reaming
- Tapping
- Honing



Examples of cutting processes

Why Machining is Important

- Variety of work materials can be machined
  - *Most frequently applied to metals*
- Variety of part shapes and special geometry features possible, such as:
  - *Screw threads*
  - *Accurate round holes*
  - *Very straight edges and surfaces*
- Good dimensional accuracy and surface finish

Disadvantages of Machining

- Wasteful of material
  - *Chips generated in machining are wasted material, at least in the unit operation*
- 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*

Machining Tools

Most modern cutting tool materials are ceramic or composite materials designed to be **very hard**.

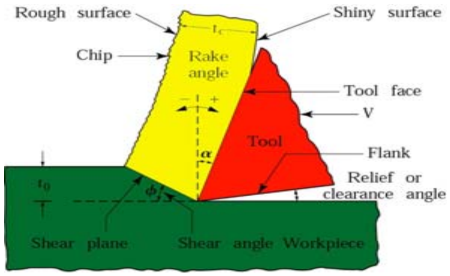
1. *Single-Point Tools*
   - One cutting edge
   - *Turning* uses single point tools
   - Point is usually rounded to form a *nose radius*
2. *Multiple Cutting Edge Tools*
   - More than one cutting edge
   - Motion relative to work usually achieved by rotating
   - *Drilling* and *milling* use rotating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

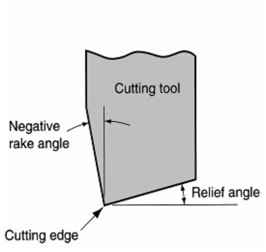
Single point

Multiple point

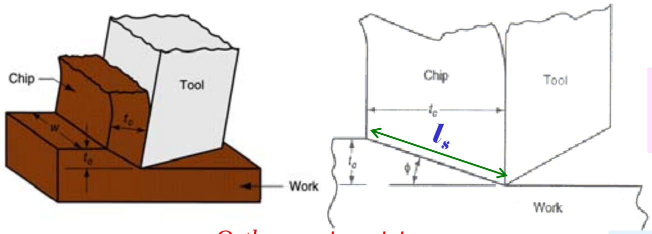
Machining Terminology

- **Speed** – surface cutting speed (v)
- **Feed** – advance of tool through the part
- **Depth of cut** – depth of tool into part
- **Rake face** – tool’s leading edge
- **Rake angle** – slant angle of tool’s leading edge (α)
- **Flank** – following edge of cutting tool
- **Relief angle** – angle of tool’s following edge above part surface





Machining Terminology



Orthogonal model

Cutting edge is perpendicular to the cutting speed

Although it is a 3D process, 2D analysis will be enough

Chip thickness – thickness of machined chip (t_c)

Depth of cut = t_o

Shear plane length – measured along shear plane chip (l_s)

Chip width – width of machined chip (w)

Shear angle – angle of shearing surface measured from tool direction (ϕ)

Cutting Conditions

Note:

- Primary cutting due to speed
- Lateral motion of tool is feed
- Tool penetration is depth of cut

The three together form the material removal rate (*MRR*):

MRR = v f d

with units of (in/min)(in/rev)(in) = in^3/min/rev

(or vol/min-rev)

Types of cuts:

Roughing:	**feeds of 0.015 – 0.05 in/rev**	**depths of 0.1 – 0.75 in**
Finishing:	**feeds of 0.005 – 0.015 in/rev**	**depths of 0.03 – 0.075 in**

Cutting Geometry

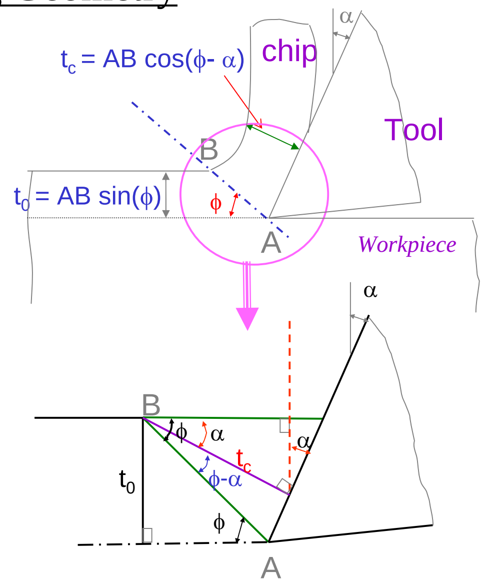
Chip thickness ratio = r = t_o / t_c

From the shear plane geometry:

$r = l_s \sin\phi / [l_s \cos(\phi - \alpha)]$

which can be arranged to get

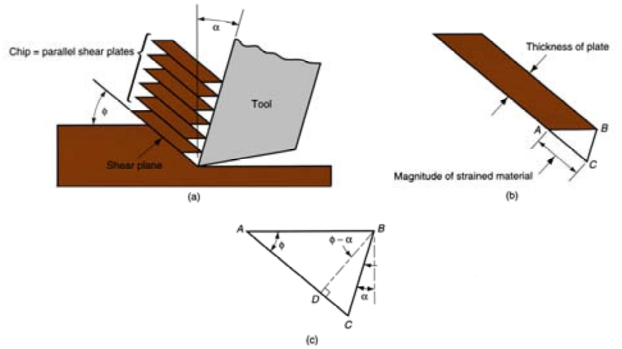
$\tan\phi = r\cos\alpha / [1 – r\sin\alpha]$



Cutting Geometry

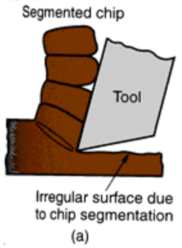
Note from the triangles in (c) that the shear strain (γ) can be estimated as

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



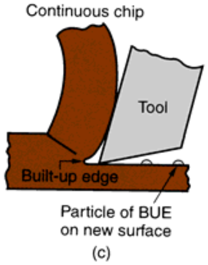
Thus, if know γ and α, can determine ϕ, and given ϕ and α, can determine γ.

Types of Chip in Machining



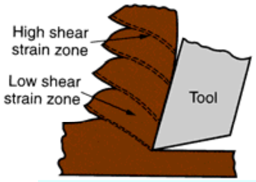
- Brittle work materials (e.g., cast iron)
- Low cutting speeds
- Large feed and depth of cut
- High tool-chip friction

- 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



- 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

Serrated Chip



- Semicontinuous
- Cyclical chip formation of alternating high then low shear strain

Most closely associated with difficult-to-machine metals at high cutting speeds

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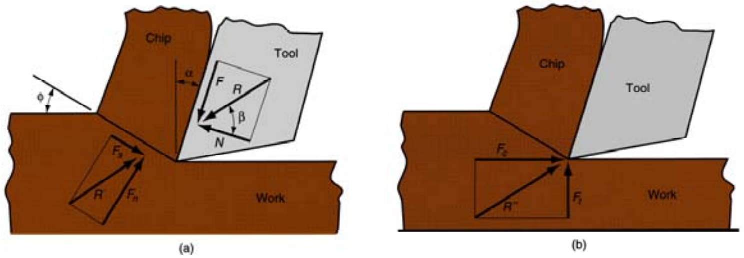
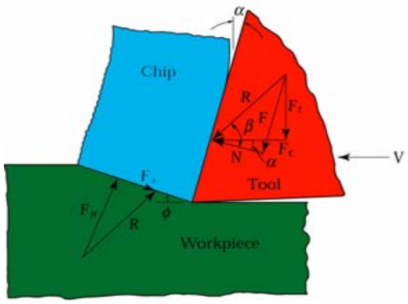
Cutting Force and Power

- Power requirements must be known to select a machine tool with enough power
- Data on cutting forces is required
  - *Machine tools can be designed to avoid excessive distortion, maintain dimensional tolerances*
  - *Determine in advance whether the workpiece is capable of withstanding the cutting forces without excessive distortion*



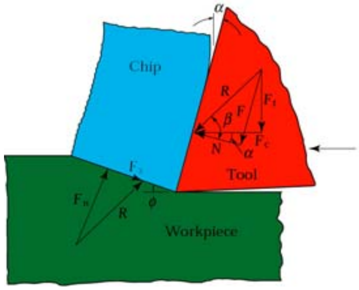
Forces in Two-Dimensional Cutting

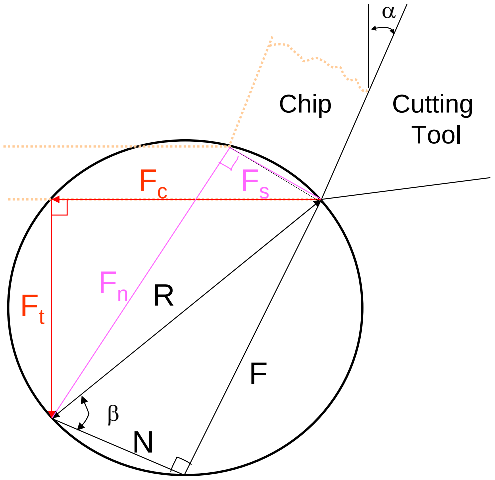


Forces acting on a cutting tool in two-dimensional cutting. Note that the resultant force, R, must be colinear to balance the forces.

- Cutting force, F_c
- Thrust force, F_t
- F_c and F_t produce resultant force R
- R can be resolved into two components on tool face
  - *Friction force, $F = R \sin \beta$*
  - *Normal force, $N = R \cos \beta$*
  - ***$\mu = F/N$***
- R is balanced by shear force, F_s, and a normal force, F_n, along the shear plane

Force Calculation with Merchant's Force Circle





Forces are presented as function of F_c and F_t because these can be measured.

Cutting Forces

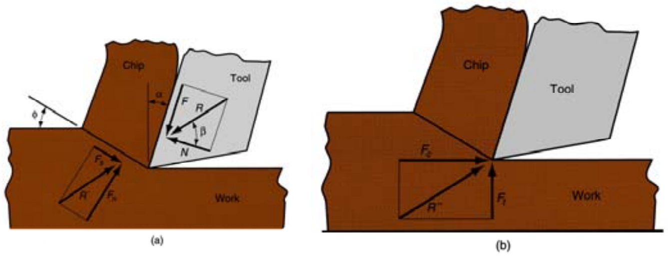
Since R = R' = R'', we can get the force balance equations:

$F = F_c \sin\alpha + F_t \cos\alpha$ F = friction force; N = normal to chip force

$N = F_c \cos\alpha - F_t \sin\alpha$ F_c = cutting force; F_t = thrust force

$F_s = F_c \cos\phi - F_t \sin\phi$ F_s = shear force; F_n = normal to shear plane force

$F_n = F_c \sin\phi + F_t \cos\phi$



(a)

(b)

Friction angle = β

$\tan\beta = \mu = F/N$

Shear plane stress:

$\tau = F_s/A_s$

where

$A_s = t_o w/\sin\phi$

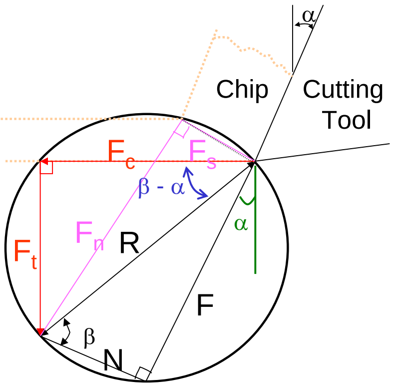
Cutting Forces Given Shear Strength

Letting τ = shear strength, we can derive the following equations for the cutting and thrust forces:

$F_s = \tau A_s$

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

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



The other forces can be determined from the equations on the previous slide.

Merchant Equations

Combining the equations from the previous slides:

$\tau = (F_c \cos\phi - F_t \sin\phi)/(t_o w/\sin\phi)$ *Merchant equation*

The most likely shear angle will minimize the energy. Applying $d\tau/d\phi = 0$ gives:

$\phi = 45° + \alpha/2 - \beta/2$ *Merchant relation*

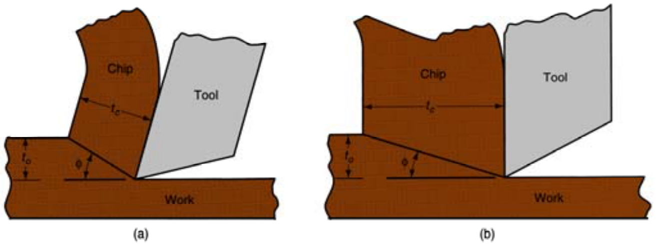
What does the Merchant relation indicate?

- increase in friction angle **decreases** shear angle
- increase in rake angle **increases** shear angle

If we increase the shear angle, we decrease the tool force and power requirements!

Merchant Equations

- Higher shear plane angle means smaller shear plane which means lower shear force
- Result: lower cutting forces, power, temperature, all of which mean easier machining



Effect of shear plane angle ϕ : (a) higher ϕ with a resulting lower shear plane area; (b) smaller ϕ with a corresponding larger shear plane area. Note that the rake angle is larger in (a), which tends to increase shear angle according to the Merchant equation

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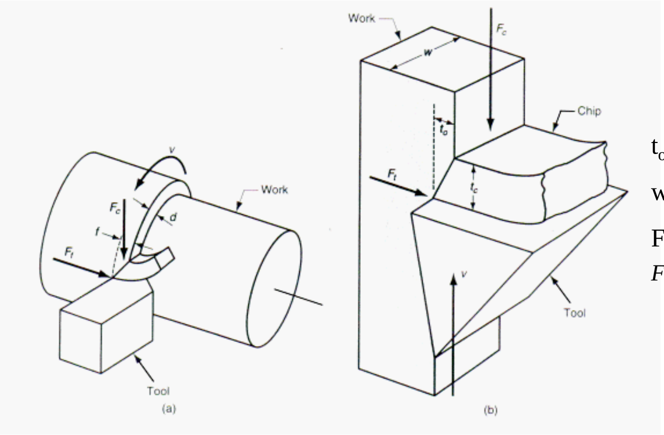
Cutting Models

The *orthogonal* model for turning approximates the complex shearing process:



t_o = feed (f)

w = depth of cut (d)

$F_f = F_t$

Feed force = Thrust force

Cutting Power

Power is force times speed:

$P = F_c v$ (ft-lb/min)

The cutting horsepower is

$hp_c = F_c v/33{,}000$ (hp)

The unit horsepower is

$hp_u = hp_c/MRR$

units?

energy per unit volume – *a material property*

Due to efficiency losses (E about 90%), the gross hp required is

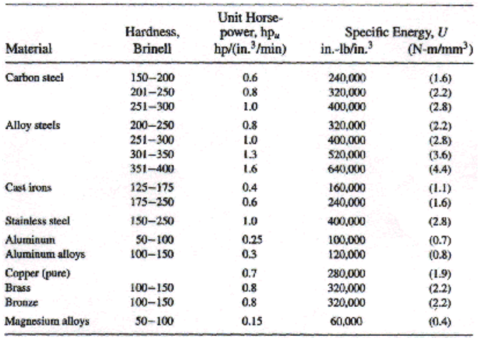
$hp_g = hp_c/E$

Cutting Energy

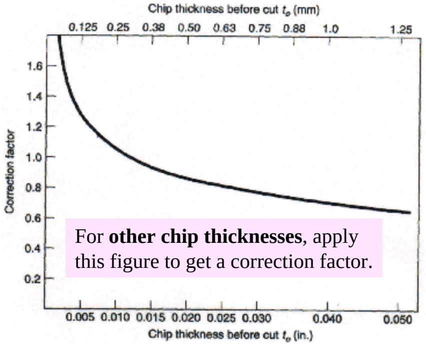
Specific energy is

$U = F_c v/(v\, t_o w) = F_c/(t_o w)$ (in-lb/in^3)

The table shown contains power and specific energy ratings for several work materials at a chip thickness of 0.01 in.



Material	Hardness, Brinell	Unit Horse-power, hp_u hp/(in.^{3}/min)	Specific Energy, U in.-lb/in.^{3}	(N-m/mm^3)
Carbon steel	150–200	0.6	240,000	(1.6)
	201–250	0.8	320,000	(2.2)
	251–300	1.0	400,000	(2.8)
Alloy steels	200–250	0.8	320,000	(2.2)
	251–300	1.0	400,000	(2.8)
	301–350	1.3	520,000	(3.6)
	351–400	1.6	640,000	(4.4)
Cast irons	125–175	0.4	160,000	(1.1)
	175–250	0.6	240,000	(1.6)
Stainless steel	150–250	1.0	400,000	(2.8)
Aluminum	50–100	0.25	100,000	(0.7)
Aluminum alloys	100–150	0.3	120,000	(0.8)
Copper (pure)		0.7	280,000	(1.9)
Brass	100–150	0.8	320,000	(2.2)
Bronze	100–150	0.8	320,000	(2.2)
Magnesium alloys	50–100	0.15	60,000	(0.4)



For **other chip thicknesses**, apply this figure to get a correction factor.

Cutting Temperature

- Approximately 98% of the energy in machining is converted into heat
- This can cause temperatures to be very high at the tool-chip
- The remaining energy (about 2%) is retained as elastic energy in the chip

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

$$\Delta T = \frac{0.4U}{\rho_C}\left(\frac{vt_o}{K}\right)^{0.333}$$

where ΔT = temperature rise at tool-chip interface; U = specific energy; ρ_C = specific heat; K = thermal diffusivity

- Experimental methods can be used to measure temperatures in machining
- Most frequently used technique is the ***tool-chip thermocouple***
- Using this method, **K. J. Trigger** determined the speed-temperature relationship to be of the form:

$$T = K\, v^m$$

where T = measured tool-chip interface temperature

Next time:

Continue Machining