Lec 3: Subtractive Processes

A. Traditional techniques

A1. Overview and machining theory

- A1.1 Chip formation
- A1.2. Mechanics of machining

A2. Processes

- A2.1. Lathe operations
- A2.2. Mill and drill operations
- A2.3. Other operations
- A2.4. Process planning
- A2.5. Cutting tools and cutting fluids

B. Nontraditional techniques

B1. Overview

B2. Processes

- B2.1. Water jet and abrasive water jet
- B2.2. Electrochemical machining
- B2.3. Electrical discharge machining
- B2.4. Energy beam machining
- B2.5. Chemical etching and photochemical etching

C. Finishing techniques

C1. Overview

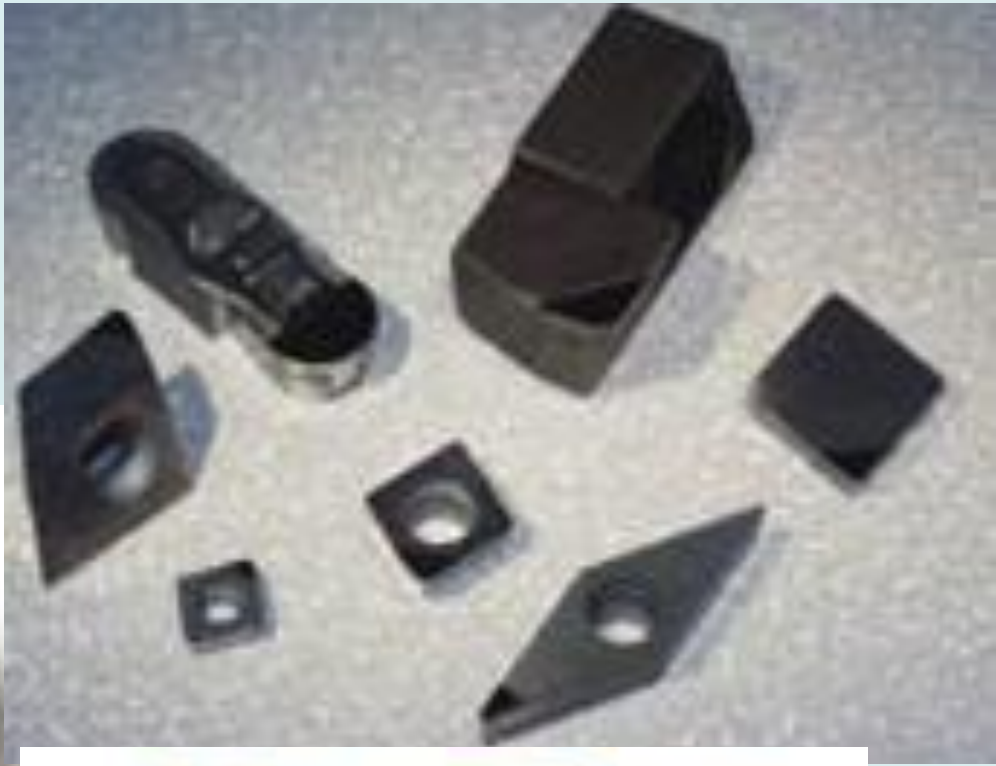
C2. Processes

- C2.1. Grinding and honing
- C2.2. Lapping
- C2.3. Polishing
- C2.4. Deburring
- C2.5. Surface treatment processes

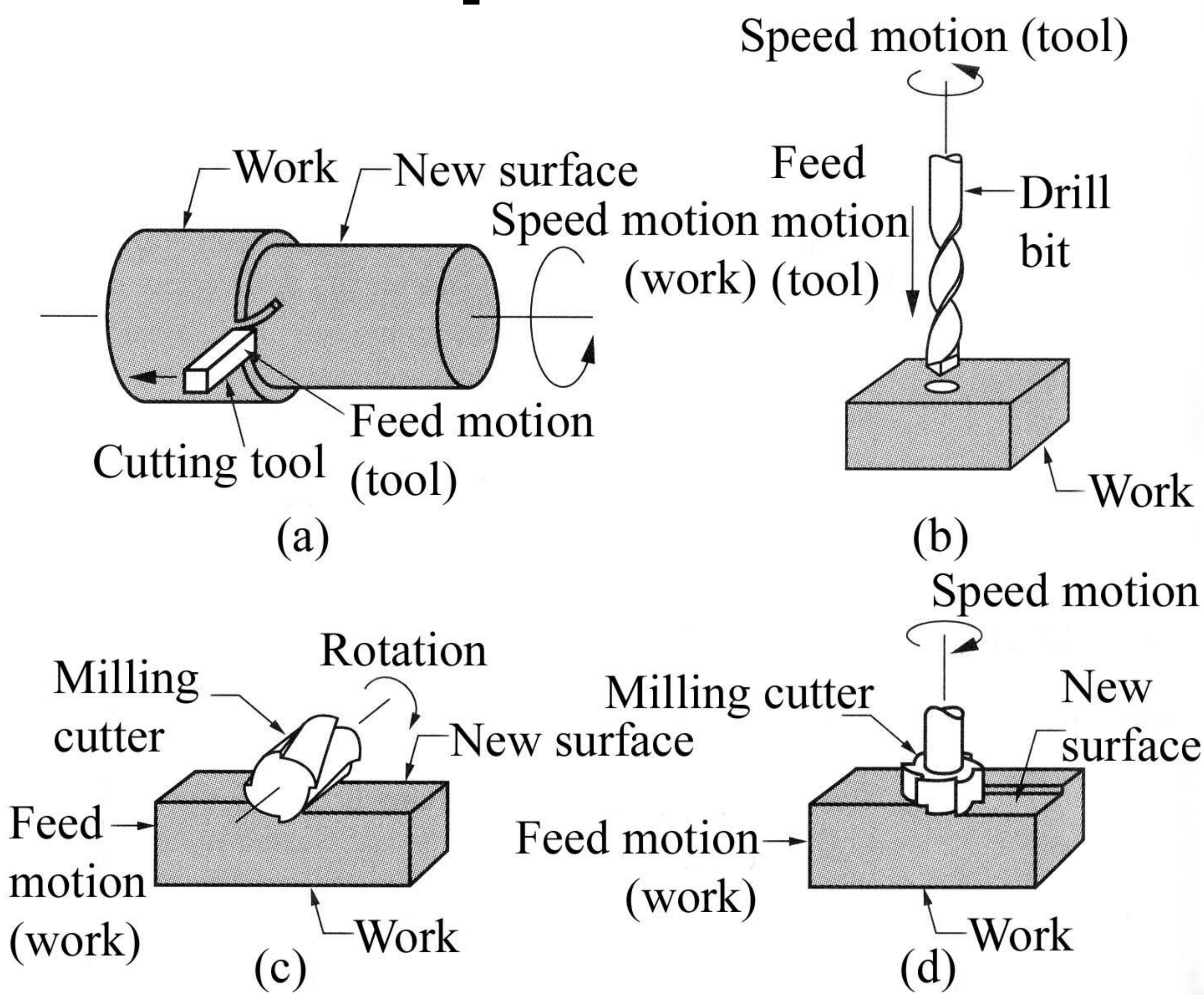
A. Classification

- **Traditional**
  - Turning, facing, grooving, threading…
  - Milling, tapping, boring…
  - Sawing, drilling…
- **Non-traditional**
  - Laser, ion beam, electron beam machining…
  - Electrochemical, electrical discharge …
  - Water jet, chemical etching plasma cutting…
- **Finishing**
  - Grinding, honing
  - Lapping, polishing, deburring…
  - Chemical mechanical polishing, sputtering…

CUTTING INSERTS



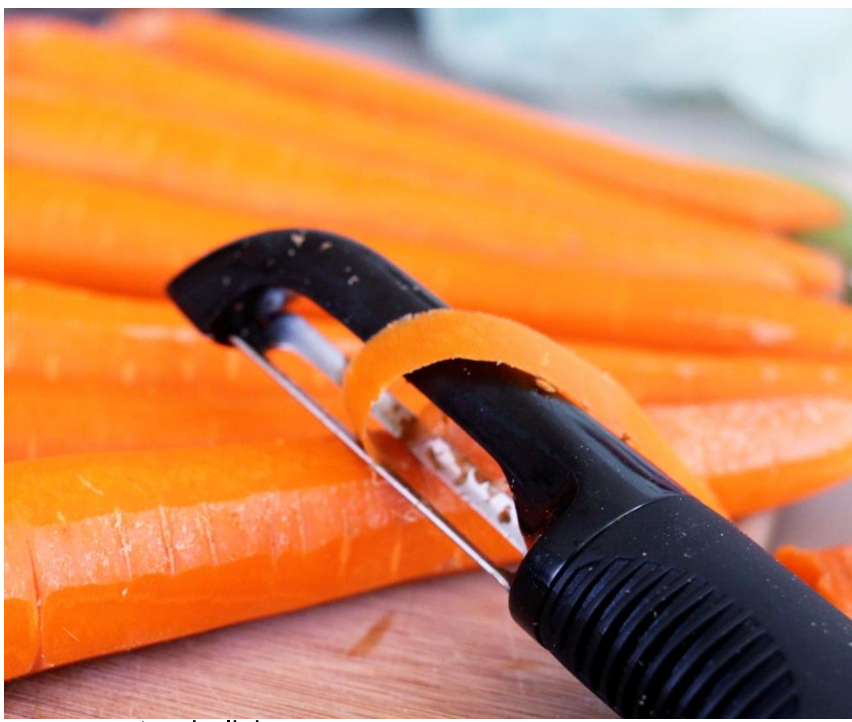
A. Traditional technique



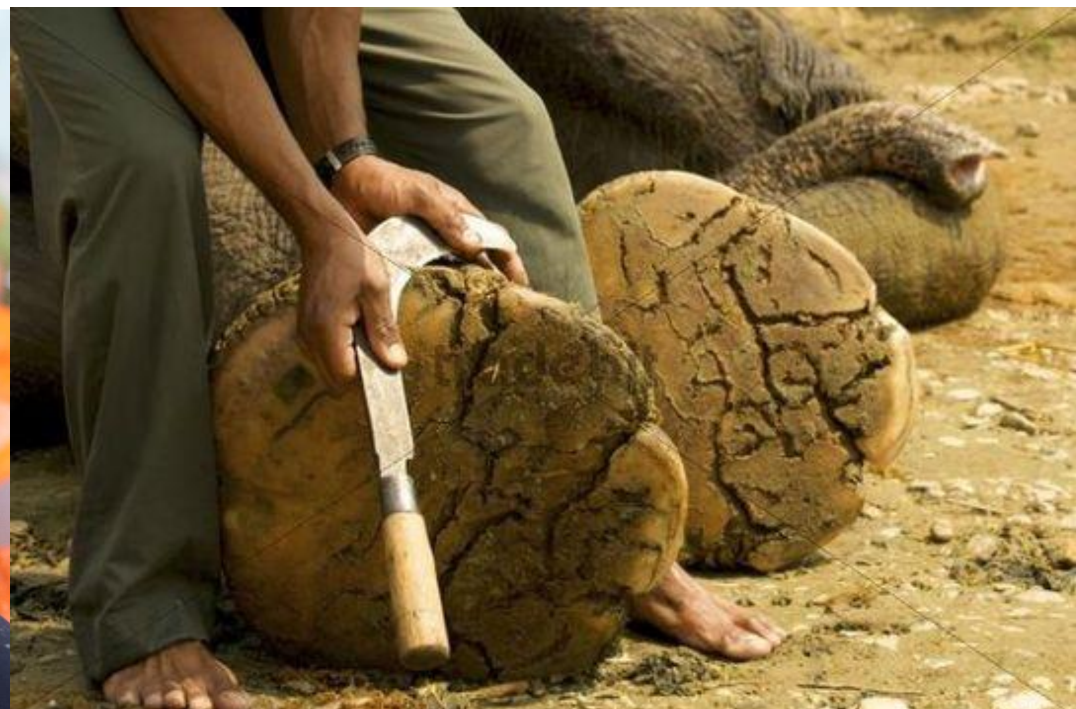
A1. Theory

Orthogonal cutting

- 2D
- Straight cutting edge
- Cutting edge ⊥ cutting direction

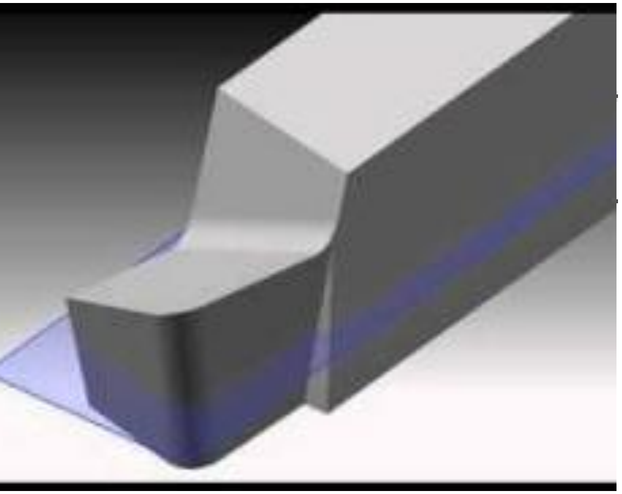


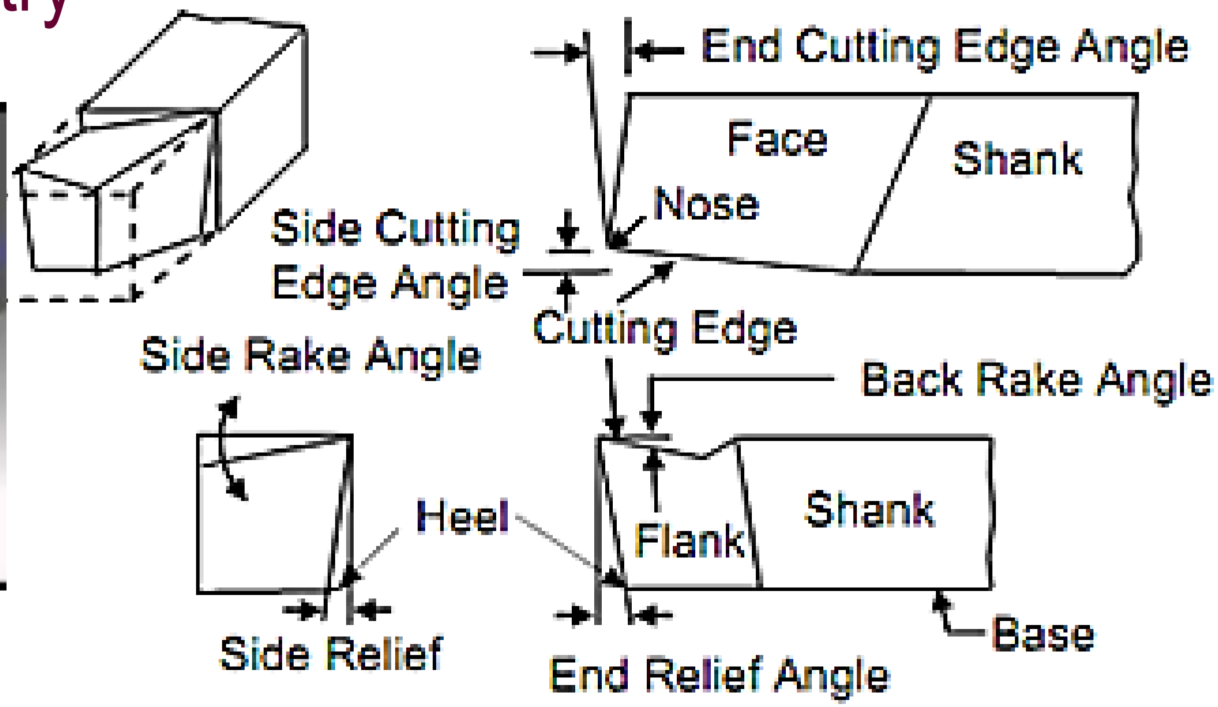
eatandrelish.com

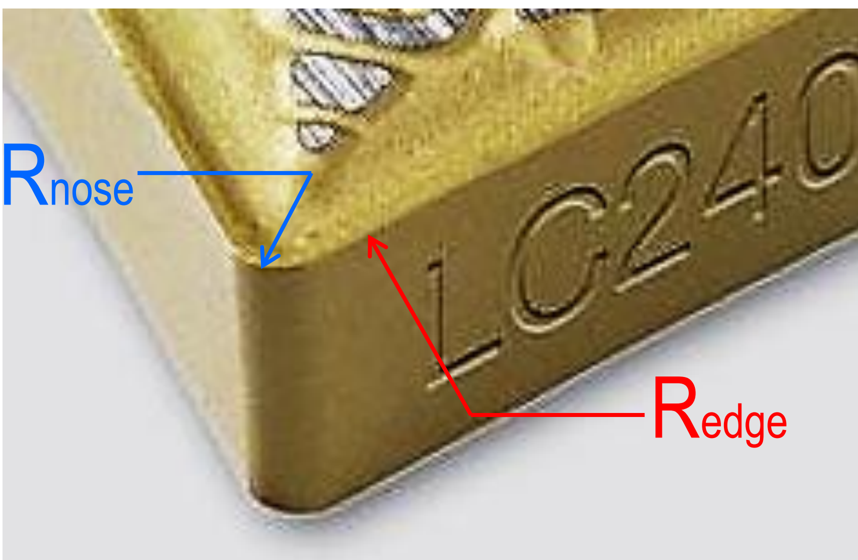


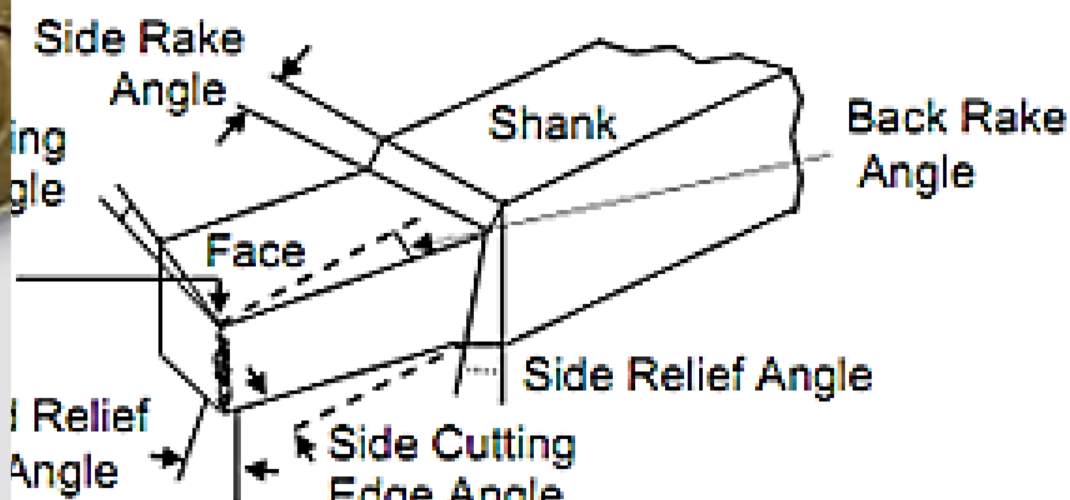
www.tradebit.com

Cutting tool geometry



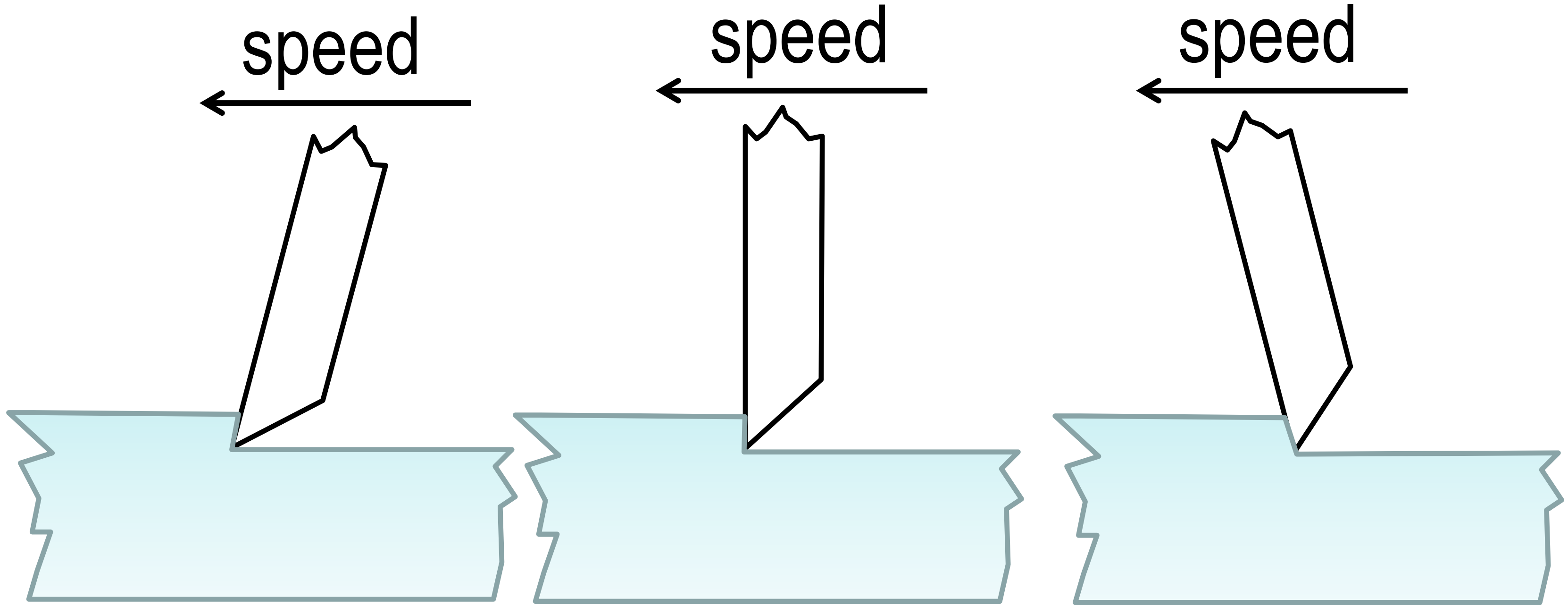




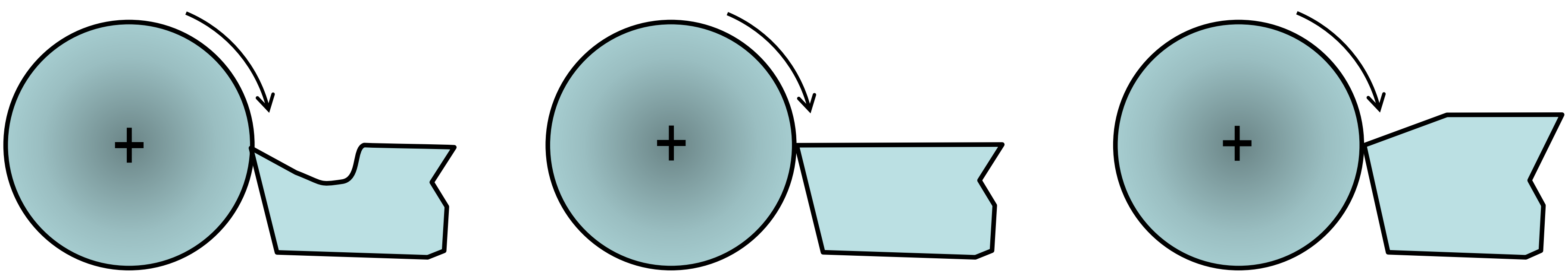


https://i.ytimg.com/vi/Mn9jpqI8rao/mqdefault.jpg

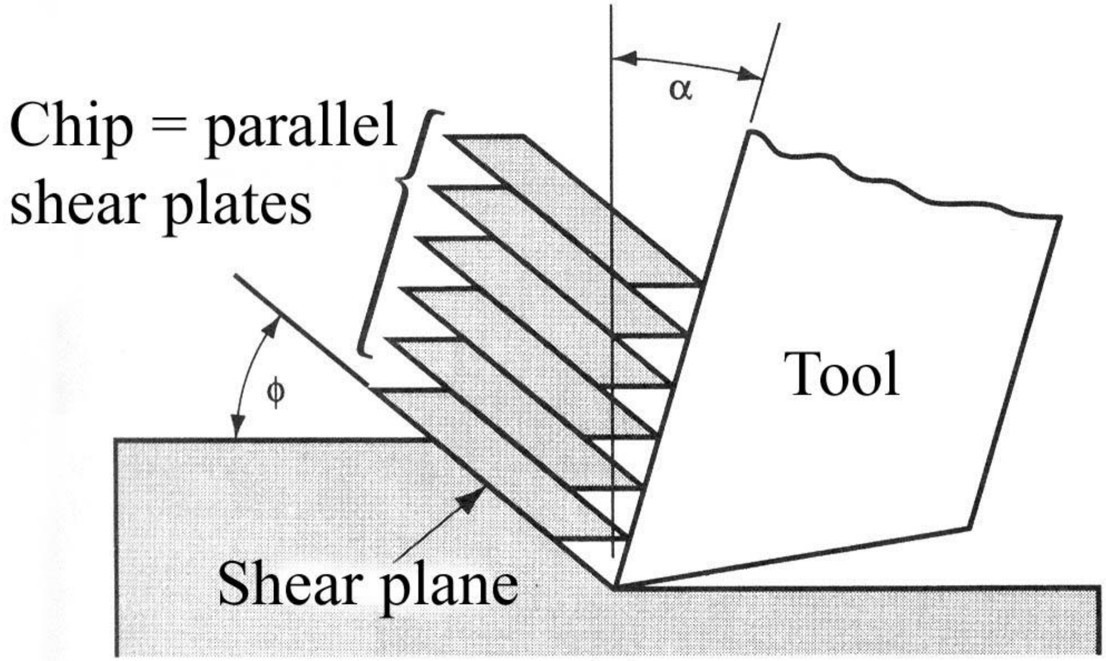
www.expertsmind.com



Rake angle $\alpha > 0$ $\alpha = 0$ $\alpha < 0$



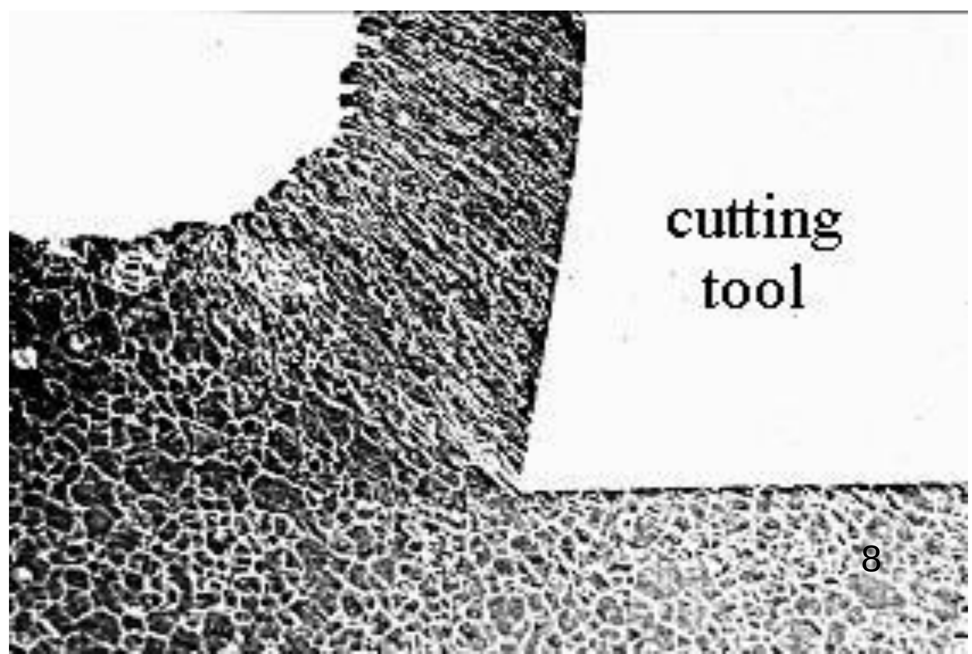
A1.1. Chip formation



$$r = \frac{t_o}{t_c}$$

$$\emptyset = \tan^{-1}\left(\frac{r\cos\alpha}{1 - r\sin\alpha}\right)$$

$$\gamma = \tan(\emptyset - \alpha) + \frac{1}{\tan\emptyset}$$

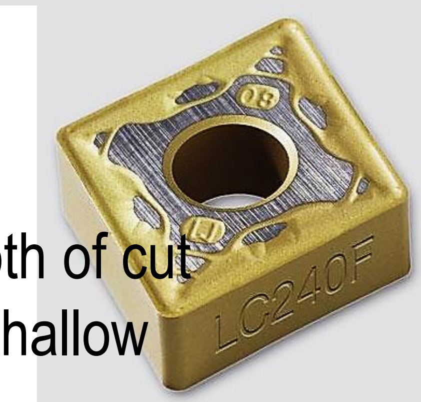


EFFECT OF TOOL EDGE RADIUS

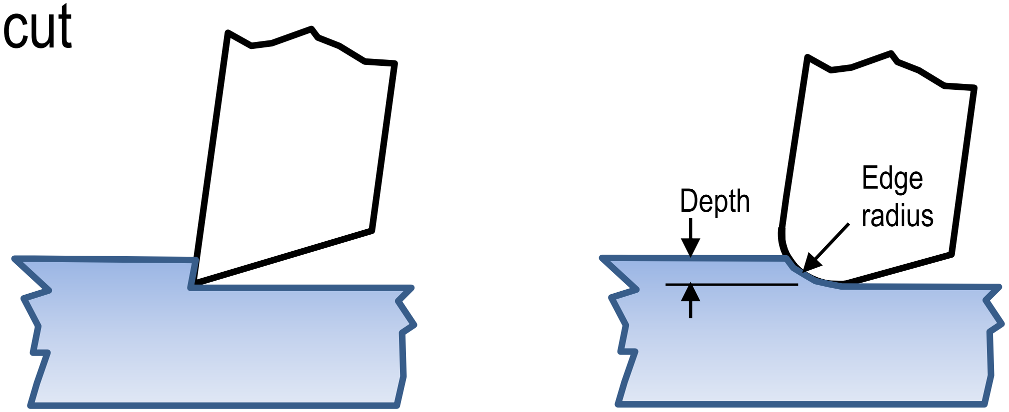
Tool will small edge radius

- Has sharp but fragile cutting edge
- Removes chip by shearing as in nor operation
- Has same effective rake angle when machining at shallow depth of cut

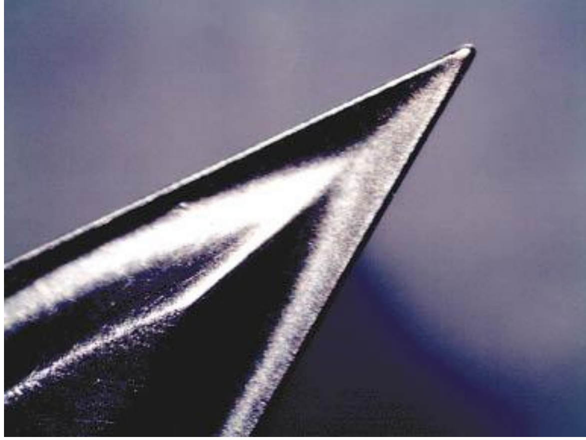
Tool with large edge radius



- Has blunt but strong cutting edge
- Removes chip by “plowing” and rubbing at shallow depth of cut
- Has negative effective rake angle when machining at shallow depth of cut



EFFECT OF TOOL NOSE RADIUS



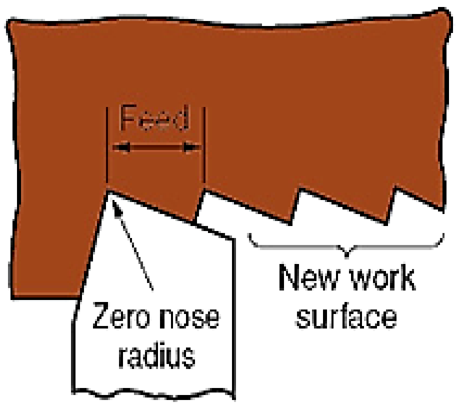
www.micromanufacturing.com

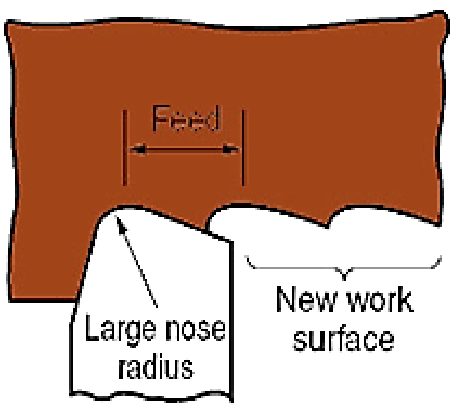
<u>Tool with small nose radius:</u>

- Has sharp but fragile cutting edge
- Produces consistent shear angle

<u>Tool with large nose radius:</u>

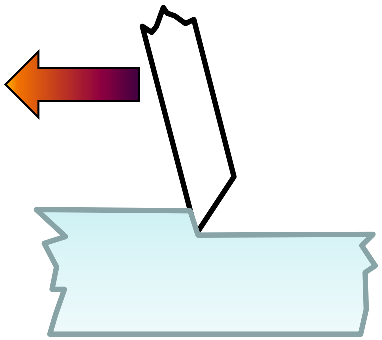
- Has blunt yet strong cutting edge
- Deforms material in front and below the tool
- Produces build up edge
- Produces inconsistent shear angle





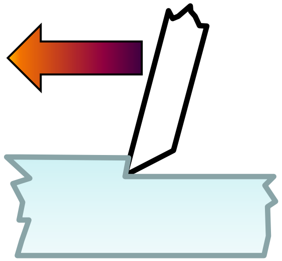
www.sanvik.com

EFFECT OF (back) RAKE ANGLE



Tool with negative rake:

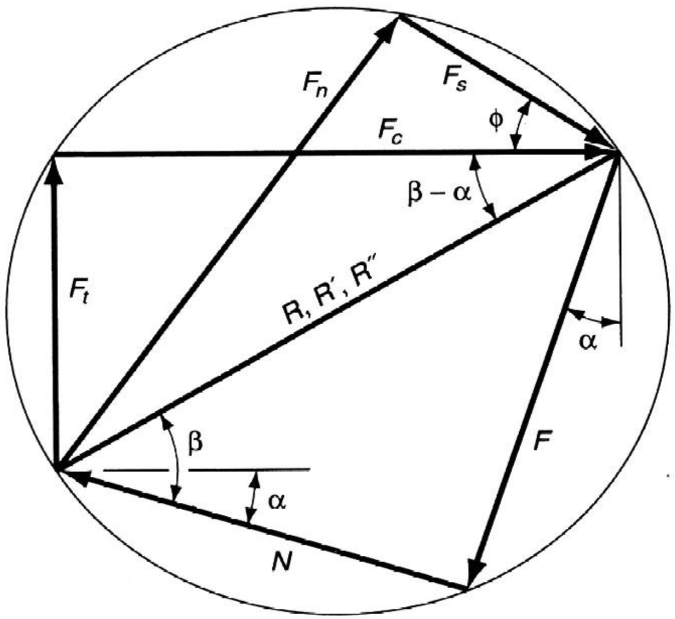
- Has blunt but strong cutting edge
- Deforms material in front and below the tool
- Produces low shear angle



Tool with positive rake:

- Has sharp yet fragile cutting edge
- Produces high shear angle
- Produces uniform chip

A1.2. Mechanics: Merchant's circle and equation



- Orthogonal machining
- Cutting force
- Cutting power

$$\vec{R} = \overrightarrow{F_c} + \overrightarrow{F_t}$$
$$= \overrightarrow{F_s} + \overrightarrow{F_n}$$
$$= \vec{F} + \vec{N}$$

$$\mu = tan\beta = \frac{F}{N}$$

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

Cutting force measurement

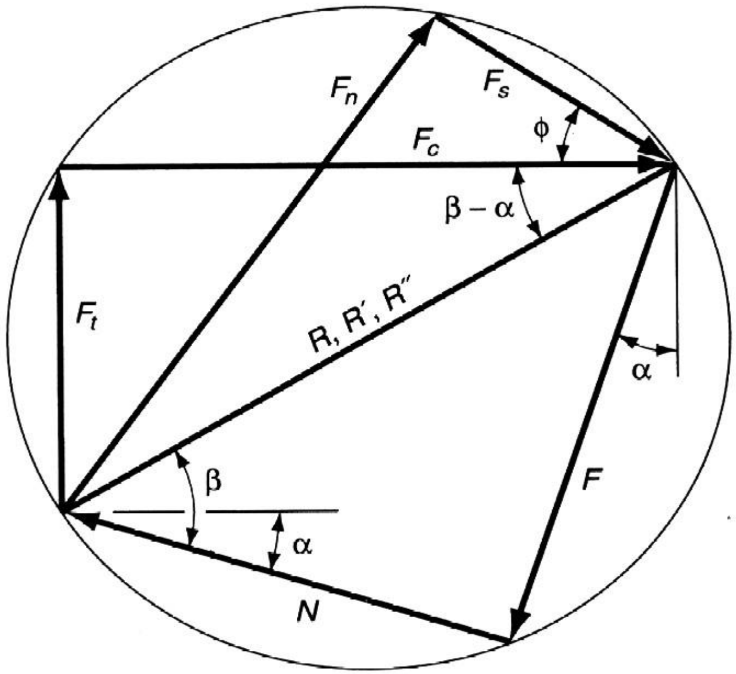
Piezzo-dynamometer

www.kistler.com

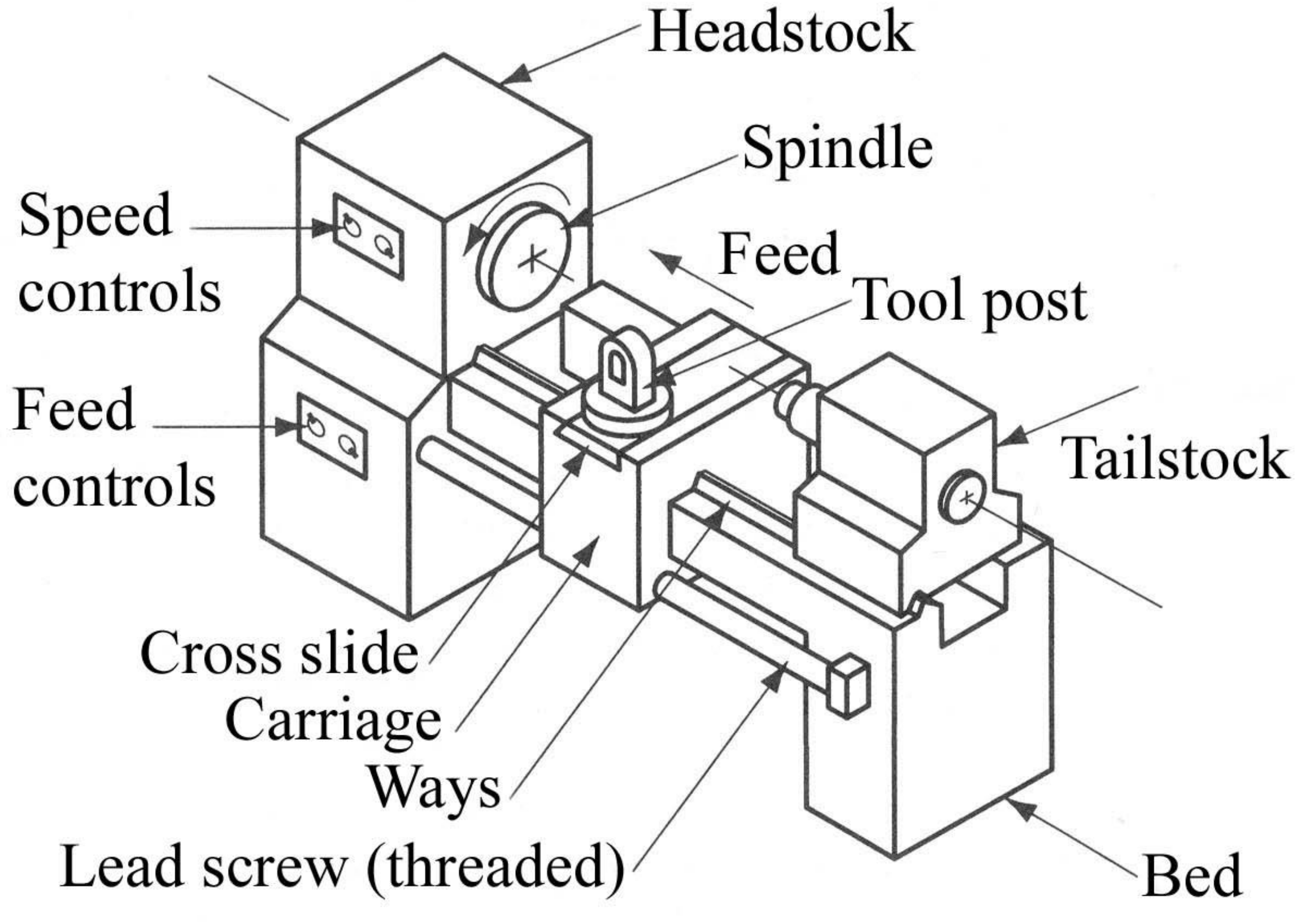
Cutting power

- Power
- Efficiency
- MRR
- Unit power

Material	Unit Power (HP/in³/min)
Hard steel	1.60
Mild steel	0.60
Cast iron	0.40
Aluminum	0.25

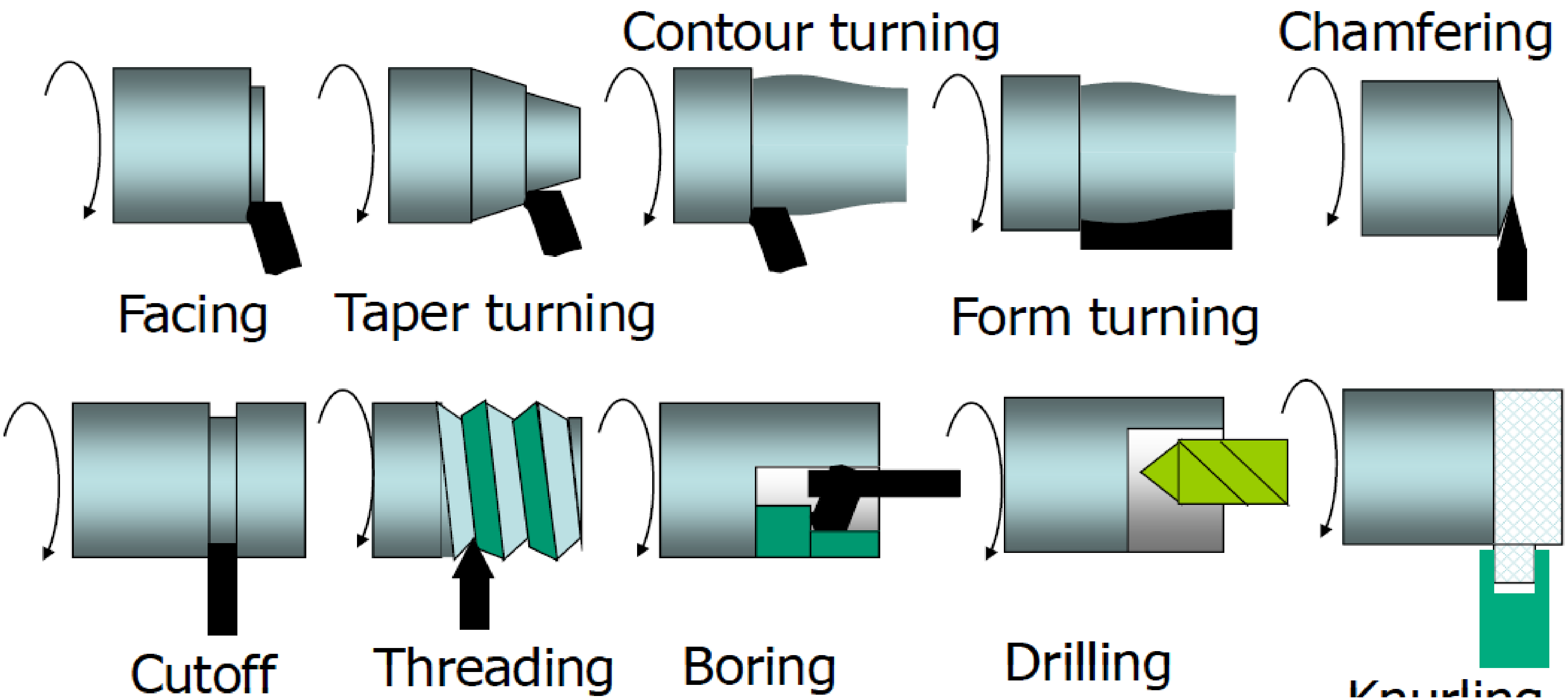


A2.1. Lathe operations



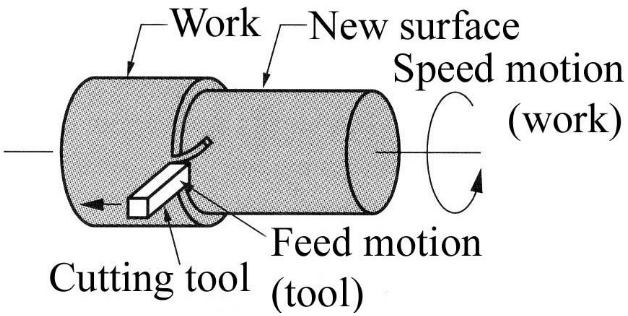
Operations related to Turning

molotilo.com



Boring operation

Turning analysis



- Cutting speed

$$V = R\omega = R(2\pi N) = \pi D N$$

- Depth of cut

$$d = \frac{D_2 - D_1}{2}$$

- Feed & feedrate

- Machining time

$$t = \frac{distance}{feedrate} = \frac{L}{fN}$$

- Material removal rate

$$MRR = \left(\frac{\text{area of cut}}{\text{revolution}}\right).\,(\text{area sweeping rate}) = (fd)V$$

f: feed (in/rev)
f_r: feed rate (in/min)
V: cutting speed (in/min)
R: workpiece radius (in)
ω: angular speed (rad/s)
N: rotation speed (rpm)
d: depth of cut (in)
L: length of cut (in)
t: machining time (min)
MRR: material removal rate (in^3/min)

Flutes = teeth = cutting edges

2-flute drill

www.precisebits.com/

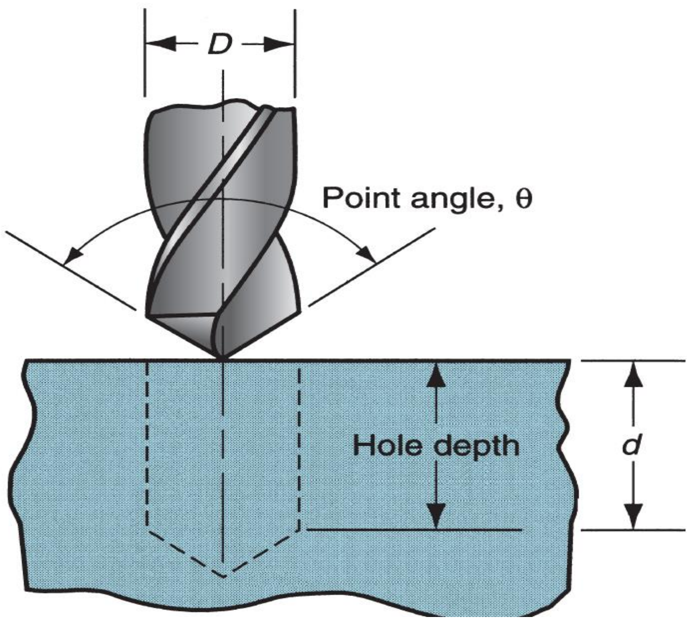
10-flute mill

www.carbideanddiamondtooling.com

5-flute mill

www.indiamart.com/

A2.2. Drilling analysis



- Cutting speed

$$V = R\omega = R(2\pi N) = \pi DN$$

- Feed, chip load

$$\text{feed rate}\left(\frac{\text{in}}{\text{min}}\right) = \left(\frac{\text{in}}{\text{flute}}\right)\left(\frac{\text{flute}}{\text{rev}}\right)\left(\frac{\text{rev}}{\text{min}}\right)$$

$$f_r = fnN$$

- Drilling time

$$t = \frac{0.5D\tan\left(90° - \frac{\theta}{2}\right) + d}{f_r}$$

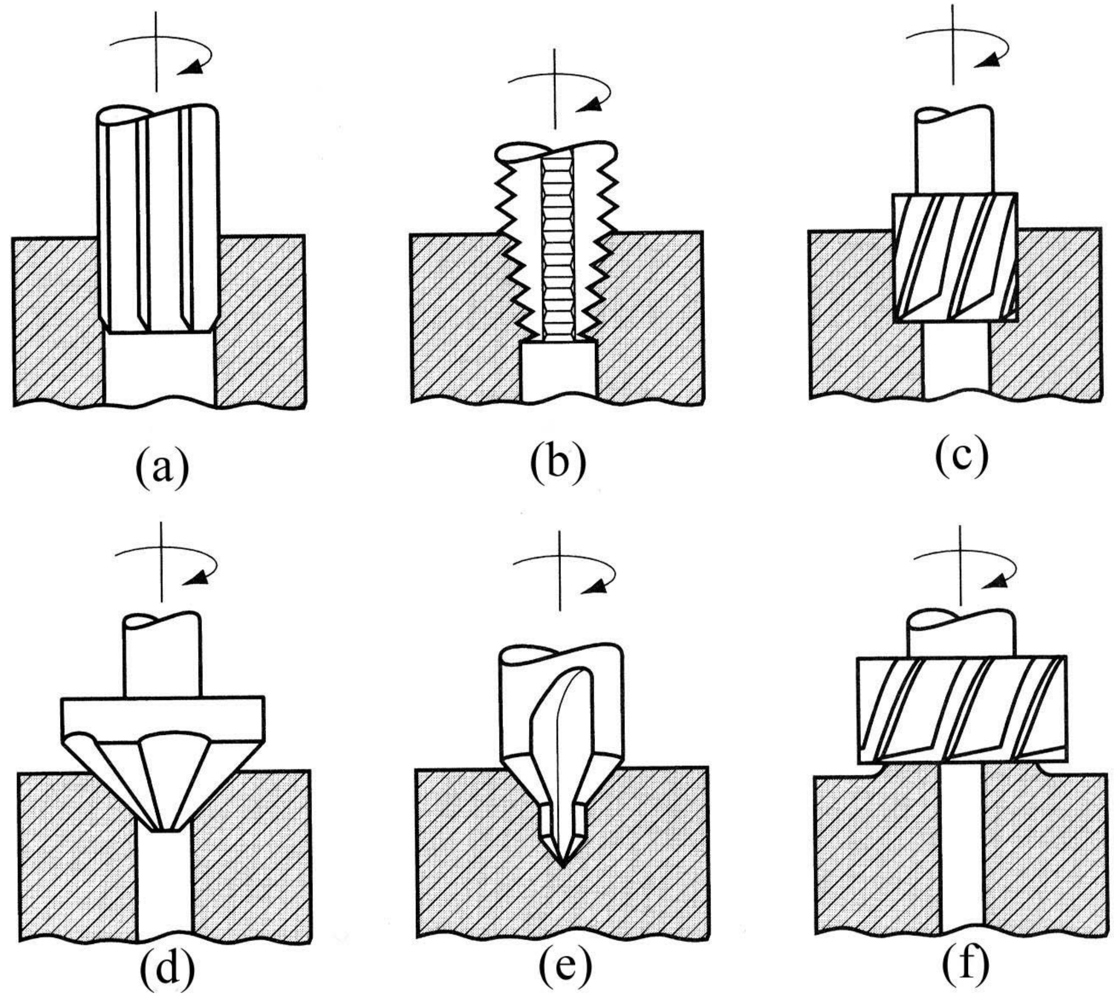
- Material removal rate

$$MRR = (area)(area\ sweep\ rate) = \frac{\pi D^2}{4} f_r$$

A2.2. Similar processes

Hole making:

1. Center drill
2. Drill
3. Bore to size
4. Ream
5. Hone
6. Deburr



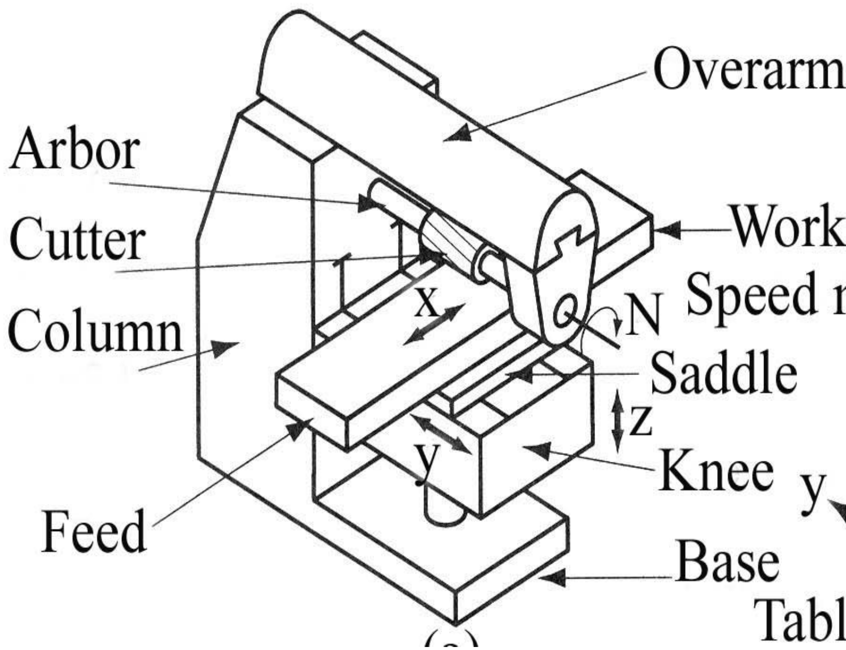
Counter bored hole for cylindrical screw head

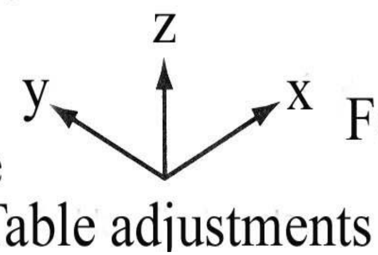
Counter sunk hole for conical screw head

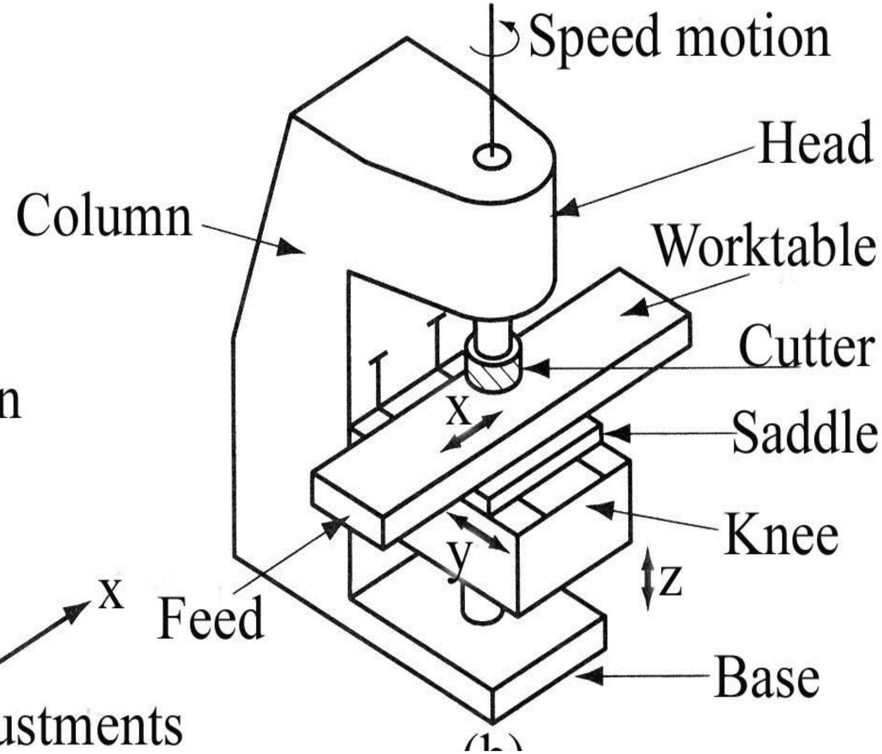
Drill smaller hole for tapping → Use a tap drill

Thread Size	Threads Per Inch	Thread Designation	Tap Drill Size	Decimal Equiv.	Theoretical % Thread Engagement	Major Diameter (inches)	Pitch Diameter (inches)	Minor Diameter (inches)	Stress Area of Installed Fastener (sq. in.)
	24	**UNC**	**16**	0.1770	72%		0.1889	0.171	0.0242
12	**28**	**UNF**	**14**	0.1820	73%	0.2160	0.1928	0.177	0.0258
	32	UNEF	3/16	0.1875	70%		0.1957	0.182	0.0270
	20	**UNC**	**7**	0.2010	75%		0.2175	0.196	0.0318
1/4	**28**	**UNF**	**3**	0.2130	80%	0.2500	0.2268	0.211	0.0364
	32	UNEF	7/32	0.2188	77%		0.2297	0.216	0.0379
	18	**UNC**	**F**	0.2570	77%		0.2764	0.252	0.0524
	20	UN	17/64	0.2656	72%		0.2800	0.258	0.0547
5/16	**24**	**UNF**	**I**	0.2720	75%	0.3125	0.2854	0.267	0.0581
	28	UN	J	0.2770	77%		0.2893	0.274	0.0606
	32	UNEF	9/32	0.2813	77%		0.2922	0.279	0.0625
	16	**UNC**	**5/16**	0.3125	77%		0.3344	0.307	0.0775
	20	UN	21/64	0.3281	72%		0.3425	0.321	0.0836
3/8	**24**	**UNF**	**Q**	0.3320	79%	0.3750	0.3479	0.330	0.0878
	28	UN	R	0.3390	78%		0.3518	0.336	0.0909
	32	UNEF	11/32	0.3438	77%		0.3547	0.341	0.0932

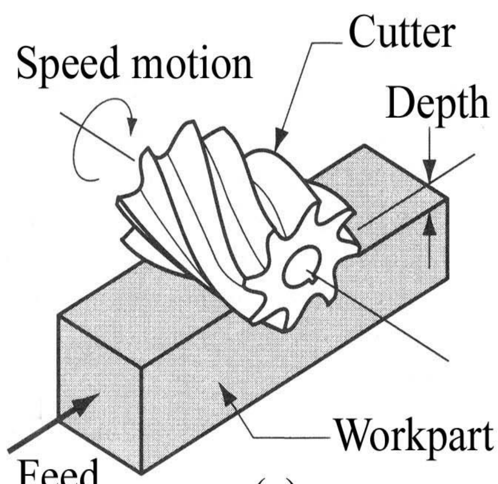
A2.2. Milling

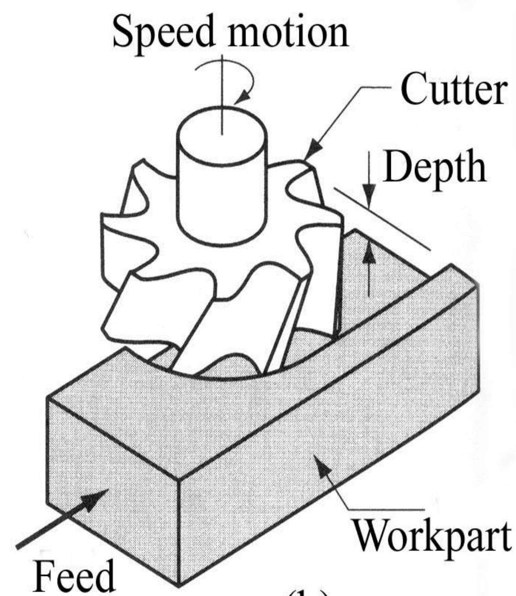






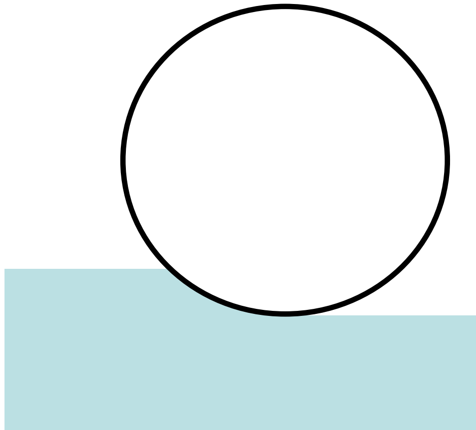
Horizontal
Peripheral
/side milling



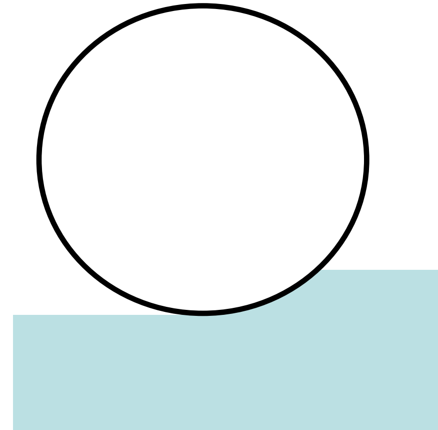


Vertical
Face
/end
milling

Milling analysis



Up milling
(conventional milling)



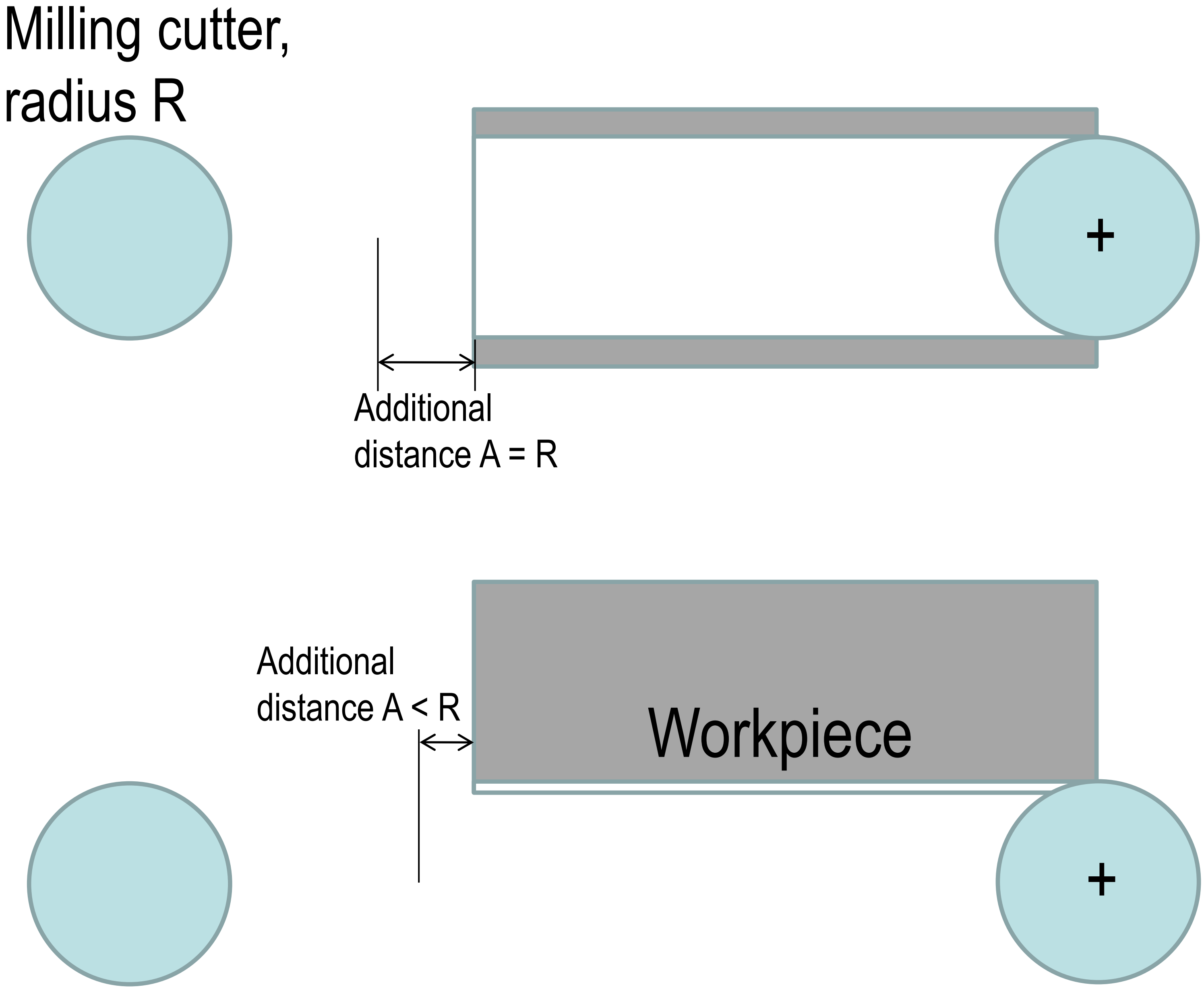
Down milling
(climb milling)

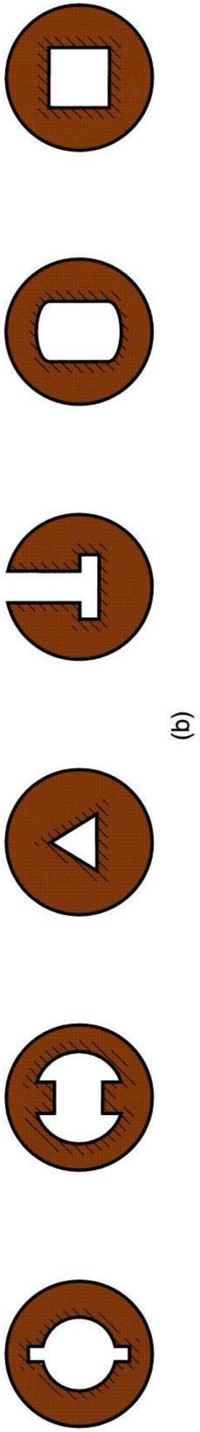
Milling analysis

- Chip load
- Speed $V = R\omega = R(2\pi N) = \pi D N$
- Feed, feed rate $f_r = f n N$
- Material removal rate

$$MRR = \left(\frac{\text{area of cut}}{\text{revolution}}\right).\,(\text{area sweeping rate}) = (wd)f_r$$

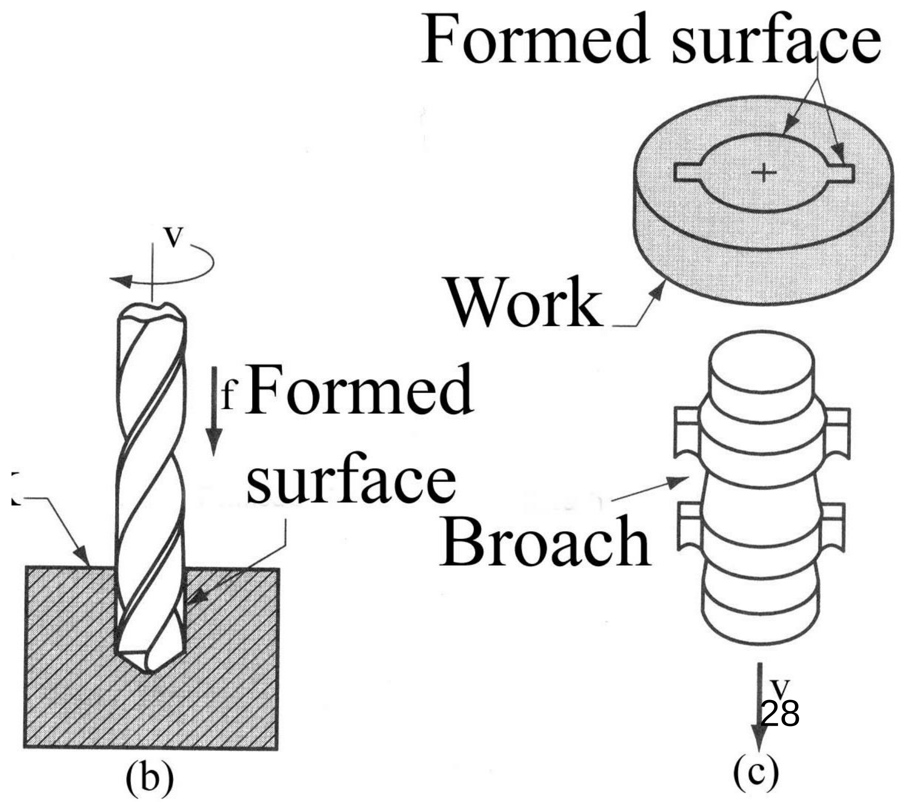
- Milling time $t = \dfrac{\text{distance}}{\text{feedrate}} = \dfrac{L + A}{f_r}$


Milling cutter,
radius R
Additional
distance A = R
Additional
distance A < R
Workpiece



A2.3. Broaching

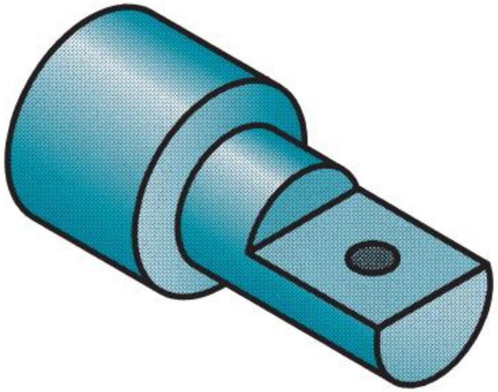
- Add features to a drilled hole
- Make non-circular hole

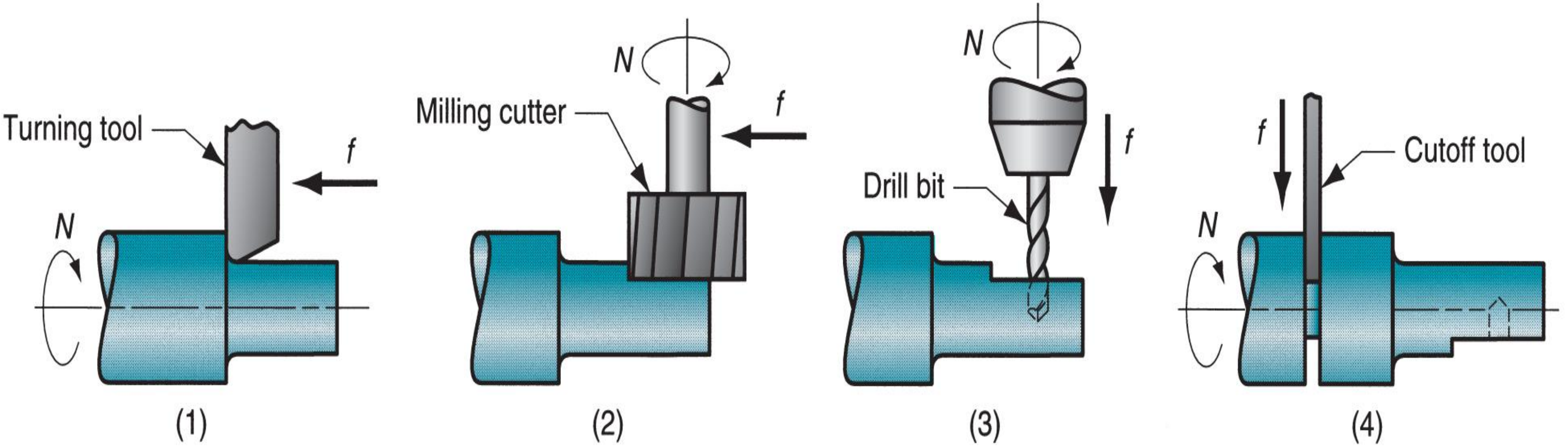


A2.4. Process plan

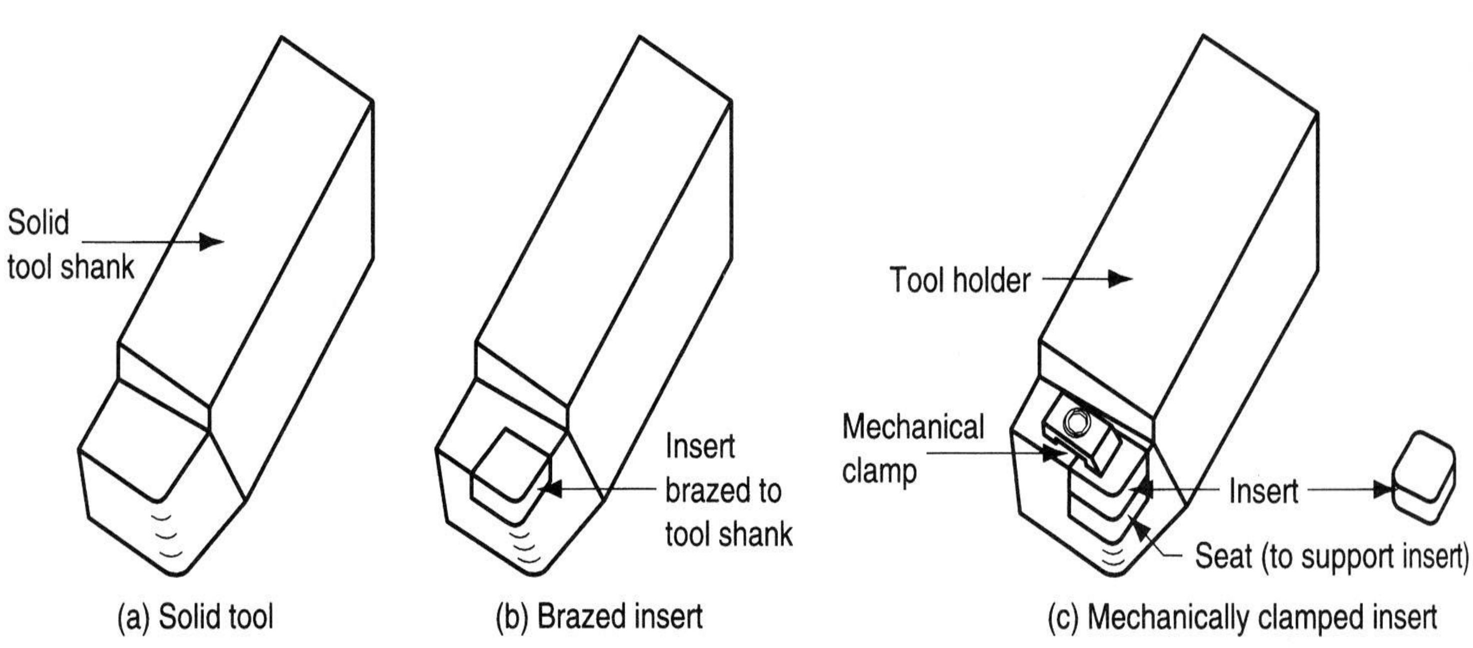
Step-by-step instructions to fabricate a part:

- Graphical illustration
- Tools, tool offset, tool sequence…
- Cutting speed, feed, depth of cut…
- Coolant / lubricant
- Deburring, packaging





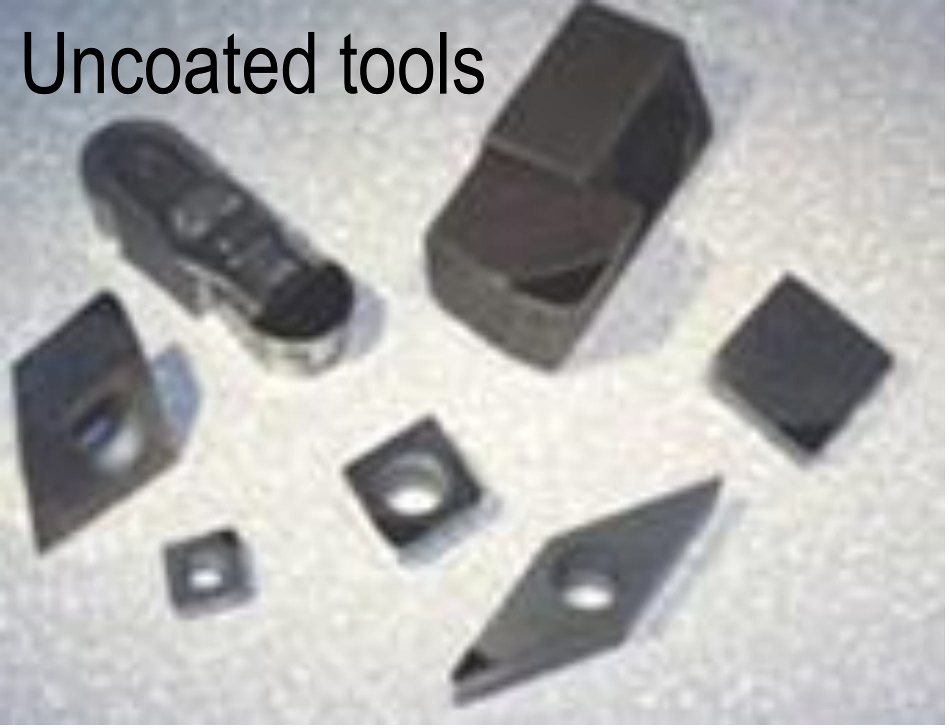
A2.5a. Cutting tools

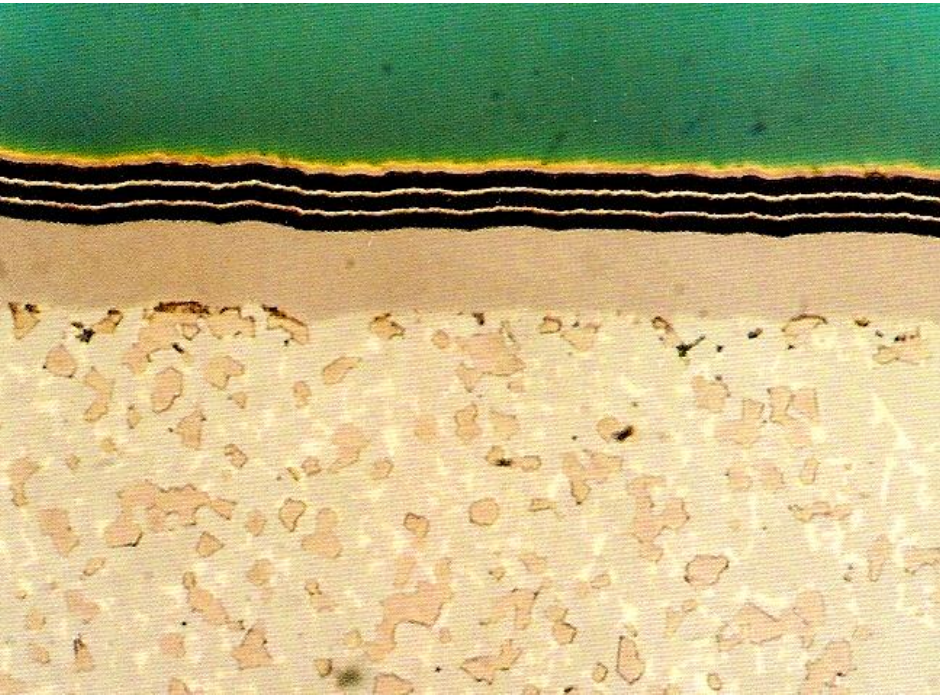


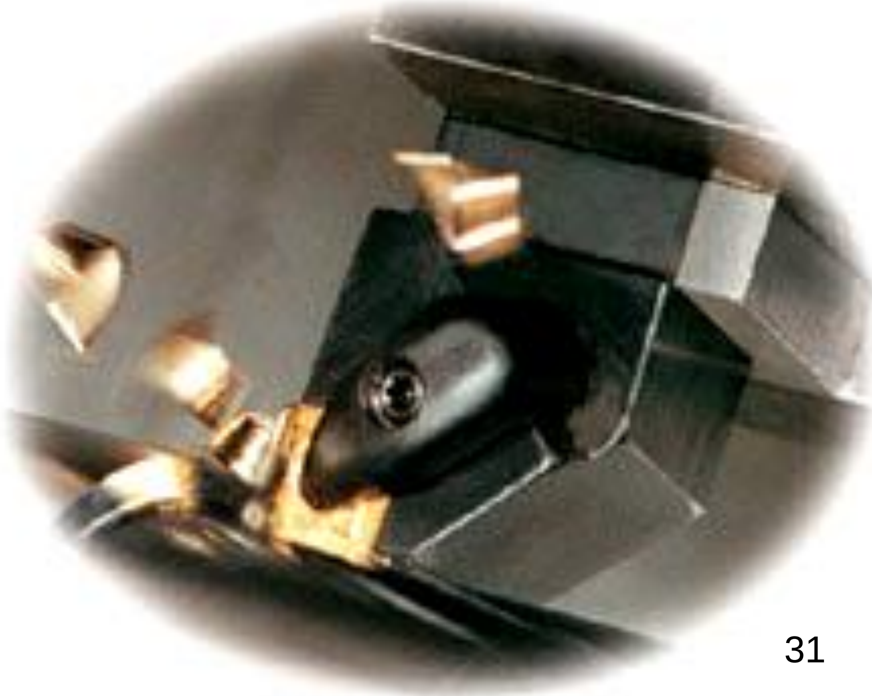
- Tool failure: wear, fracture, burnt…
- Tool life: machining distance, or time to replace a worn-out cutting tool

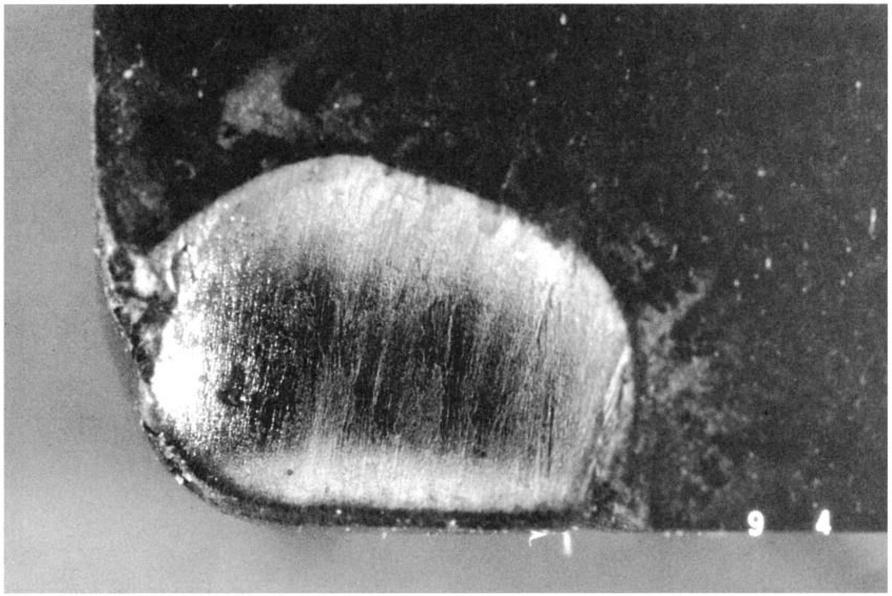
Uncoated tools

Coated tools



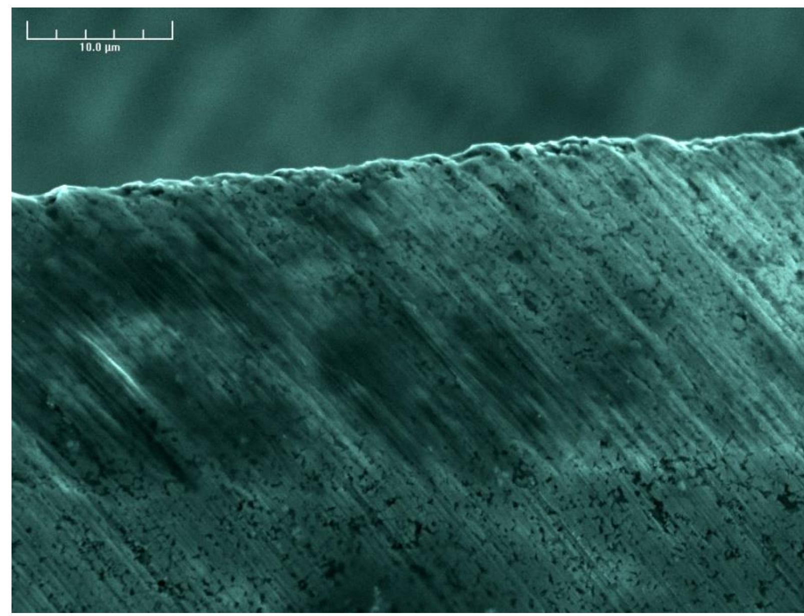






Crater wear
(top view)

Replace tool when
flank wear ≥ 0.3 mm



Flank wear (side view)

Tool materials

Selection criteria: crack resistance (toughness)
hardness
wear resistance
chemical resistance
geometry
cost, etc…

- HSS (high speed steel)
- WC (tungsten carbide)
- Coated WC
- CBN (cubic boron nitride)
- Diamond

Machinery's Handbook, 29th edition

Table 13. Cutting Feeds and Speeds for Milling Stainless Steels

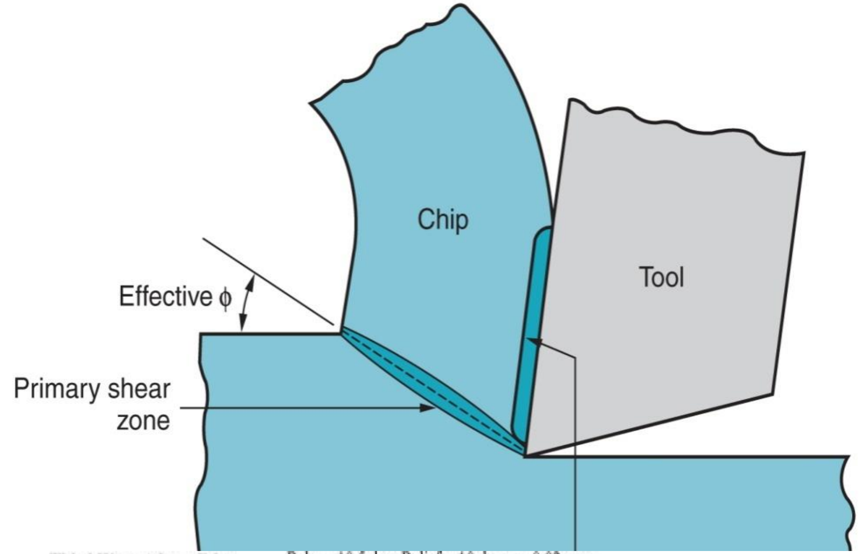
Material	Brinell Hardness	HSS Speed (fpm)		End Milling HSS Opt.	End Milling HSS Avg.	End Milling Uncoated Carbide Opt.	End Milling Uncoated Carbide Avg.	End Milling Coated Carbide Opt.	End Milling Coated Carbide Avg.	Face Milling Coated Carbide Opt.	Face Milling Coated Carbide Avg.	Slit Milling Uncoated Carbide Opt.	Slit Milling Uncoated Carbide Avg.	Slit Milling Coated Carbide Opt.	Slit Milling Coated Carbide Avg.
			f = feed (0.001 in./tooth), s = speed (ft/min)												
Free-machining stainless steels (Ferritic): 430F, 430FSe	135–185	110	f	7	4	7	4	7	4	39	20	39	20	39	20
			s	30	80	305	780	420	1240	210	385	120	345	155	475
(Austenitic): 203EZ, 303, 303Se, 303MA, 303Pb, 303Cu, 303 Plus X	135–185	100	f	7	4	7	4					39	20		
	225–275	80	s	20	55	210	585					75	240		
(Martensitic): 416, 416Se, 416 Plus X, 420F, 420FSe, 440F, 440FSe	135–185	110													
	185–240	100													
	275–325	60													
	375–425	30													

Average: high speed, low feed→ high quality

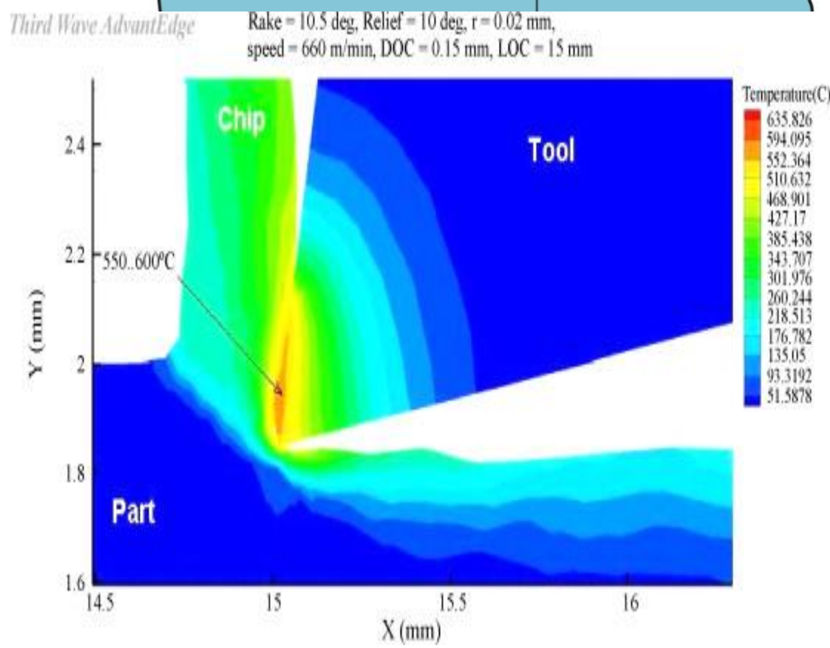
Optimal: low speed, high feed → low tool wear/ cost

A2.5.b. Cutting fluid

Why
- Heat generates at shear zone
- Friction at tool/chip interface



Cutting fluid
- Coolant: water base + additives
- Lubricant: oil base + additives



Latest technology: micromist
- Minimum fluid
- Most effective for external micromachining
- Environmental concern

http://www.fabricatingandmetalworking.com/2013/04/fea-optimizes-cutting-processes-machining-strategies/