446.305A MANUFACTURING PROCESSES

Chapter 8. Material-Removal Processes: Cutting

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Machining (기계가공)

- **Machining is the broad term used to describe removal of material from a workpiece.**
  - Cutting (절삭가공)
  - Abrasive processes (입자가공)
  - Advanced machining processes (특수기계가공)

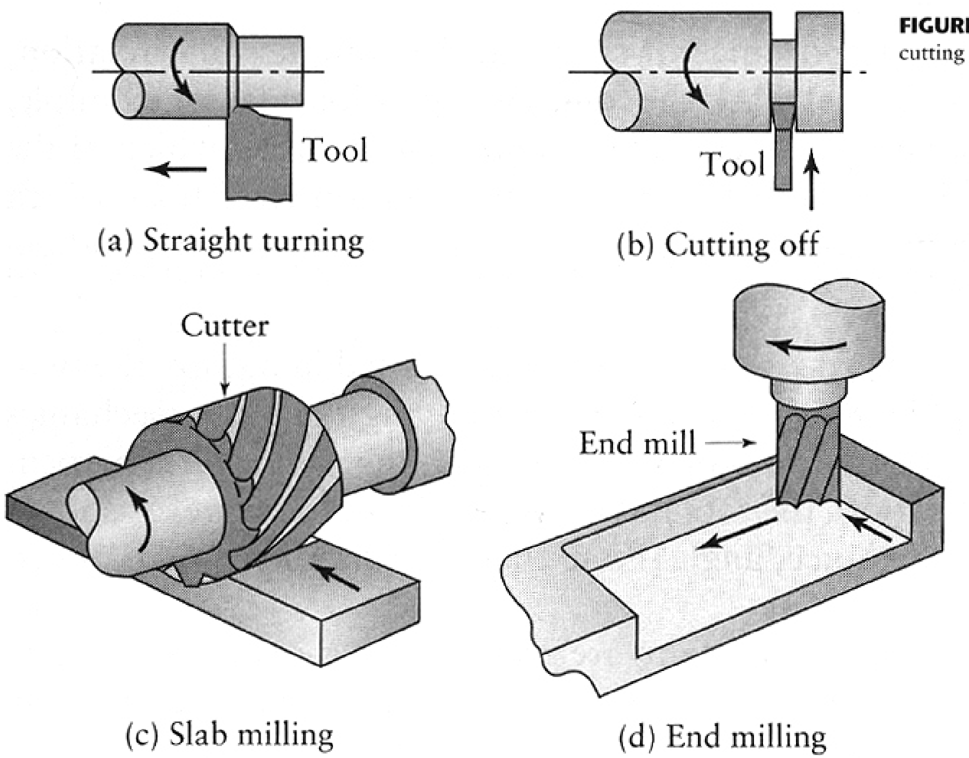


FIGURE 8.1 Examples of cutting processes.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

High speed machining

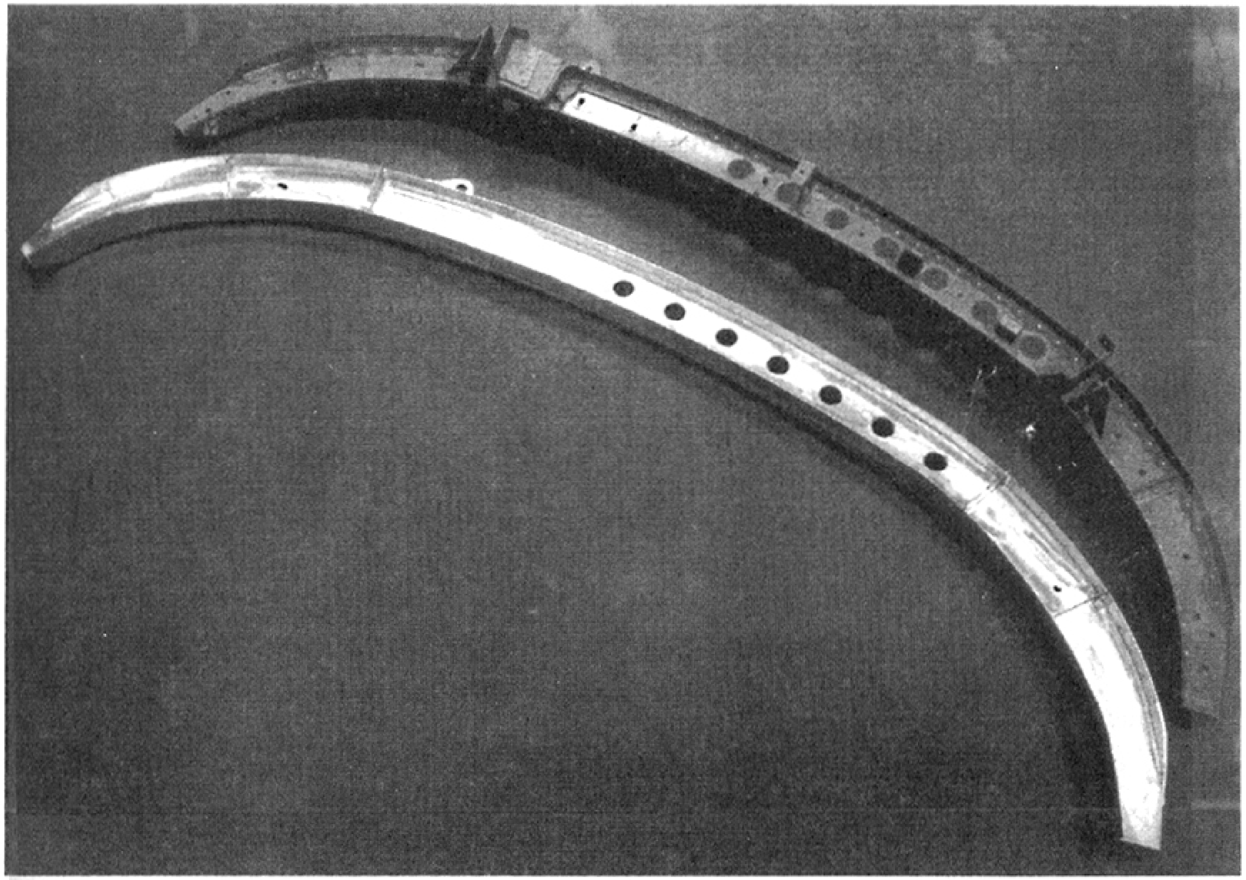


FIGURE 11.1 Integrated product and process design allows this aerospace component to be completely machined from the solid as shown in the lower photograph (Courtesy of Dr. Donald Sandstrom, The Boeing Company)

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Chip formation (칩형성)

- **Orthogonal cutting (직교절삭)**
- **Oblique cutting (경사절삭)**

- **Positive Rake angle (경사각)**
  - Chip away from the workpiece
- **Negative Rake angle**
  - Sturdy

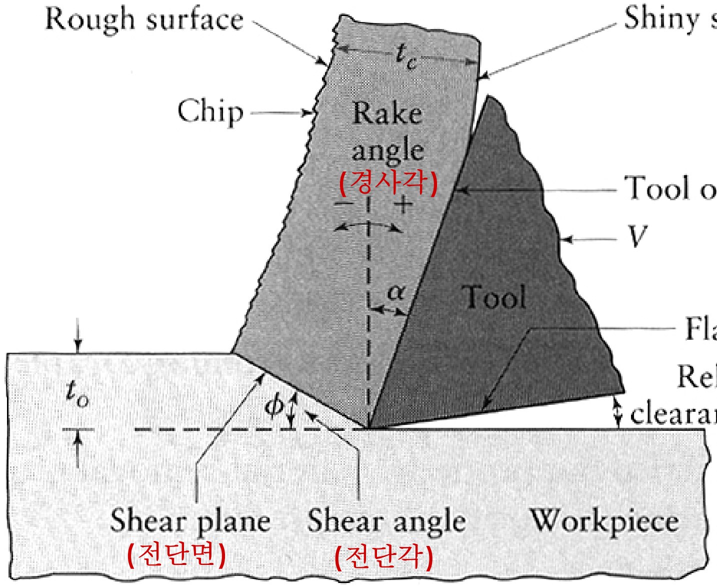
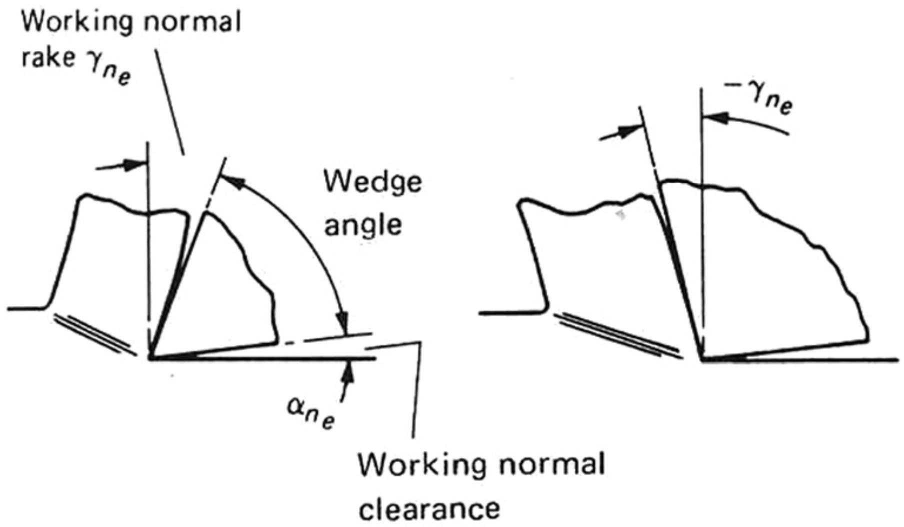


FIGURE 8.2 Schematic illustration of a two-dimensional cutting process, also called *orthogonal cutting*.



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Orthogonal cutting model

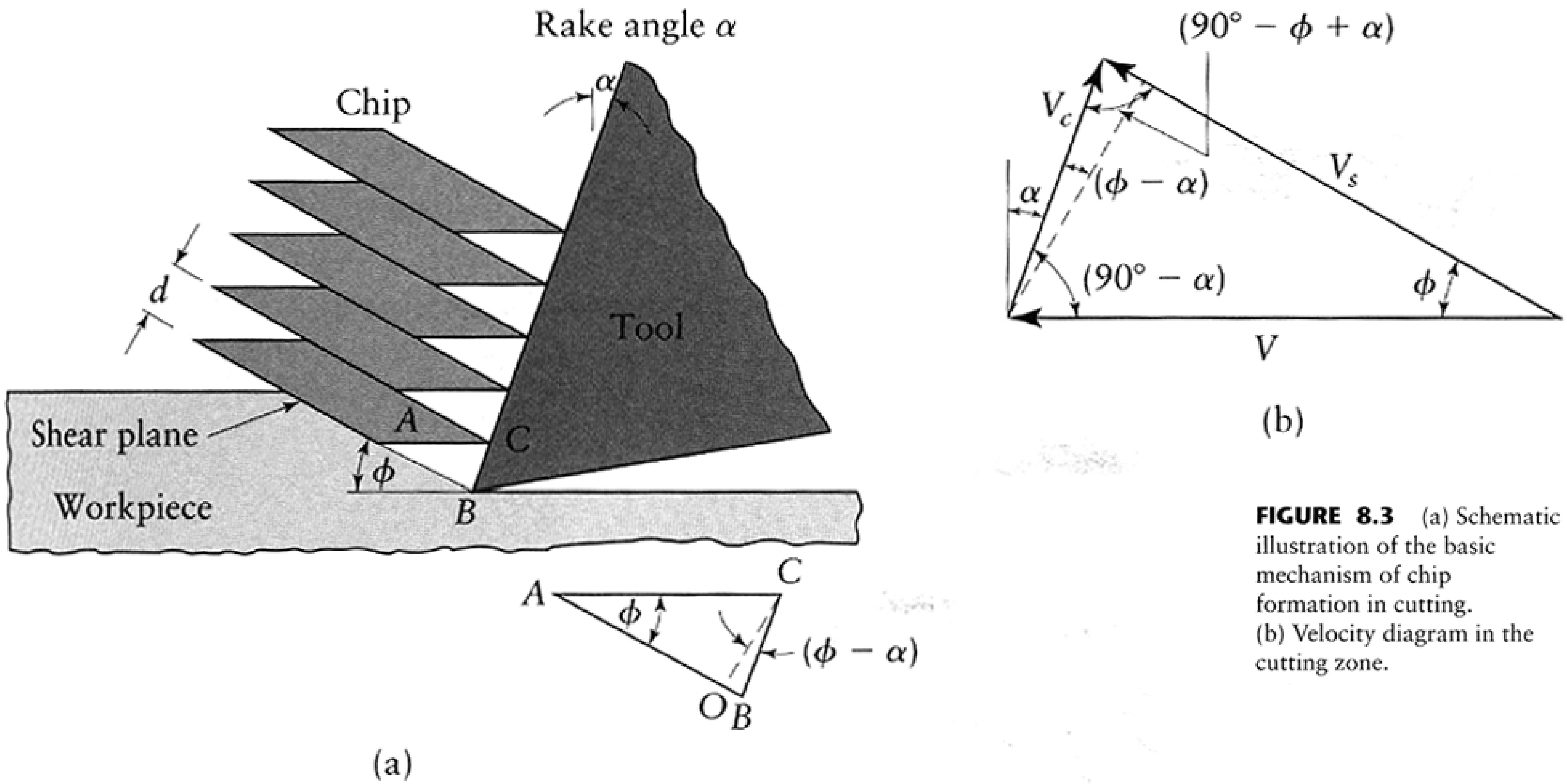


FIGURE 8.3 (a) Schematic illustration of the basic mechanism of chip formation in cutting. (b) Velocity diagram in the cutting zone.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Shear-angle relationships – Merchant model

$$OD = \frac{t}{\sin\phi} = \frac{t_C}{\cos(\phi-\alpha)} \quad \text{where} \quad r = \frac{t}{t_C} < 1$$

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

$$F_R = F_C \sin\alpha + F_T \cos\alpha$$

$$F_N = F_C \cos\alpha - F_T \sin\alpha$$

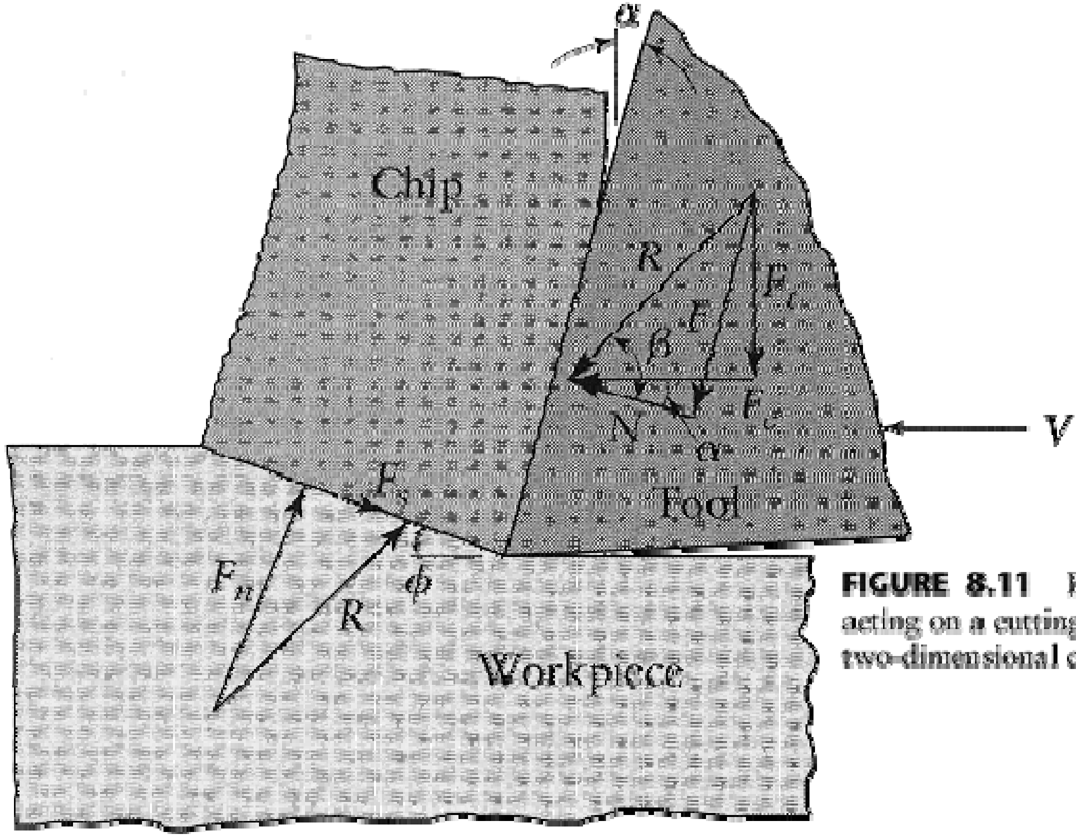


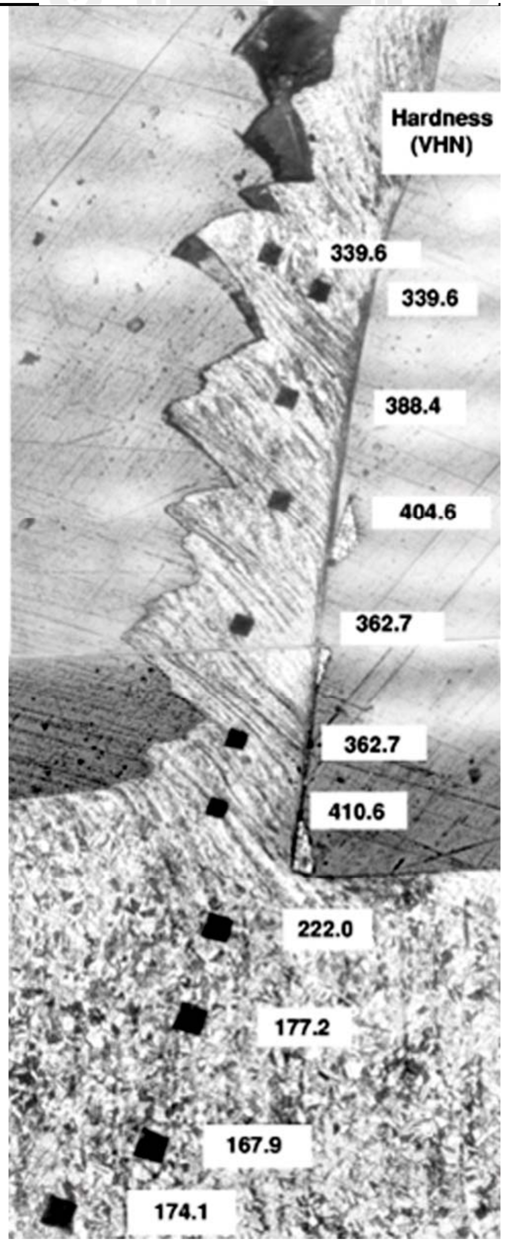
FIGURE 8.11 Forces acting on a cutting tool in two-dimensional cutting.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Strain hardening

- **Machined material (chip) has higher hardness than uncut material due to high strain hardening (shear strain, γ ~20)**

- **Vickers indentation test :**



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Chip morphology (칩형상) (1)

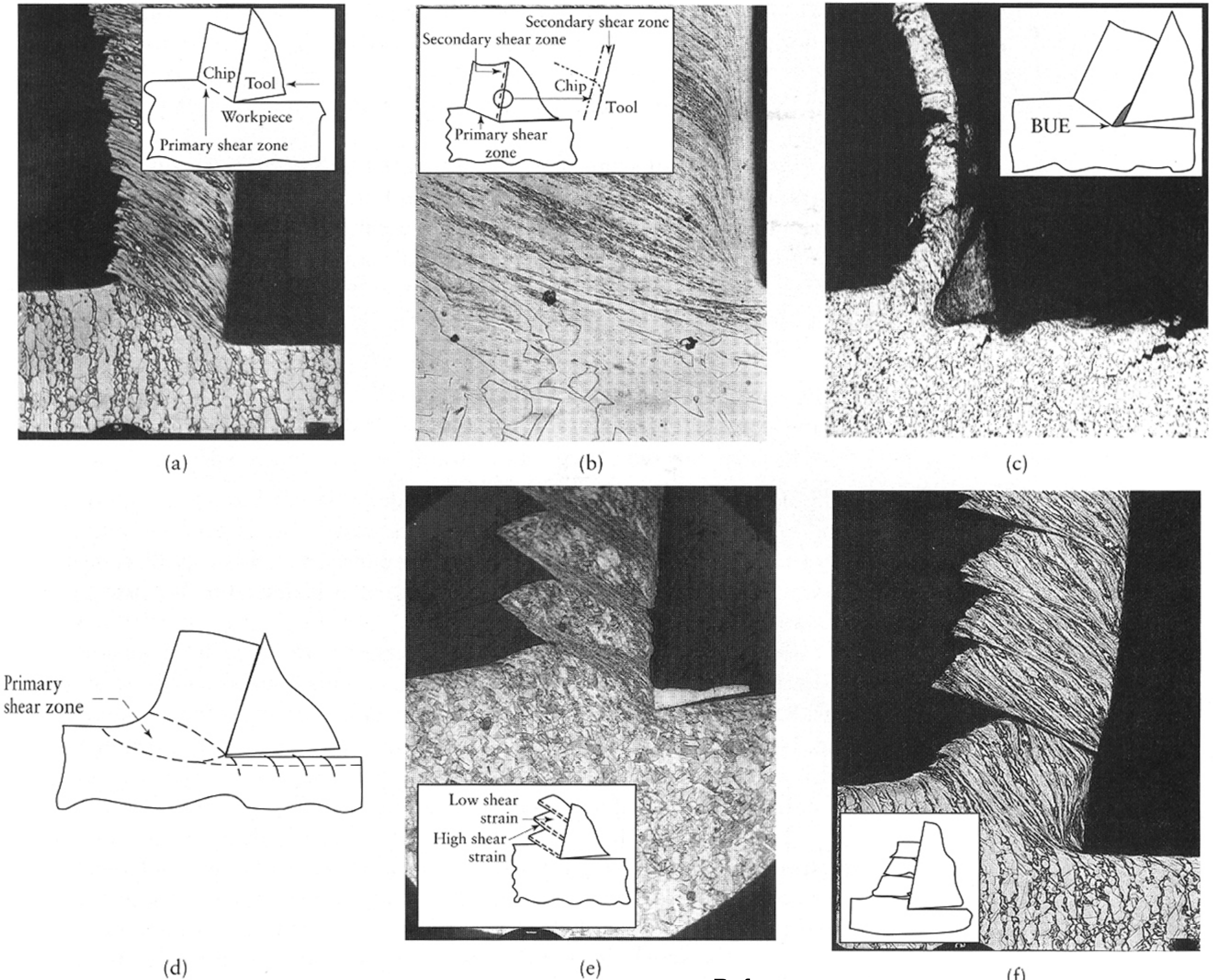


FIGURE 8.4 Basic types of chips produced in metal cutting and their micrographs: (a) continuous chip with narrow, straight primary shear zone; (b) secondary shear zone at the tool–chip interface; (c) continuous chip with built-up edge; (d) continuous chip with large primary shear zone; (e) segmented or nonhomogeneous chip; and (f) discontinuous chip. *Source*: After M. C. Shaw, P. K. Wright, and S. Kalpakjian.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Chip morphology (칩형상) (2)

- **Continuous chips (연속형 칩)**
  - High cutting speeds / high rake angles (secondary shear zone)
  - Good for tool life & surface finish (may need chip breaker)
  - Ductile materials with low coefficient of friction
- **Built-up Edge chips (BUE, 구성인선)**
  - High friction coefficient – workpiece weld on the tool edge
  - Periodical separation of material → bad surface
  - It can be reduced by increasing the cutting speed and the rake angle, decreasing the depth of cut, using a tool with a small tip radius and effective cutting fluid.
- **Serrated chips (톱니형 칩)**
  - Nonhomogeneous / segmented chips
  - Zones of low and high shear strain
  - Ti : sharp decrease of strength and thermal conductivity with increased temperature
- **Discontinuous chips (불연속 칩)**
  - Brittle materials (ductile materials with high friction coefficient) : Cast iron, bronze
  - Chatter, vibration

Chip morphology (칩형상) (3)

- **Depending on :**

  cutting speed, temperature,
  tool angle, friction, vibration

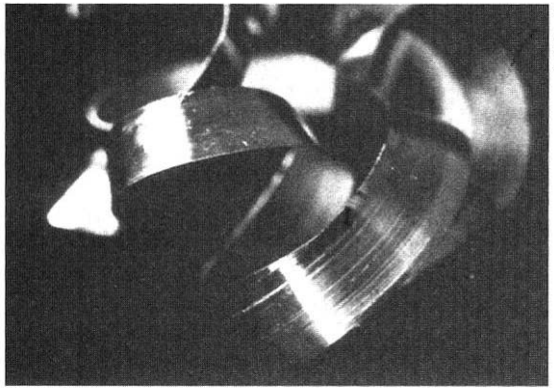


FIGURE 8.5 Shiny (burnished) surface on the tool side of a continuous chip produced in turning.

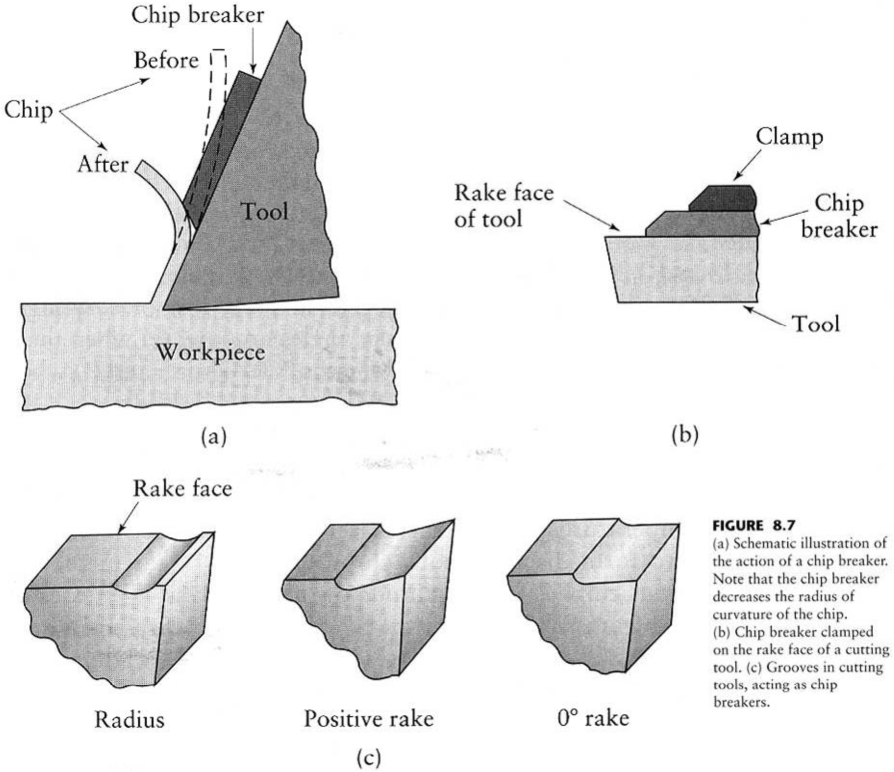


FIGURE 8.7 (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip. (b) Chip breaker clamped on the rake face of a cutting tool. (c) Grooves in cutting tools, acting as chip breakers.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Oblique cutting (경사절삭)

- **Inclination angle (기울각), *i***

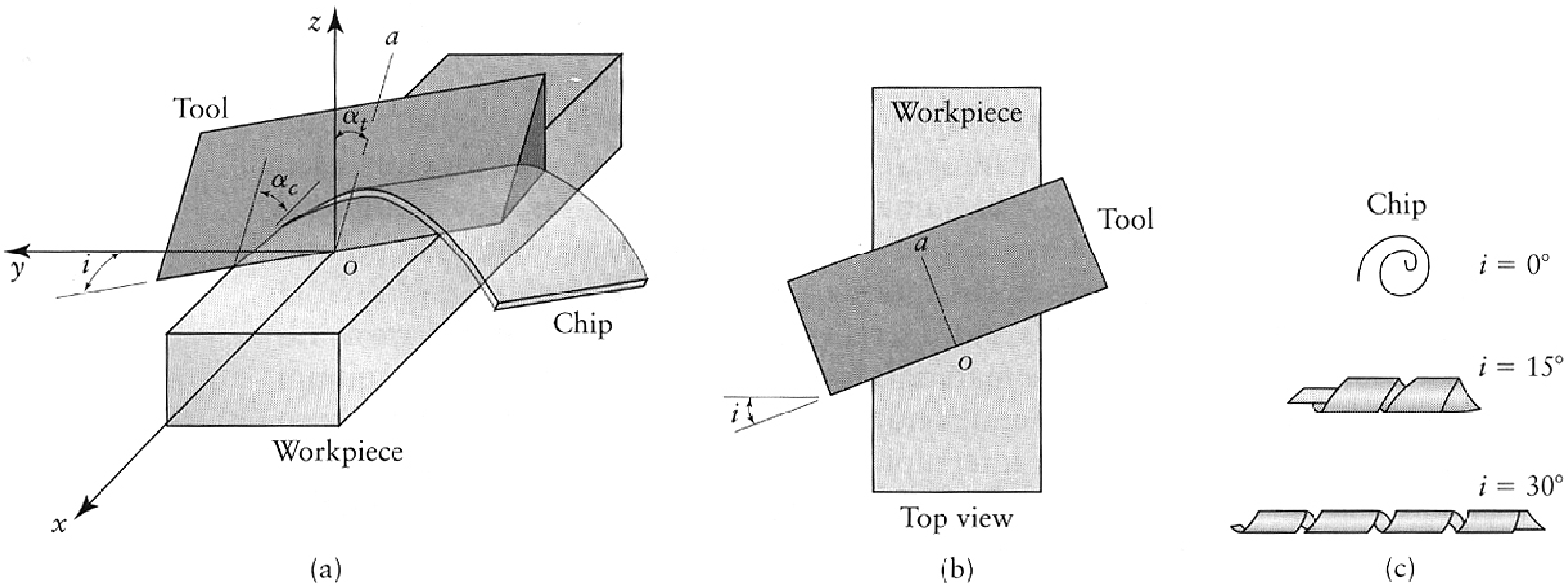


FIGURE 8.9 (a) Schematic illustration of cutting with an oblique tool. (b) Top view, showing the inclination angle, *i*. (c) Types of chips produced with different inclination angles.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Turning tool

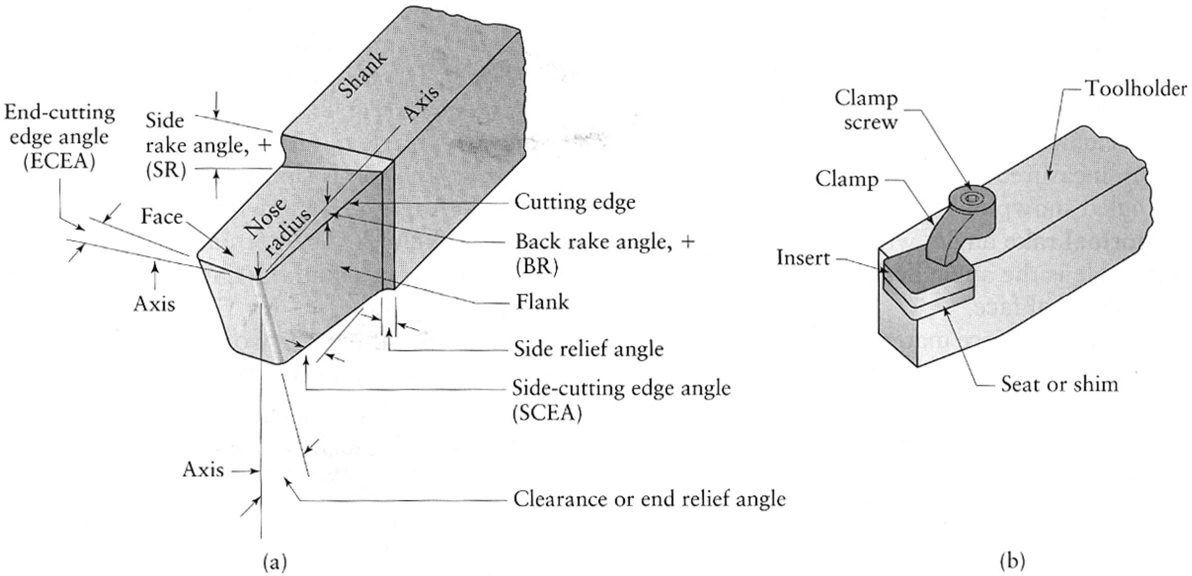
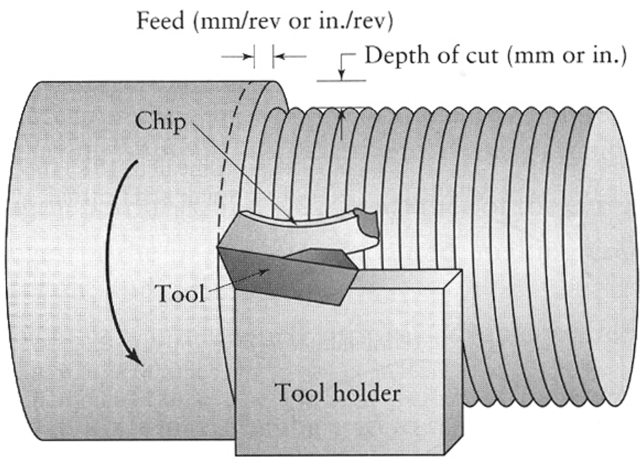


FIGURE 8.10 (a) Schematic illustration of a right-hand cutting tool. Although these tools have traditionally been produced from solid tool-steel bars, they have been largely replaced by carbide or other inserts of various shapes and sizes, as shown in (b).

$$\text{Rate of removal} = Vfw$$

FIGURE 8.19 Terminology used in a turning operation on a lathe, where f is the feed (in in./rev or mm/rev) and d is the depth of cut. Note that feed in turning is equivalent to the depth of cut in orthogonal cutting (Fig. 8.2), and the depth of cut in turning is equivalent to the width of cut in orthogonal cutting. See also Fig. 8.42.



Where

V : cutting speed (m/min)

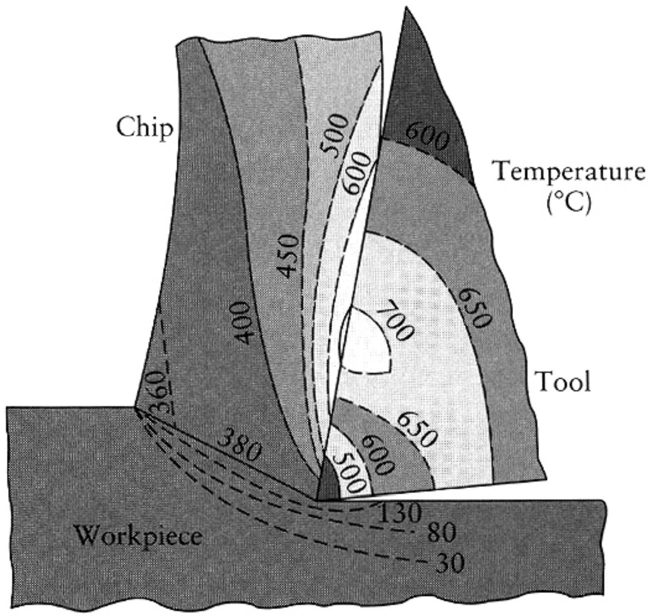
f : feed (mm/rev)

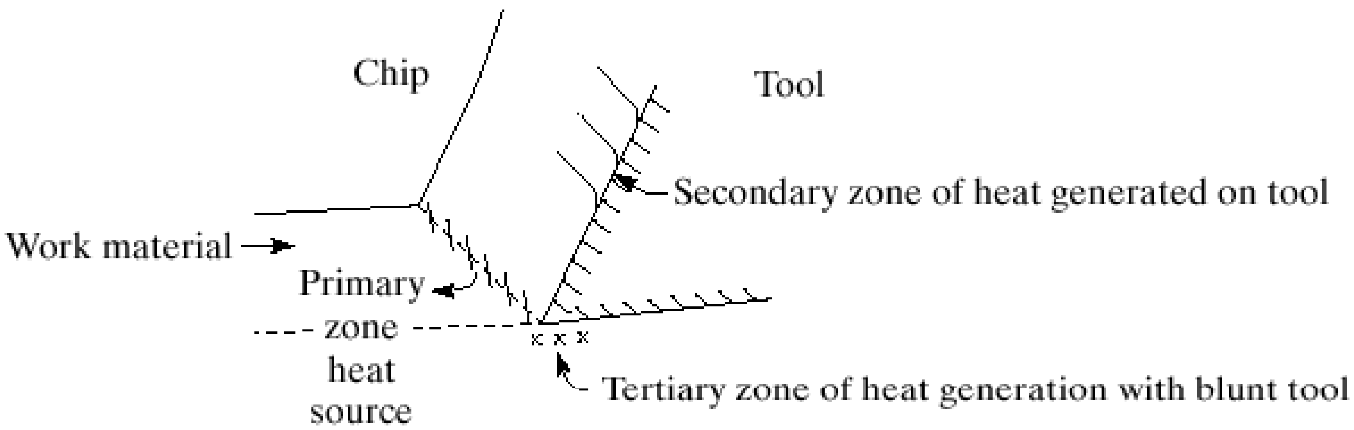
w : depth of cut (mm)

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Temperature

FIGURE 8.16 Typical temperature distribution in the cutting zone. Note that the maximum temperature is about halfway up the rake face of the tool and that there is a steep temperature gradient across the thickness of the chip. Some chips may become red hot, causing safety hazards to the operator and thus necessitating the use of safety guards. *Source*: After G. Vieregge.





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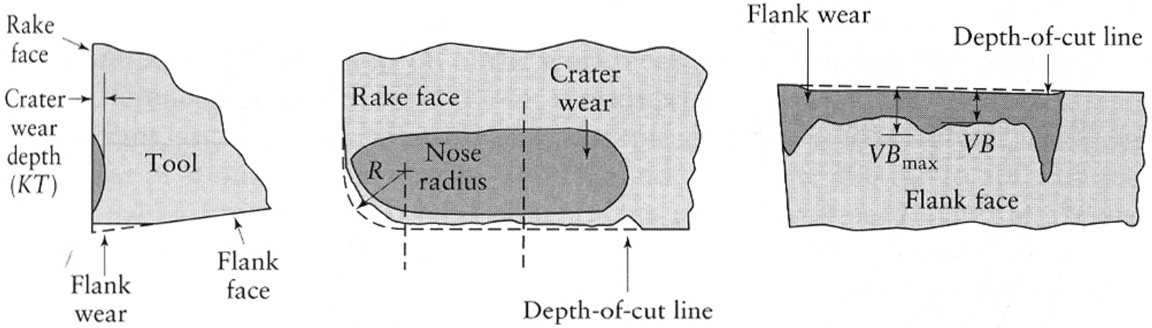
Tool wear (공구마멸)

- **Flank wear**
- **Crater wear**
- **Chipping**



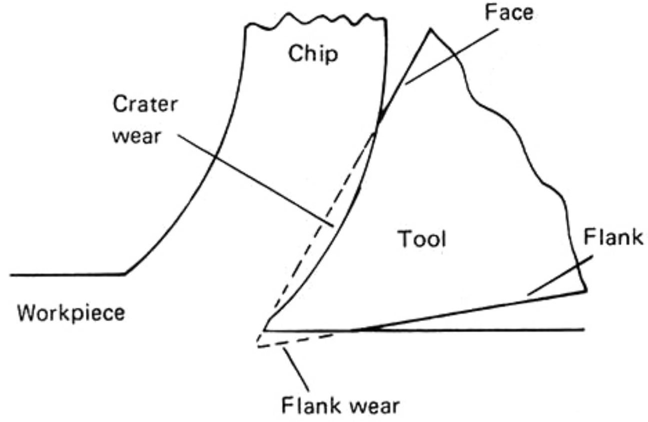
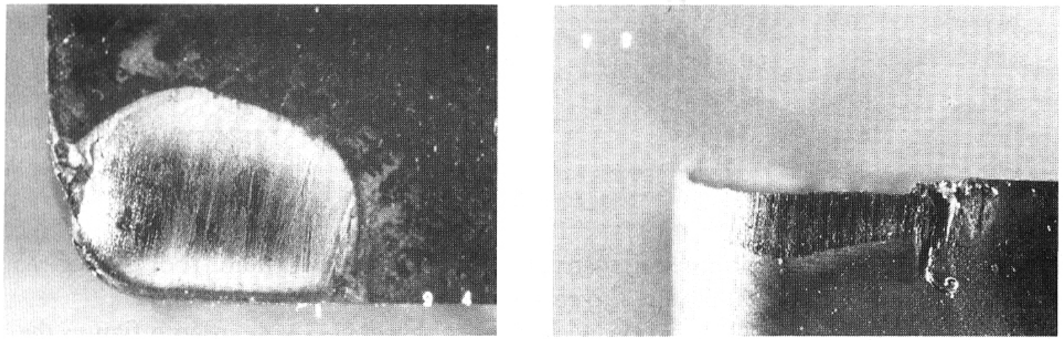


Figure 4.1 Regions of tool wear in metal cutting.



(a) (b)

FIGURE 8.21 (a) Crater wear and (b) flank wear on a carbide tool. *Source:* J. C. Keefe, Lehigh University.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Flank wear

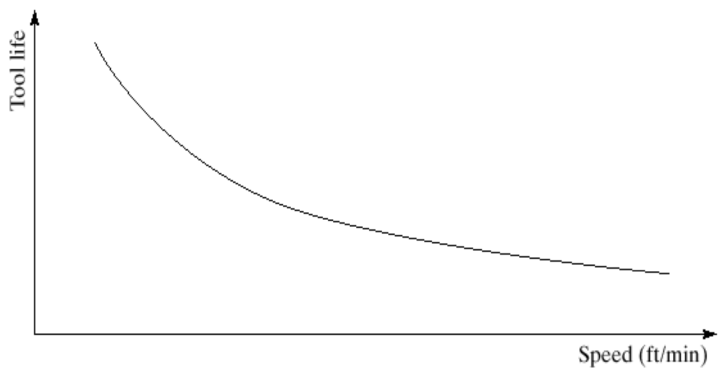
- **F. W. Taylor's tool life equation**

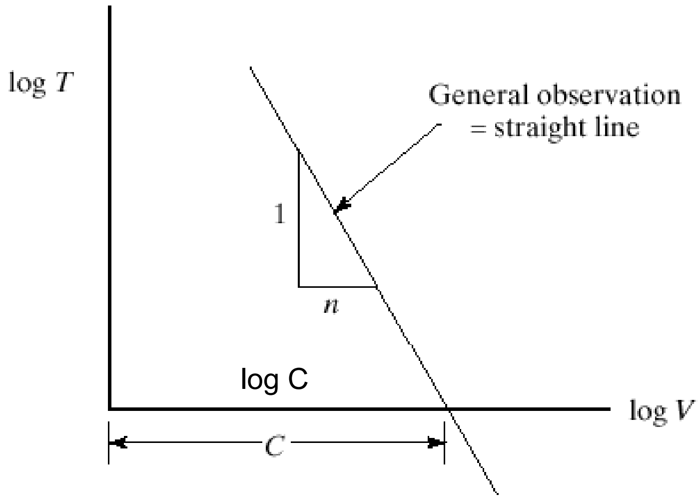
$$VT^n = C$$

$$\log V = \log C - n \log T$$

$n(\text{HSS}) = 0.15, \quad V = 50\text{m/min}$

$n(\text{Tungsten Carbide}) = 0.25, \quad V = 70\text{m/min}$





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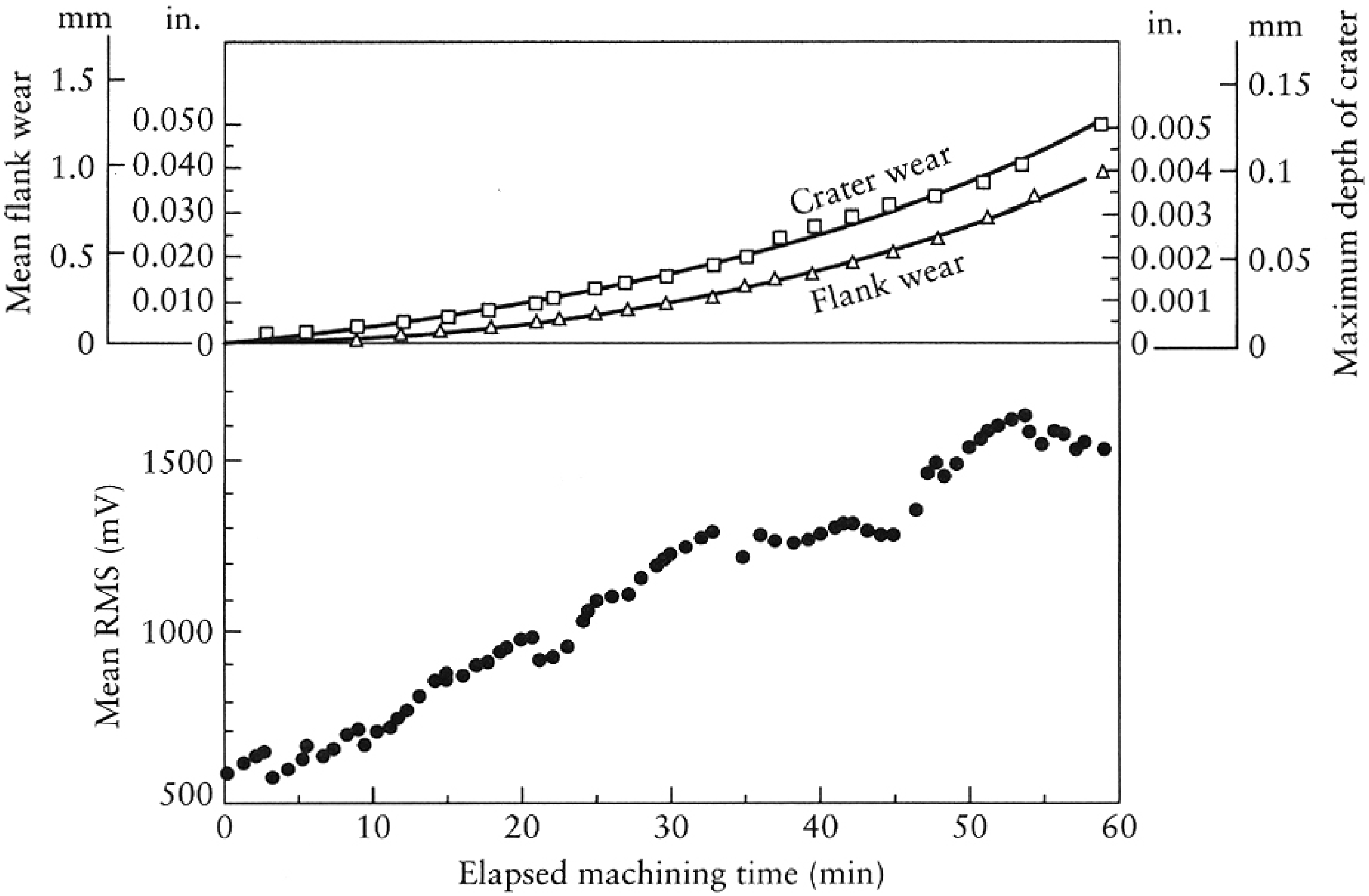
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Tool condition monitoring

FIGURE 8.26
Relationship between mean flank wear, maximum crater wear, and acoustic emission (noise generated during cutting) as a function of machining time. This technique is being developed as a means for monitoring wear rate in various cutting processes without interrupting the operation. *Source*: After M. S. Lan and D. A. Dornfeld.



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S. Kalpakjian, "Manufacturing Processes for Engineering Materials", $3^{rd}/4^{th}$ ed. Addison Wesley

Surface finish

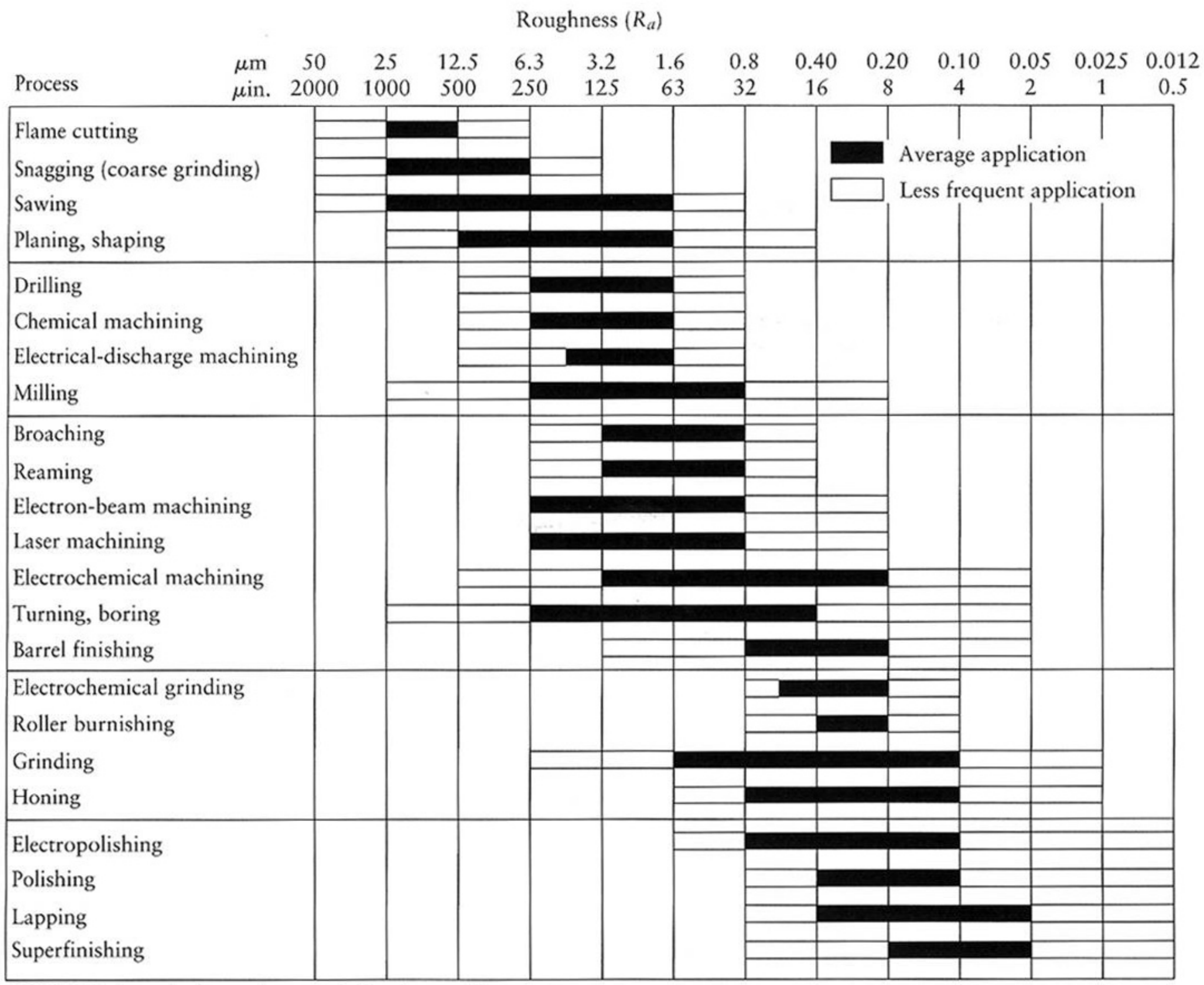

FIGURE 8.27 Range of surface roughnesses obtained in various machining processes. Note the wide range within each group. (See also Fig. 9.27).

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Machinability (절삭성)

- **Surface finish & integrity**
- **Tool life**
  - Machinability rating: cutting speed per 60min, e.g. 100 → 100ft/min (0.5m/s)
- **Force and power requirements**
- **Chip control**
- **Free-machining steel (쾌삭강)**
  - Steel with : lead, bismuth, sulfur, calcium
- **Easy to machine : aluminum, brass, magnesium**
- **Difficult to machine : wrought-copper, titanium, tungsten**

Cutting-tool materials

- **Carbon steels**
- **High Speed Steels (HSS, 고속도강)**
  - (M and T series)
- **Cast cobalt alloys**
- **Carbides (초경합금)**
  - WC (tungsten carbide)
  - TiC (titanium carbide)
- **Inserts**
  - Easy to replace tools

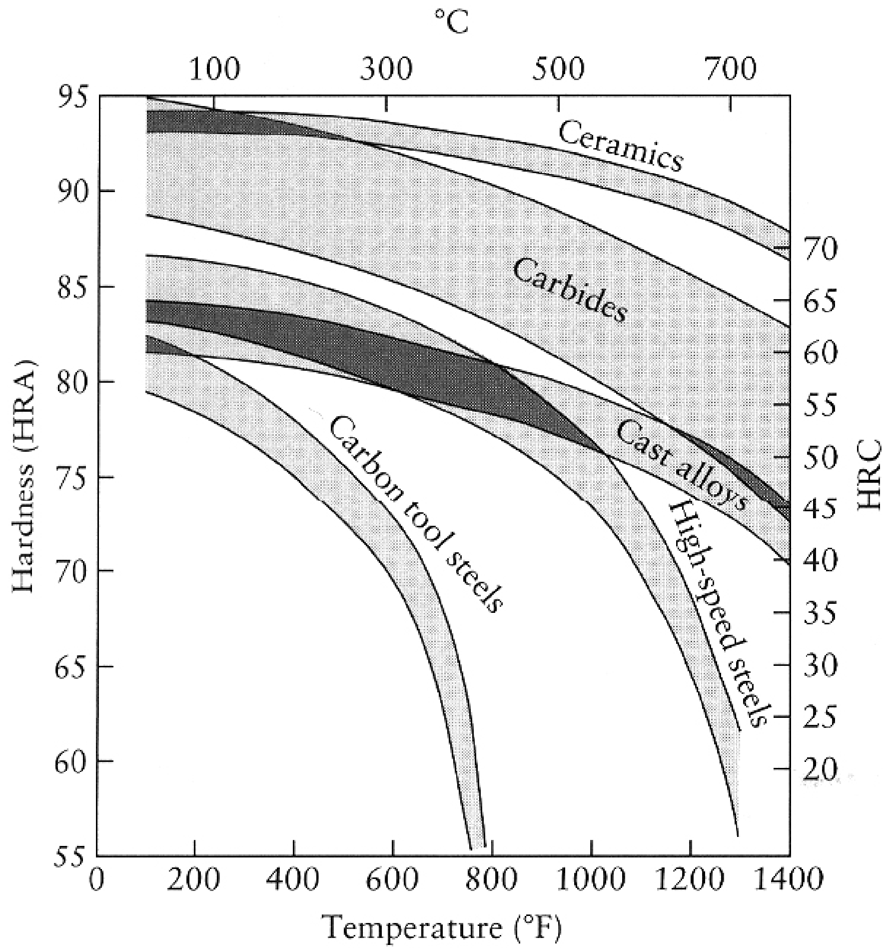

FIGURE 8.31 Hardness of various cutting-tool materials as a function of temperature (hot hardness). The wide range in each group of materials results from the variety of tool compositions and treatments available for that group.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Coated tool (피복공구)

- **TiN, TiC, TiCN**
- **Al_2O_3(알루미나)**
- **Diamond**
- **Ion implantation**
- **Multiphase**

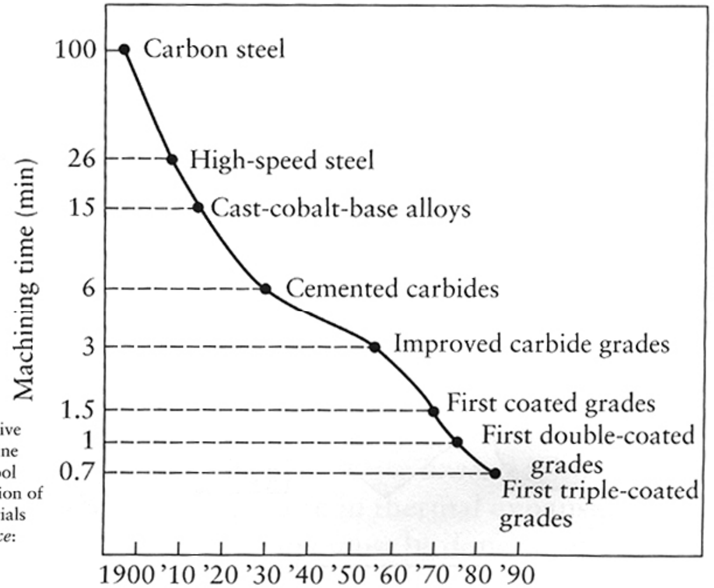

FIGURE 8.35 Relative time required to machine with various cutting-tool materials, with indication of the year the tool materials were introduced. *Source*: Sandvik Coromant.

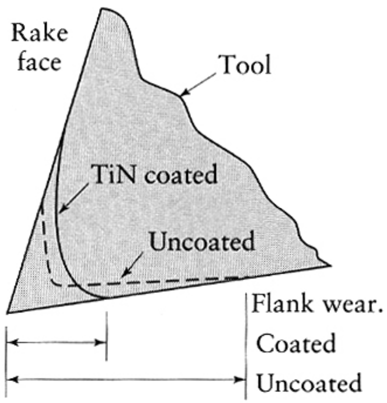

FIGURE 8.36 Wear patterns on high-speed-steel uncoated and titanium-nitride-coated tools. Note that flank wear is lower for the coated tool.

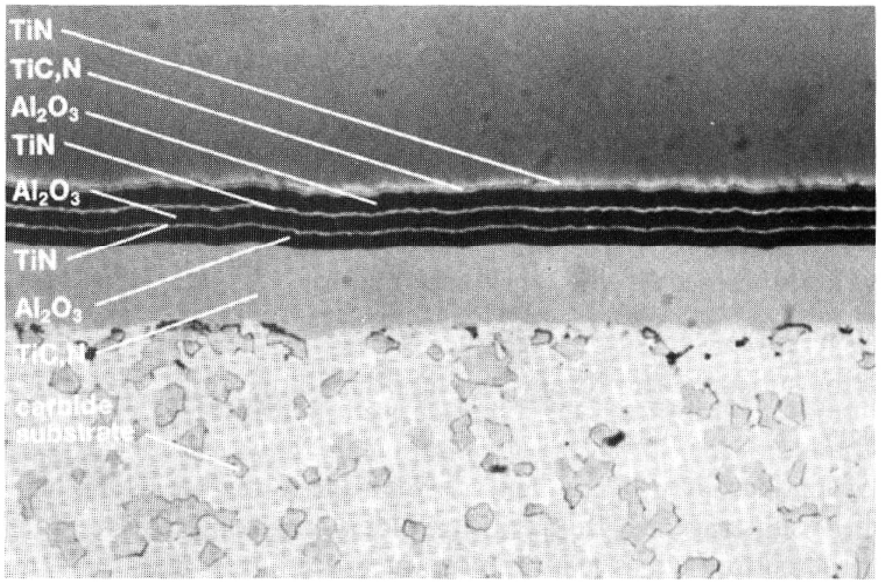

FIGURE 8.37 Multiphase coatings on a tungsten-carbide substrate. Three alternating layers of aluminum oxide are separated by very thin layers of titanium nitride. Inserts with as many as 13 layers of coatings have been made. Coating thicknesses are typically in the range of 2–10 μm (80–400 $\mu in.$). *Source*: Courtesy of Kennametal, Inc., and *Manufacturing Engineering*, Society of Manufacturing Engineers.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Cutting Processes

TABLE 8.7

General Characteristics of Machining Processes

Process	Characteristics	Commercial tolerances (±mm)
Turning	Turning and facing operations are performed on all types of materials; requires skilled labor; low production rate, but medium to high rates can be achieved with turret lathes and automatic machines, requiring less skilled labor.	Fine: 0.05–0.13 Rough: 0.13 Skiving: 0.025–0.05
Boring	Internal surfaces or profiles, with characteristics similar to those produced by turning; stiffness of boring bar is important to avoid chatter.	0.025
Drilling	Round holes of various sizes and depths; requires boring and reaming for improved accuracy; high production rate, labor skill required depends on hole location and accuracy specified.	0.075
Milling	Variety of shapes involving contours, flat surfaces, and slots; wide variety of tooling; versatile; low to medium production rate; requires skilled labor.	0.13–0.25
Planing	Flat surfaces and straight contour profiles on large surfaces; suitable for low-quantity production; labor skill required depends on part shape.	0.08–0.13
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; suitable for low-quantity production; labor skill required depends on part shape.	0.05–0.13
Broaching	External and internal flat surfaces, slots, and contours with good surface finish; costly tooling; high production rate; labor skill required depends on part shape.	0.025–0.15
Sawing	Straight and contour cuts on flats or structural shapes; not suitable for hard materials unless the saw has carbide teeth or is coated with diamond; low production rate; requires only low labor skill.	0.8

Ref.
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Lathe-round shape

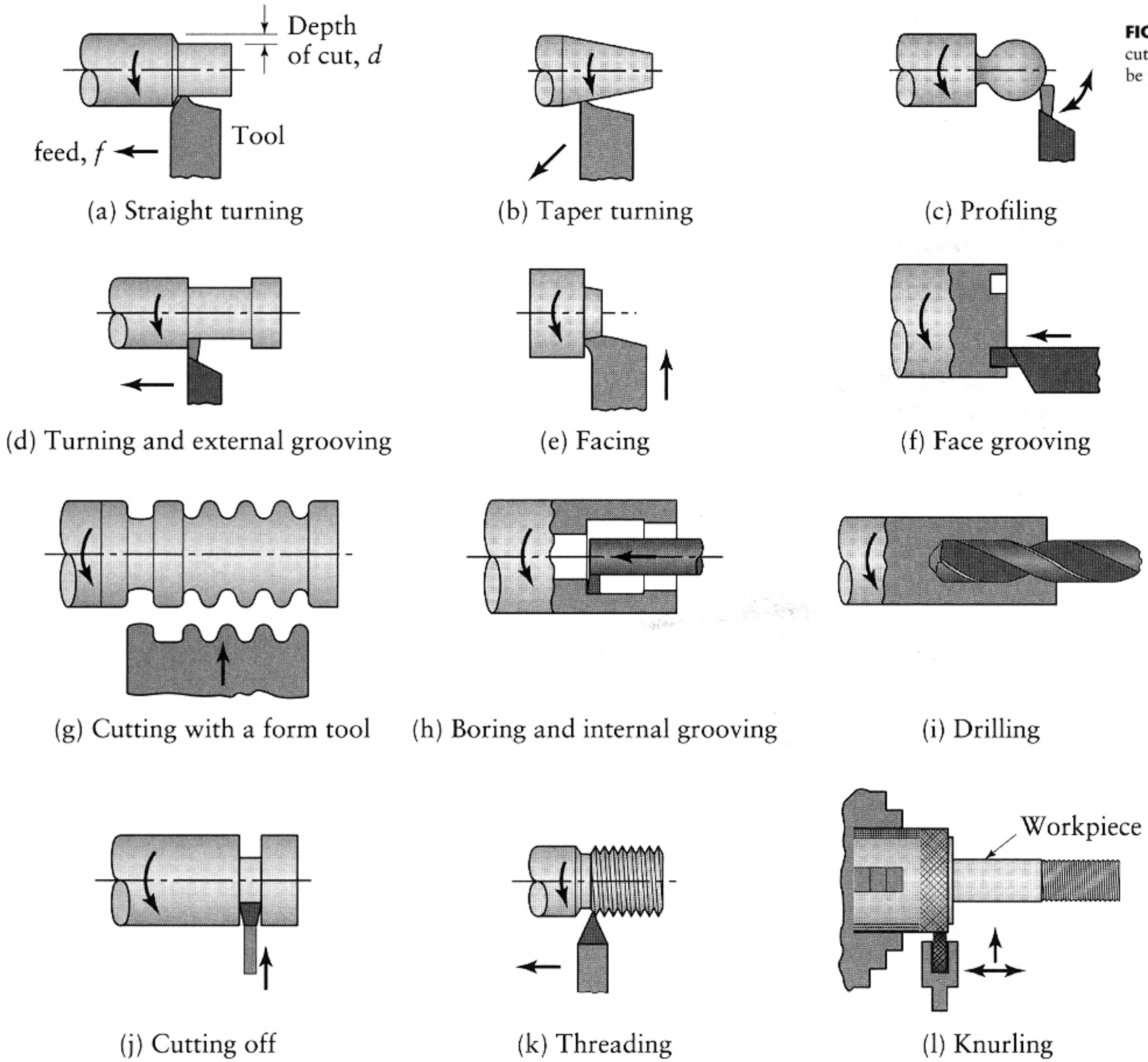

FIGURE 8.40 Various cutting operations that can be performed on a lathe.

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S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Lathe components

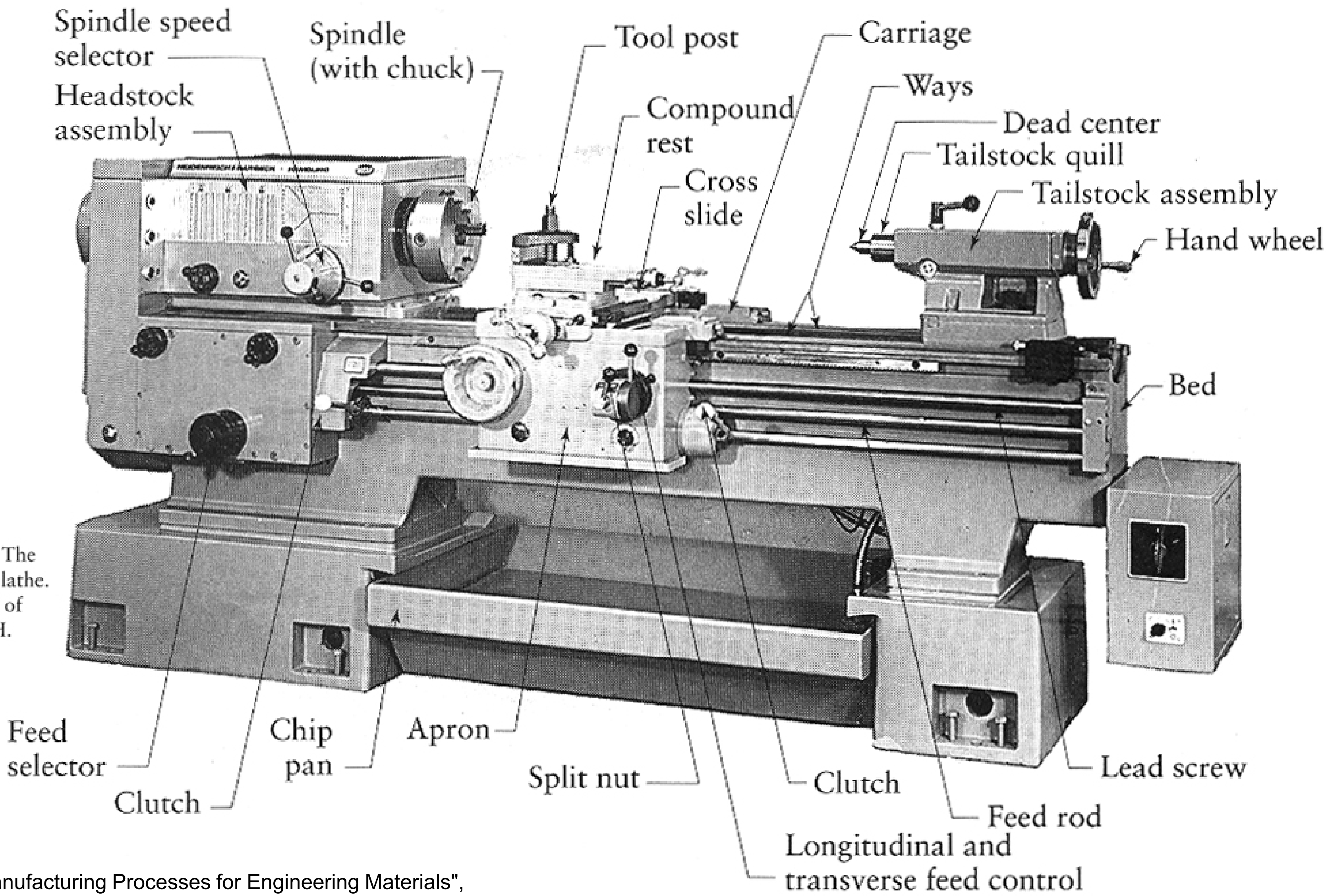


FIGURE 8.44 The components of a lathe. *Source*: Courtesy of MAKINO GmbH.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Drill

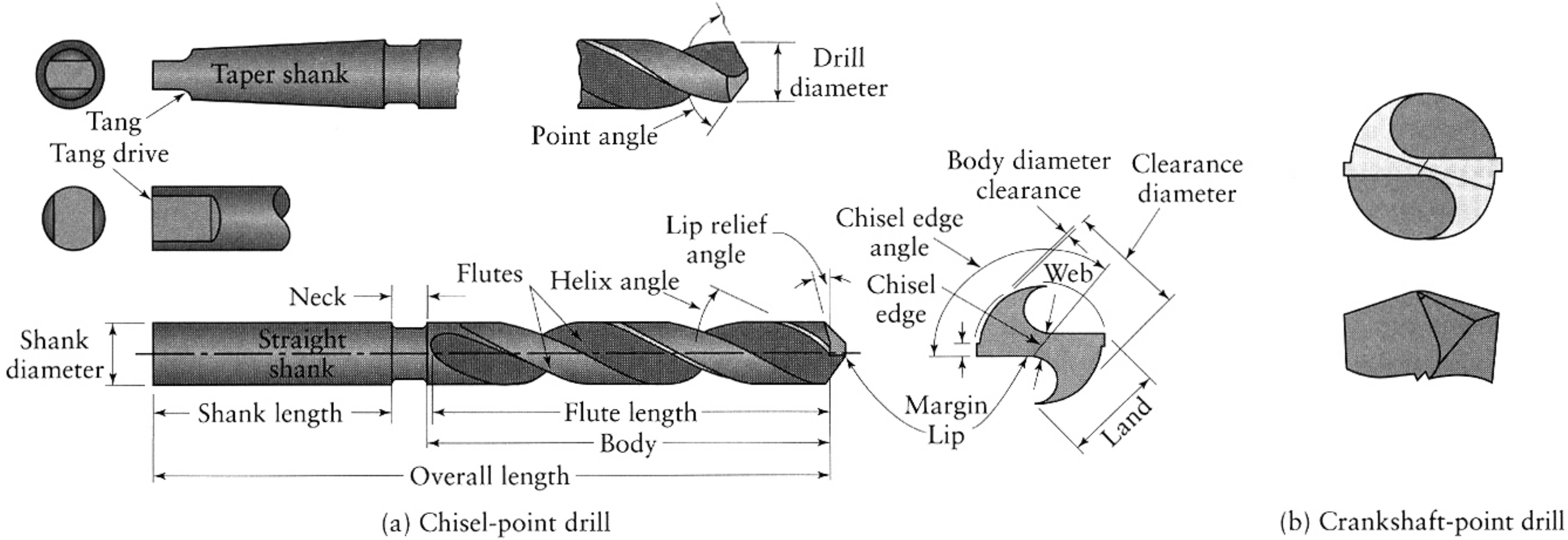


FIGURE 8.48 (a) Standard chisel-point drill, with various features indicated. (b) Crankshaft-point drill.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Drilling operations

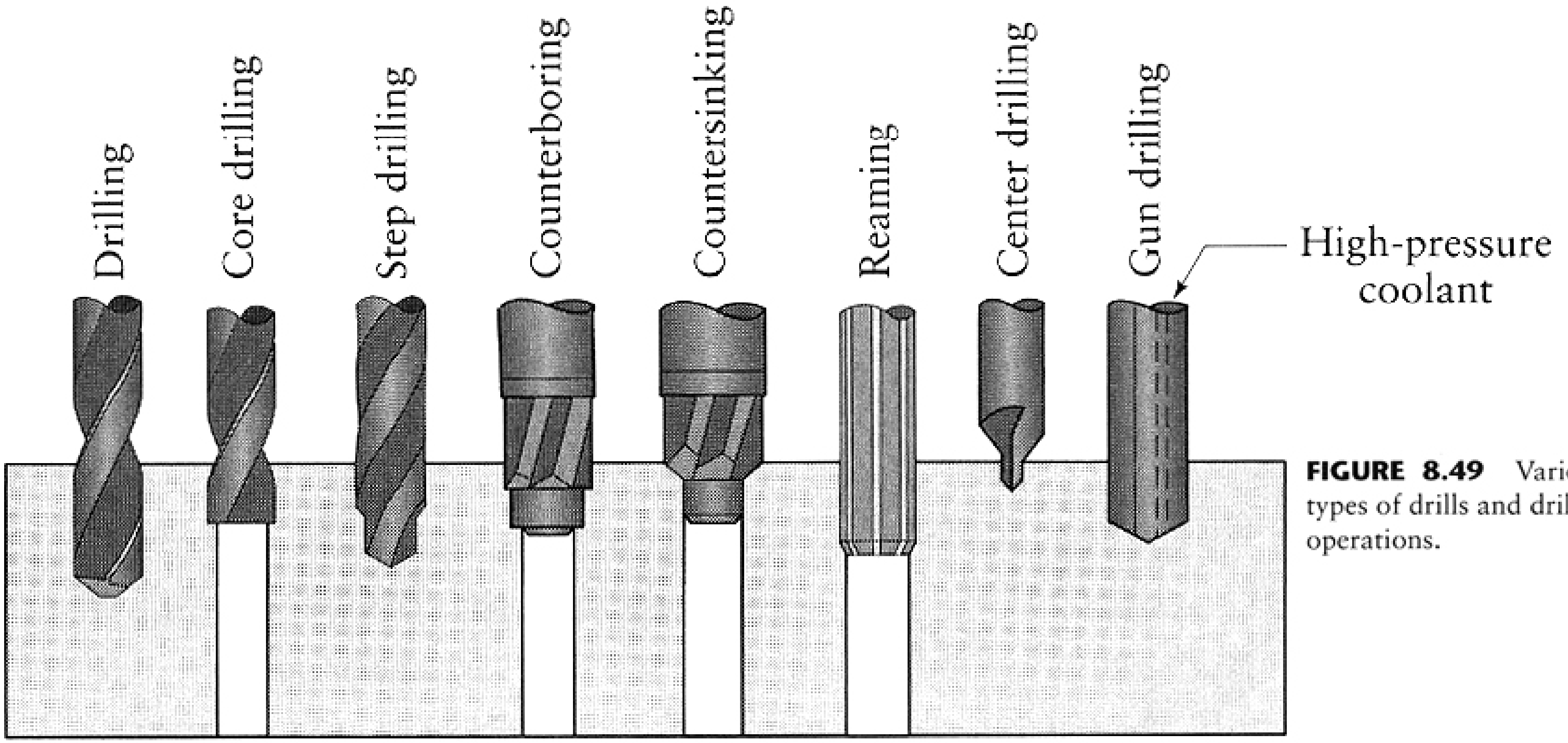


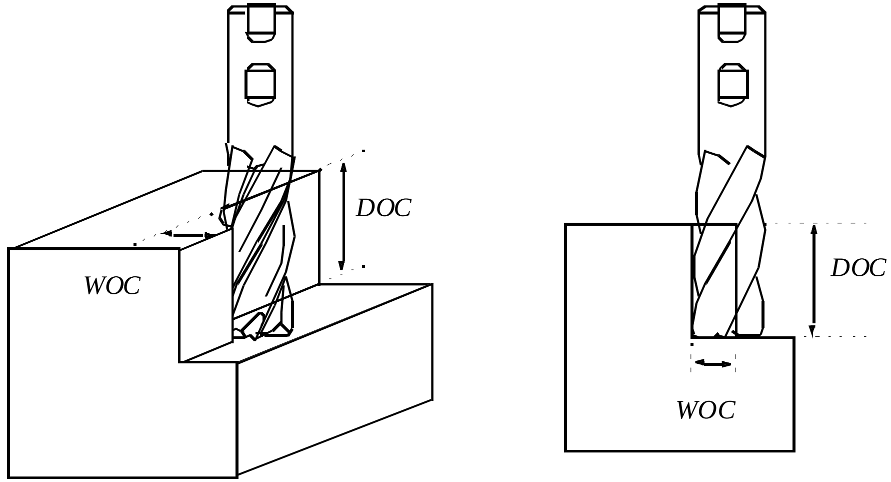
FIGURE 8.49 Various types of drills and drilling operations.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Milling

- **Depth of Cut (DOC)**
- **Width of Cut (WOC)**

- **Slab milling (평밀링)**
- **Conventional Milling (up milling, 상향절삭)**
  - Recommended, clean surface before machine
- **Climb Milling (down milling, 하향절삭)**
  - Efficient cut (larger chip)
  - Less chatter
  - Production work



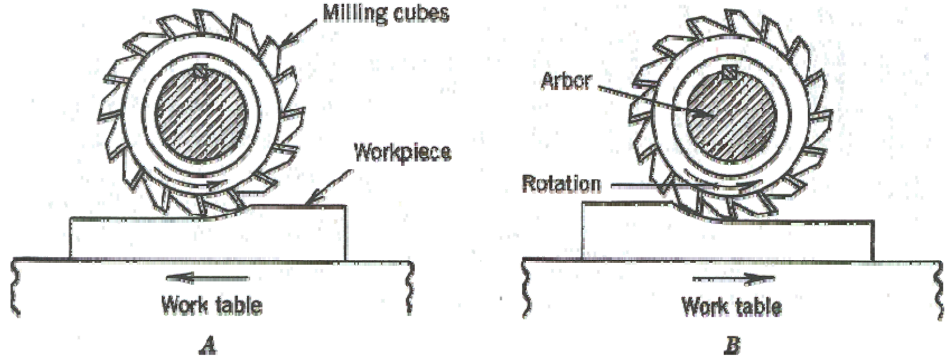


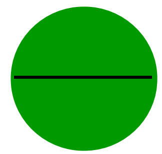
Figure 11.32
Methods of feeding work on milling machine. *A*, Conventional or up milling. *B*, Climb or down milling.

Material removal by milling

- **Cutting speed (m/min)**
  - V = πDN

  (D : diameter of cutter(m), N : rotational speed of the cutter(rpm))

- **Material Removal Rate (MRR)**
  - MRR = WOC * DOC * f
  - f = feed rate (mm/min) = n * N * t



Cutting Tool
- cross section

- **Example**
  - V = 50 m/min, t = 0.1 mm/tooth, number of tooth (n)= 2,
  - D = 4 mm, DOC = 0.2, WOC = 3, Cutter RPM (N) = 50000/(πx4) = 3979
  - f = 2 *3979 * 0.1 = 796 mm/min, MRR = 3* 0.2 * 796 = 4776 mm^3/min

Burr Formation

	TYPE I	TYPE II	TYPE III
Burr Type	Uniform with a drill cap		Crown
Burr Height(mm)	~0.15	0.15~1.0	(1.1~1.5)(d/2)
Height/Thickness	0.8~1.6	1.5~3.2	3.8~5.3

Table 1 Burr classifications.

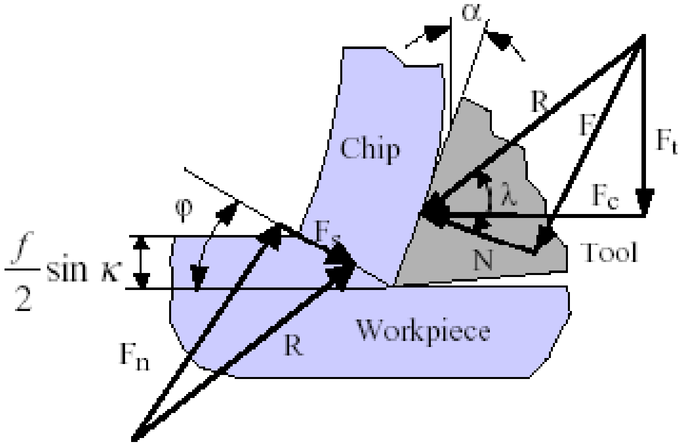


Figure 1. Shear plan model of the drill cutting edge

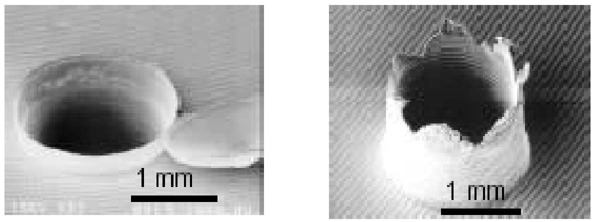


Figure 2 Two types of drilling burr of stainless steel
(a) Uniform burr with drill cap (b) Crown burr

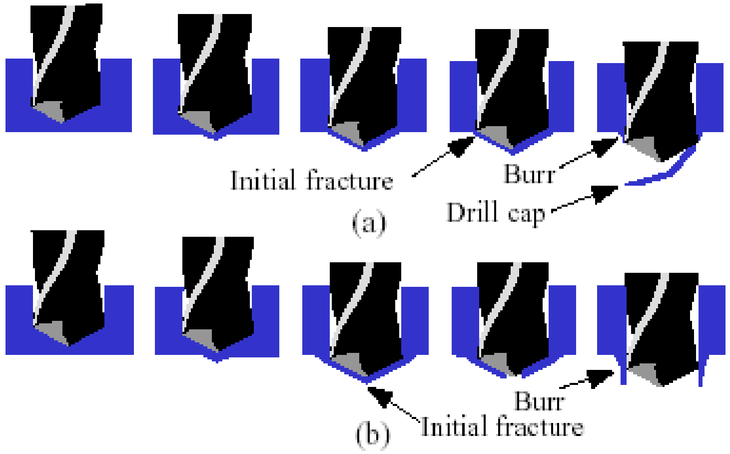


Figure 3 Proposed burr formation mechanism [3]
(a) Uniform burr with drill cap (b) Crown burr

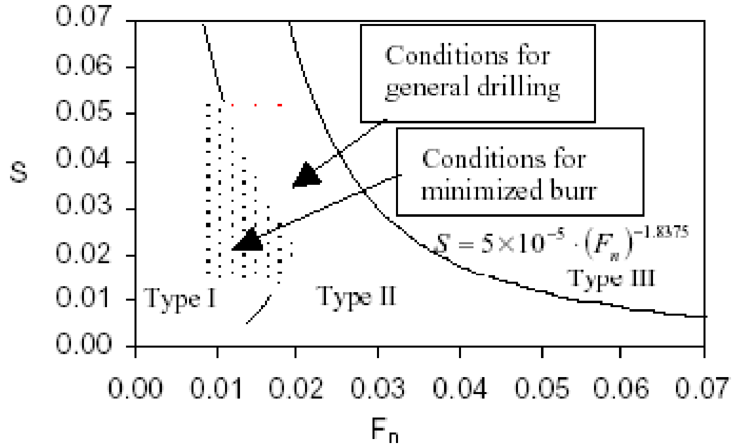
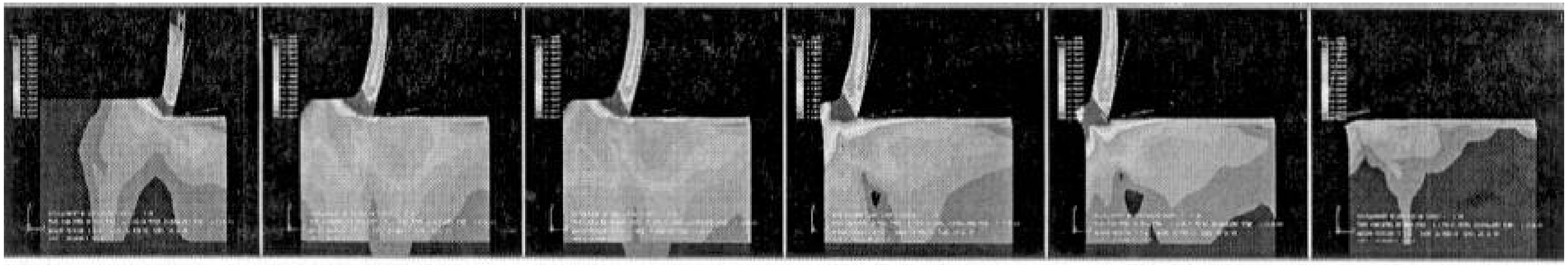


Figure 4 Drilling burr control chart.

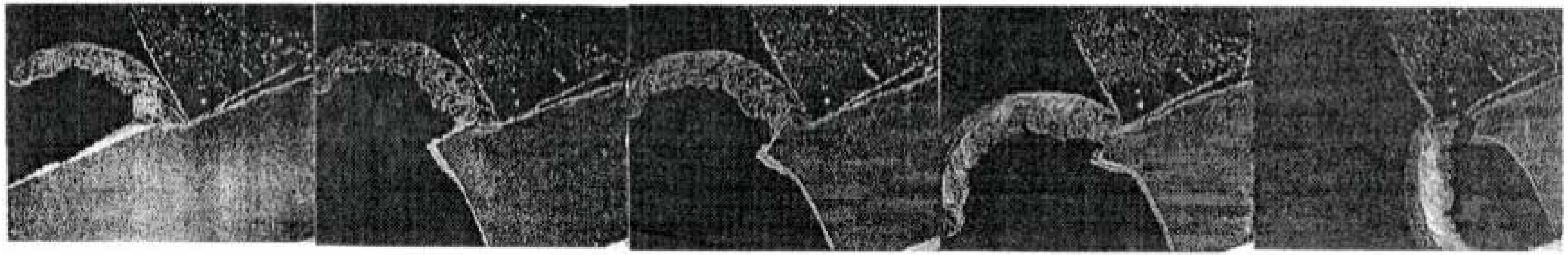
http://lma.berkeley.edu/tools

FEM Simulation

- **Demo: EMSIM**
- **http://mtamri.me.uiuc.edu/testbeds/emsim/html/index2.shtml**



(a) Steady-state (b) Initiation (c) Development (d) Pivoting (e) Final (f) Burr



(g) Steady-state (h) Initiation (i) Pivoting (j) Final (k) Burr

Cost Estimation

The cost to produce each component in a batch is given by

$$C_{\text{PER PART}} = WT_L + WT_M + WT_R\left[\frac{T_M}{T}\right] + y\left[\frac{T_M}{T}\right] \qquad (7.16)$$

In this equation, the symbols include

- W = the machine operator's wage plus the overhead cost of the machine.
- WT_L = "nonproductive" costs, which vary depending on loading and fixturing.
- WT_M = actual costs of cutting metal.
- WT_R = the tool replacement cost shared by all the components machined. This cost is divided among all the components because each one uses up T_M minutes of total tool life, T, and is allocated of $\frac{T_M}{T}$ of WT_R.
- Using the same logic, all components use their share $\frac{T_M}{T}$ of the tool cost, y.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Turning conditions

TABLE 8.8

Approximate Ranges of Recommended Cutting Speeds for Turning Operations

	CUTTING SPEED	
WORKPIECE MATERIAL	m/min	ft/min
Aluminum alloys	200–1000	650–3300
Cast iron, gray	60–900	200–3000
Copper alloys	50–700	160–2300
High-temperature alloys	20–400	65–1300
Steels	50–500	160–1600
Stainless steels	50–300	160–1000
Thermoplastics and thermosets	90–240	300–800
Titanium alloys	10–100	30–330
Tungsten alloys	60–150	200–500

Note: (a) The speeds given in this table are for carbides and ceramic cutting tools. Speeds for high-speed-steel tools are lower than indicated. The higher ranges are for coated carbides and cermets. Speeds for diamond tools are significantly higher than any of the values indicated in the table.
(b) Depths of cut, *d*, are generally in the range of 0.5–12 mm (0.02–0.5 in.).
(c) Feeds, *f*, are generally in the range of 0.15–1 mm/rev (0.006–0.040 in./rev).

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Drilling conditions

TABLE 8.10

General Recommendations for Speeds and Feeds in Drilling

WORKPIECE MATERIAL	SURFACE SPEED m/min	SURFACE SPEED ft/min	FEED, mm/rev (in./rev) DRILL DIAMETER 1.5 mm (0.060 in.)	FEED, mm/rev (in./rev) DRILL DIAMETER 12.5 mm (0.5 in.)	RPM 1.5 mm (0.060 in.)	RPM 12.5 mm (0.5 in.)
Aluminum alloys	30–120	100–400	0.025 (0.001)	0.30 (0.012)	6400–25,000	800–3000
Magnesium alloys	45–120	150–400	0.025 (0.001)	0.30 (0.012)	9600–25,000	1100–3000
Copper alloys	15–60	50–200	0.025 (0.001)	0.25 (0.010)	3200–12,000	400–1500
Steels	20–30	60–100	0.025 (0.001)	0.30 (0.012)	4300–6400	500–800
Stainless steels	10–20	40–60	0.025 (0.001)	0.18 (0.007)	2100–4300	250–500
Titanium alloys	6–20	20–60	0.010 (0.0004)	0.15 (0.006)	1300–4300	150–500
Cast irons	20–60	60–200	0.025 (0.001)	0.30 (0.012)	4300–12,000	500–1500
Thermoplastics	30–60	100–200	0.025 (0.001)	0.13 (0.005)	6400–12,000	800–1500
Thermosets	20–60	60–200	0.025 (0.001)	0.10 (0.004)	4300–12,000	500–1500

Note: As hole depth increases, speeds and feeds should be reduced. Selection of speeds and feeds also depends on the specific surface finish required.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Milling conditions

TABLE 8.11

Approximate Range of Recommended Cutting Speeds for Milling Operations

	CUTTING SPEED	
WORKPIECE MATERIAL	m/min	ft/min
Aluminum alloys	300–3000	1000–10,000
Cast iron, gray	90–1300	300–4200
Copper alloys	90–1000	300–3300
High-temperature alloys	30–550	100–1800
Steels	60–450	200–1500
Stainless steels	90–500	300–1600
Thermoplastics and thermosets	90–1400	300–4500
Titanium alloys	40–150	130–500

Note: (a) These speeds are for carbides, ceramic, cermets, and diamond cutting tools. Speeds for high-speed-steel tools are lower than those indicated in this table.
(b) Depths of cut, *d*, are generally in the range of 1–8 mm (0.04–0.3 in.).
(c) Feeds per tooth, *f*, are generally in the range of 0.08–0.46 mm/rev (0.003–0.018 in./rev).

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Broaching(브로칭) & Sawing(톱작업)

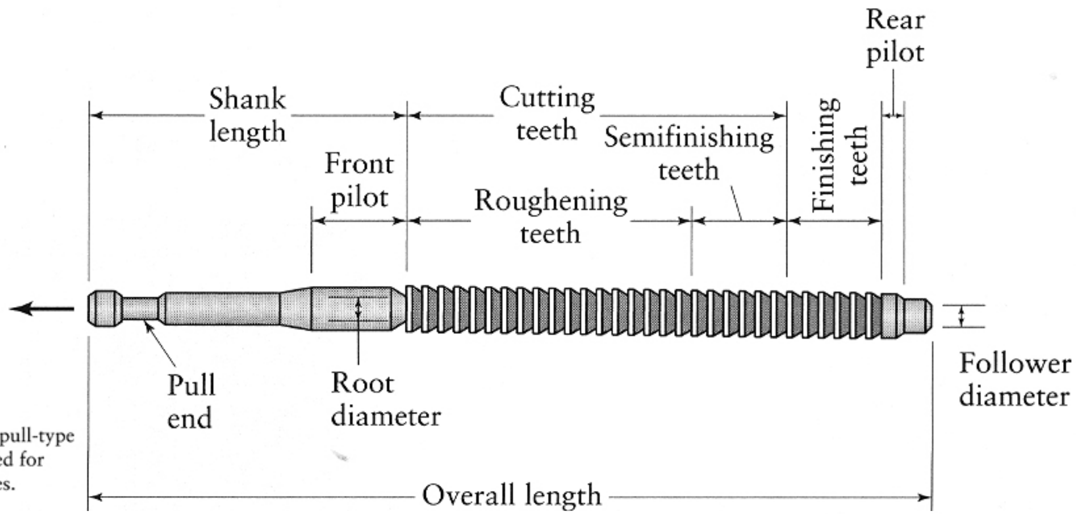


FIGURE 8.62 Terminology for a pull-type internal broach used for enlarging long holes.

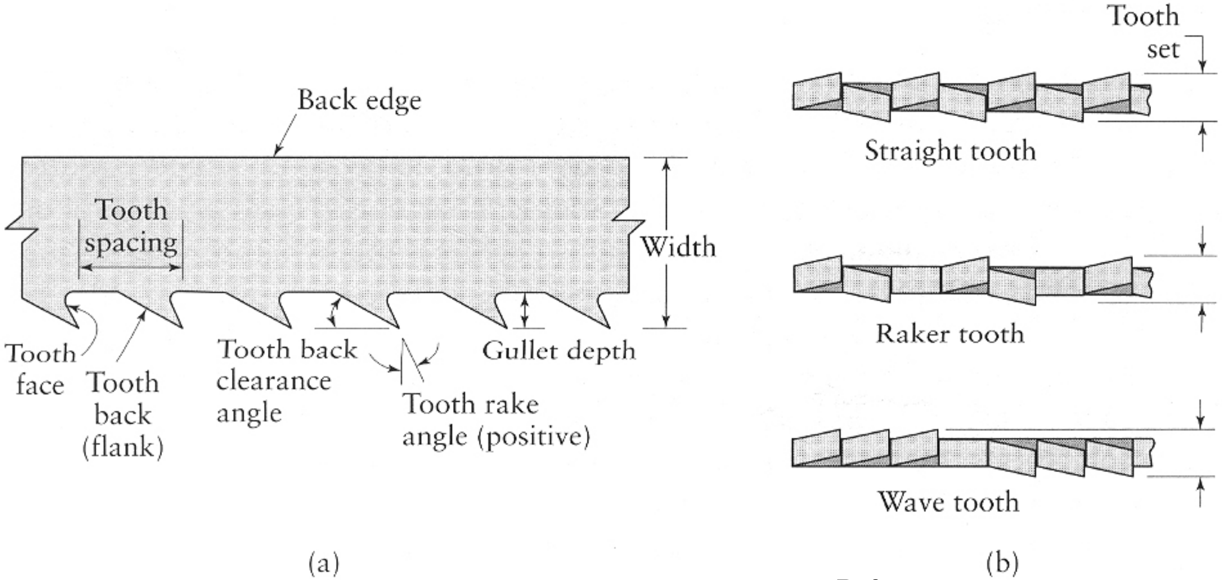
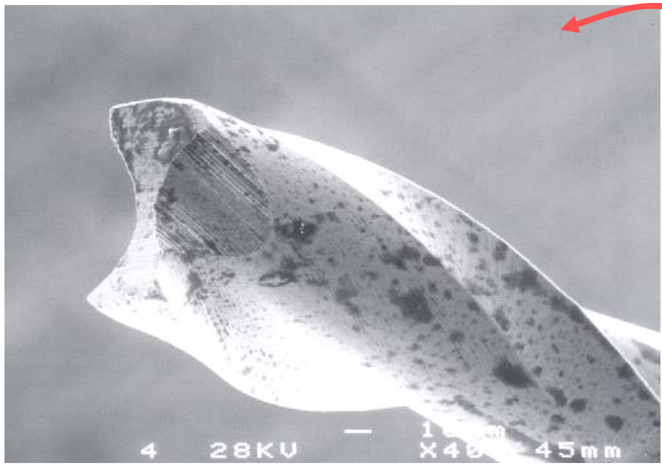


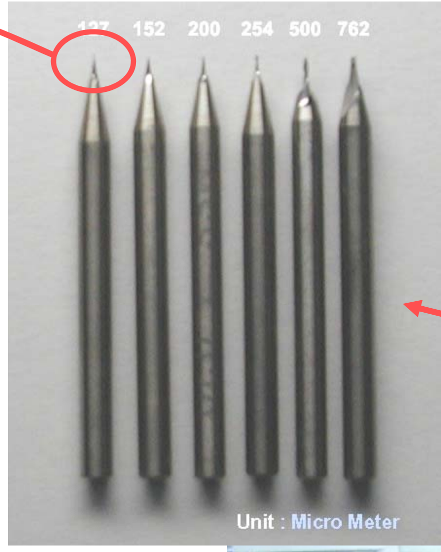
FIGURE 8.63 (a) Terminology for saw teeth. (b) Types of saw teeth, staggered to provide clearance for the saw blade to prevent binding during sawing.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Micro Machining System

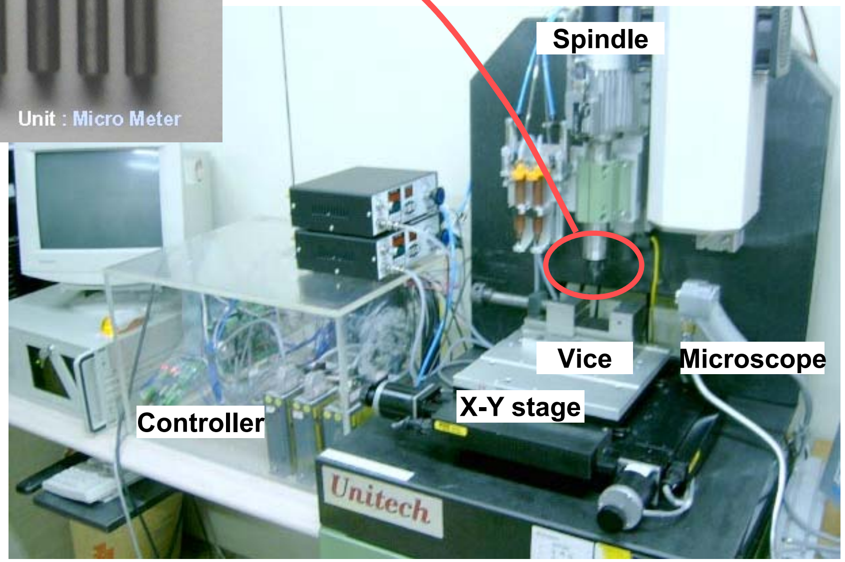


Tip of 127μm endmill



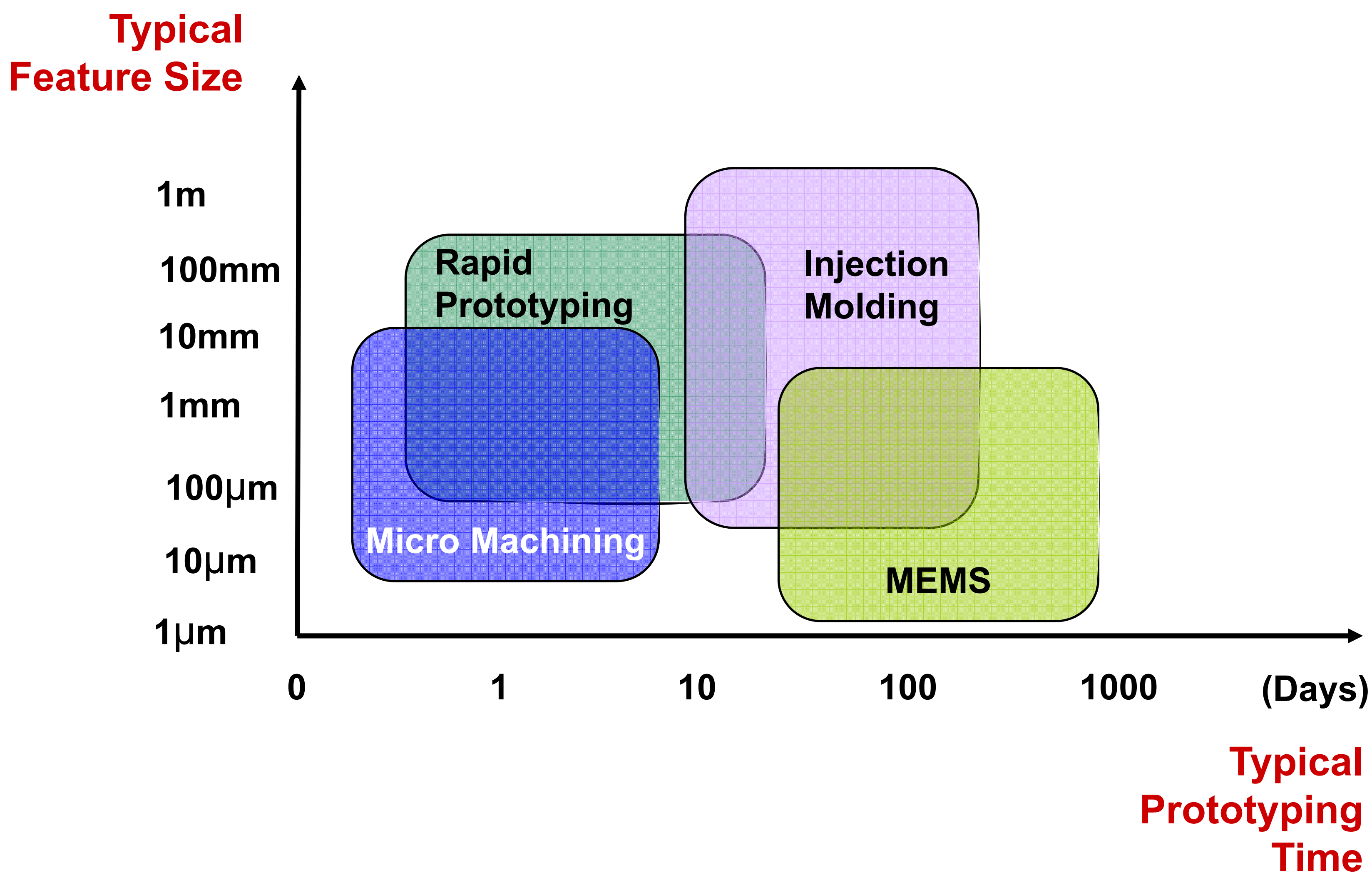
Micro endmills

- Positional resolution : 1 ㎛
- Tool diameter : 50 ㎛~1000 ㎛
- High speed : 46,000 RPM
- Tool material : HSS & TiN coating
- Work piece : Metal, Polymer, etc



Precision stage

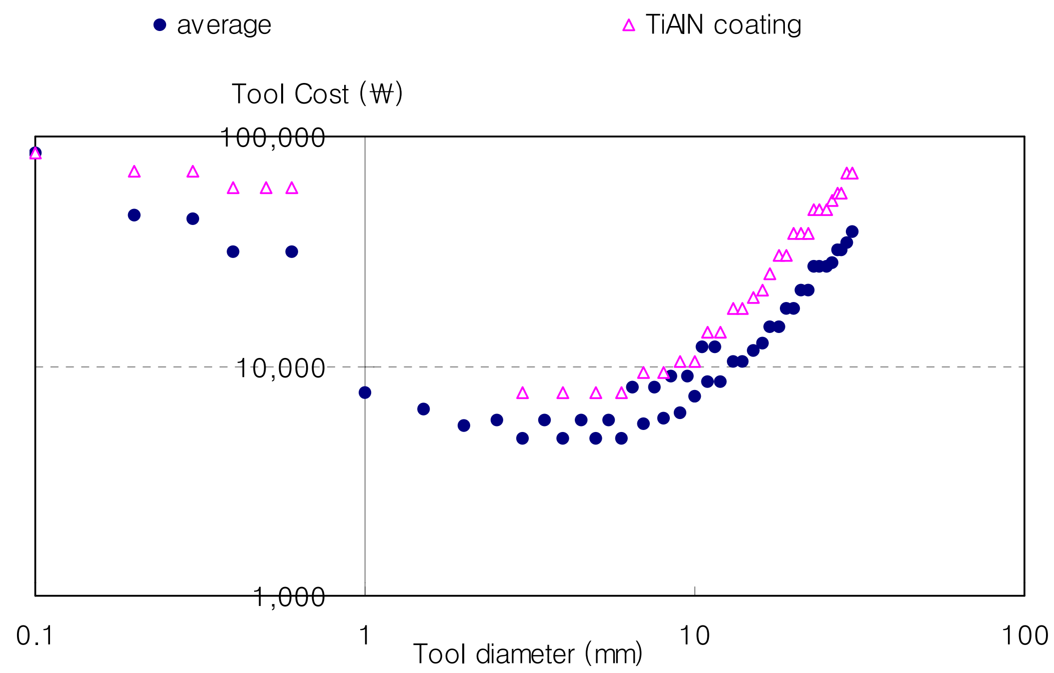
Prototyping Size & Time



DFM - Micro Milling

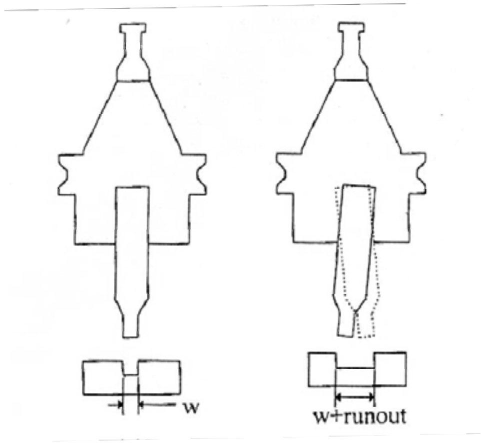
- **10mm endmill**
  - 10μm stage error
  - 0.1% for slot cutting
- **100μm endmill**
  - 10μm stage error
  - 10% for slot cutting
- **Cost structure of micro machining is different from that of macro machining.**
  - Tool cost dominates

A tip is not exact edge in micro scale

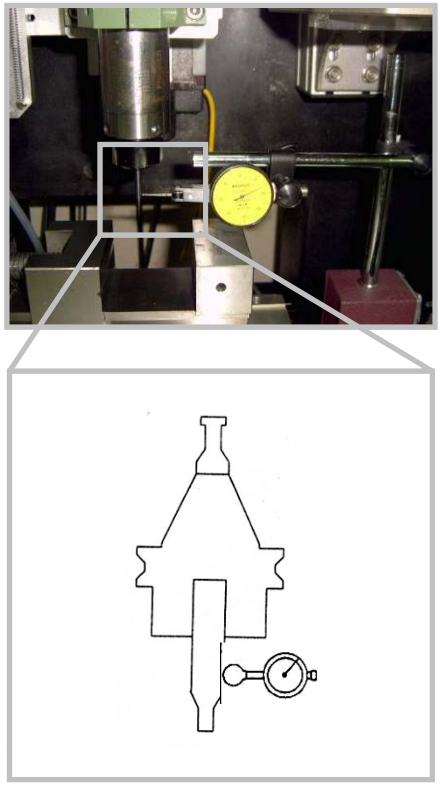


Spindle run-out

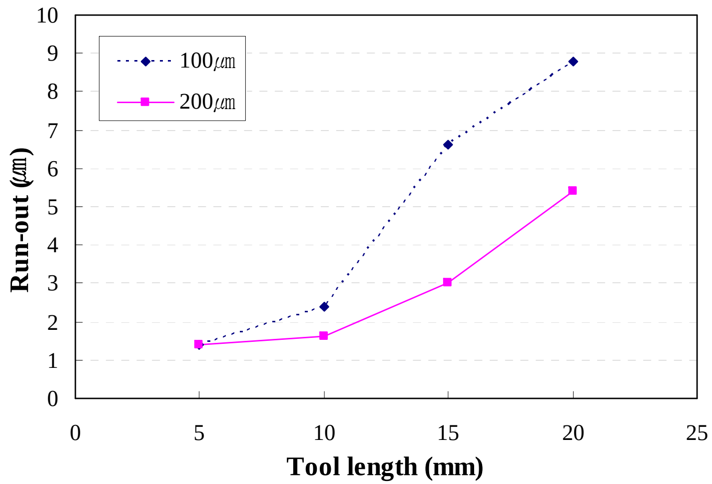
- Run-out effect on the final geometry is critical in micro machining
- Total run-out = TIR (Total Indicator Reading) + Error Terms (vibration, thermal deformation, etc)



< Concept of run-out >



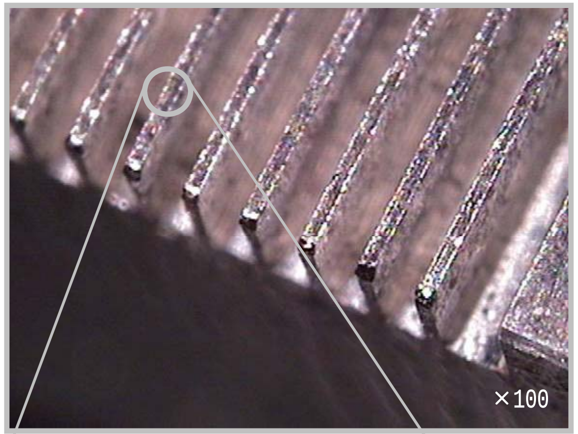
< Total Indicator Reading (TIR) Measurement >



< Result of Total Indicator Reading (TIR) >

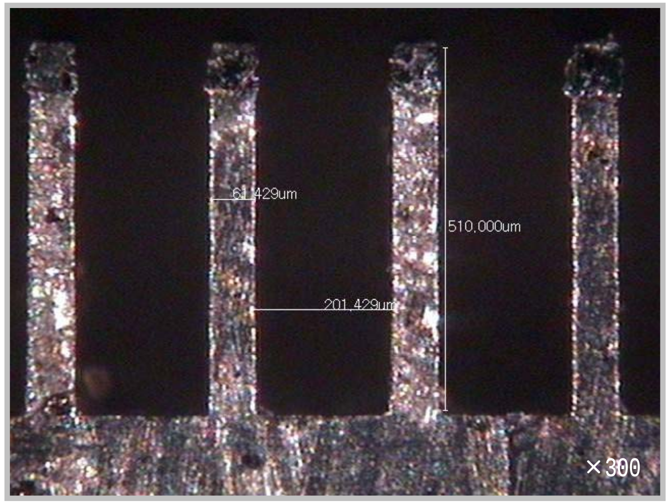
Micro walls

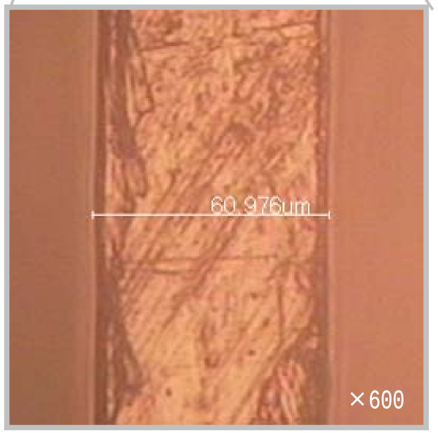
Barrier ribs

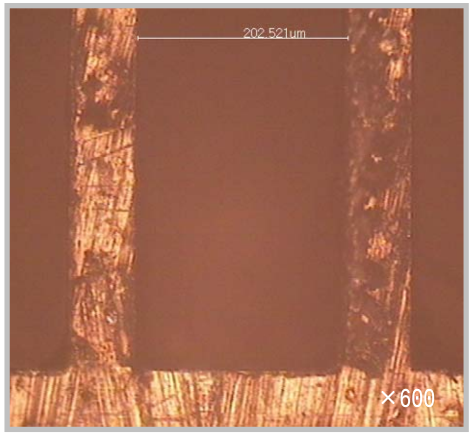


Rib width: 60㎛
Height: 500 ㎛
Tool: φ200 ㎛

Spindle: 24,000rpm
DOC: 25㎛
Feed rate: 100㎛/s
Time: 3hr 28min

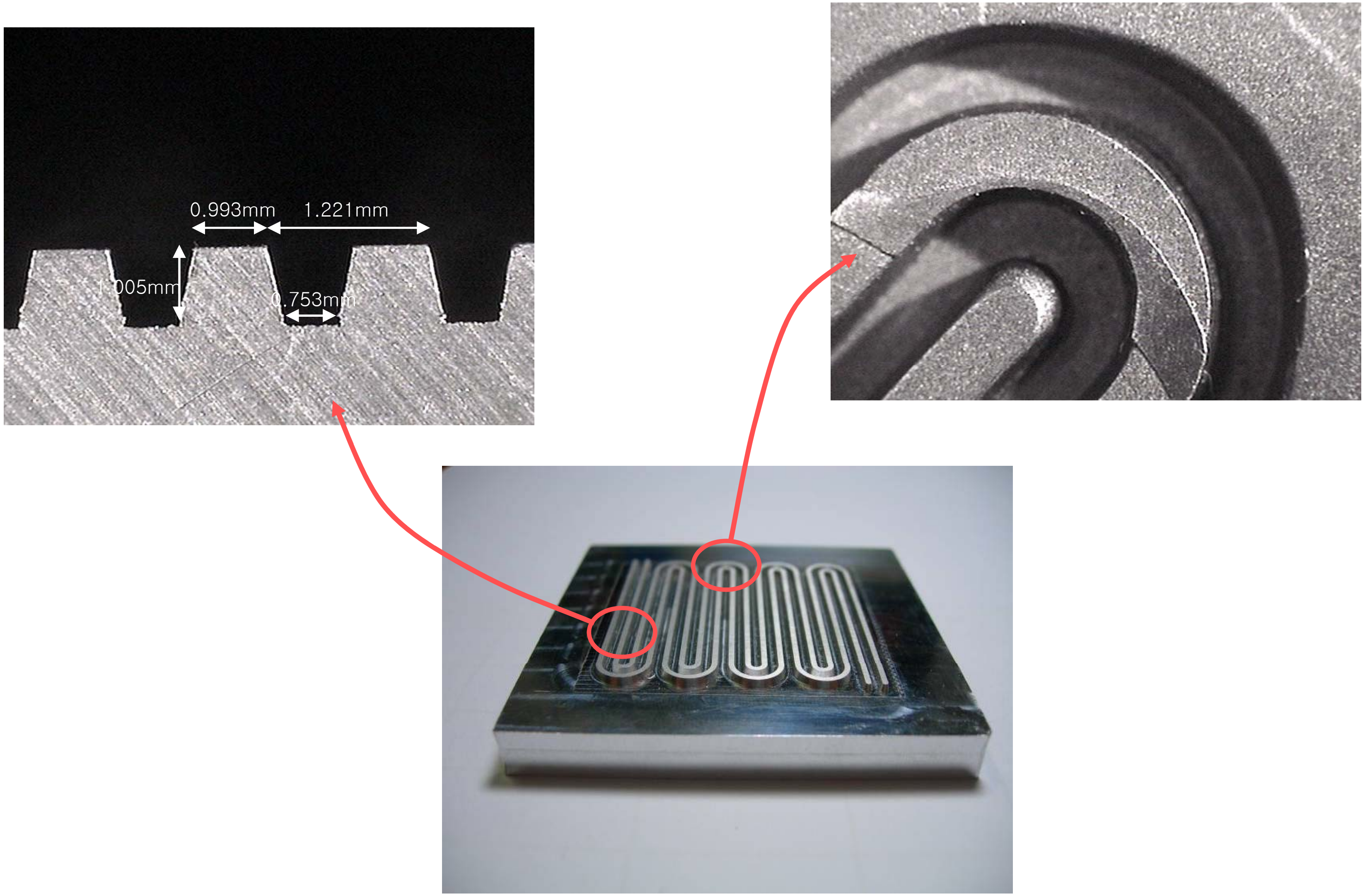






Geometric error: ~ 5 ㎛ (including error of microscope)

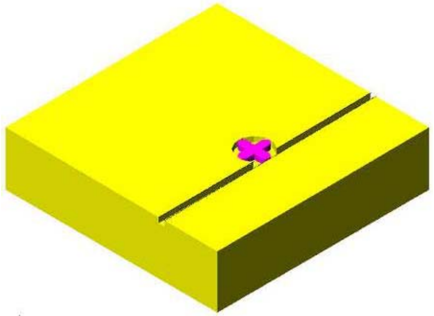
Micro machined mold



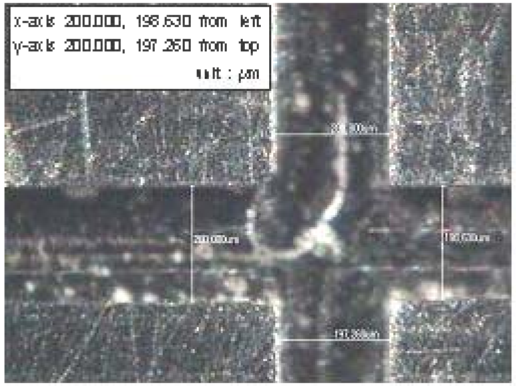
From Concept to Part

- Part for UAV/MAV
- ABS plastic
- l = 2.9mm,
- t= 300mm,
- Pivot D=250 mm

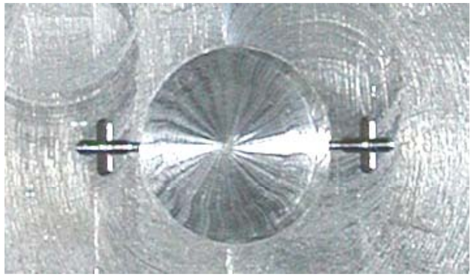
Specification



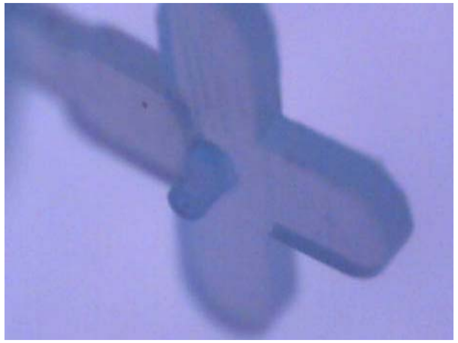
CAD design



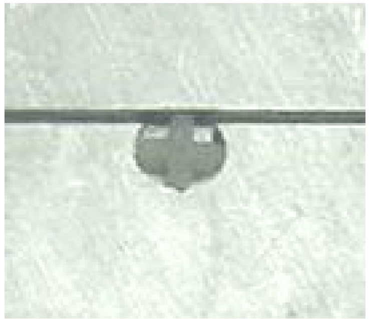
Micro machining



Aluminum mold



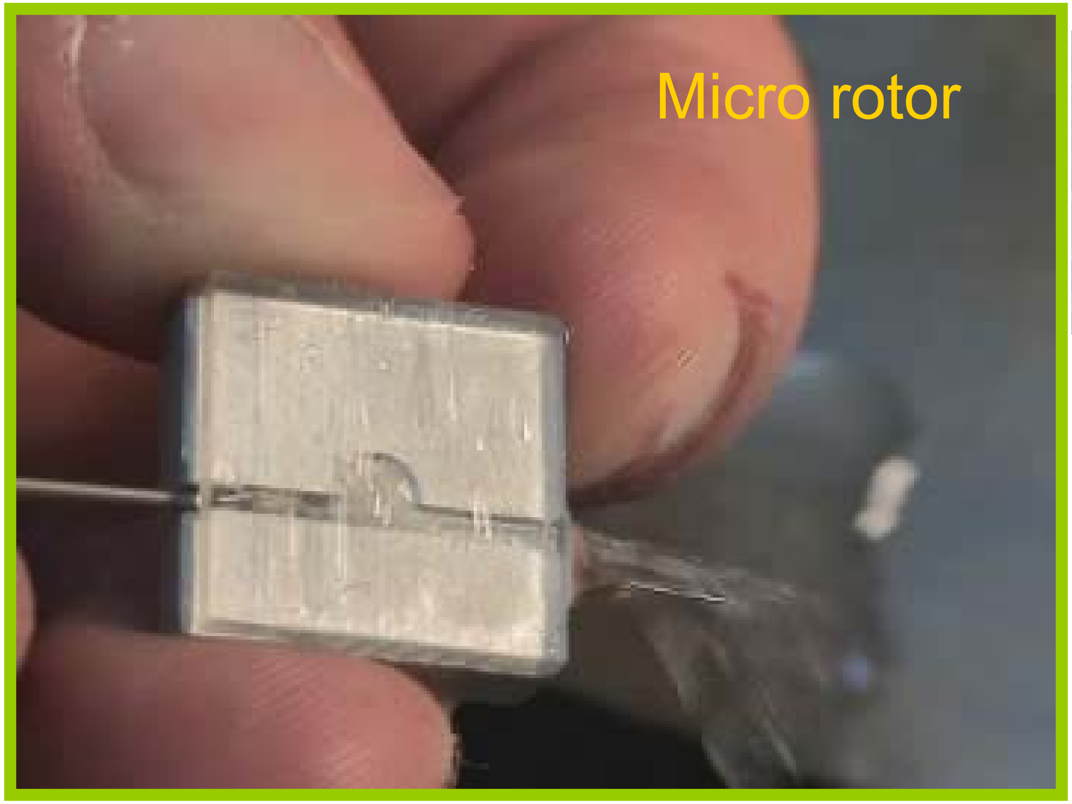
Micro injection molded rotor

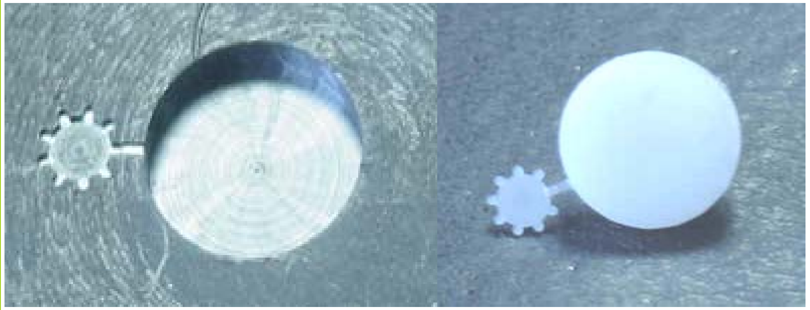


Rotor with micro channel

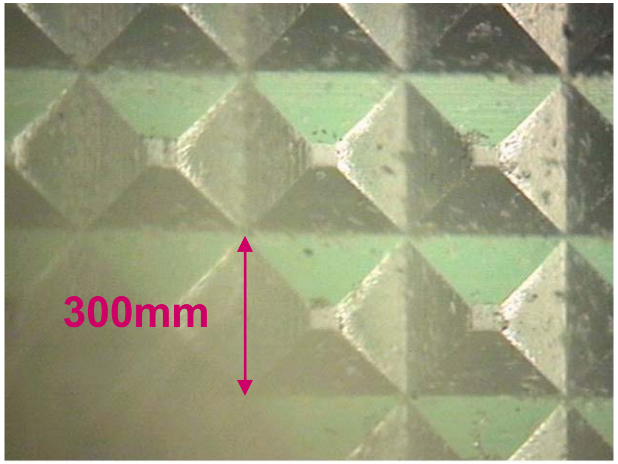
Total time: 5 days

More Meso/Micro Parts



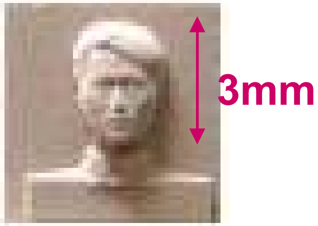


Micro molding (ABS)



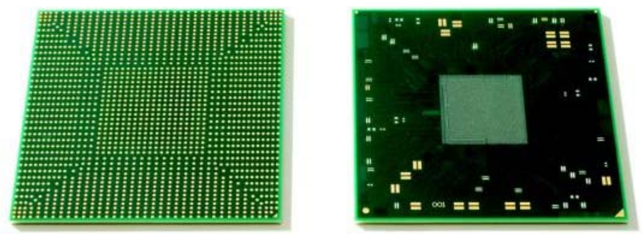
Micro pyramid

Freeform surface

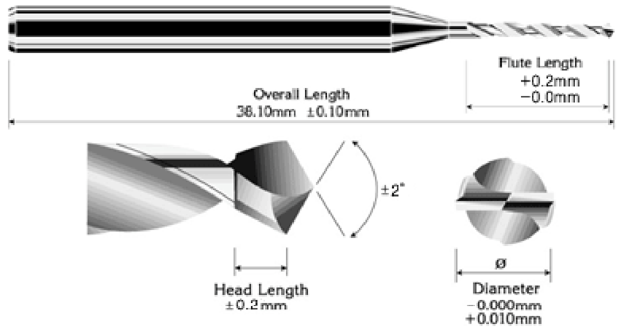


Micro Tools

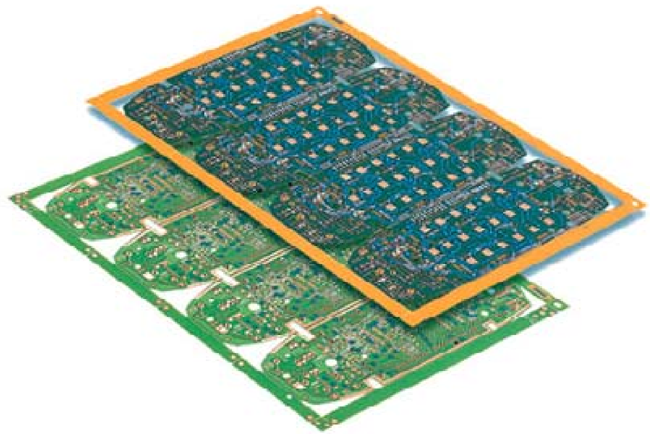
- **Drill**



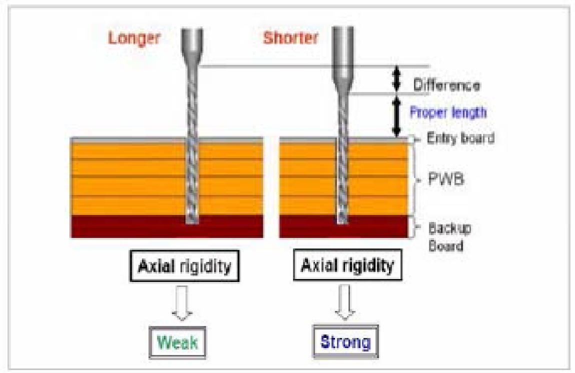
PCBs for semiconductor



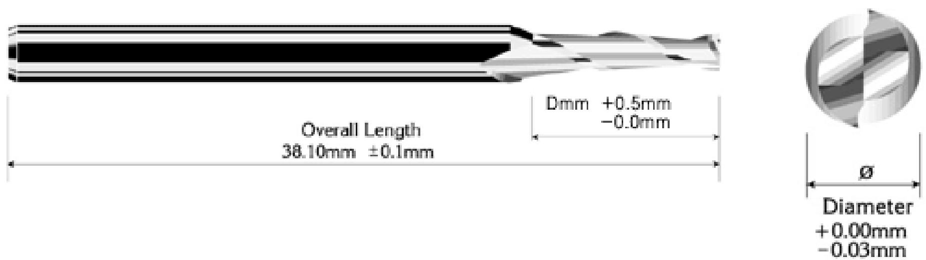
Shape of Micro drill



PCBs for cell phone

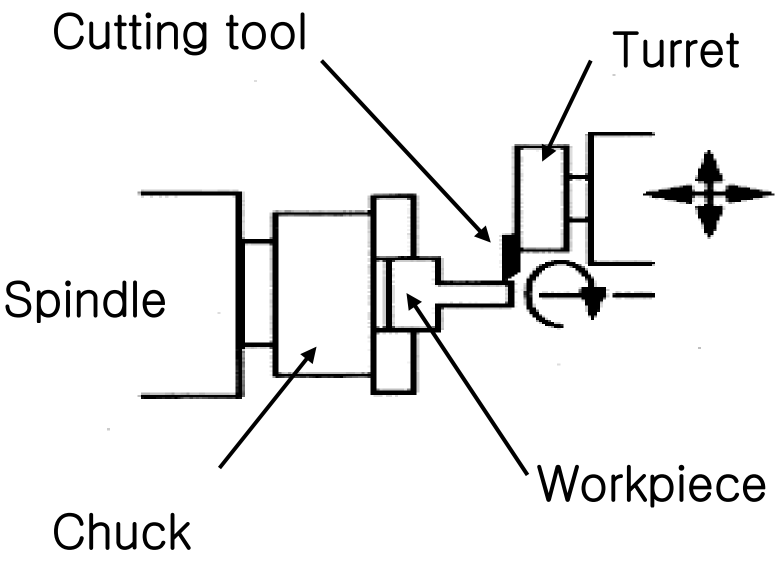


- **End mill**

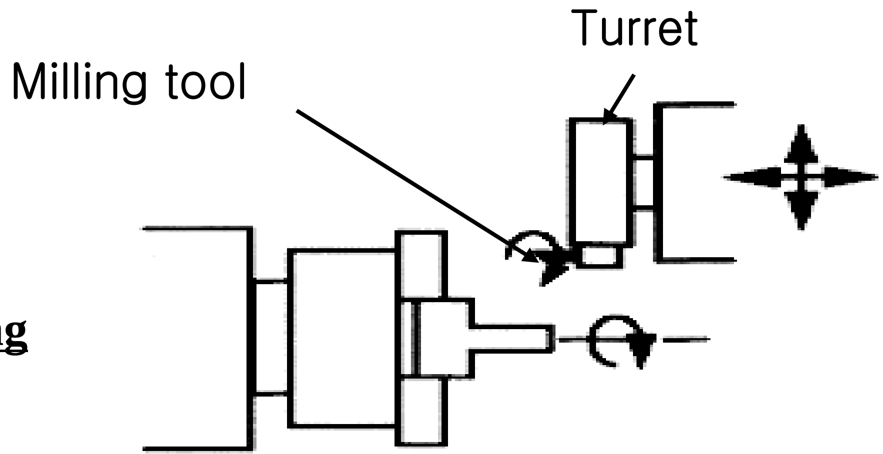


CNC Lathe

- CNC lathe can achieve multi-functional machining using attached milling turret, sub-spindle, etc.

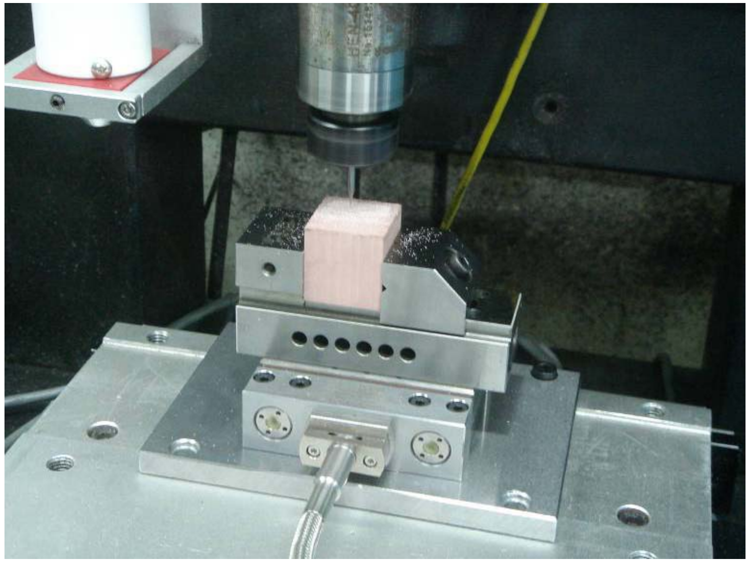


Cutting

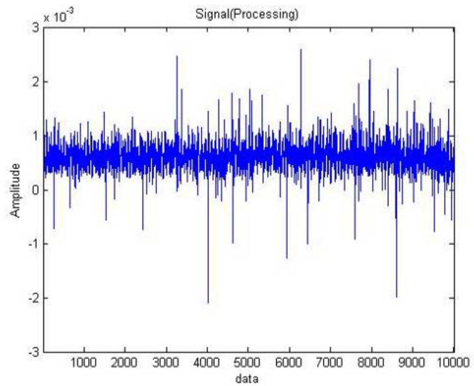


Cutting + Milling

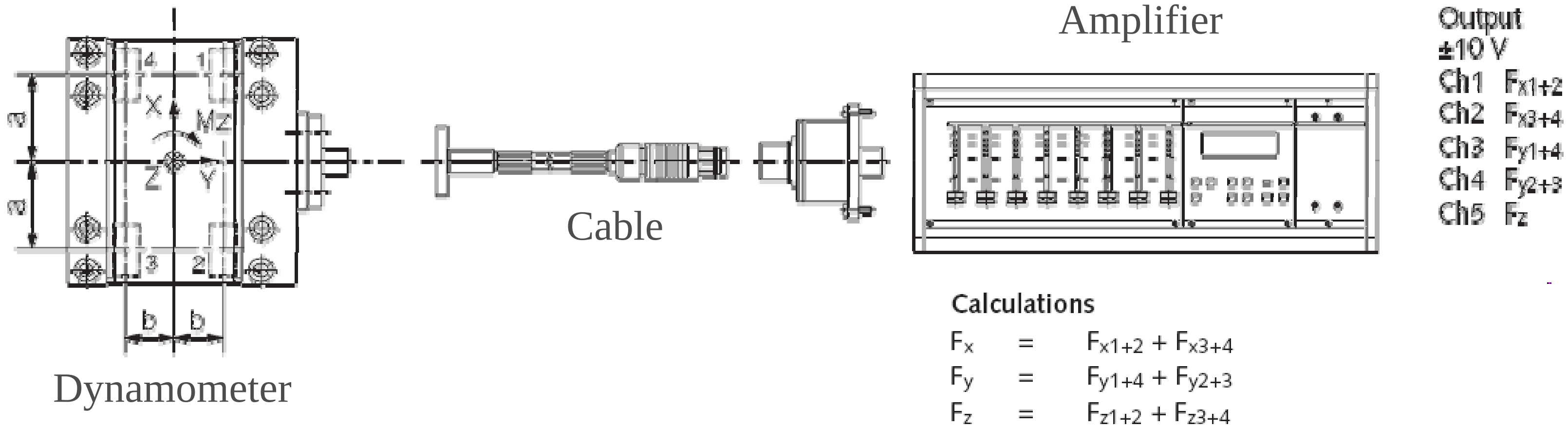
Dynamometer (공구동력계)



Measured Signal



The whole system configuration



Calculations

$F_x = F_{x1+2} + F_{x3+4}$

$F_y = F_{y1+4} + F_{y2+3}$

$F_z = F_{z1+2} + F_{z3+4}$

$M_x = b \bullet (F_{z1+2} - F_{z3+4})$

$M_z = b \bullet (-F_{x1+2} + F_{x3+4}) + a \bullet (F_{y1+4} - F_{y2+3}$