M2794.006900 DESIGN FOR MANUFACTURING

Week 9, November 02

Manufacturing Processes
1. Subtractive Processes

Fall 2017

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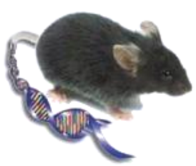
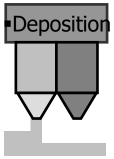
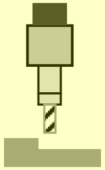
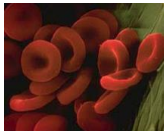
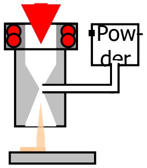
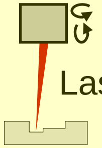
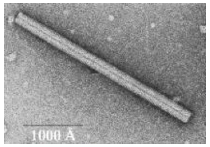
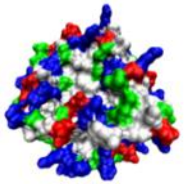
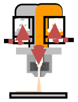
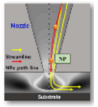
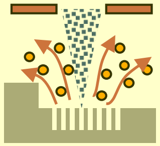
Outline

- Multi-scale fabrication
  - Subtractive processes
  - Additive processes
- Mechanical machining
  - Introduction
  - DFM: Micro machining (drilling and milling)
- Laser machining
  - Introduction
  - DFM: Laser machining
- Focused ion beam (FIB) fabrication
  - Introduction
  - DFM: FIB
- Conclusions

Multi-scale fabrication

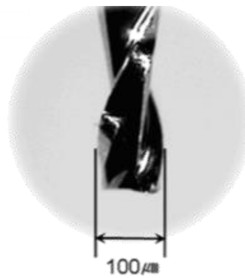
Today's class

Scale	Example	Additive process	Subtractive process
macro/meso (100 mm) 10^{-1}	 ▪Mouse  ▪CD-ROM  ▪Mobile phone	 Rapid Prototyping	 Precision machining
micro (100 μm) 10^{-4}	 Human hair ~ 60-120 μm wide  MicroElectroMechanical (MEMS) devices 10 -100 μm wide  Red blood cells (~7-8 μm)	 Cold spray	 Laser machining
nano (100 nm) 10^{-7}	 ▪Virus  ▪Smoke  ▪Protein	 Nano particle deposition  AFN printing	 Focused ion beam

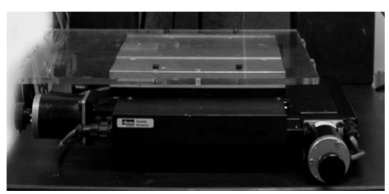
#1 Precision machining (정밀가공)

- Type : Subtractive
- Scale : 100 μm~ 100 mm
- Material : metal, polymer, etc
- Characteristic: High speed spindle, precision stage, micro-tool

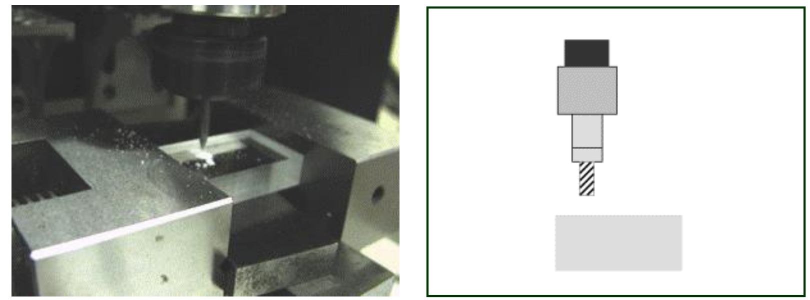
High speed spindle
(43,000 rpm)



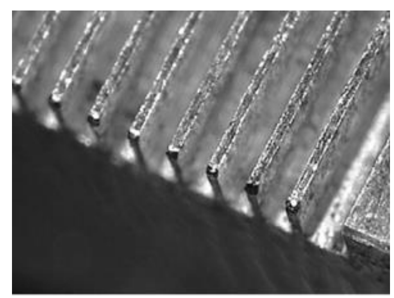
Micro tool
(Material: HSS & TiN coating)



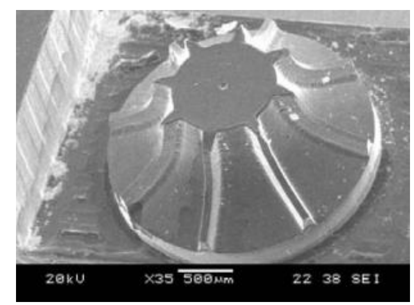
Precision micro stage
(1μm resolution)



Machining process of 3-axis micro-stage



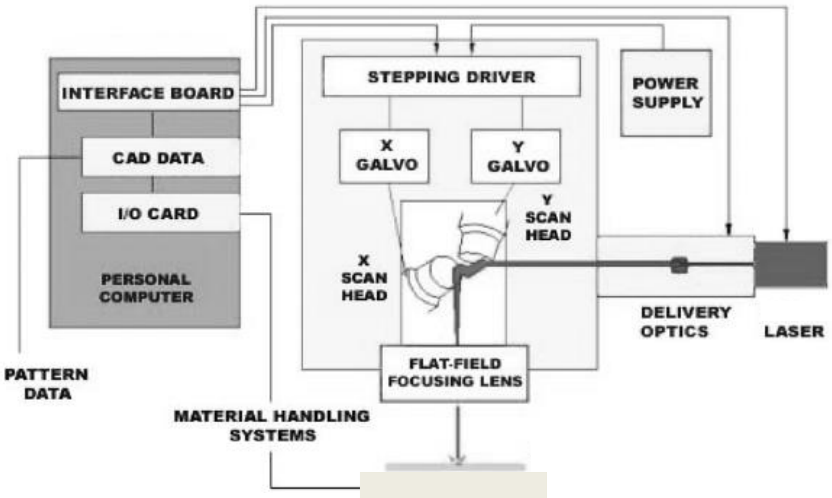
Micro-wall



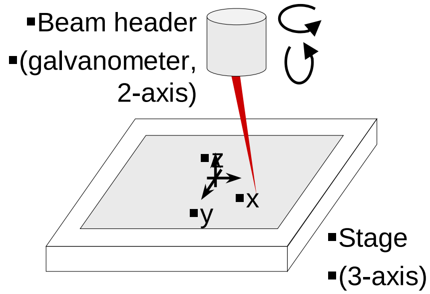
Micro-rotor

#2 Laser machining (레이저 가공)

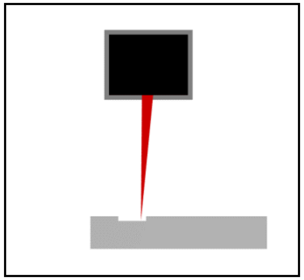
- Type: Subtractive
- Scale : tens of μm ~ several mm
- Material : metal, polymer, ceramic
- Characteristics : no tool-tip change



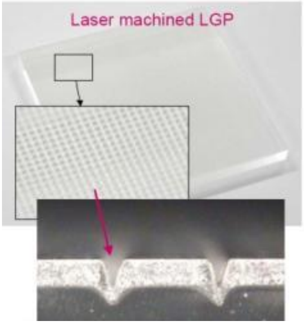
Schematics of laser machining system



Scan area & stage



Machining process

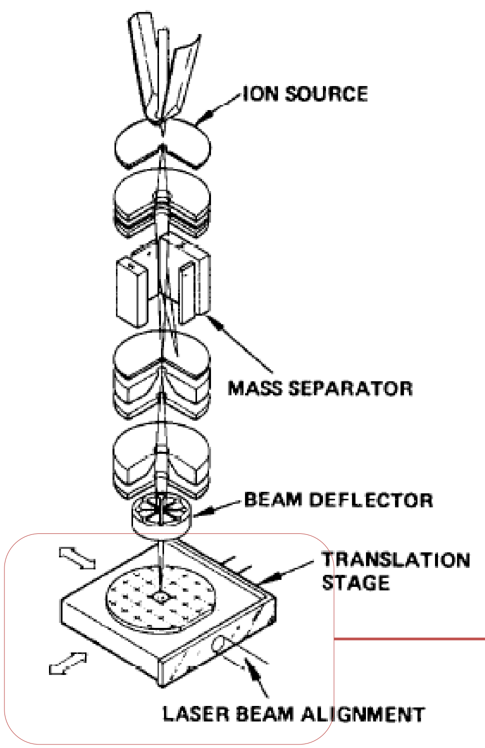


Light guide

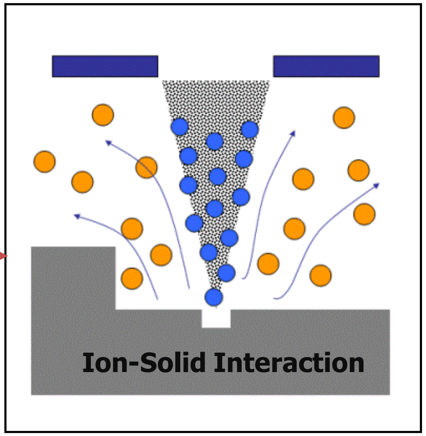
Cell phone key pad

#3 Focused ion beam (FIB) (집속이온빔)

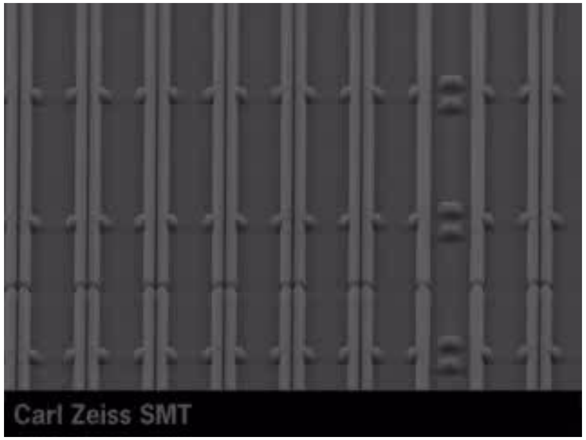
- Type: hybrid (Additive + Subtractive)
- Scale: 10 nm ~ 100 μm
- Metal: all solid
- Characteristics : ultra precision, direct writing
- Cost : 200,000 won / hr.



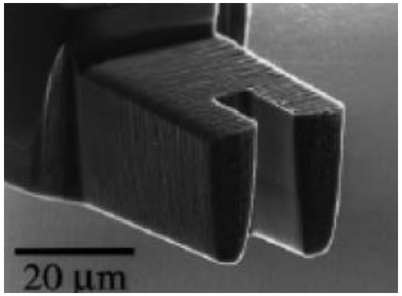
Focused ion beam system



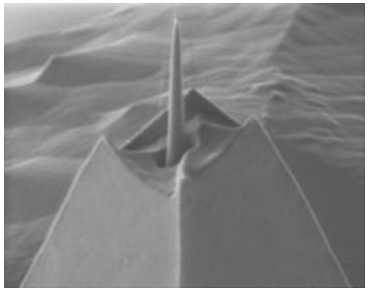
▪Incident Ion
▪Sputtered Particle
▪(Ion, Neutron, Electron)



FIB Milling Process

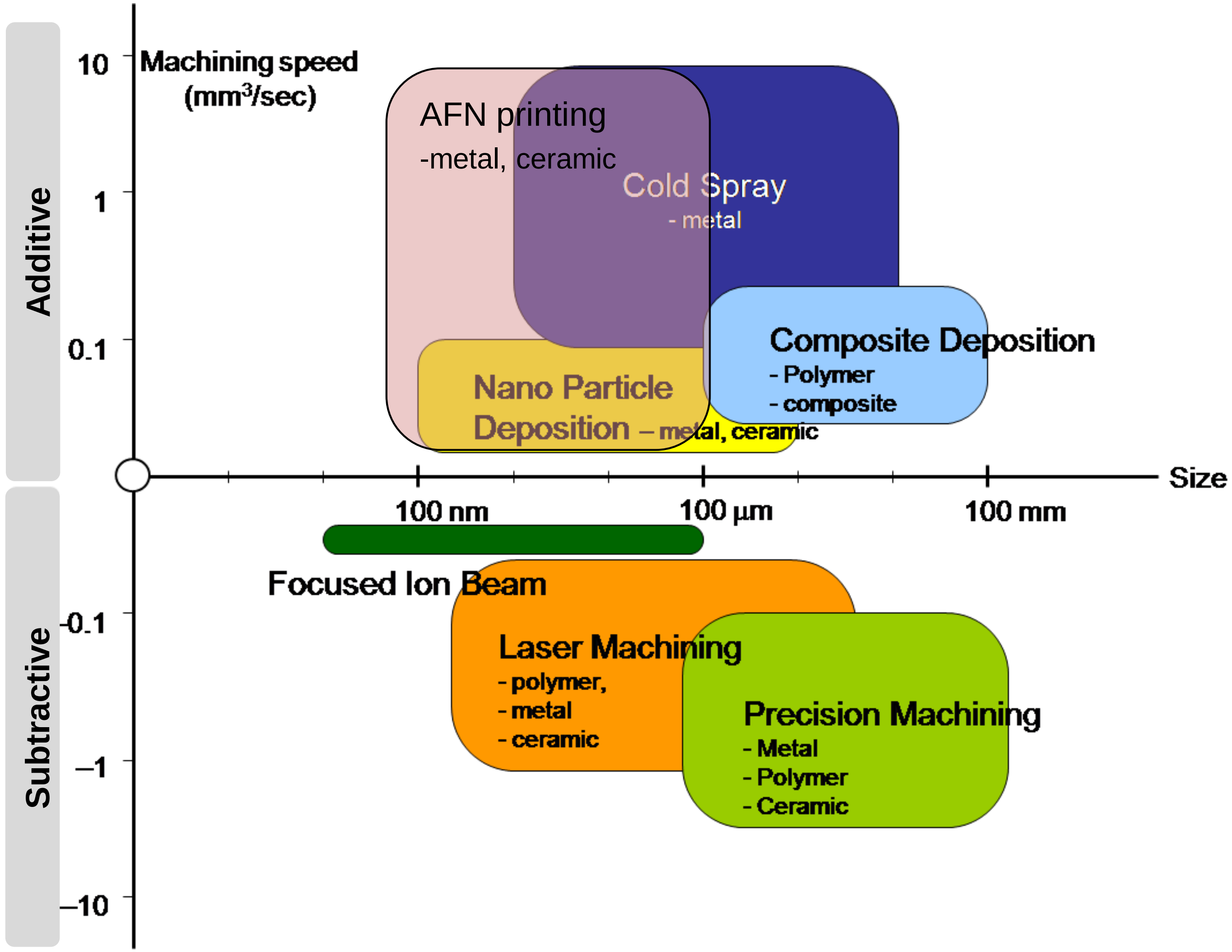


Micro-Tool



Micro/Nano Probe

Process envelope



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)

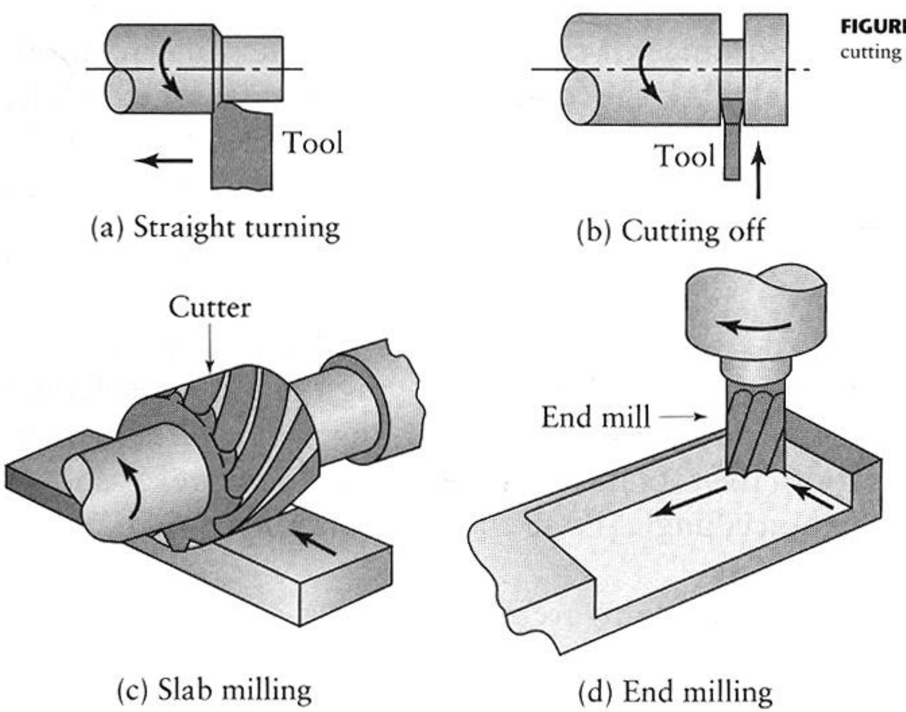


FIGURE 8.1 Examples of cutting processes.

High speed machining

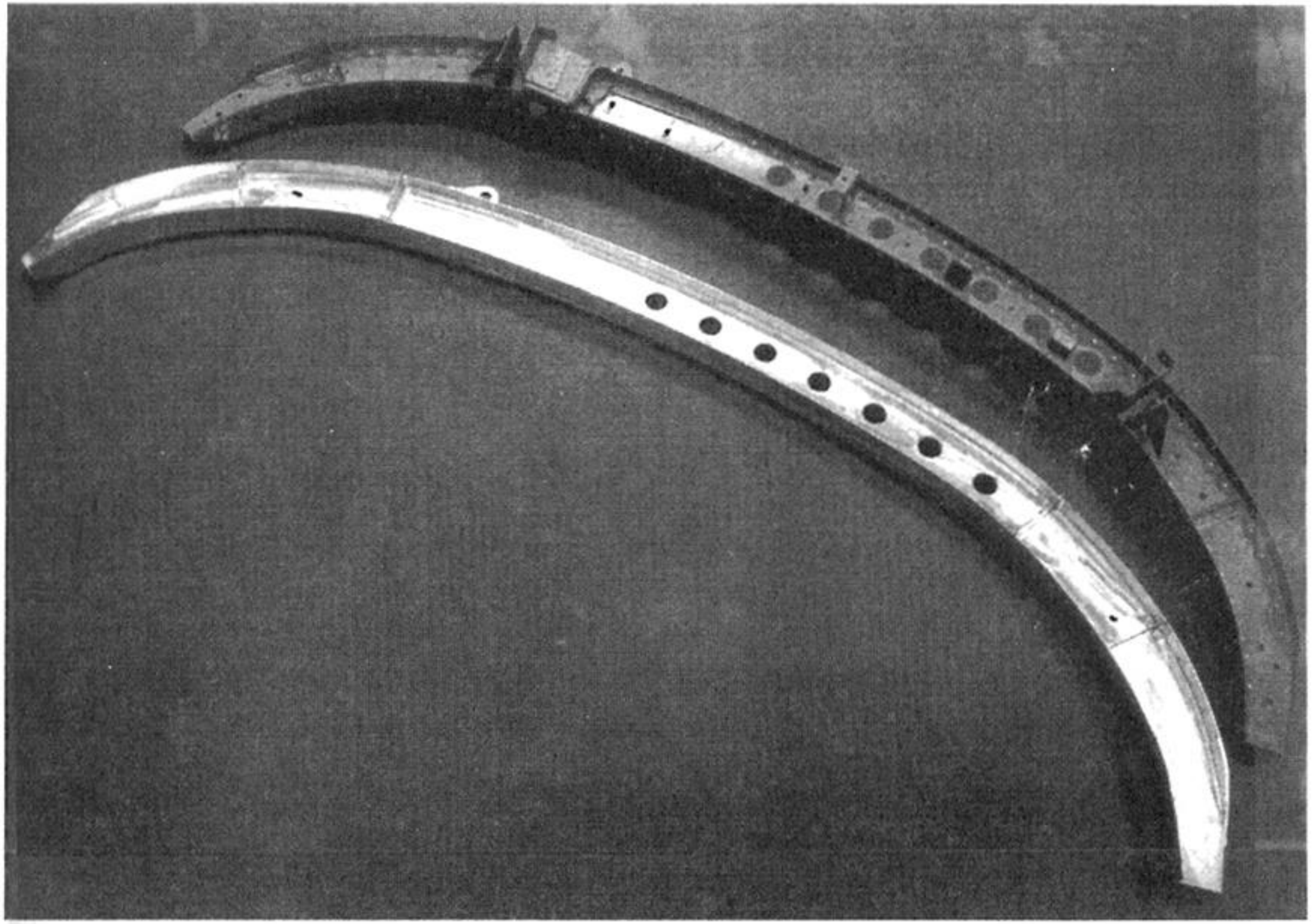
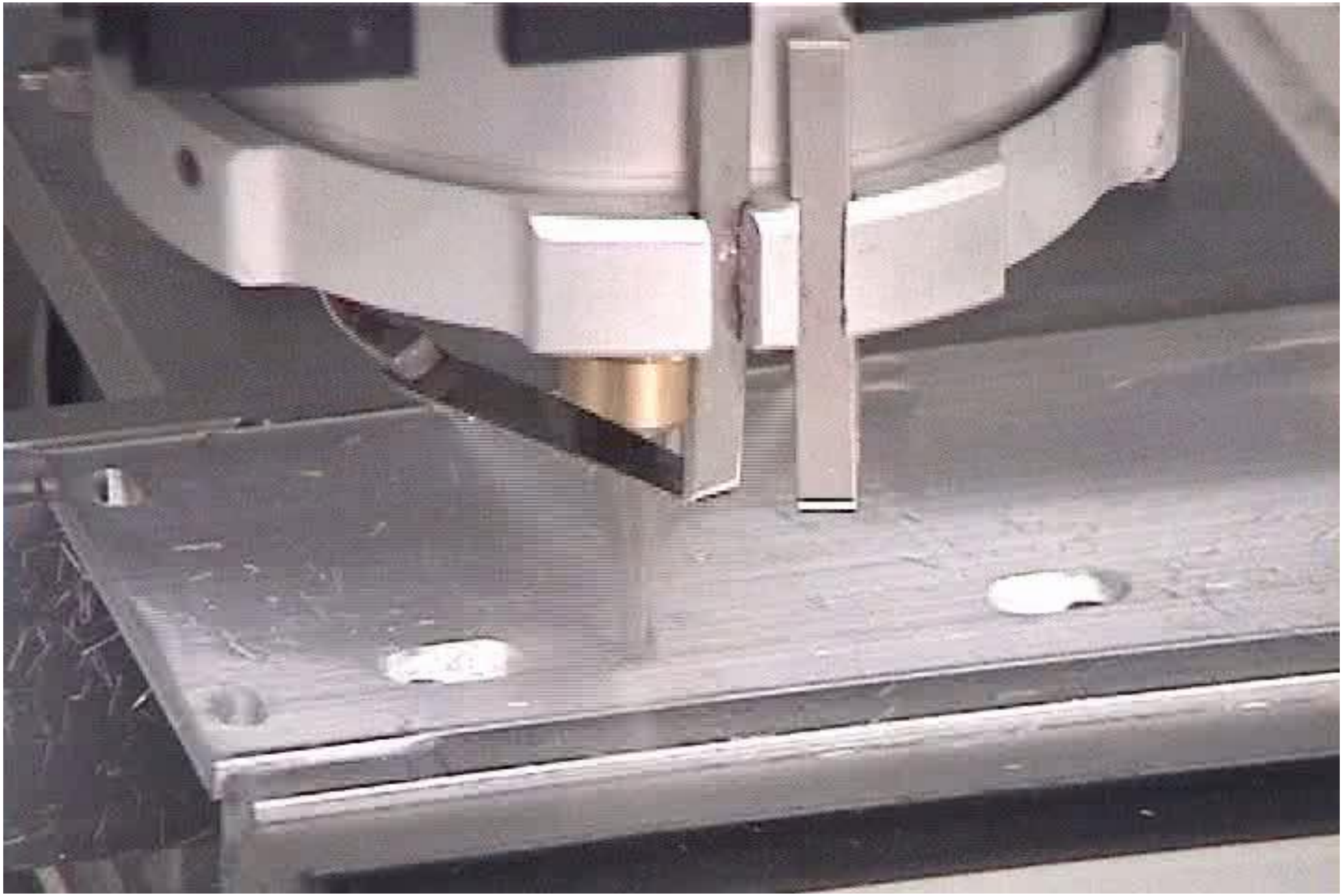


FIGURE 11.1 Integrated product and process design allows this aerospace component to be completely machined from the solid as shown in the lower photograph (Courtesy of Dr. Donald Sandstrom, The Boeing Company)

High speed machining



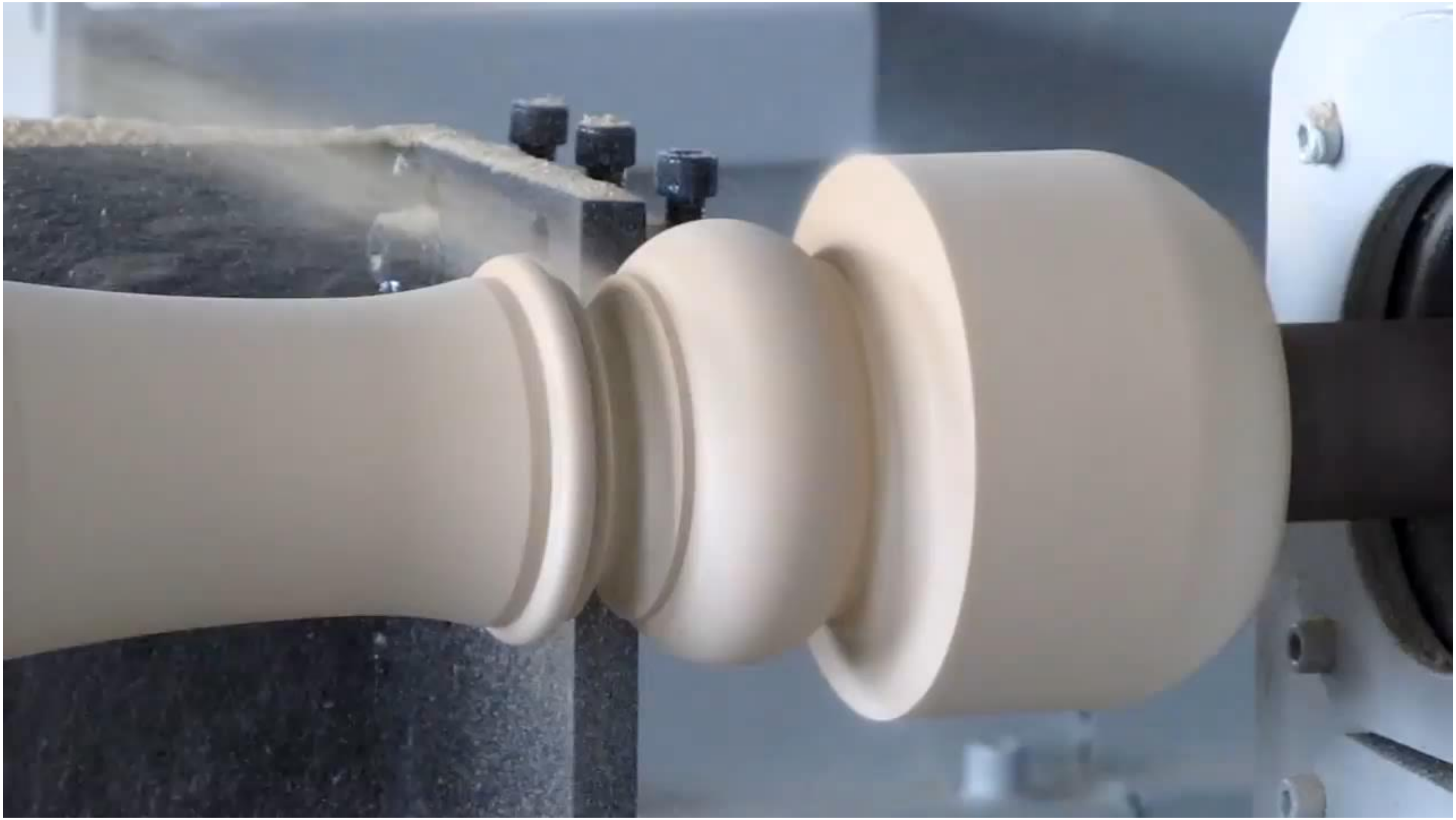
Cutting processes

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

Lathe



(x2 Speed)

(http://youtube.com/watch?v=r_KUIx3aBhQ)

Turning (선삭)

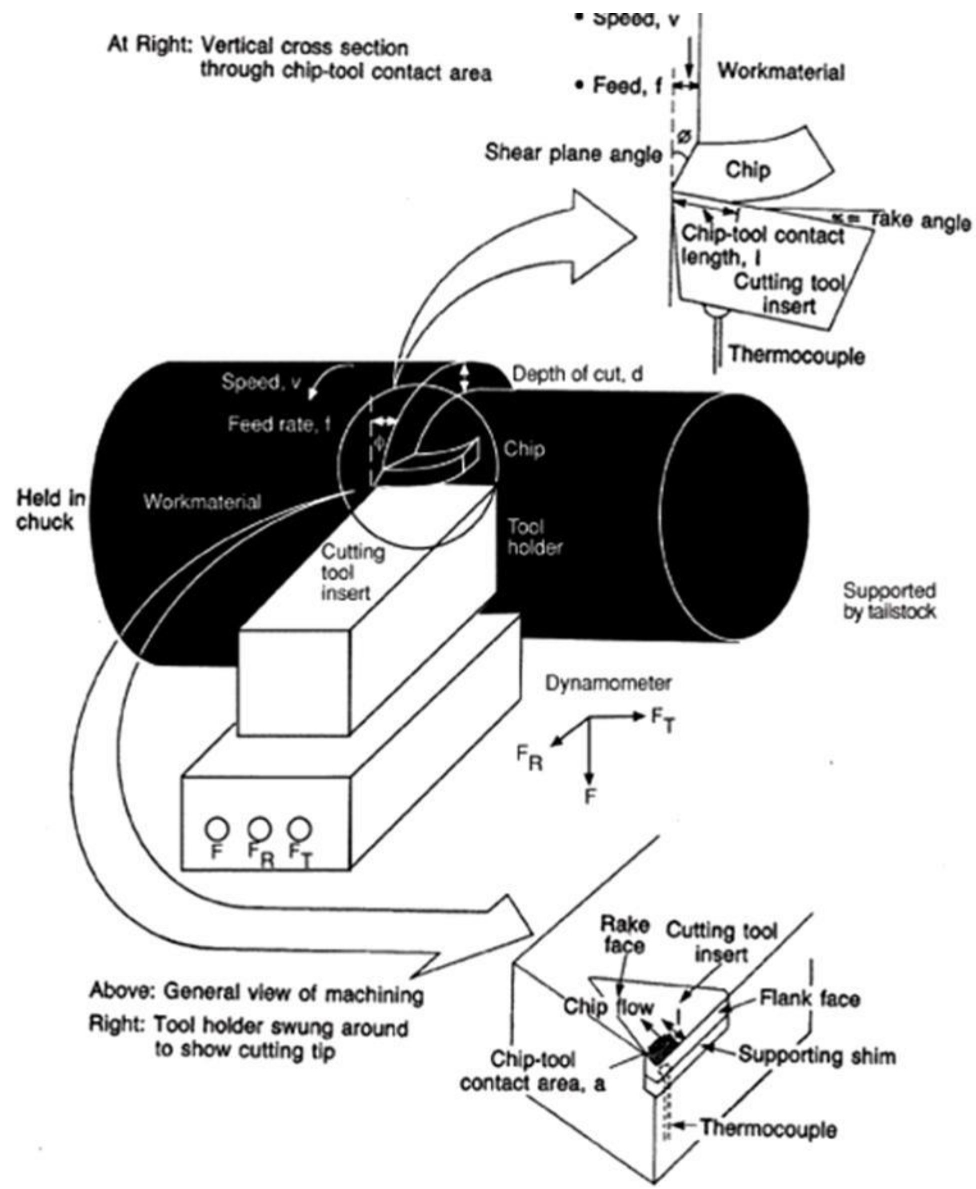
$$\text{Rate of removal} = Vfw$$

Where

V : cutting speed (m/min)

f : feed (mm/rev)

w : depth of cut (mm)



Lathe-round shape

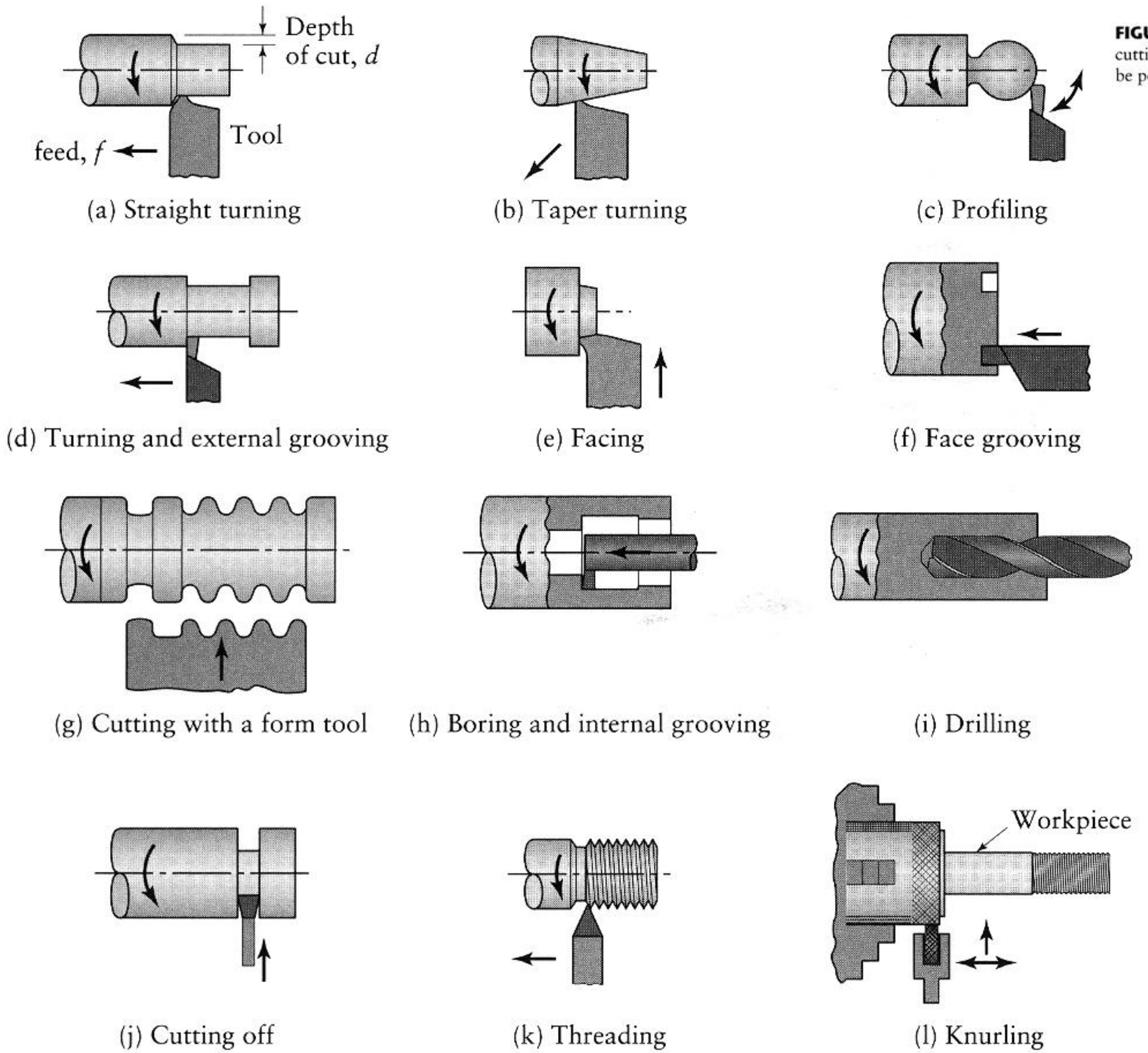


FIGURE 8.40 Various cutting operations that can be performed on a lathe.

Lathe components (선반)

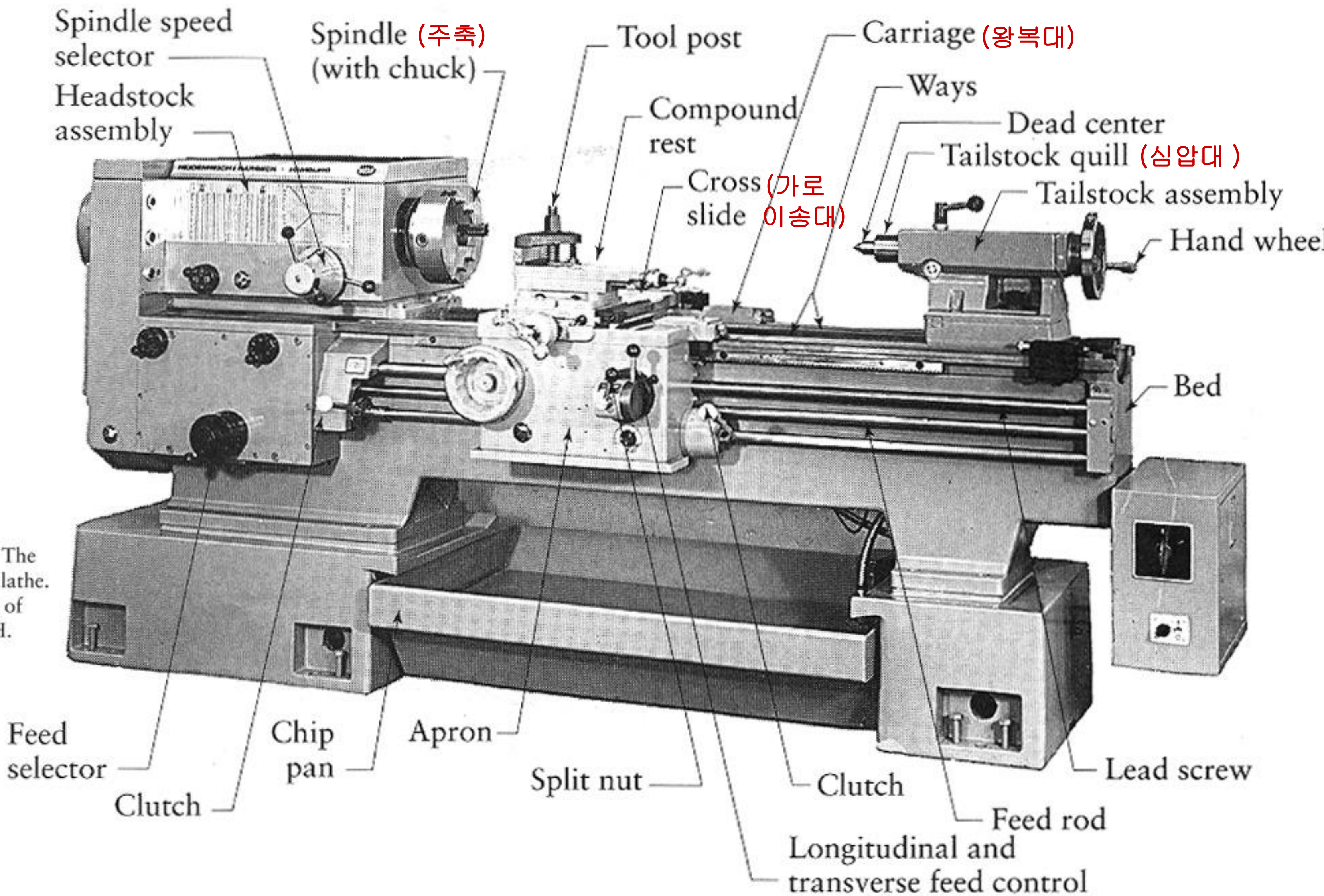


FIGURE 8.44 The components of a lathe. *Source*: Courtesy of MAKINO GmbH.

Drill

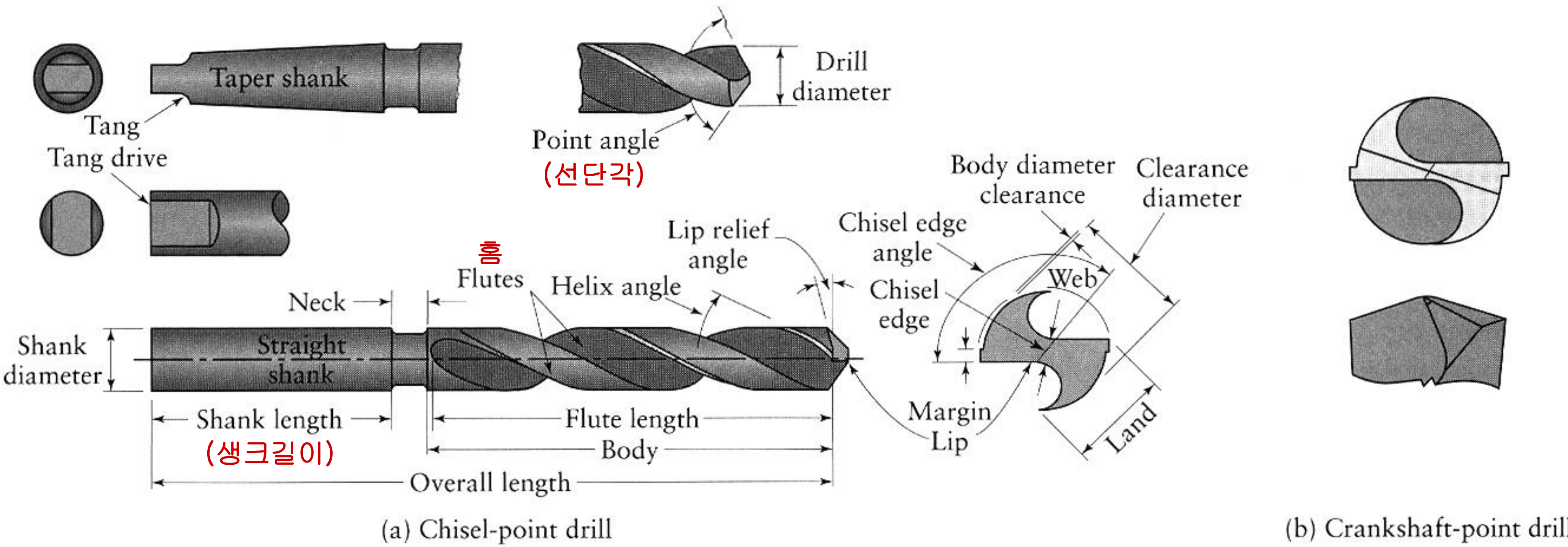
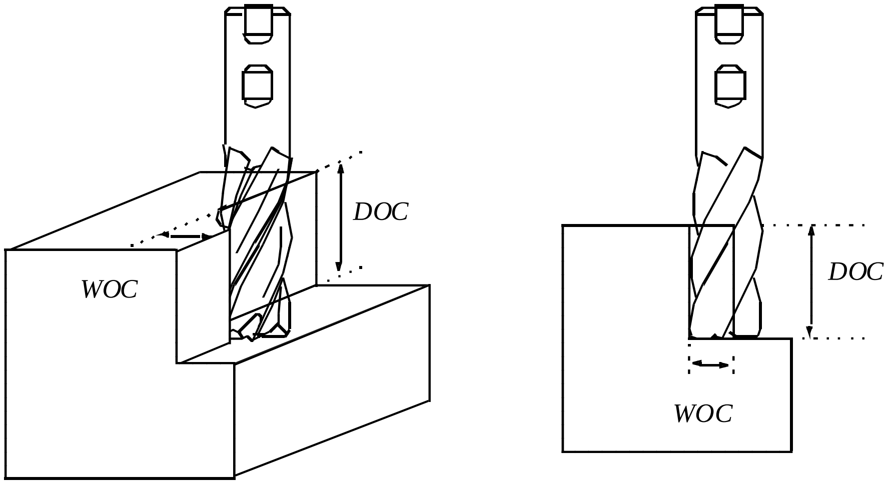


FIGURE 8.48 (a) Standard chisel-point drill, with various features indicated. (b) Crankshaft-point drill.

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



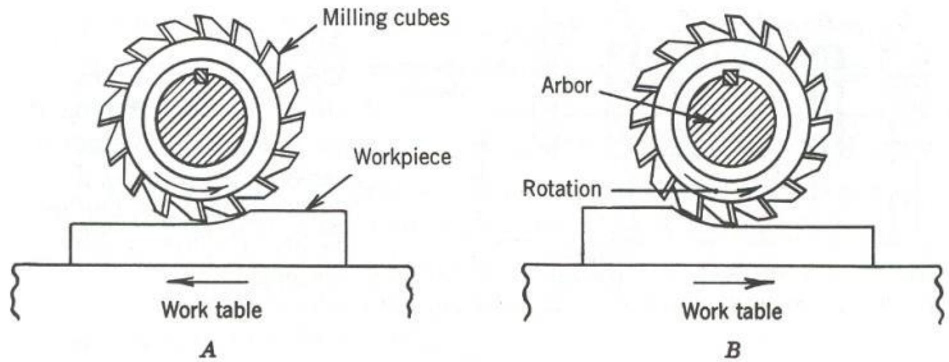
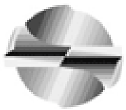


Figure 11.32
Methods of feeding work on milling machine. *A*, Conventional or up milling. *B*, Climb or down milling.

Material removal by milling

- Cutting speed (m/min)
  - $V = \pi DN$

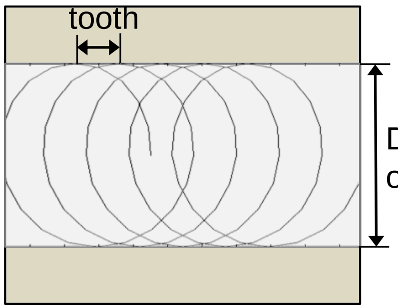
  (D : diameter of cutter(m), N : rotational speed of the cutter(rpm))



Cutting Tool
- cross section

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

  (n: number of tooth, t : feed per tooth,
  N : rotational speed of the cutter)



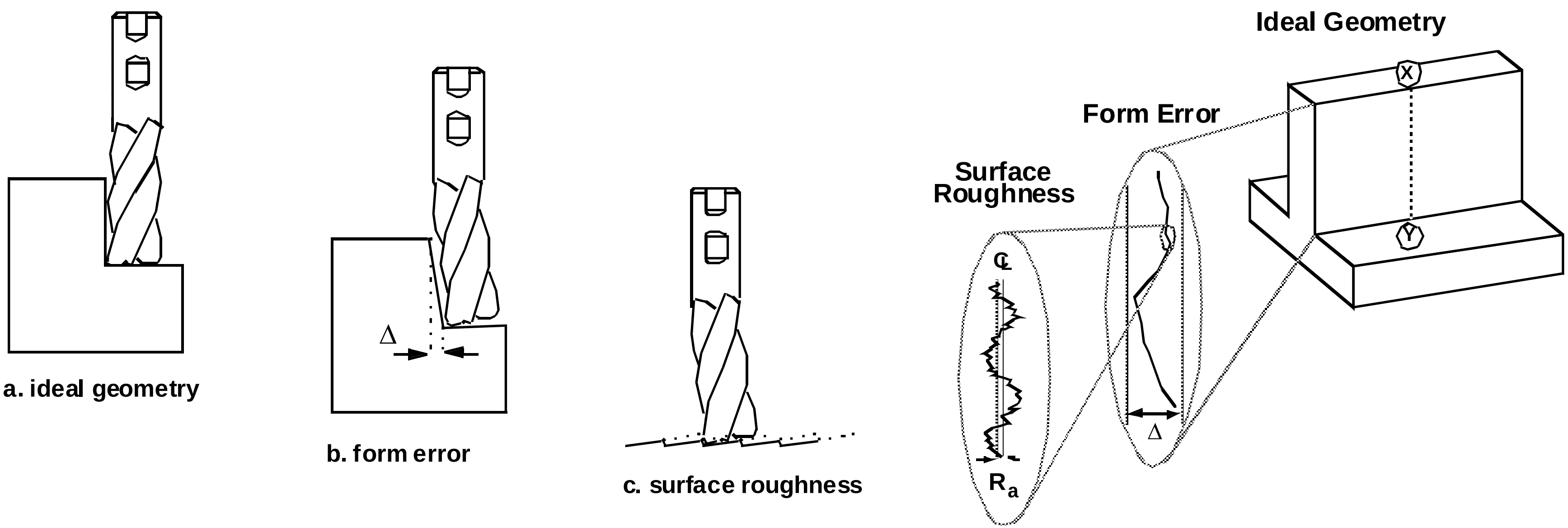
- Example
  - V = 50 m/min, t = 0.1 mm/tooth, number of tooth (n)= 2, D = 4 mm, DOC = 0.2, WOC = 3, Cutter RPM (N) = 50000/(πx4) = 3979
  - f = 2 *3979 * 0.1 = 796 mm/min, MRR = 3* 0.2 * 796 = 4776 mm^3/min

Sources of Errors

- Vibration (chatter)
- Tool deflection
- Temperature change

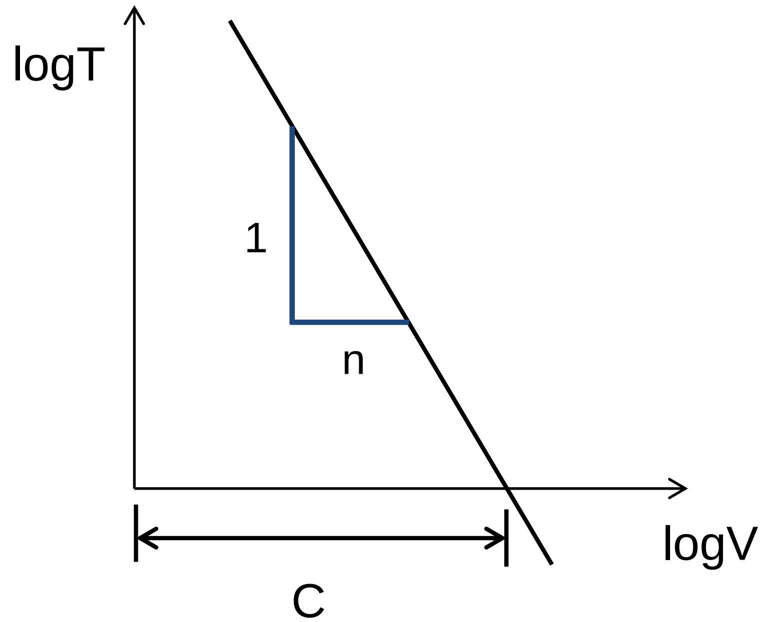
→

- Run-out
- Form Errors
- Surface Roughness



Taylor's equation, $VT^n = C$

- V = cutting speed
- T = tool life
- n, C = Taylor constants (empirical)
- f = feed rate, d = depth of cut



Tool life-Feed rate (log scale)

- $VT^n = C$
- $logV = \frac{1}{n} logV + \frac{1}{n} logC$
- $T = \left(\frac{c}{v}\right)^{\frac{1}{n}}$ (f, d: constant)

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.

More cost estimation

- Ostwald model
  - American Machinist Cost Estimator
  - Demo
  - Data for wage
    - http://www.kosis.kr/ (통계청)
    - http://laborstat.molab.go.kr/ (노동부)

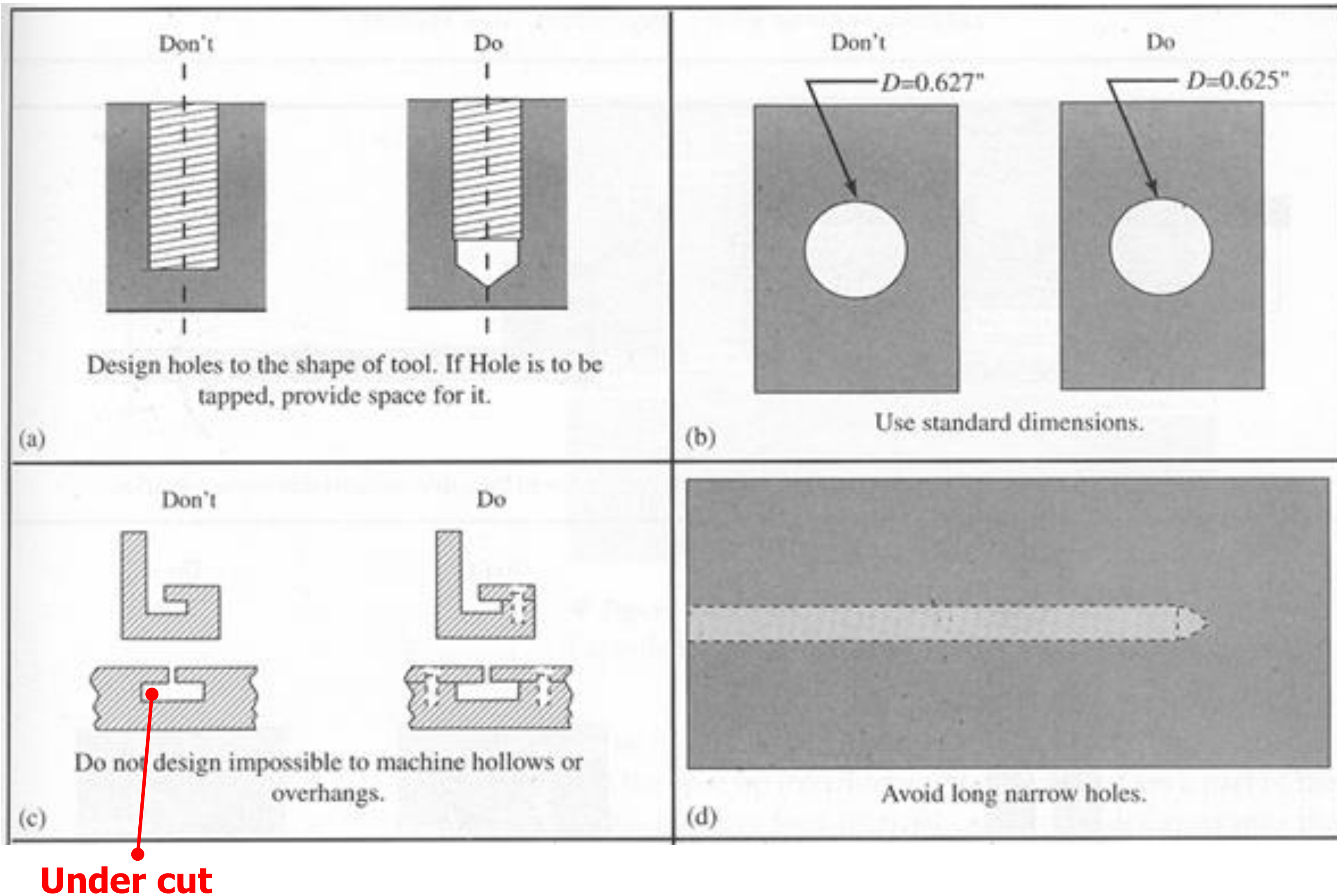
Material costs

Description	Quantity	1987–1988 Cost
	Weight	*Cost: $ per 100 lb*
Structural shapes, carbon steel; 6 × 4 × ½-in., angles, 350/400-in. long; ASTM specification A-7. FOB service center for less than base quantity; FOB mill for base quantity.	500 lb 2,000 lb 4,000 lb 6,000 lb Base quantity: 10,000 lb	.31 .25 .24 .23 .21
FOB: freight-on-board, warehouse	*Weight*	*Cost: $ per 100 lb*
Structural steel shape, carbon steel, 8-in. wide flange, 24 lb per ft wide flange section × 20 ft; ASTM specification A-36. FOB service center for less than base quantity; FOB mill for base quantity.	480 lb 2,000 lb Base quantity: 10,000 lb	.31 .30 .26
Pipe, tube	*Weight*	*Cost: $ per 100 lb*
Tubing, mechanical, carbon steel, electric weld; 1½-in. OD × 14 ga, 1.256 lb per ft, random mill lengths. FOB service center for less than mill quantity; FOB mill for base quantity.	2,000 lb 6,000 lb Base quantity: 10,000 lb	1.04 .96 .92
NONFERROUS PRODUCTS	*Weight*	*Cost: $ per 1 lb*
Bar, aluminum; 1 × 2 in. × standard stock lengths of 12 ft; specification 6061-T6511. FOB destination.	28.2 lb 500 lb 2,000 lb Base quantity: 6,000 lb	3.07 1.71 1.38 1.30

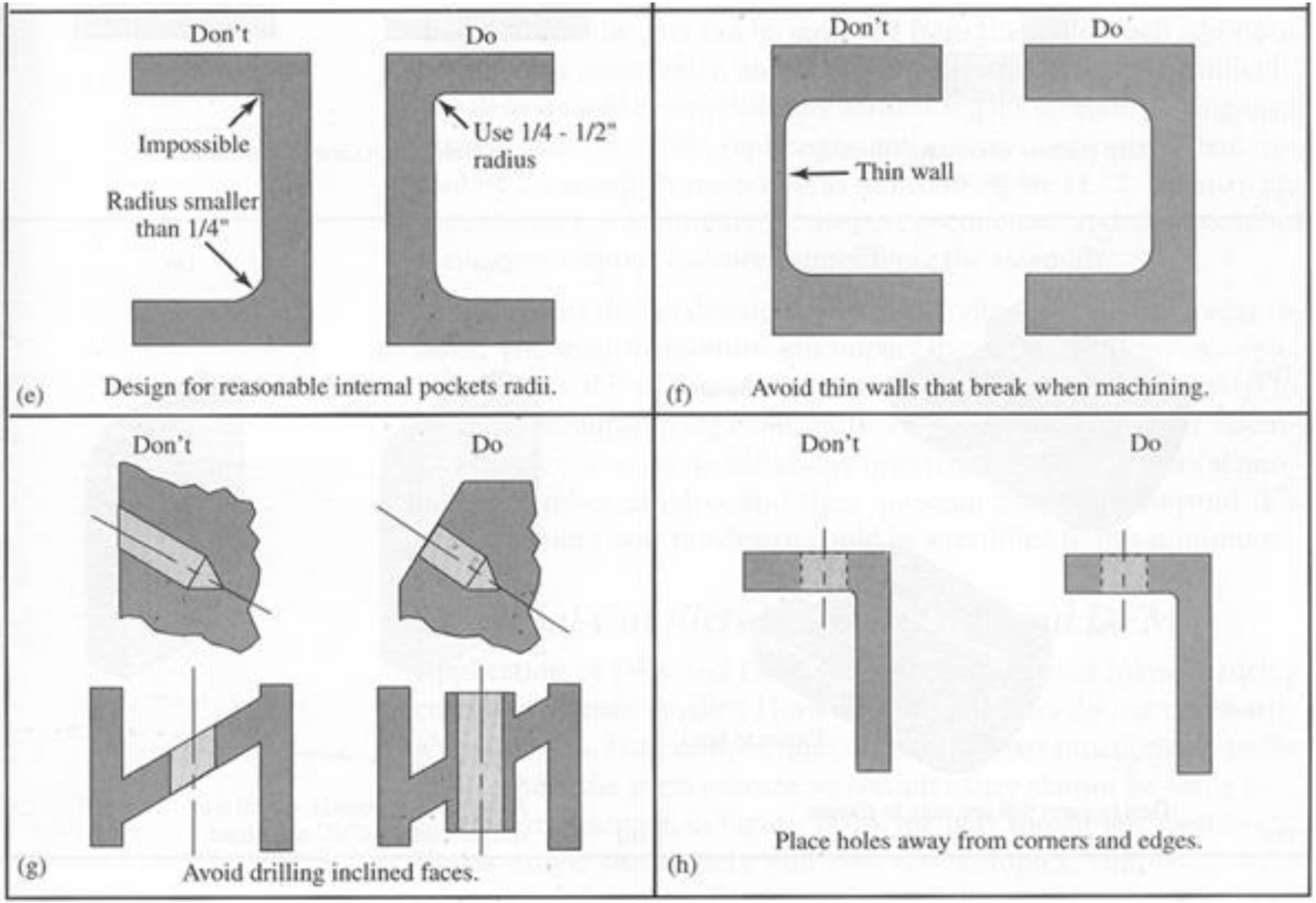
Productive hour costs

MACHINE, PROCESS, OR BENCH	PORTLAND & WASHINGTON	ST. LOUIS & ILLINOIS	SAN FRANCISCO & OAKLAND	TULSA	WORCESTER
3.10 Tube bending	11.58	12.03	12.13	10.46	11.84
3.11 Ironworker	11.58	12.03	12.13	10.46	11.84
4.1 Marking	9.04	10.17	11.79	9.70	10.70
4.2 Screen printing	11.74	10.17	12.45	10.75	10.91
4.3 Laser marking	9.04	10.17	11.79	9.70	10.70
4.4 Pad printing	11.74	10.17	12.45	10.75	10.91
5.1 Forging	12.76	13.89	15.80	12.75	13.53
5.2 Explosive forging	12.99	13.89	15.80	12.92	13.68
6.1 Engine lathe	12.99	13.89	15.80	13.41	13.65
6.2 Turret lathe	12.99	13.89	15.80	12.92	13.68
6.3 Vertical turret lathe	12.99	13.89	15.80	12.92	13.68
6.4 Numerical controlled turning lathe	13.06	13.62	15.80	12.76	13.14
6.5 Numerical controlled chucking lathe	13.06	13.62	15.80	12.76	13.14
6.6 Single spindle automatic screw machine	12.76	13.89	15.80	12.75	13.53
6.7 Multispindle automatic screw machine	12.76	13.89	15.80	12.75	13.53
7.1 Milling machine setup	13.06	14.19	15.80	12.94	13.49
7.2 Knee and column milling	13.06	14.19	15.80	12.94	13.49
7.3 Bed milling	12.11	13.08	13.95	11.09	10.78
7.4 Vertical-spindle ram-type milling	13.06	14.19	15.80	12.94	13.49

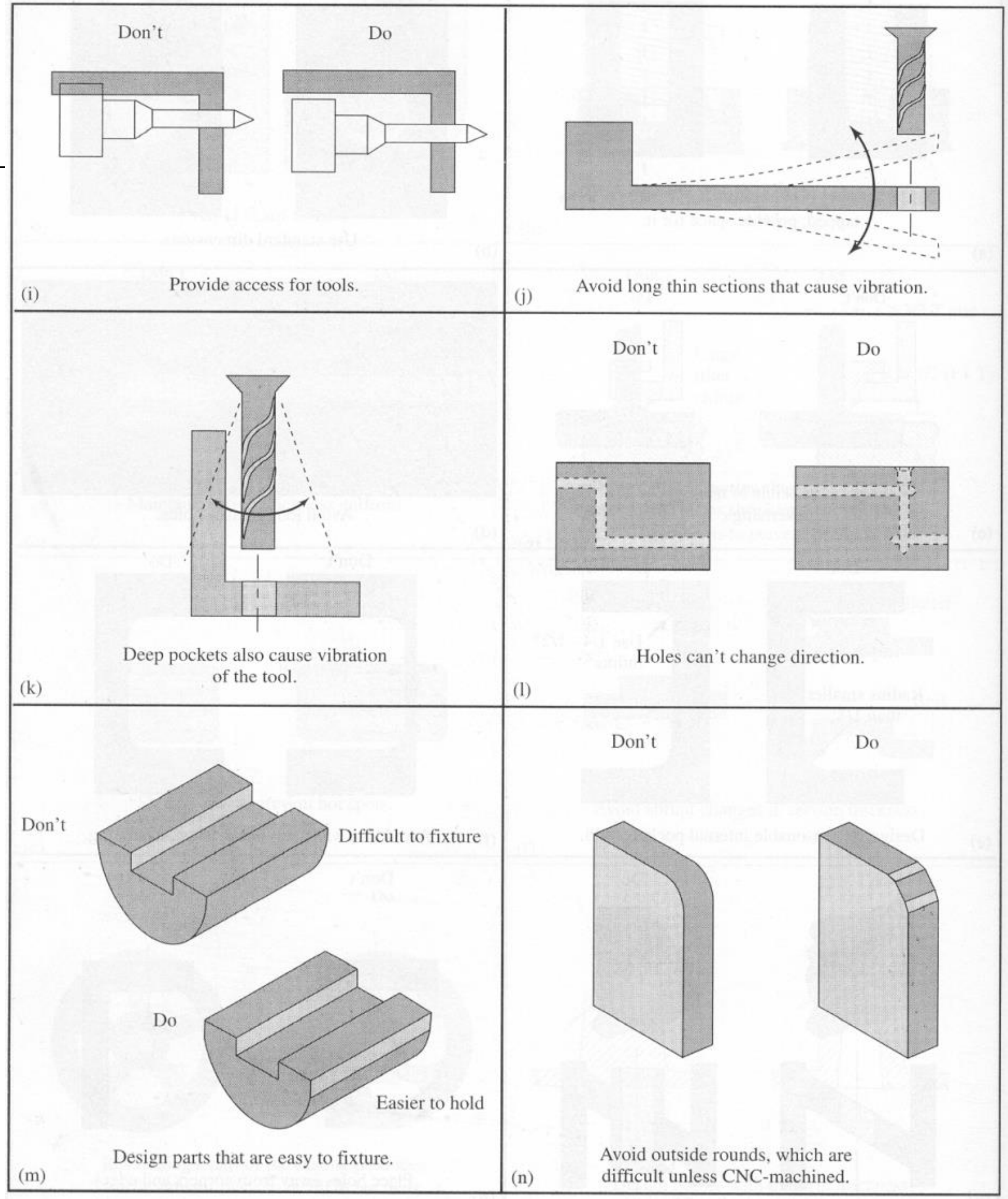
DFM: machining



DFM: machining (2)



DFM: machining (3)



Including deburring cost

(Dornfeld *et al.* 2001)

$$C_{deburring} = \frac{C_T}{N_P} + C_L(1 + D_o)t_{deburring}$$

where:

C_T: Cost of deburring tool including equipment and tool replacement

N_P: Number of parts deburred with the tool

C_L: Labor costs for deburring

D_0: Overhead costs for deburring

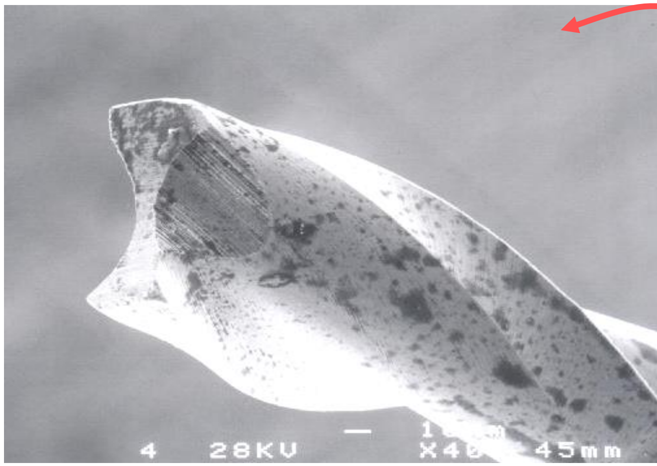
$t_{deburring}$: Time for deburring the part

$$C_{burr-min} = C_{burr-min-tool} + C_{burr-min-machining}$$

$$C_{burr-removal} = minimum\{C_{deburring}, C_{burr-min}\}$$

$$C_{total} = C_{part} + C_{burr-removal}$$

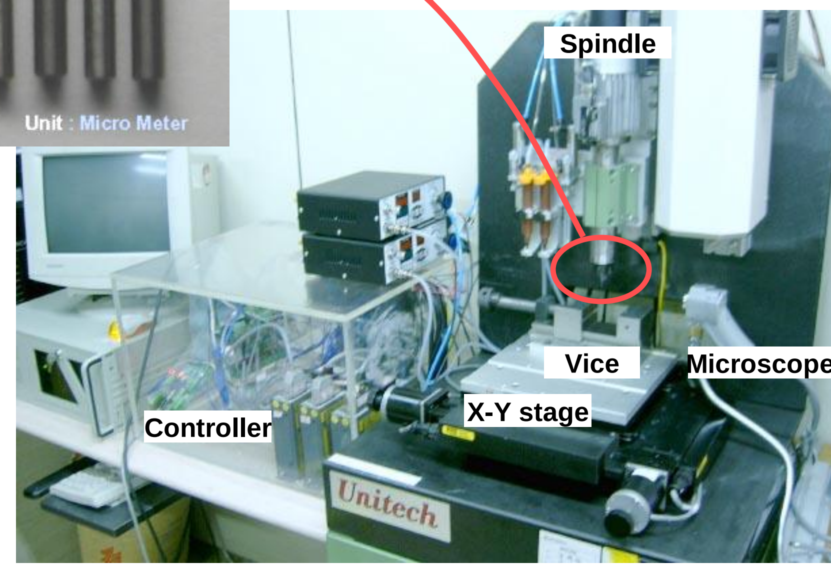
Micro Machining System



Tip of 127μm endmill

Micro endmills

- **Positional resolution : 1 ㎛**
- **Tool diameter : 50 ㎛~1000 ㎛**
- **High speed : 200,000 RPM**
- **Tool material : HSS & TiN coating**
- **Work piece : Metal, Polymer, etc**

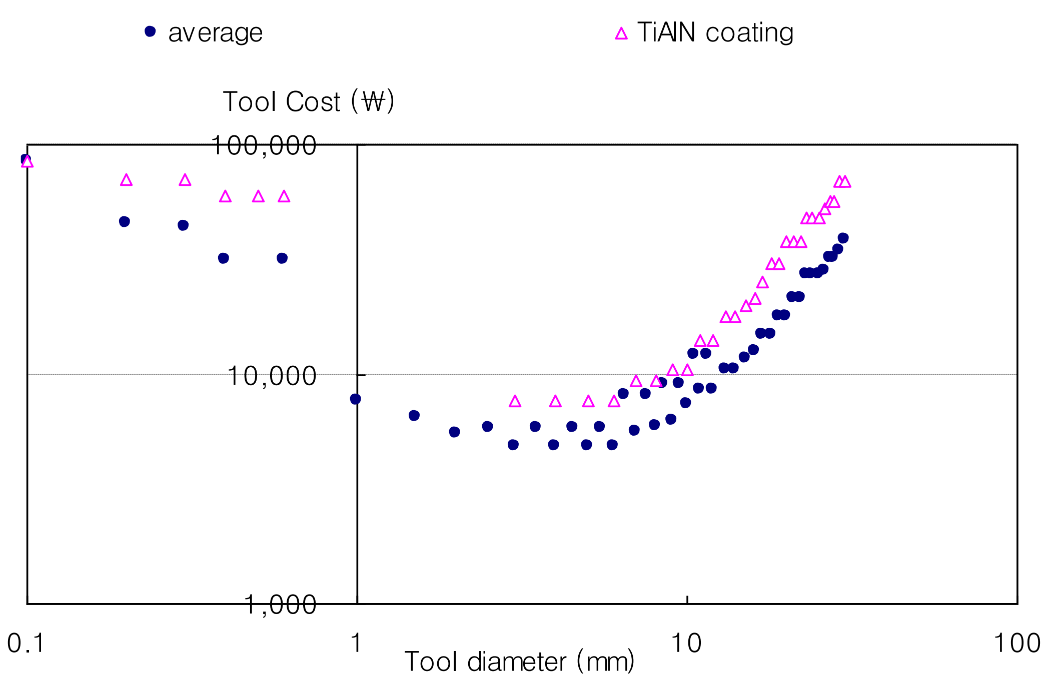


Precision stage

DFM: micro milling

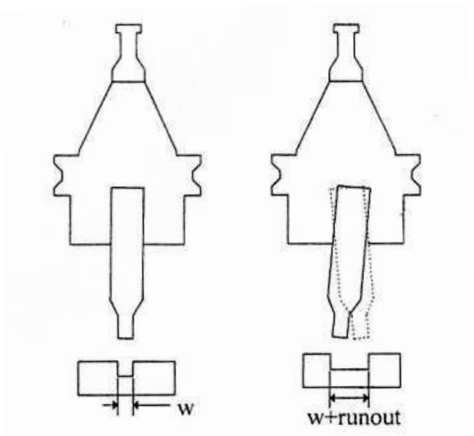
- 10 mm endmill
  - 10 μm stage error
  - 0.1% for slot cutting
- 100 μm endmill
  - 10μm stage error
  - 10% for slot cutting
- Cost structure of micro machining is different from that of macro machining.
  - Tool cost dominates

A tip is not exact edge in micro scale

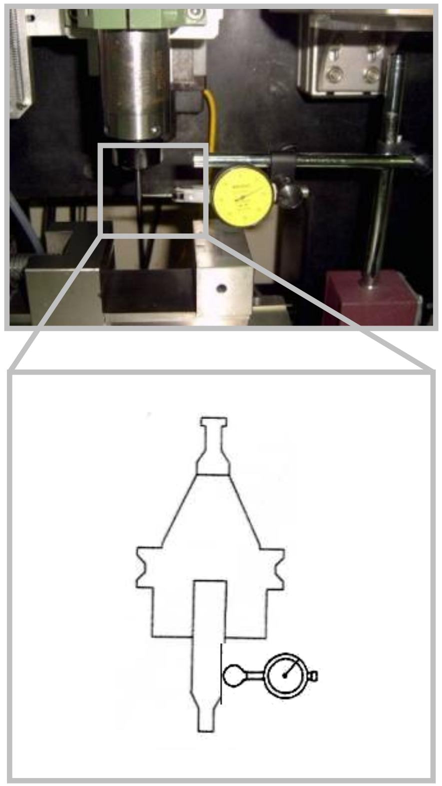


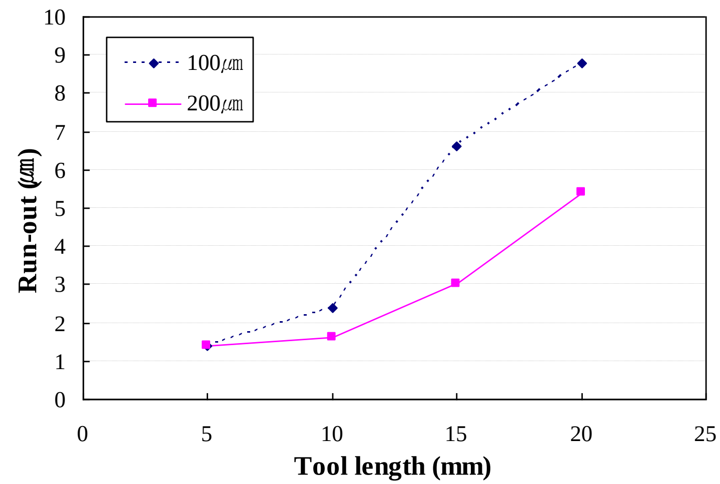
Spindle run-out

- 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 >



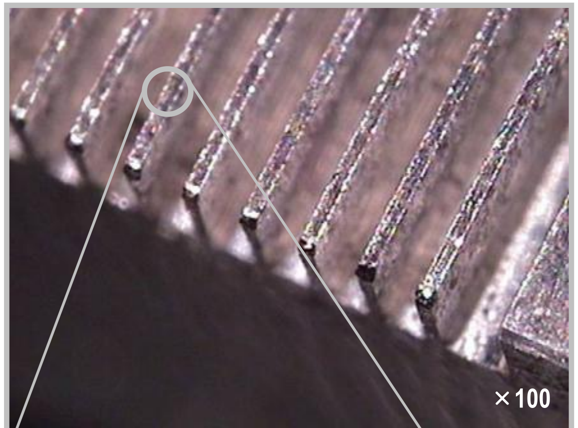


< Result of Total Indicator Reading (TIR) >

< Total Indicator Reading (TIR) Measurement >

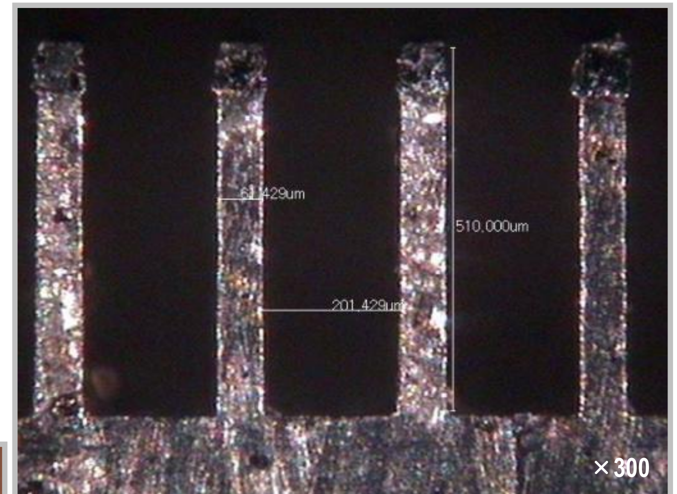
Micro walls

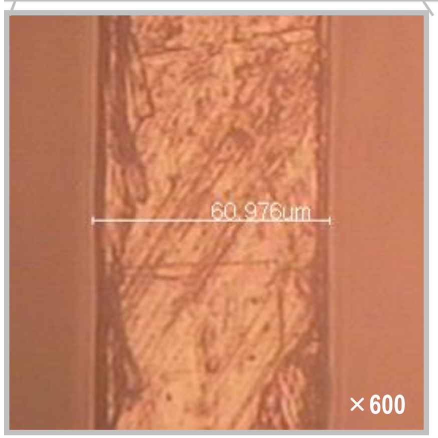
- Barrier ribs

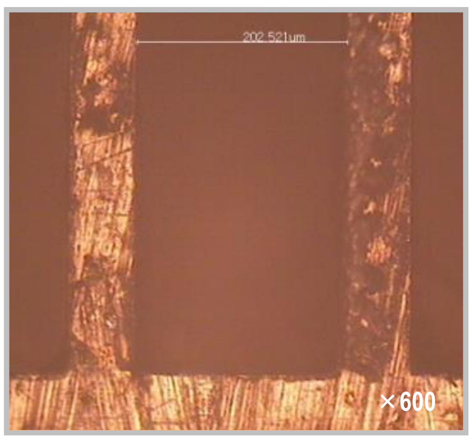


Rib width: 60㎛
Height: 500 ㎛
Tool: φ200 ㎛

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

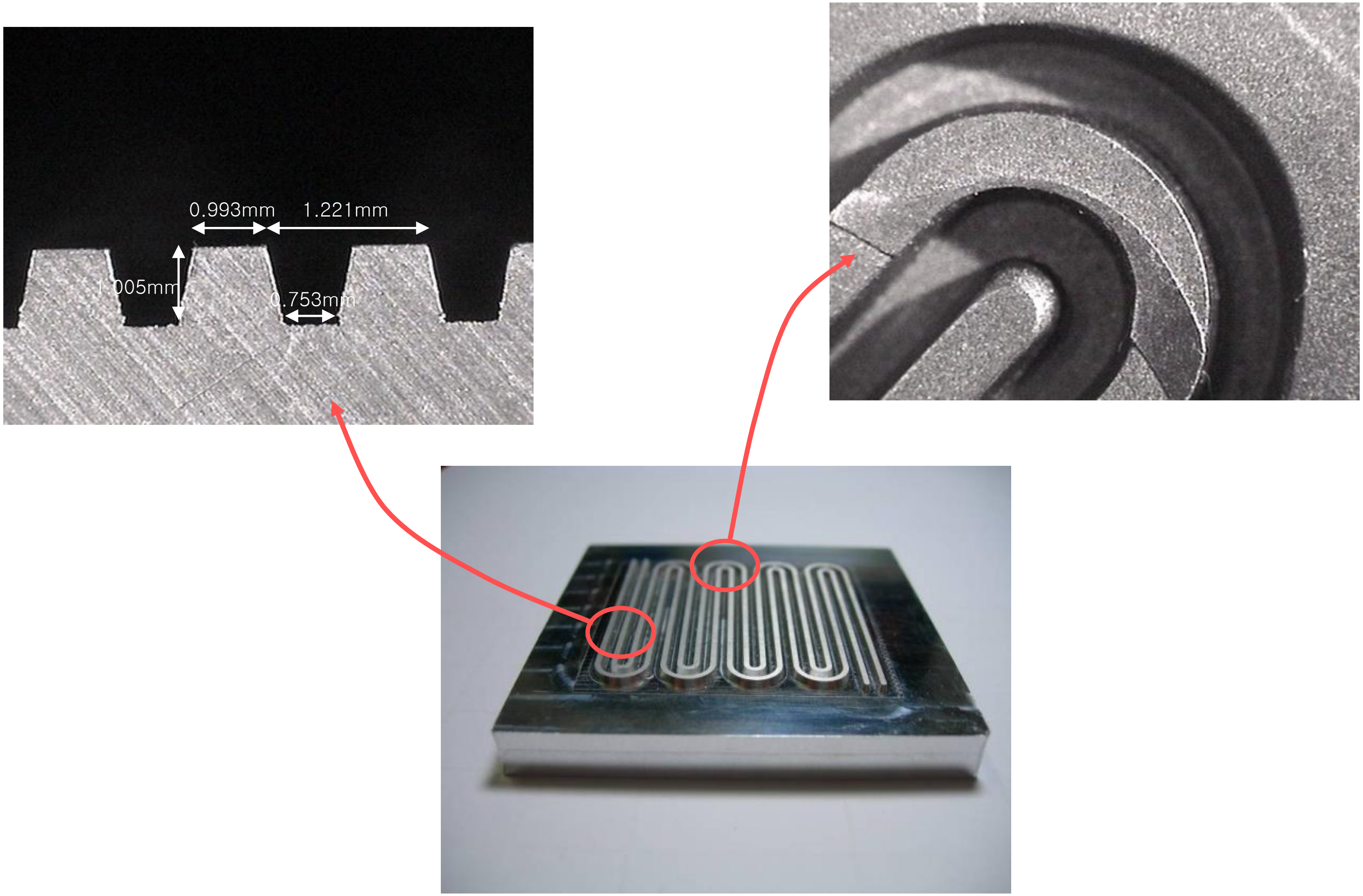




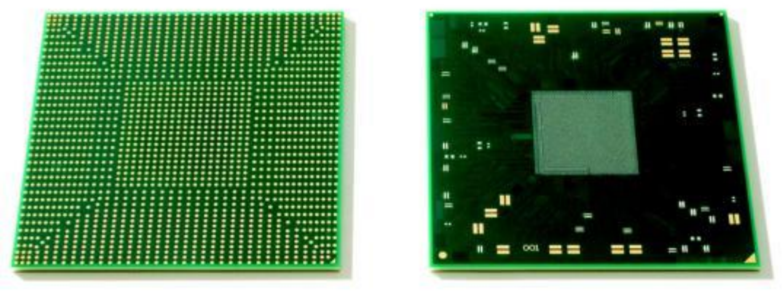


Geometric error: ~ 5 ㎛ (including error of microscope)

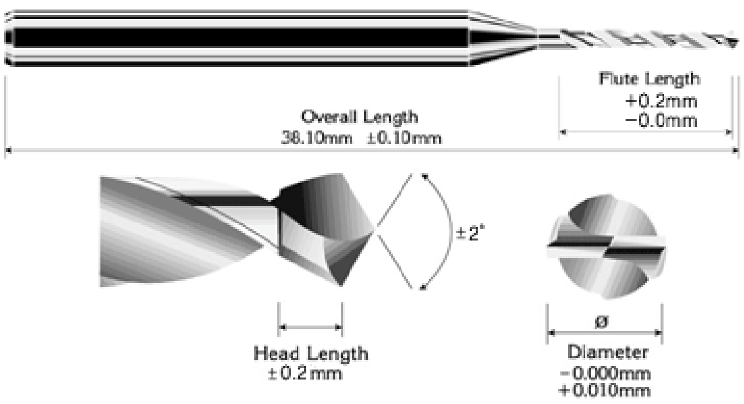
Micro machined mold



Micro drilling and milling

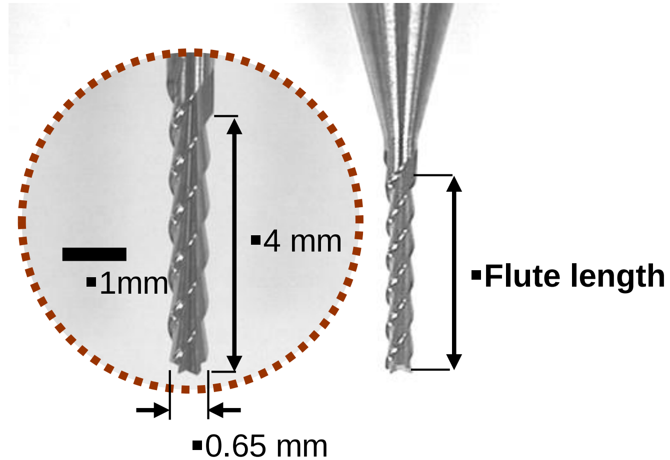


PCBs for semiconductor



Shape of Micro drill

PCBs for cell phone



PCB machining micro end mill

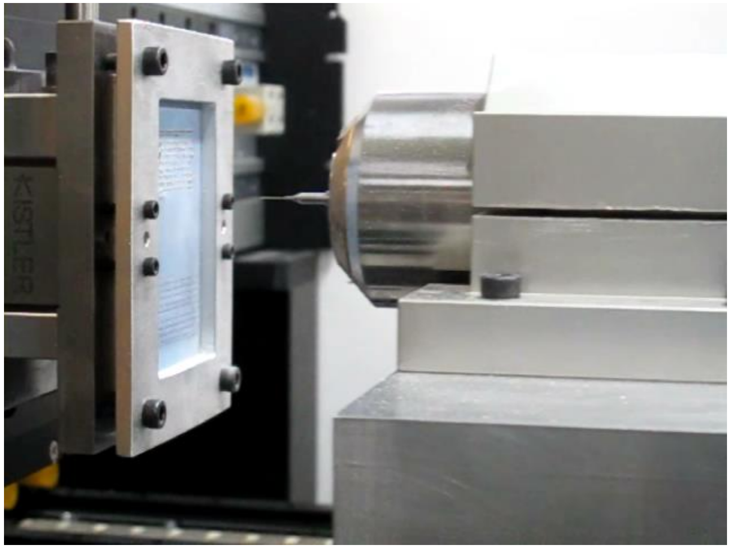
Energy Consumption Model for Micro drilling

Measuring and decomposition of energy consumption of machine tool

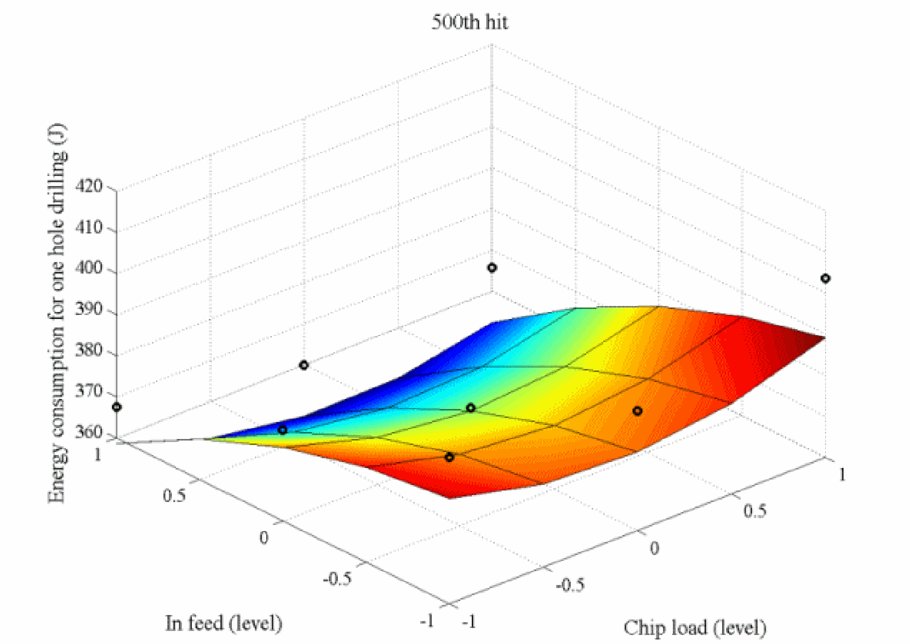
Consists of P_{BASIC} ($P_{PERIPHERAL}$), P_{STAGE}, $P_{SPINDLE}$, $P_{MACHINING}$

$$P_{TOTAL} = P_{BASIC} + P_{SPINDLE} + P_{STAGE} + P_{MACHINING}$$
$$= P_{BASIC} + (a_1 V^{b1} + c_1) + (a_2 f^{b2} + c_2) + (T \times f + M \times V)$$

(H.S. Yoon, J.S. Moon, M.Q. Pham, G.B. Lee, and S.H. Ahn, paper accepted)



PCB drilling configurations



Energy Control Chart

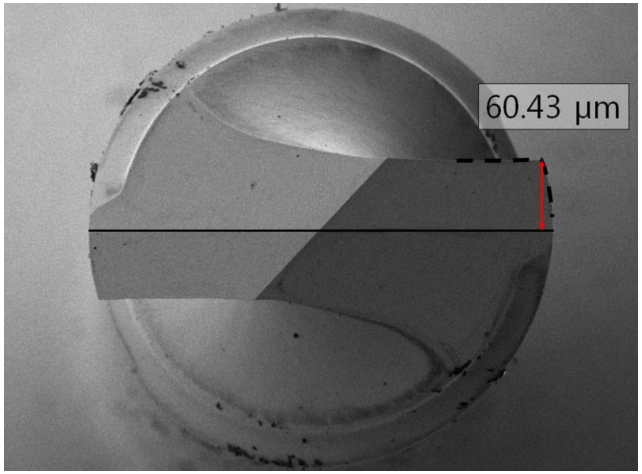
Manufacturing Cost Model for Micro drilling

Considering tool wear

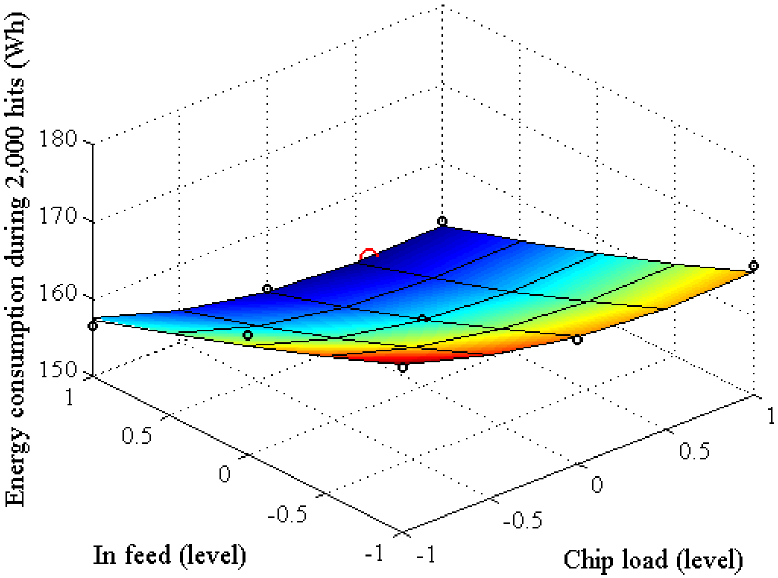
Consists of C_{TOOL}, C_{ENERGY}, $C_{PERIPHERAL}$

$$C_{TOTAL} = n/L \times (c^{1/\gamma} / (V D^{\alpha} f^{\beta})^{1/\gamma}) \times C_{TOOL} + t \times (P_{BASIC} + (a_1 V^{b1} + c_1) + (a_2 f^{b2} + c_2)) \times C_{ENERGY} + C_{PERIPHERAL}$$

(H.S. Yoon, J.S. Moon, M.Q. Pham, G.B. Lee, and S.H. Ahn, paper accepted)

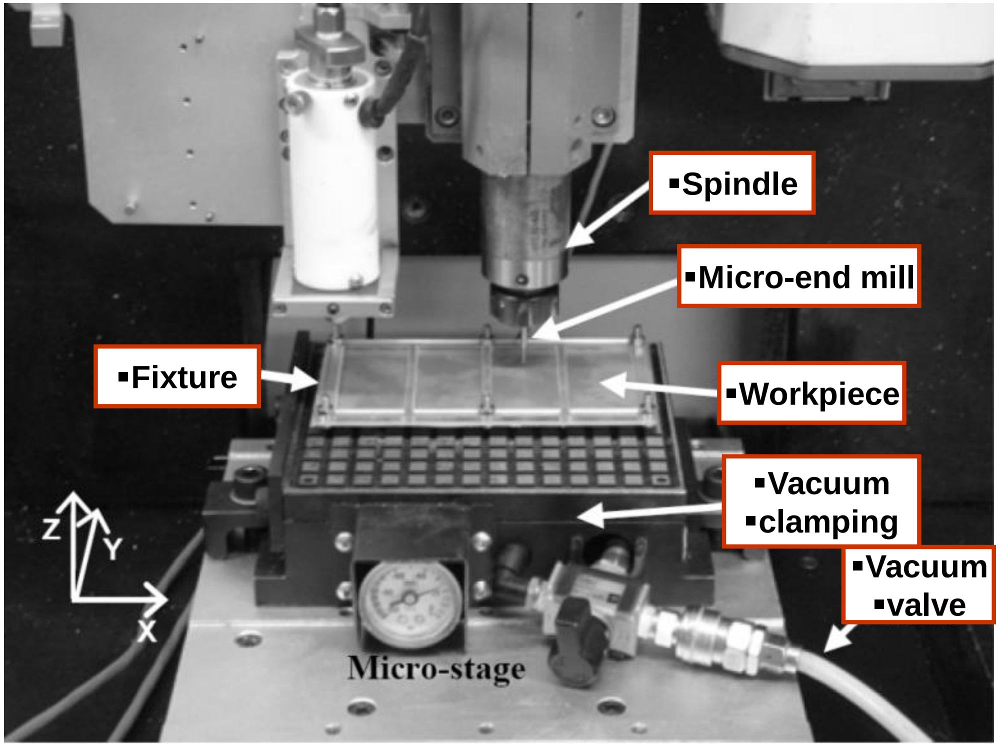


Schematic of tool tip wear



Integrated energy consumption during 0~2,000 holes **(Integral)**

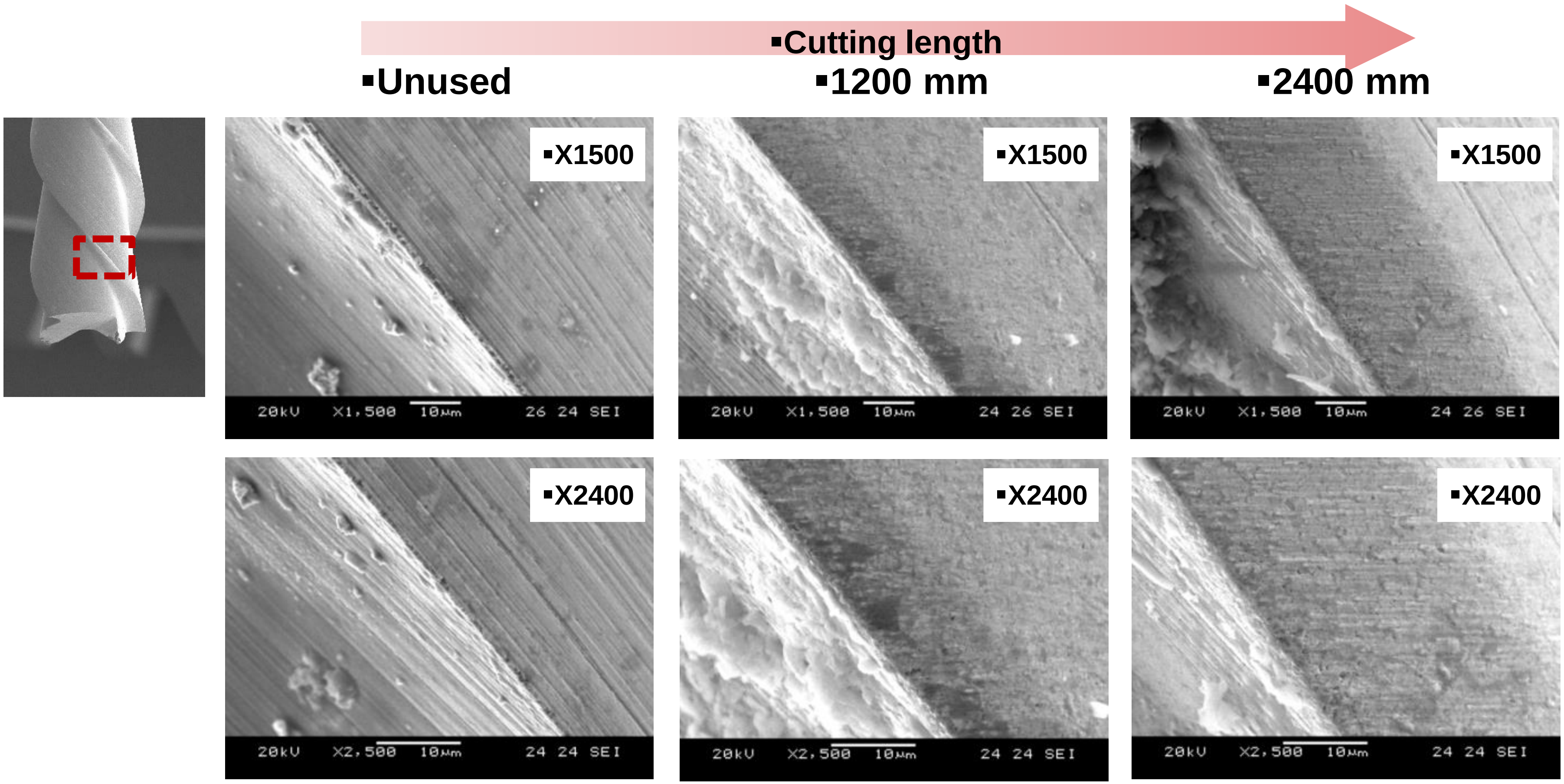
DFM: end mill wear estimation



- Milling condition
  - Cutting speed 60 m/min
  - Feed rate 0.003 m/min

- High speed spindle (HEN-40 ,Fisher, Swiss)
  - Max. 42,000 rpm, Run out <2 μm (TIR)
- Precision micro-stage(404150XR , PAKER)
  - resolution 1 μm
- Programmable multi-axis Controller (PMAC2, Delta Tau Data Systems Inc.)

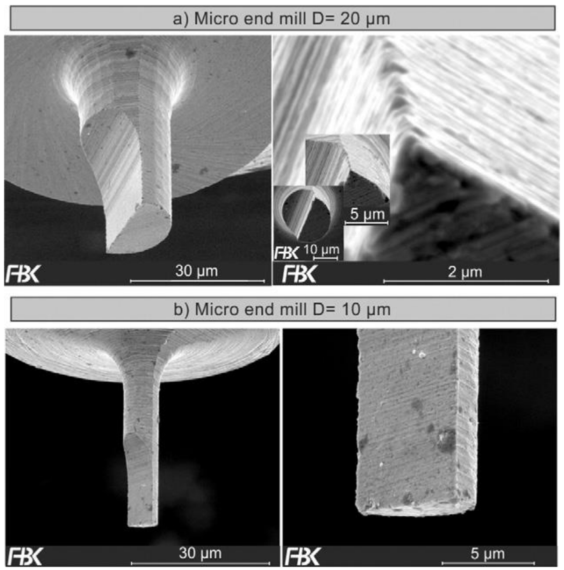
End mill wear



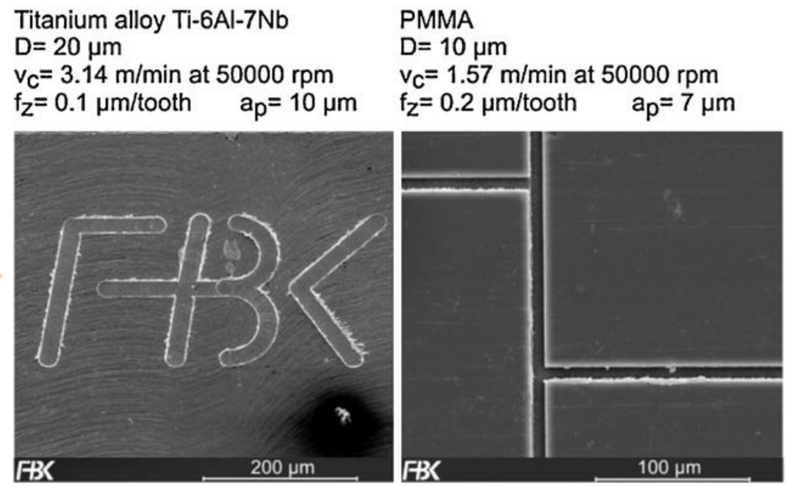
As the milling distance was increased, the wear at cutting blade was greater

REF) Park, J. B., Wie, K. H., Park, J. S., and Ahn, S. H.*, 2009, "Evaluation of machinability in the micro end milling of printed circuit boards," Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture (England), Vol. 223, No. 11, pp. 1465-1474

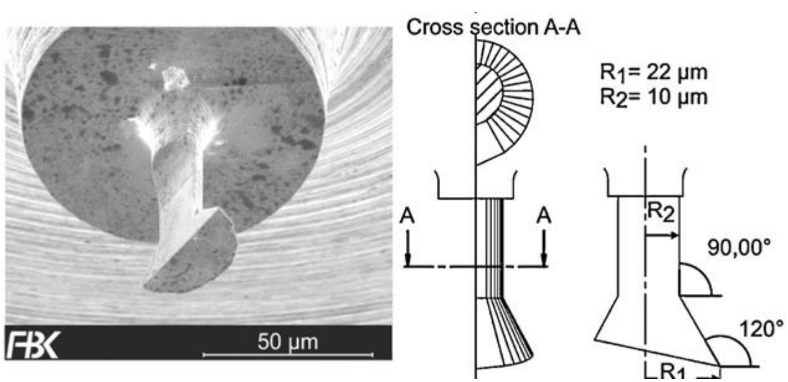
Ultra-small Micro End Mill



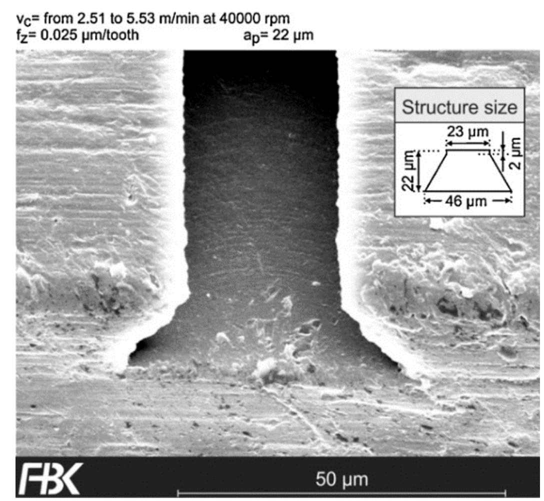
Micro end mill



SEM pictures of slot milled structures



Micro profile end mill



Micro milled undercut-dovetail structure in PMMA.

REF) Aurich, Jan. C.*, Reichenbach, Ingo G., Schuler, M. Guido, 2012, "Manufacture and application of ultra-small micro end mills," CIPR Annals – Manufacturing Technology, Vol. 61, pp. 83-86

Generation of Ion Beam Path: Description

Generation of ion beam path for the improvement of precision and accuracy: roundness, concentricity and precision of dimension

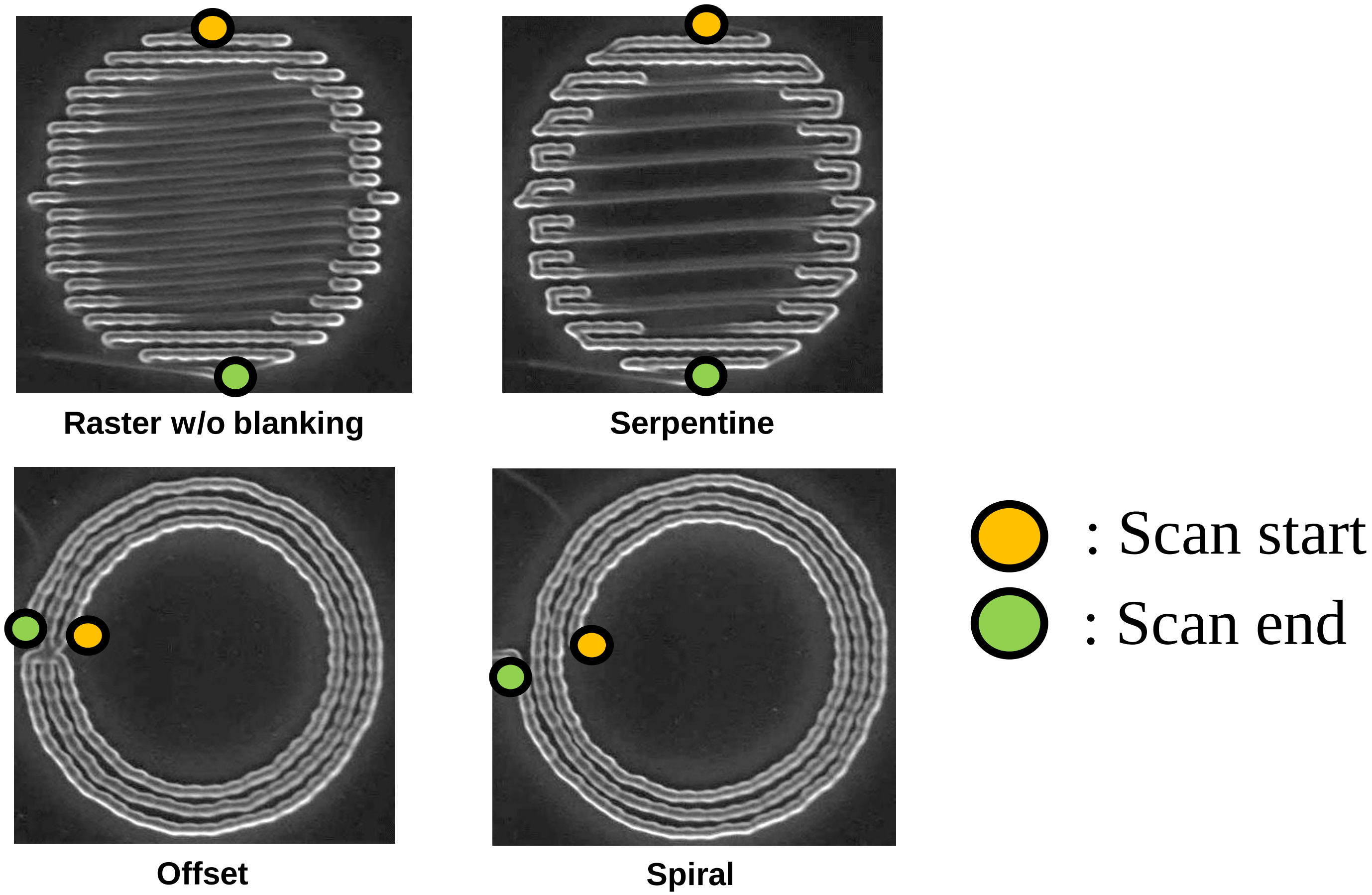
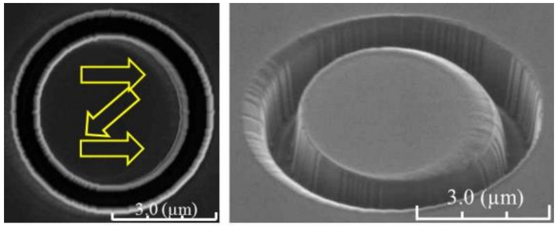


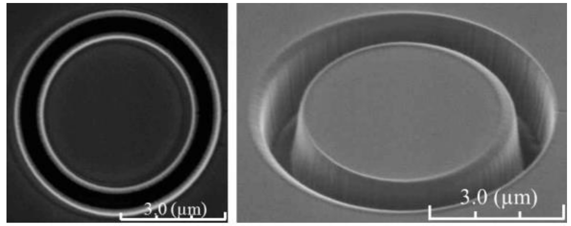
Illustration of ion beam paths: beam traces by different ion beam paths using FIB-CVD

Generation of Ion Beam Path: Experimental Results

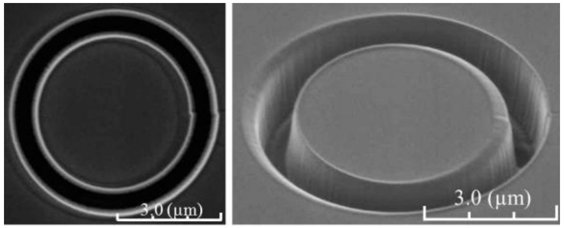
Raster scan



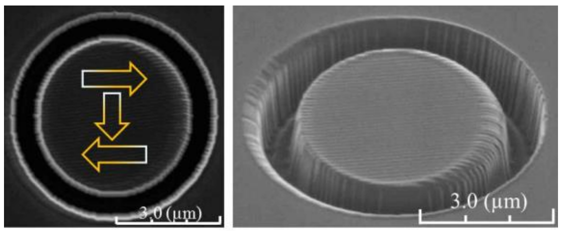
Offset (in) scan



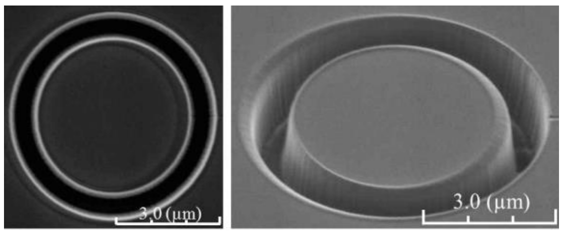
Spiral (in) scan



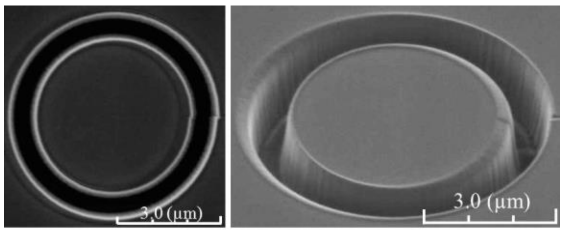
Serpentine scan

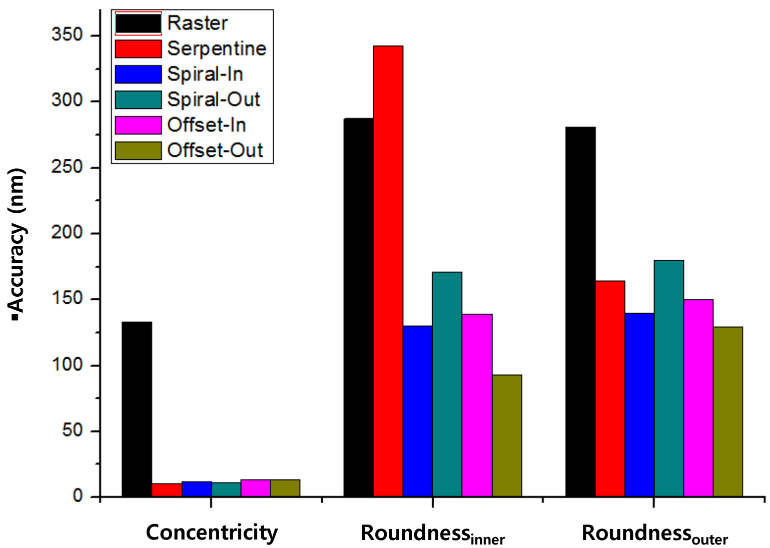


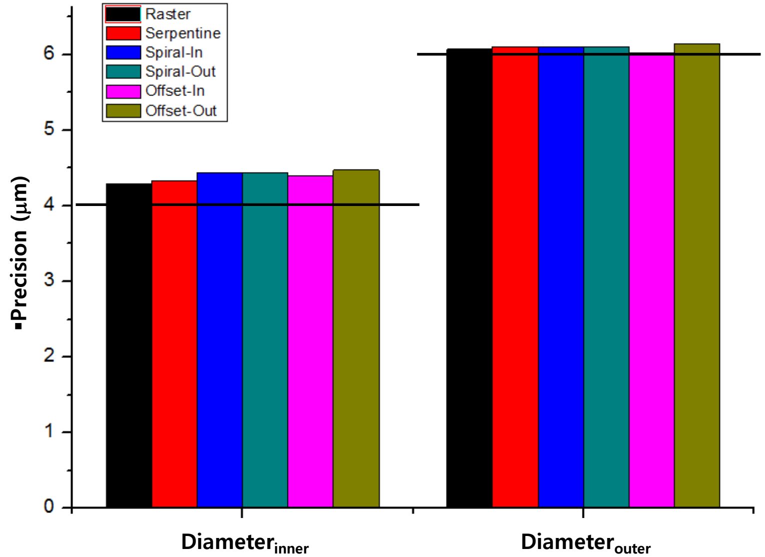
Offset (out) scan



Spiral (out) scan





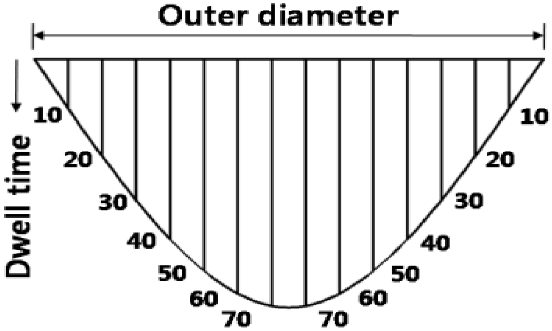


Accuracies and precision of 2.5D circular pocket

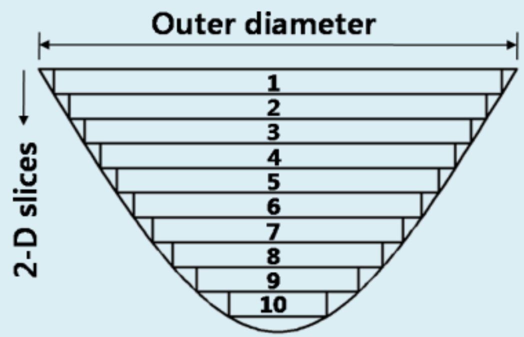
Fabrication of 3D microstructure by FIB

- Characteristics of Continuous Slicing Method
  - Reduction of material redeposition by spiral scan
  - Angle dependent cutting enhancement

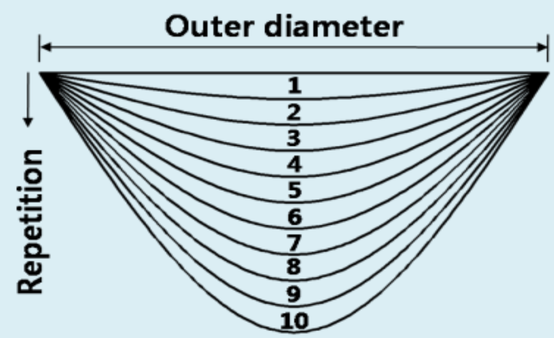
Variable pixel dwell time method

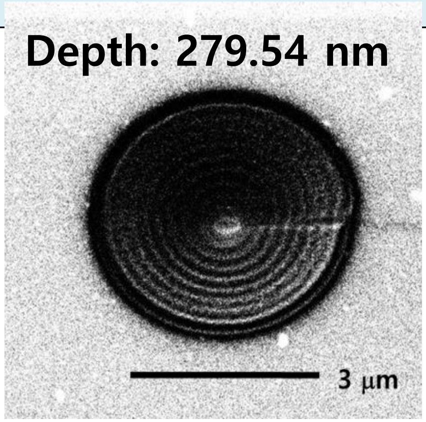


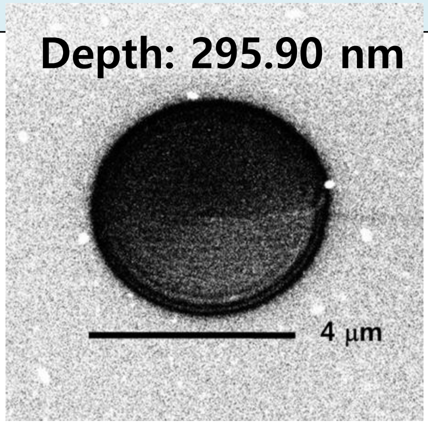
Slice-by-slice method



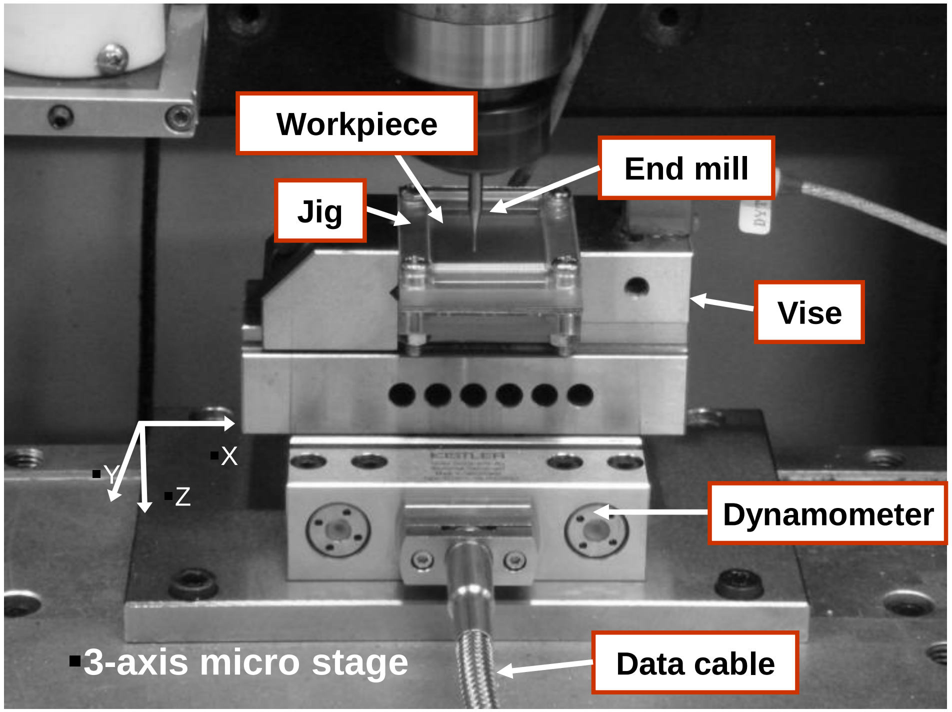
Continuous slicing method

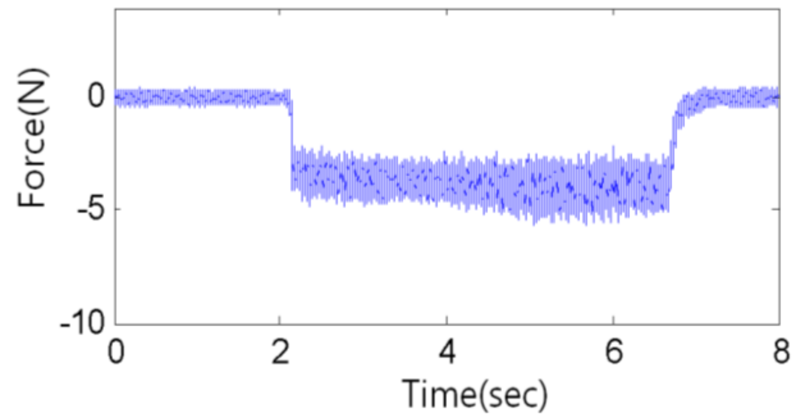


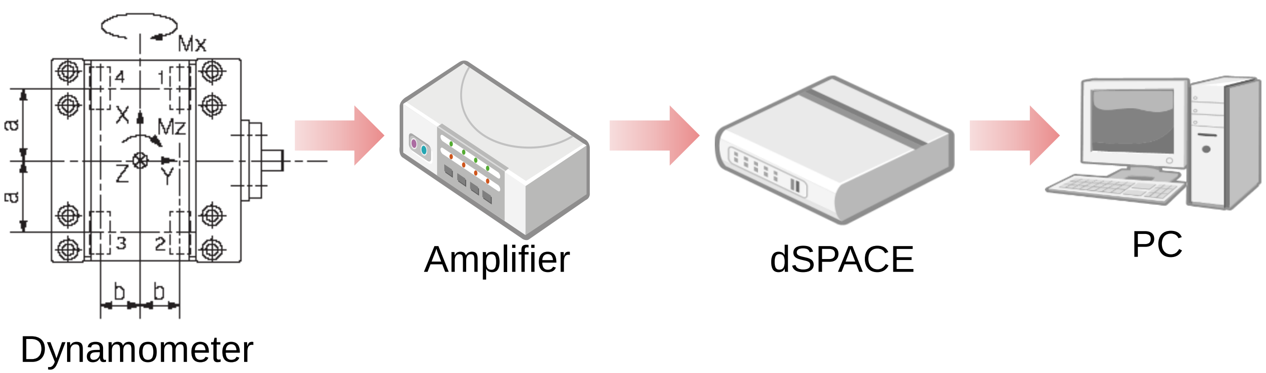


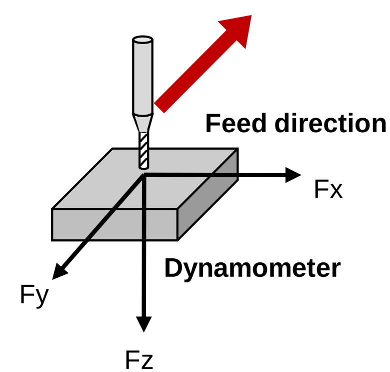


DFM: cutting force estimation

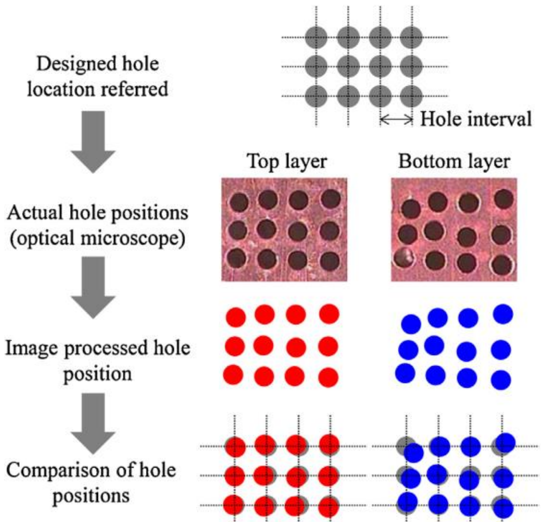








Backstitch tool path on micro-drilling



Method of measuring the positioning errors for the drilled holes

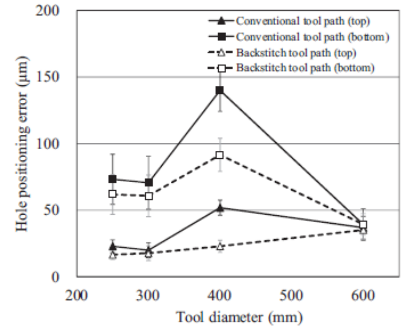


Fig. 6. Effect of the tool diameter on the hole positioning error. The hole interval was twice the tool diameter.

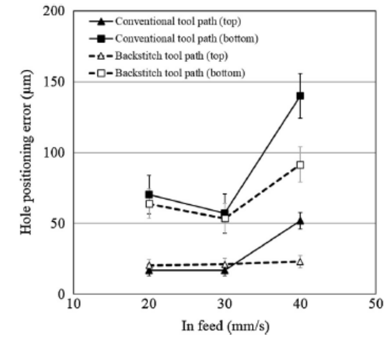


Fig. 9. Effect of the in-feed rate on the hole positioning error (tool diameter: 400 μm, spindle speed: 90,000 r/min).

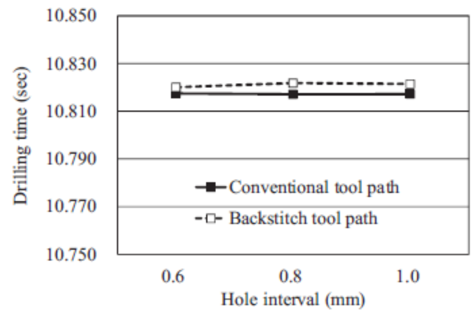


Fig. 11. Drilling time for ten holes.

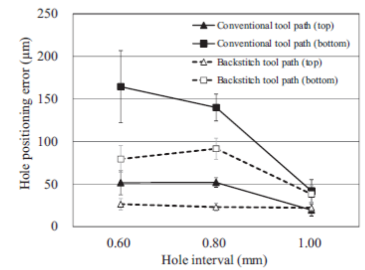
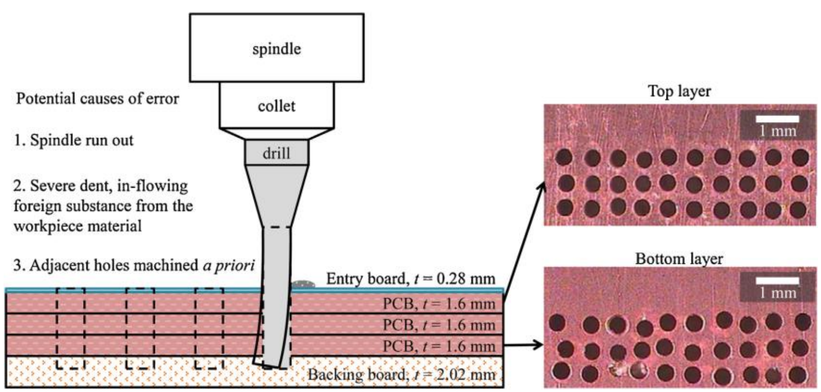
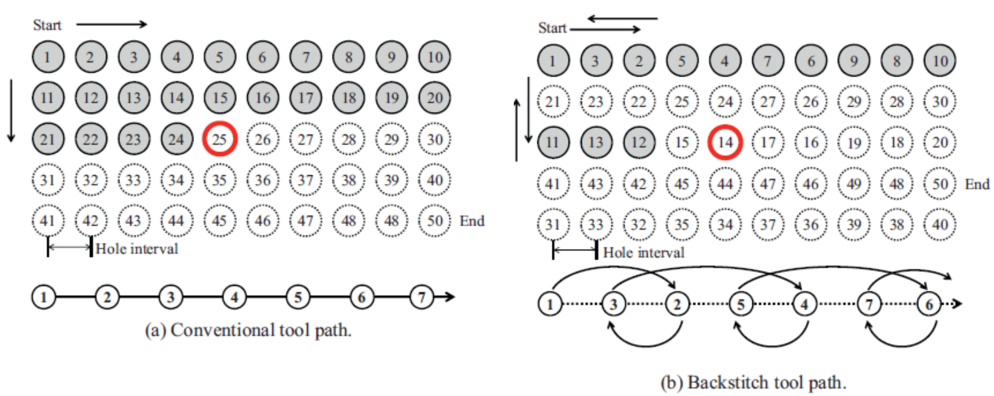


Fig. 8. Effect of the hole interval on the hole positioning error (tool diameter: 400 μm, spindle speed: 90,000 r/min, in-feed rate: 40 mm/s).



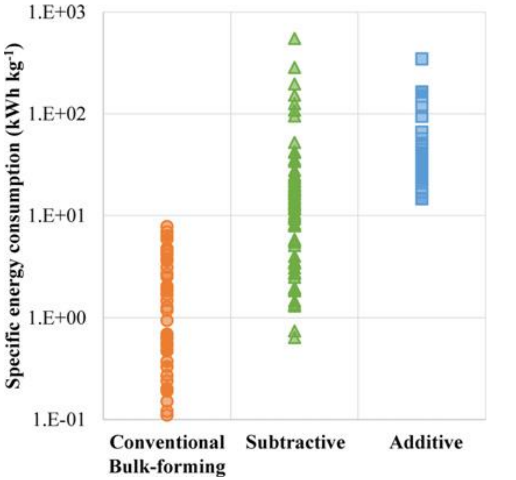
Hole misalignment



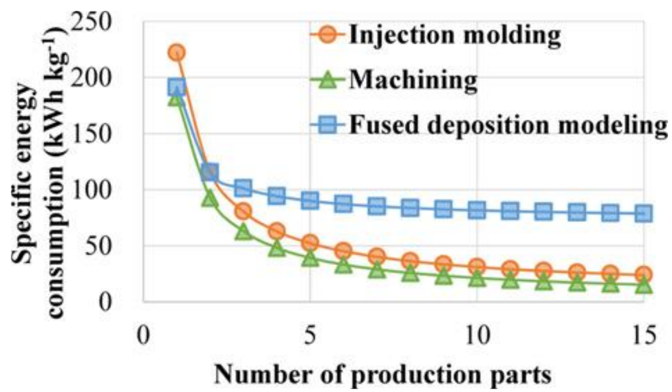
Comparison of the backstitch tool path with a conventional tool path

Moon, J. S., Yoon, H. S., Lee, G. B., and Ahn, S. H., 2014, "Effect of Backstitch Tool Path on Micro-drilling for Printed Circuit Board," Precision Engineering - Journal of the International Societies for Precision Engineering and Nanotechnology

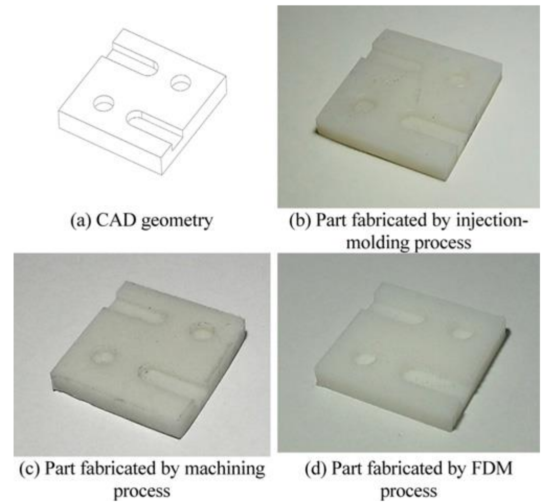
A Comparison of Energy Consumption in Bulk Forming, Subtractive, and Additive Processes



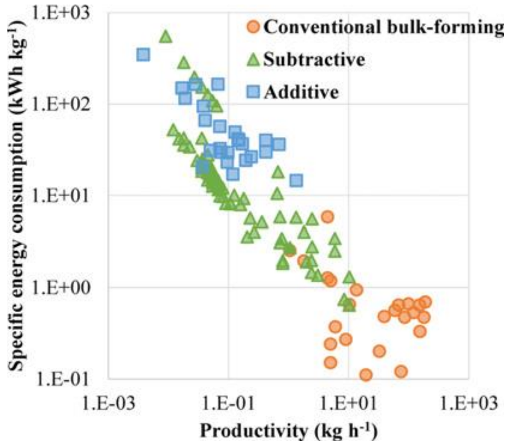
Specific Energy Consumption (SEC) for the three categories of manufacturing process



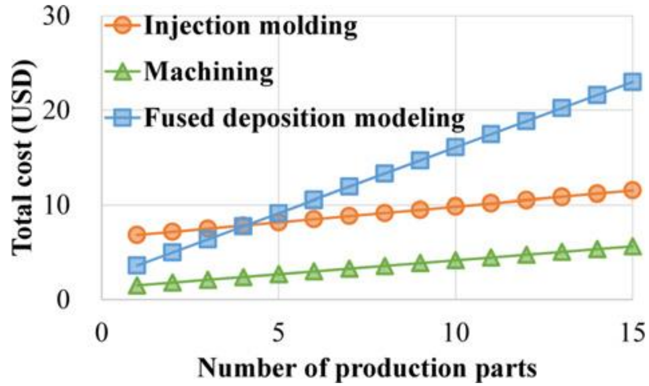
SEC in terms of number of parts



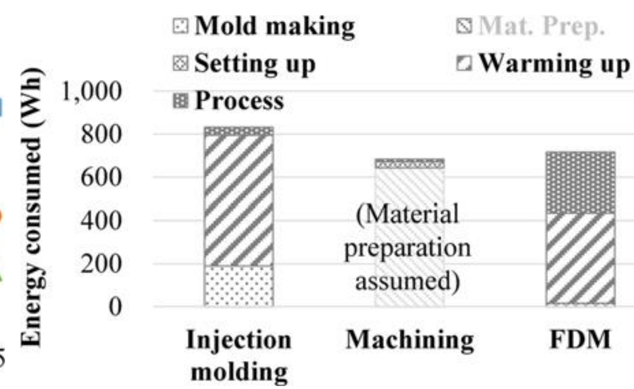
Test geometry



SEC versus productivity



Production costs



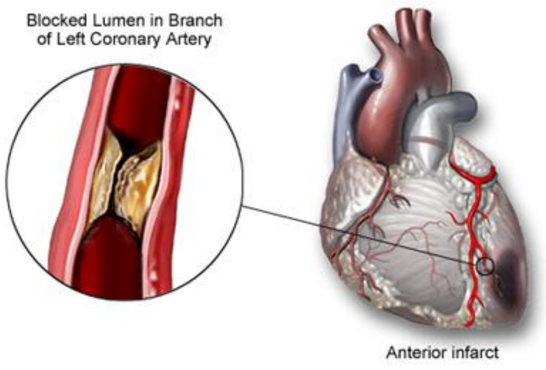
Energy consumption results for the case studies

Yoon, H. S., Lee, J. Y., Kim, H. S., Kim, M. S., Kim, E. S., Shin, Y.J., Chu, W. S., and Ahn, S. H., 2014, "A Comparison of Energy Consumption in Bulk Forming, Subtractive, and Additiv Processes: Review and Case Study," International Journal of Precision Engineering and Manufacturing - Green Technology, IJPEM - GT

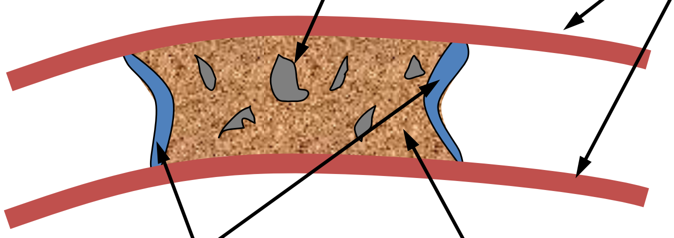
Applications of Subtractive Processes

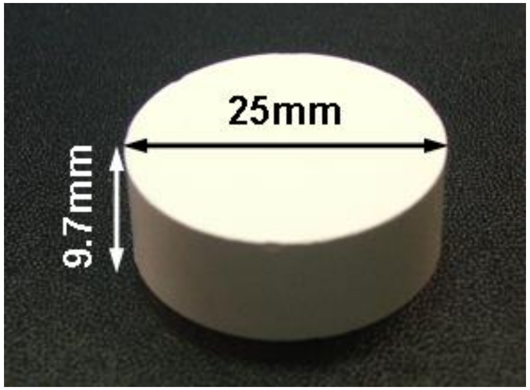
DFM: Micro drilling for biomedical application

- Chronic Total Occlusion (CTO)
  - Complete obstructions or blockages of an artery
  - About 50% of severe CVD patients having CTO
    (*Christofferson et al., Am J Cardiol, 2005*)
  - Success rates of less than 70% for CTO treatment
    (*Segev and Strauss, J Interven Cardiol, 2004*)



▪***2008 Nucleus Medical Art, Inc.***

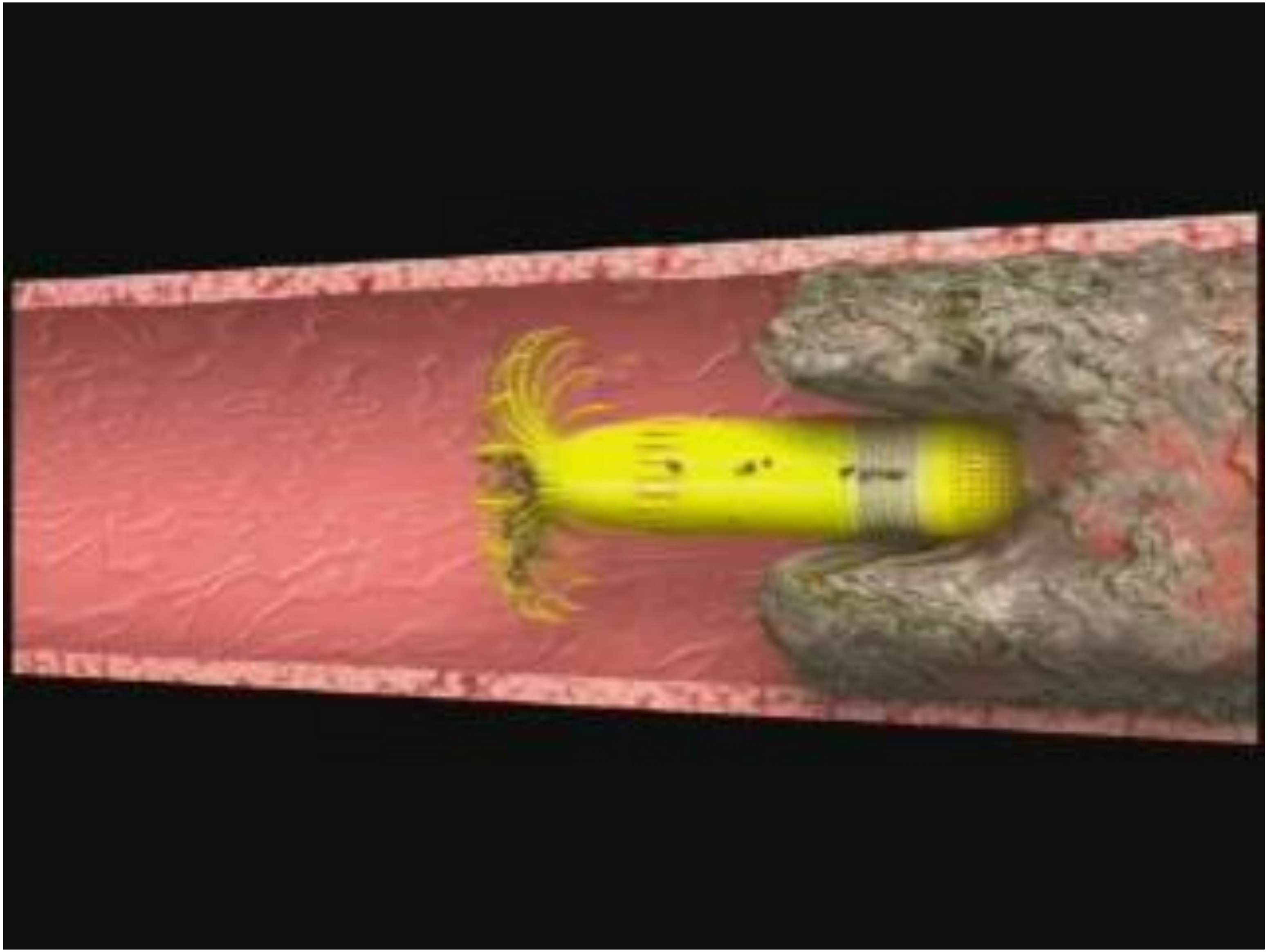




Porous hydroxyapatite

Micro drilling test using a porus hydroxyapatite instead of CTO material

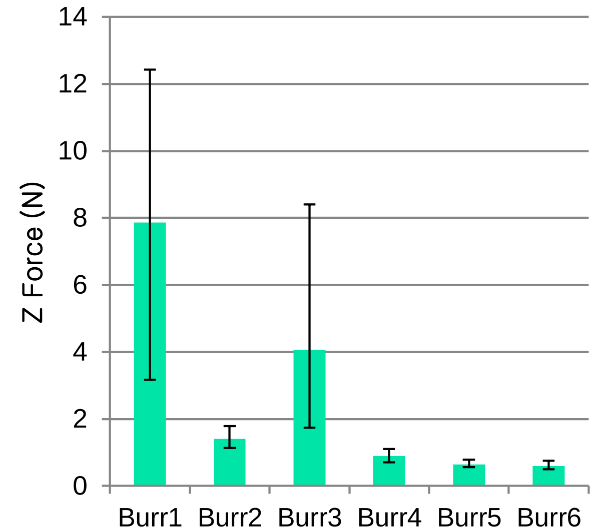
Blood Vessel Surgery Robot



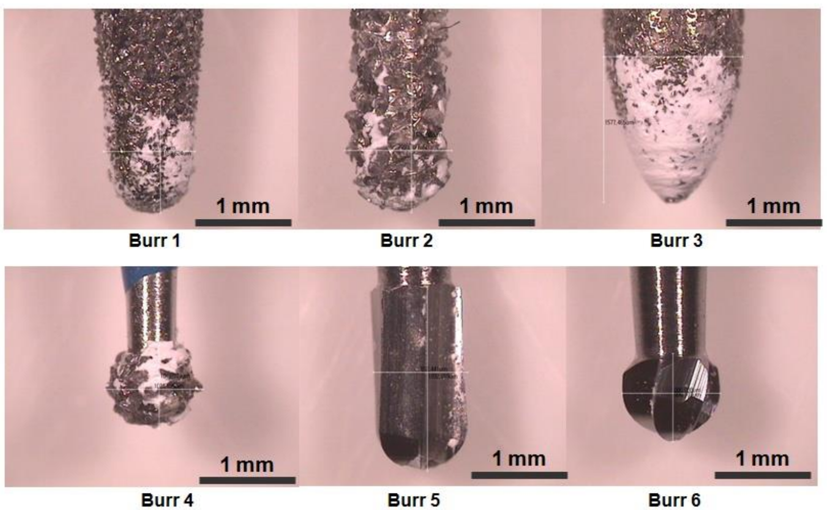
DFM: force, torque, and wear

- Tests for 6 different types of burrs

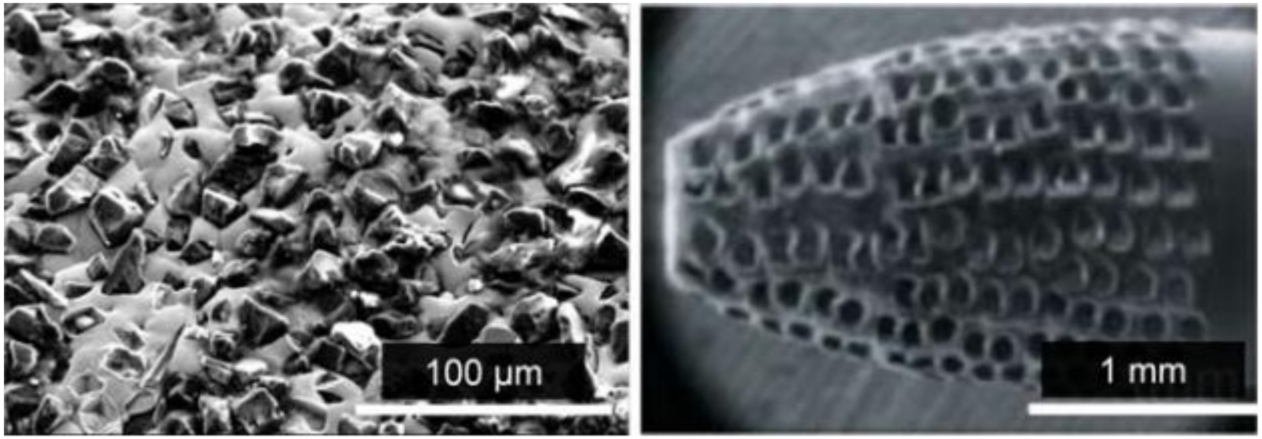
▪Burr 1 ▪Burr 2 ▪Burr 3 ▪Burr 4 ▪Burr 5 ▪Burr 6



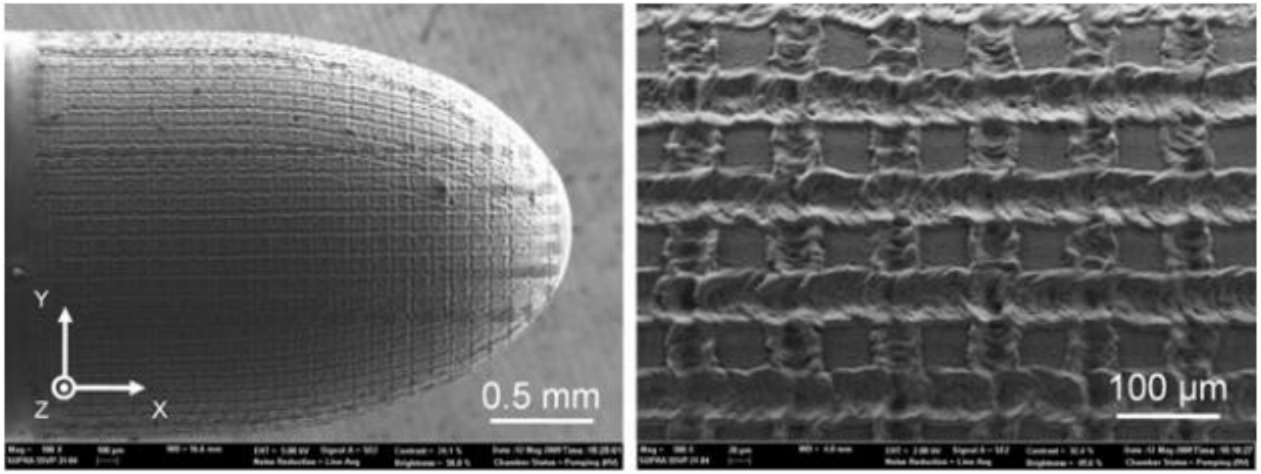
- Drilling speed : 120,000 ± 30,000 RPM
- Pressure : 3 kgf/cm^2
- Flow rate : 15 Liter/min
- Feed : 2 mm/sec
- Max. depth : 3 mm
- Repeat number : 3 times
- Test condition : No water
- Test specimen : porous hydroxyapatite



Surface of the burrs after drilling test



SEM images of the Rotablator burr (left) and a burr with greater-like microblades (right) (Nakao et al. 2005)

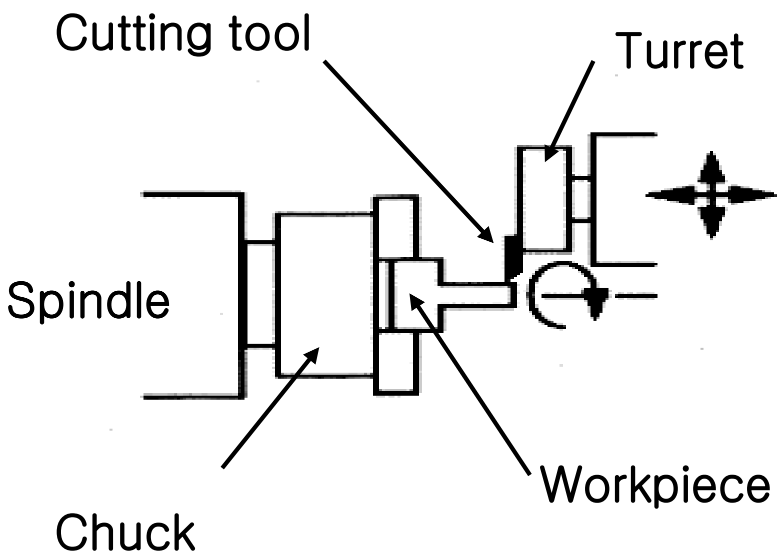


FESEM images of the laser beam-engraved tool surface

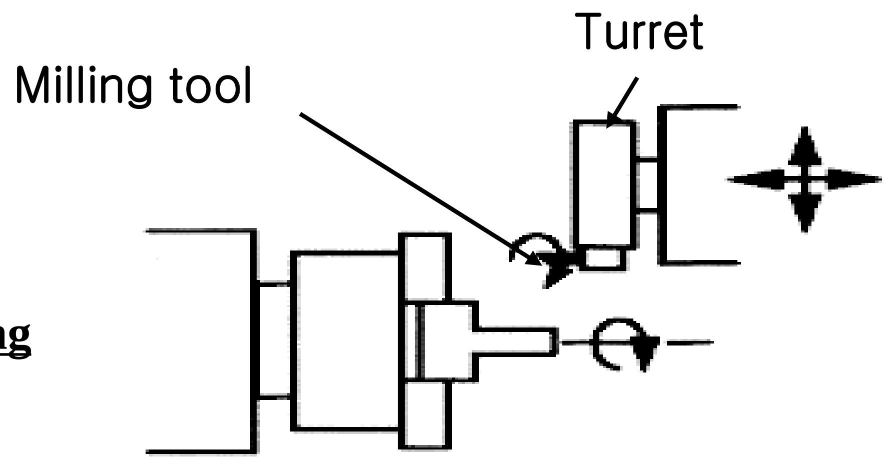
REF) Kim, M. H., Kim, H. J., Kim, N. N., Yoon, H. S. and Ahn, S. H.*, 2011, "A rotational ablation tool for calcified atherosclerotic plaque removal," Biomedical Microdevice, Springer (Netherlands), Volume 13, No. 6, pp. 963-971

CNC Lathe

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



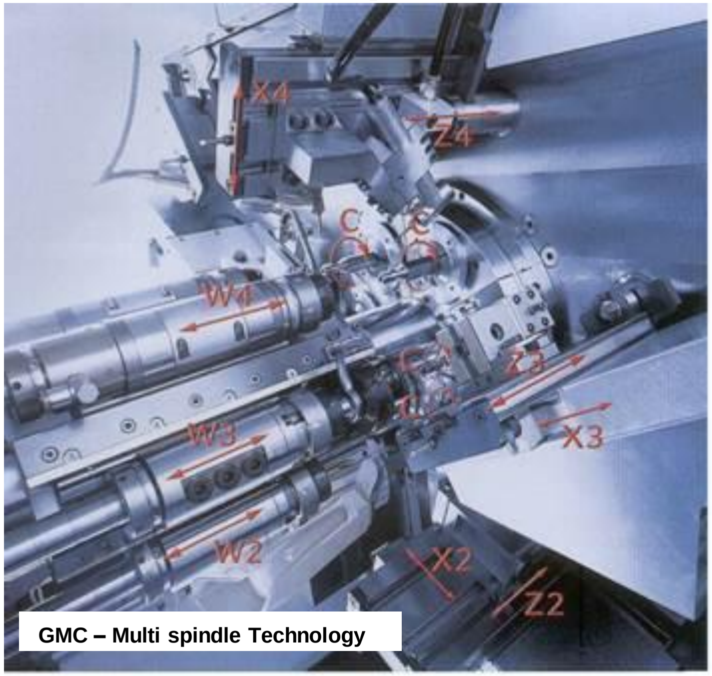
Cutting



Cutting + Milling

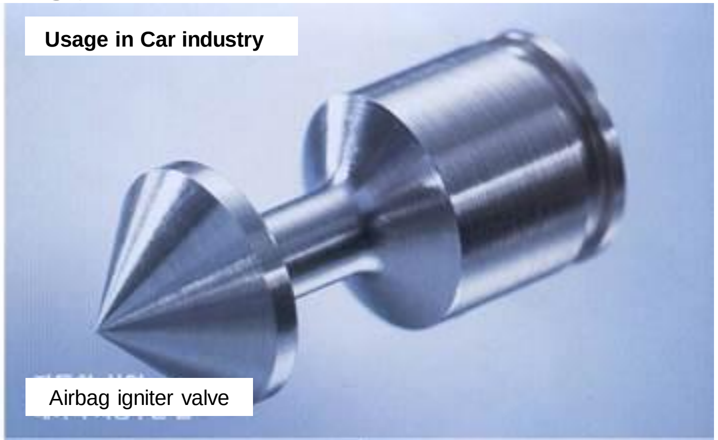
Precision machining

- **GMC – Multi spindle Technology**



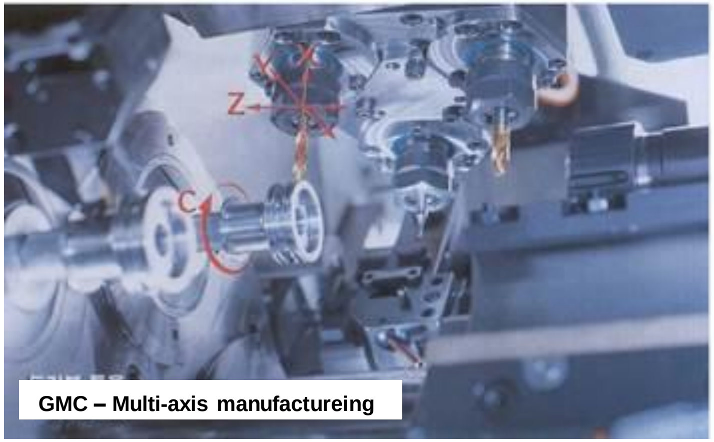
GMC – Multi spindle Technology

Usage in Car industry


Airbag igniter valve


Camshaft


Stud Bolt



GMC – Multi-axis manufactureing


Joint

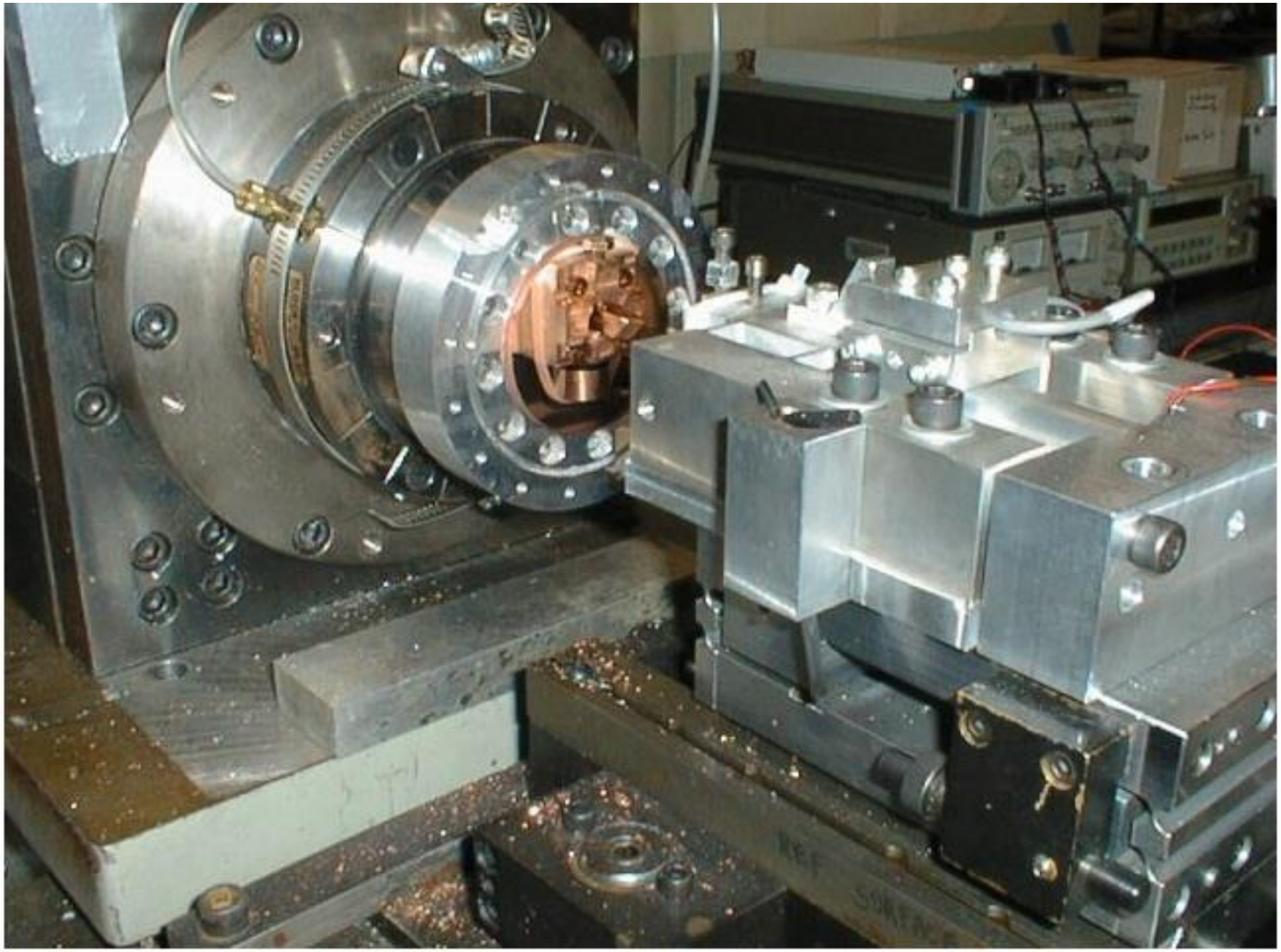

High pressure linkage


Pulley


Spray nozzle

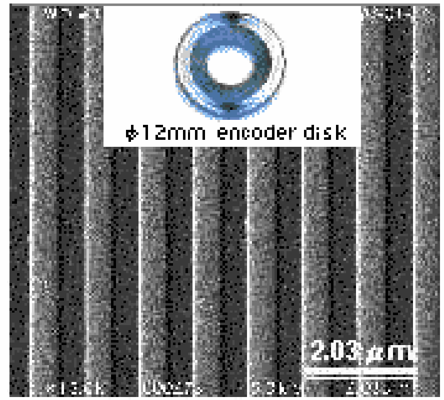
Precision machining

- **Pneumo Diamond Turning Machine**

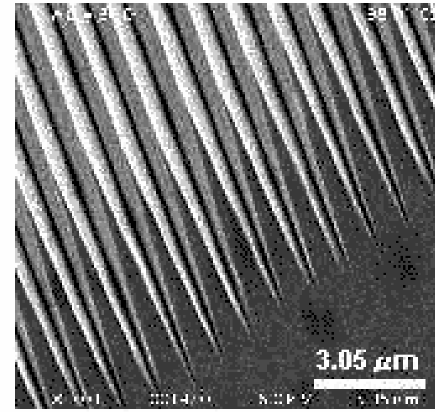


FANUC ROBOnano U*i*

Diffractive grating machined radially on the diameter 12 mm disk, Ra < 1 nanometer



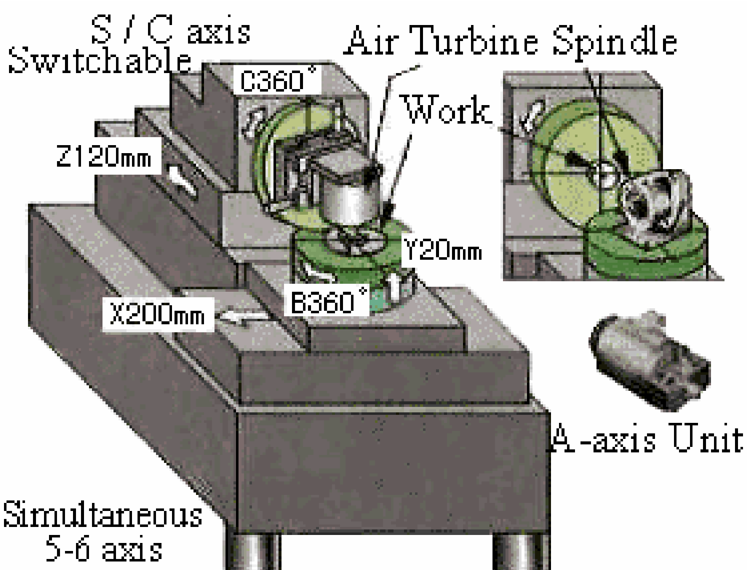
1 μm V groove grating



Edge of line " No micro bur "

diameter 1 mm NOU mask

Cut by rotating diamond tool

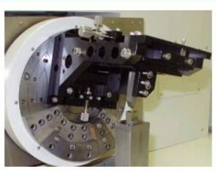


- Resolution X,Y,Z: 1nm A,B,C: 1/100,000deg.
- Building Block Structure with Super Precision Units
- Column-less 5 axes machine with turning function

FANUC ROBOnano α-0*i*B

Ultraprecision machining

Various machining options supporting all types of nano machining



Scribing (5-axis)

Milling (5-axis)

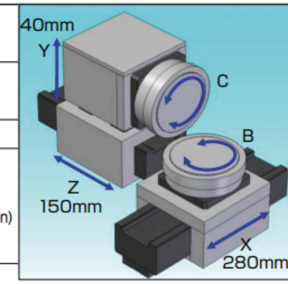
Turning

Spherical lens mold

Material : NiP plate
Size : ϕ3 mm
Figure accuracy :
PV 52nm
Surface roughness :
Ra 1.3 nm

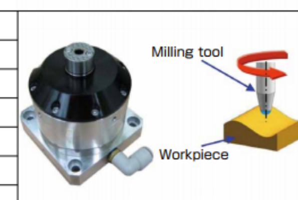
Main specifications

Stroke	X axis (horizontal linear)	280mm
	Z axis (horizontal linear)	150mm
	Y axis (vertical linear)	40mm
	B axis (horizontal rotation)	360° (continuous rotation)
	C axis (vertical rotation)	
Bearing type	Hydrostatic air bearing (all axes)	
Command resolution	X, Z, and Y axes	1nm
	B and C axes	0.000001°
Work-table area	B and C axes	Φ210mm
Maximum feedrate	X and Z axes	500mm/min
	Y axis	50mm/min
	B axis	3600°/min
	C axis	3600°/min
		$250 min^{-1}$ (S axis mode)
Straightness	X axis	0.2μm/280mm
	Z axis	0.2μm/150mm
	Y axis	0.2μm/40mm
Run out	B and C axes	0.05μm
Mass of the machine	Approx. 1700 kg	
Standard accessories	Supplying cutting fluid unit Tool holder Counter weight Angle plate Precision compressed air temperature control system Speed display	



Milling air turbine spindle

Diameter of shank	ϕ6mm
Maximum speed	$50{,}000 min^{-1}$
Dimensions/mass	ϕ74×84mm／1.5kg
Bearing type	Hydrostatic air bearing
Run out	0.05μm (NRRO)
Speed display function provided	
●The balance can be corrected by two sides.	



LASER machining

- Light Amplification by Stimulated Emission of Radiation (LASER)

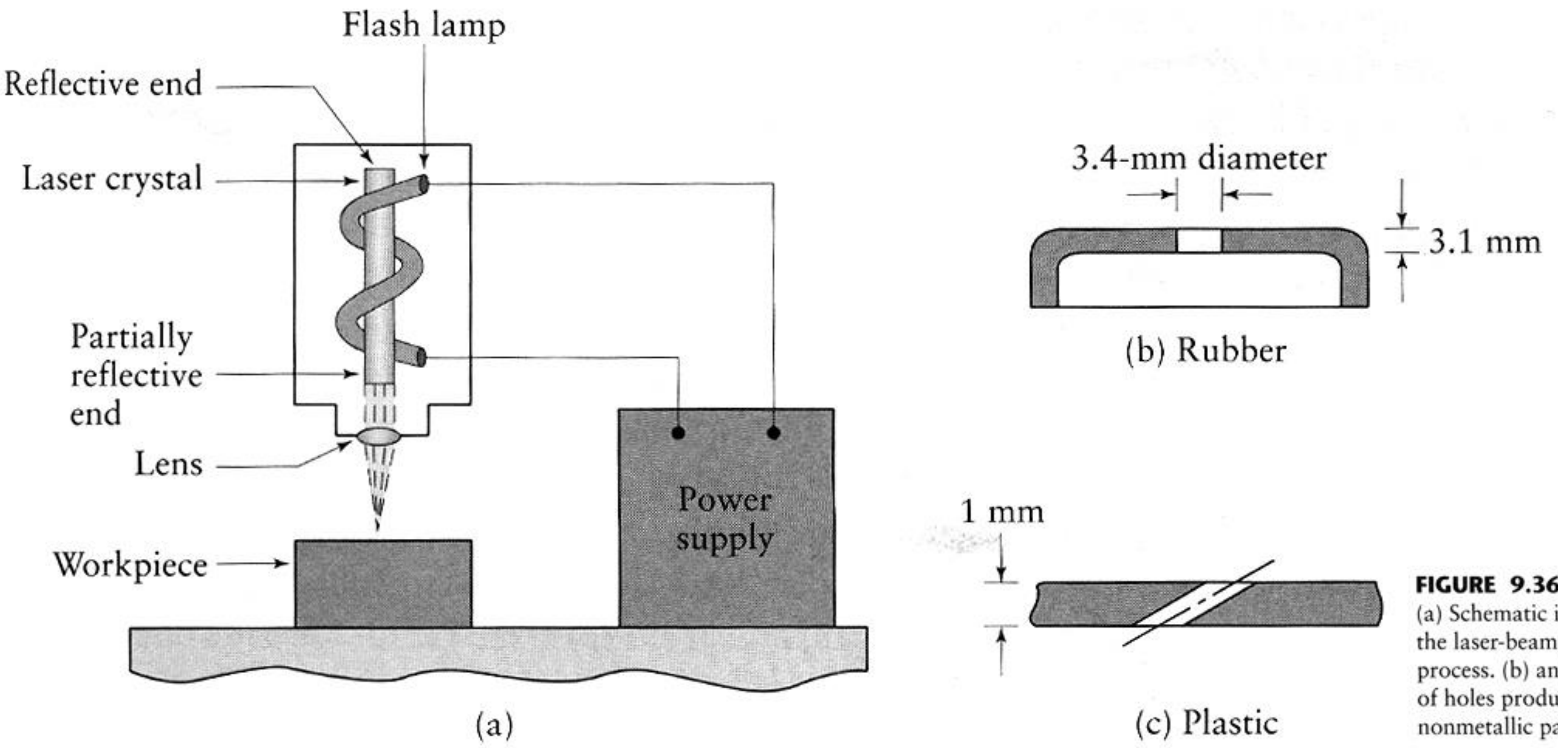
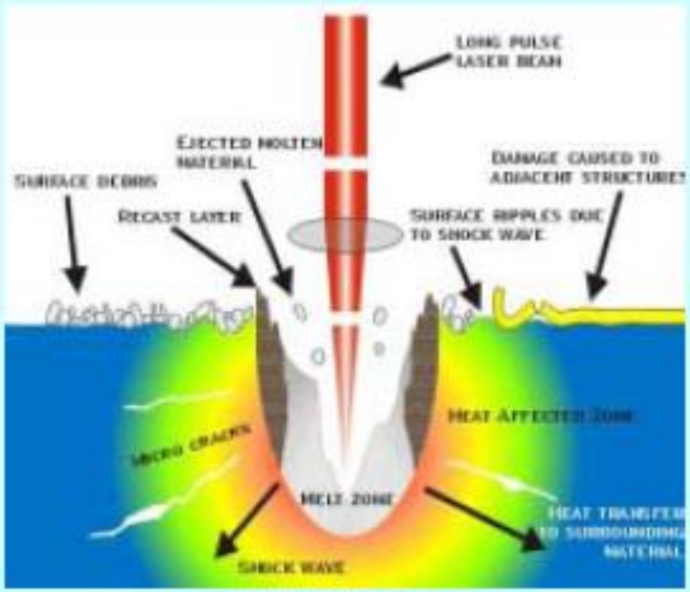


FIGURE 9.36 (a) Schematic illustration of the laser-beam-machining process. (b) and (c) Examples of holes produced in nonmetallic parts by LBM.

- Laser machining
  - Thermal process, removes mass by concentrating high energy
  - Small mass removal: cutting, drilling, welding . . .
  - No tool deflection from the contact → high aspect ratio shape

Pulsed Laser

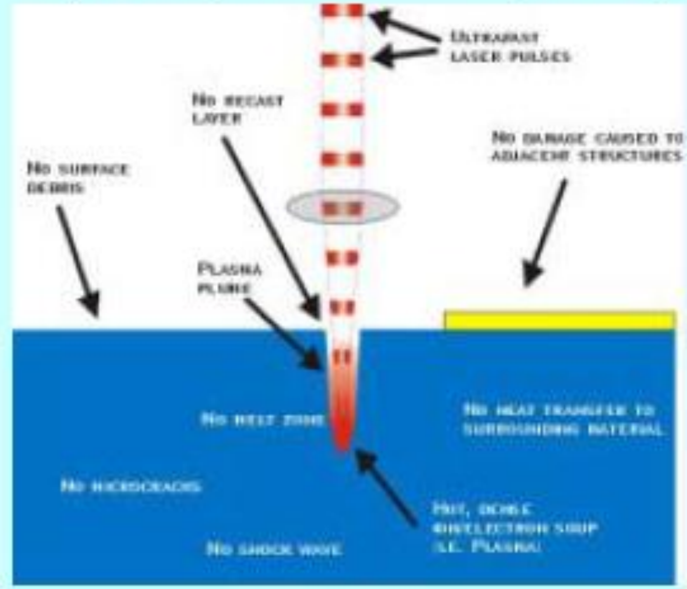
ns(나노초) : nanosecond(10^{-9} sec)



ns 가공 원리

4.2Joule/cm² @ 3.3ns

fs(펨토초) : femtosecond(10^{-15}sec)

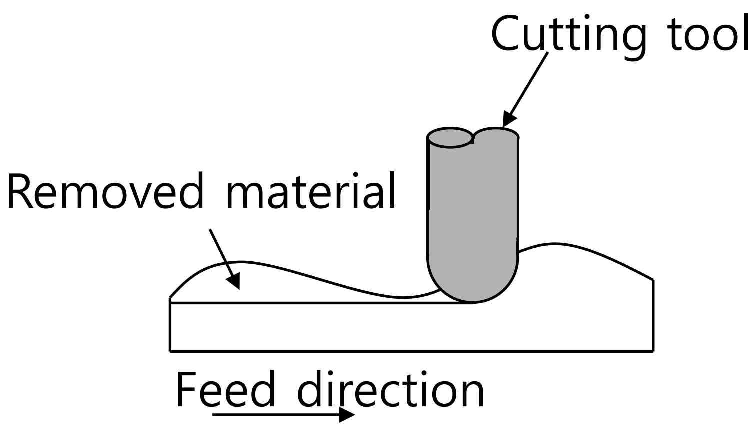


fs 가공원리

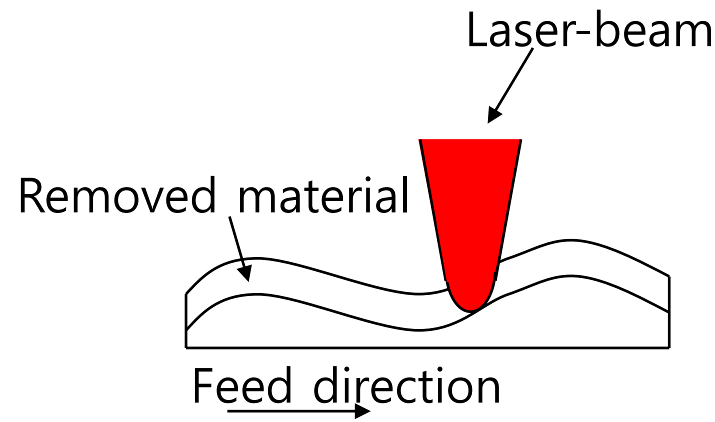
금속 박판, 두께=100µm

0.5Joule/cm² @ 200fs

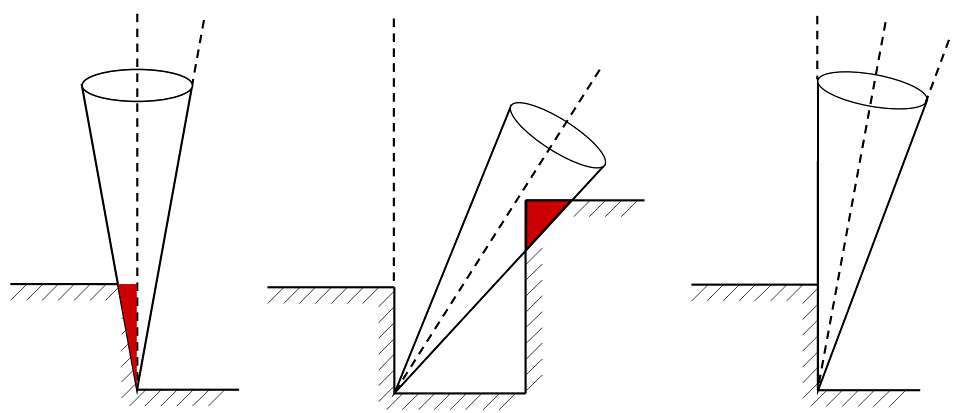
Mechanical machining vs. Laser machining



Mechanical machining



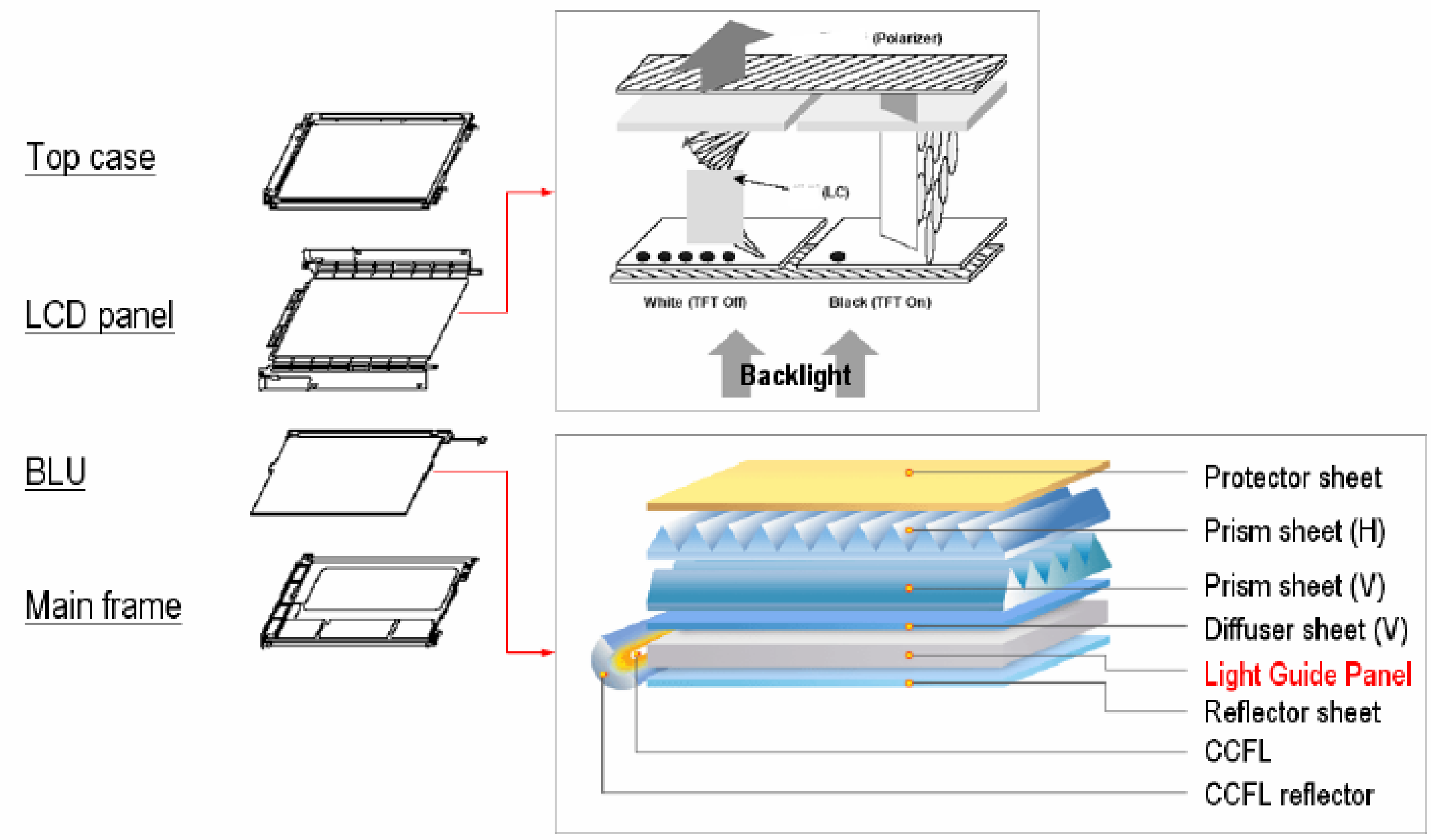
Laser machining



Interference problem

Light guide panel (LGP)

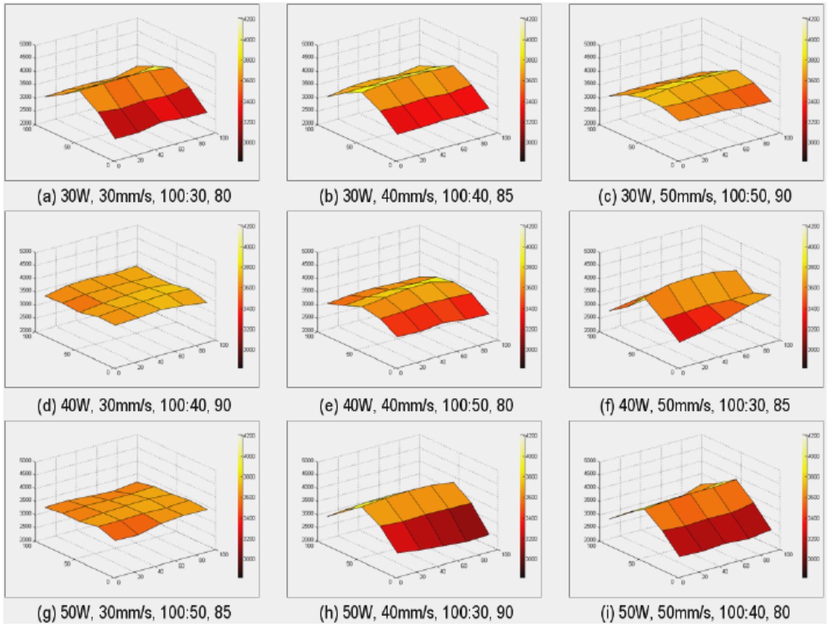
- Light guide panel is an element of the LCD back light unit
- Design of experiment using Taguchi method
  - Power, scanning speed, ratio of line gap, and number of line were investigated



The structure of TFT-LCD

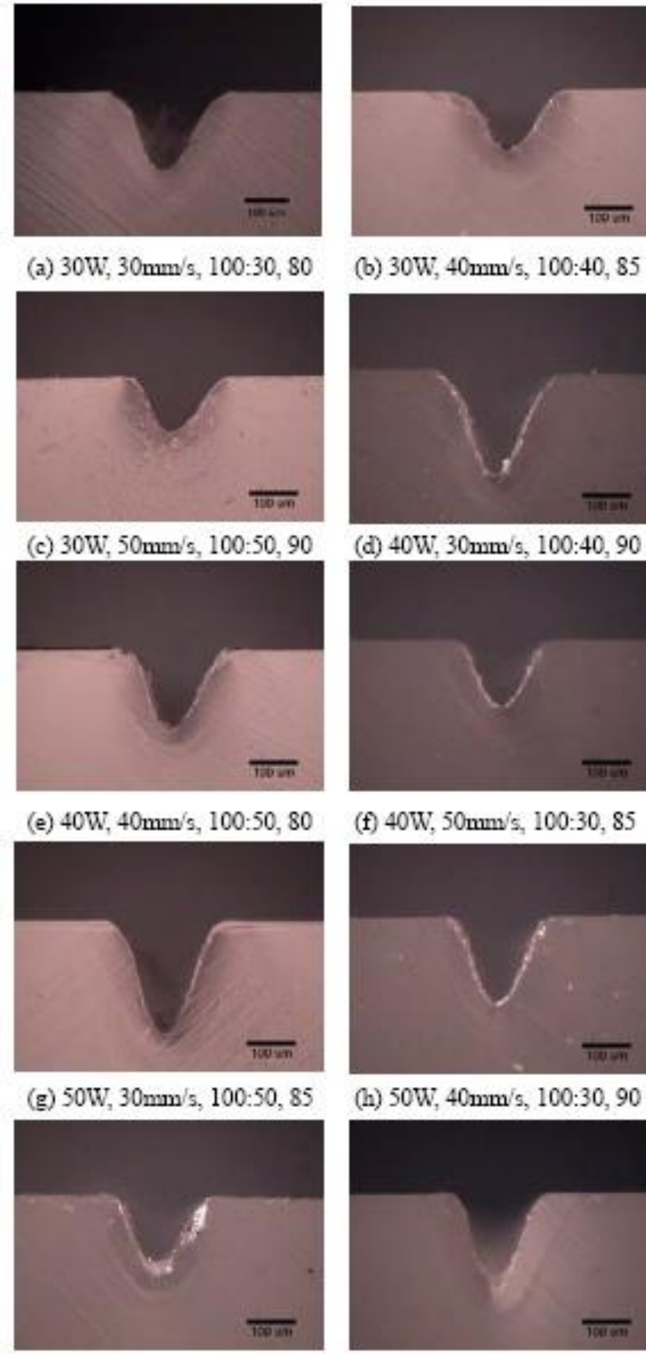
Design of experiment

Orthogonal arrays and experimental results



(a) 30W, 30mm/s, 100:30, 80
(b) 30W, 40mm/s, 100:40, 85
(c) 30W, 50mm/s, 100:50, 90
(d) 40W, 30mm/s, 100:40, 90
(e) 40W, 40mm/s, 100:50, 80
(f) 40W, 50mm/s, 100:30, 85
(g) 50W, 30mm/s, 100:50, 85
(h) 50W, 40mm/s, 100:30, 90
(i) 50W, 50mm/s, 100:40, 80

Exp. No.	A	B	C	D	Average luminance (cd/m^2)	Uniformity (%)	Time (sec)
1	1	1	1	1	3339	68.4	56
2	1	2	2	2	3415	72.5	59
3	1	3	3	3	3425	80.4	71
4	2	1	2	3	3523	92.0	49
5	2	2	3	1	3353	77.9	52
6	2	3	1	2	3442	66.6	63
7	3	1	3	2	3452	85.2	62
8	3	2	1	3	3326	62.2	47
9	3	3	2	1	3280	65.4	55

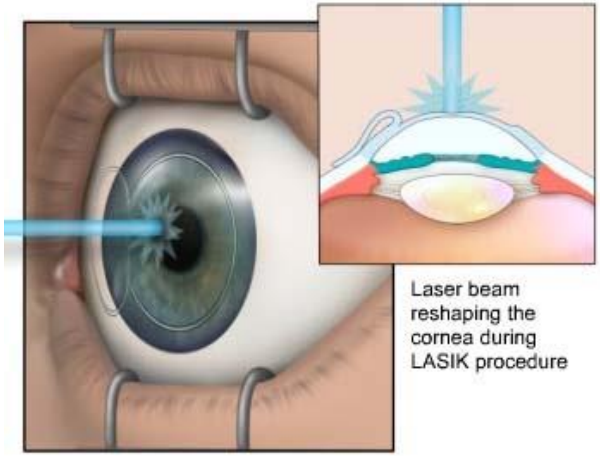


(a) 30W, 30mm/s, 100:30, 80
(b) 30W, 40mm/s, 100:40, 85
(c) 30W, 50mm/s, 100:50, 90
(d) 40W, 30mm/s, 100:40, 90
(e) 40W, 40mm/s, 100:50, 80
(f) 40W, 50mm/s, 100:30, 85
(g) 50W, 30mm/s, 100:50, 85
(h) 50W, 40mm/s, 100:30, 90

Laser-machined Light Guide Panel

Laser therapy and surgery

Laser therapy can release the pain and heal the body

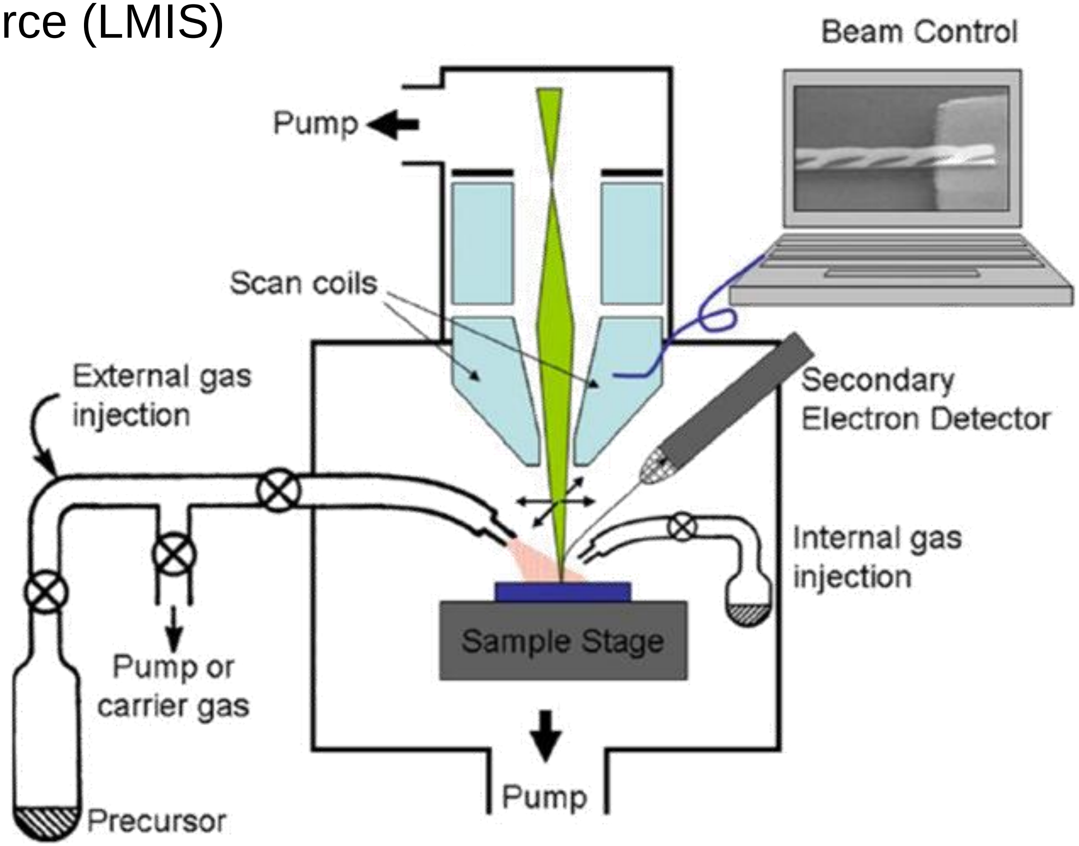


LASIK surgery for dry eye syndrome using laser

Cosmetic surgery: moles, warts, wrinkles, scars, hairs, tatoos, etc.

Focused ion beam (FIB) system

- Ion gun
  - Liquid metal ion source (LMIS)
- Ion optical column
  - Electrostatic lens
  - Scan coil
  - Stigmator
- Specimen chamber
- Vacuum system



Schematics of focused ion beam system

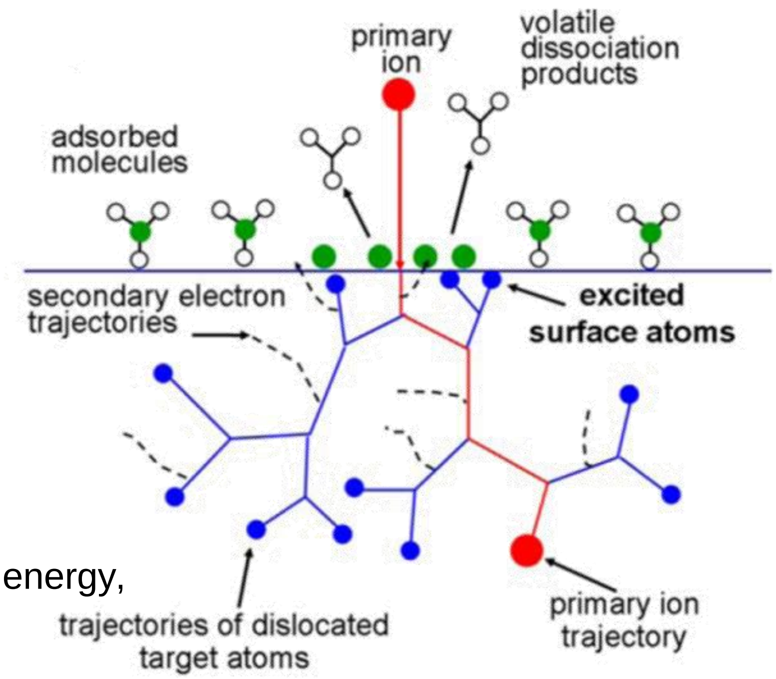
Utke *et al.* J. Vac. Sci. Technol. B 26 (4) 2008

Principle of FIB fabrication

- Elastic collision (nuclear collision)
  - Dislocation of surface atom by primary ion (PI)
  - Binary collision (collision cascade)

- Inelastic collision (electronic collision)
  - Secondary electron (SE) by PI
  - SE by inelastic collision
  - Backscattered electron (BSE) by SE

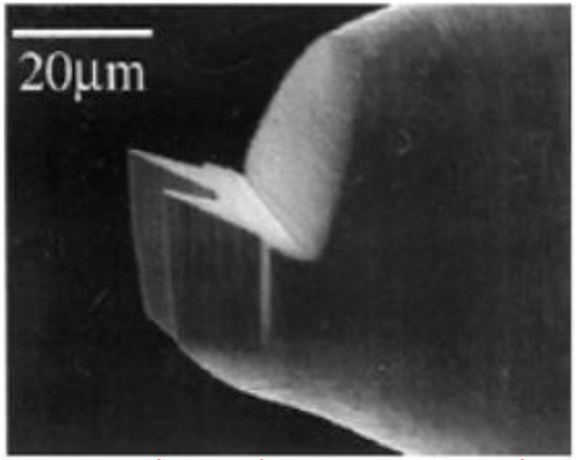
- Initiation of material removal
  - Excited surface atom (ESA) by nuclear collision
  - For Si substrate, the binding energy is 2.5 eV
  - When ion energy is exceed the substrate binding energy, the excited surface atom will be removed.



Utke *et al.* J. Vac. Sci. Technol. B 26 (4) 2008

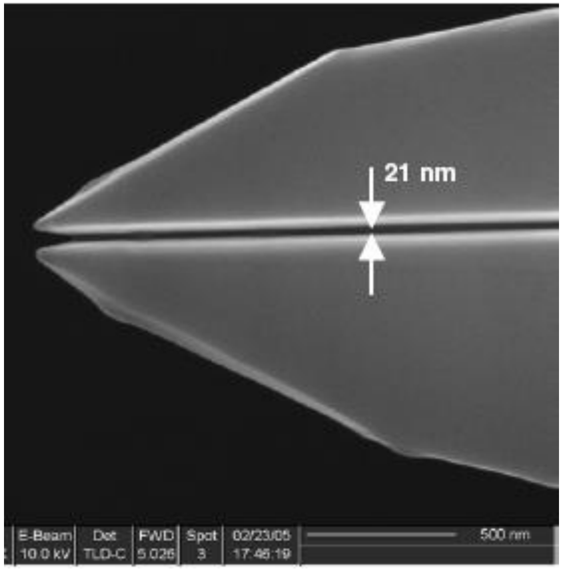
FIB technology

- Merits
  - High throughput, low penetration depth
- Hybrid process
  - Material destruction & construction
- Various material
  - Destruction: all solid materials
  - Construction: C, W, Pt
- Various application
  - MEMS/NEMS, SPM tips
  - Micro/nanoscale medical devices
  - Photonic devices
  - Micro/nanoscale mould



Two-tip micro-tool having triangular cutting facet

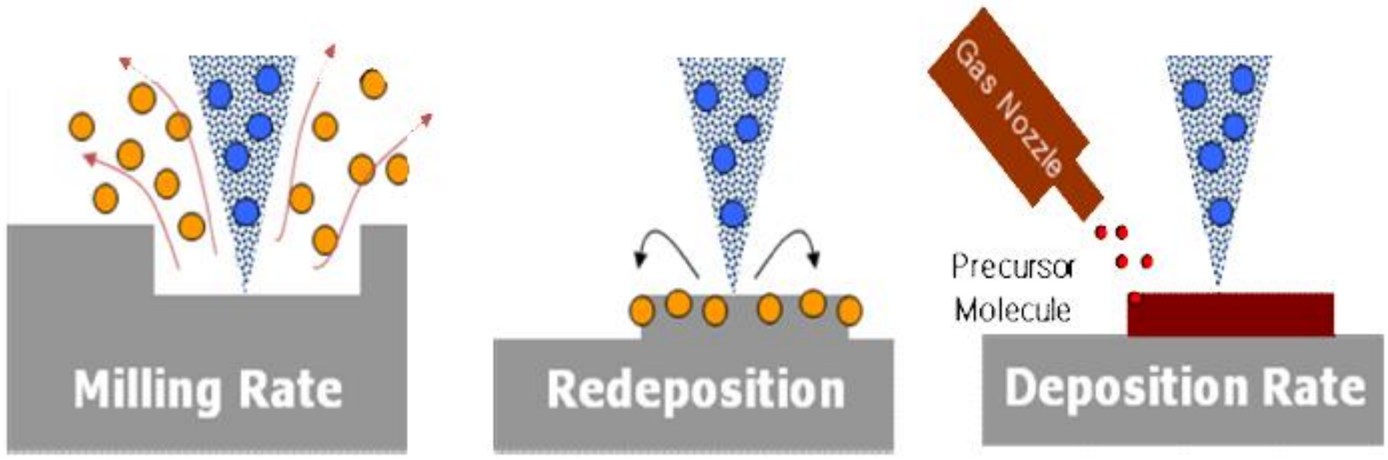
D P Adams Precision Engineering 25 (2001) 107



Nano-fluidic emitter having 21 nm capillary slots

S. Arscott Nanotechnology 16 (2006) 2295

Considerations on DFM in FIB

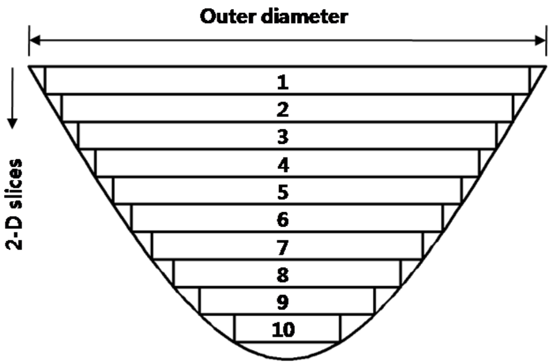


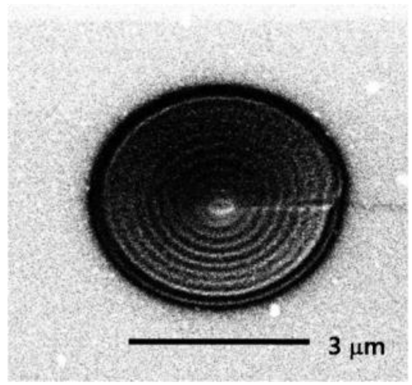
Geometrical and efficiency issues related to DFM in FIB fabrication

REF) Kim, C. S., Ahn, S. H., Jang, D. Y., 2011, "Review: Developments in Micro/Nanoscale Fabrication by Focused ion beams ," Vacuum, Elsevier (Netherlands), Volume. 86, No. 8, pp. 1014-1035.

DFM on FIB (1)

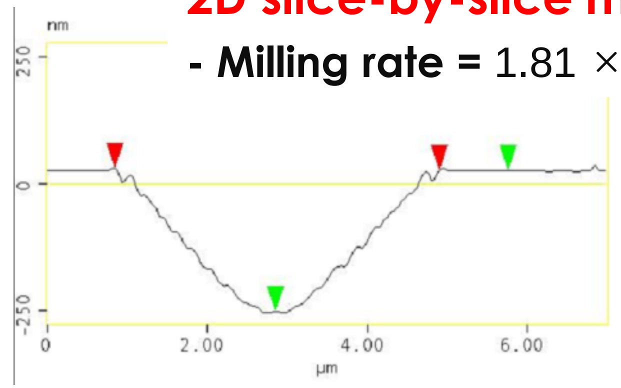
- Better surface roughness
- Better milling rate



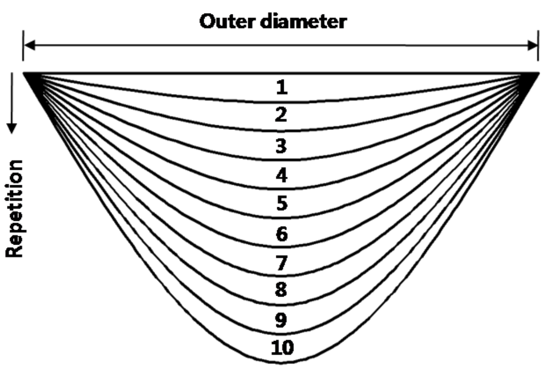


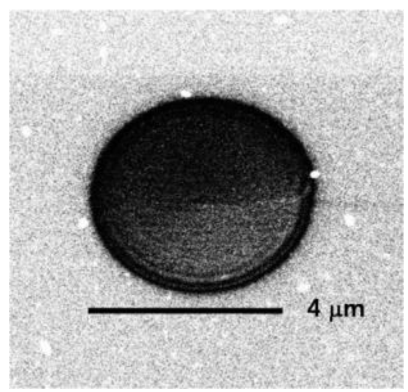
2D slice-by-slice method

- Milling rate = 1.81 × ions/cm^2



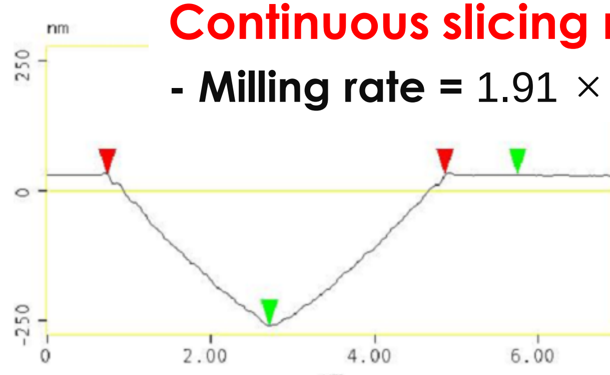
Fabrication method | SIM 60 ° tilt view | AFM cross-section view





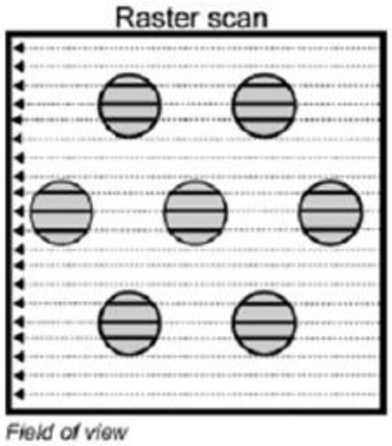
Continuous slicing method

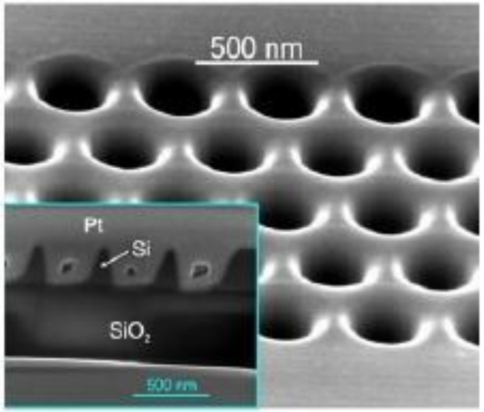
- Milling rate = 1.91 × ions/cm^2



DFM on FIB (2)

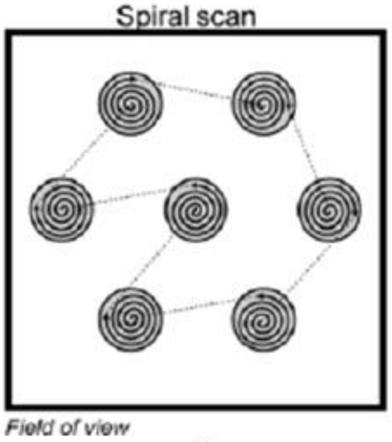
- To have vertical sidewalls
- To have bilateral-symmetry

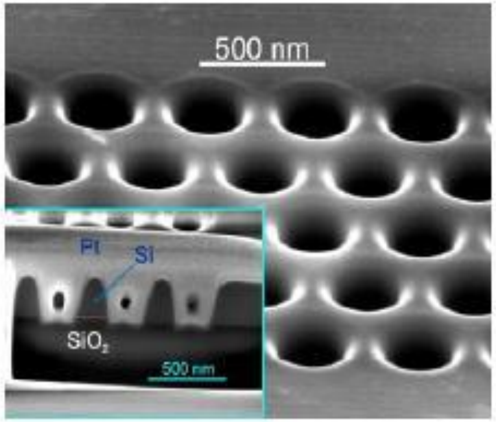




Raster scan routine

- Asymmetry





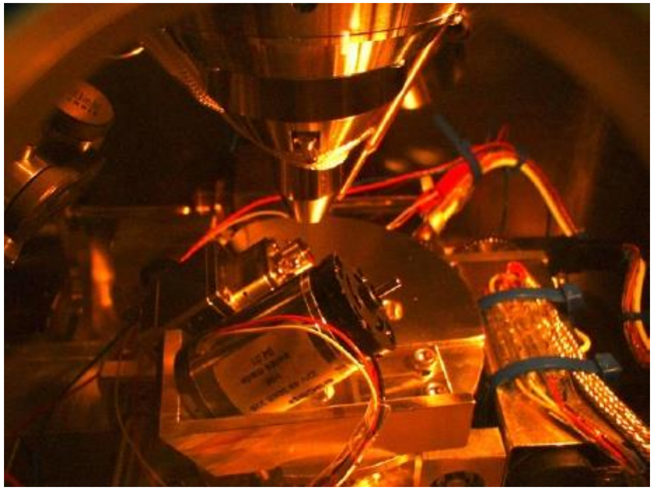
Spiral scan routine

- Symmetry

W C hopman Nanotechnology 18 (2007) 195305

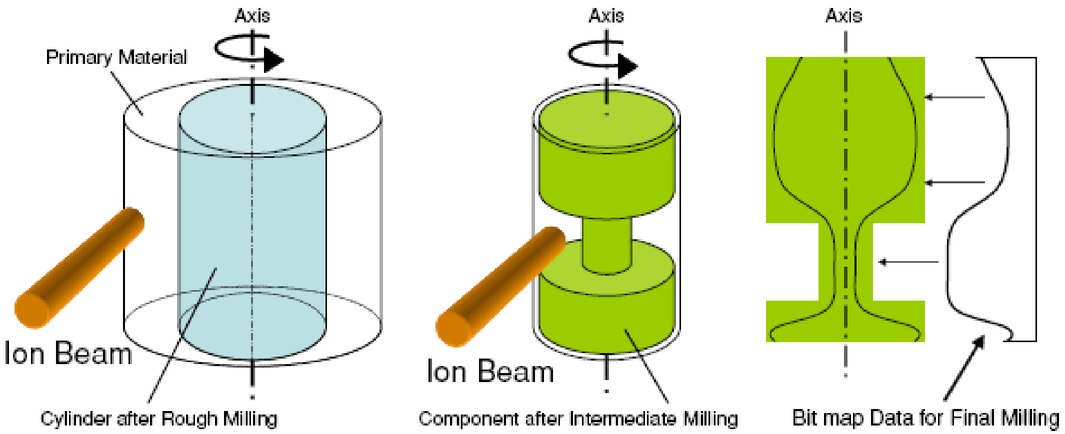
Nano-lathe (나노선반)

- Conventional lathe in FIB system

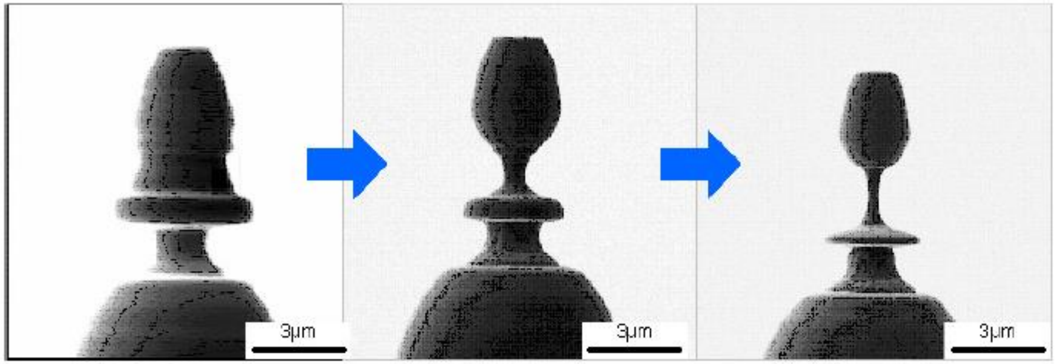


Precision wheel stage attached to the FIB system

T Fijii J. Micromech. Microeng. 15 (2005) S286



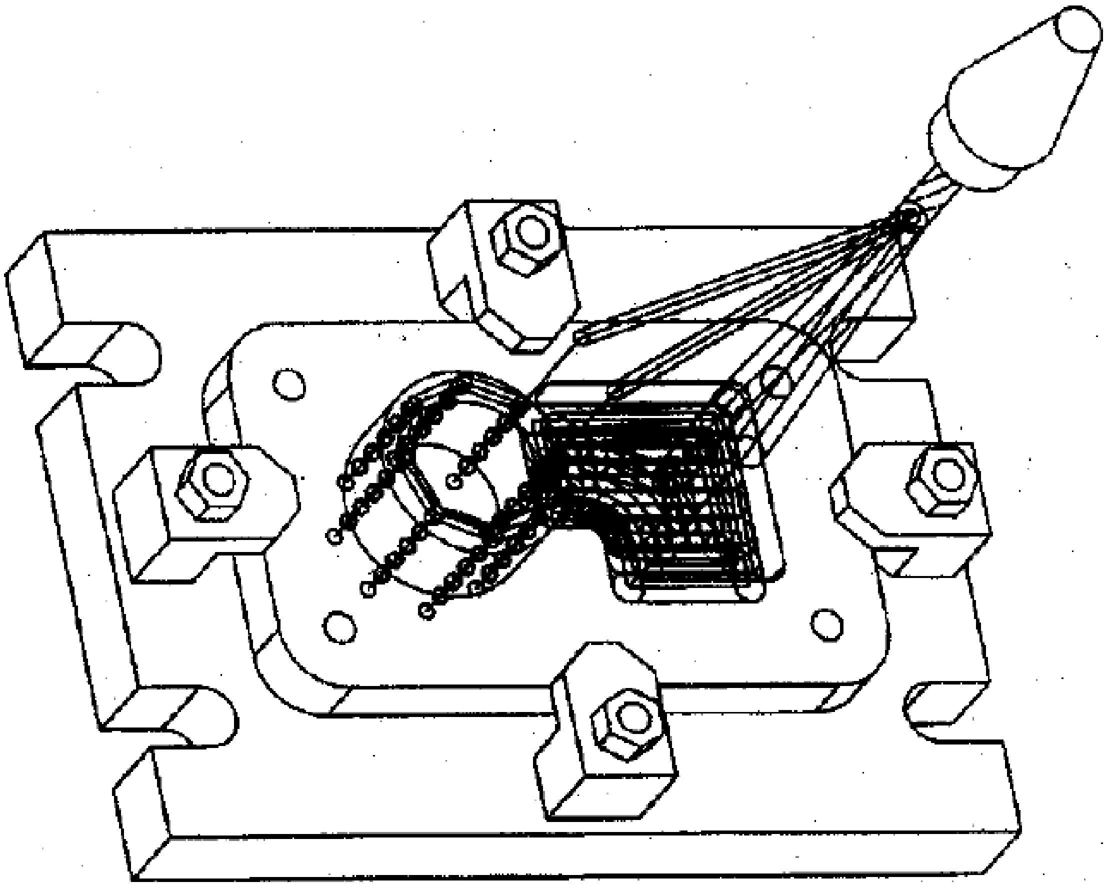
Process outline of nano-lathe



Scanning ion scope image showing the intermediate processing

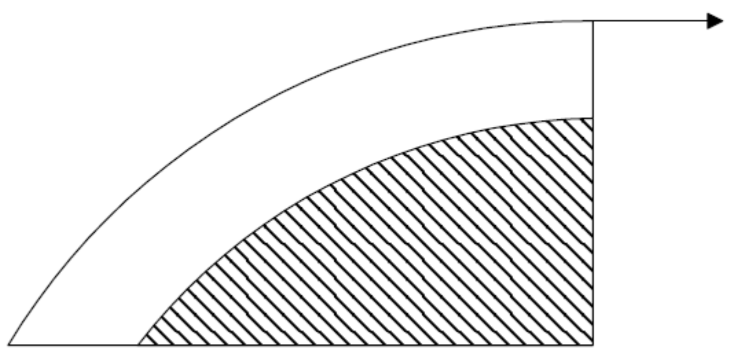
Tool Path Generation

- Concept of pocketing

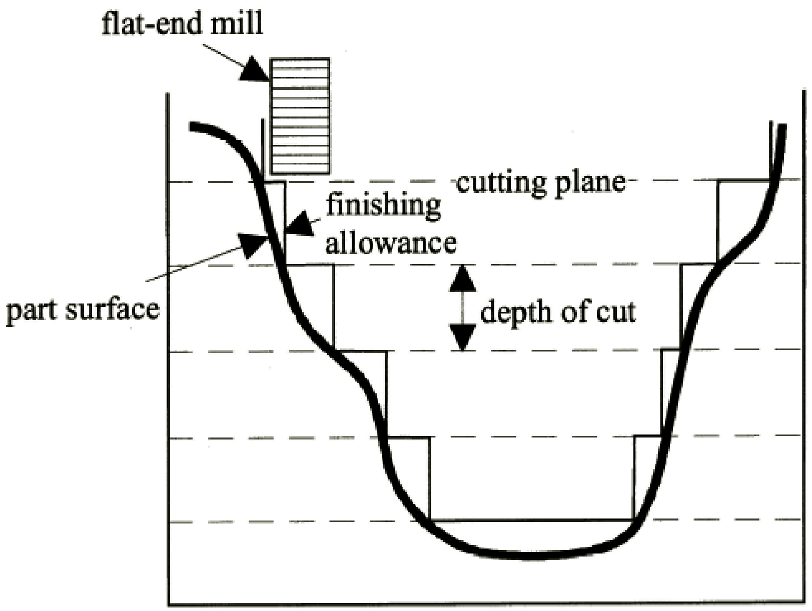


Tool Path Generation (cont.)

- Rough Cutting
  - Remove bulk material
  - One type: the raw material has a shape close to the final shape
  - Second type: the raw material is provided in the form of block



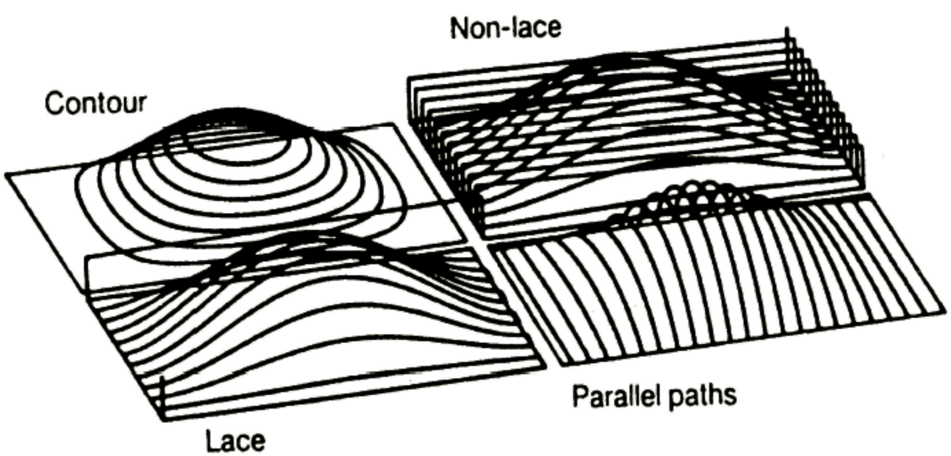
< One type of rough cutting >



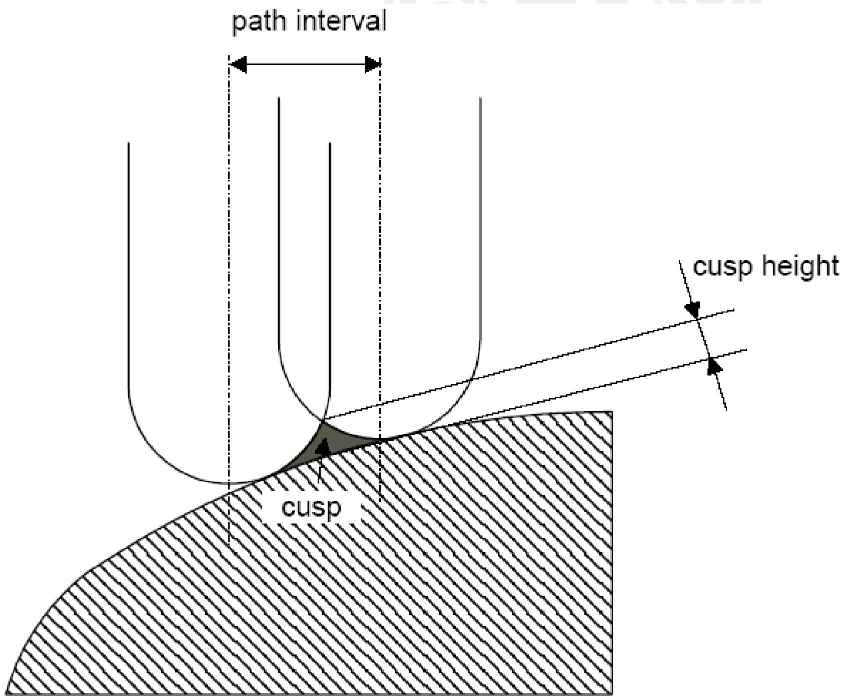
< Second type of rough cutting >

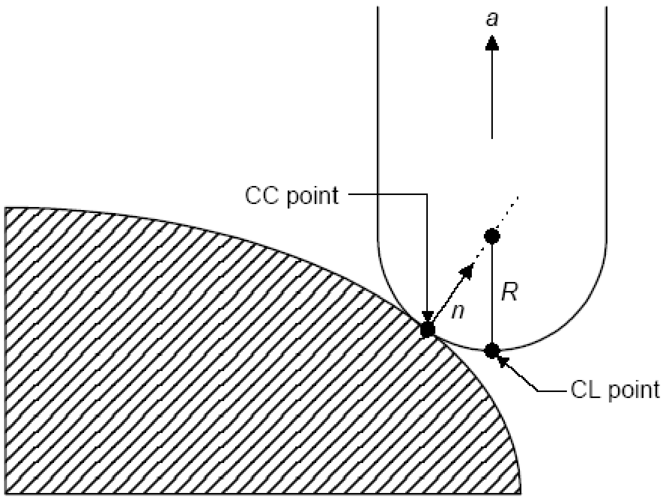
Tool Path Generation

- Finish cutting
  - Path interval and cups height
  - Step length and deviation
  - Generation of CC points and CL point



< Various cutter paths on a surface >

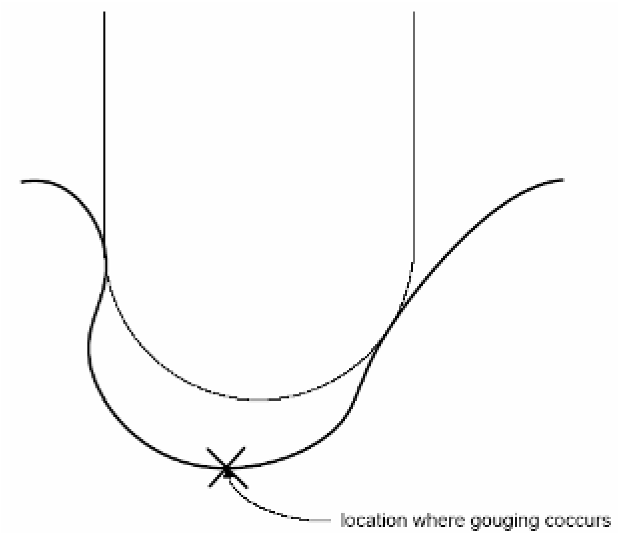




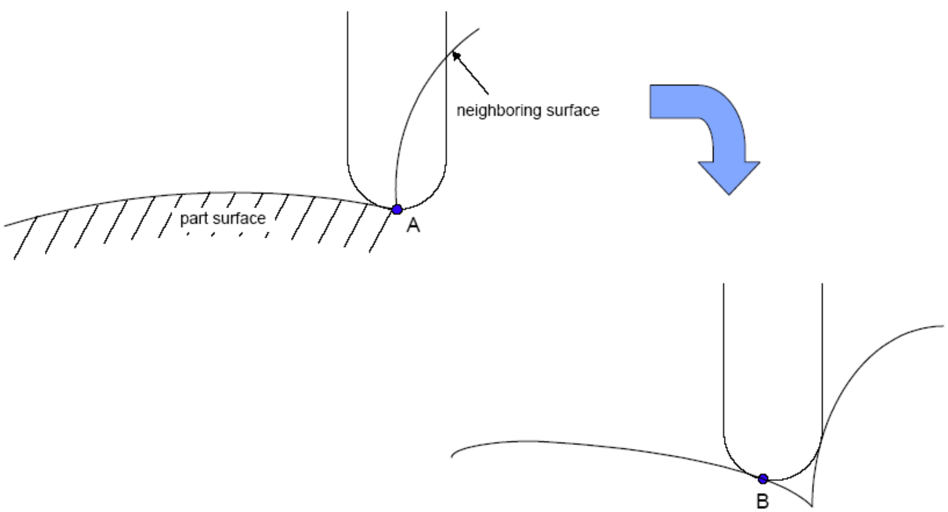
$$\mathbf{r}_{cl} = \mathbf{r}_{cc} + R(\mathbf{n}(u,v) - \mathbf{a})$$

Tool Path Generation (cont.)

- Gouging Problem
  - Choosing a tool whose radius is smaller than the minimum radius of curvature of the part surface
  - However, too small tool may result in inefficient machining

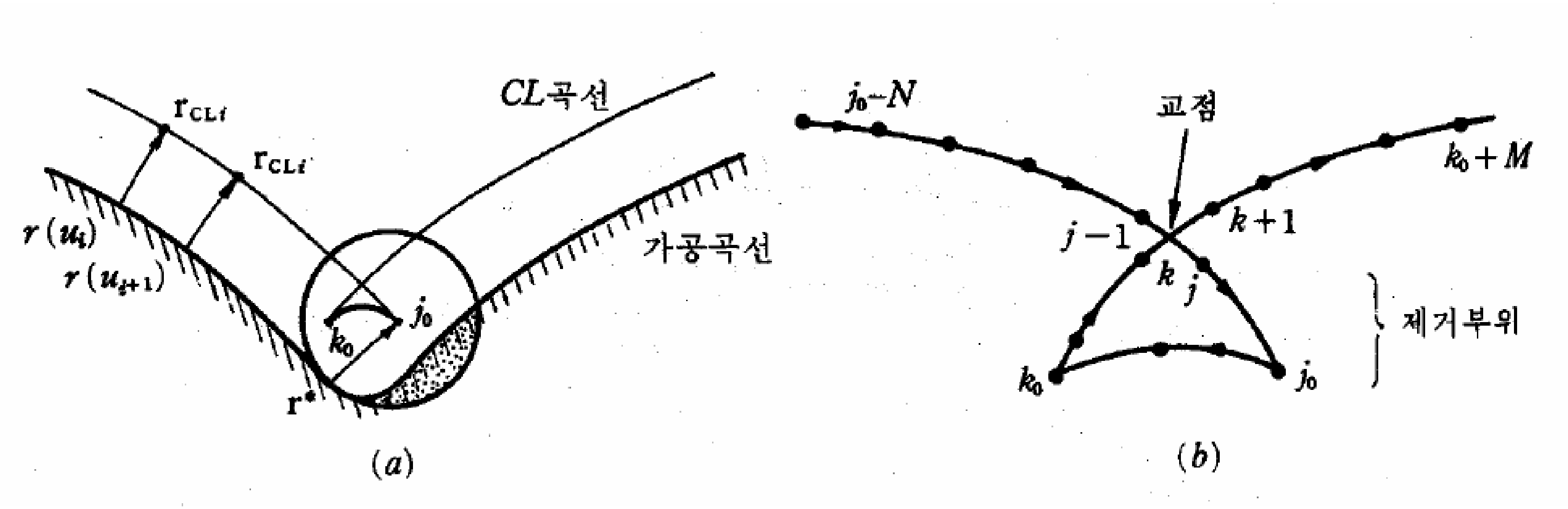


< Gouging of a surface >



< Gouging at a neighboring surface >

Overcut



Overcut (cont.)

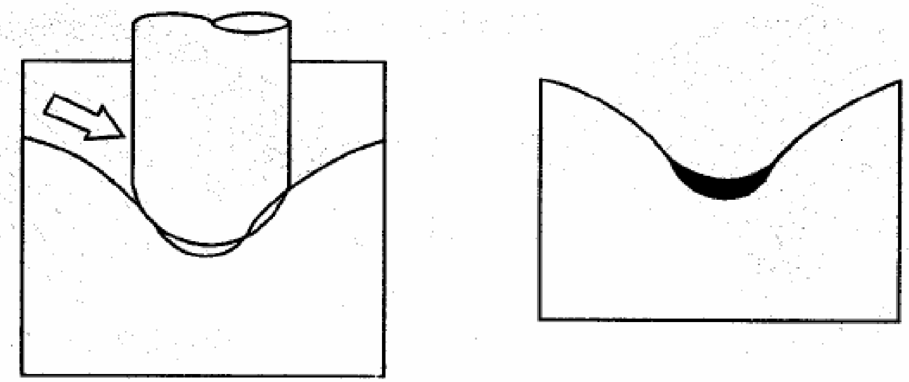


그림 11.24 곡면가공시의 공구간섭(overcut)과 undercut.

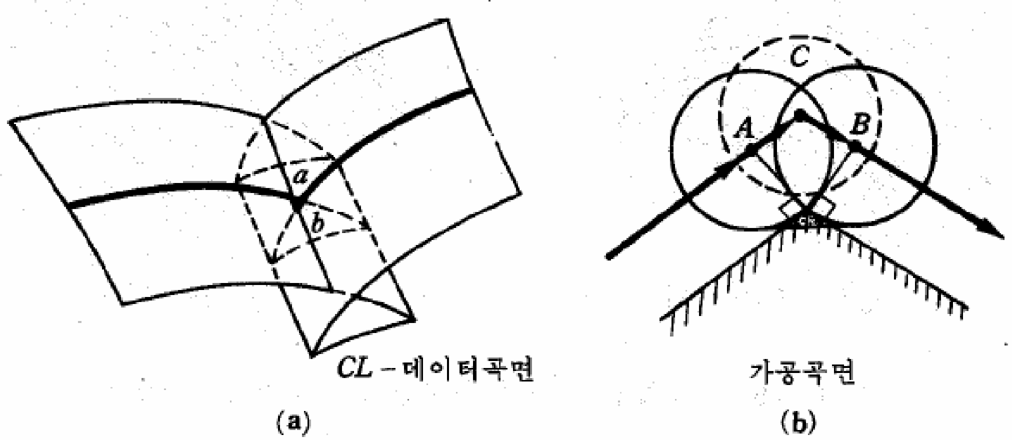
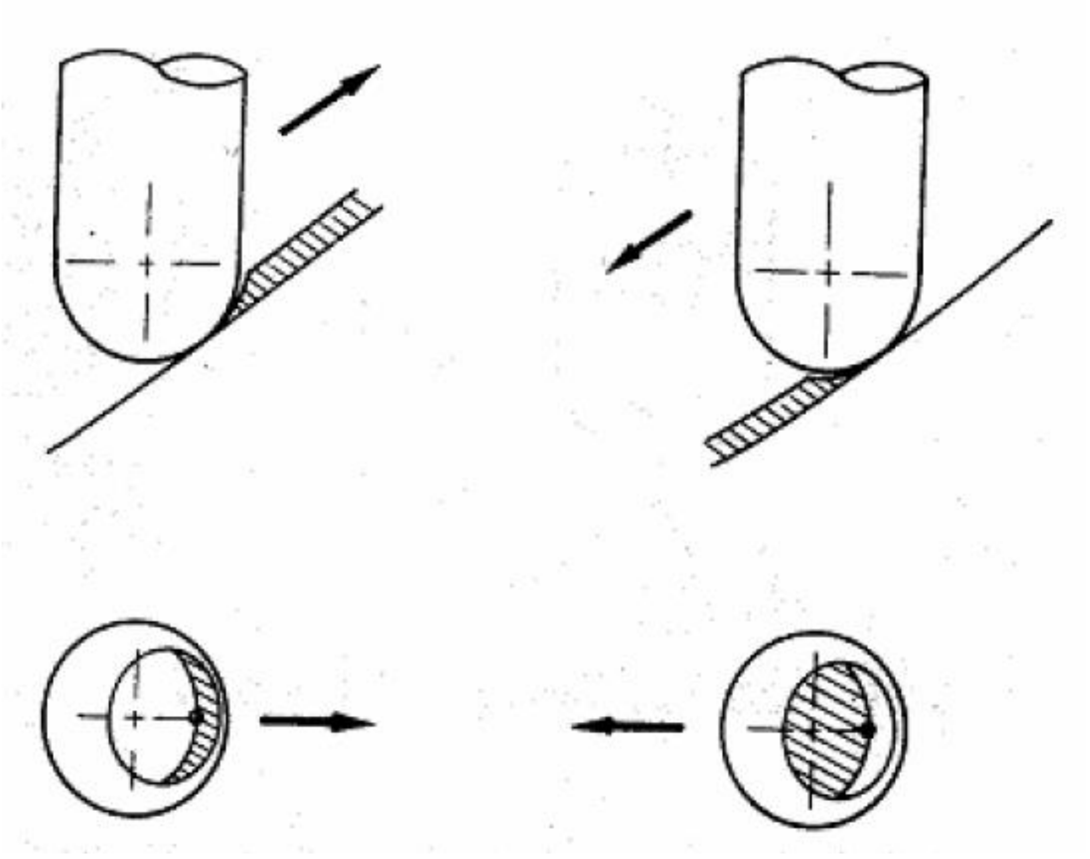


그림 11.25 공구간섭 현상의 발견과 제거

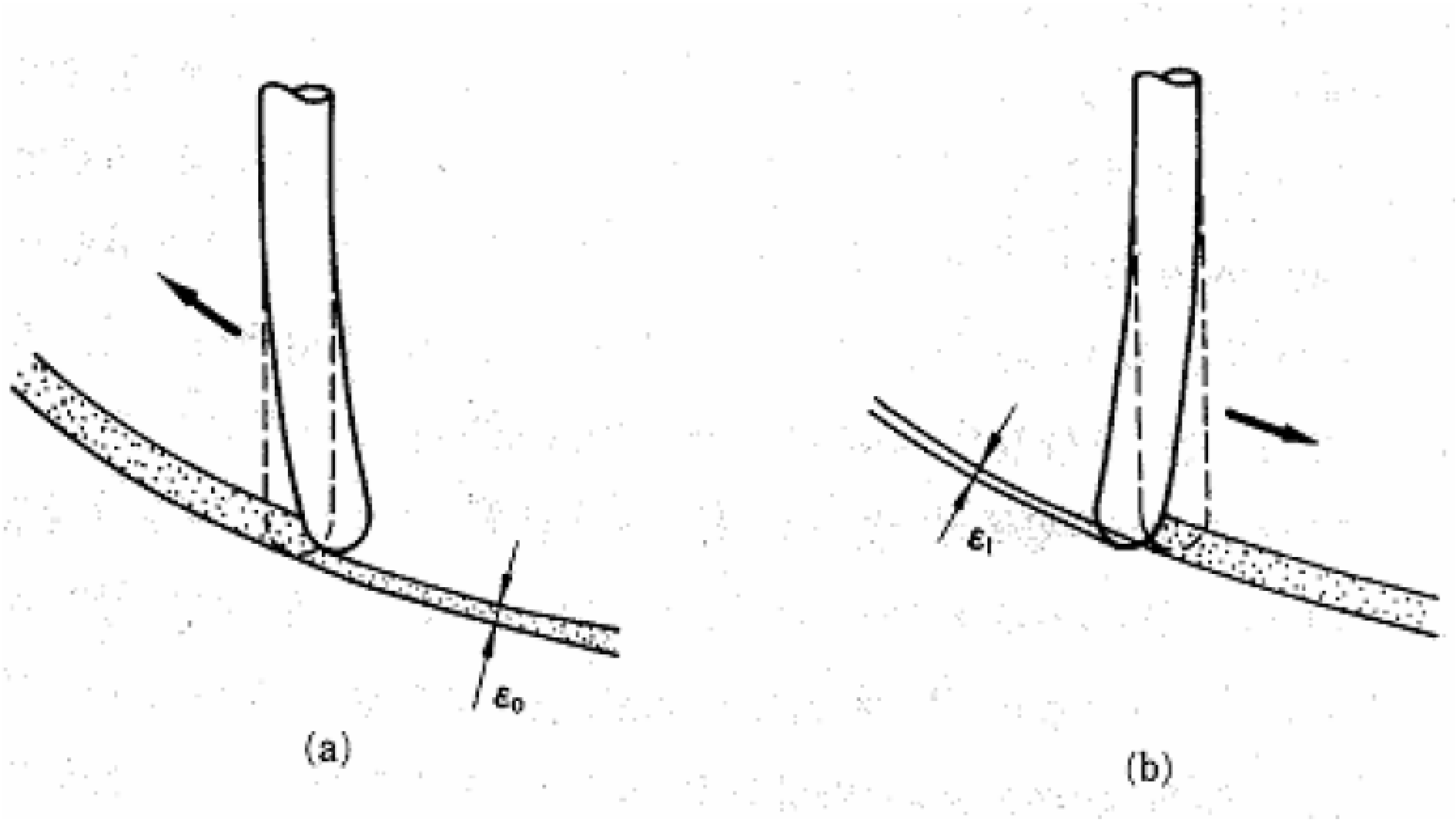
Area of Cutting

- Upward cutting vs. downward cutting
- Zero velocity zone may occur

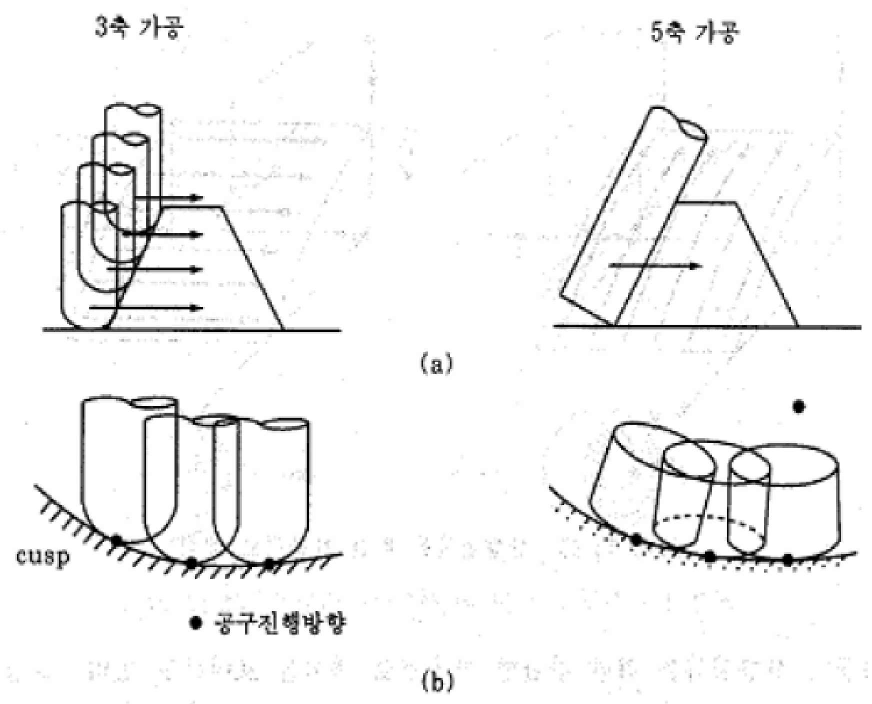


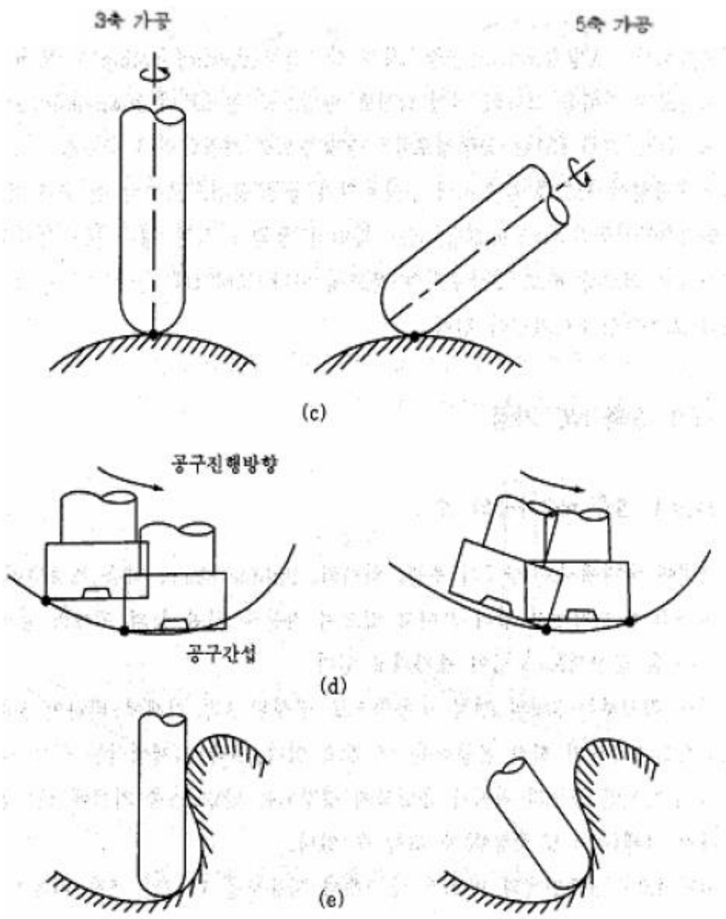
Deflection of Tool

- Undercut vs. overcut



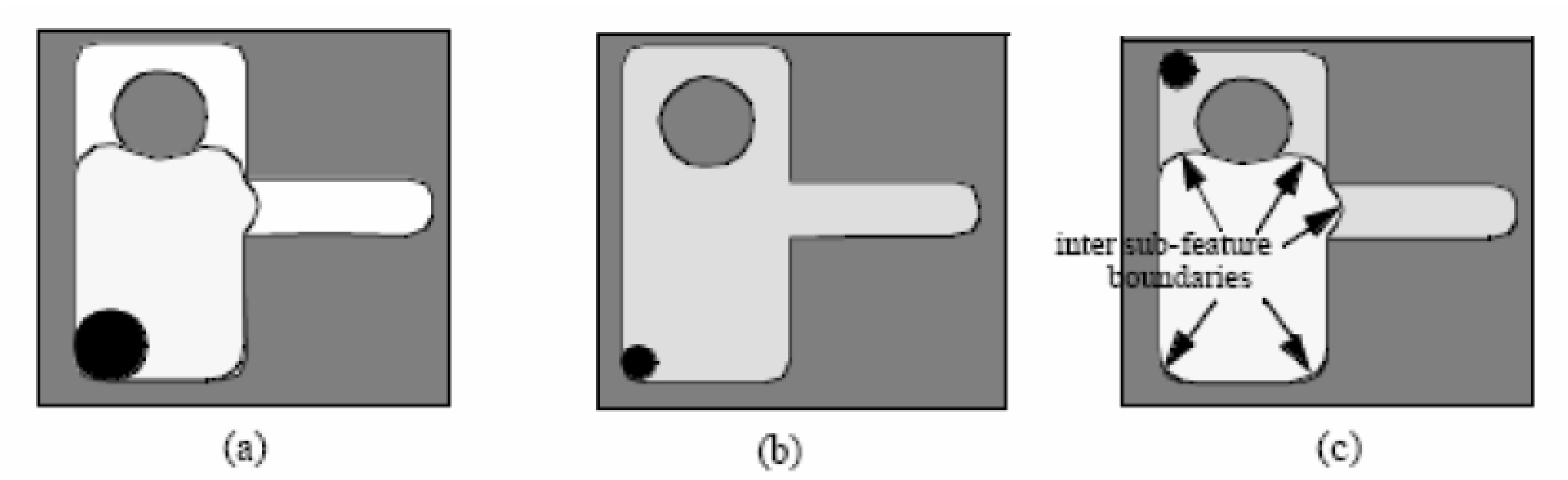
5-axis Machining



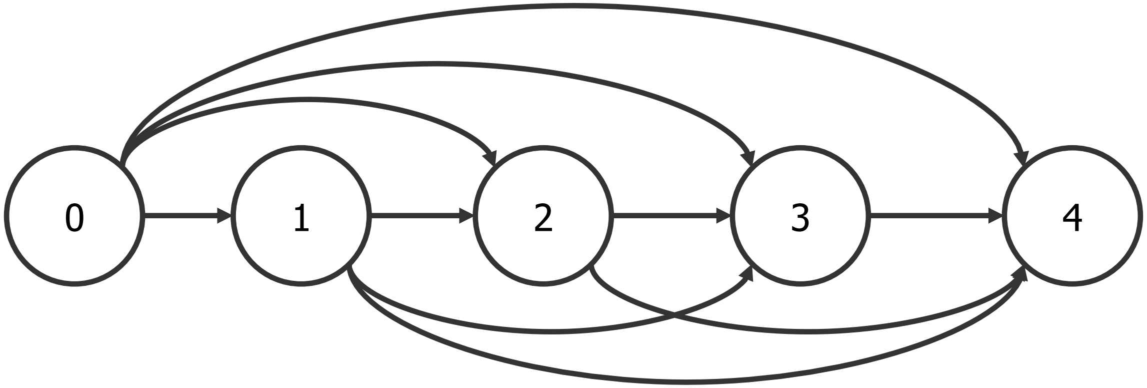


Selection of tool size

- Considering cost and time



(a) (b) (c)



Conclusion

- Material removal
  - Material removal rate (MRR) is important
- Under cut is usually not easy to fabricate
- Contact (mechanical machining) vs. non-contact (laser & FIB)
  - Direct tool shape transfer: the Gaussian beam shape for laser and FIB
  - Substrate properties dependency

Contact Information

- Precision machining
  - http://nmrc.yonsei.ac.kr/ (EDM)
  - http://www.sharp-eng.com/web/ (EDM & Machining)
- Laser machining
  - http://nmrc.yonsei.ac.kr/
  - http://www.laserpix.co.kr/
- Focused ion beam
  - http://nmrc.yonsei.ac.kr/
  - http://msp.or.kr
  - http://www.aac.re.kr/index.html