Chapter 9. Material-Removal Processes: Abrasive, Chemical, Electrical, and High-Energy Beams

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Grinding (연삭) (1)

- **Hardness**
- **Friability (깨짐성)**
    - Self sharpening (자생작용)
    - Grain fragments rapidly
- **Grain size (입도)**
    - Grit number (입도지수)
    - 10 > 100 > 500

TABLE 9.1

Knoop Hardness Range for Various Materials and Abrasives

Common glass	350–500	Titanium nitride	2000
Flint, quartz	800–1100	Titanium carbide	1800–3200
Zirconium oxide	1000	Silicon carbide	2100–3000
Hardened steels	700–1300	Boron carbide	2800
Tungsten carbide	1800–2400	Cubic boron nitride	4000–5000
Aluminum oxide	2000–3000	Diamond	7000–8000

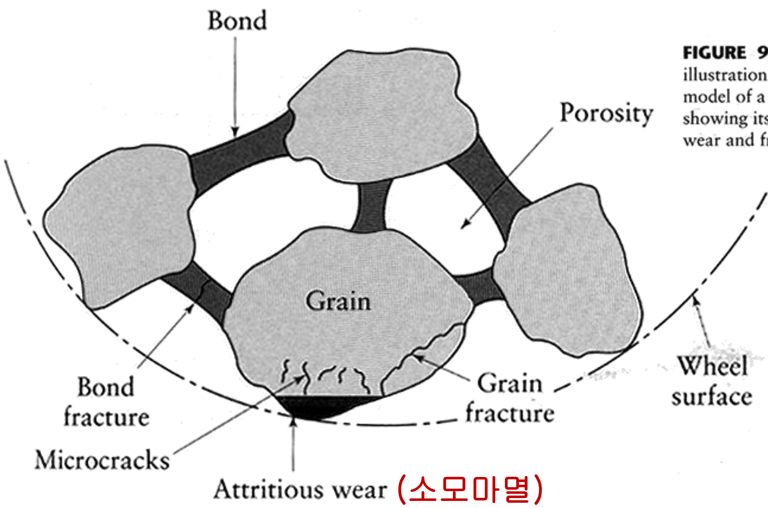


FIGURE 9.1 Schematic illustration of a physical model of a grinding wheel, showing its structure and wear and fracture patterns.

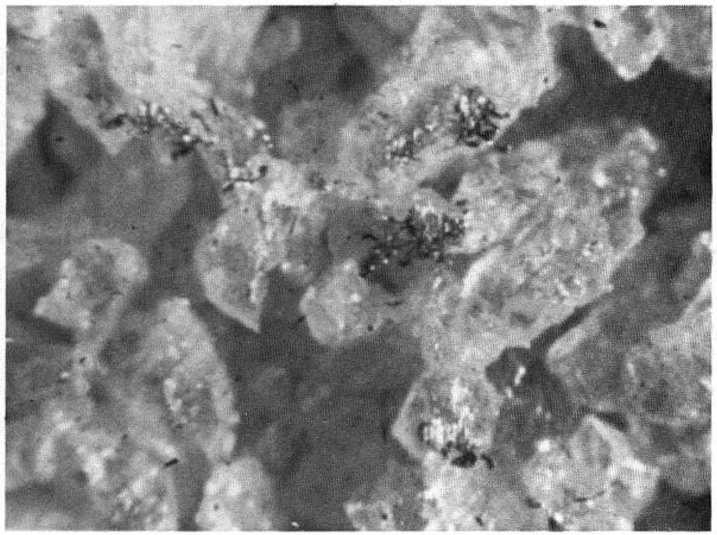


FIGURE 9.5 The grinding surface of an abrasive wheel (A46–J8V), showing grains, porosity, wear flats on grains (see also Fig. 9.9), and metal chips from the workpiece adhering to the grains. Note the random distribution and shape of the abrasive grains. Magnification: 50×.

Grinding (연삭) (2)

- Irregular geometry of grains.
- Highly negative rake angle : -60° or even lower.
- The radial positions of the grains in a grinding wheel vary.
- High cutting speed : ~30m/s

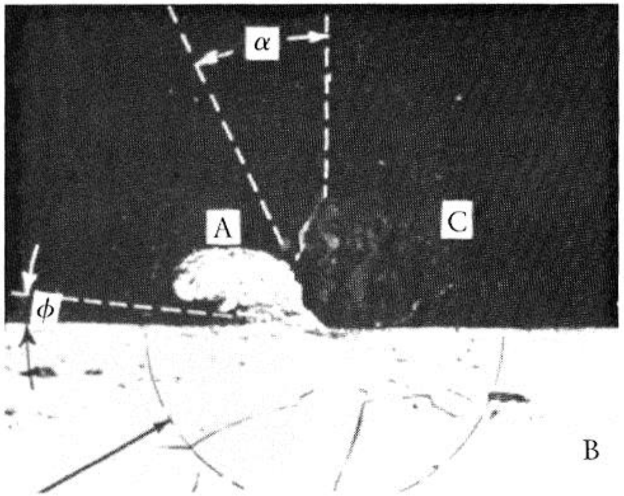
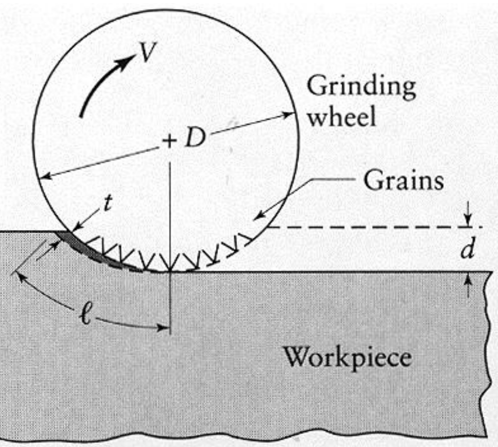


FIGURE 9.6 Grinding chip being produced by a single abrasive grain: (A) chip, (B) workpiece, (C) abrasive grain. Note the large negative rake angle of the grain. The inscribed circle is 0.065 mm (0.0025 in.) in diameter. *Source*: M. E. Merchant.

FIGURE 9.7 Variables in surface grinding. In actual grinding, the wheel depth of cut, *d*, and contact length, *ℓ*, are much smaller than the wheel diameter, *D*. The dimension *t* is called the *grain depth of cut.*



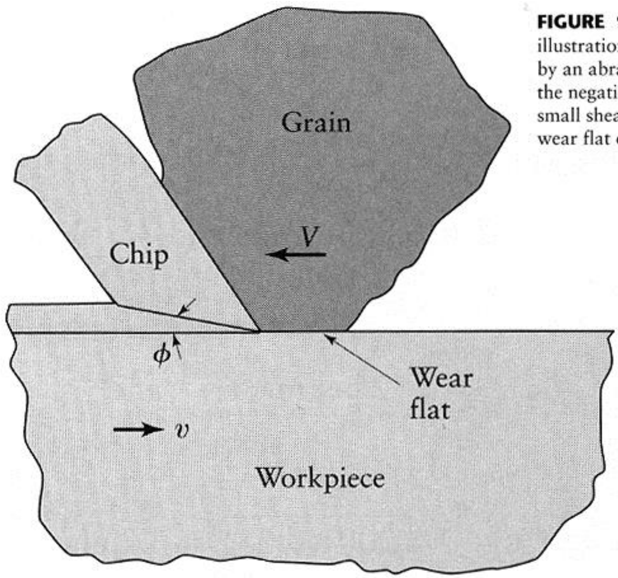


FIGURE 9.9 Schematic illustration of chip formation by an abrasive grain. Note the negative rake angle, the small shear angle, and the wear flat on the grain.

Residual stresses

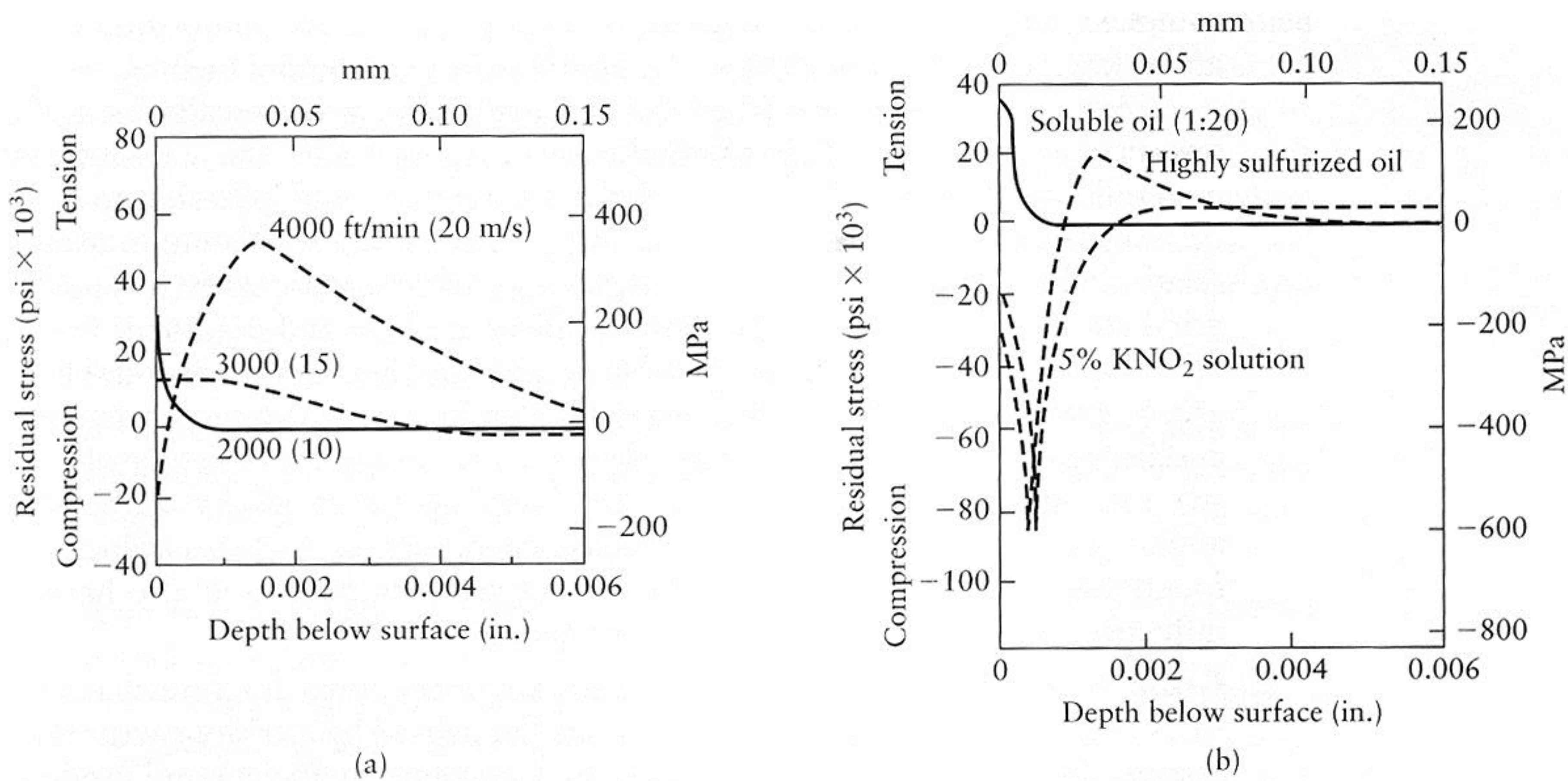


FIGURE 9.10 Residual stresses developed on the workpiece surface in grinding tungsten: (a) effect of wheel speed and (b) effect of grinding fluid. Tensile residual stresses on a surface are detrimental to the fatigue life of ground components. The variables in grinding can be controlled to minimize residual stresses, a process known as *low-stress grinding*. *Source*: After N. Zlatin et al., 1963.

Surface Grinding (평면연삭)

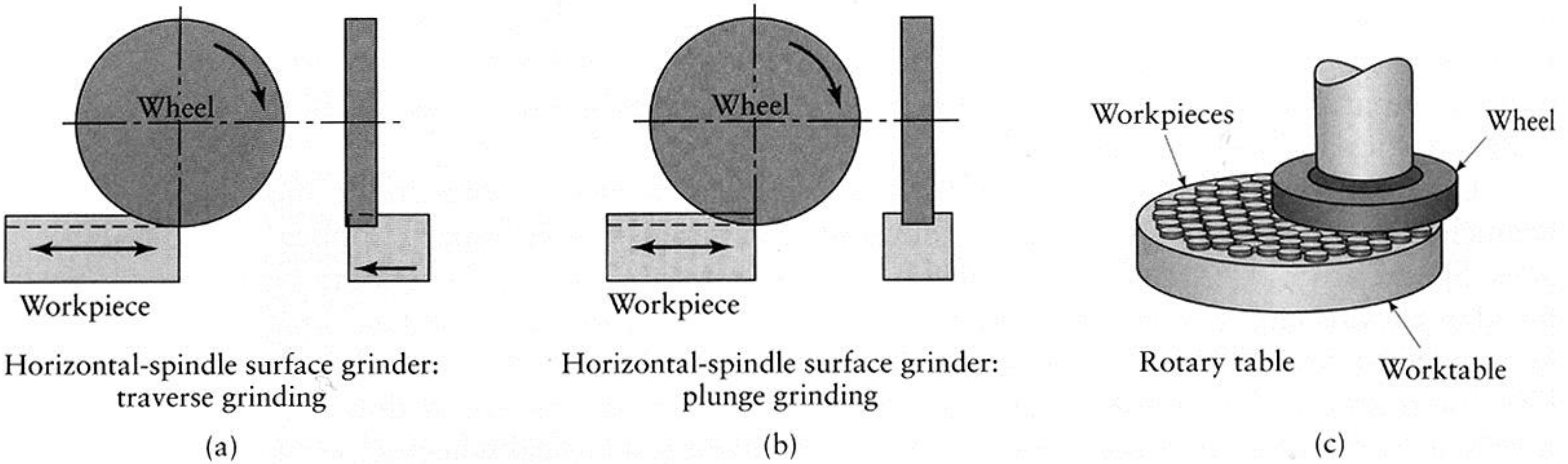


FIGURE 9.12 Schematic illustrations of surface-grinding operations. (a) Traverse grinding with a horizontal-spindle surface grinder. (b) Plunge grinding with a horizontal-spindle surface grinder, producing a groove in the workpiece. (c) Vertical-spindle rotary-table grinder (also known as the *Blanchard-type* grinder).

Cylindrical Grinding (원통연삭)

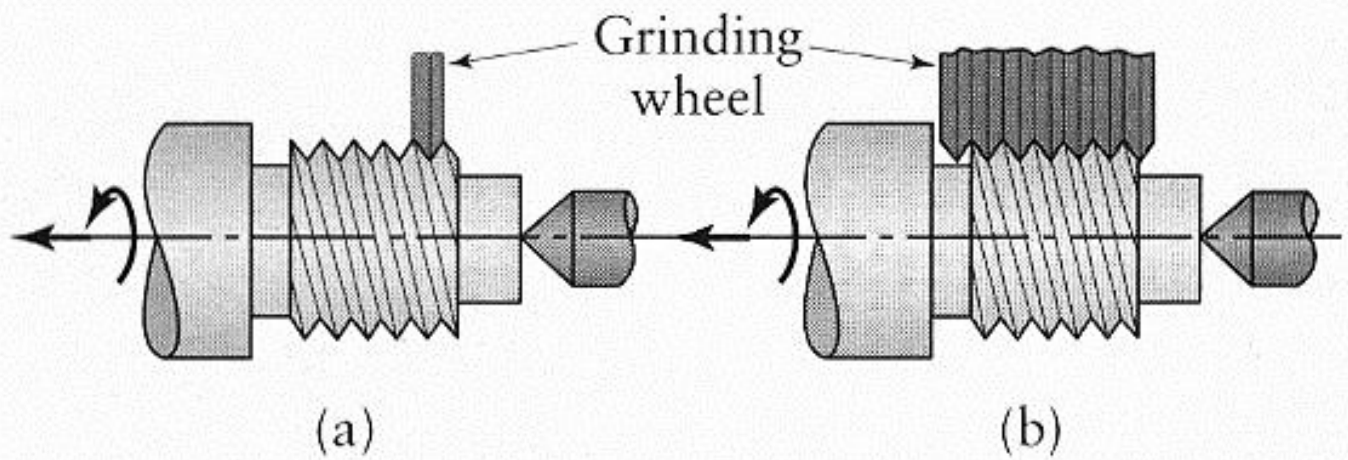


FIGURE 9.14 Thread grinding by (a) traverse and (b) plunge grinding.

Internal Grinding (내면연삭)

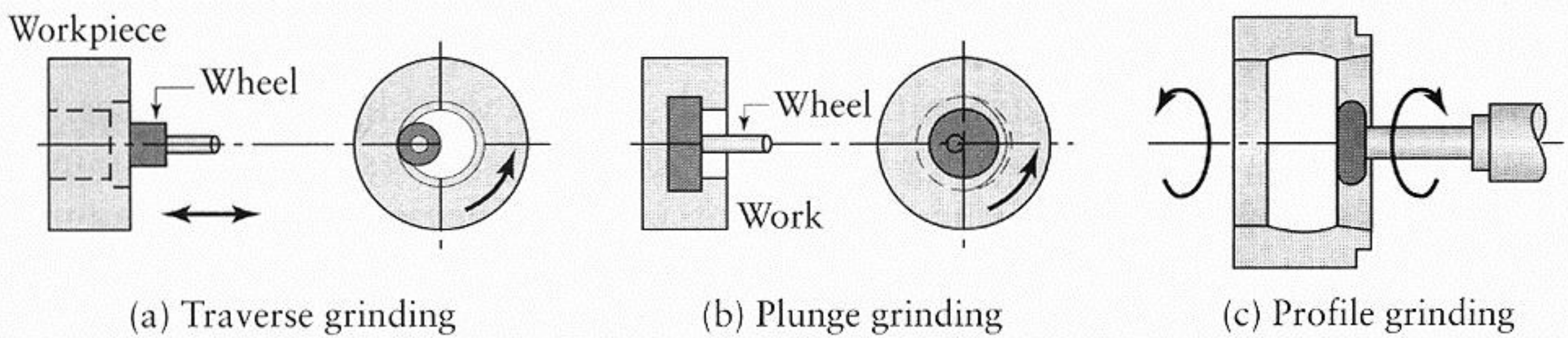


FIGURE 9.15 Schematic illustrations of internal-grinding operations.

Centerless Grinding (무심연삭)

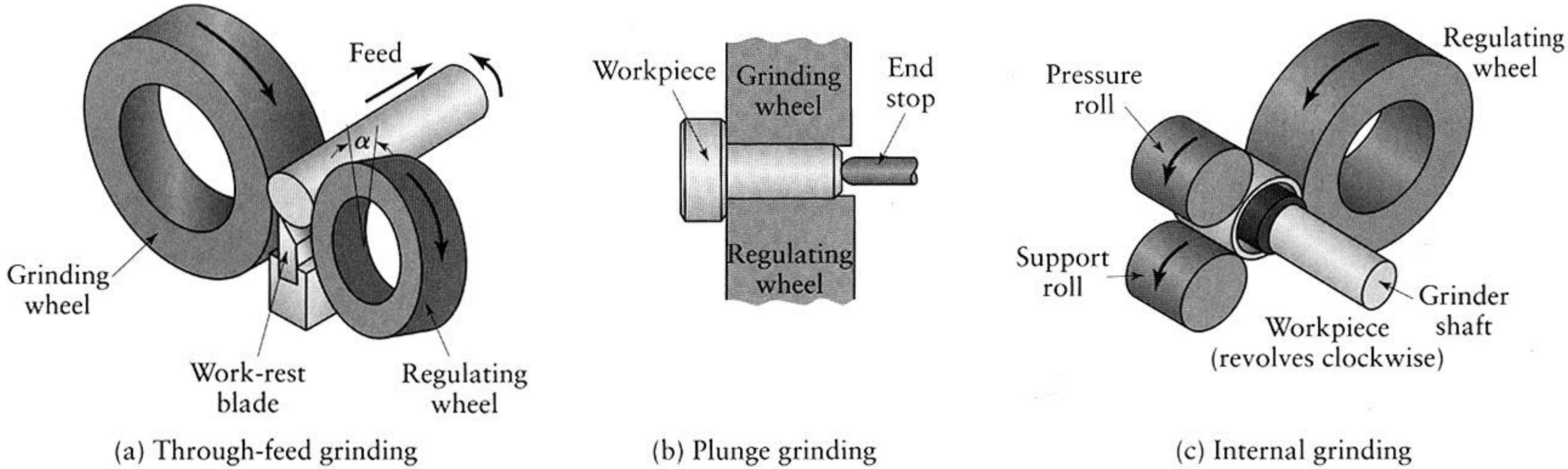


FIGURE 9.16 Schematic illustrations of centerless-grinding operations.

Ultrasonic Machining (초음파가공)

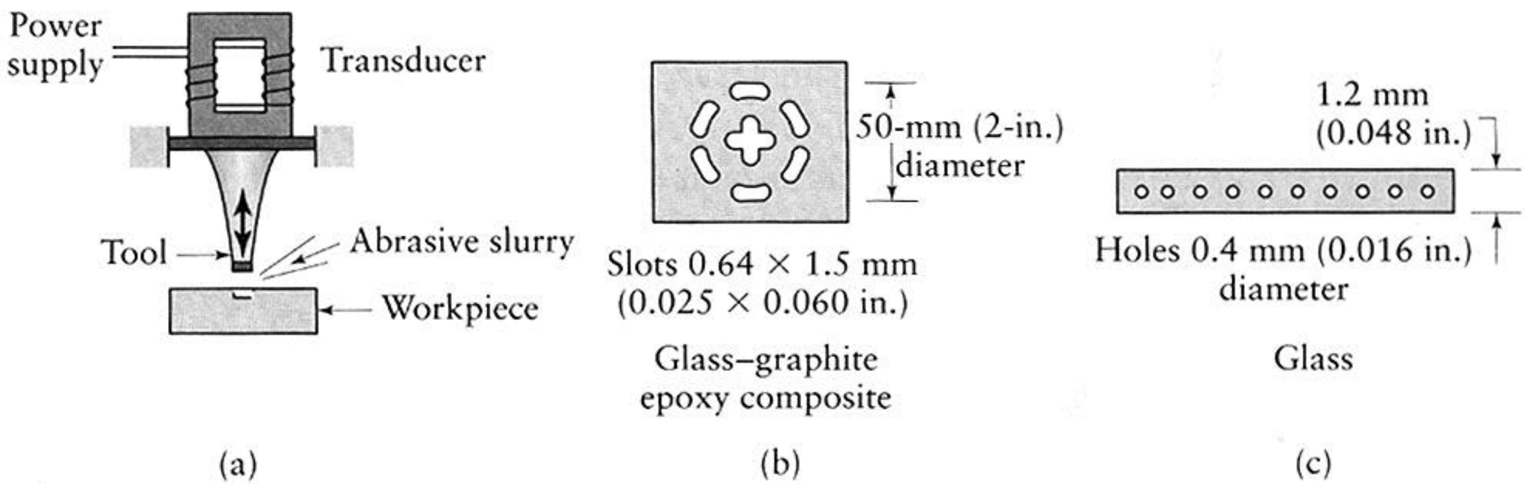


FIGURE 9.19 (a) Schematic illustration of the ultrasonic-machining process by which material is removed through microchipping and erosion. (b) and (c) Typical examples of holes produced by ultrasonic machining. Note the dimensions of cut and the types of workpiece materials.

Finishing Operations (마무리공정)

- **Honing (호닝)**
  - Superfinishing

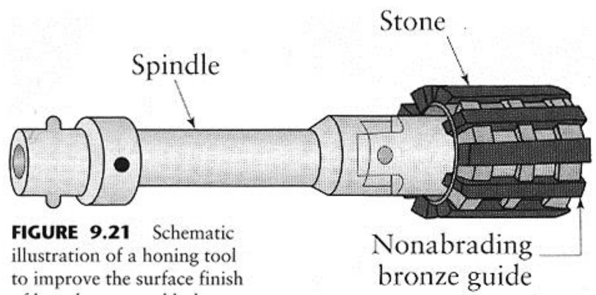


FIGURE 9.21 Schematic illustration of a honing tool to improve the surface finish of bored or ground holes.

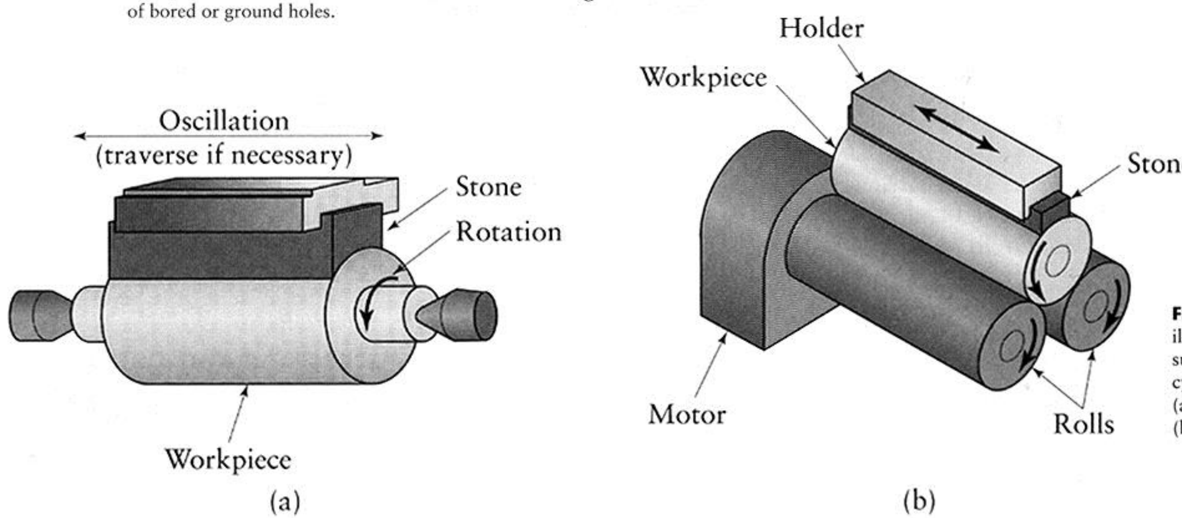


FIGURE 9.22 Schematic illustration of the superfinishing process for a cylindrical part: (a) cylindrical microhoning; (b) centerless microhoning.

- **Lapping (래핑)**

- **Polishing (연마) / Buffing (버핑)**

Lapping

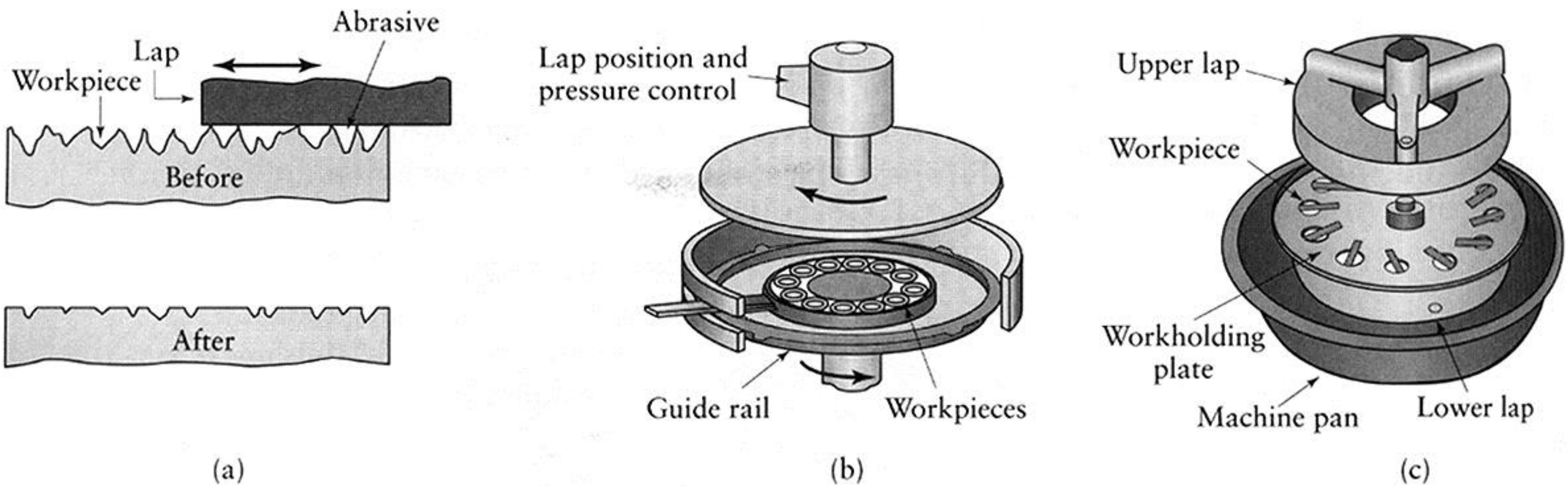


FIGURE 9.23 (a) Schematic illustration of the lapping process. (b) Production lapping on flat surfaces. (c) Production lapping on cylindrical surfaces.

TABLE 9.4

General Characteristics of Advanced Machining Processes

Process	Characteristics	Process Parameters and Typical Material Removal Rate or Cutting Speed
Chemical machining (CM)	Shallow removal (up to 12 mm) on large flat or curved surfaces; blanking of thin sheets; low tooling and equipment cost; suitable for low production runs.	0.025–0.1 mm/min.
Electrochemical machining (ECM)	Complex shapes with deep cavities; highest rate of material removal; expensive tooling and equipment; high power consumption; medium to high production quantity.	V: 5–25 dc; A: 1.5–8 A/mm^2; 2.5–12 mm/min, depending on current density.
Electrochemical grinding (ECG)	Cutting off and sharpening hard materials, such as tungsten-carbide tools; also used as a honing process; higher material removal rate than grinding.	A: 1–3 A/mm^2; typically 1500 mm^3/min per 1000 A.
Electrical-discharge machining (EDM)	Shaping and cutting complex parts made of hard materials; some surface damage may result; also used for grinding and cutting; versatile; expensive tooling and equipment.	V: 50–380; A: 0.1–500; typically 300 mm^3/min.
Wire EDM	Contour cutting of flat or curved surfaces; expensive equipment.	Varies with workpiece material and its thickness.
Laser-beam machining (LBM)	Cutting and hole making on thin materials; heat-affected zone; does not require a vacuum; expensive equipment; consumes much energy; extreme caution required in use.	0.50–7.5 m/min.
Electron-beam machining (EBM)	Cutting and hole making on thin materials; very small holes and slots; heat-affected zone; requires a vacuum; expensive equipment.	1–2 mm^3/min.
Water-jet machining (WJM)	Cutting all types of nonmetallic materials to 25 mm (1 in.) and greater in thickness; suitable for contour cutting of flexible materials; no thermal damage; environmentally safe process.	Varies considerably with workpiece material.
Abrasive water-jet machining (AWJM)	Single or multilayer cutting of metallic and nonmetallic materials.	Up to 7.5 m/min.
Abrasive-jet machining (AJM)	Cutting, slotting, deburring, flash removal, etching, and cleaning of metallic and nonmetallic materials; tends to round off sharp edges; some hazard because of airborne particulates.	Varies considerably with workpiece material.

Chemical Machining (화학적가공)

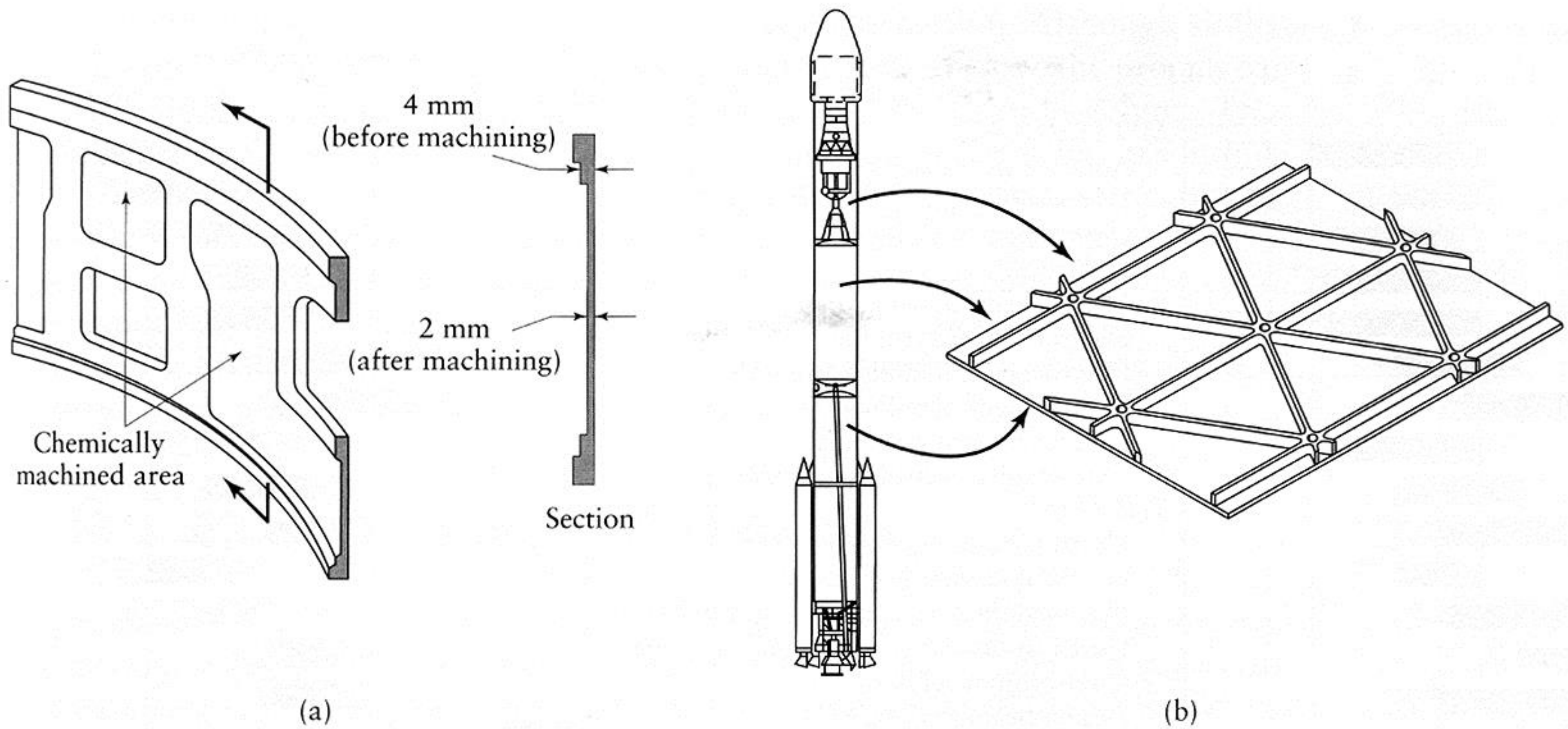


FIGURE 9.25 (a) Missile skin-panel section contoured by chemical milling to improve the stiffness-to-weight ratio of the part. (b) Weight reduction of space launch vehicles by chemical milling of aluminum-alloy plates. These panels are milled after the plates have first been formed into shape, such as by roll forming or stretch forming. The design of the chemically machined rib patterns can readily be modified at minimal cost. *Source: Advanced Materials and Processes*, ASM International, December 1990, p. 43.

Electrochemical Machining / Grinding

- **ECM (전해가공)**

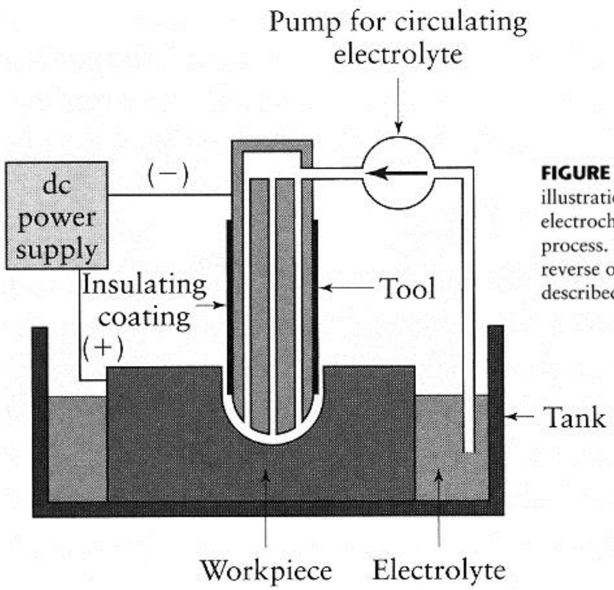


FIGURE 9.29 Schematic illustration of the electrochemical-machining process. This process is the reverse of electroplating, described in Section 4.5.1.

- **ECG (전해연삭)**

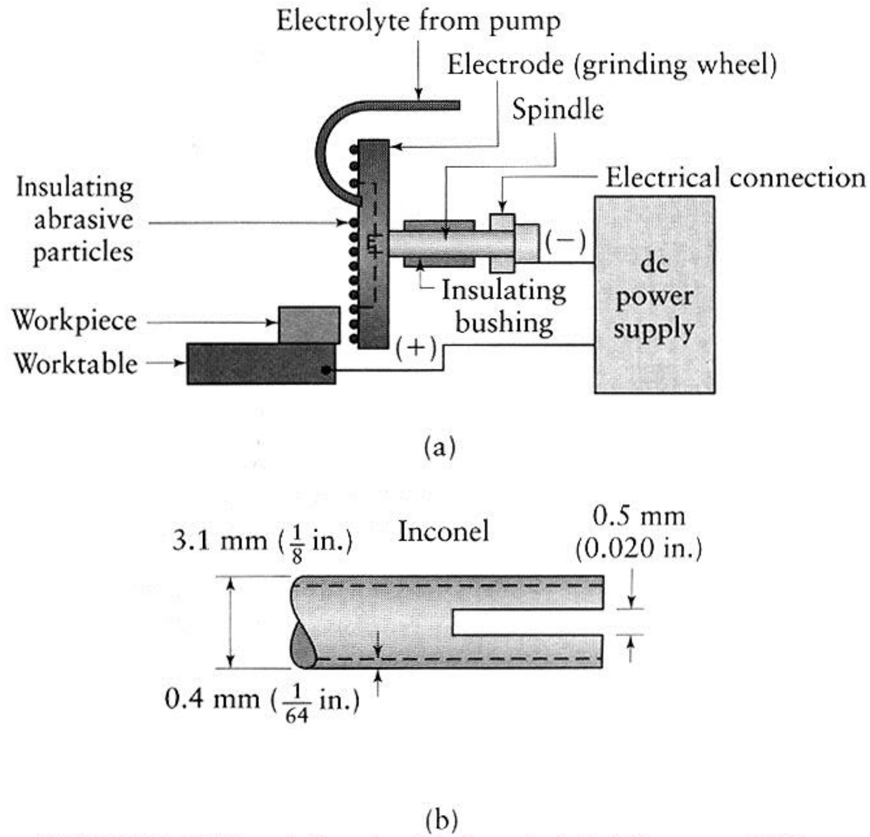


FIGURE 9.31 (a) Schematic illustration of the electrochemical-grinding process. (b) Thin slot produced on a round nickel-alloy tube by this process.

Electro Discharge Machining (EDM)

- **EDM (방전가공)**

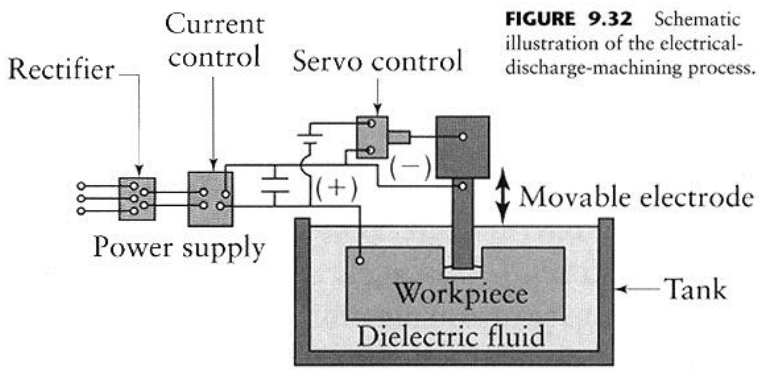


FIGURE 9.32 Schematic illustration of the electrical-discharge-machining process.

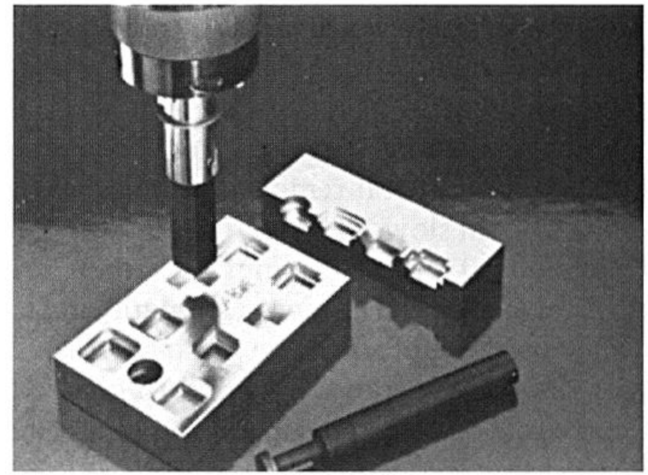
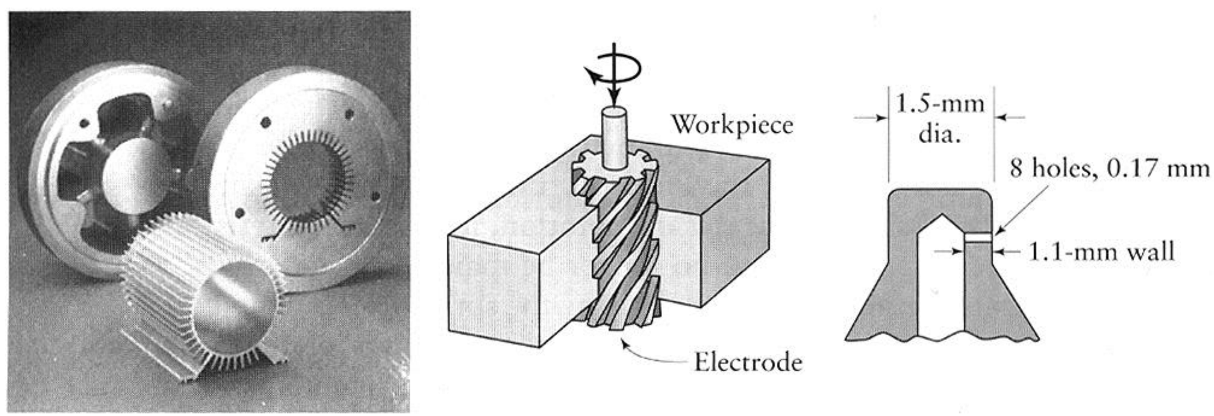


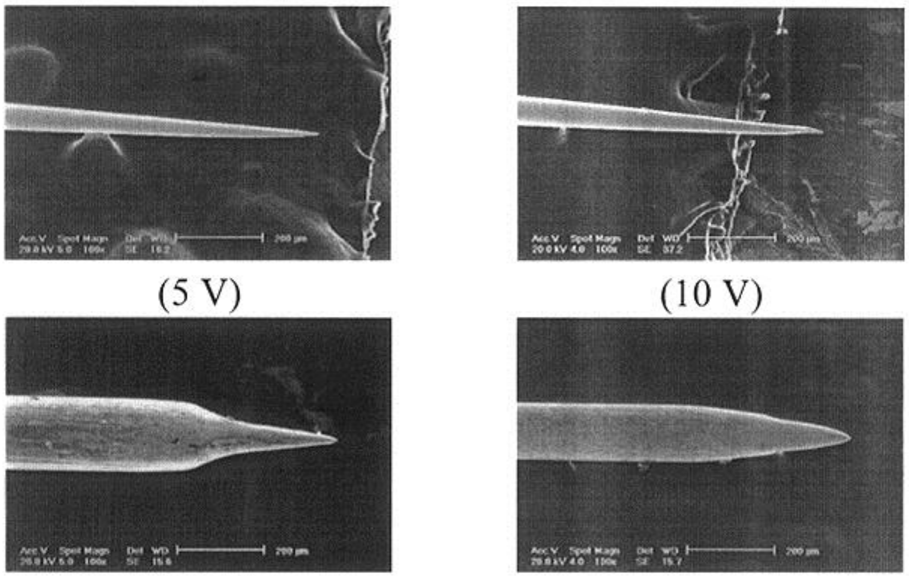
FIGURE 9.34 Stepped cavities produced with a square electrode by EDM. The workpiece moves in the two principal horizontal directions, and its motion is synchronized with the downward movement of the electrode to produce various cavities. Also shown is a round electrode capable of producing round or elliptical cavities. *Source*: Courtesy of AGIE USA Ltd.



(a) (b) (c)

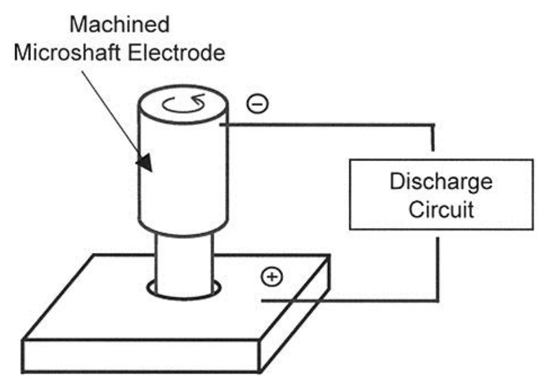
FIGURE 9.33 (a) Examples of cavities produced by the electrical-discharge-machining process, using shaped electrodes. The two round parts (rear) are the set of dies for extruding the aluminum piece shown in front. *Source*: Courtesy of AGIE USA Ltd. (b) A spiral cavity produced by a rotating electrode. *Source*: *American Machinist*. (c) Holes in a fuel-injection nozzle made by electrical-discharge machining. Material: Heat-treated steel.

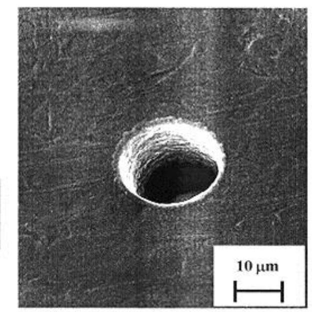
Micro ECM / EDM



(5 V) (10 V)

(15 V) (20 V)





Diameter 20μm
Depth 50μm
SUS 304

Ref.: Prof. C. N. Chu

Wire EDM

- **Wire EDM (방전와이어 커팅)**

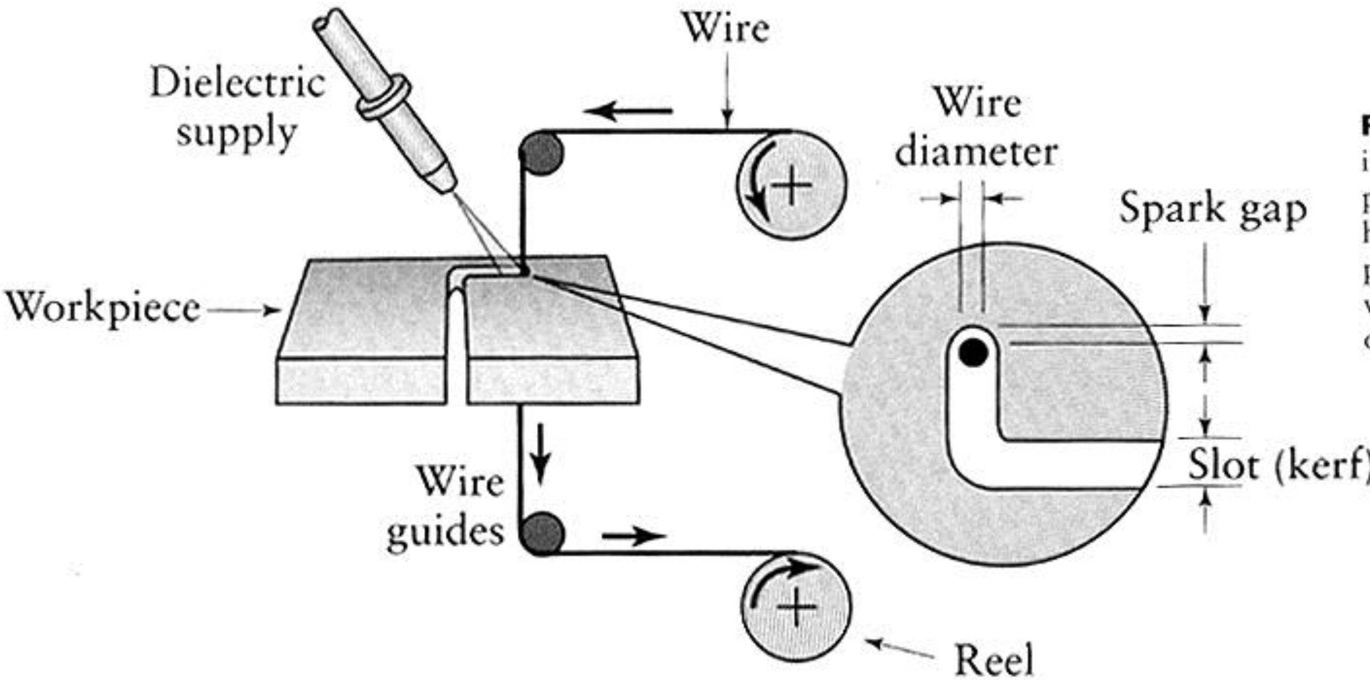


FIGURE 9.35 Schematic illustration of the wire EDM process. As much as 50 hours of machining can be performed with one reel of wire, which is then discarded or recycled.

Laser beam machining (LBM)

- **Light Amplification by Stimulated Emission of Radiation (LASER)**

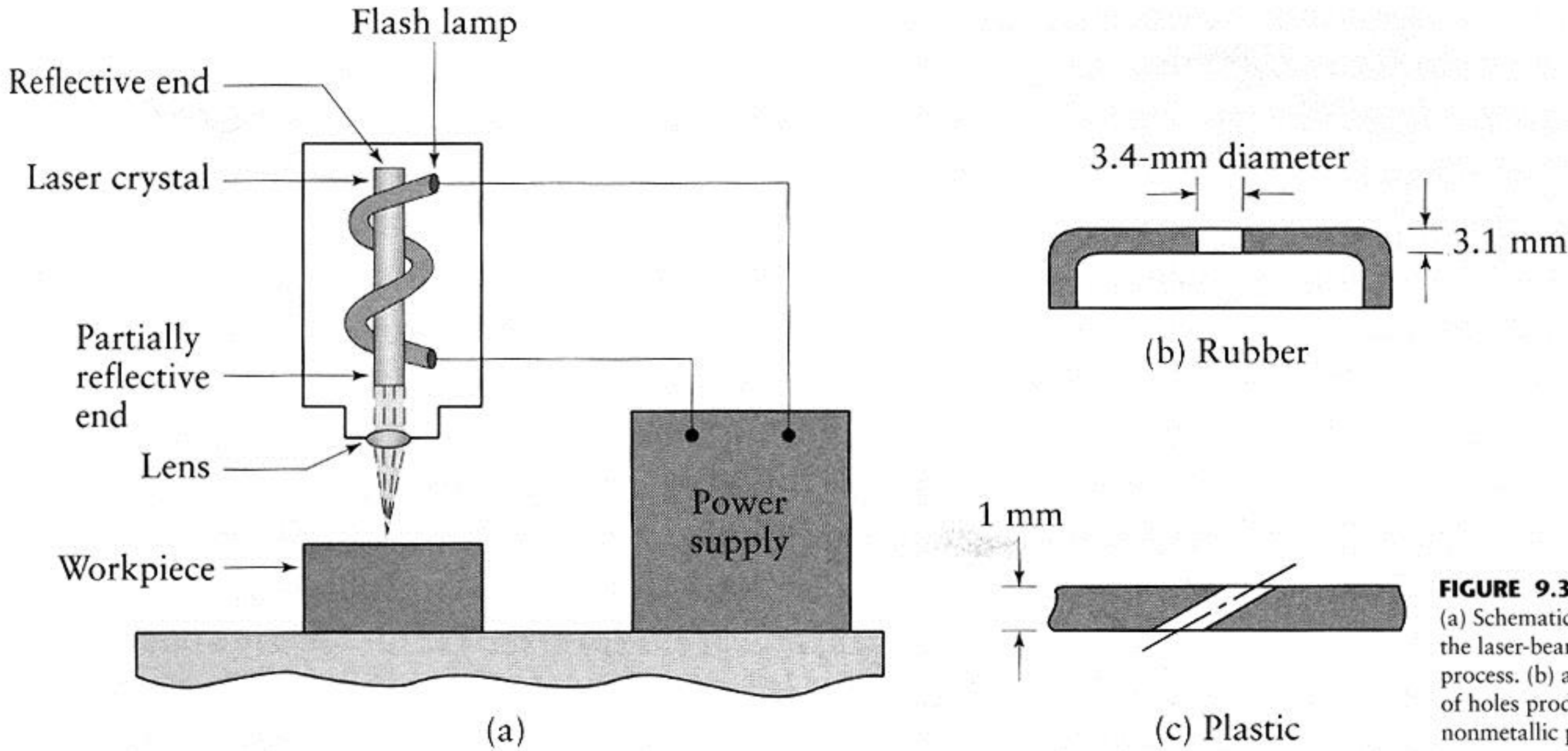
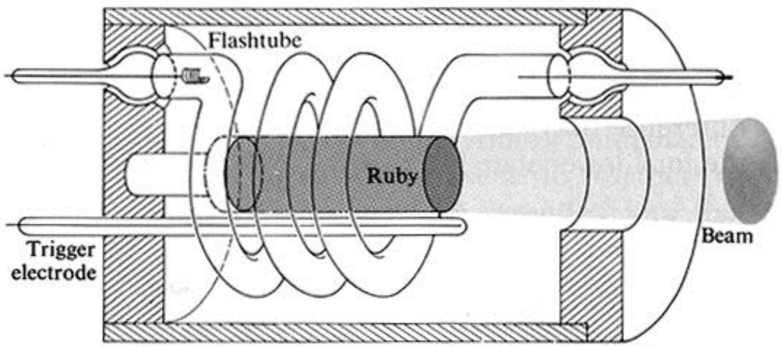
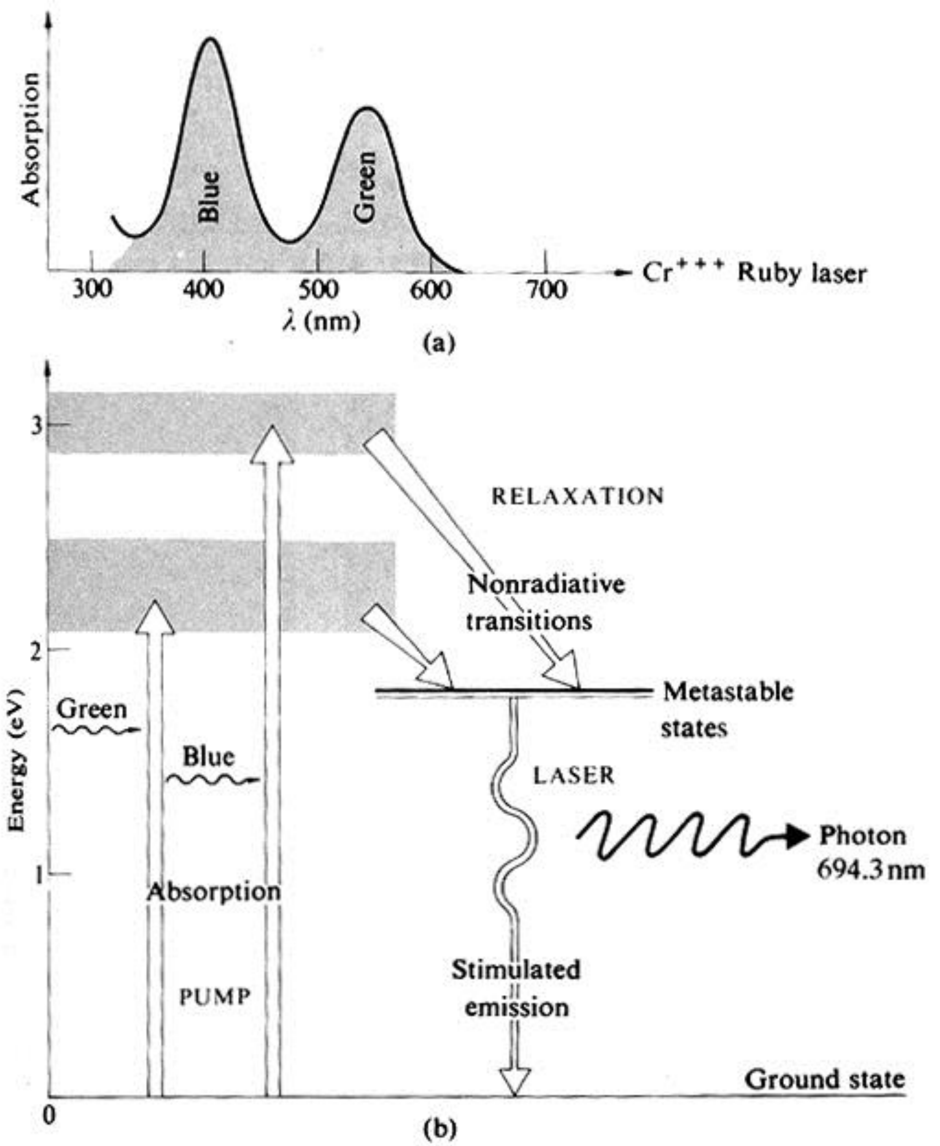


FIGURE 9.36 (a) Schematic illustration of the laser-beam-machining process. (b) and (c) Examples of holes produced in nonmetallic parts by LBM.

First Ruby Laser

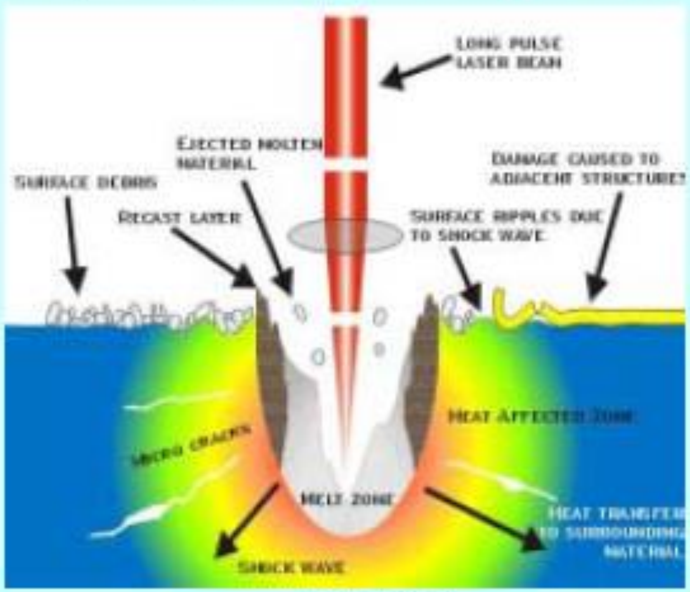
1960, Theodore Maiman, USA





Pulsed Laser

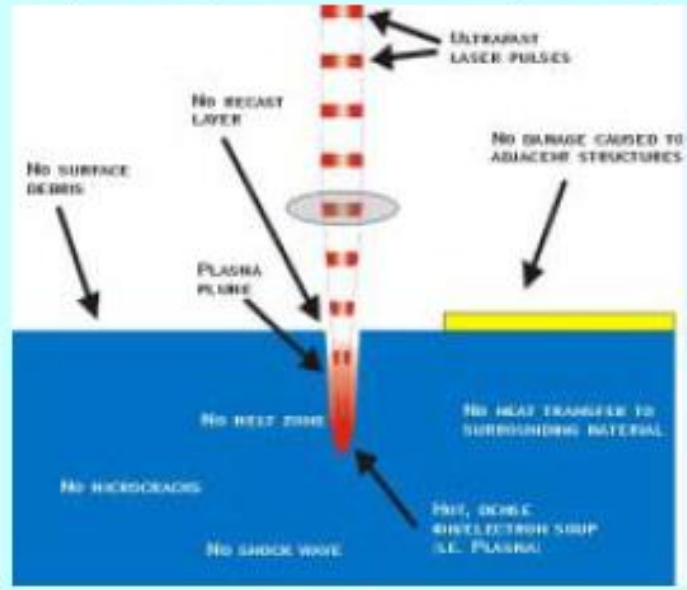
ns(나노초) : nanosecond(10^{-9} sec)



ns 가공 원리

4.2Joule/cm² @ 3.3ns

fs(펨토초) : femtosecond(10^{-15}sec)



fs 가공원리

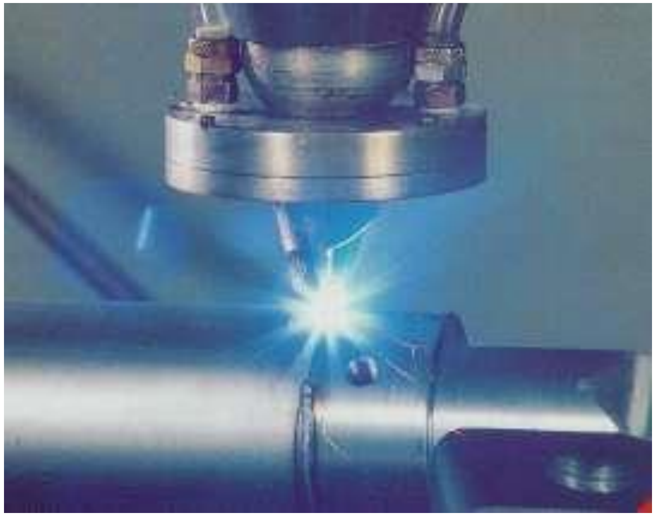
0.5Joule/cm² @ 200fs

금속 박판, 두께=100μm

Applications of Laser

Cutting

Heat treating

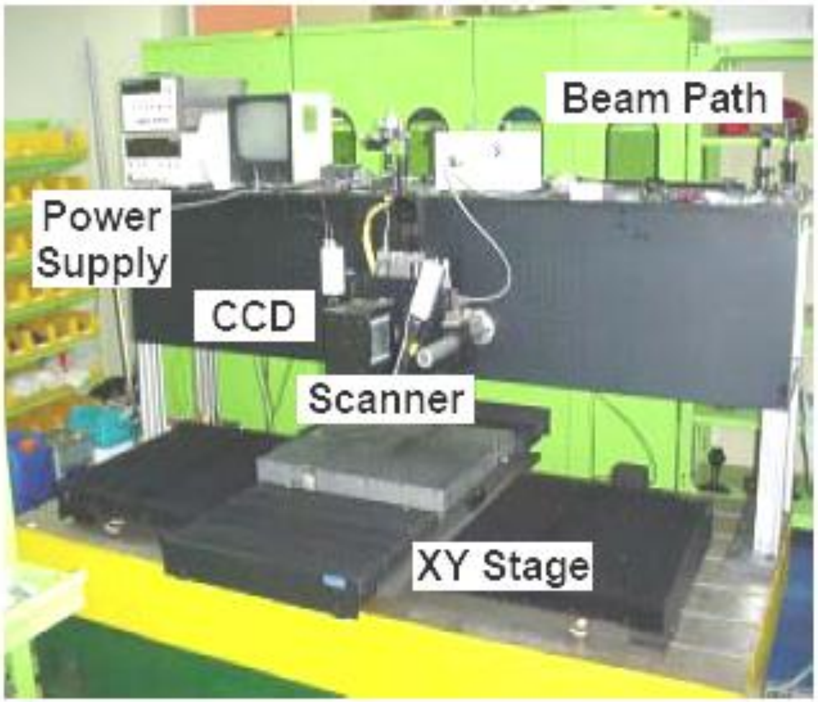


Welding

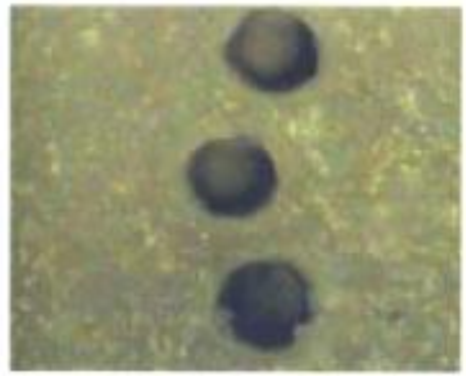
Table 9.5 General Applications of Laser in Manufacturing

Applications	Workpiece materials	Laser type
Cutting	Metal	PCO_2, $CWCO_2$, Nd:YAG, ruby
	Plastics	$CWCO_2$
	Ceramic	PCO_2
Drilling	Metal Plastics	PCO_2, $CWCO_2$, Nd:glass, ruby Excimer
Marking	Metal	PCO_2, Nd:YAG
	Plastics	Excimer
	Ceramic	Excimer
Surface treatment	Matal	$CWCO_2$
Welding	Matal	PCO_2, $CWCO_2$, Nd:YAG, Nd:glass, ruby

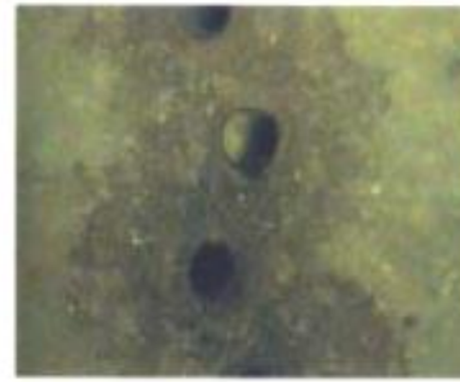
Laser Micro Drilling



- Ceramic : 300㎛ 두께

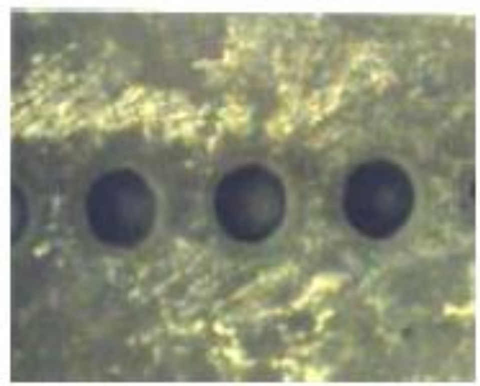


Entrance (90㎛)

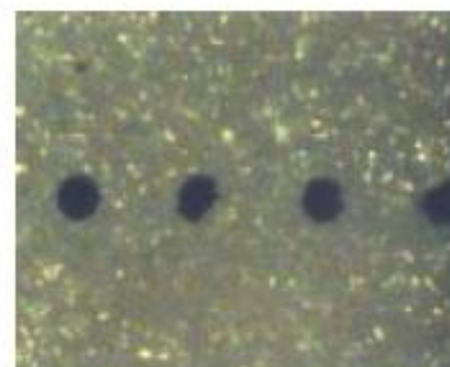


Exit (70㎛)

- Ceramic : 500㎛ 두께

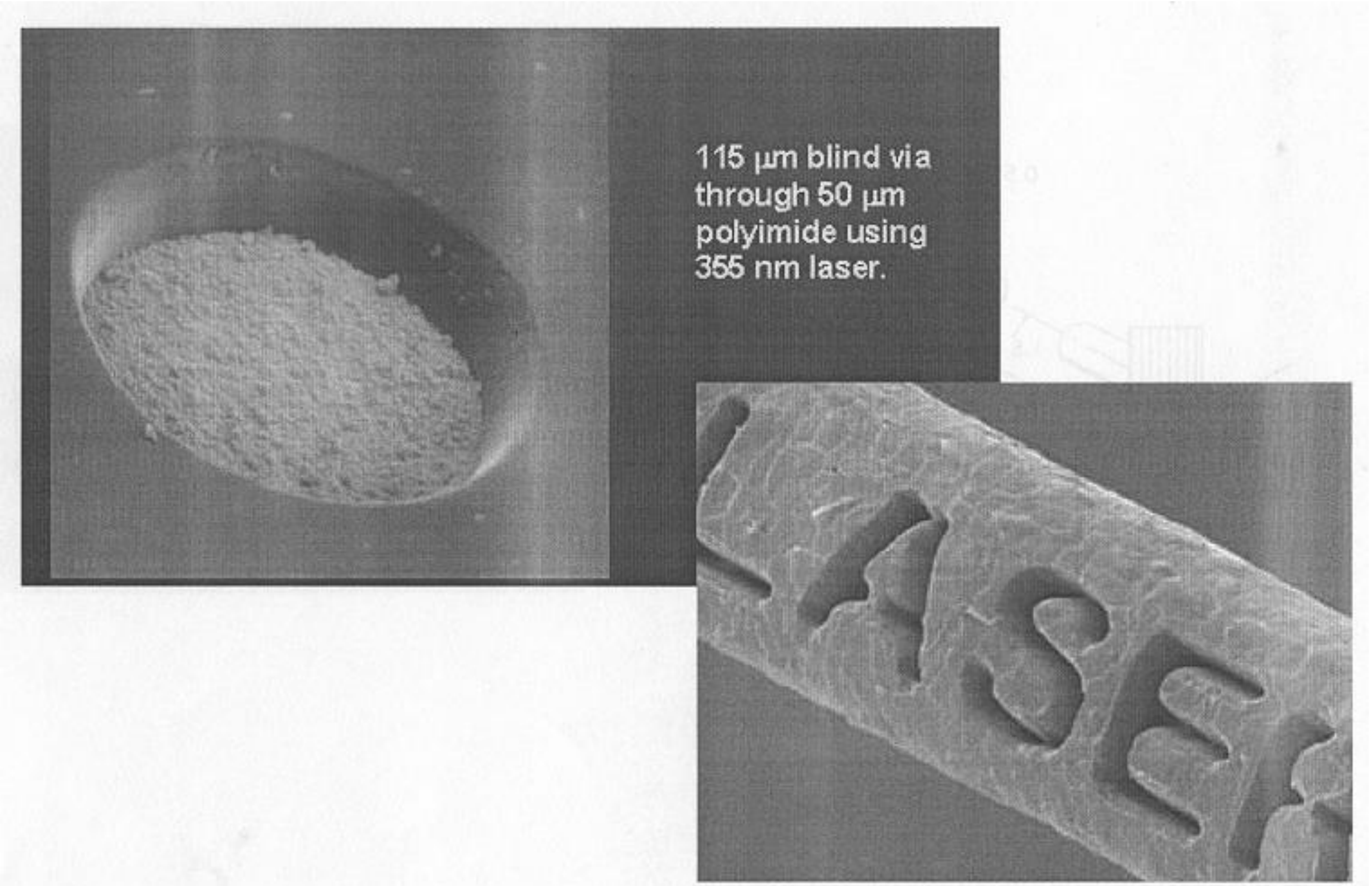


Entrance (85㎛)



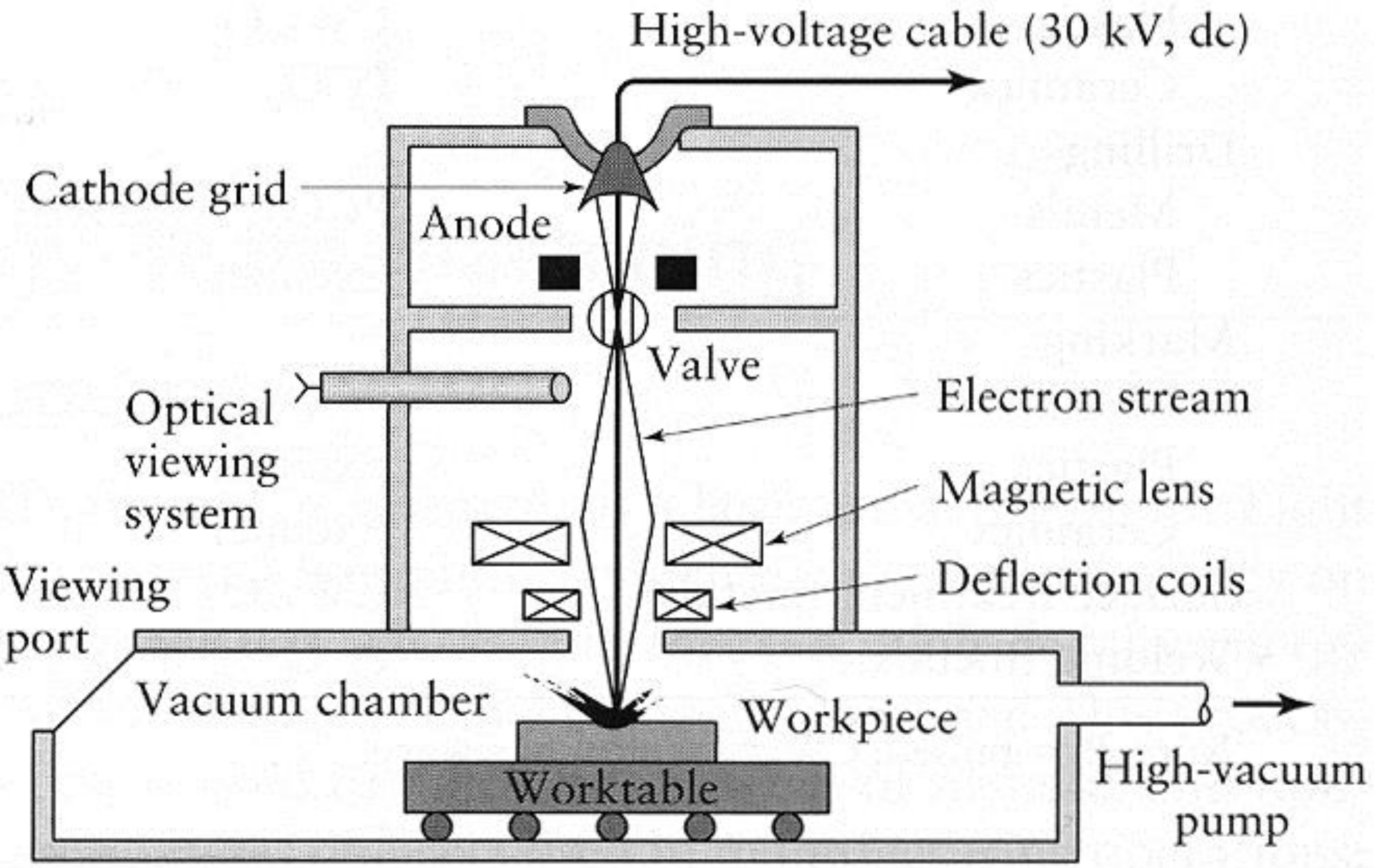
Exit (50㎛)

Micro LBM


115 µm blind via
through 50 µm
polyimide using
355 nm laser.
ASE

Electron Beam Machining

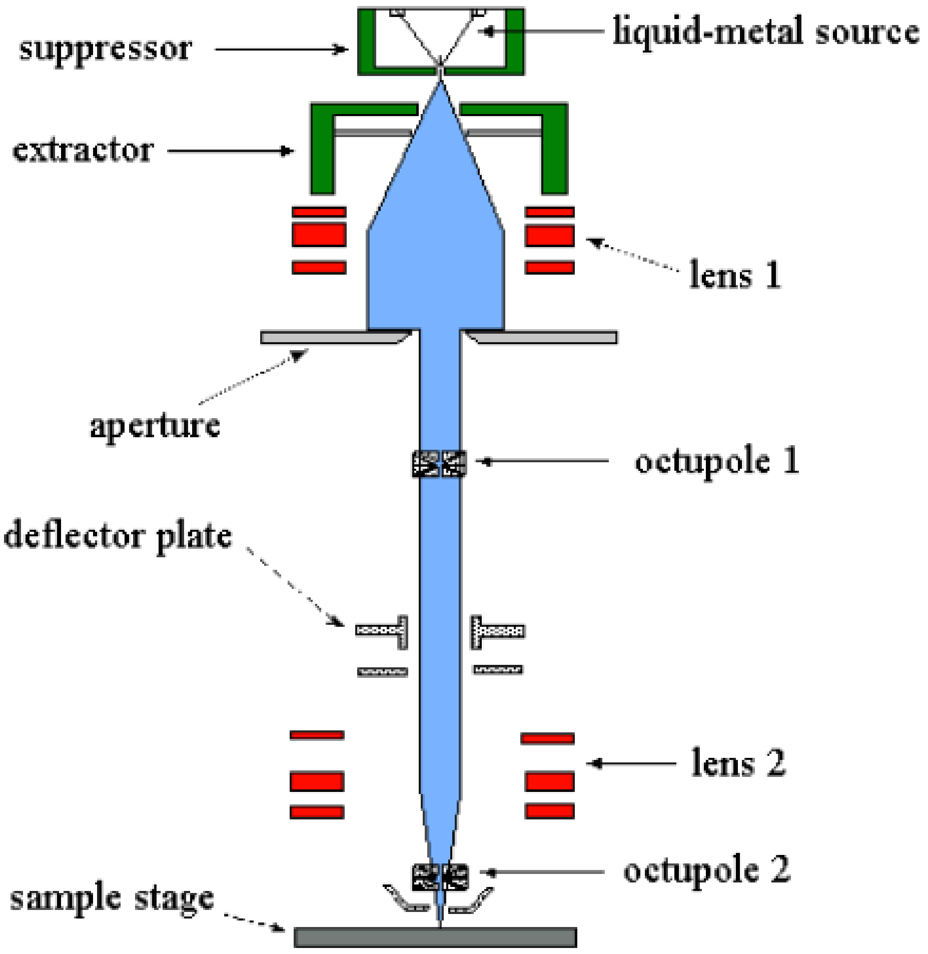
FIGURE 9.37 Schematic illustration of the electron-beam-machining process. Unlike LBM, this process requires a vacuum, and hence workpiece size is limited.



Focused Ion Beam System (1)

- **What is Focused Ion Beam ?**
  - Nanoscale Hybrid Fabrication Tool
    - Sputtering
    - Deposition

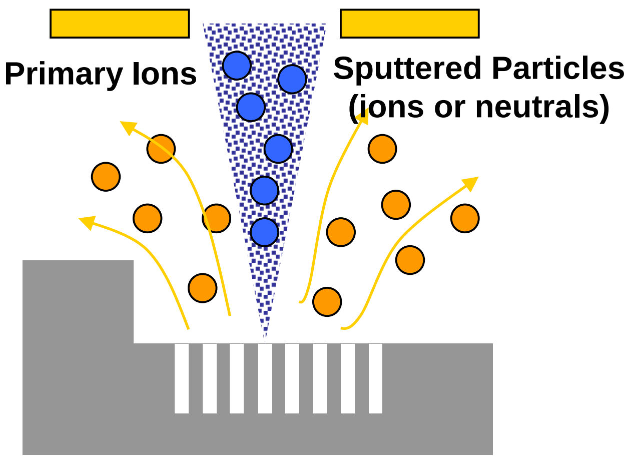
- **FIB Components**
  - Ion Gun (10^{-7} torr)
    - Liquid Metal Ion Source (LMIS)
  - Ion Optical Column
    - Electrostatic Lens
    - Variable Aperture
  - Vacuum Chamber (10^{-6} torr)
  - Specimen Stage
    - Eucentric Stage
  - Gas Nozzle
    - Carbon
    - Platinum
    - Tungsten



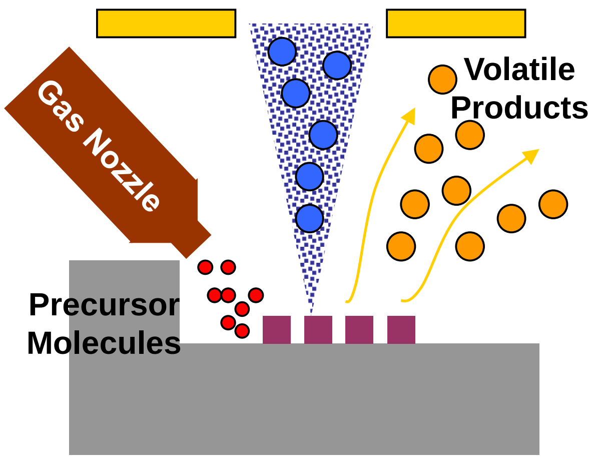
Schematics of FIB System

Focused Ion Beam System (2)

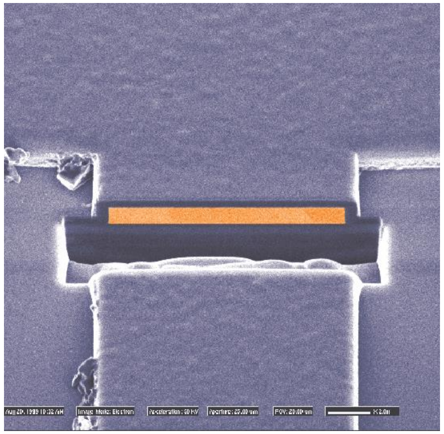
- **Hybrid Fabrication Methods**

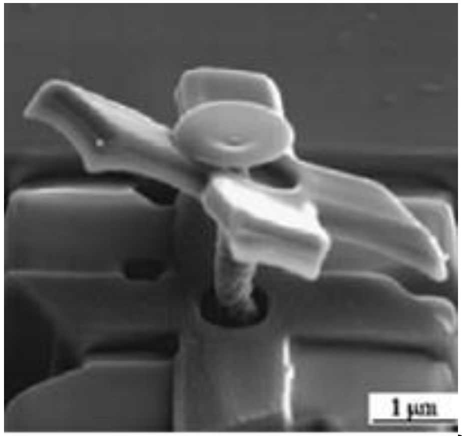


Sputtering (Milling)

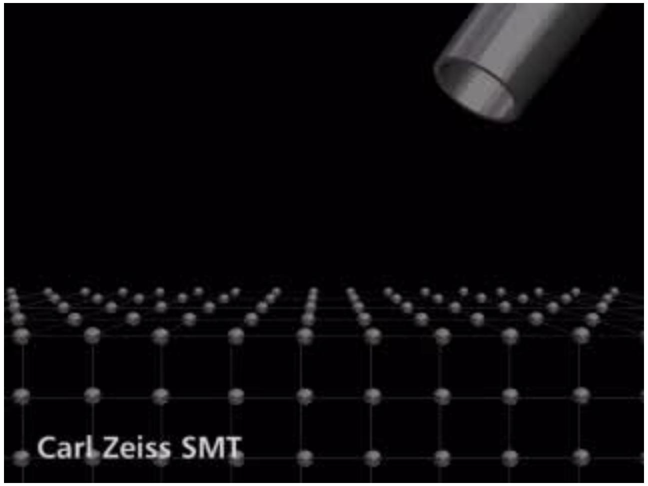


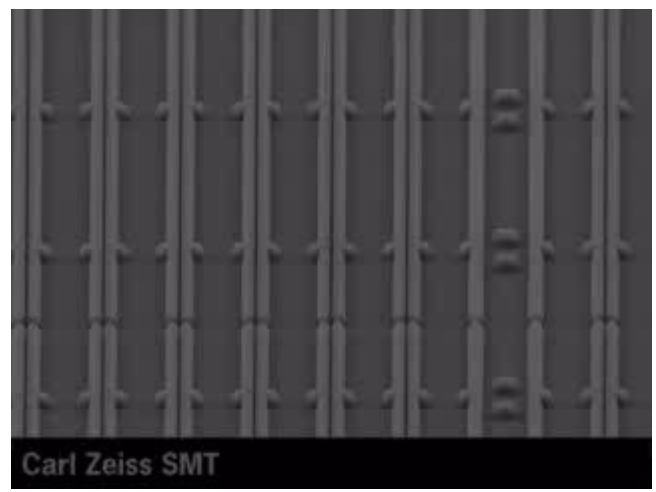
Deposition





Focused Ion Beam System (3)





Case study: Stent

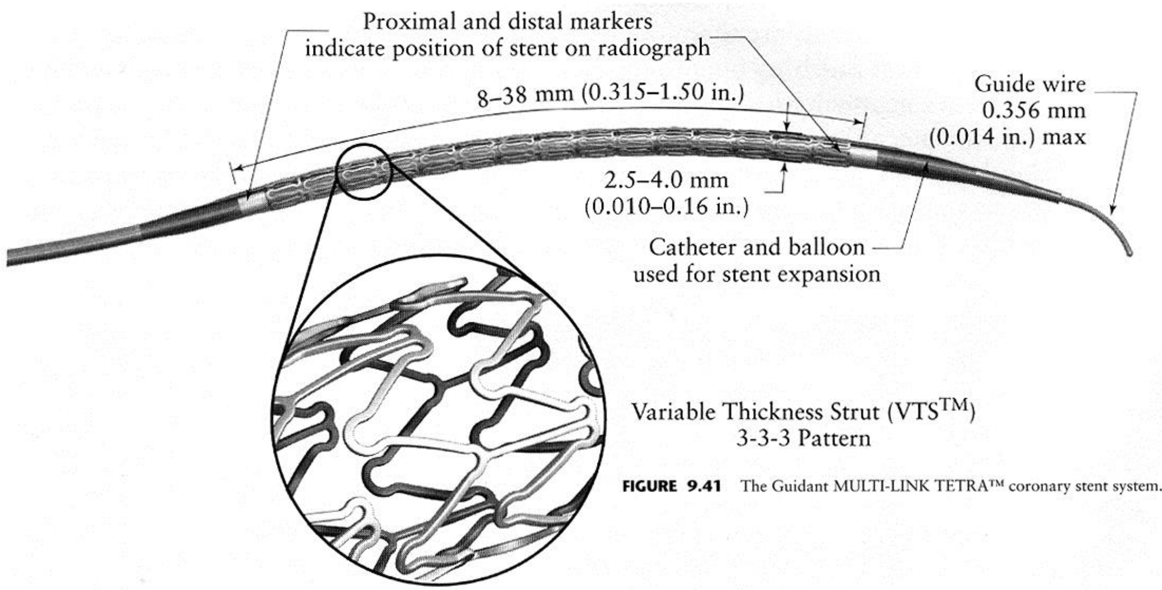


FIGURE 9.41 The Guidant MULTI-LINK TETRA™ coronary stent system.

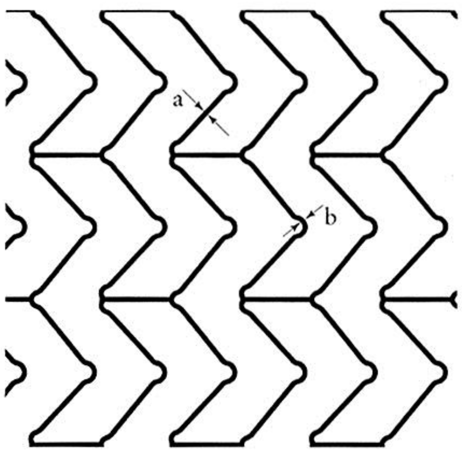


FIGURE 9.42 Detail of the 3-3-3 MULTI-LINK TETRA™ pattern.

Notes:
a. 0.12 mm (0.0049 in.) section thickness to provide radiopacity
b. 0.091 mm (0.0036 in.) thickness for flexibility

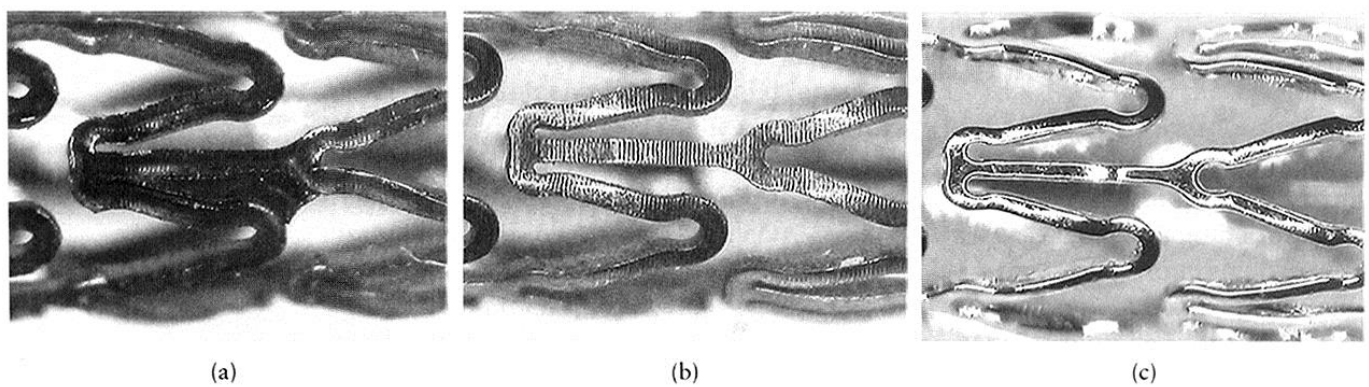
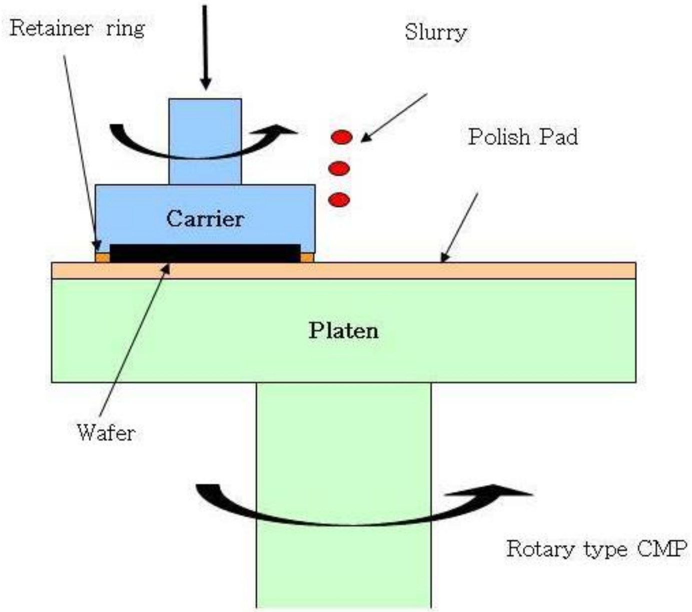
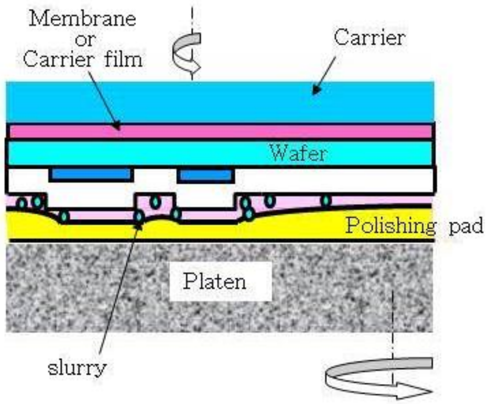


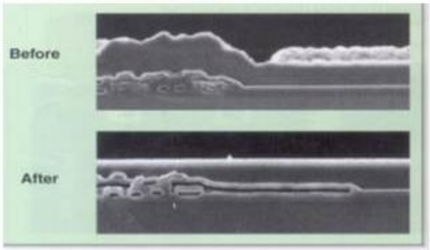
FIGURE 9.43 Evolution of the stent surface. (a) MULTI-LINK TETRA™ after lasing. Note that a metal slug is still attached. (b) After removal of slag. (c) After electropolishing.

CMP

Planarization using both chemical and mechanical process

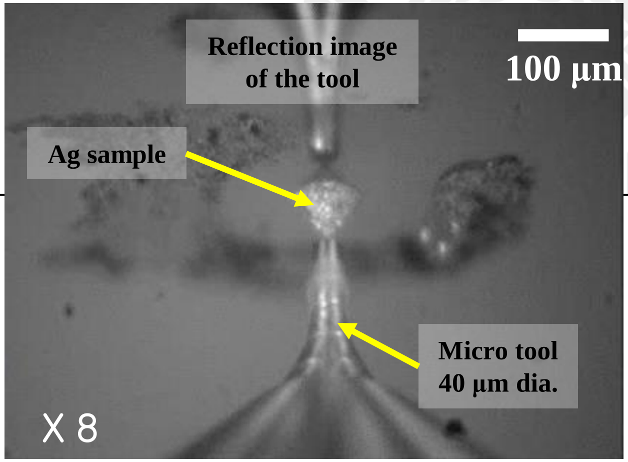




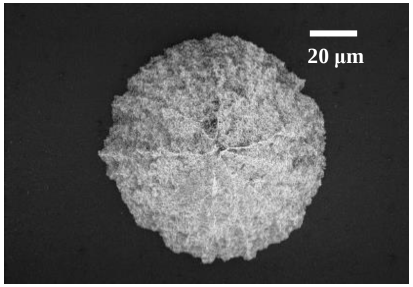


Nano grinding

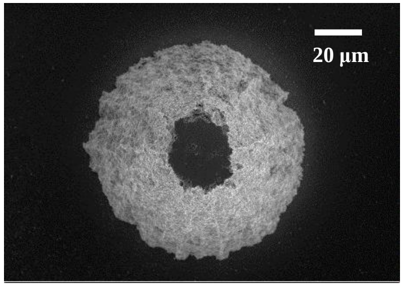
- **Local planarization**
  - Height control (resolution < 1 um)
  - Surface roughness (Ra < 20 nm)
- **Micro Tool**
  - Tungsten Carbide (WC ISO K30)



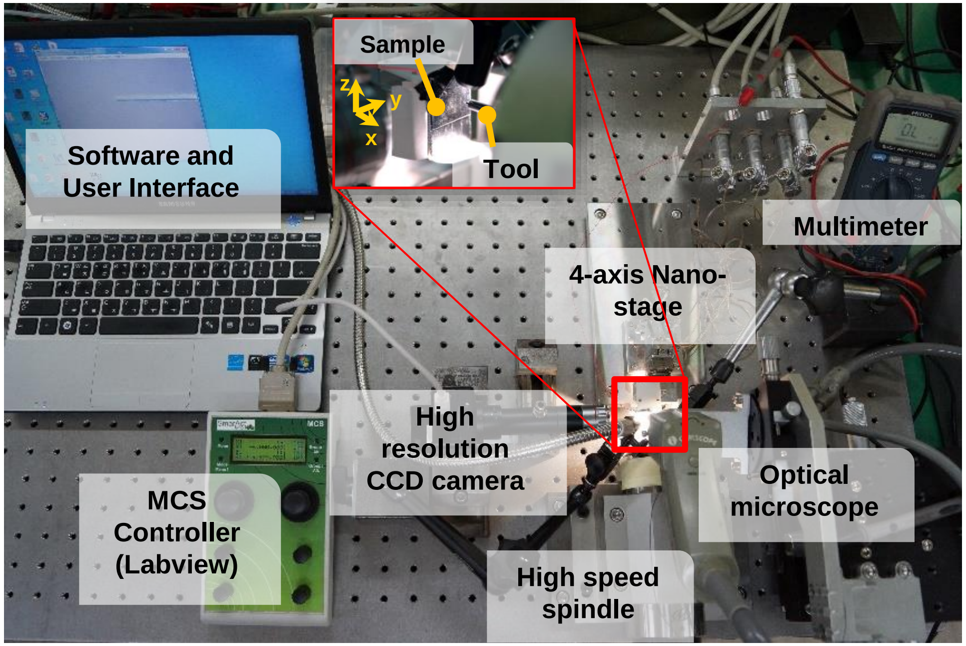
Movie. Nano grinding process



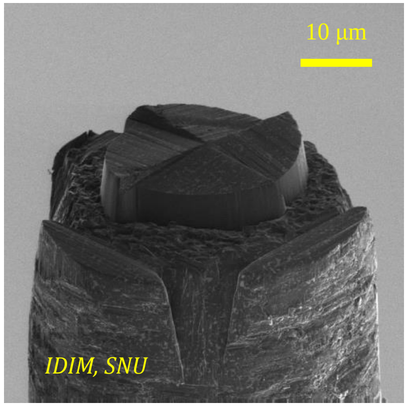
Before



After

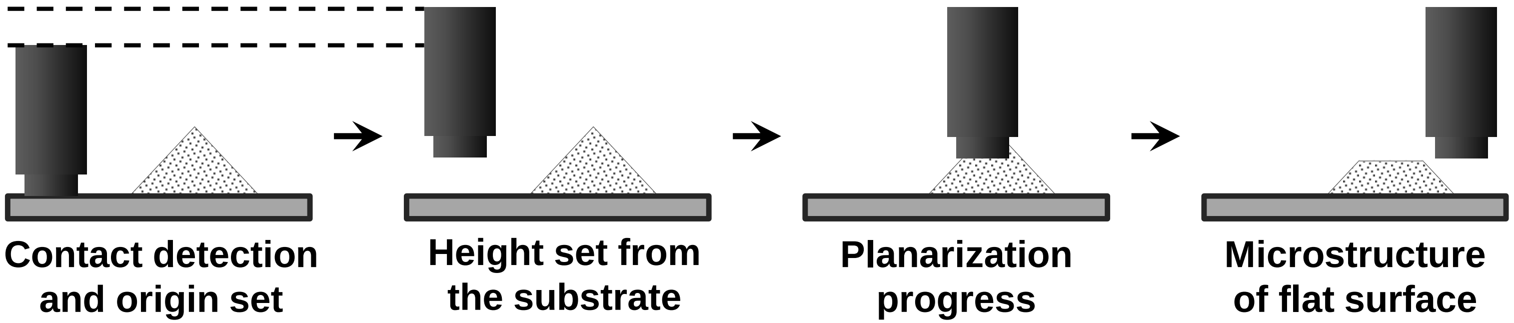


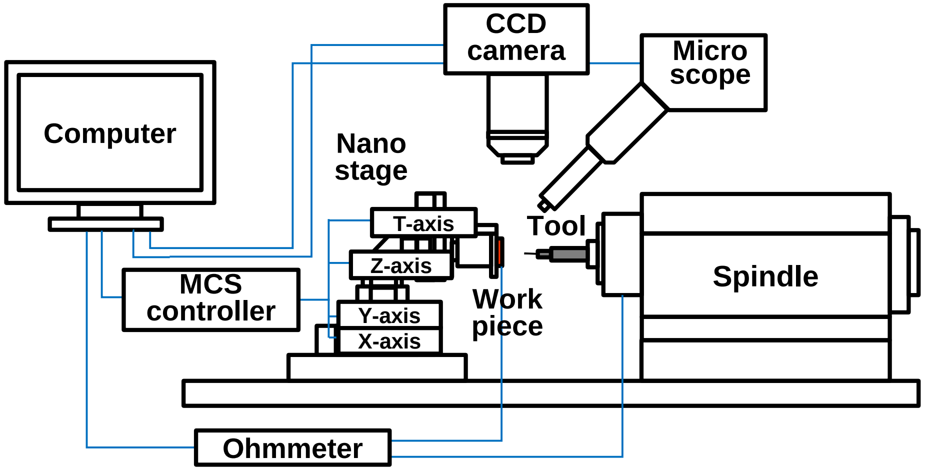
Hardware configuration of nano grinding system

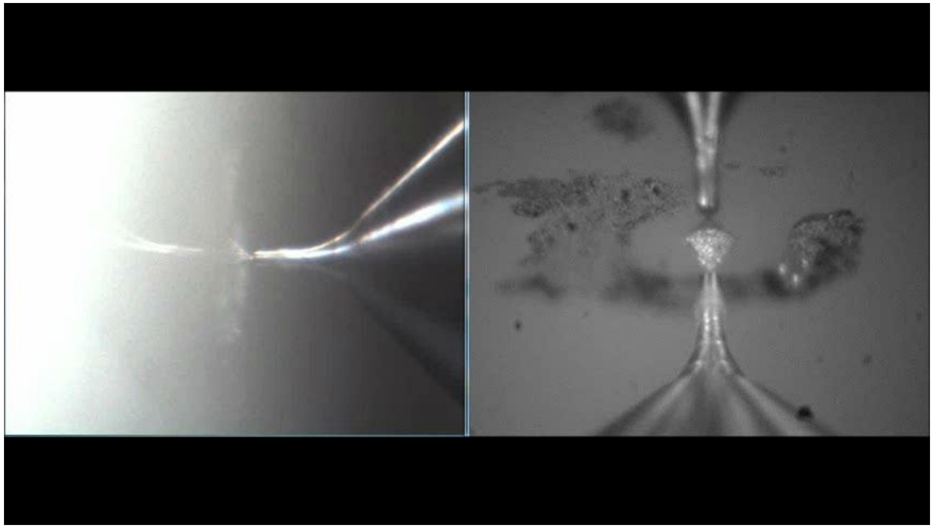


4 edge nano grinding tool fabricated by FIB

Nano grinding







Nanoscale 3D Printing System

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Nano Printing Laboratory

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