446.305A MANUFACTURING PROCESSES

Chapter 10. Properties and Processing of Polymers and Reinforced Plastics; Rapid Prototyping and Rapid Tooling

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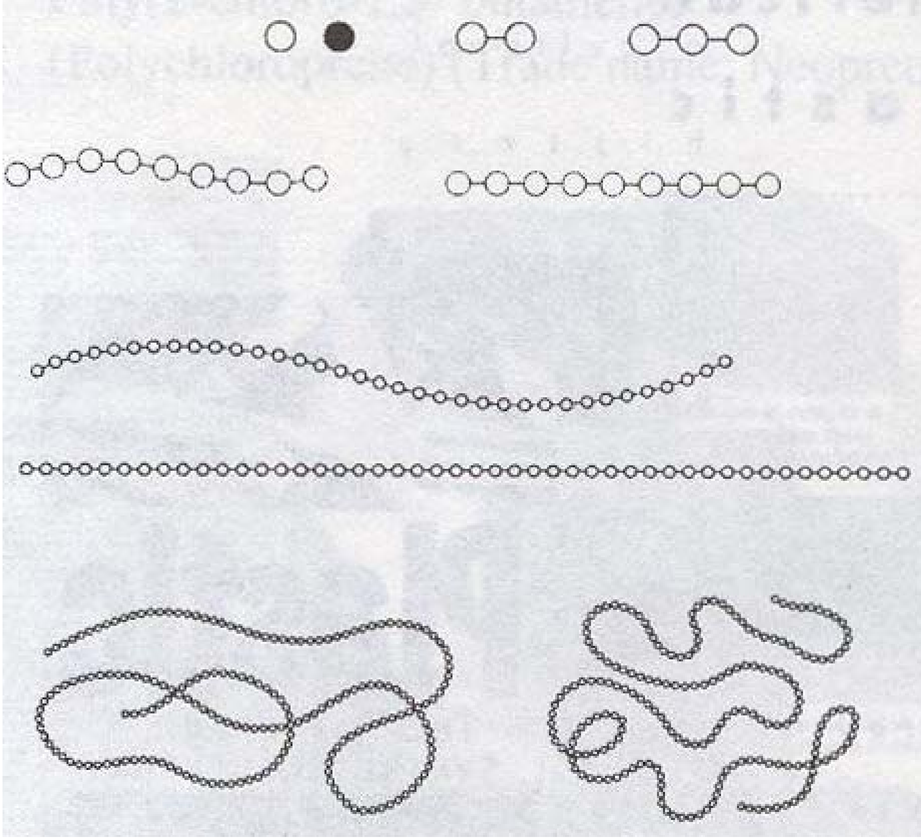
Introduction

- **Advantages of polymers**
  - High strength-to-weight ratio
  - Design possibilities
  - Wide choice of colors and transparencies
  - Ease of manufacturing
  - Relatively low cost

- **Compared with metals**
  - Low density
  - Low strength
  - Low stiffness
  - Low electrical & thermal conductivity
  - Good resistance to chemicals
  - High coefficient of thermal expansion
  - Low useful temperature range (up to 350°C)

Polymers

- **Monomer (단량체), dimer, trimer**
- **Multimer**
- **Oligomer**
  (N=30~200)
- **Polymer (many parts)**
  (N≥200)



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

Structure of polymers

- **Primary bonds : covalent bonds (공유결합)**

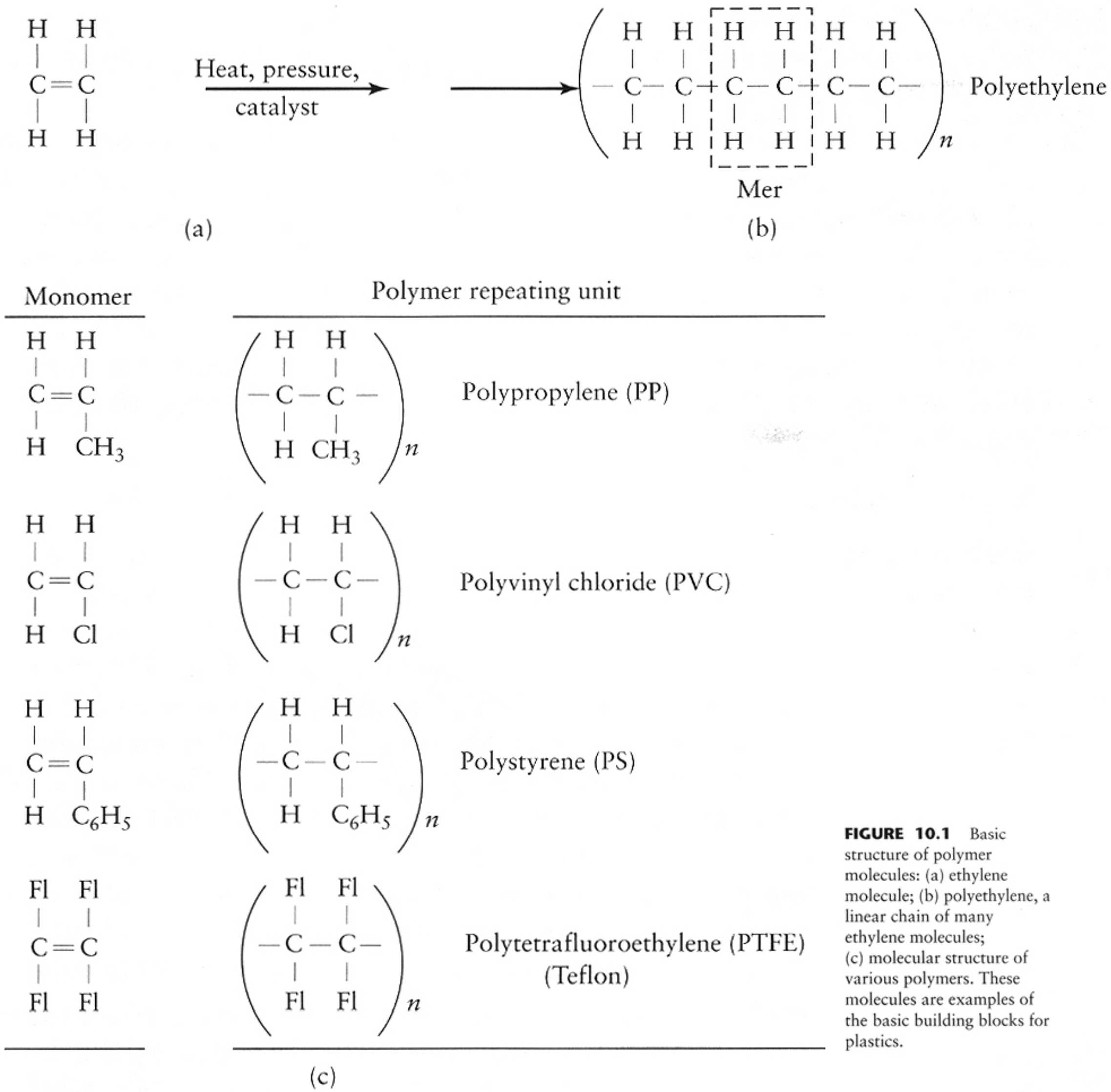


FIGURE 10.1 Basic structure of polymer molecules: (a) ethylene molecule; (b) polyethylene, a linear chain of many ethylene molecules; (c) molecular structure of various polymers. These molecules are examples of the basic building blocks for plastics.

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

Polymerization

- **Monomer → Polymer**
  중합
  (Polymerization)

- **Degree of polymerization (DP, 중합도)**
  - $$\frac{\text{Molecular weight of the polymer (폴리머의 분자량)}}{\text{Molecular weight of the repeat unit (단위체의 분자량)}}$$
  - Number of repeat unit per polymer

- **Effects of crystallinity (결정도)**
  - High crystallinity : stiffer, harder, less ductile, more dense, less rubbery, and more resistant to solvents and heat.

- **Glass-transition temperature (유리전이 온도)**
  - Distinct change in mechanical behavior across a narrow range of temperature.
  - At low temp. : hard, rigid, brittle, and glassy.
  - At high temp. : rubbery and leathery.

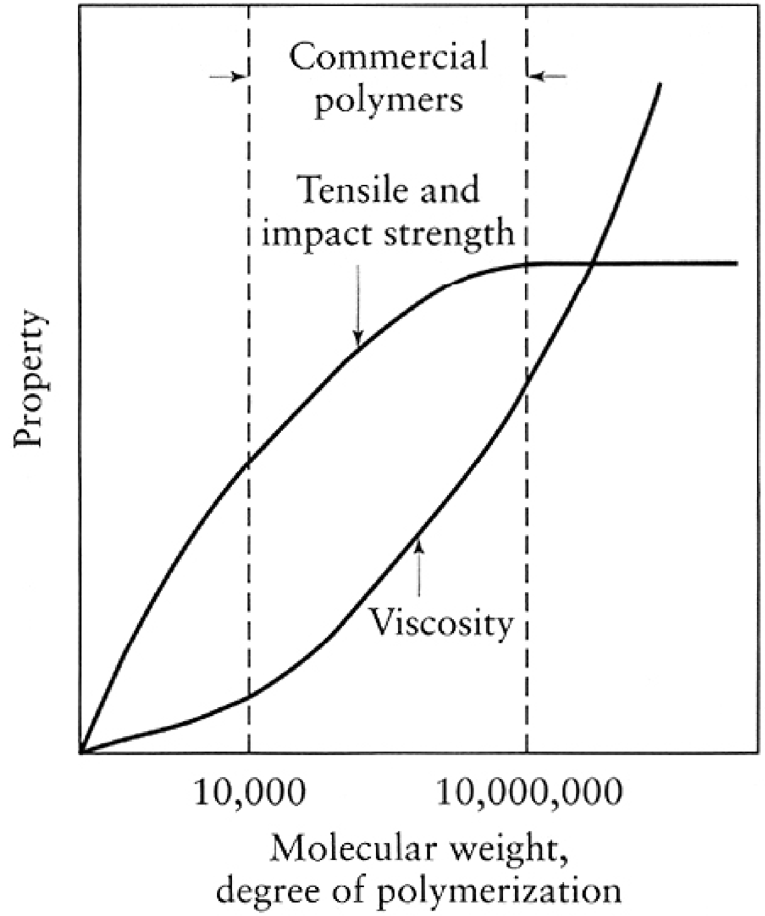


FIGURE 10.2 Effect of molecular weight and degree of polymerization on the strength and viscosity of polymers.

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

Polymer chains

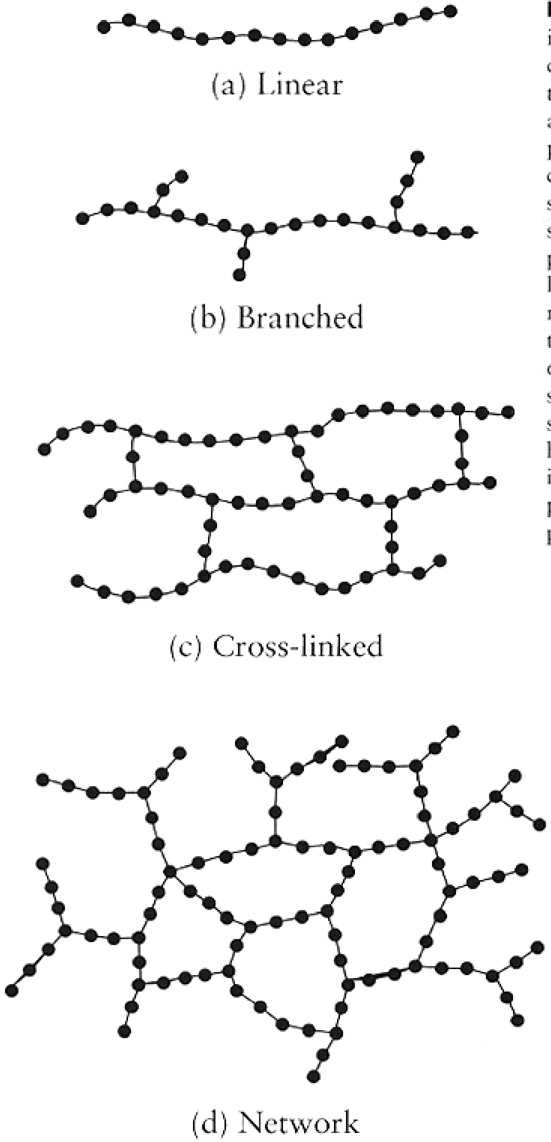


FIGURE 10.3 Schematic illustration of polymer chains. (a) Linear structure; thermoplastics such as acrylics, nylons, polyethylene, and polyvinyl chloride have linear structures. (b) Branched structure, such as in polyethylene. (c) Cross-linked structure; many rubbers and elastomers have this structure. Vulcanization of rubber produces this structure. (d) Network structure, which is basically highly cross-linked; examples include thermosetting plastics, such as epoxies and phenolics.

- **Secondary bonds :**
  van der Waals, hydrogen bonds, and ionic bonds

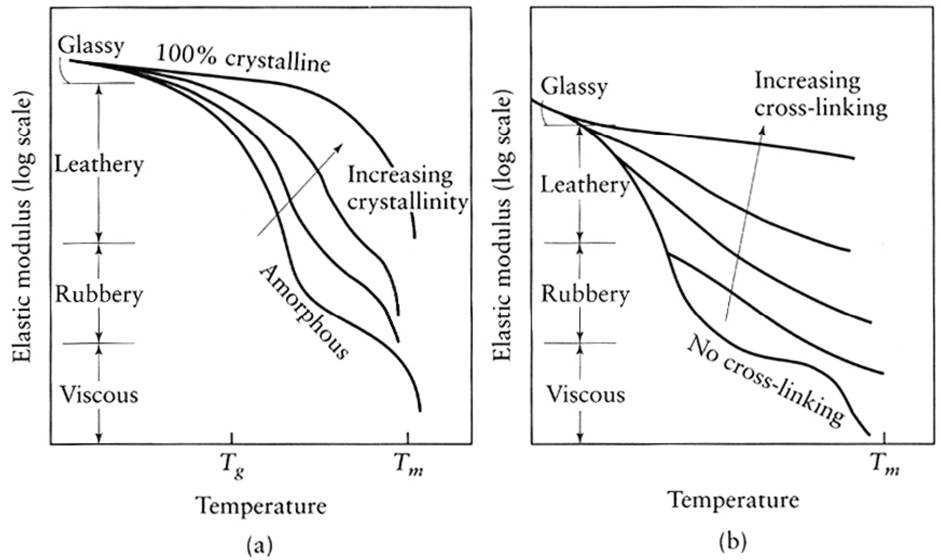


FIGURE 10.4 Behavior of polymers as a function of temperature and (a) degree of crystallinity and (b) cross-linking. The combined elastic and viscous behavior of polymers is known as *viscoelasticity*.

Ref.
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Crystallinity

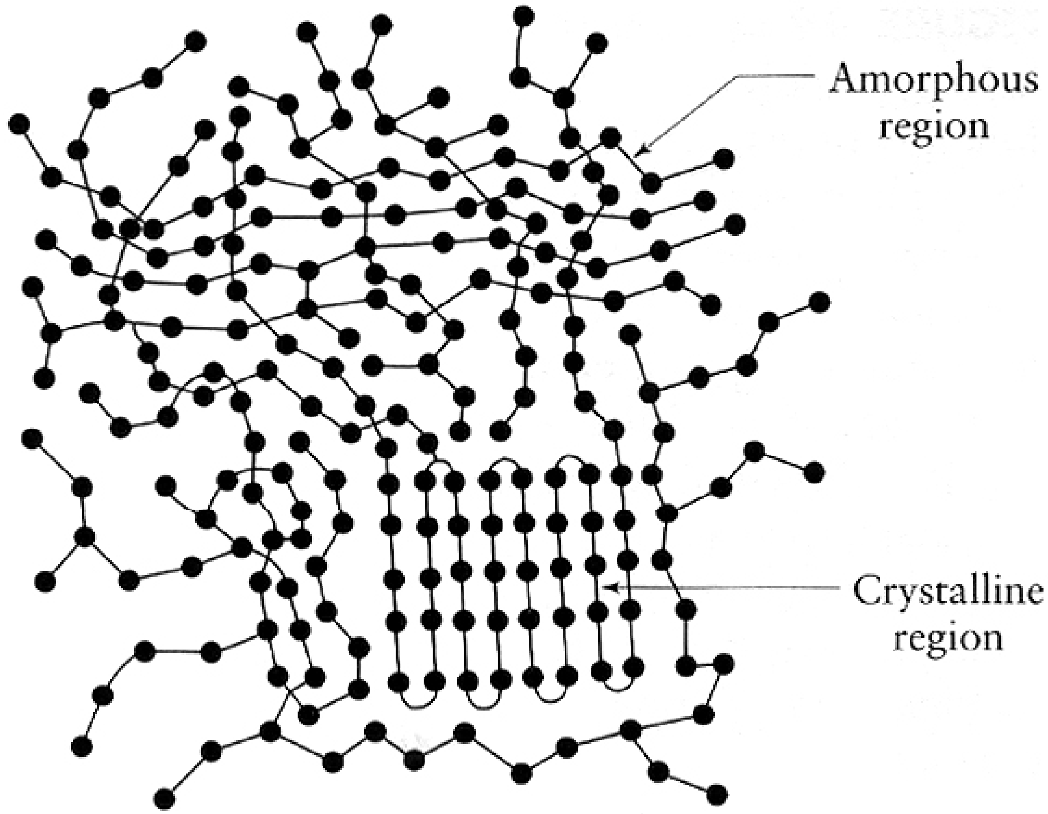

FIGURE 10.5 Amorphous and crystalline regions in a polymer. The crystalline region (crystallite) has an orderly arrangement of molecules. The higher the crystallinity, the harder, stiffer, and less ductile is the polymer.

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

Thermoplastics (열가소성 플라스틱)

- Linear and branched polymers have weak secondary bonds.
- As the temperature is raised above the T_g or T_m polymers become easier to form or mold into desired shapes.
- If the polymer is then cooled, it returns to its original hardness and strength; in other words the effects of the process are reversible.
- Polymethylmethacrylate (PMMA, 아크릴), cellulosics (셀룰로오스), nylon (나일론), ABS (acrylonitrile-butadiene-styrene), polyesters (폴리에스터), polyethylene (폴리에틸렌), PVC (polyvinyl chloride)

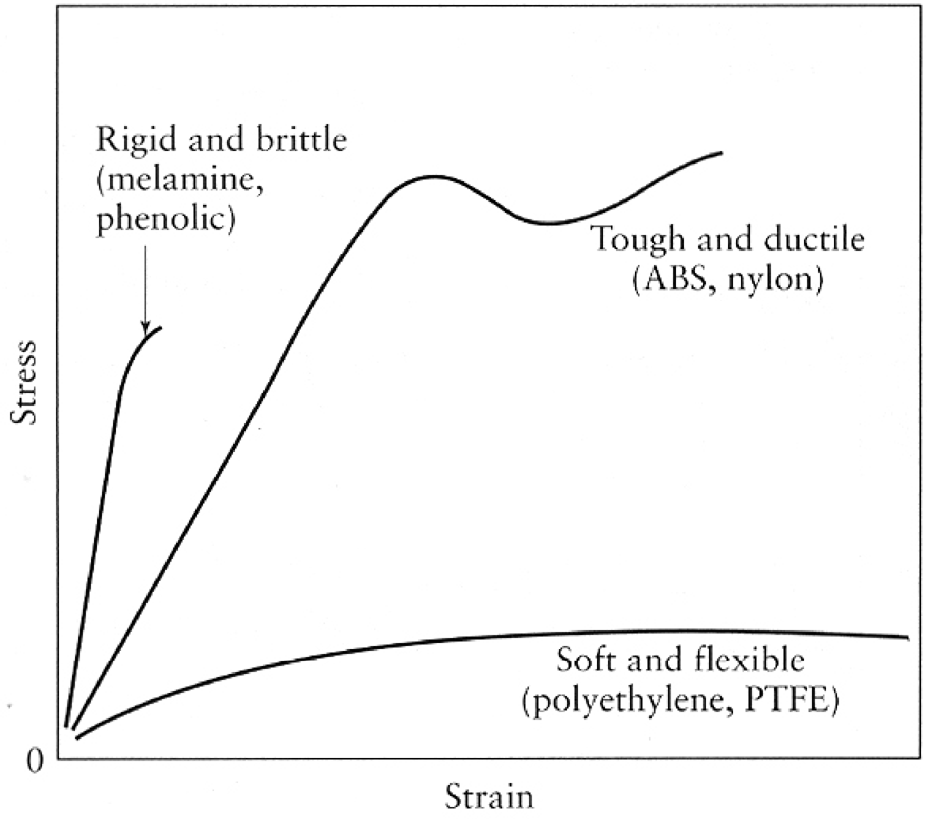

FIGURE 10.8 General terminology describing the behavior of three types of plastics. PTFE (polytetrafluoroethylene) is Teflon, a trade name. *Source:* R. L. E. Brown.

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Viscoelastic behavior (점탄성) (1)

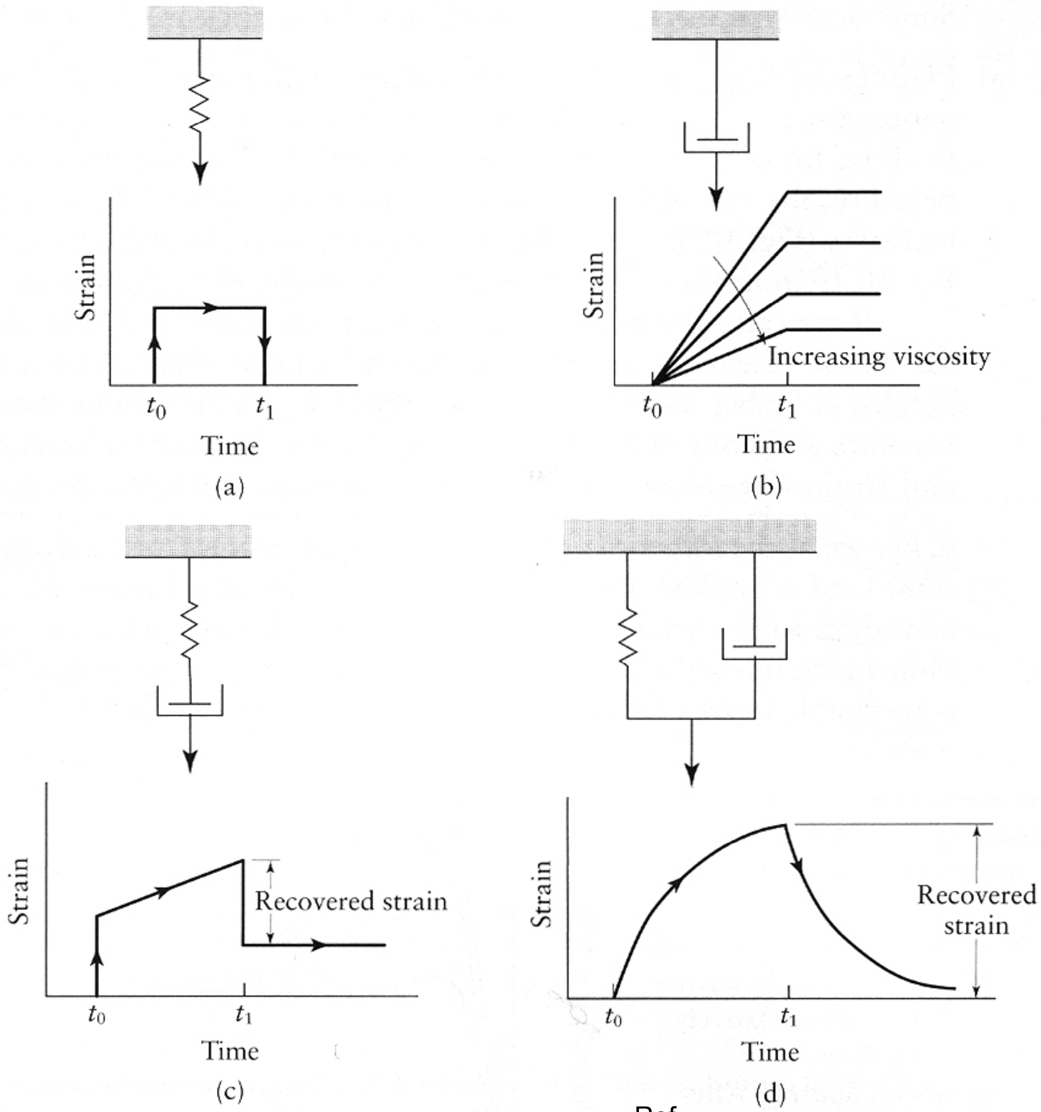

FIGURE 10.7 Various deformation modes for polymers: (a) elastic; (b) viscous; (c) viscoelastic (Maxwell model); and (d) viscoelastic (Voigt or Kelvin model).

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Viscoelastic behavior (점탄성) (2)

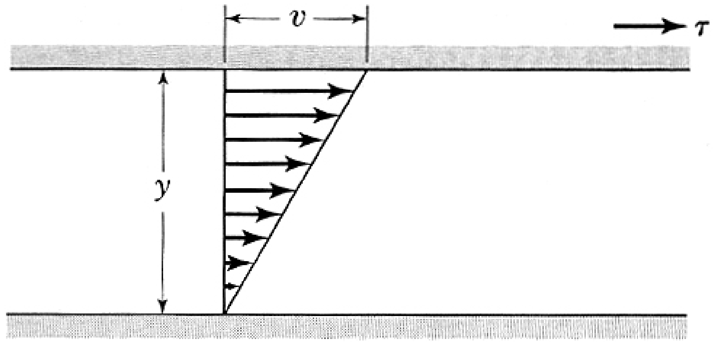
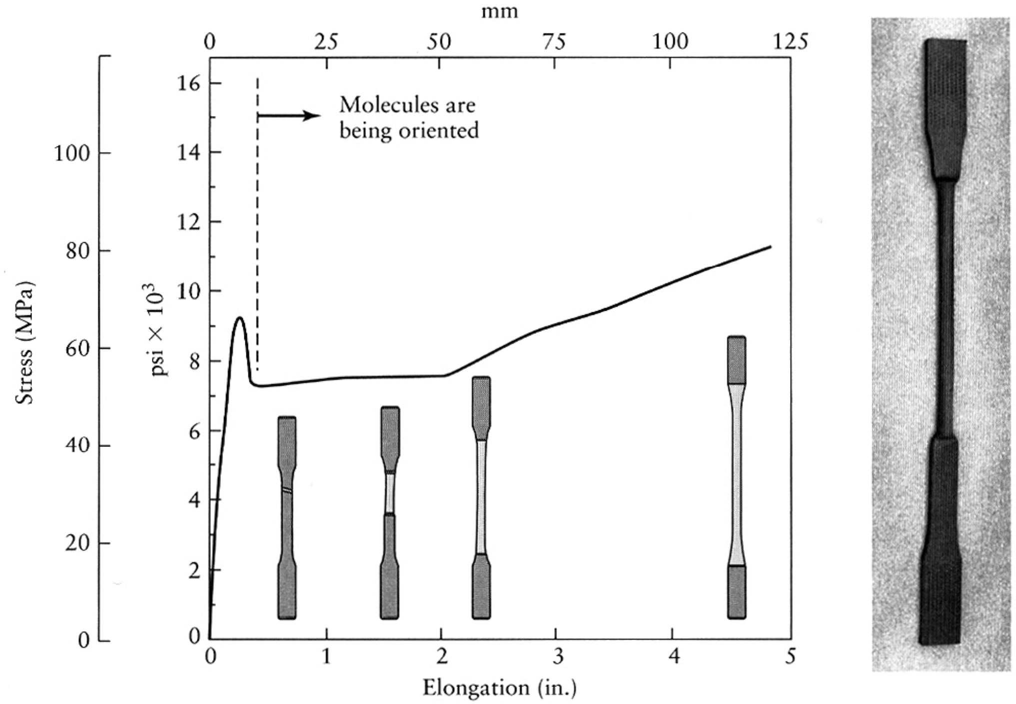


FIGURE 10.11
Parameters used to describe viscosity; see Eq. (10.3).



(a)

(b)

FIGURE 10.13
(a) Load–elongation curve for polycarbonate, a thermoplastic. *Source:* R. P. Kambour and R. E. Robertson. (b) High-density polyethylene tension-test specimen, showing uniform elongation (the long, narrow region in the specimen).

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Thermosetting plastics (열경화성 플라스틱)

- When the long-chain molecules in a polymer are cross-linked in a three-dimensional arrangement, the structure in effect becomes one giant molecule with strong covalent bonds.

- During polymerization, the network is completed, and the shape of the part is permanently set.

- Epoxies (에폭시), phenolics (페놀수지), polyesters (폴리에스터), aminos (아미노), silicones

Elastomers (rubbers, 탄성중합체)

- **Amorphous polymers with low T_g**
- **Vulcanization (가황처리) - Charles Goodyear**

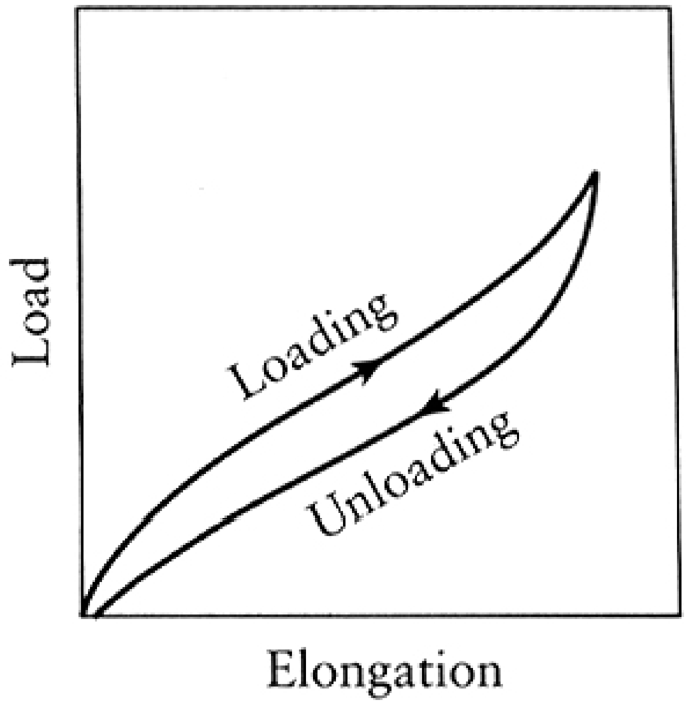

FIGURE 10.14 Typical load–elongation curve for rubbers. The clockwise loop, indicating loading and unloading paths, is the hysteresis loss. Hysteresis gives rubbers the capacity to dissipate energy, damp vibration, and absorb shock loading, as in automobile tires and vibration dampeners placed under machinery.

Ref.
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Reinforced plastics (강화플라스틱) (1)

- **Composite materials (복합재료)**

  A combination of two or more chemically distinct and insoluble phases whose properties and structural performance are superior to those of the constituents acting independently.

- **History**
  - Clay (진흙) + straw (짚) (B.C. 4000)
  - Concrete + iron rods (1800s)

- **Structure of reinforced plastics**
  - Fibers / particles
    - Glass, graphite, aramids (Kevlar), boron, talc, mica
    - Strong and stiff, but brittle, abrasive, and lack toughness
  - Plastic matrix : tougher than the fibers.

Reinforced plastics (강화플라스틱) (2)

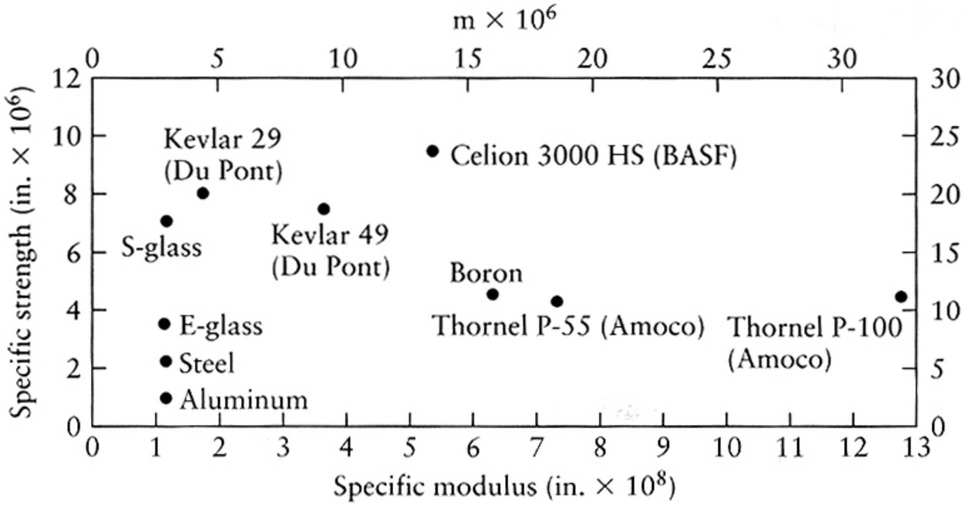

FIGURE 10.15 Specific tensile strength (ratio of tensile strength to density) and specific tensile modulus (ratio of modulus of elasticity to density) for various fibers used in reinforced plastics. Note the wide range of specific strengths and stiffnesses available.

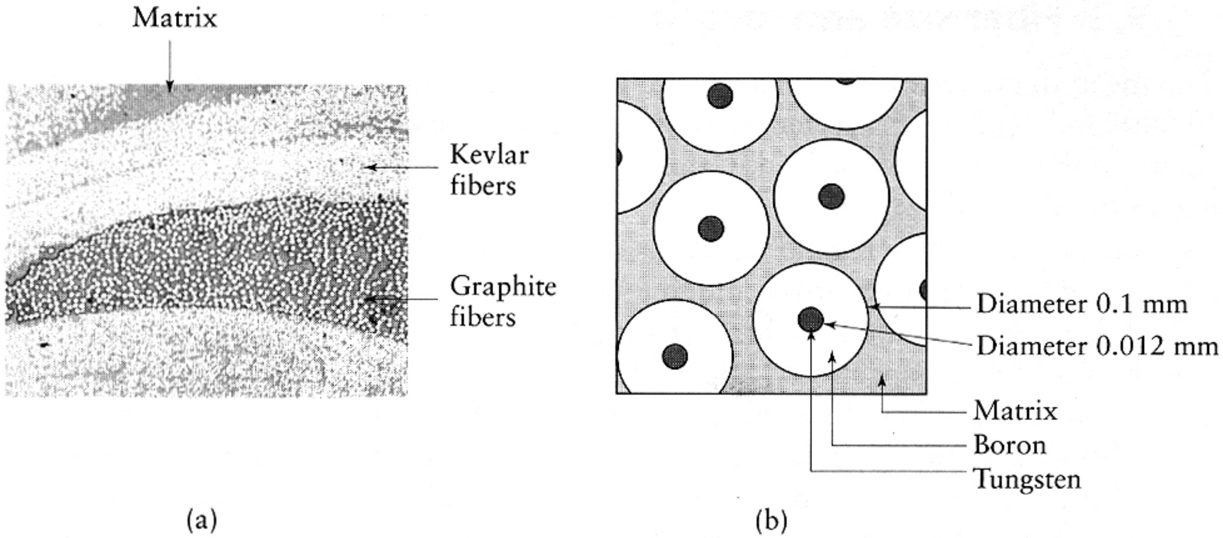

FIGURE 10.16 (a) Cross-section of a tennis racket, showing graphite and aramid (Kevlar) reinforcing fibers. *Source*: J. Dvorak, Mercury Marine Corporation, and F. Garrett, Wilson Sporting Goods Co. (b) Cross-section of boron-fiber-reinforced composite material.

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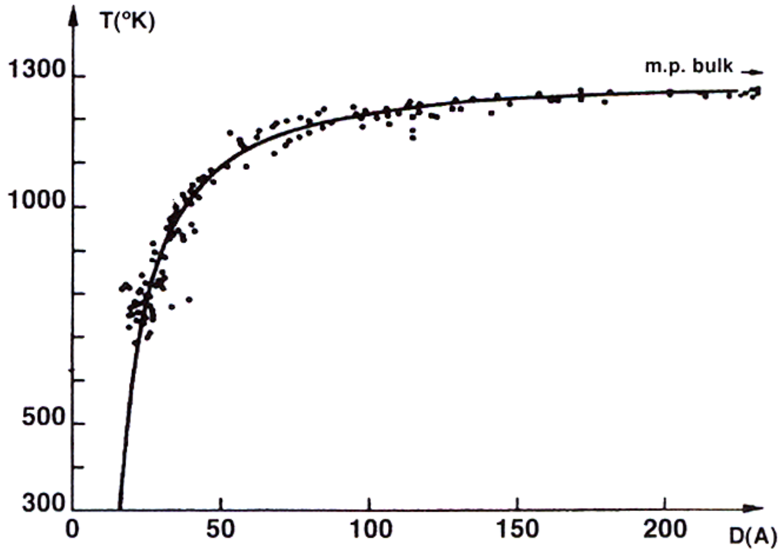
Effect of Nano Scale



Melting point of gold particles as a function of particle size.

- **Sintering temperature of ceramic decreases :**

1800°C → 900°C for nano size.

- Hall-Petch equation

$$Y = Y_i + kd^{-\frac{1}{2}}$$

$$N = 2^{n-1}$$

Material with smaller grain size is stronger

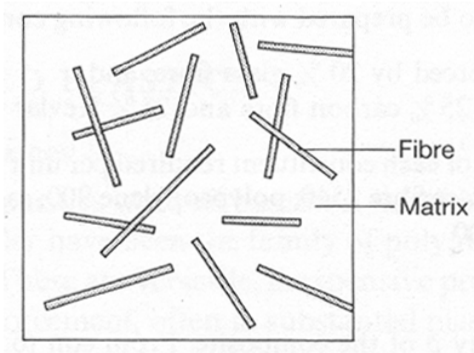
- **Ductile cutting for sub-micro meter size machining tool tip**

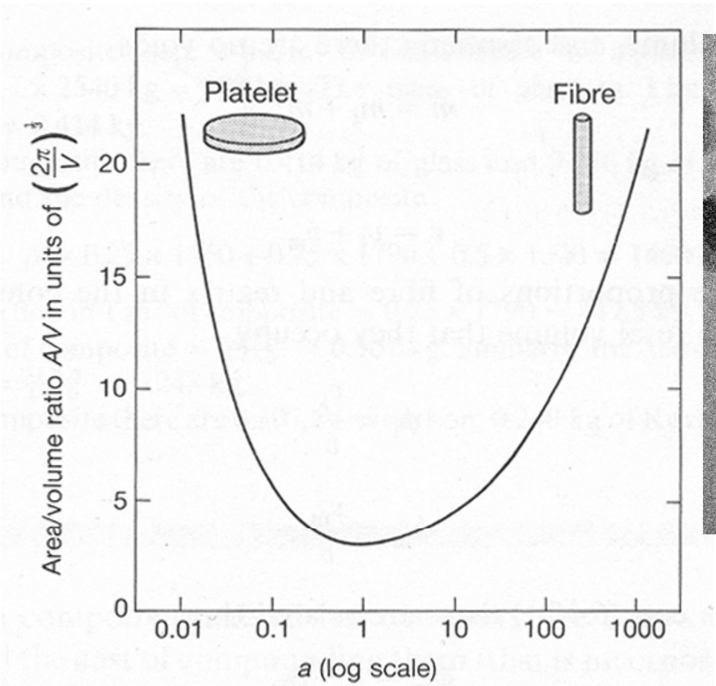
→ Easier to cut hard materials.

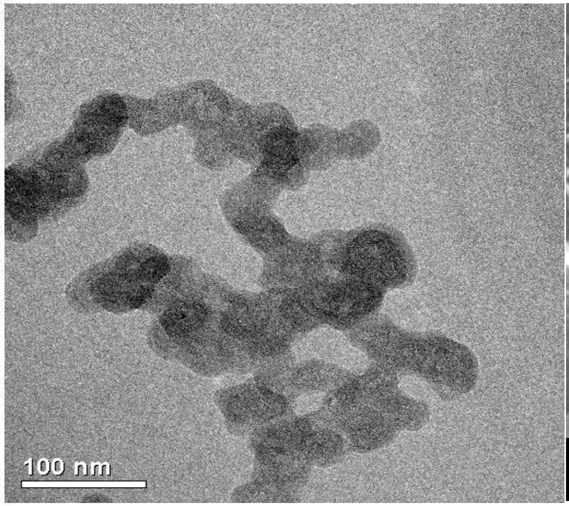
Reinforcement

- **Nano composites :**

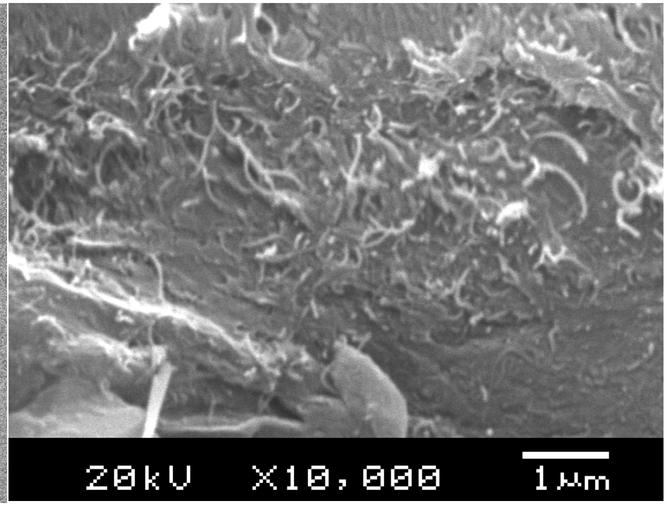
  Carbon Nano Tube (CNT), nano platelets, nano particles







Nano Carbon black powder



CNT + epoxy

Ref.

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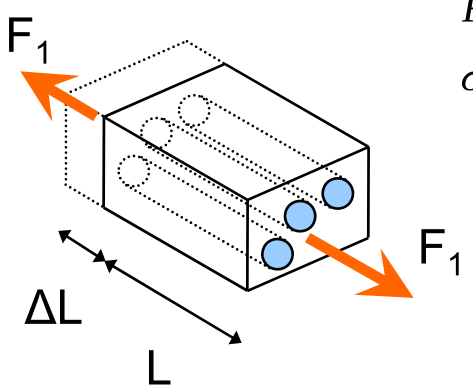
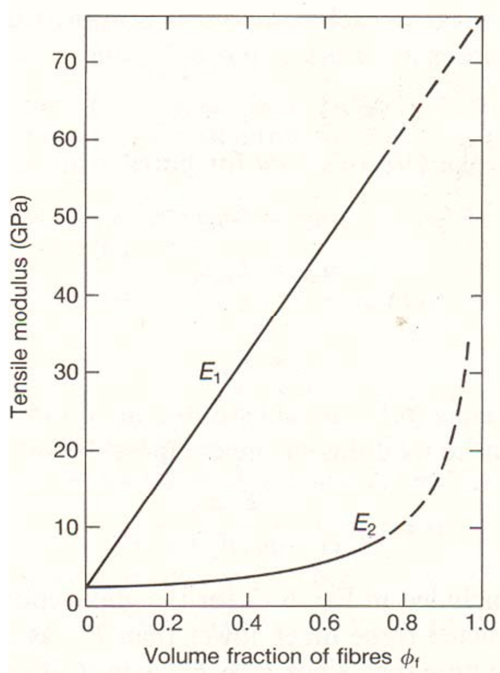
Averaged properties

Longitudinal Young's Modulus

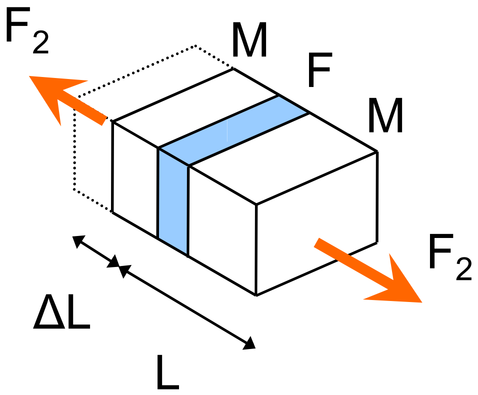


$$F_1 = \sigma_1 A = A_f \sigma_{f1} + A_m \sigma_{m1}$$
$$\sigma_1 = \varepsilon_1 E_1 = v_f \sigma_{f1} + v_m \sigma_{m1}$$

$$\Delta L = \varepsilon_1 L = \varepsilon_{f1} L = \varepsilon_{m1} L$$
$$\varepsilon_1 = \varepsilon_{f1} = \varepsilon_{m1}$$
$$\sigma_{f1} = \varepsilon_{f1} E_{f1}$$
$$\sigma_{m1} = \varepsilon_{m1} E_{m1}$$
$$E_1 = v_{f1} E_{f1} + v_{m1} E_{m1}$$



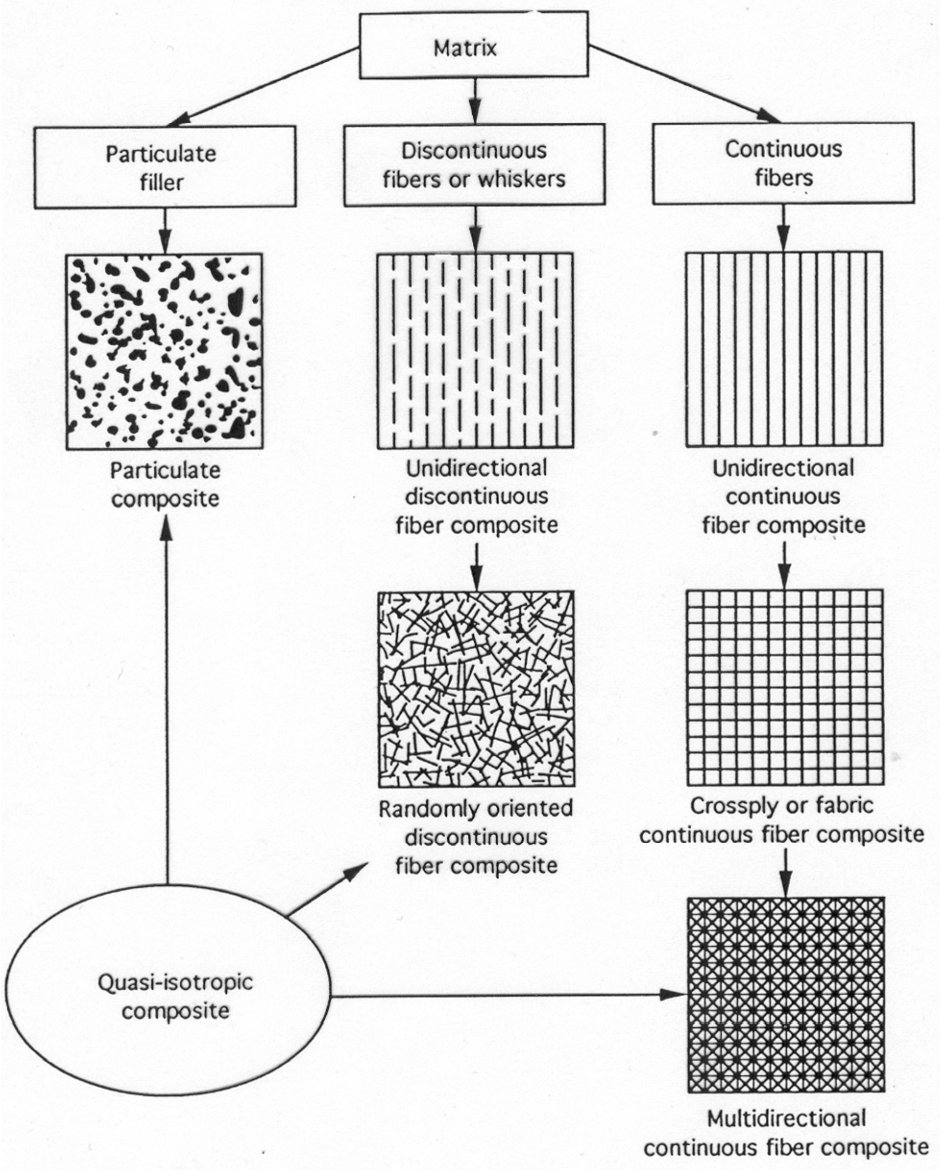
Transverse Young's Modulus

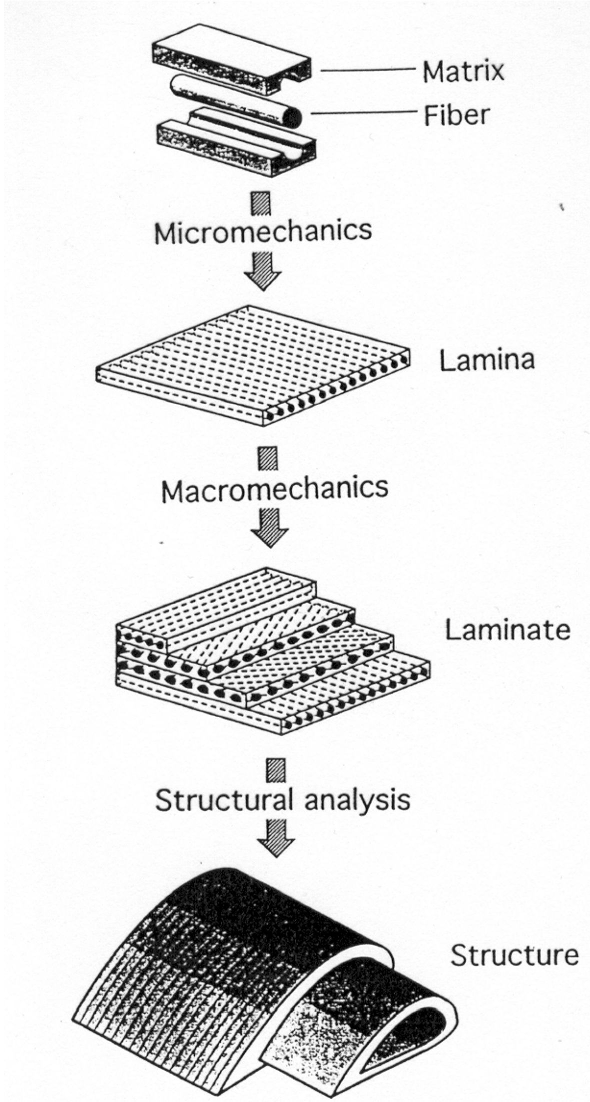


$$F_2 = \sigma_2 A = E_2 \varepsilon_2 A$$
$$\varepsilon_2 = \frac{\Delta L}{L}$$
$$\Delta L = 2 L_m \varepsilon_{m2} + L_f \varepsilon_{f2}$$

$$\sigma_2 = E_2 \varepsilon_2 = E_2 \left(2 \frac{L_m}{L} \varepsilon_{m2} + \frac{L_f}{L} \varepsilon_{f2} \right)$$
$$\varepsilon_{m2} = \frac{\sigma_{m2}}{E_{m2}}, \varepsilon_{f2} = \frac{\sigma_{f2}}{E_{f2}}$$
$$\sigma_2 = \sigma_{f2} = \sigma_{m2}$$
$$E_2 = \left(\frac{v_m}{E_{m2}} + \frac{v_f}{E_{f2}} \right)^{-1}$$

Classification of reinforced plastics





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

Processing of plastics

TABLE 10.6

Characteristics of Processing Plastics and Reinforced Plastics

Process	Characterisics
Extrusion	Long, uniform, solid or hollow, simple or complex cross-sections; wide range of dimensional tolerances; high production rates; low tooling cost.
Injection molding	Complex shapes of various sizes and with fine detail; good dimensional accuracy; high production rates; high tooling cost.
Structural foam molding	Large parts with high stiffness-to-weight ratio; low production rates; less expensive tooling than in injection molding.
Blow molding	Hollow thin-walled parts of various sizes; high production rates and low cost for making beverage and food containers.
Rotational molding	Large hollow shapes of relatively simple design; low production rates; low tooling cost.
Thermoforming	Shallow or deep cavities; medium production rates; low tooling costs.
Compression molding	Parts similar to impression-die forging; medium production rates; relatively inexpensive tooling.
Transfer molding	More complex parts than in compression molding, and higher production rates; some scrap loss; medium tooling cost.
Casting	Simple or intricate shapes, made with flexible molds; low production rates.
Processing of reinforced plastics	Long cycle times; dimensional tolerances and tooling costs depend on the specific process.

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Extrusion / Injection molding

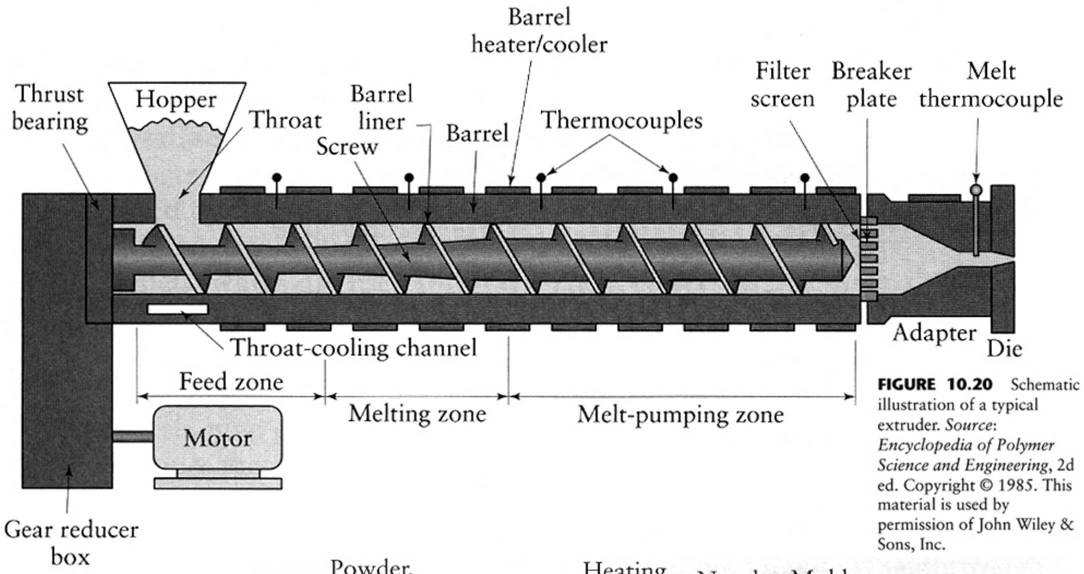


FIGURE 10.20 Schematic illustration of a typical extruder. *Source: Encyclopedia of Polymer Science and Engineering*, 2d ed. Copyright © 1985. This material is used by permission of John Wiley & Sons, Inc.

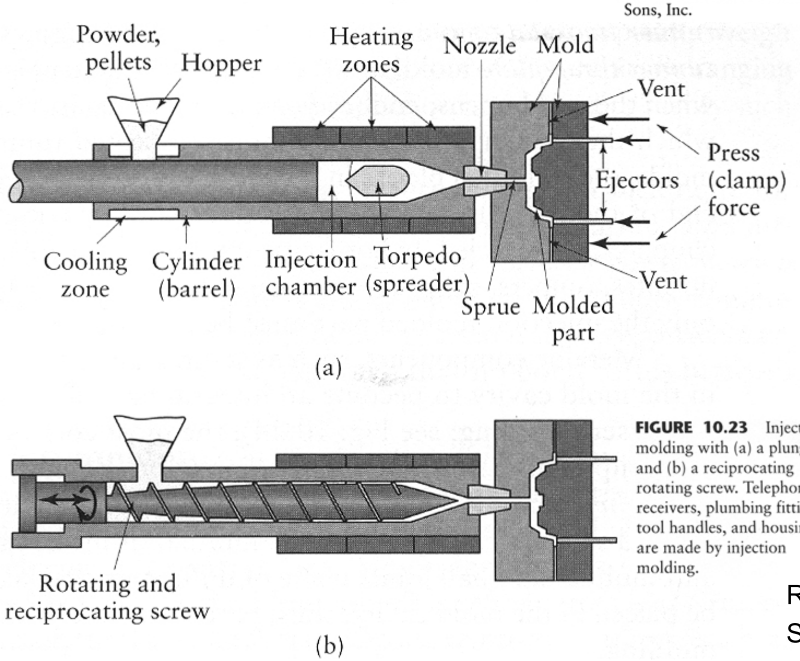


FIGURE 10.23 Injection molding with (a) a plunger and (b) a reciprocating rotating screw. Telephone receivers, plumbing fittings, tool handles, and housings are made by injection molding.

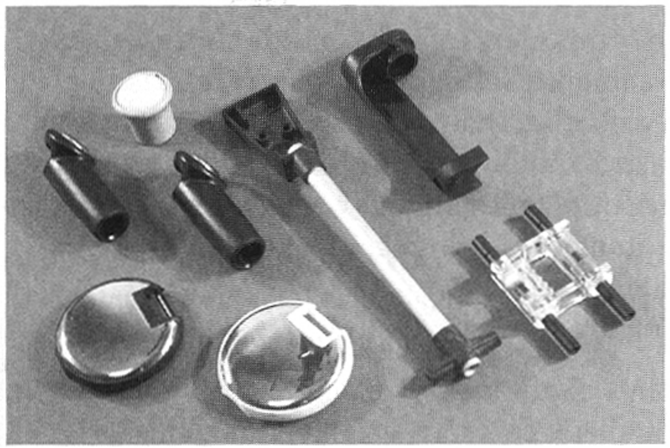


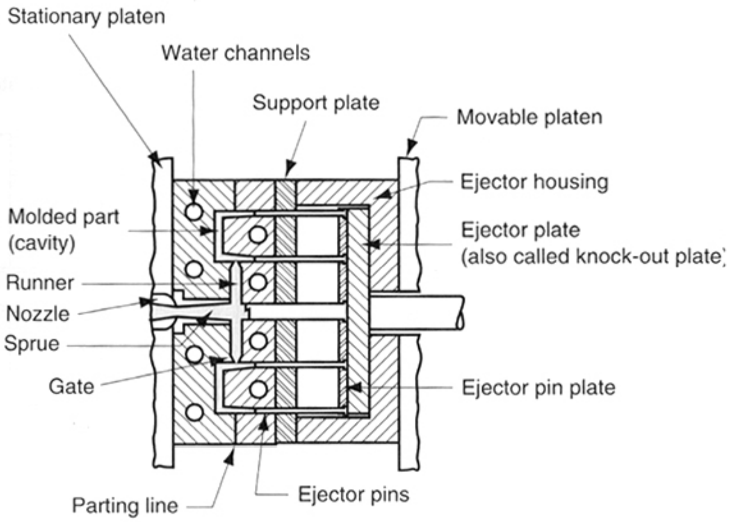
FIGURE 10.24 Products made by insert injection molding. Metallic components are embedded in these parts during molding. *Source*: Rayco Mold and Mfg. LLC.

Metal inserts

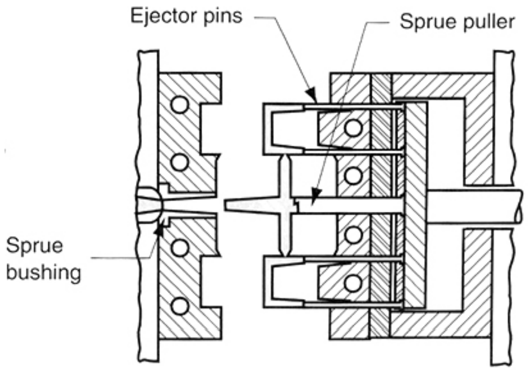
Ref.

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

Sprue, Runner, and Gate



(a)



(b)

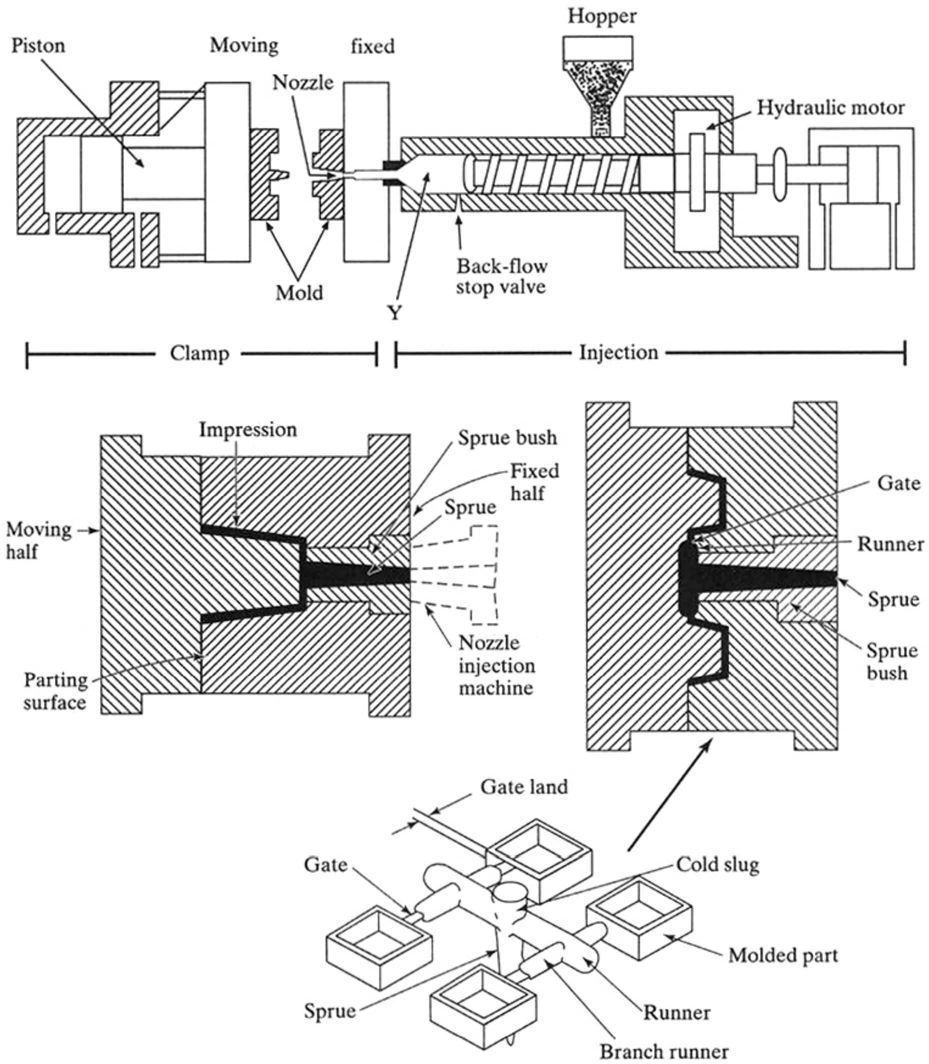


Figure 8.5 Injection molding with reciprocating-screw machine.

Ref.

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

Types of Gate

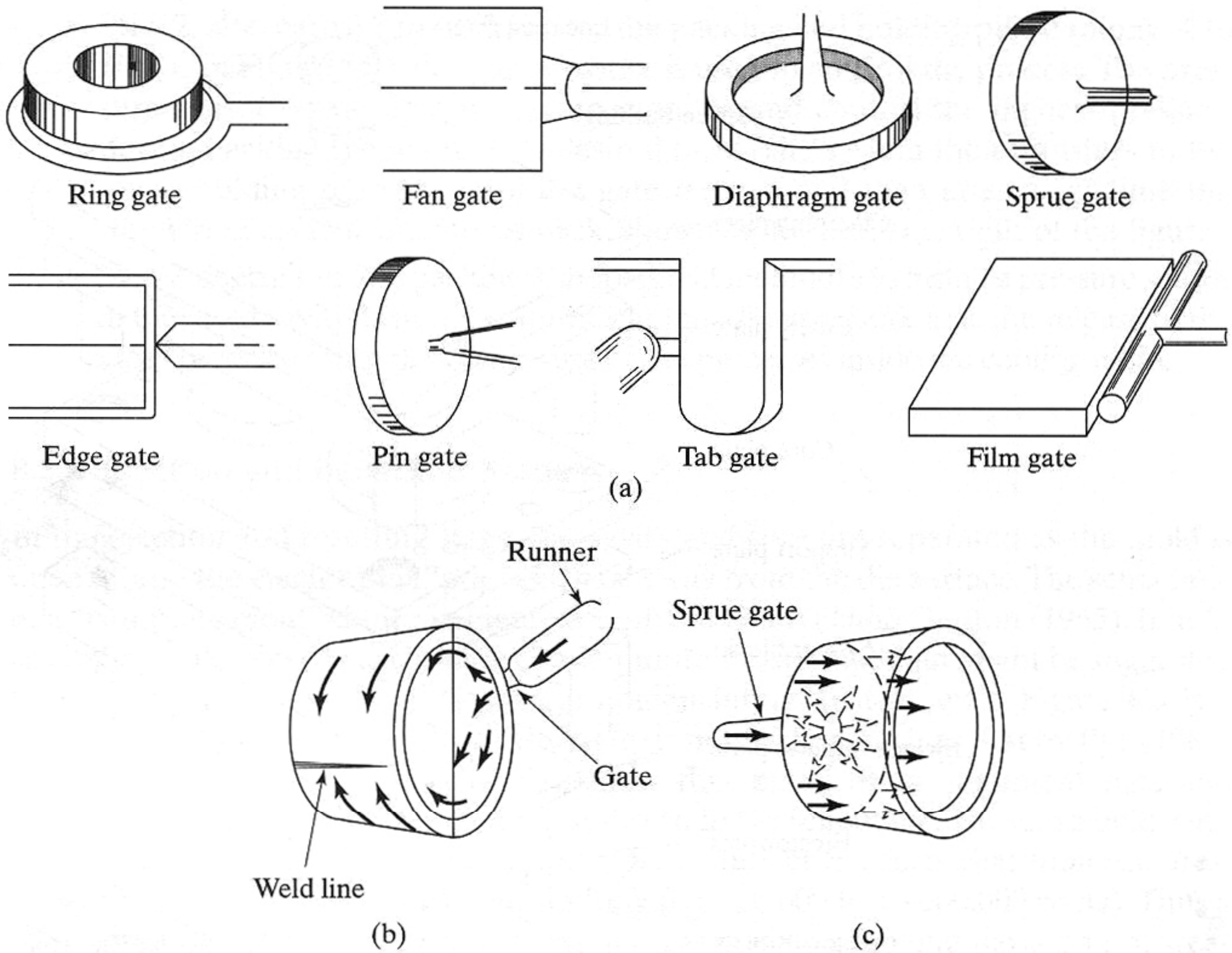


Figure 8.10 (a) Various gate designs in the top figure. The lower figure shows (b) an inefficient gating method and (c) the preferred method (on the right) to fill a cup (adapted from ICI and Pye).

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

Reaction-injection molding / Blow molding

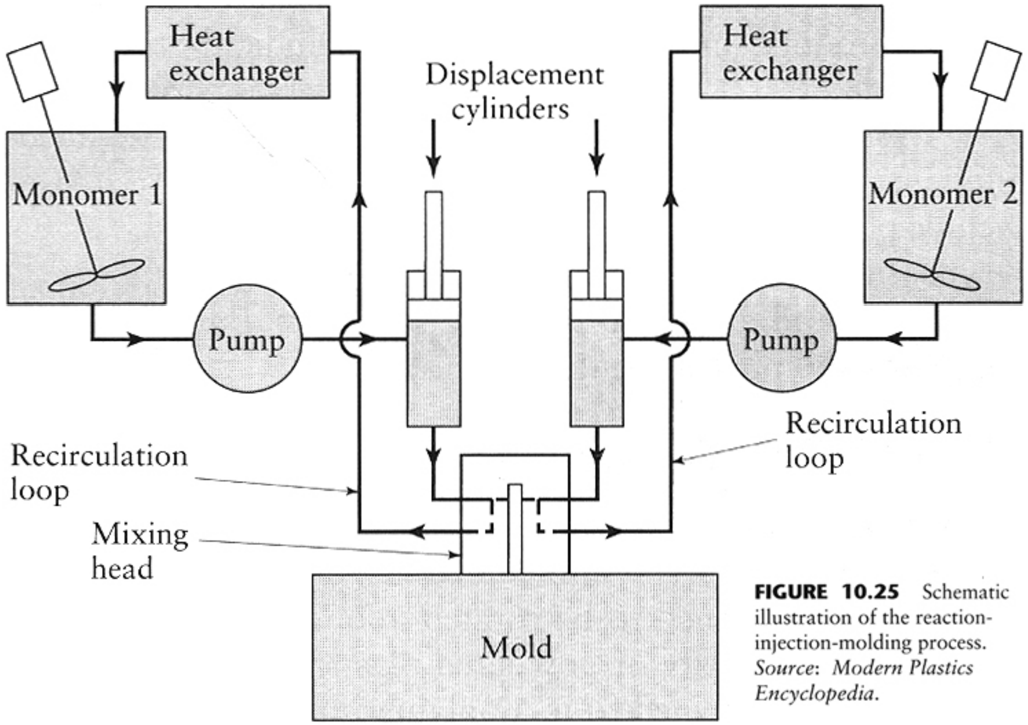
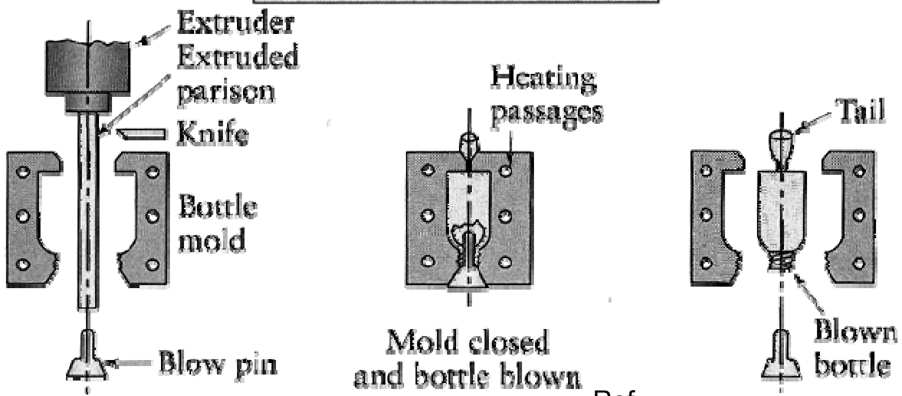


FIGURE 10.25 Schematic illustration of the reaction-injection-molding process. *Source: Modern Plastics Encyclopedia.*



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Thermoforming / Compression molding

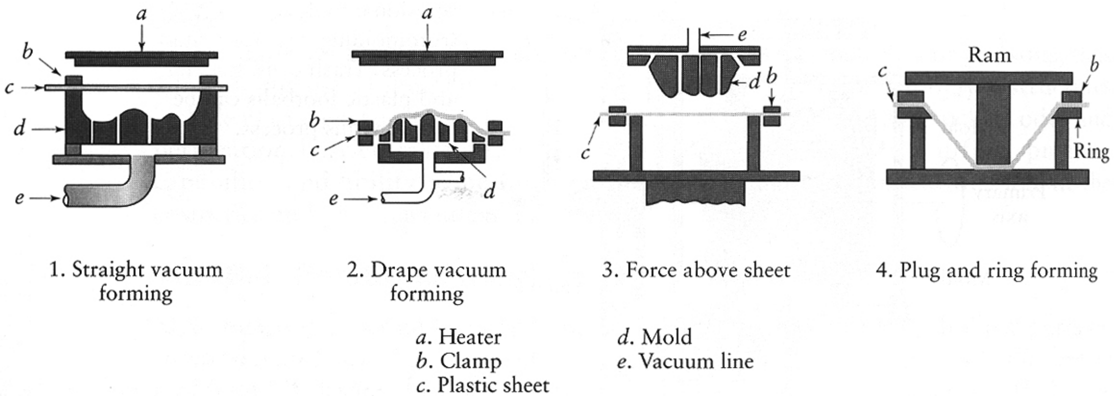


FIGURE 10.28 Various thermoforming processes for thermoplastic sheet. These processes are commonly used in making advertising signs, cookie and candy trays, panels for shower stalls, and packaging.

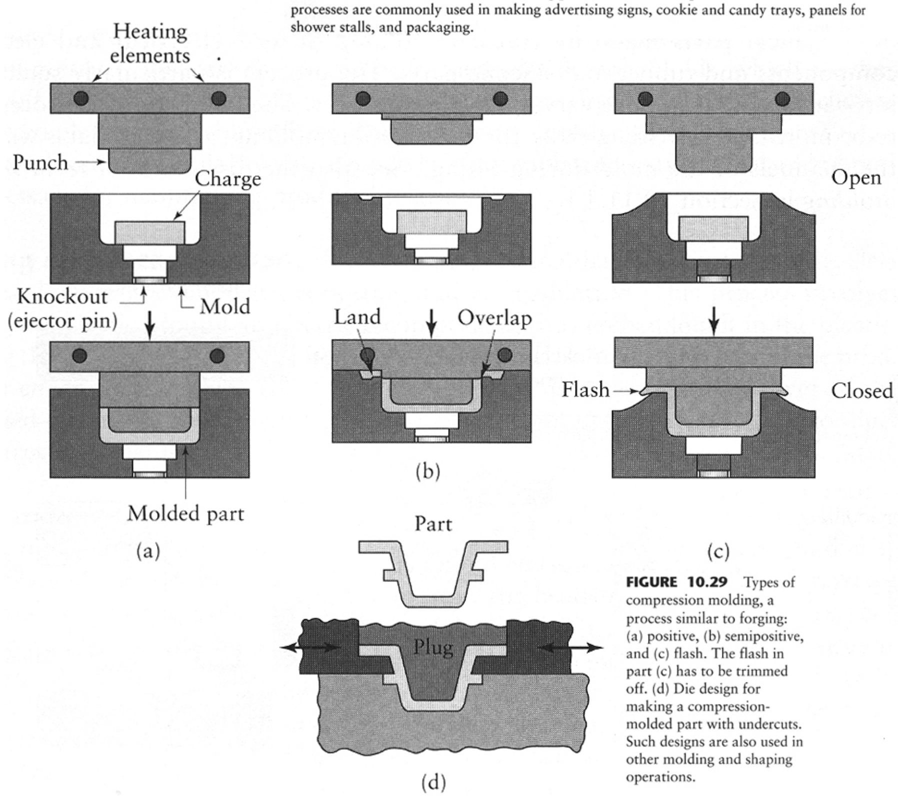


FIGURE 10.29 Types of compression molding, a process similar to forging: (a) positive, (b) semipositive, and (c) flash. The flash in part (c) has to be trimmed off. (d) Die design for making a compression-molded part with undercuts. Such designs are also used in other molding and shaping operations.

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

Transfer molding / Casting

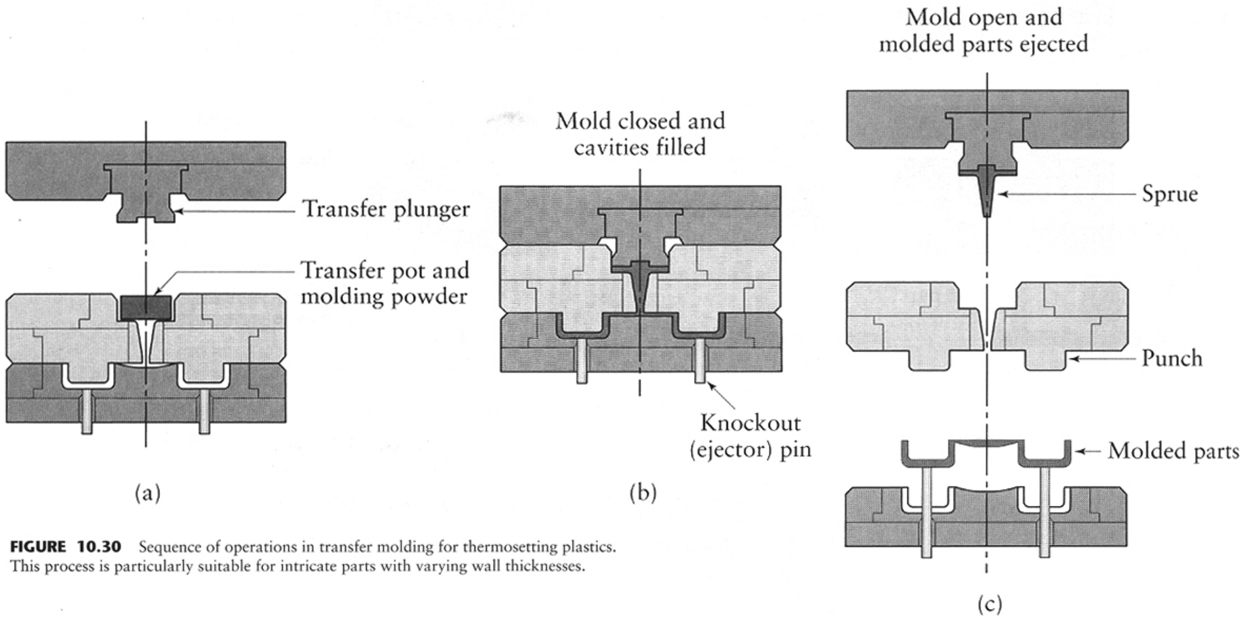


FIGURE 10.30 Sequence of operations in transfer molding for thermosetting plastics. This process is particularly suitable for intricate parts with varying wall thicknesses.

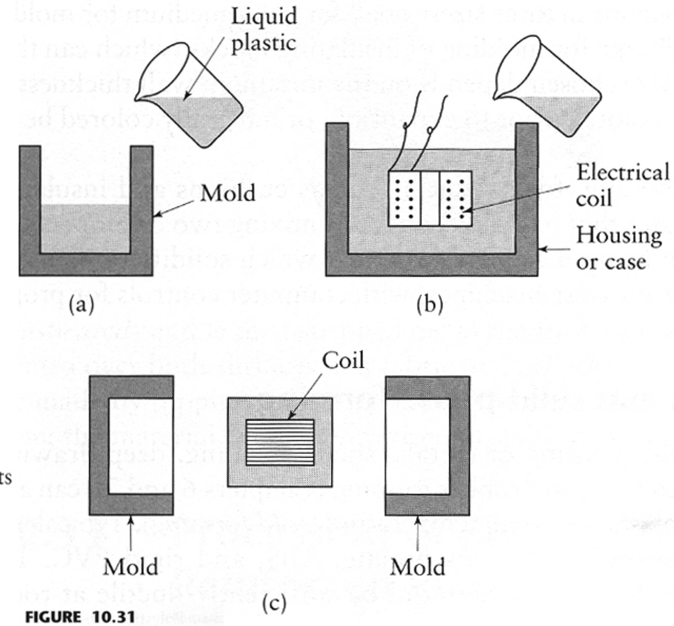


FIGURE 10.31 Schematic illustration of (a) casting, (b) potting, and (c) encapsulation of plastics.

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

Polymer matrix reinforced plastics

- **Prepregs**
- **Sheet-molding compound (SMC)**
- **Bulk-molding compound (BMC)**
- **Thick molding compound (TMC)**

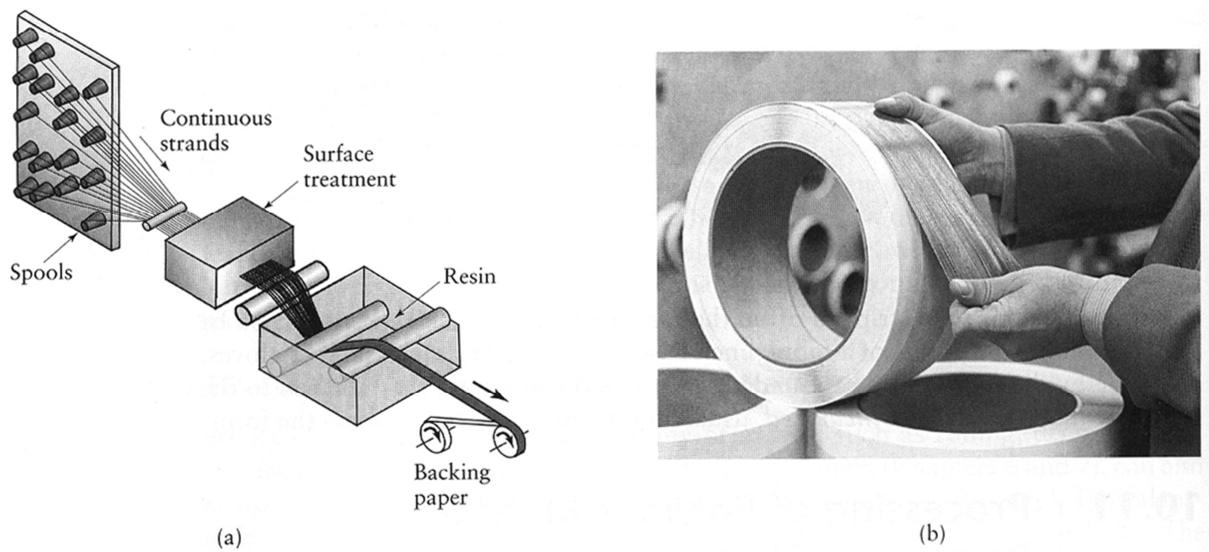


FIGURE 10.34 (a) Manufacturing process for polymer-matrix composite. *Source*: T.-W. Chou, R. L. McCullough, and R. B. Pipes. (b) Boron–epoxy prepreg tape. *Source*: Textron Systems.

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

Manufacturing of polymer matrix reinforced plastics

- **Molding**
  - Compression molding
  - Vacuum-bag molding
    - Autoclave
  - Contact molding
    - Hand lay-up
  - Resin transfer molding
  - Injection molding
- **Filament winding**
- **Pultrusion**

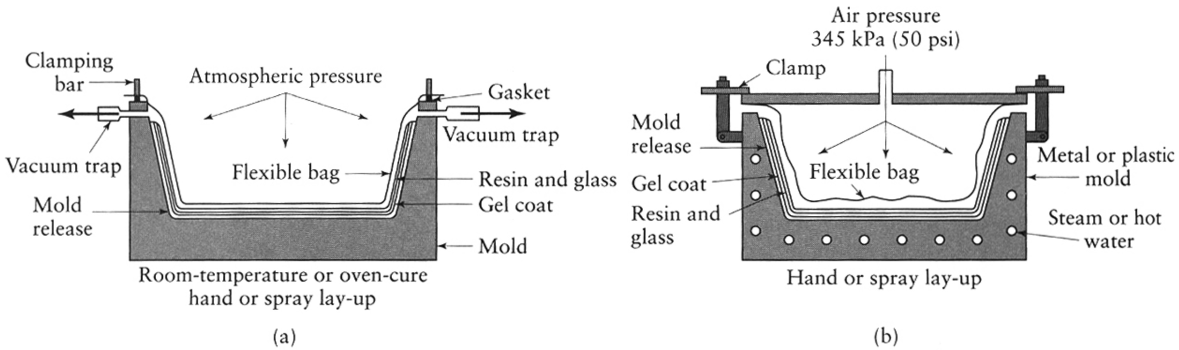
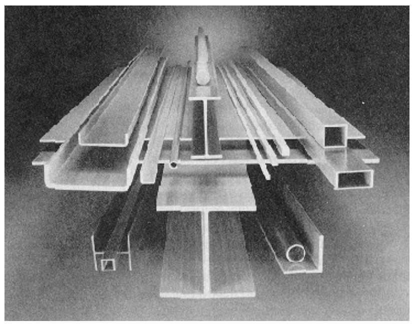


FIGURE 10.36 (a) Vacuum-bag forming. (b) Pressure-bag forming. *Source:* T. H. Meister.



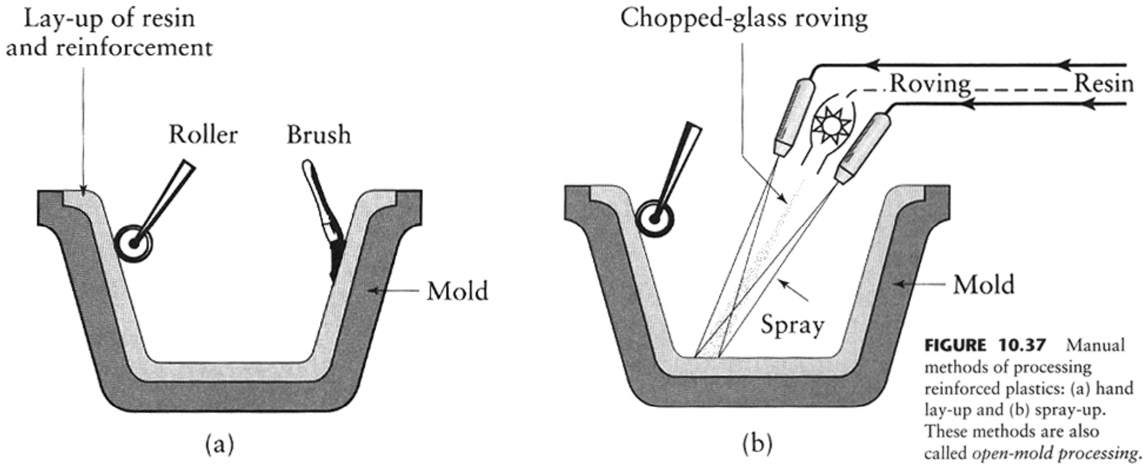


FIGURE 10.37 Manual methods of processing reinforced plastics: (a) hand lay-up and (b) spray-up. These methods are also called *open-mold processing*.

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

Introduction to Rapid Prototyping (RP)

- **Other names of RP**
  - Layered Manufacturing
  - Desktop Manufacturing
  - Solid Free-form Fabrication (SFF)

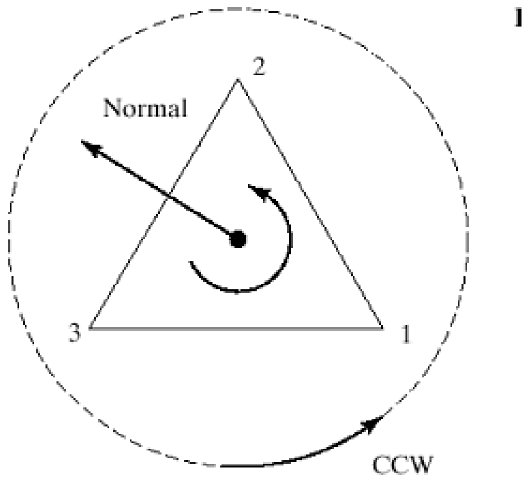
- **A group of related technologies is used for fabricating physical objects directly from CAD data.**

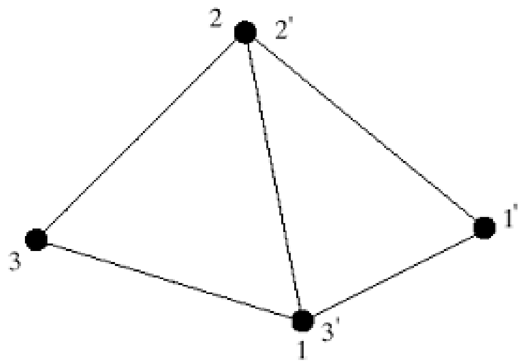
- **Objects are formed by adding and then bonding the materials in layers.**

- **The RP offers advantages compared to conventional subtractive fabrication methods.**

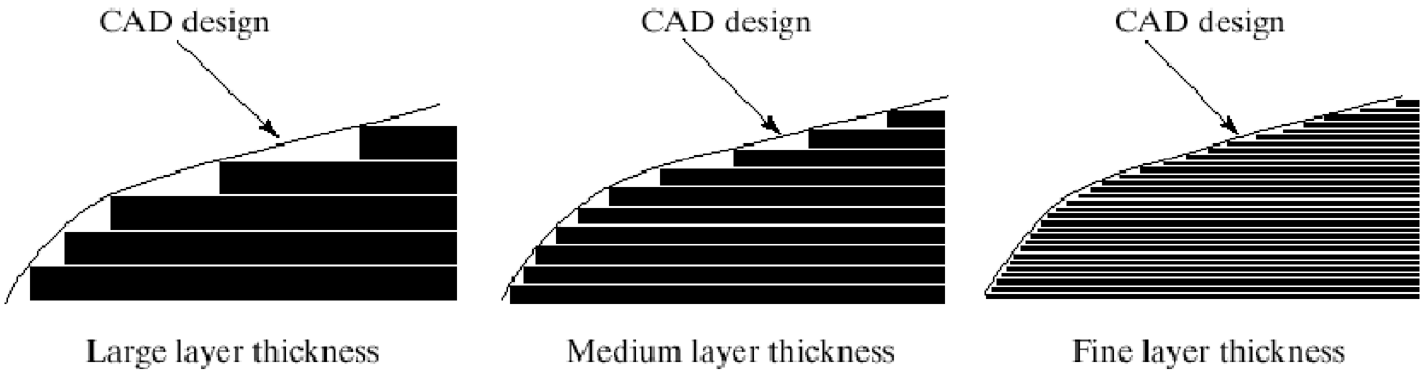
STL File

- Developed for StreoLithography
- De facto standard for RP data
- Most CAD systems support STL format





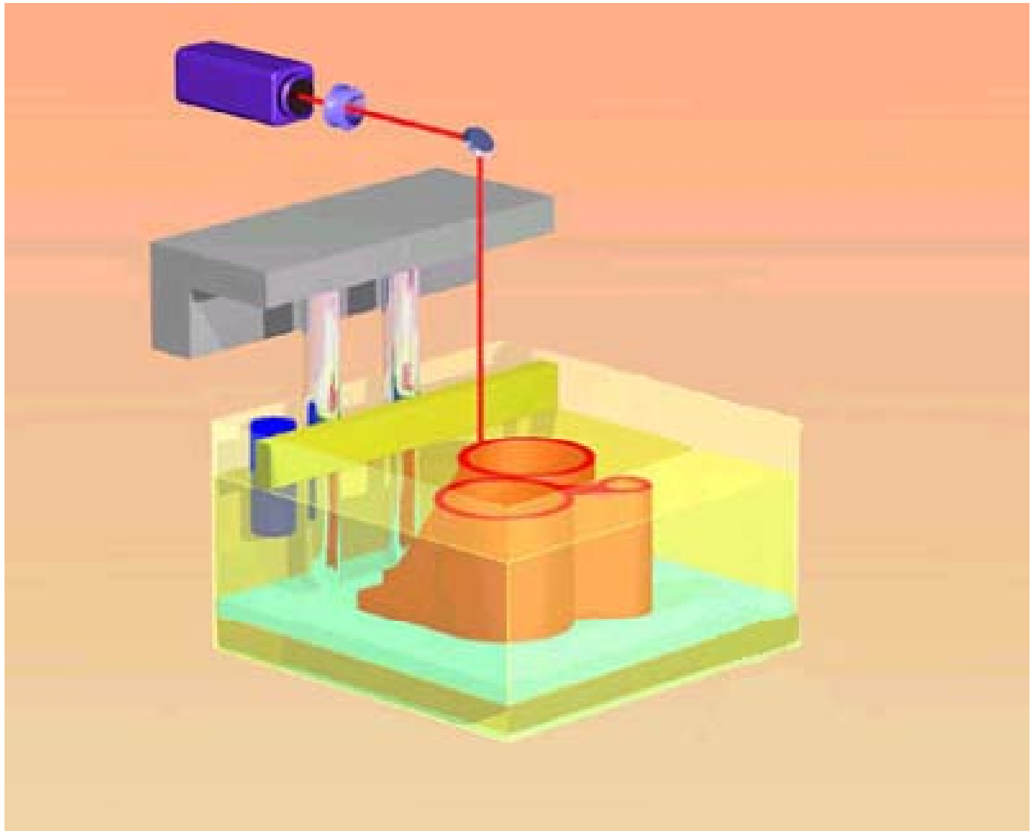
Stair-Step Effect



Surface roughness vs. build time

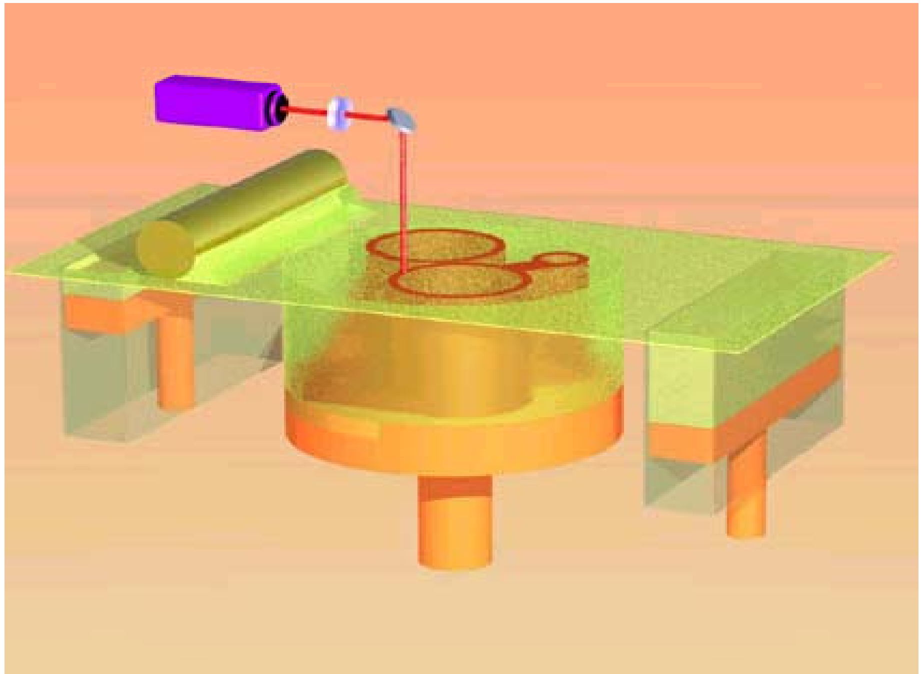
Stereolithography Apparatus (SLA)

- Developed by 3D Systems, Inc
- The laser beam will scan the surface following the contours of the slice.

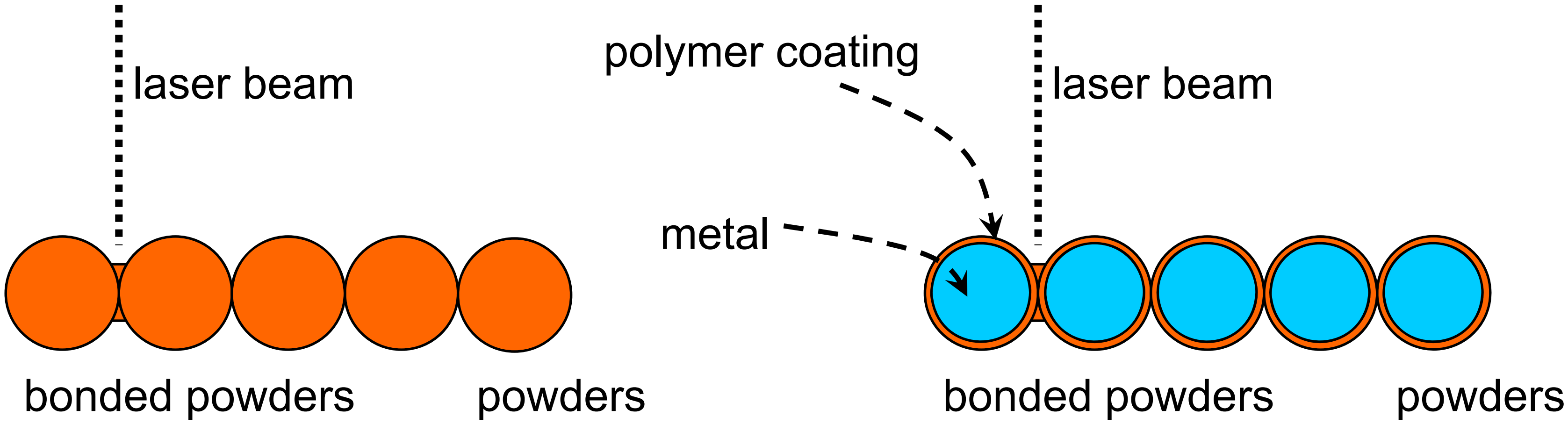


Selective Laser Sintering (SLS) (1)

- Developed by The University of Texas at Austin.
- Powders are spread over a platform by a roller.
- A laser sinters selected areas causing the particles to melt and then solidify.

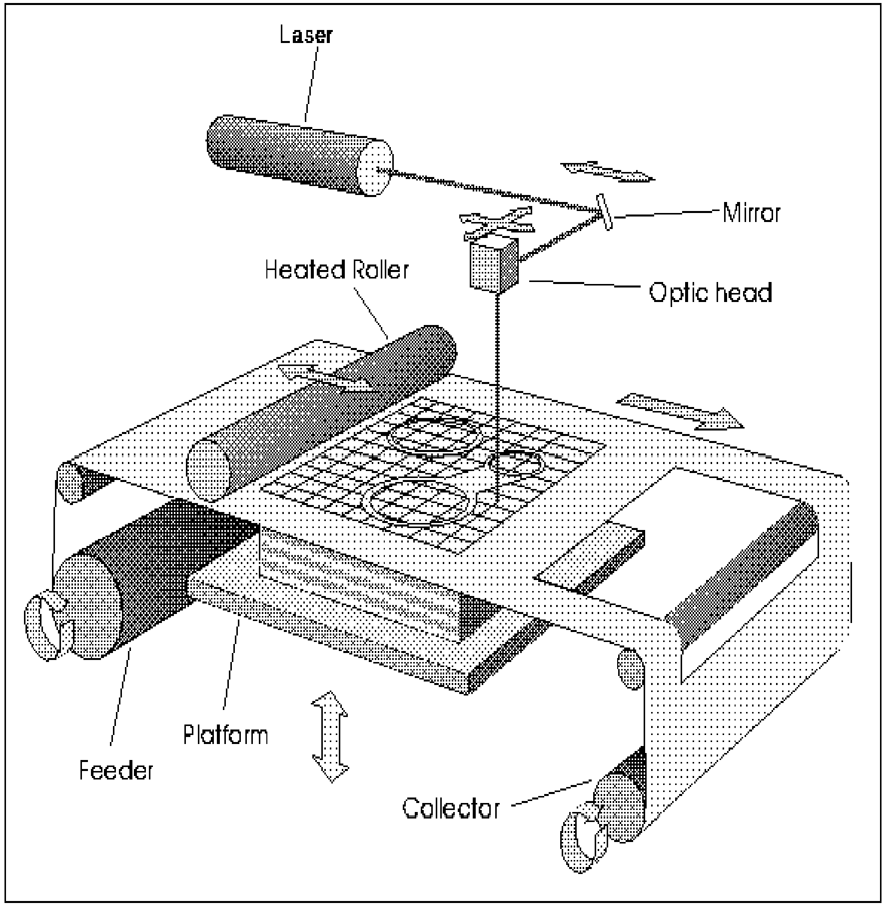


Selective Laser Sintering (SLS) (2)

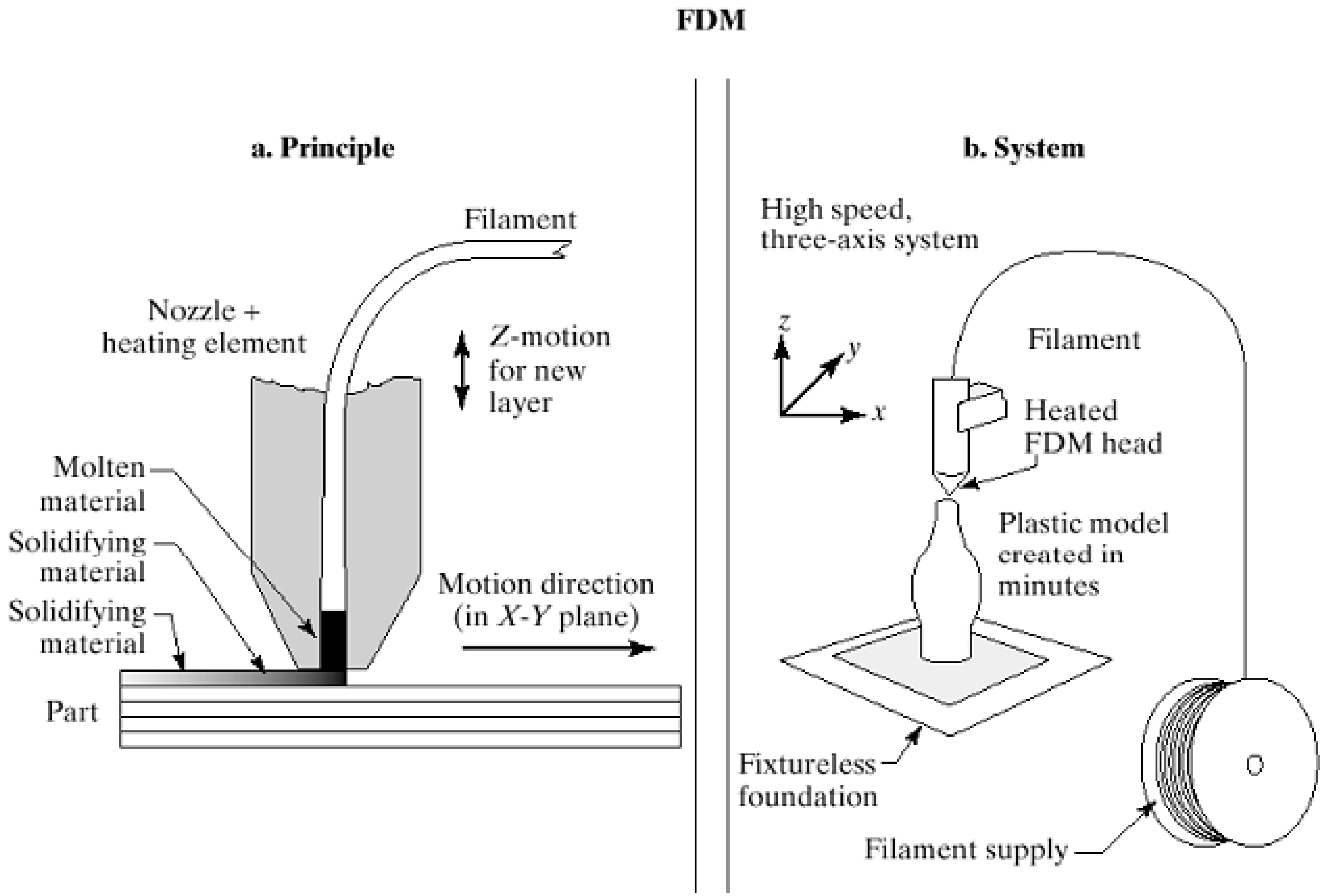


Laminated-Object Manufacturing (LOM)

- **Developed by Helysis.**
- **LOM uses layers of paper or plastic sheets with a heat-activated glue on one side to produce parts.**
- **The desired shapes are burned into the sheet with a laser beam, and the parts are built layer by layer.**

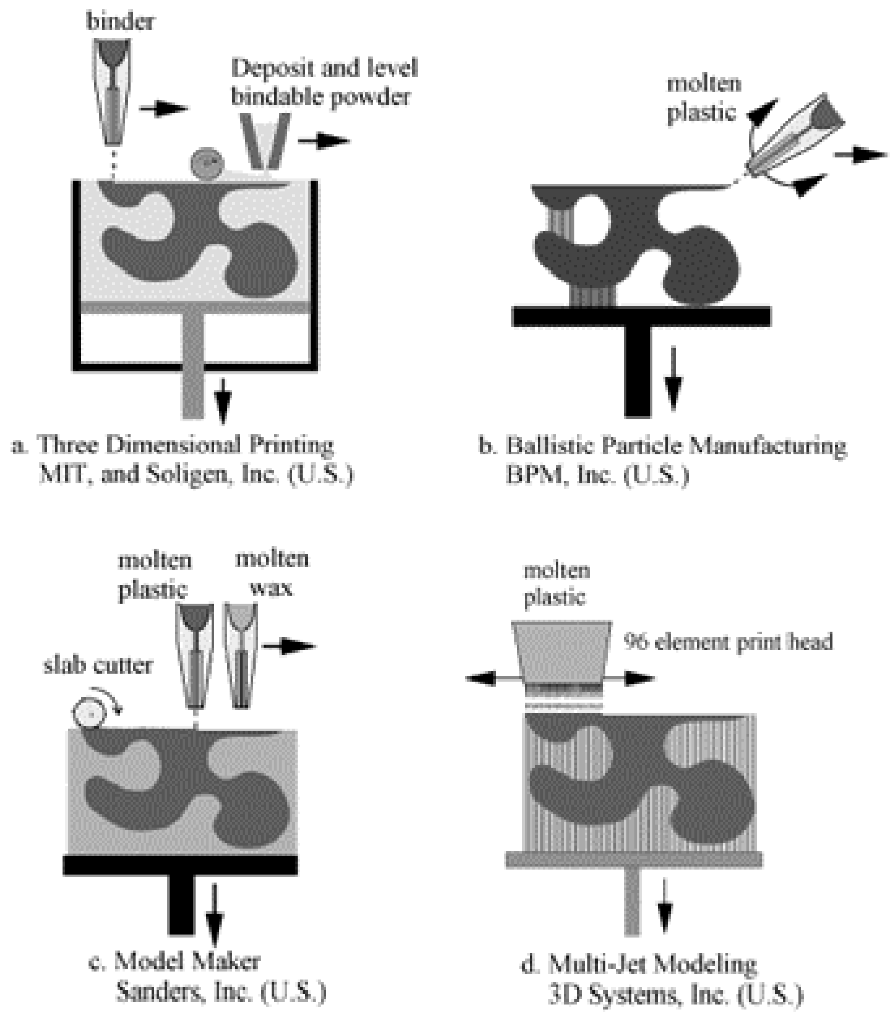


Fused Deposition Modeling (FDM)



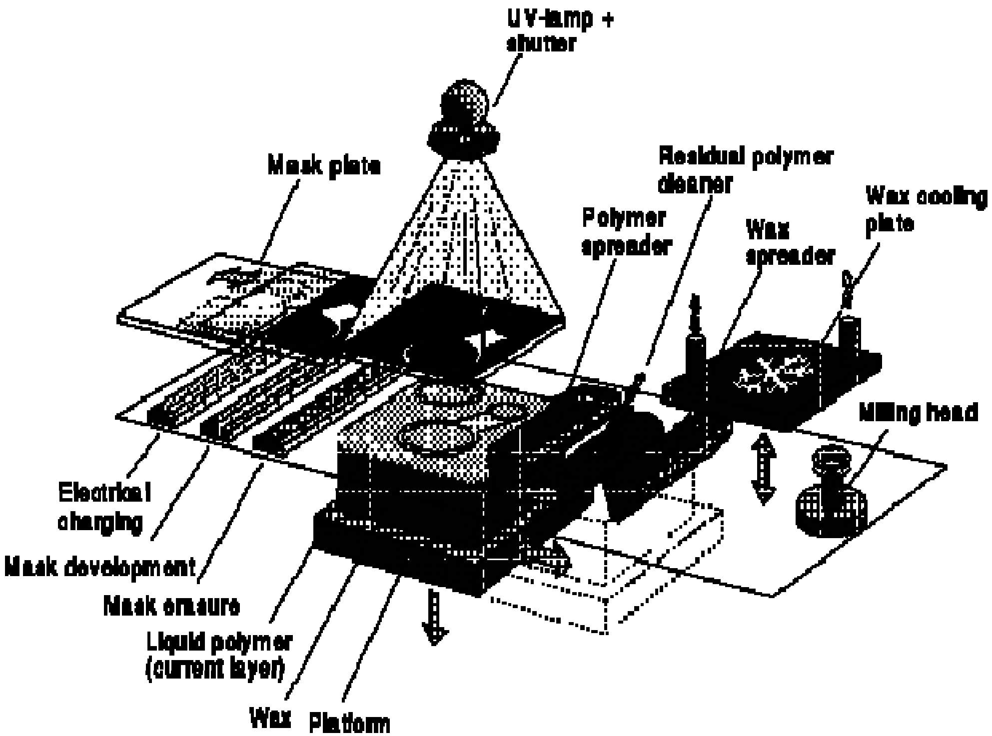
3D Printers

- **Developed at MIT.**
- **Parts are built upon a platform situated in a bin full of powder material.**



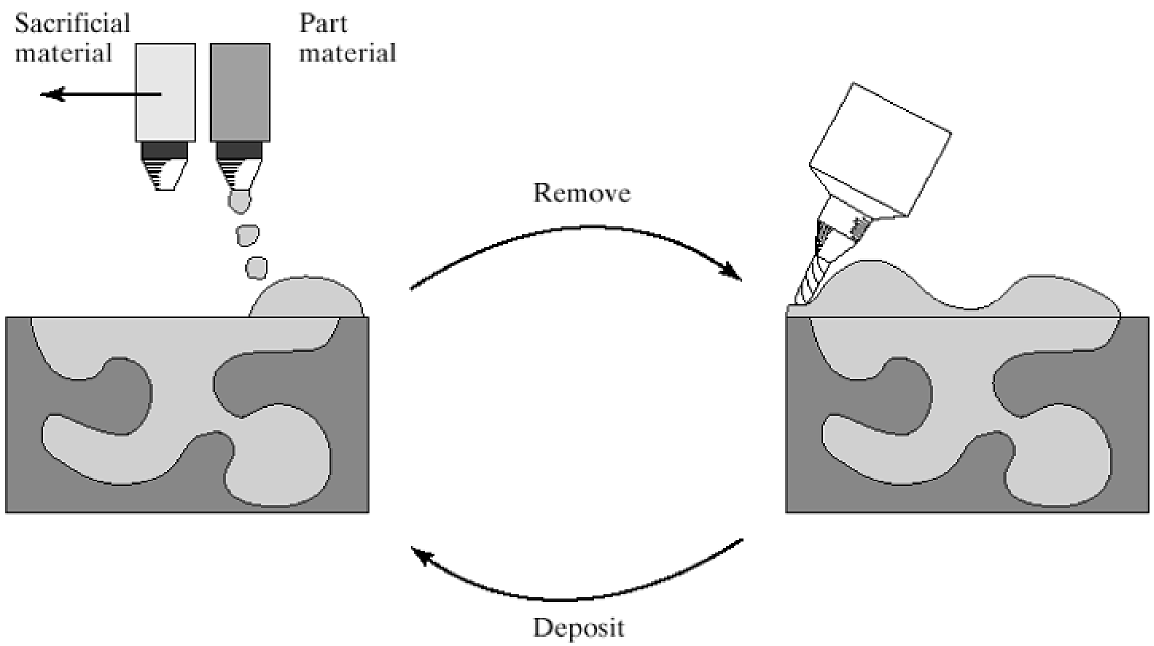
Solid Ground Curing (SGC)

- **Developed and commercialized by Cubital Ltd. (Israel).**
- **Uses a photopolymer, which is sensitive to UV-light.**
- **The vat moves horizontally as well as vertically.**
- **The horizontal movements take the workspace to different stations in the machine.**



Shape Deposition Manufacturing (SDM)

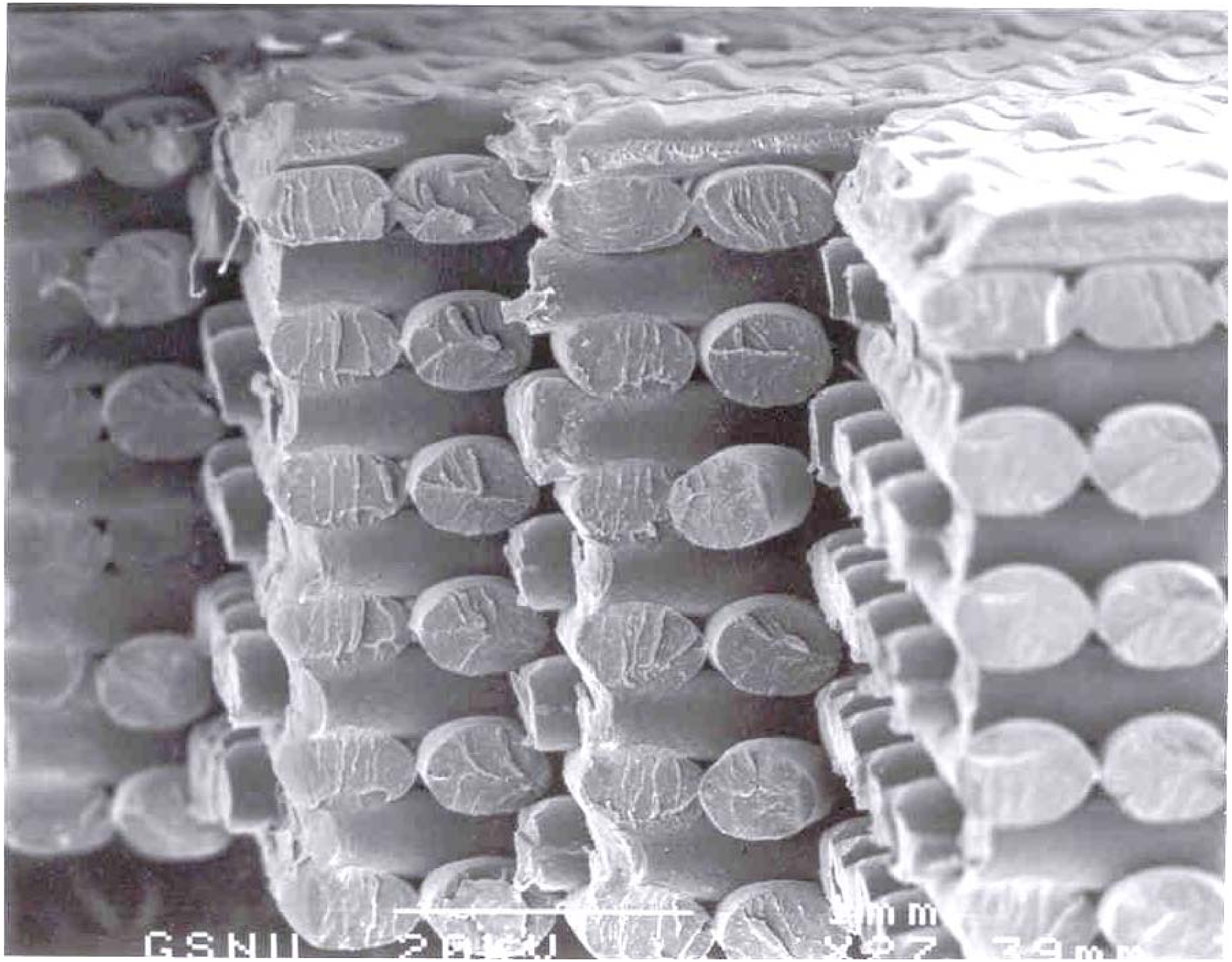
- **Developed by Stanford University / CMU.**
- **Uses deposition and milling.**
- **Provides good surface finish.**



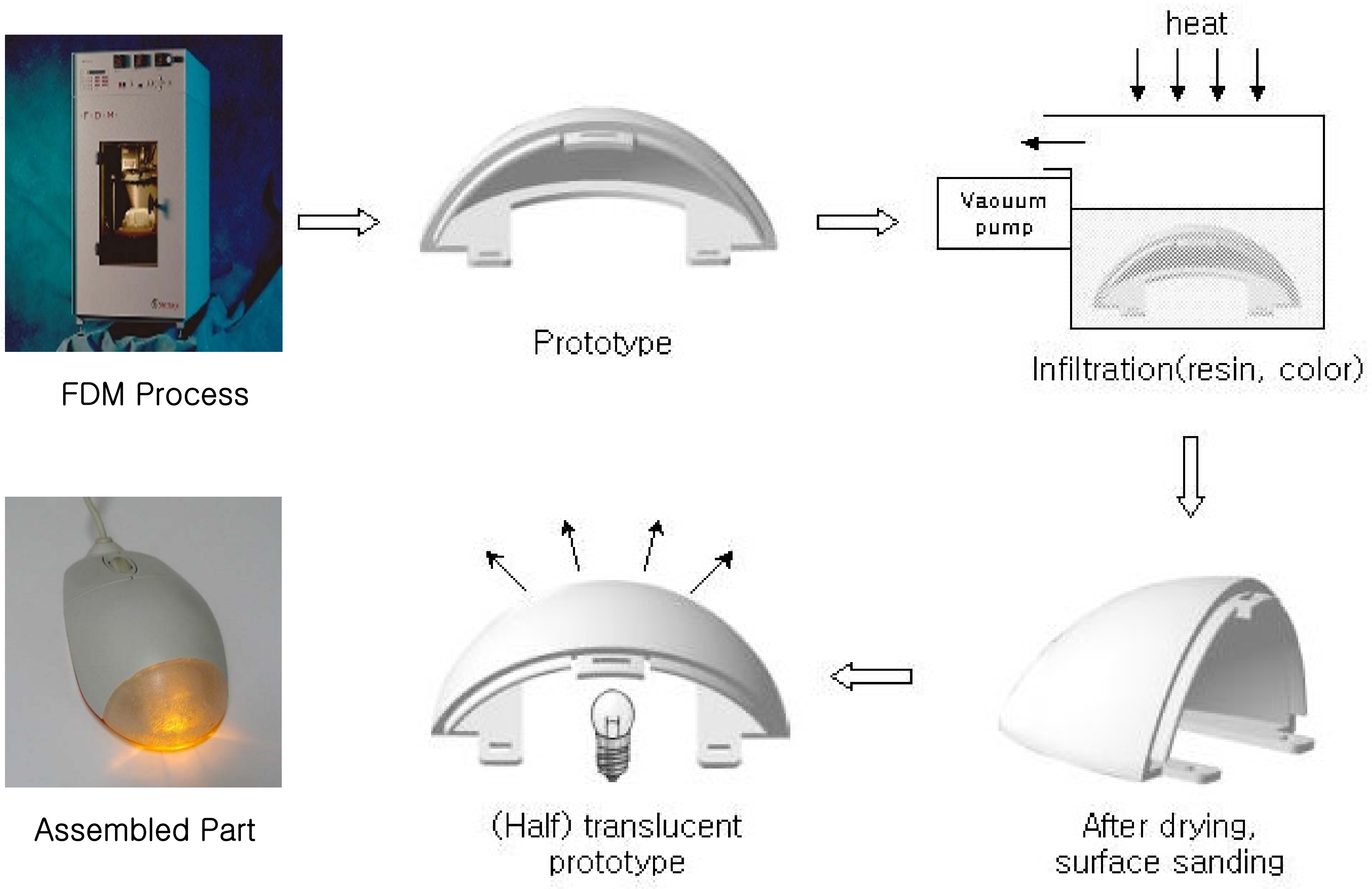
Issues in RP Materials

- **Rapid Fabrication of functional parts**
  - Structural
  - Optical
  - Surface Roughness
  - Electrical
  - Thermal
  - Color
  - Etc.

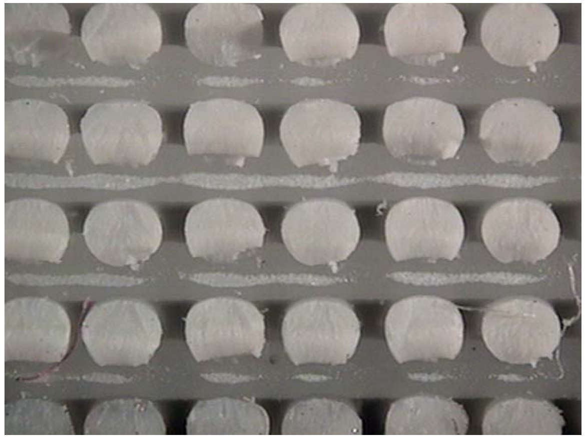
Micro Structure of FDM Part



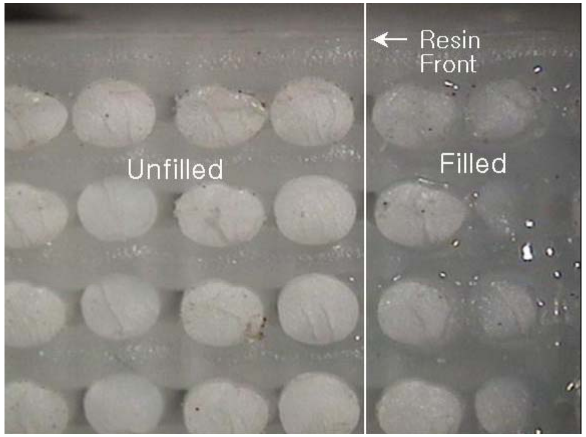
Post-processes of FDM



Resin Infiltration

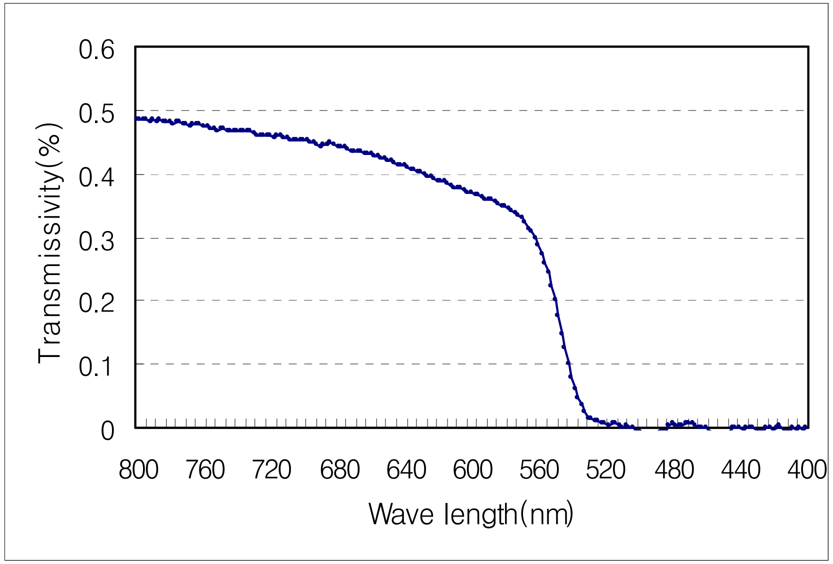


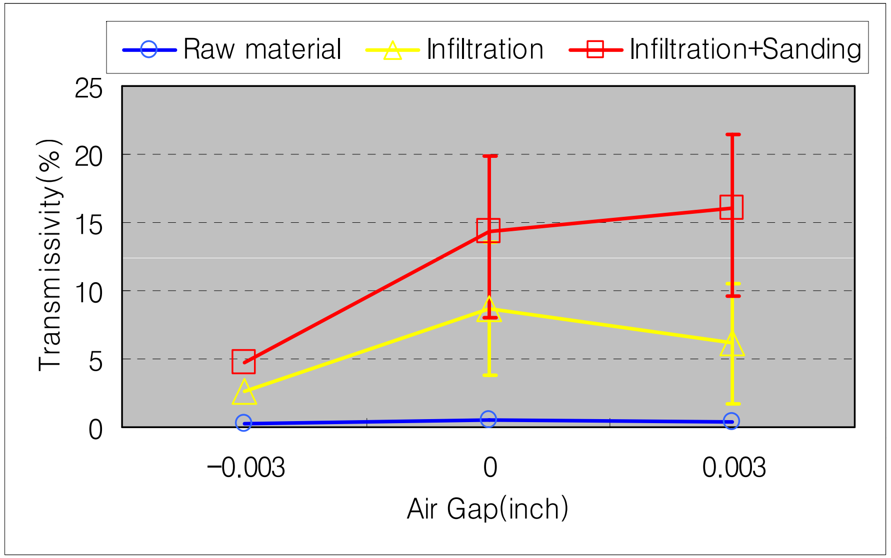
Raw FDM ABSi



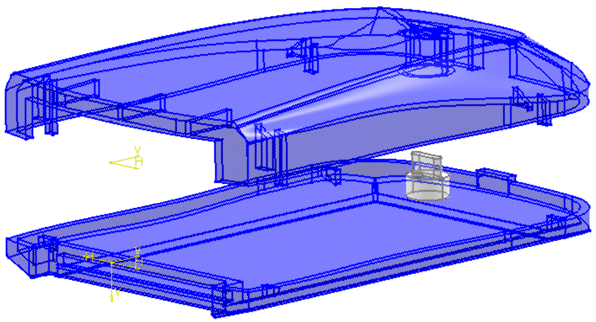
During Infiltration

After Infiltration





Flash Memory Reader

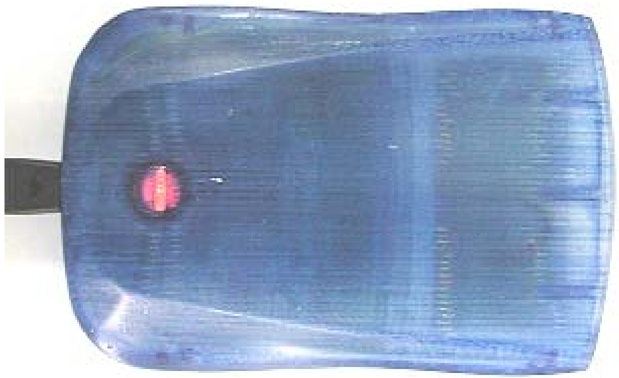


CATIA modeling:

5 hours

FDM process:

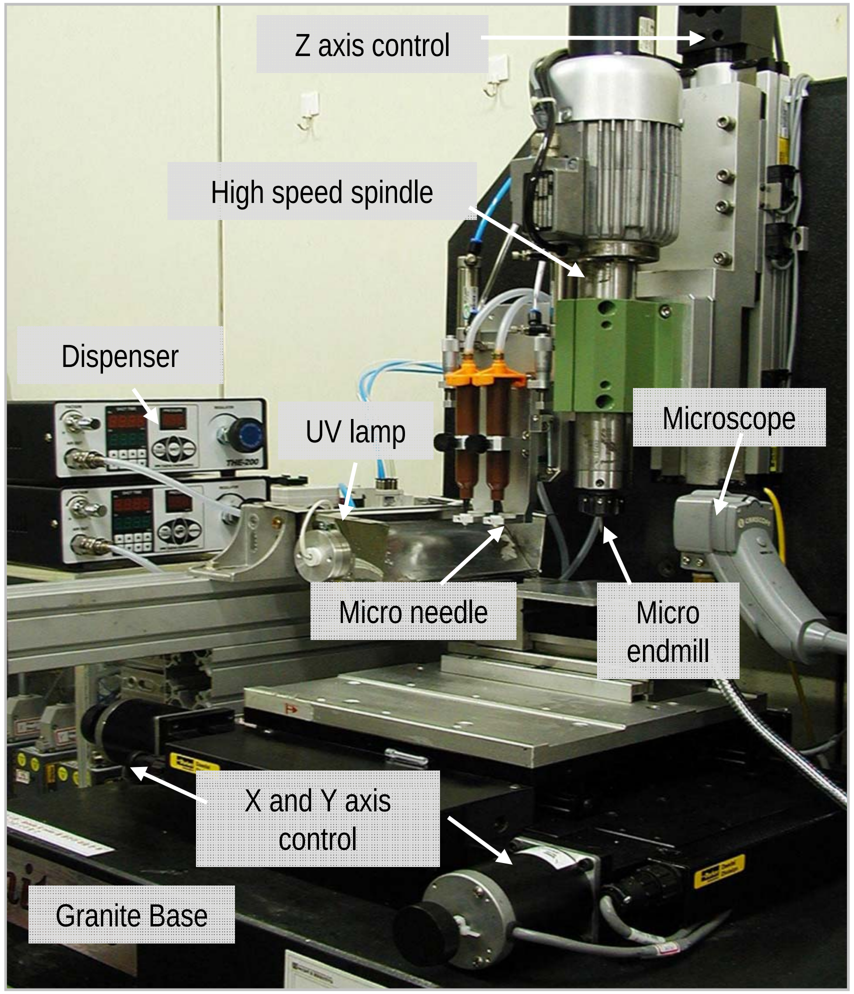
10 hours



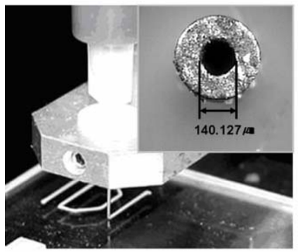
Post-processes : 24 hours

Total prototyping time : 39 hours

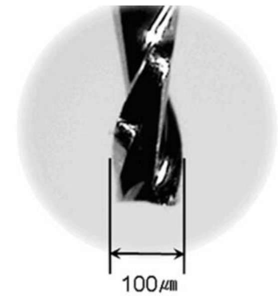
Component of Hardware



- ✓ ***Deposition; Rapid Prototyping***
- ✓ ***Cutting; Milling***
- ✓ ***Hybrid; Both***



Micro needle

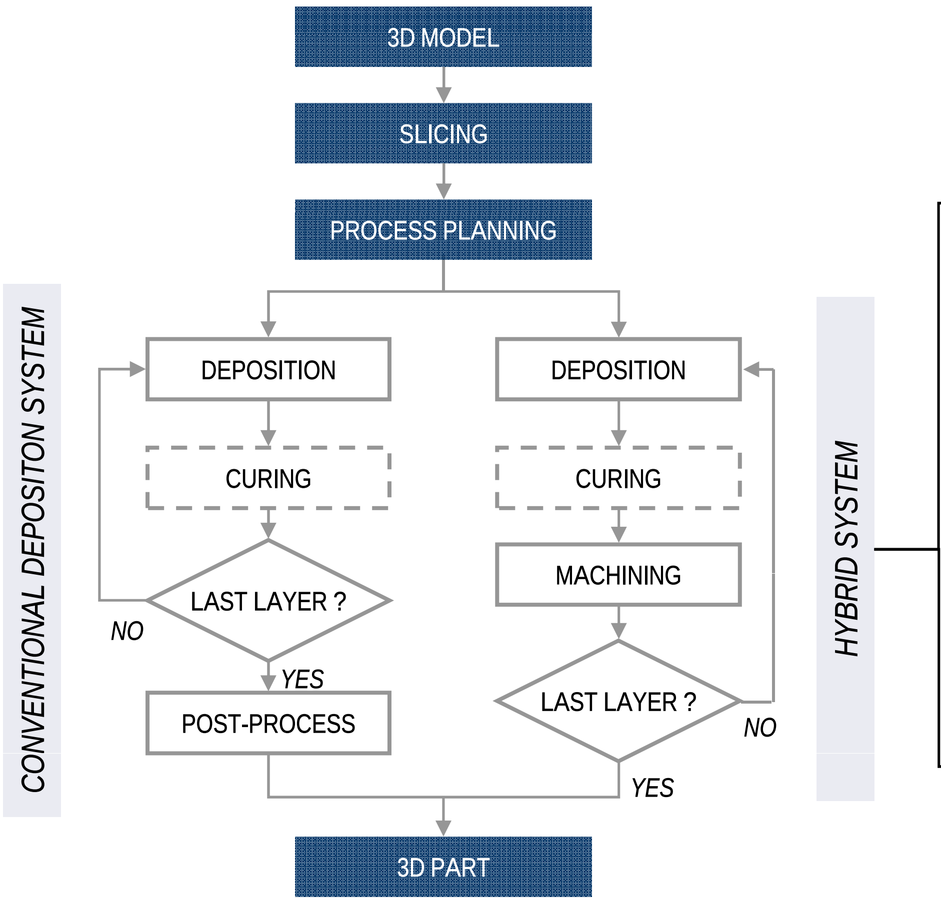


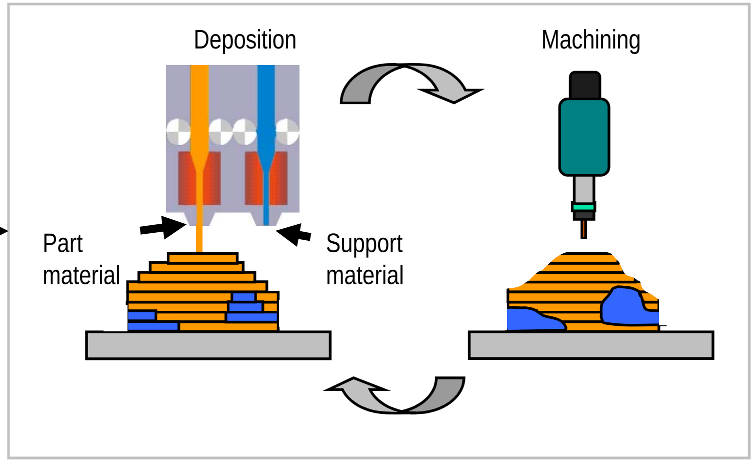
Micro endmill

SPECIFICATIONS

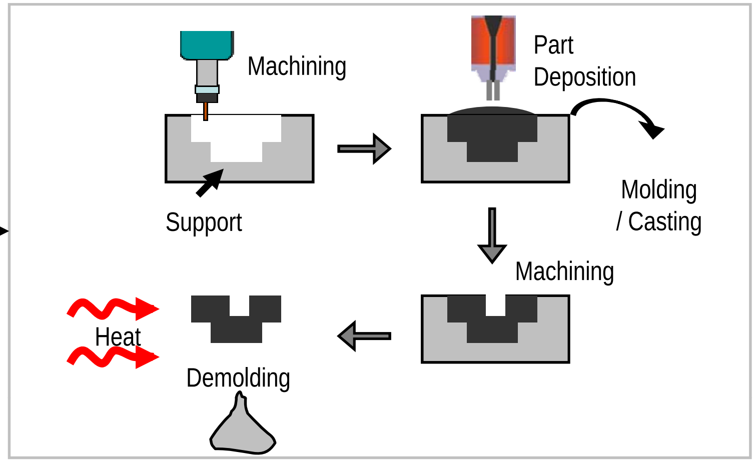
▪**3 Axes-stage**	▪1㎛ resolution
▪**Dispenser**	▪15 ~ 700 kPa
▪**Micro needle**	▪ ϕ140 ㎛ ~ ϕ800 ㎛
▪**Micro tool**	▪ ϕ 100 ㎛ ~ ϕ 1000 ㎛
▪**High speed spindle**	▪Max. 46,000rpm
▪**UV curing system**	▪0 ~ 400 W, λ = 365 ㎚
▪**Controller**	▪PMAC (Multi-tasking board)

Hybrid Process





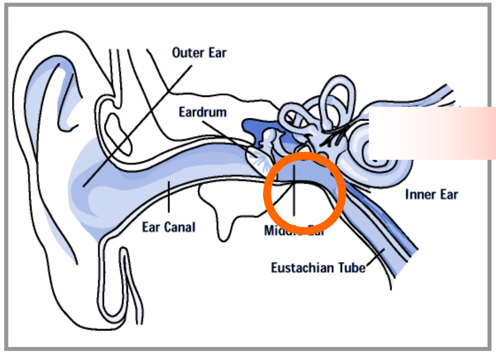
Deposition and Machining

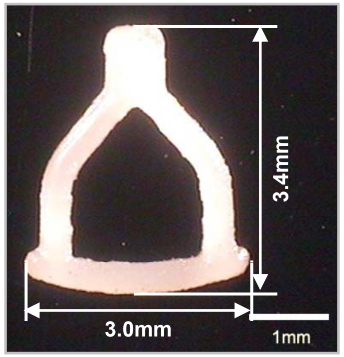


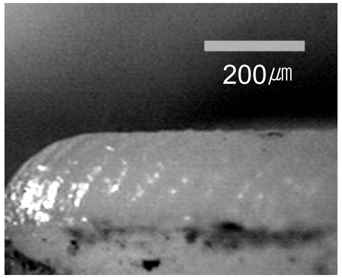
Stapes

3-dimesional part

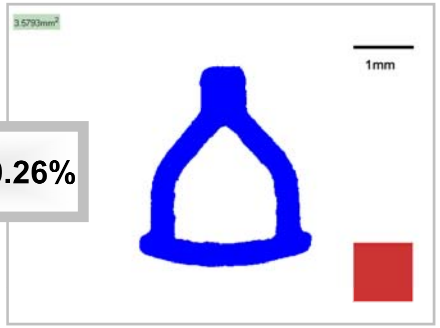
- ✓ The smallest bone in human body, width 2.5mm / height 3.5mm
- ✓ 40wt% Hydroxyapatite + Acrylic resin
- ✓ Dispensing process using ϕ 140㎛ needle
- ✓ Micro milling using ϕ 100㎛ flat endmill







Error : 0.26%



Area measurement using imaging processing

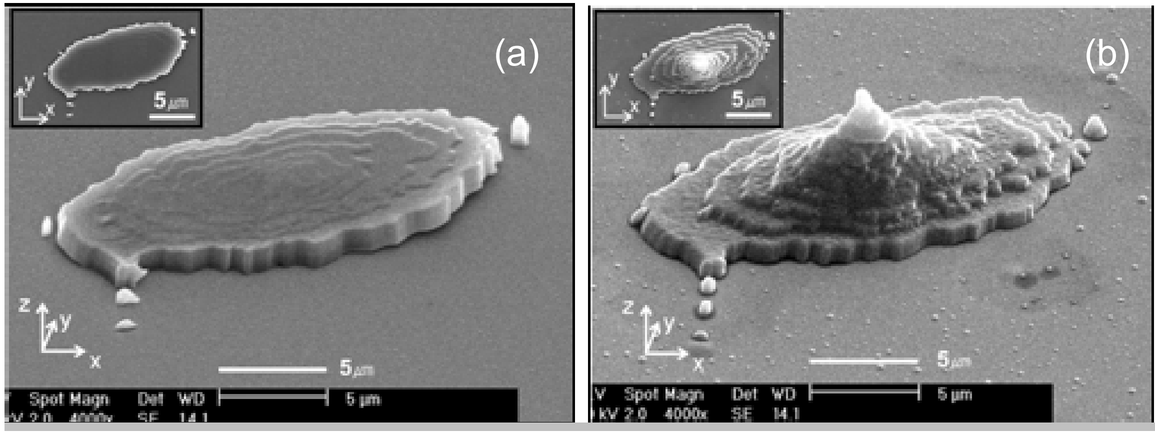
PROCESS

Mold (using wax) machining → part deposition → surface machining → demolding

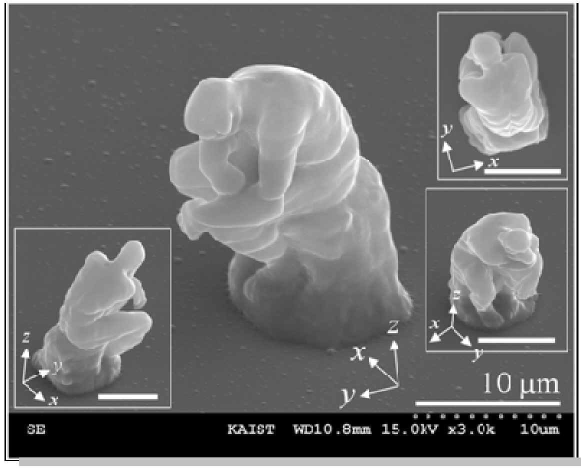
3D Nano / Micro Parts

- **Nano Stereolithography**

•D. Y. Yang, KAIST

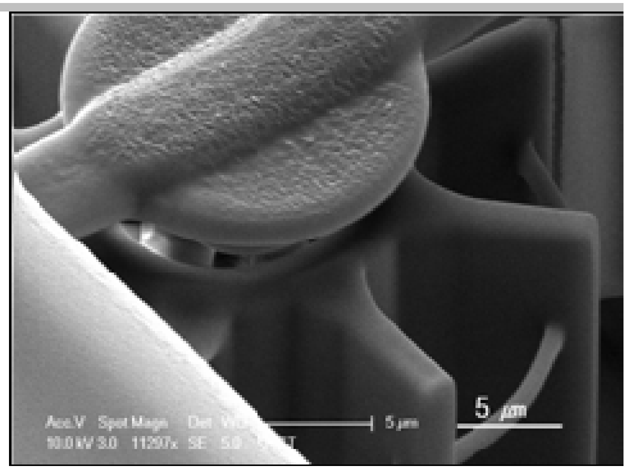


SEM images of fabricated islands with (a) actual and (b) exaggerated ratio of height vs. width by controlling both exposure time and laser power simultaneously. Inset is top view of the structure



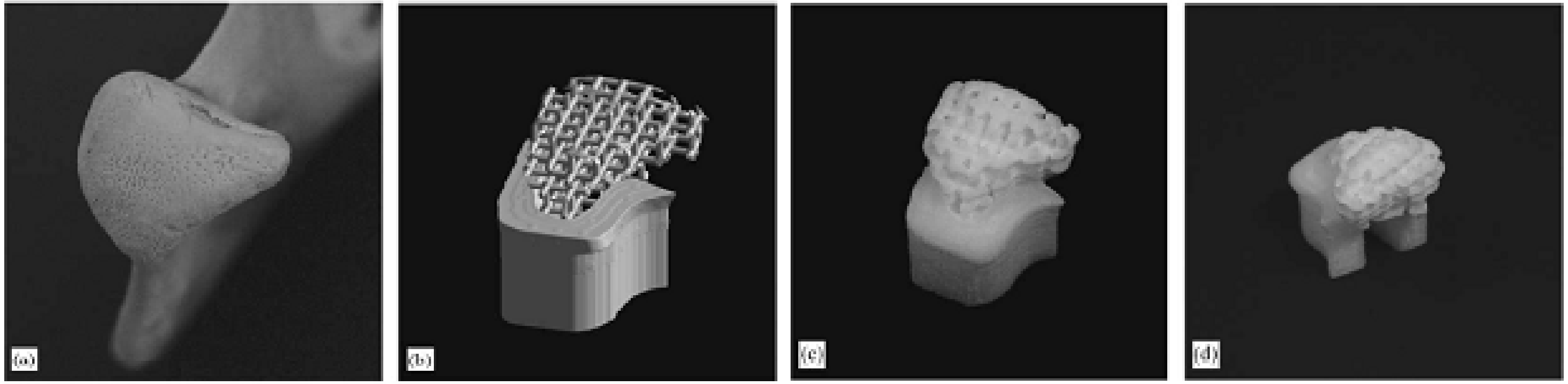
SEM images of fabricated micro-Thinker by double-scanning path. The insets are the same micro-Thinker with various view angles, and the scale bars are 10 ㎛

Fabricated micro-prototypes of a micro rotor



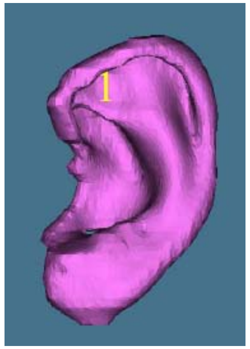
Porous Structure

- **PCL; poly(e-caprolactone)** (The University of Michigan)



(a) An actual pig condyle, (b) surface rendering of STL design file for pig condyle scaffold, (c) front view, and (d) back view of pig condyle PCL scaffold fabricated by SLS.

- **Rehabilitation** (Yan, et al)



CAD modeling

RP part

Rehabilitated ear