

# manufacturing processes - overview

Part 1: mechanisms of geometry formation

Part 2: performance (rate, quality, cost, energy)

2.810

T. Gutowski

Page references are to Kalpakjian and Schmid 6th ed

# Mechanisms of Geometry Formation

1. Subtractive
2. Additive
3. Continuous
4. Net shape

# Material phase

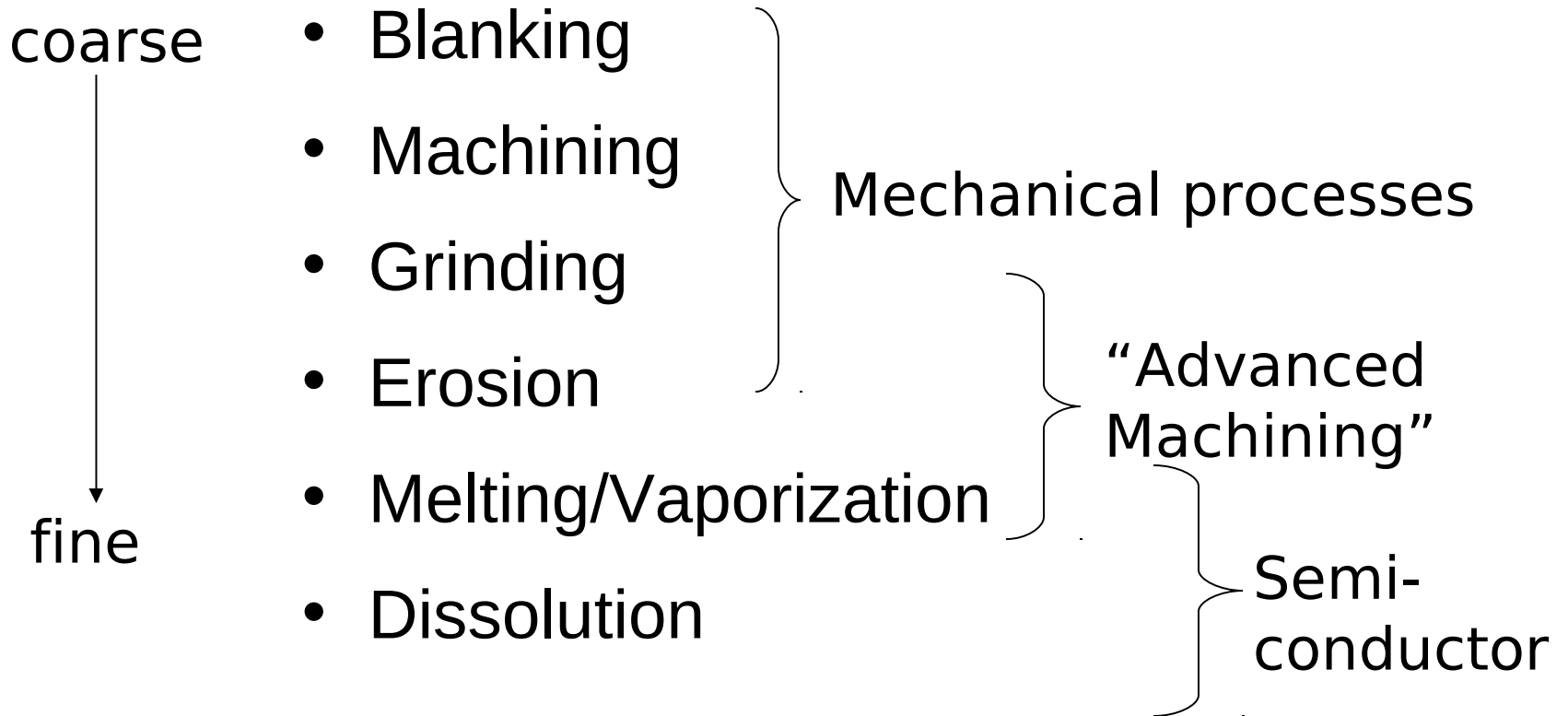
- Solid phase - e.g. machining, bending
- Liquid phase - e.g. casting, injection molding
- Mixed phase - e.g. composites molding
- Vapor phase - e.g. chemical vapor deposition

# 1. Subtractive Processes

- Processes
  - Machining: Turning, milling, boring, grinding
  - Non-traditional machining: EDM, chemical milling, waterjet, etc.
  - Micro-electronics processes: Primarily etching type processes using either masks or beam, chemical mechanical polishing...



# 1. Material Removal



# 1. Material Removal

coarse



fine

- Blanking
- Machining
- Grinding
- Erosion
- Melting/Vaporization
- Dissolution

fast



slow

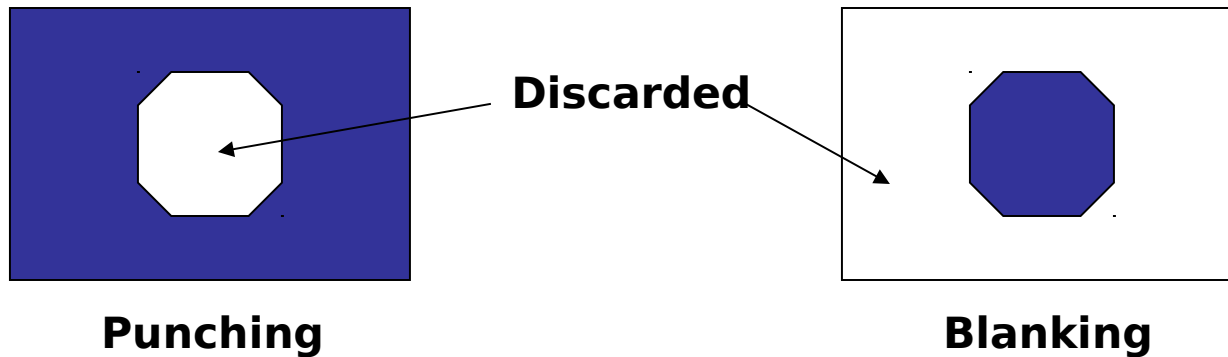
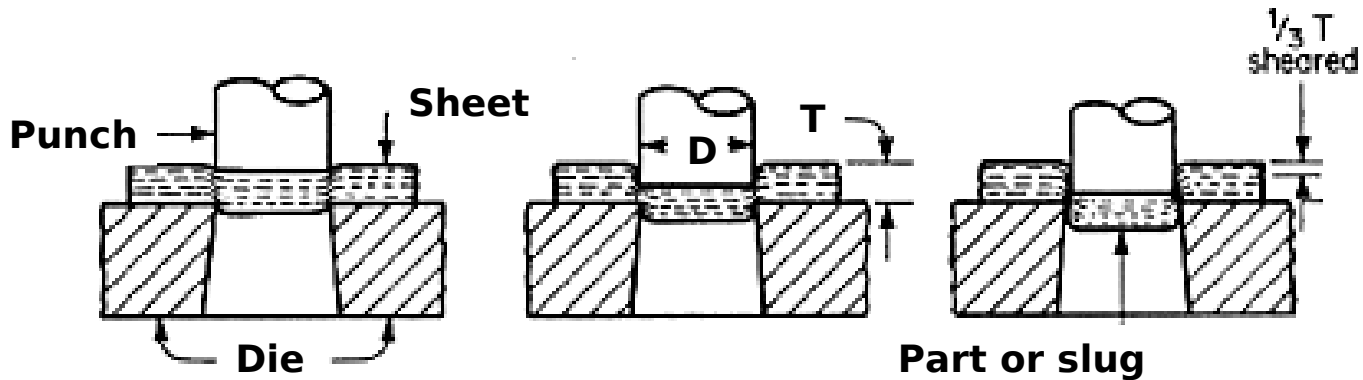
recycle



destroy

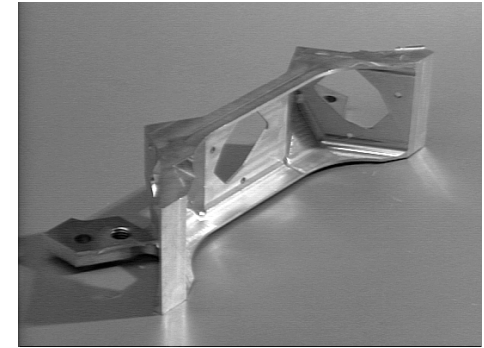
# Blanking and Punching

\*





# Machining



- Conventional Machining processes:
  - To first approx mat'l properties are independent of process
  - Very flexible
  - Good dimensional control (possible)
  - Good surface finish (possible)

# Milling-rotating cutter



# Turning-rotating part



Sub-spindle not available on GA series

# grinding



Surface grinding



Cylindrical grinding

# Variations

- Single point
- Multiple cutting teeth
- Form tools
- Multiple heads
- Fixturing
- Work handling
- Chip removal

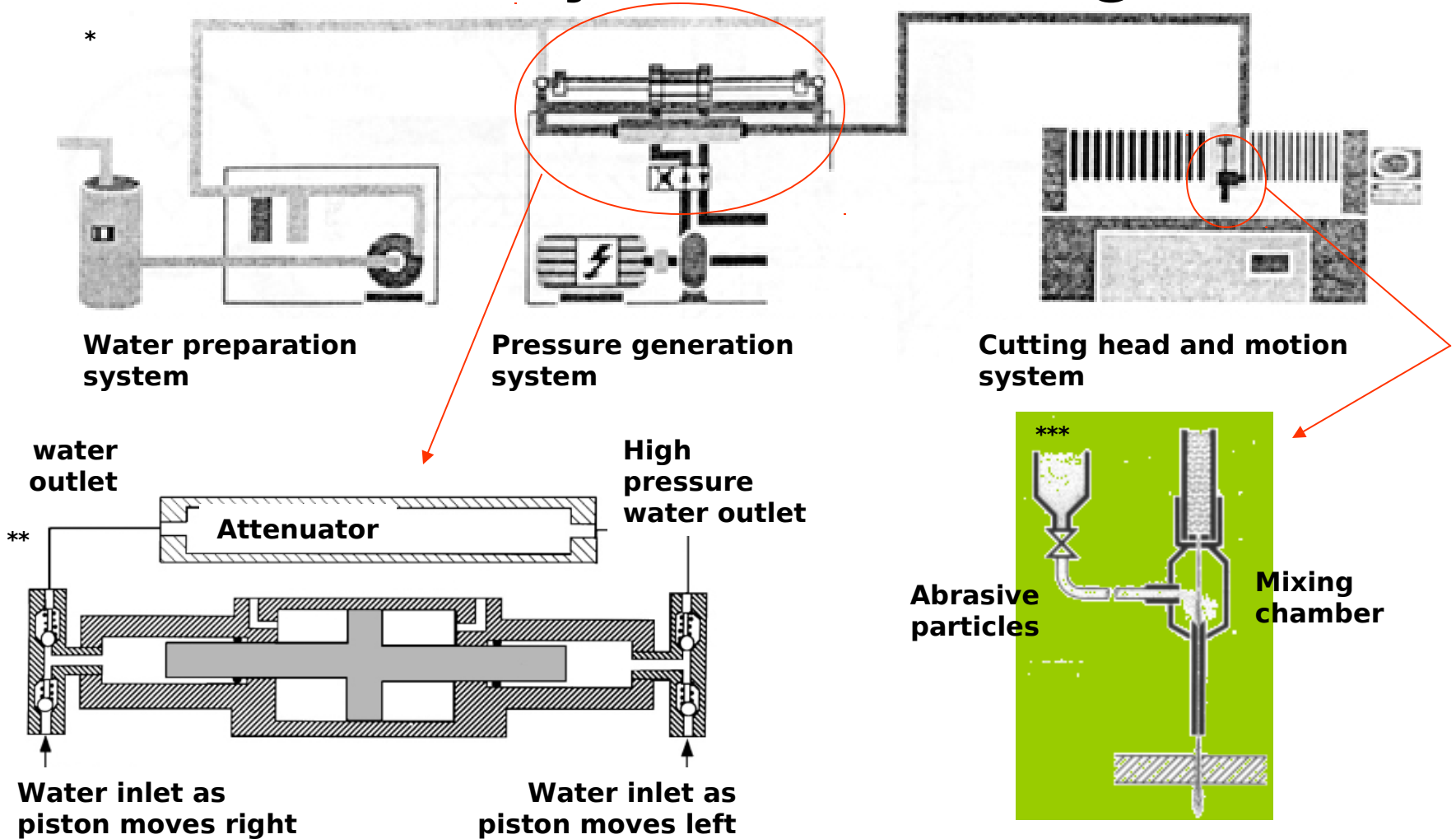




# Removal by erosion



# Waterjet Machining

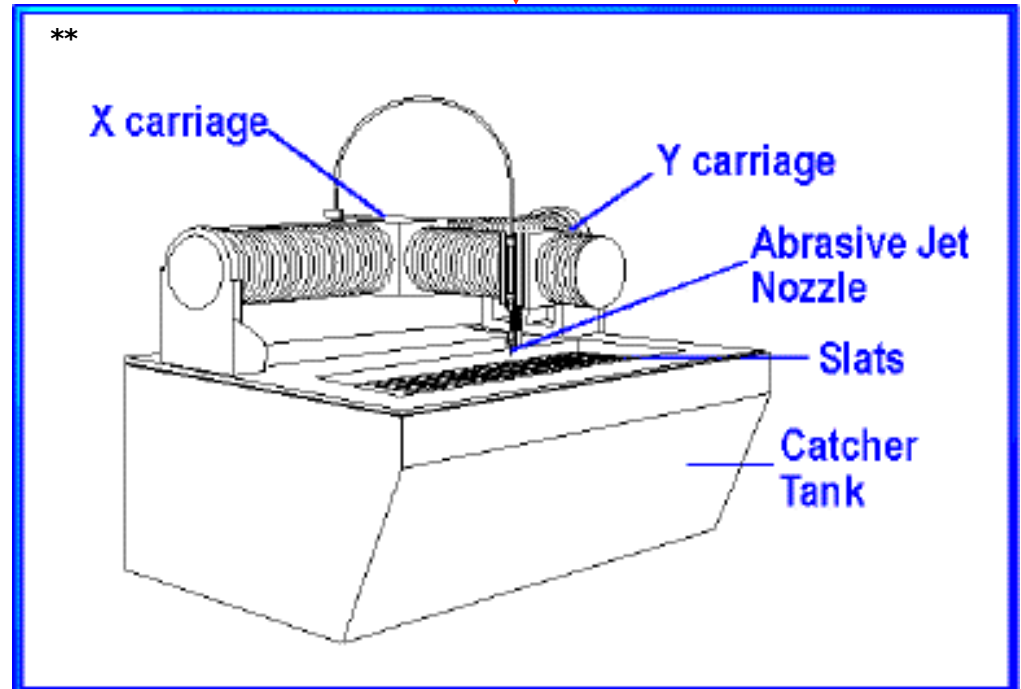
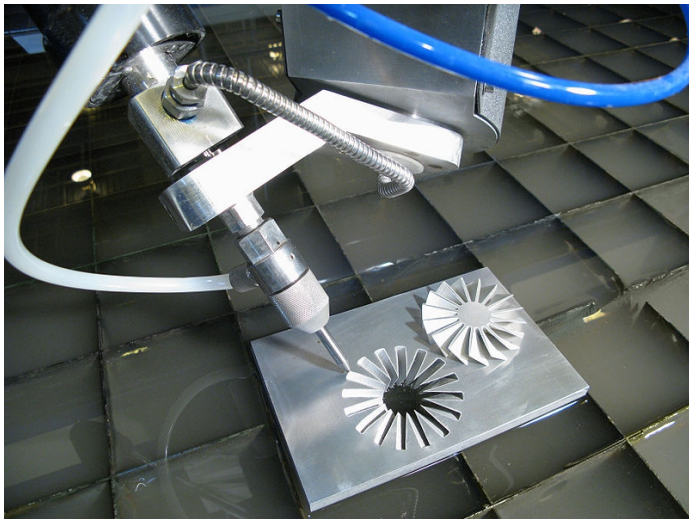
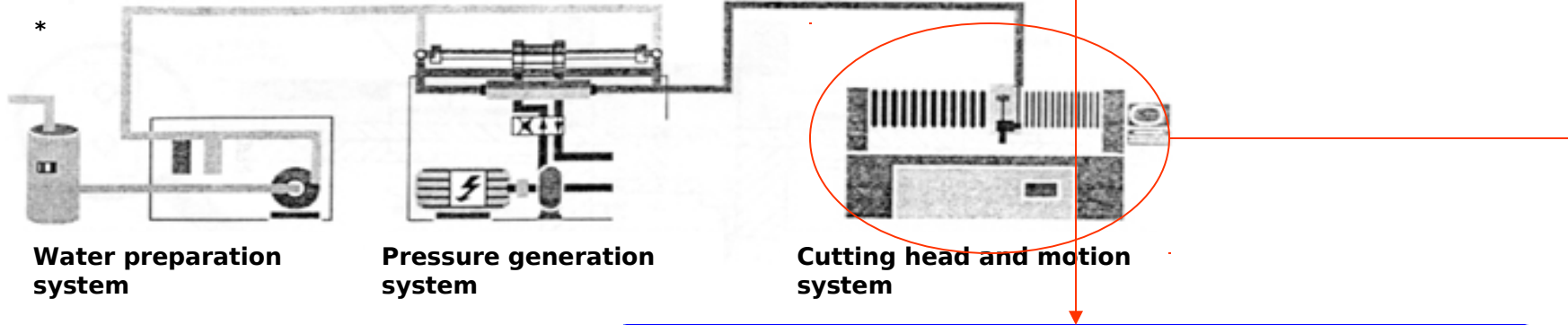


\* Source: <http://www.seas.smu.edu/rcam/research/waterjet/par1.html>; \*\* <http://www.seas.smu.edu/rcam/research/waterjet/par3.html>;

\*\*\* <http://kbm.mt.polsl.gliwice.pl/wjm/basics.html>

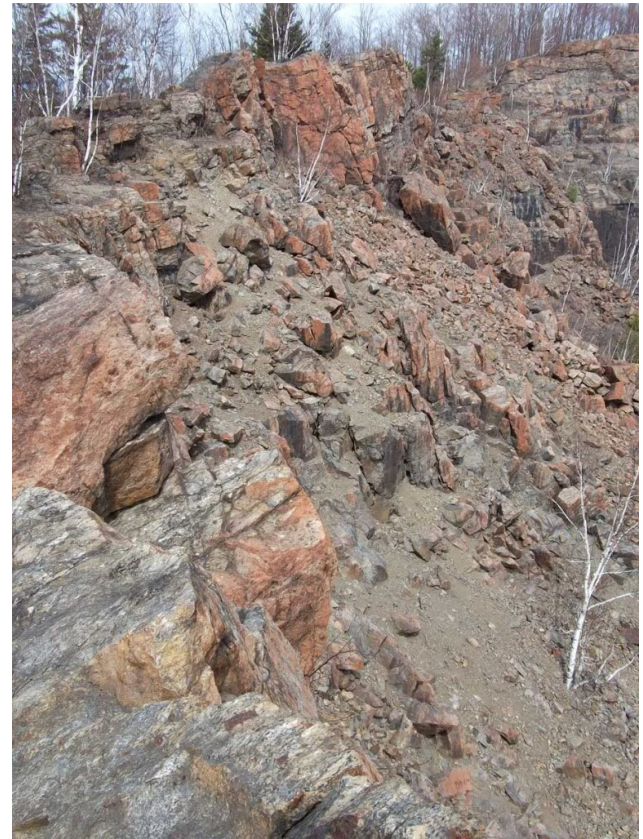
[http://www.youtube.com/watch?v=\\_FIsrYzyvlg](http://www.youtube.com/watch?v=_FIsrYzyvlg)

# Waterjet Machining

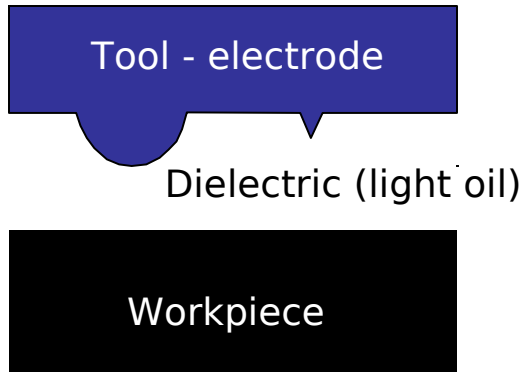




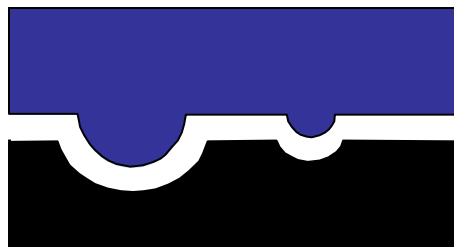
# Gore Mt, New York



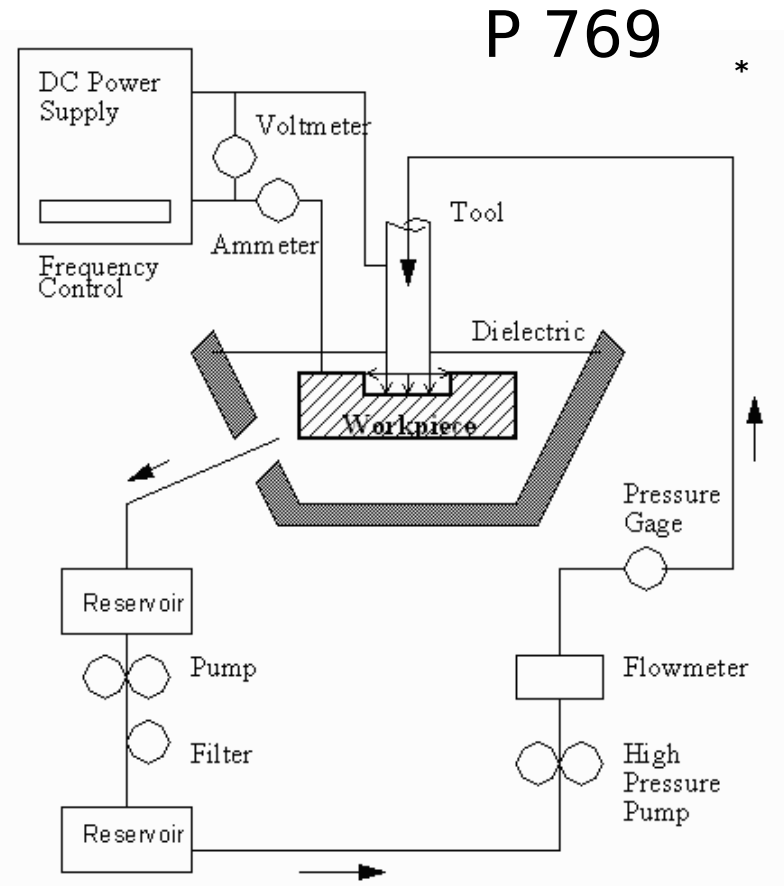
# EDM (ElectroDischarge Machining)



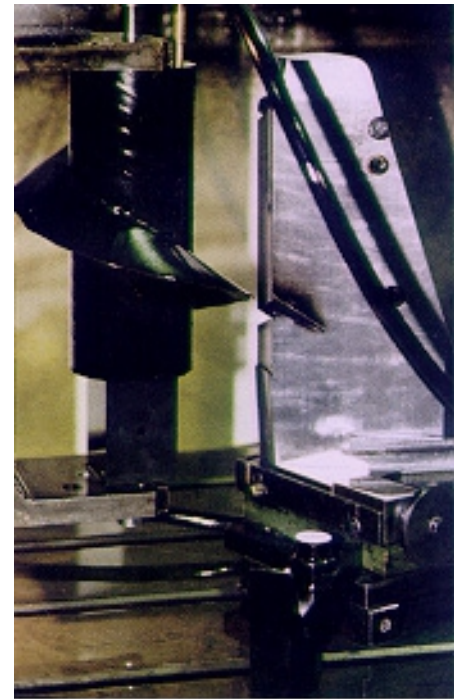
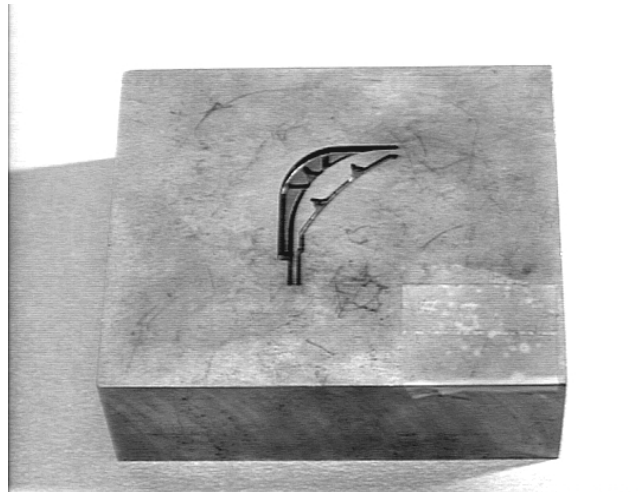
Initial shapes of electrode and workpiece



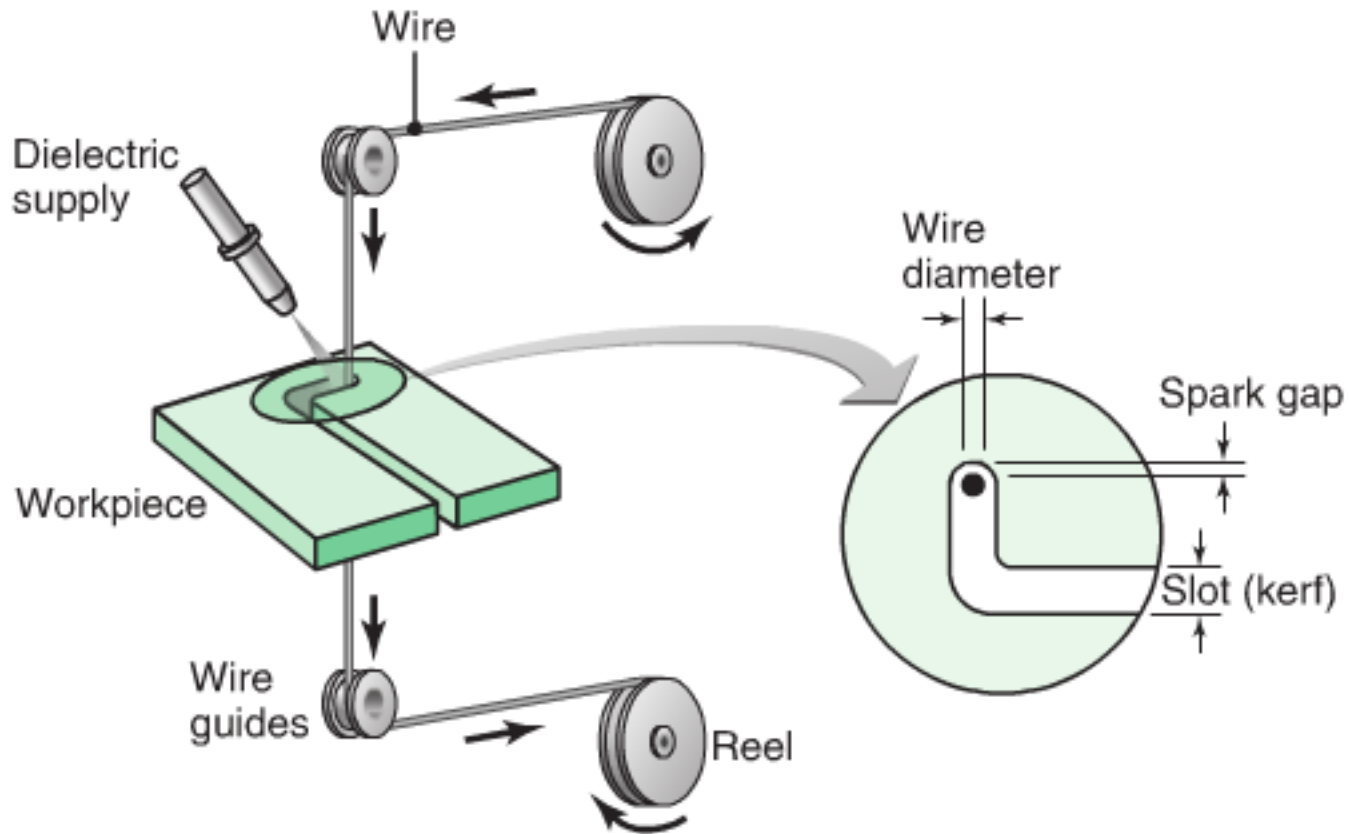
Final complementary shapes of electrode and workpiece



\* Source: <http://cybercut.berkeley.edu/mas2/html/processes/edm/index.html>



***Mounted Electrode***

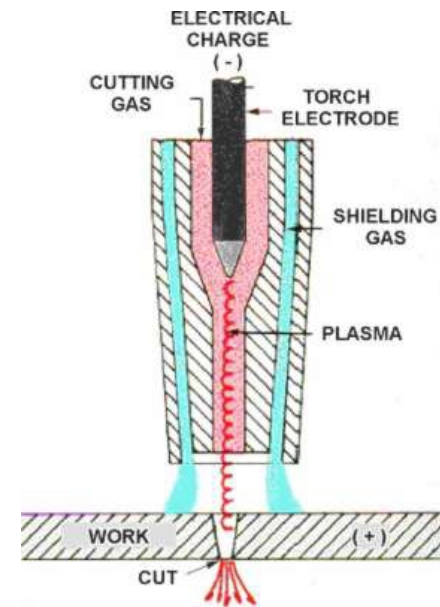
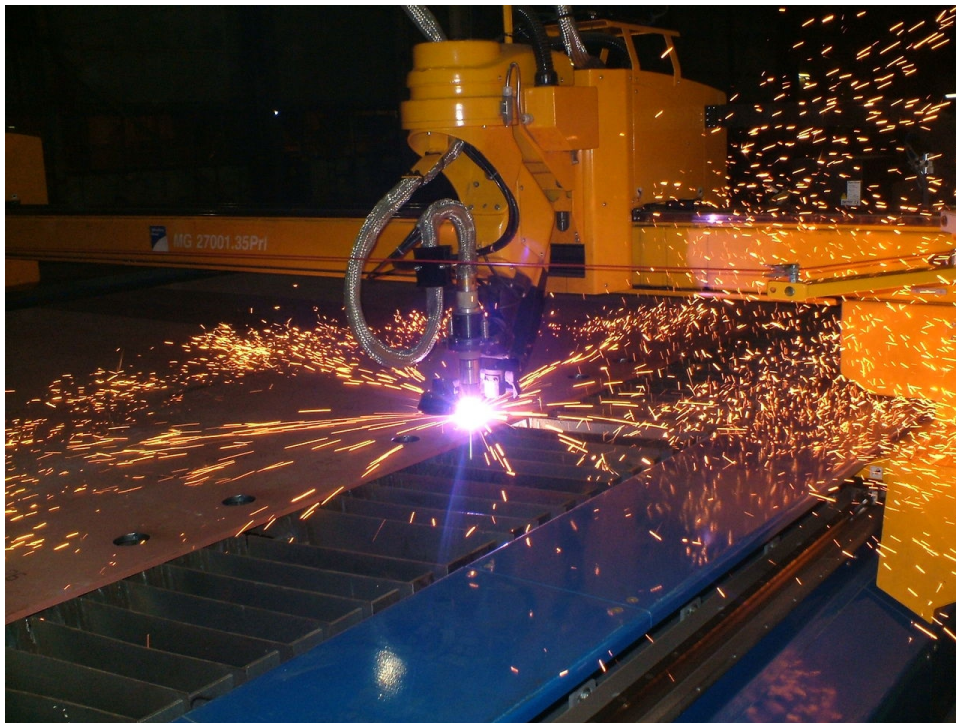


**FIGURE 27.12** Schematic illustration of the wire EDM process. As many as 50 hours of machining can be performed with one reel of wire, which is then discarded.

Wire EDM p 772

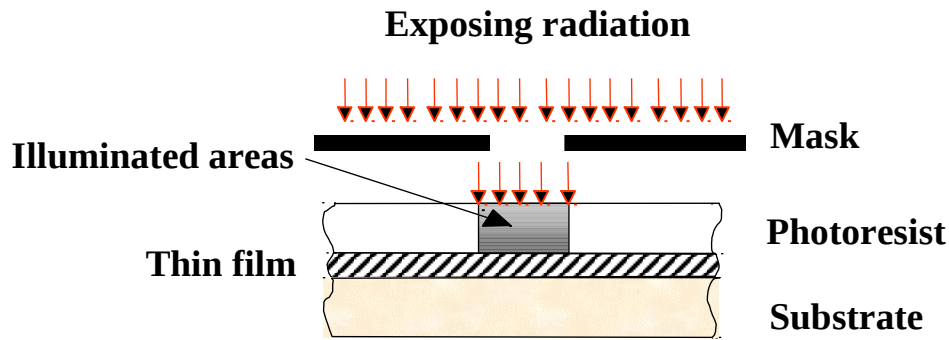


# Plasma arc cutting

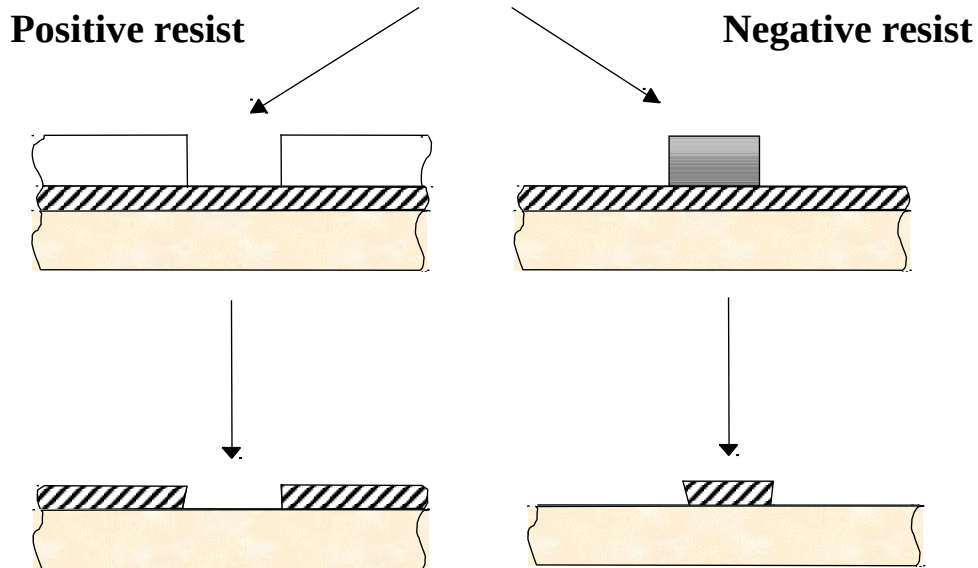




# Lithography (additive + subtractive)



**EXPOSURE**



**DEVELOPING**

**ETCHING AND STRIPPING**

# 2. Additive Processes

- Processes
  - Rapid Prototyping
    - Very flexible to part shape; usually limited in material choices; slow rates; fully automated
  - Advanced Composites Processes
    - Combination of additive and net shape processes
  - Microelectronics Processes
    - Physical and chemical vapor deposition processes and coating methods
  - Joining & Assembly
    - Broad category includes welding, adhesives, and mechanical assembly

# 2. Additive Processes

coarse



fine

Joining

mechanical

adhesives

melt/solidification

Assembly

Composites layup

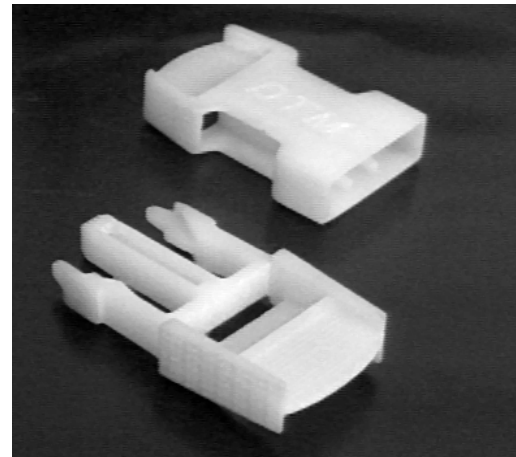
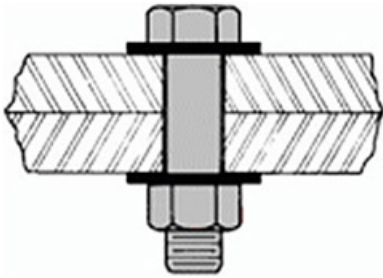
Coating, plating

Vapor deposition

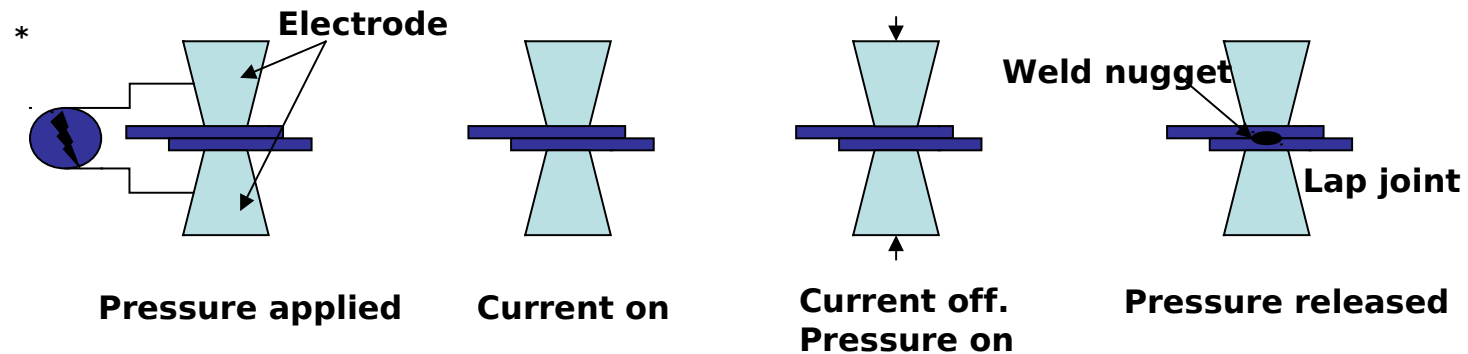
Sputtering

Ion implant

# Mechanical joints

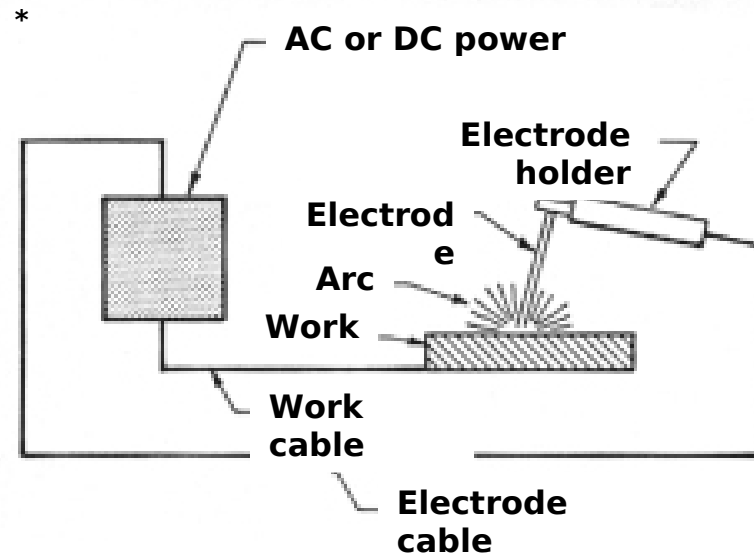


# Welding

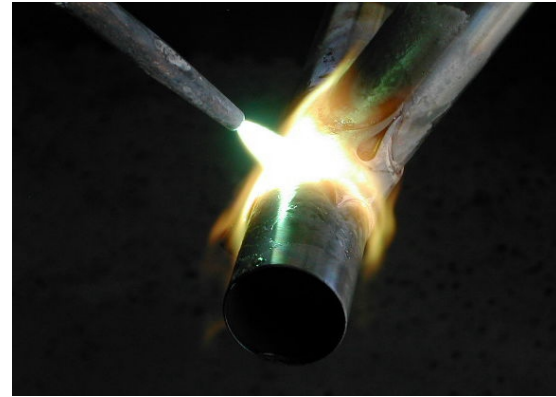
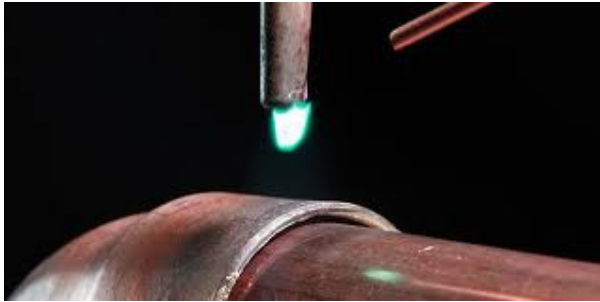


**[Sequence in the resistance spot welding process]**

**[Schematic illustration of the shielded metal-arc welding operation]**



# Brazing



Furnace brazing

<http://www.youtube.com/watch?v=3UBd1HIXegM>

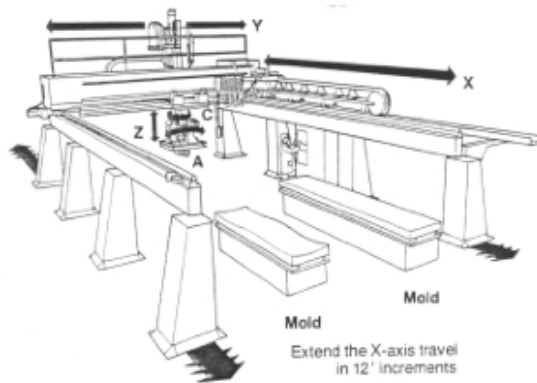
# Lay-Up of Advanced Composites



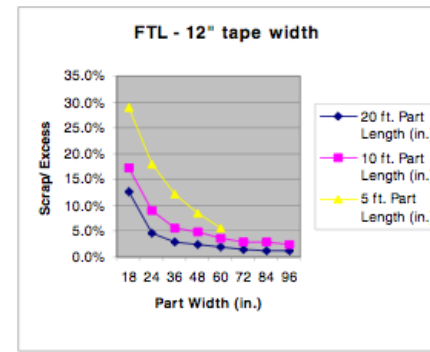
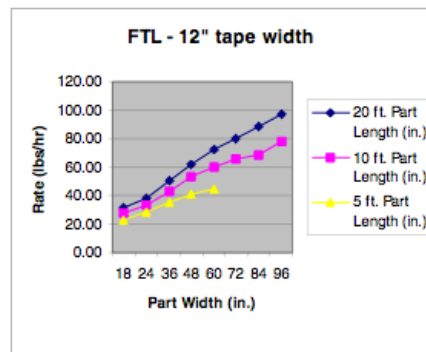
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# Automated tape layup



**Fig 1.0** Tape Layer Configuration and Axis of Movement



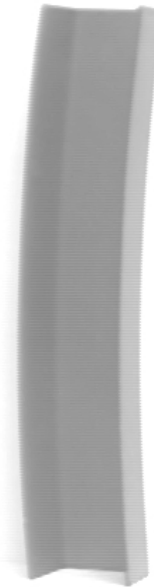
**Fig 3.0** Simulation of FTLM Lay up and Scrap Rates



# More complex shapes

Lay up

Forming



Sam Truslow, MIT,

**Aviation Week:  
Skunk Works'  
Cargo X-Plane  
Complete**

Posted by  
Graham Warwick  
at 3/6/2009  
12:14 PM CST

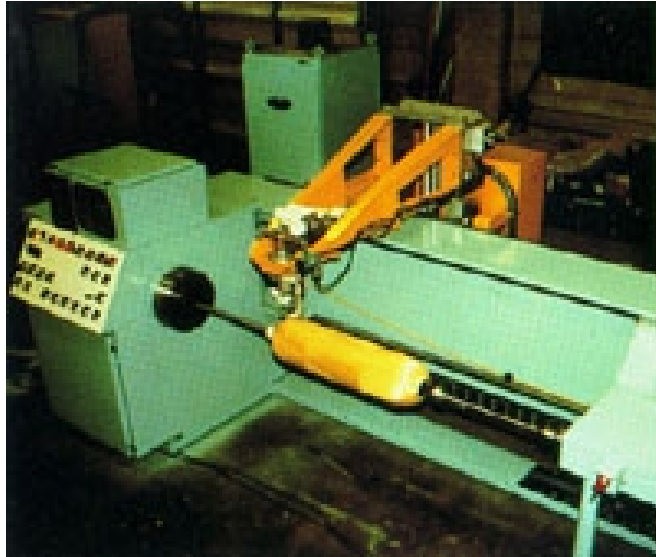
Wu, Tatting, Smith  
And Thornburg



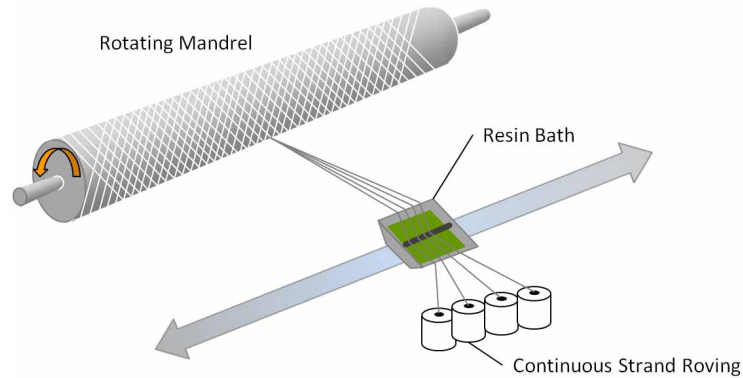
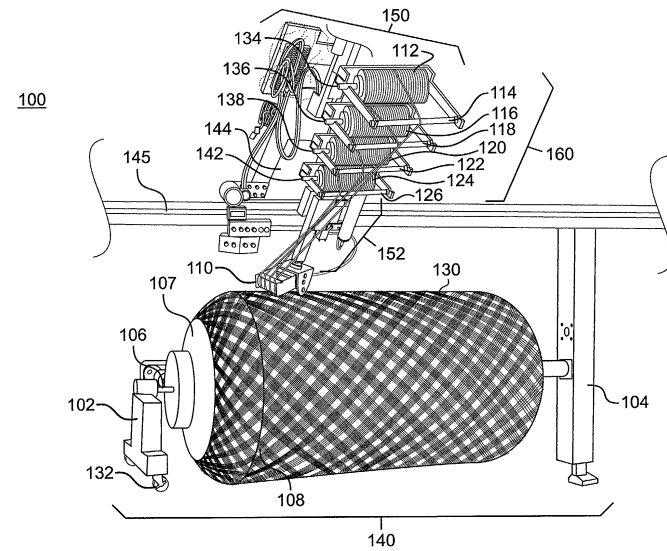
Figure 2. Fiber placement machine.



# Filament Winding



Filament winding



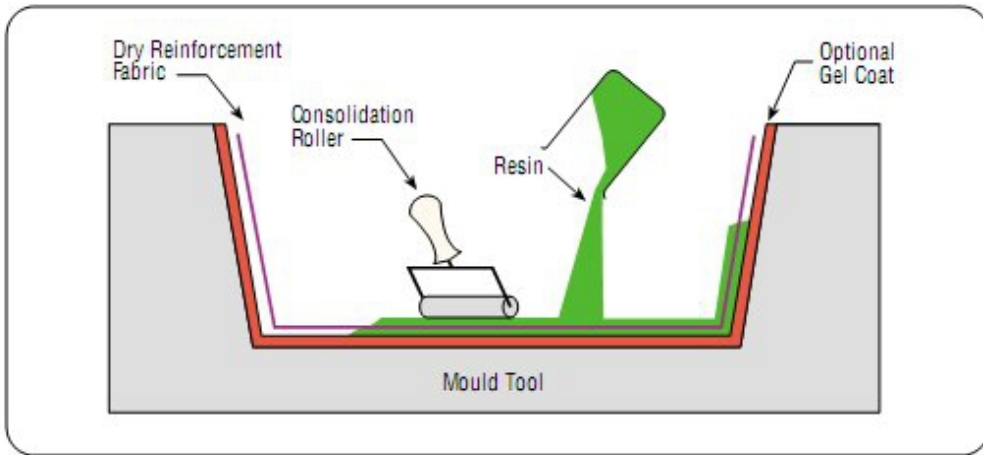
# braiding



**Braiding Videos** <http://www.youtube.com/watch?v=zOhj7X1-x10>

<http://www.youtube.com/watch?v=j19na8LMBnE&NR=1>





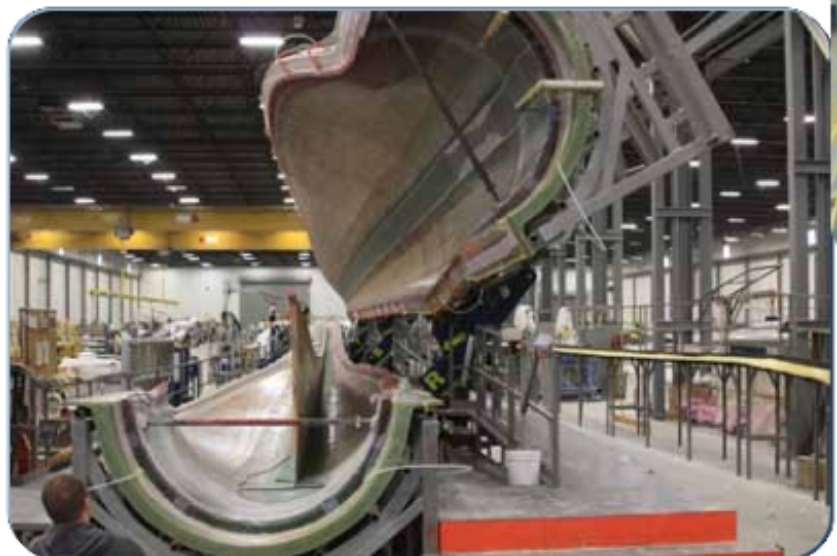
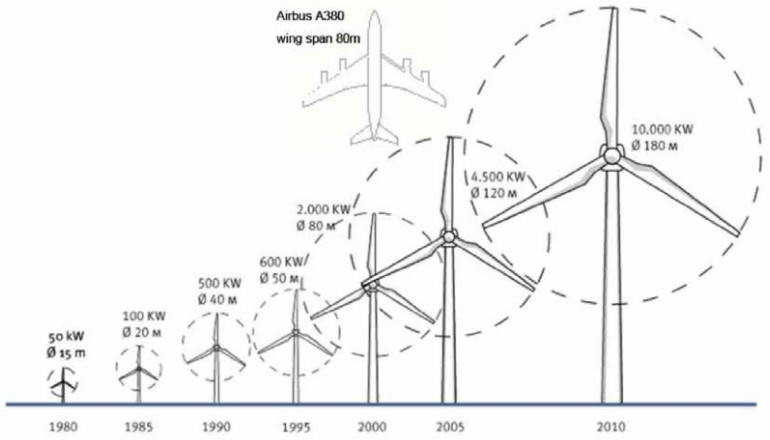
- Hand lay-up
- Spray-up
- Vacuum molding



Vacuum mold video  
Jump to 4 min

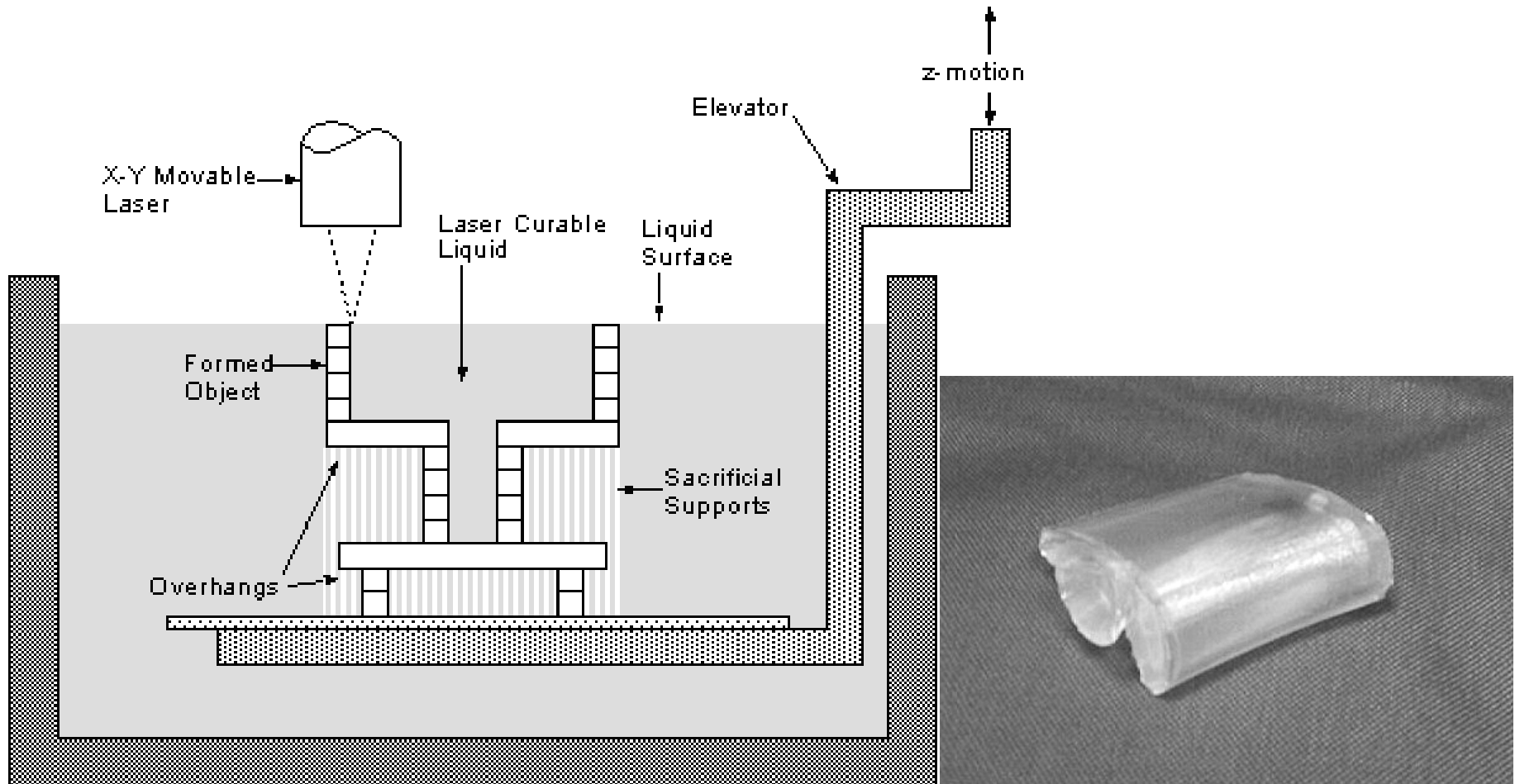
<http://www.youtube.com/watch?v=YZAkf1E2Jcs>

# Growing Wind Turbine Size

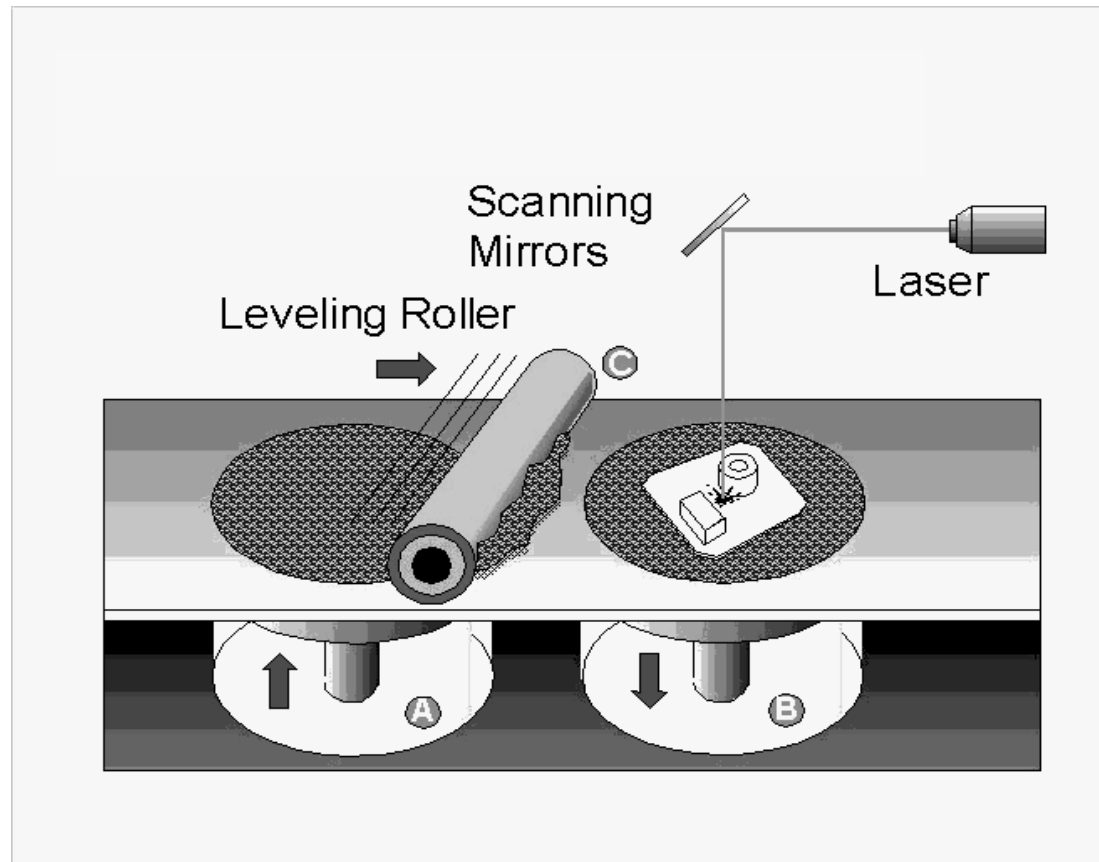


# Stereolithography (SLA)

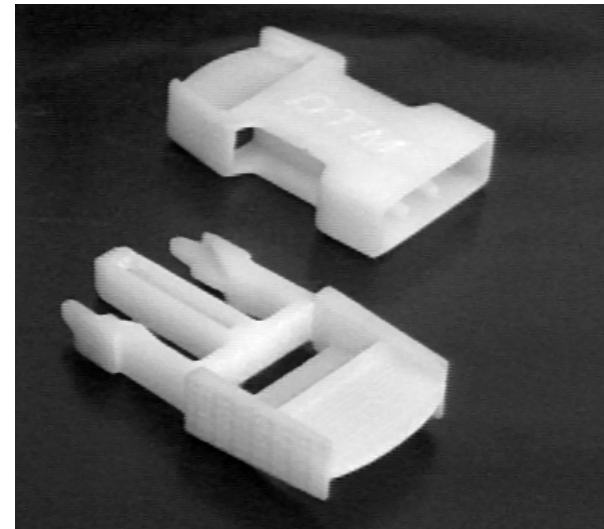
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# Selective Laser Sintering (SLS)



# Selective Laser Sintering (SLS)



[http://web.mit.edu/2.810/www/lecture/sinter\\_movie.mov](http://web.mit.edu/2.810/www/lecture/sinter_movie.mov)

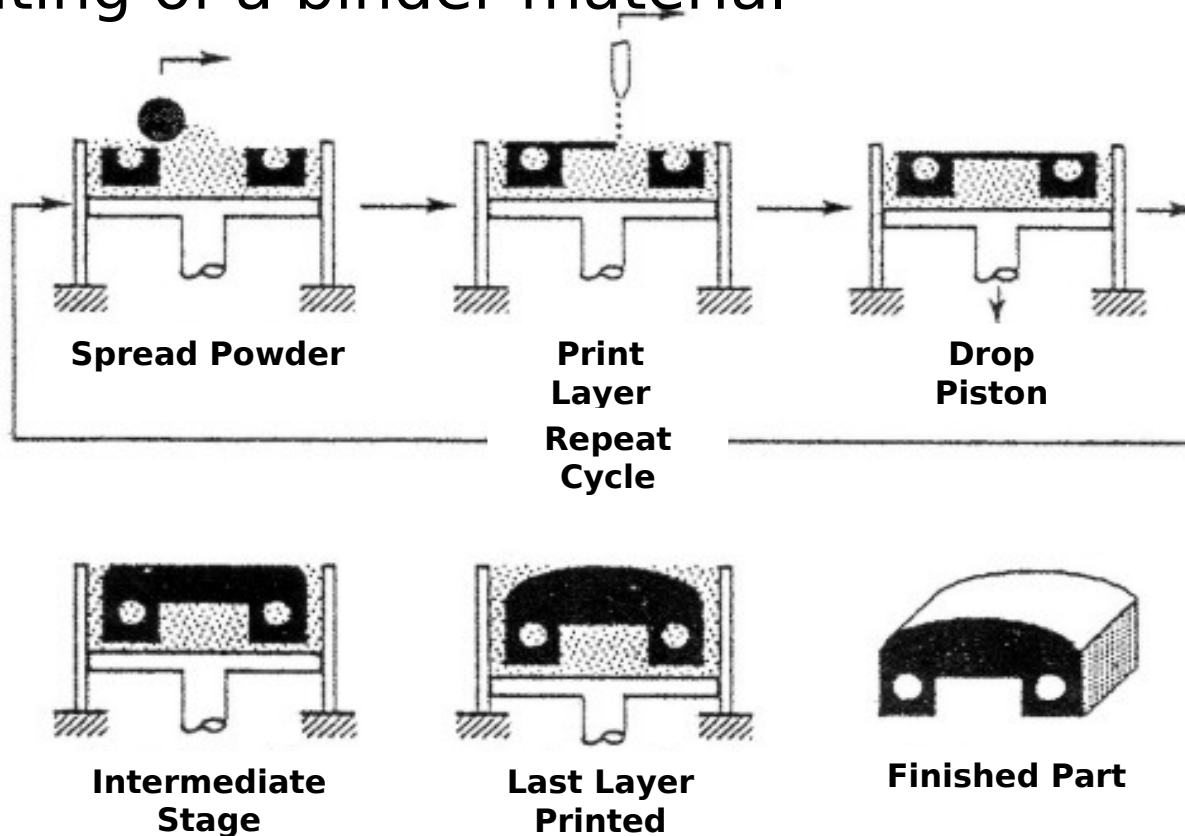
<http://www.youtube.com/watch?v=SVkUwqzjGJY>

<http://www.youtube.com/watch?v=gLxve3ZOmvc>

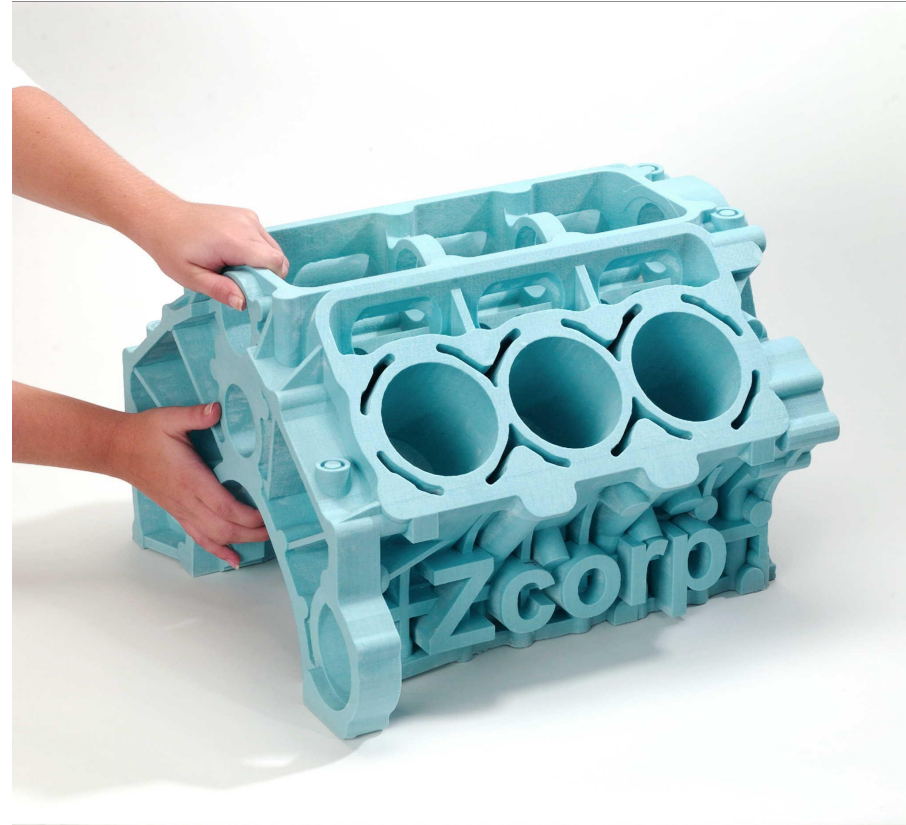


# 3D Printing

Selective joining of powder using ink-jet printing of a binder material



# Z corp rapid prototyping



<http://www.youtube.com/watch?v=u7h09dTVkdw>

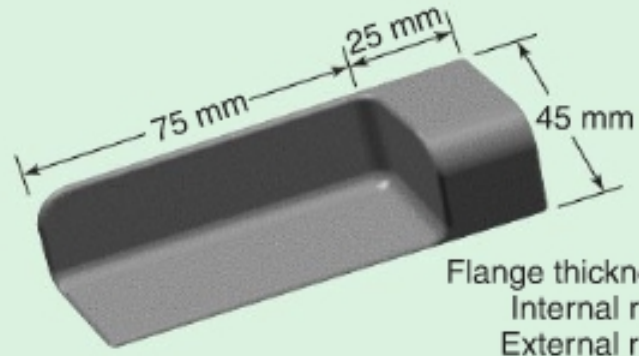
# Direct Printing of Metal Tooling;

## ExtrudeHone Corp., Irwin, PA

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- Directly print metal parts and tooling.
  - Polymer binder into



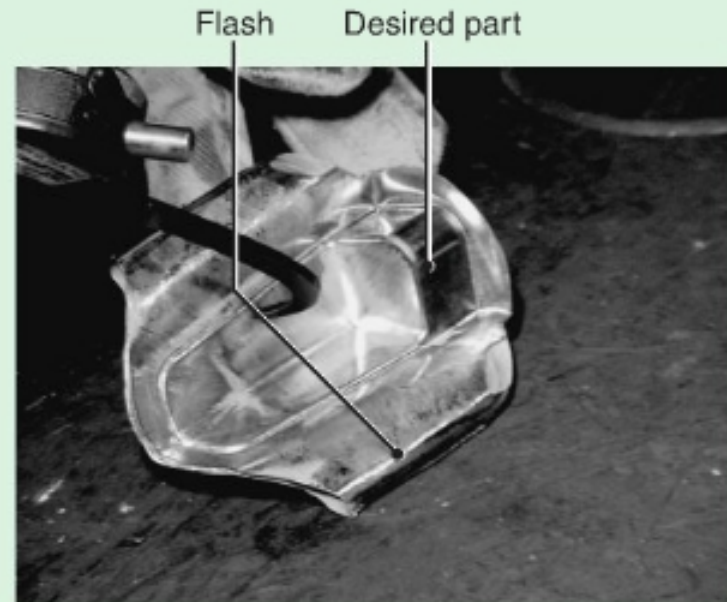


Flange thickness = 3 mm  
Internal radii = 5 mm  
External radii = 10 mm

(a)



(b)



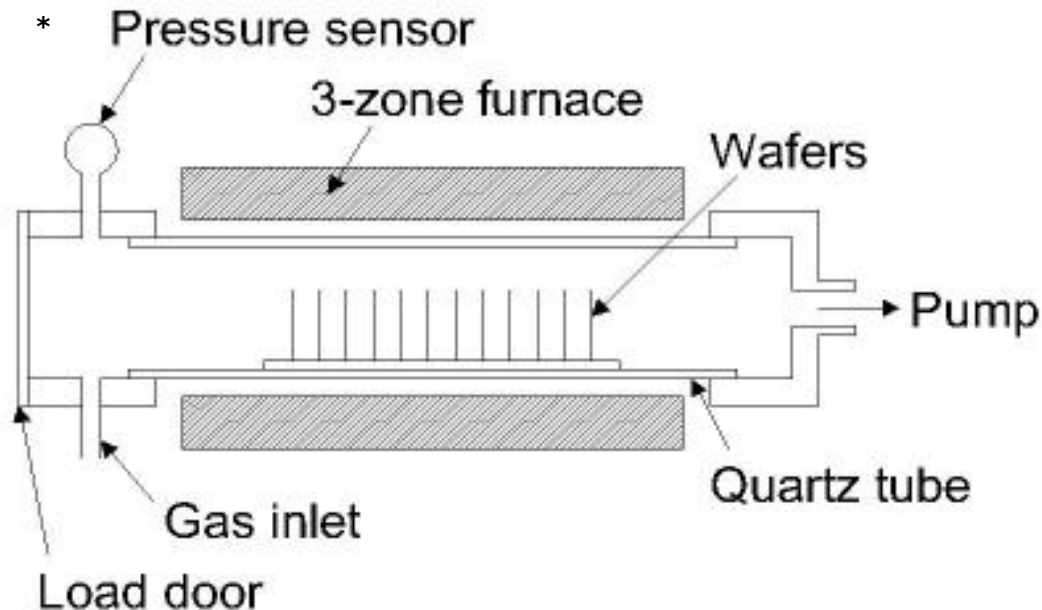
(c)

Forging Die made by 3D printing

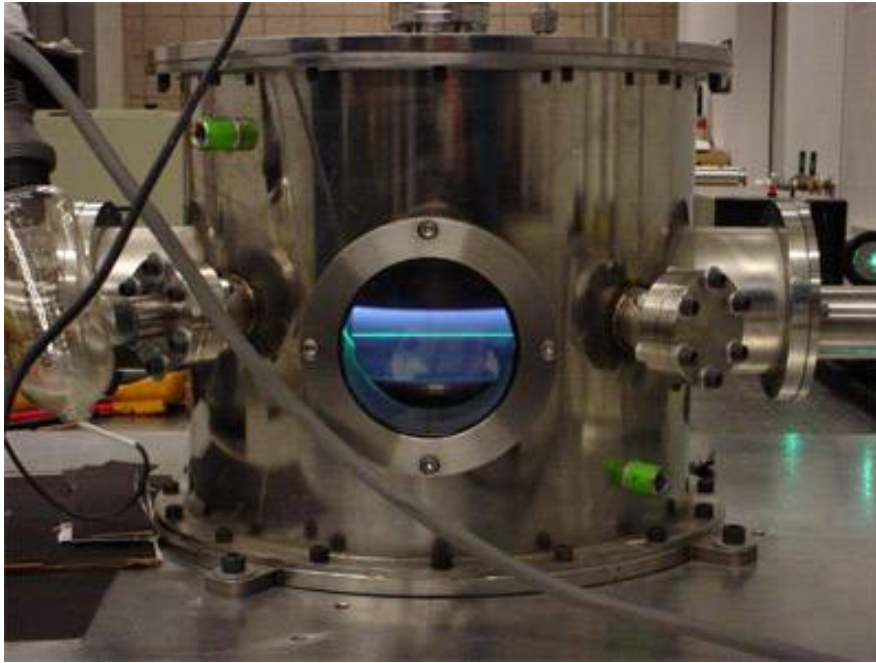
# CVD (Chemical Vapor Deposition)

- Creates solid materials directly from chemical reactions in gas and/or liquid compositions or with the substrate material
- LP(Low Pressure) CVD, PE(Plasma Enhanced) CVD

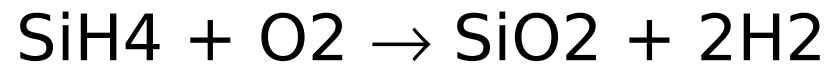
## Typical hot-wall LP(Low Pressure) CVD







Deposition of SiO<sub>2</sub> from  
Silane gas by PECVD



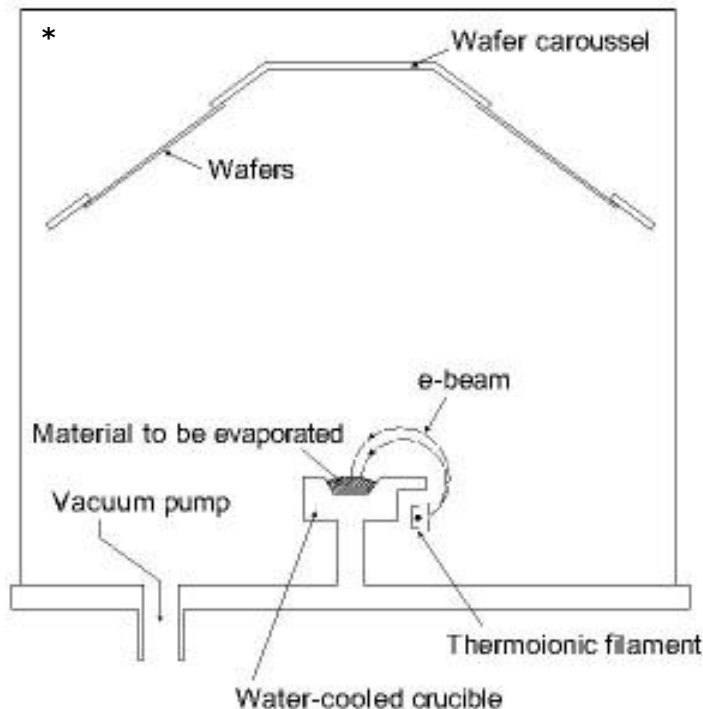
Siemens CVD  
Process for the  
Purification of Si



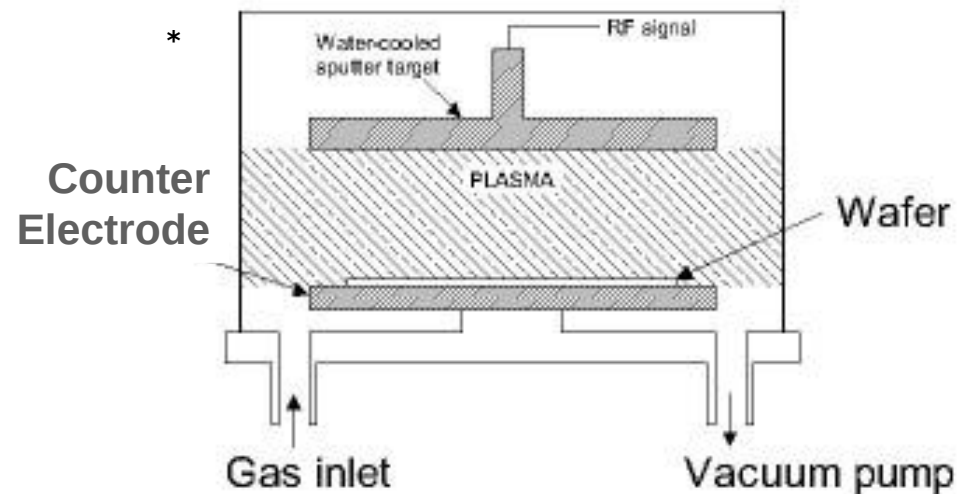


# PVD (Physical Vapor Deposition)

- Material to be deposited is released from a source and transferred to the substrate
- Evaporation, Sputtering



**e-beam evaporation system**



**RF sputtering system**

# Thin film PV cell - CIGS

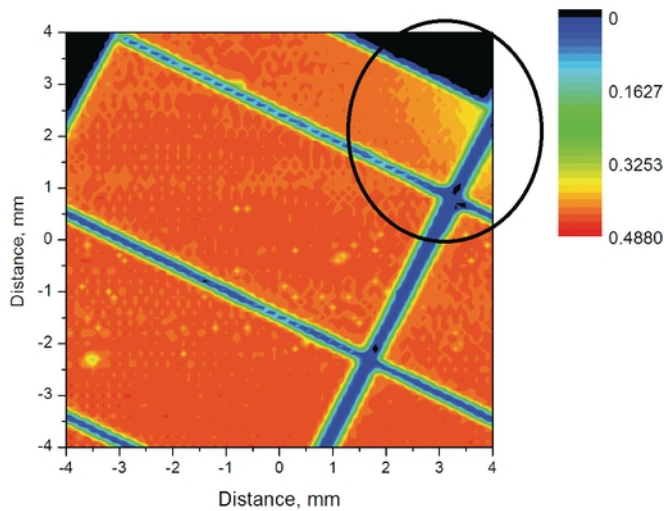
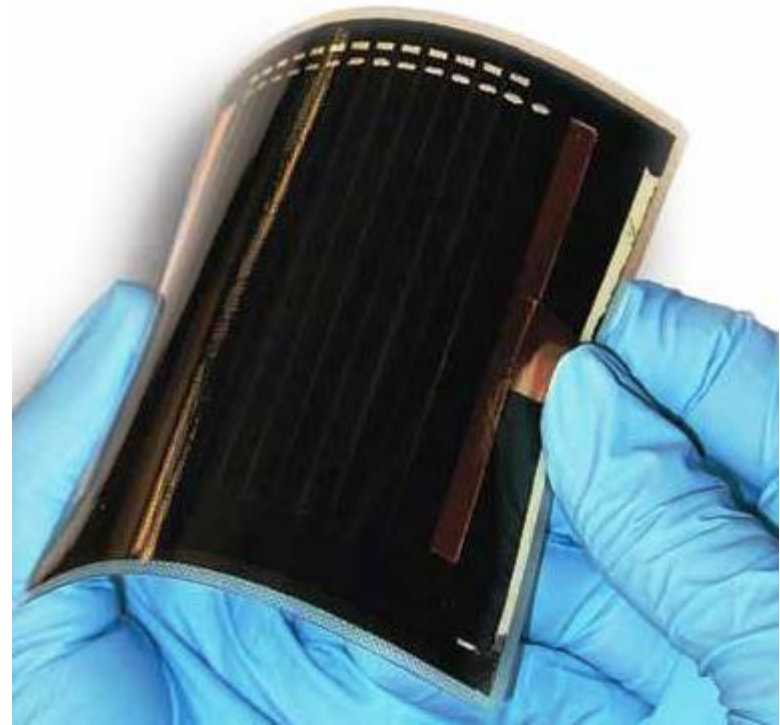


Photo-response mapping  
Of a CIGS cell



Ascent CIGS Solar Cell

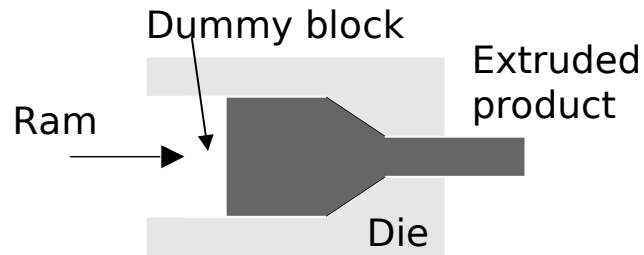
# 3. Continuous Processes

- Pushing
  - Metals extrusion
  - Plastics extrusion
  - Continuous casting
- Pulling
  - Pultrusion of composites
  - Crystal pulling (Czochralski process)
  - String ribbon process (Ely Sachs)

# Pros and Cons

- + Low unit cost for large runs
- + Low unit cost for large runs
- + Low unit cost for large runs
  
- - constant cross section
- - constant cross section
- - constant cross section

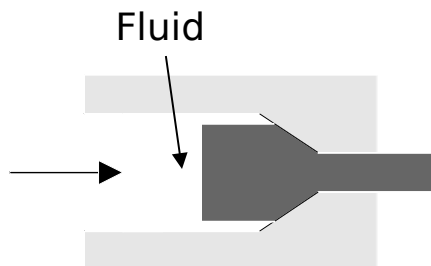
# Metal Extrusion



Direct extrusion process



Indirect extrusion process

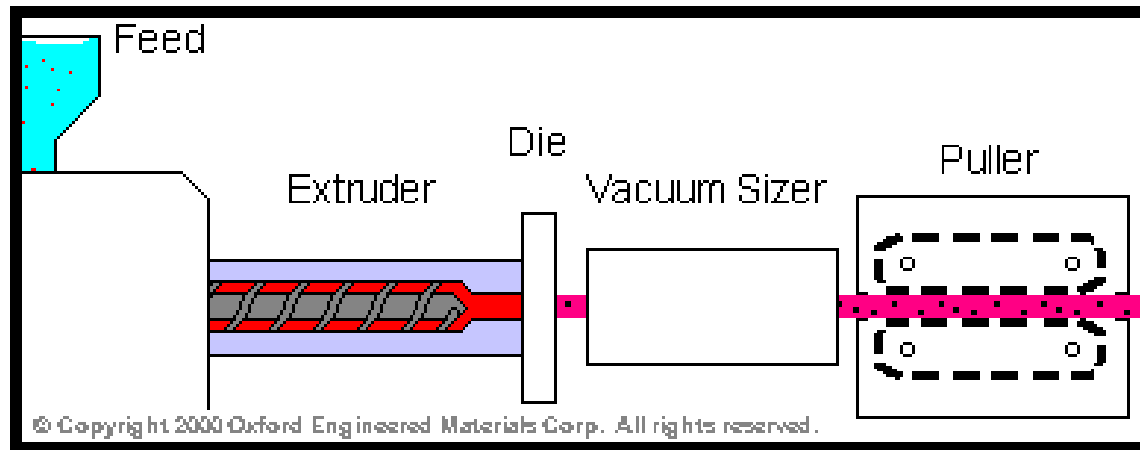


Hydrostatic extrusion process



\* Source: <http://www.eaa.net/pages/material/extruded.html>

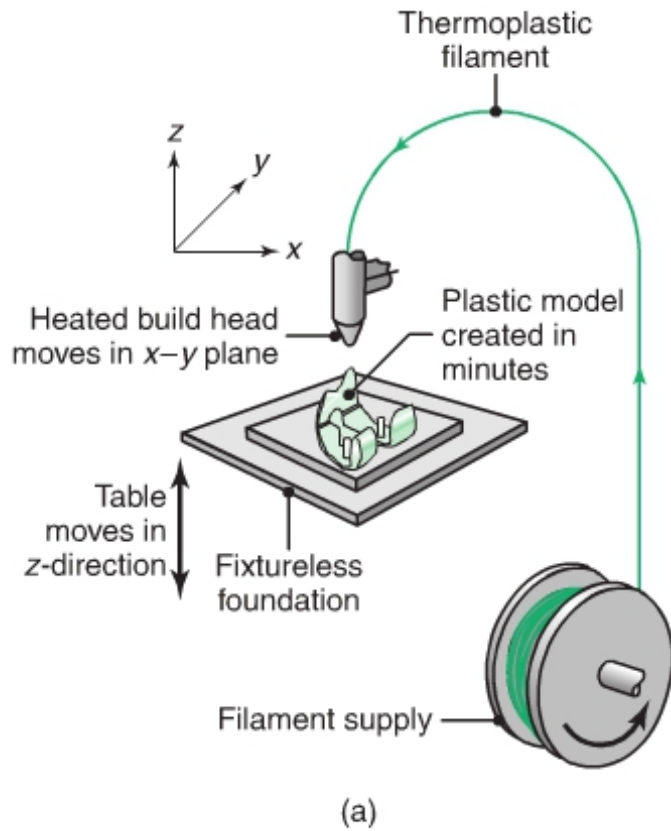
# Plastic Extrusion



**Single Screw  
Plastics Extruder**





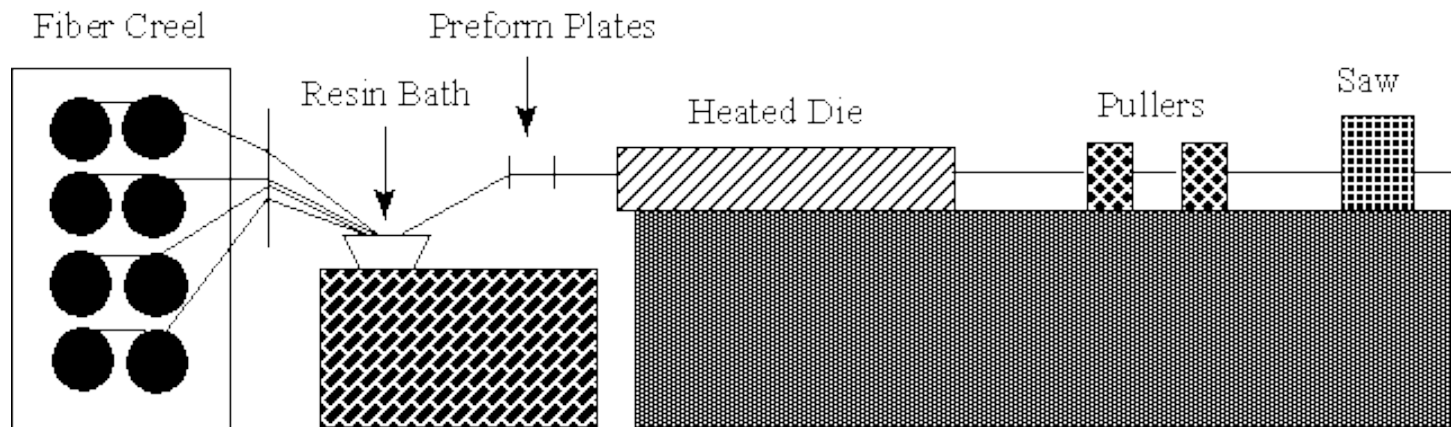


**FIGURE 20.4** (a) Schematic illustration of the fused-deposition-modeling process. (b) The FDM 900mc, a fused-deposition-modeling machine. *Source:* Courtesy of Stratasys, Inc.

Plastic extrusion used in rapid prototyping, p 532

# Pultrusion of Composites

\*

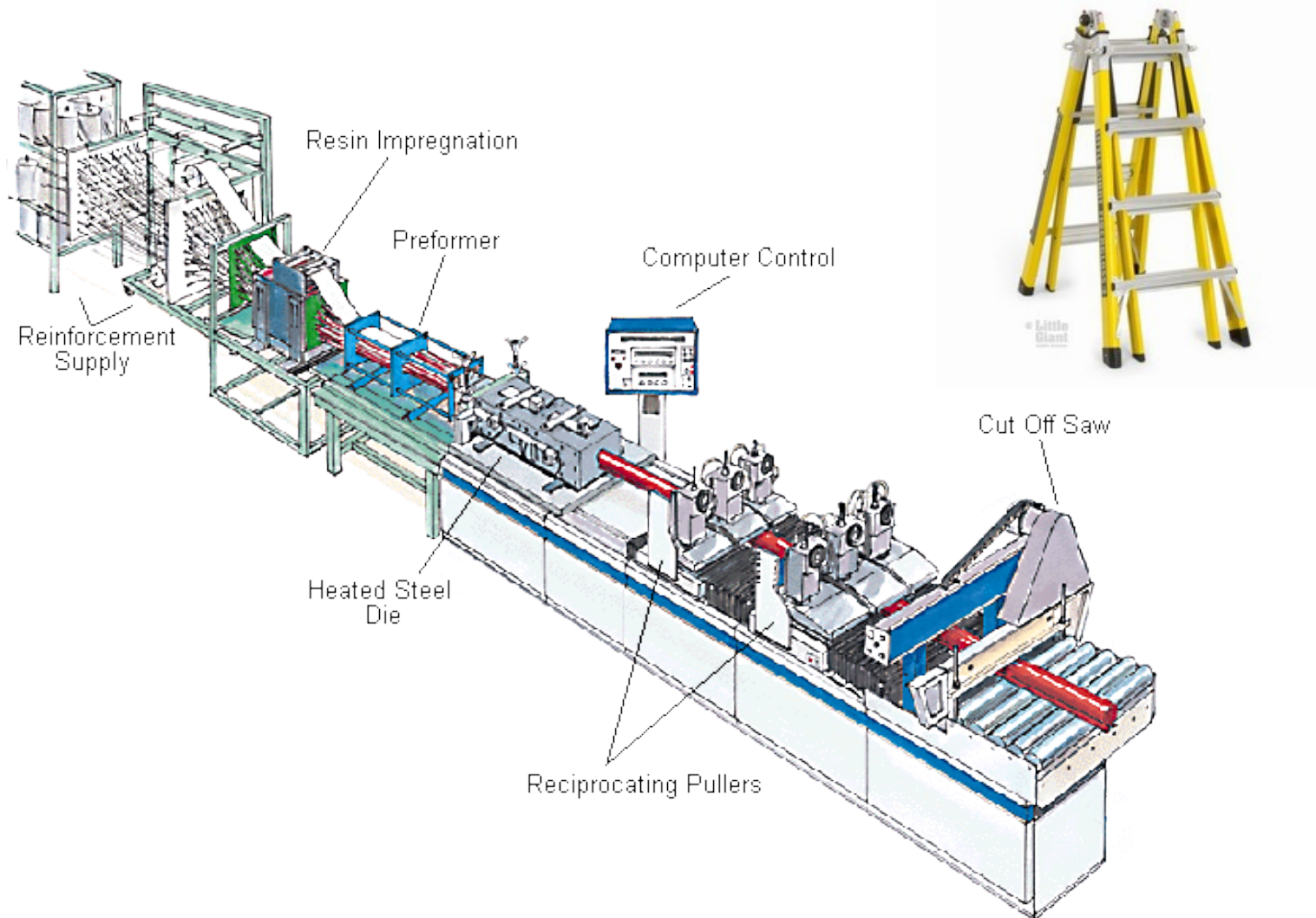


Schematic Diagram of the Pultrusion Process

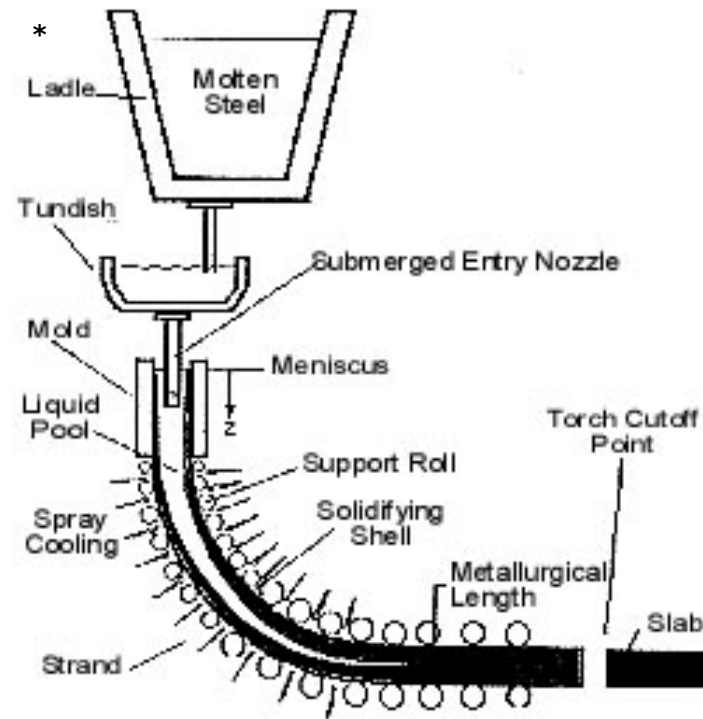
[http://www.youtube.com/watch?v=4MoHNZB5b\\_Y](http://www.youtube.com/watch?v=4MoHNZB5b_Y)

# Pultrusion machine

\*

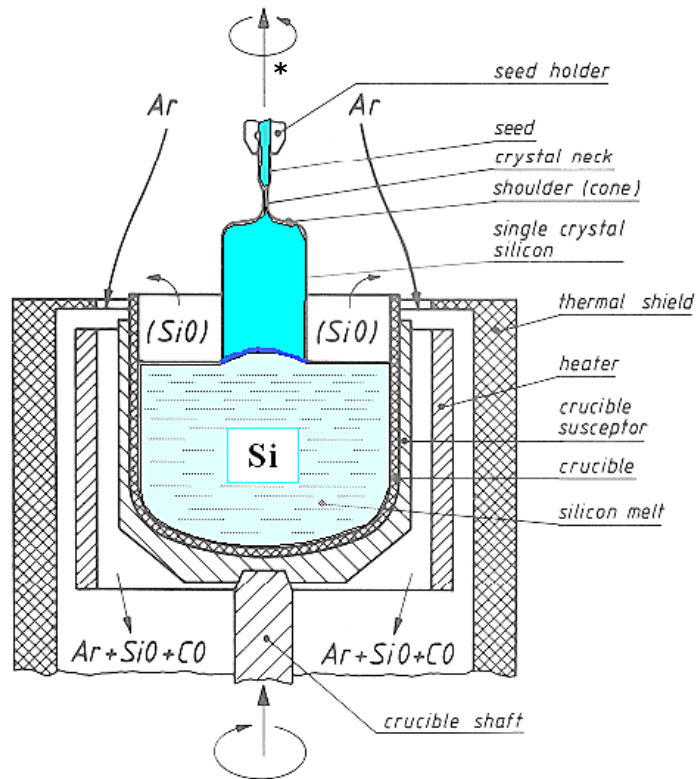


# Continuous Casting



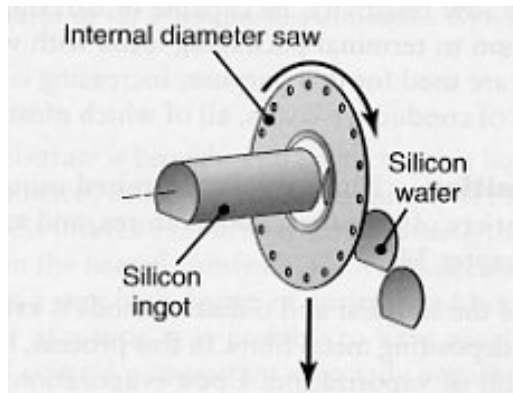
# Czochralski(CZ) Crystal Growth

Beginning of crystal growth



[http://www.youtube.com/watch?v=cYj\\_vqcyI78](http://www.youtube.com/watch?v=cYj_vqcyI78)

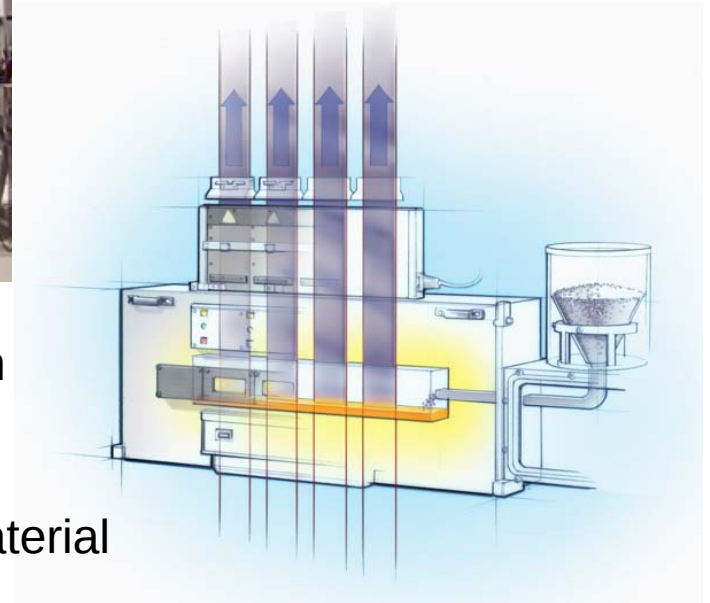
# String Ribbon Process



In ID and wire sawing of Si ingots, the kerf material represents lost energy



String-Ribbon  
Invented by  
Ely Sachs  
saves this material

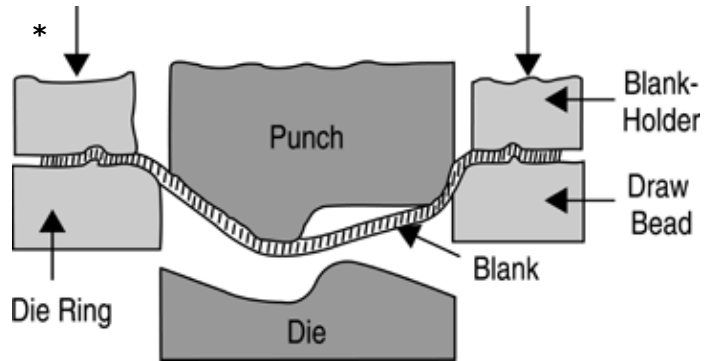




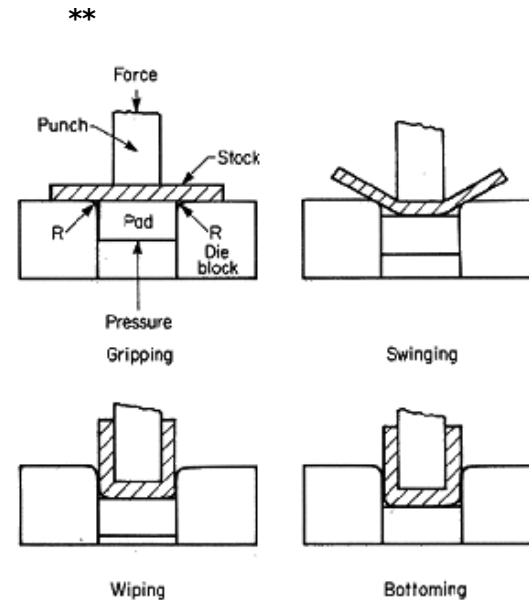
# 4. Net Shape: Molding

- Types
  - Solids: Metal Forming, Powders, Others
  - Liquids: Casting, Injection Molding, Others
  - Mixtures: Infiltration, Viscoelastics, Others
- Characteristics
  - Hard tooling
  - Solid forming – very fast cycle time
  - Thermal processes – slower and depend upon cooling rate
  - Dimensional control is not as good as machining

# Sheet Metal Stamping



**Typical Stamping Die**



**Drawing**

GM stamping plant go to  
Around 2:39

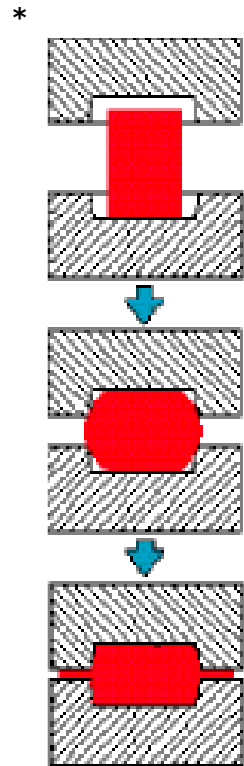
<http://www.youtube.com/watch?v=ixPhogfZTHU&feature=related>

## Forming

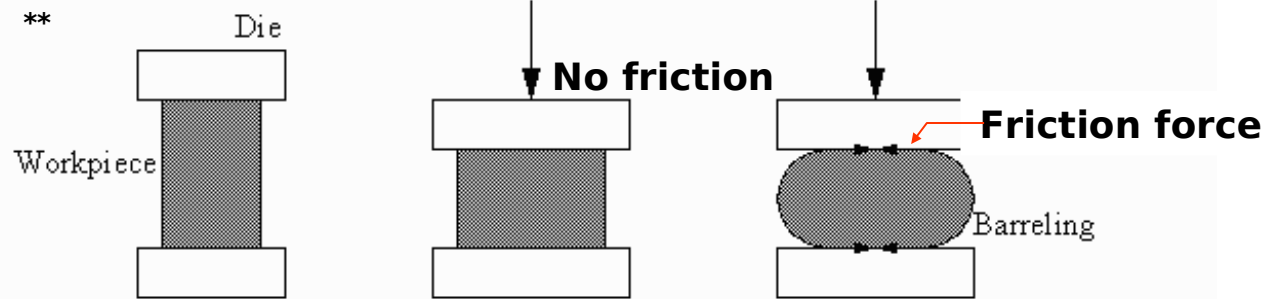
<http://www.youtube.com/watch?v=PXVWiGqeltM>

Video

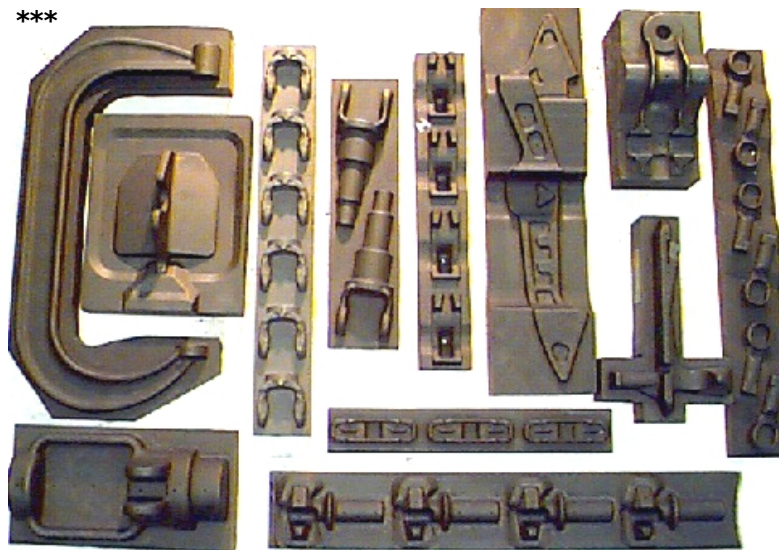
# Forging



**Closed Die Forging**

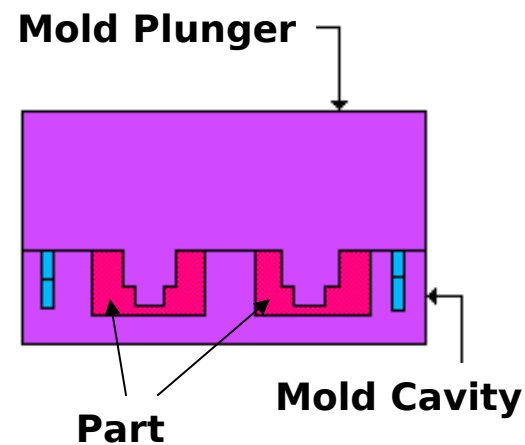
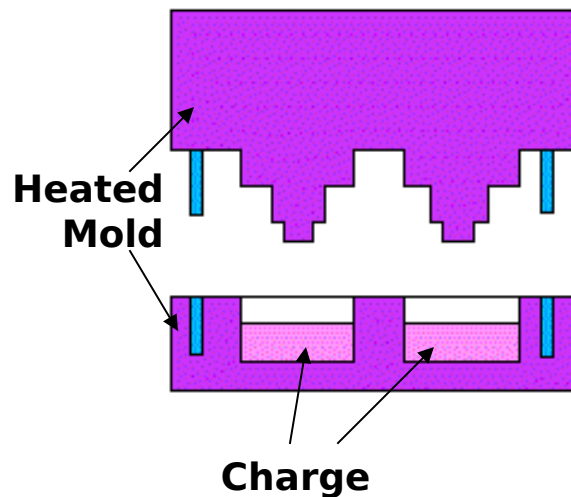


**Open Die Forging**

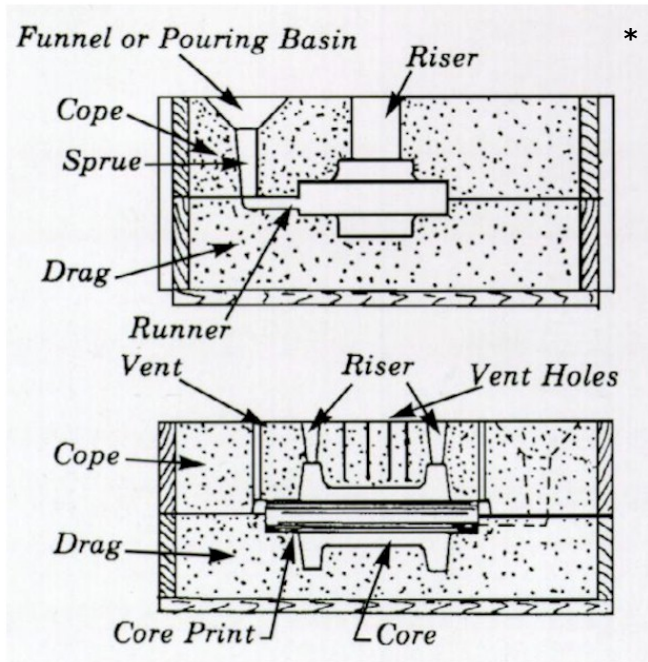


# Compression Molding

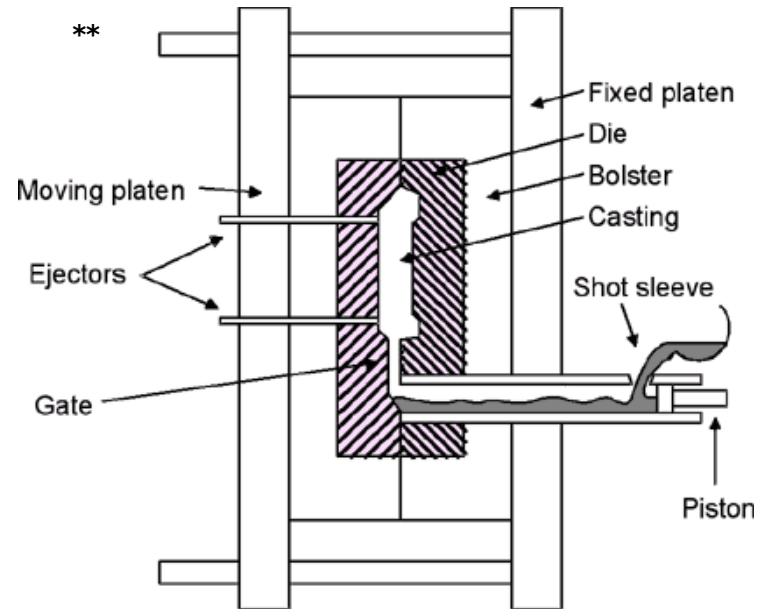
- Similar to metal forging process
- Most common method of processing thermos



# Metal Casting

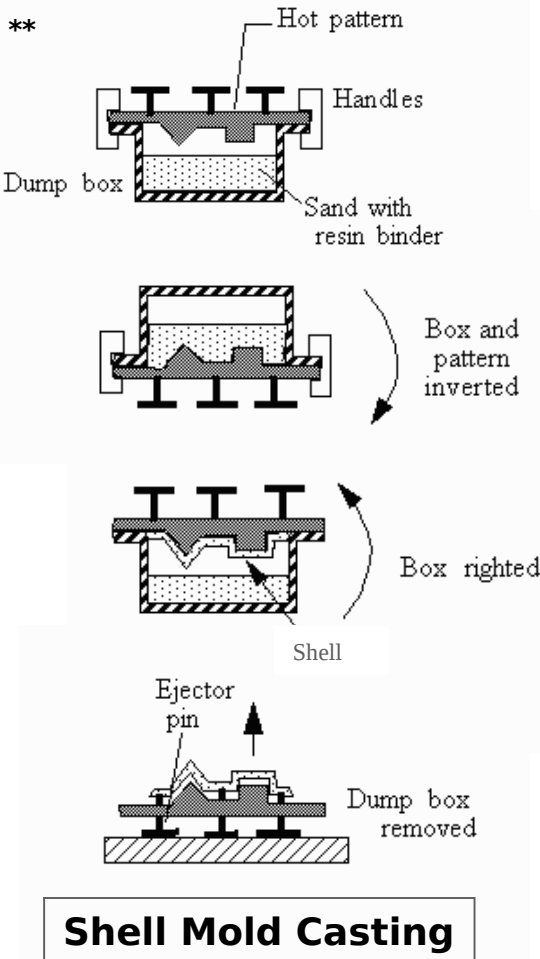
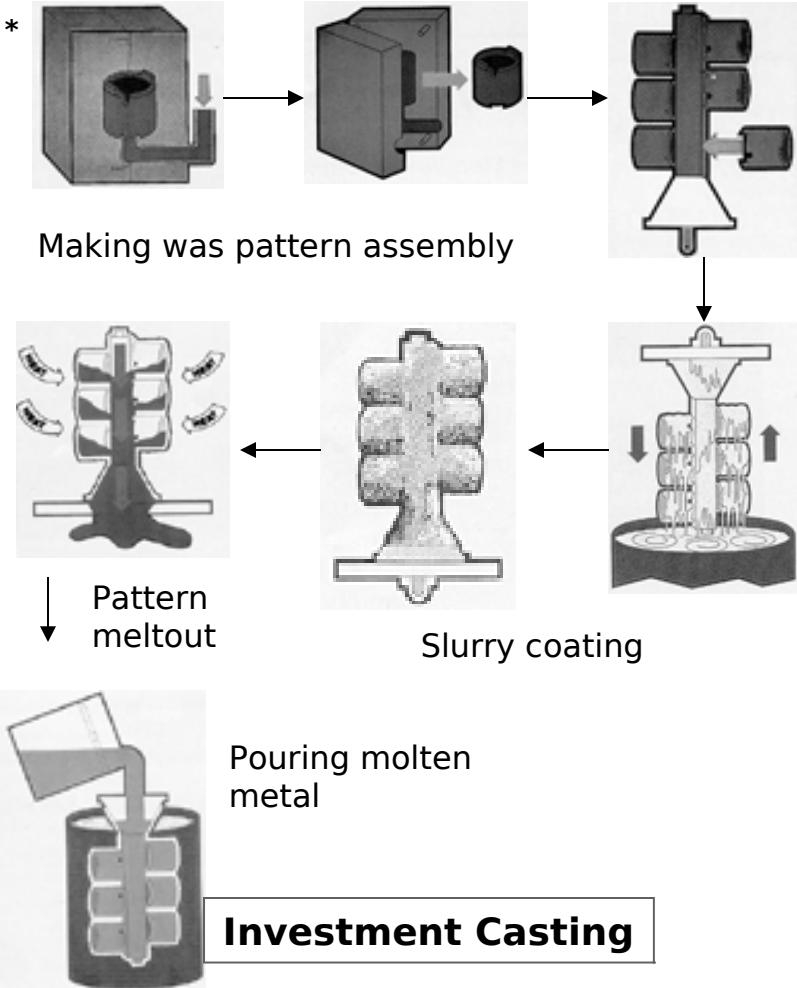


**Sand Casting Mold**



**Die Casting machine**

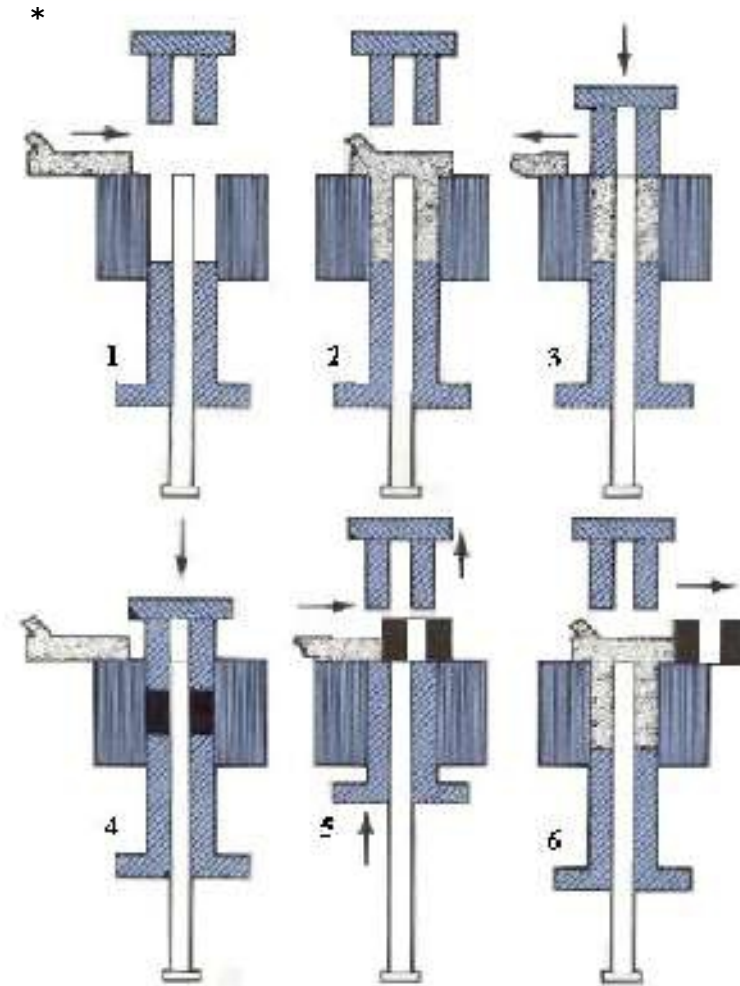
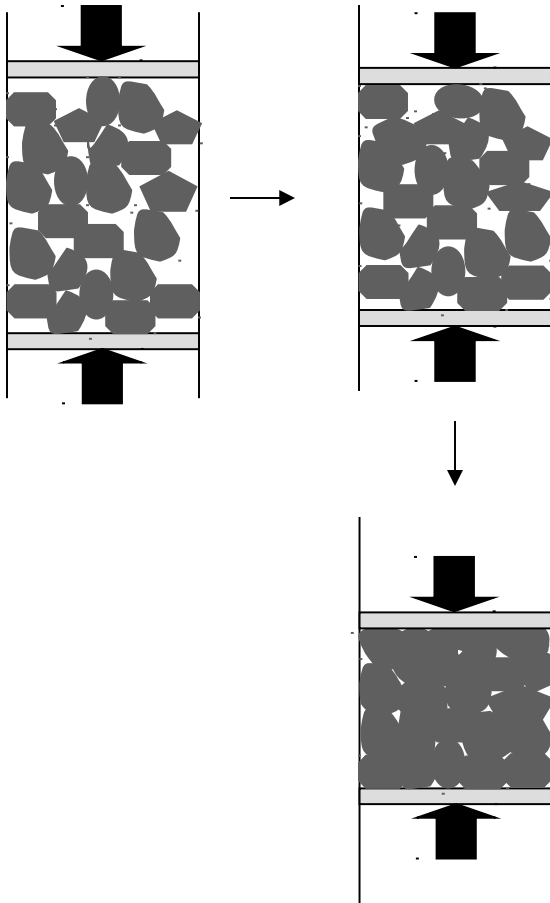
# Metal Casting



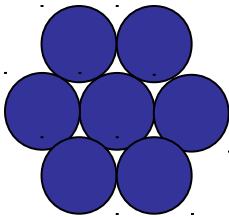
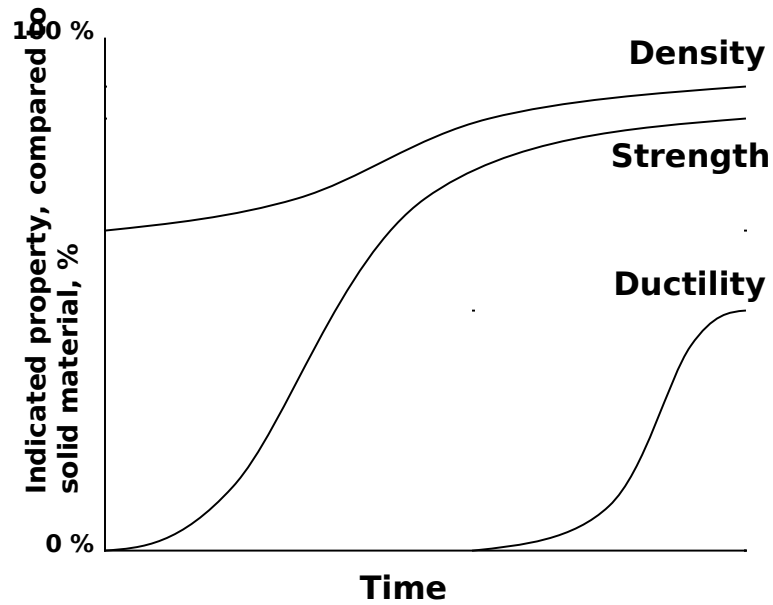
\* Source: Kalpakjian, "Manufacturing Engineering and Technology"; \*\* <http://cybercut.berkeley.edu/mas2/html/processes/castshell/more.html>



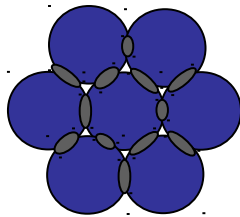
# P/M: Powder Compaction



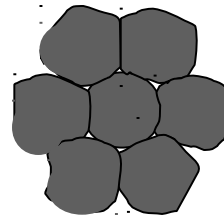
# Sintering



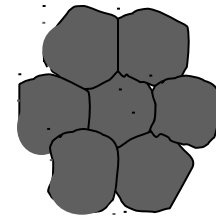
Green compact



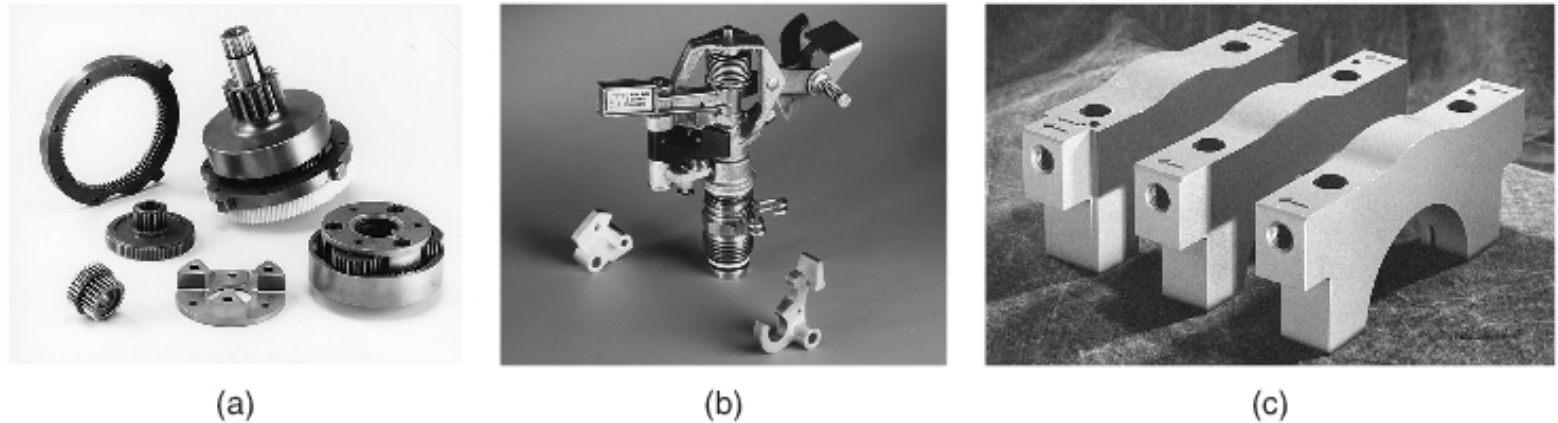
Necks formed



Pore size reduced

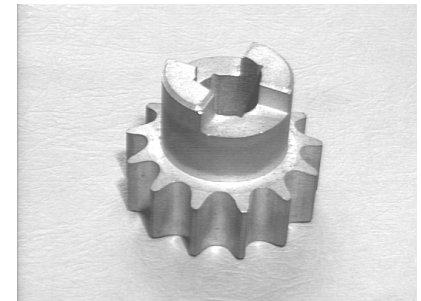
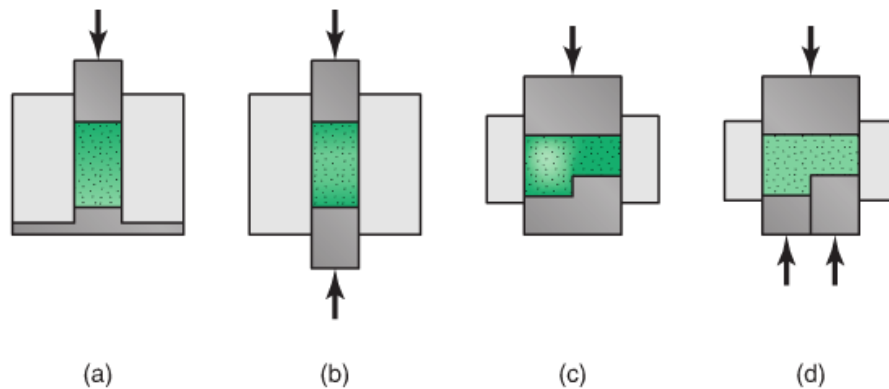


Fully sintered

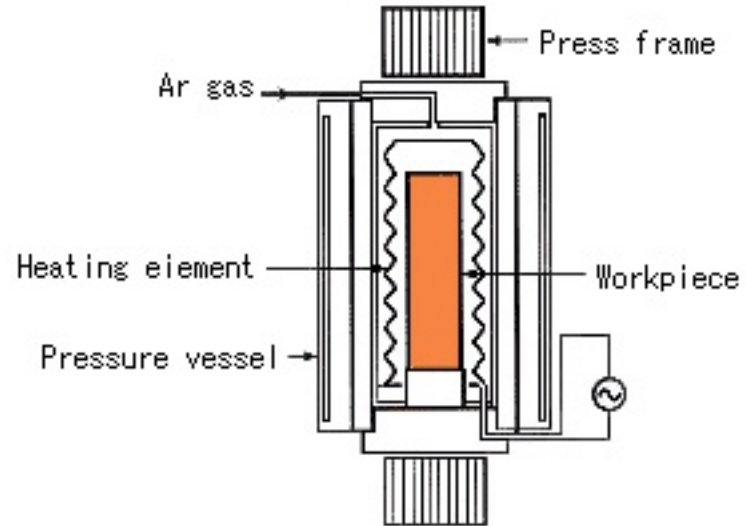


**FIGURE 17.1** (a) Examples of typical parts made by powder-metallurgy processes. (b) Upper trip lever for a commercial irrigation sprinkler made by PM. This part is made of an unleaded brass alloy; it replaces a die-cast part with a 60% cost savings. (c) Main-bearing metal-powder caps for 3.8- and 3.1-liter General Motors automotive engines. *Source:* (a) and (b) Reproduced with permission from *Success Stories on PM Parts*, 1998. Metal Powder Industries Federation, Princeton, New Jersey, 1998. (c) Courtesy of Zenith Sintered Products, Inc., Milwaukee, Wisconsin.

Video-  
Back 2

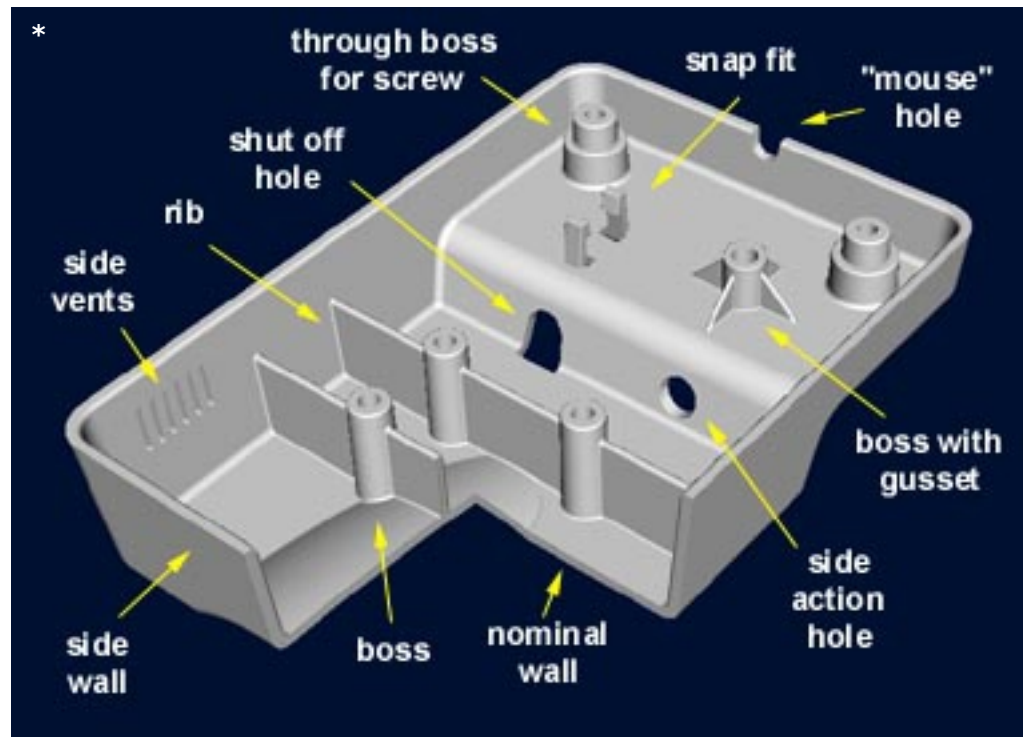
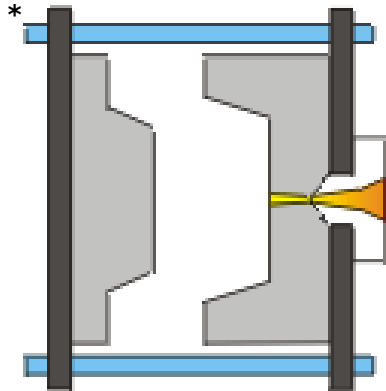


# Hot Isostatic Pressing - HIP

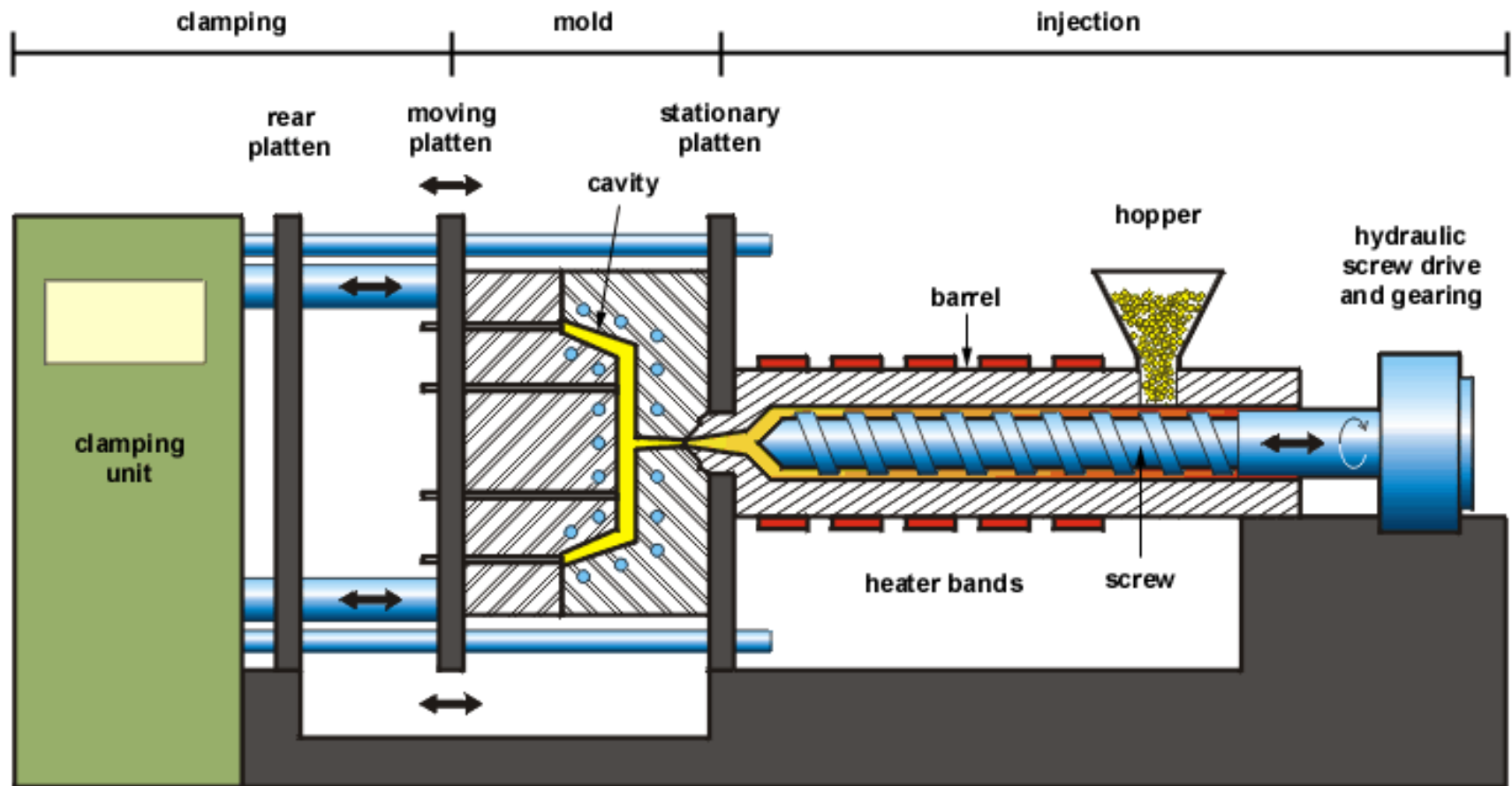


[http://www.youtube.com/watch?v=BsnzgsEXT\\_A](http://www.youtube.com/watch?v=BsnzgsEXT_A)

# Injection Molding



# Injection Molding

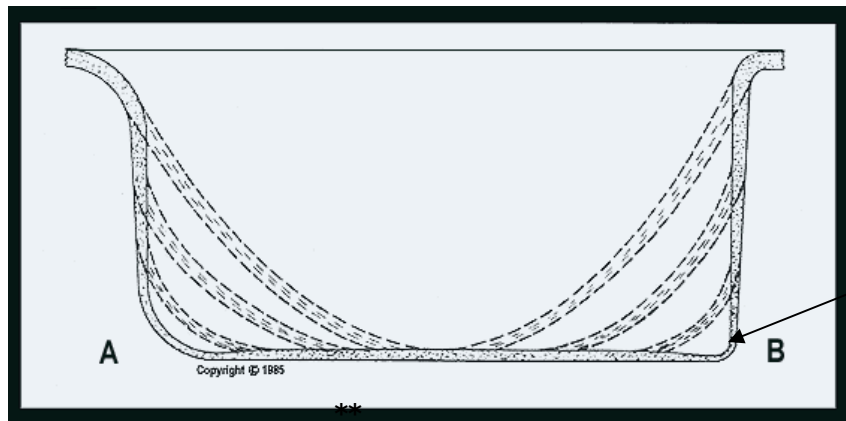
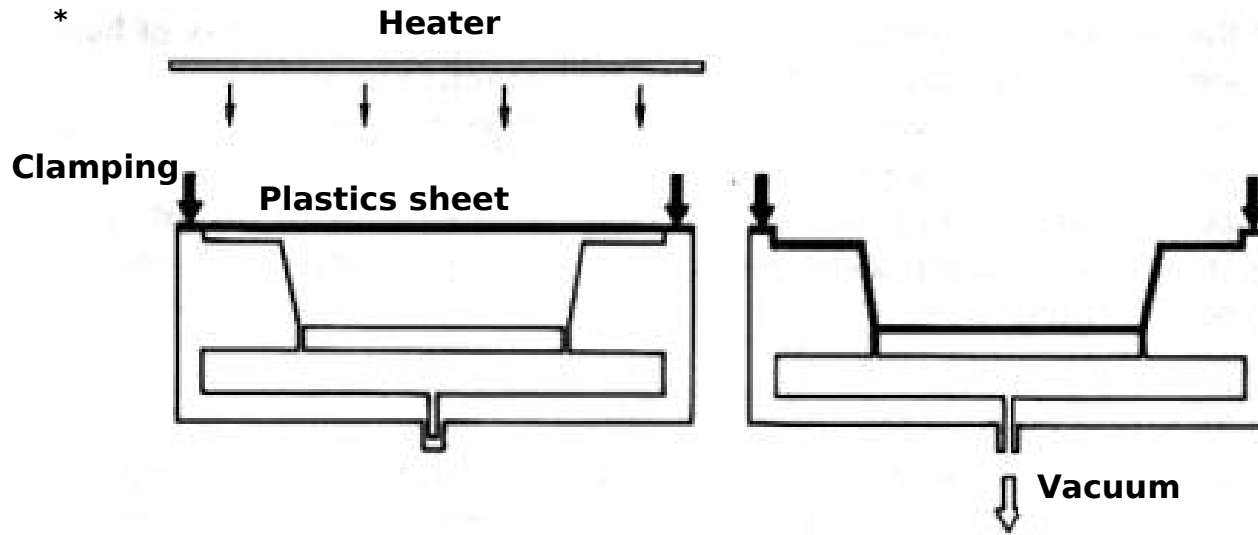


schematic of thermoplastic injection molding machine

\* Source: [http://www.idsa-mp.org/proc/plastic/injection/injection\\_process.htm](http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm)



# Thermofforming



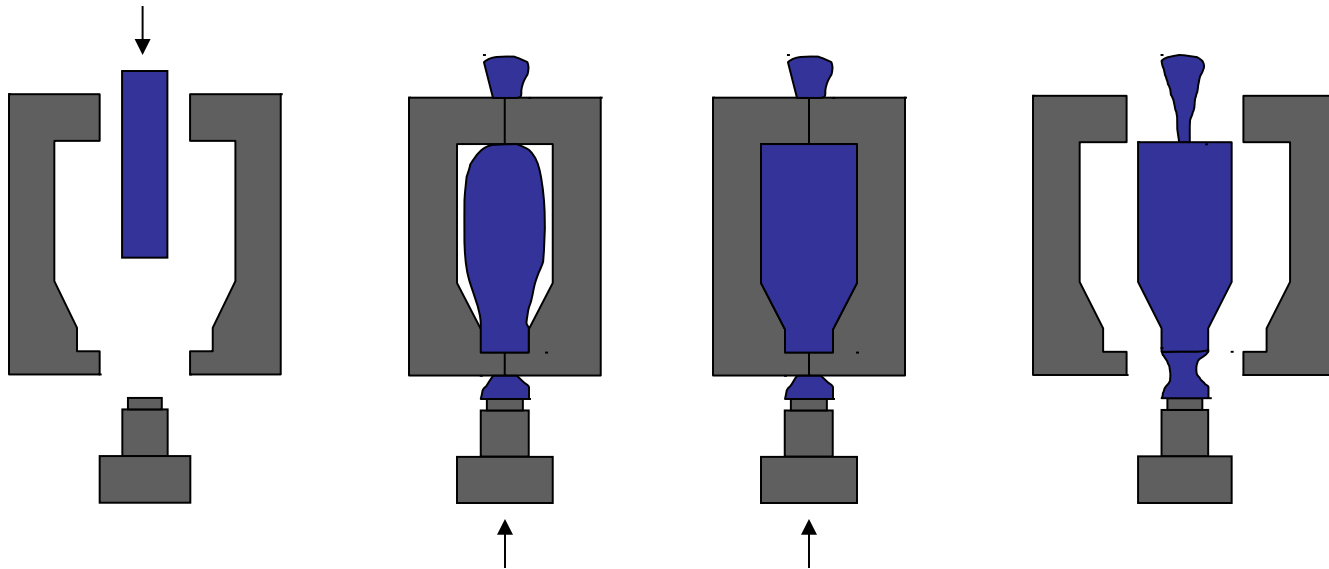
**Thin corner**



# Blow Molding



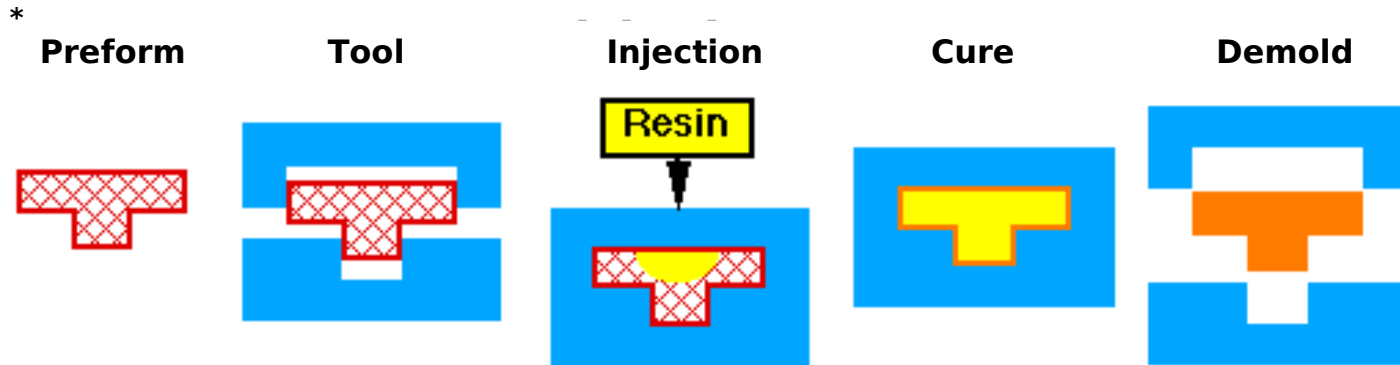
**Descending parison**



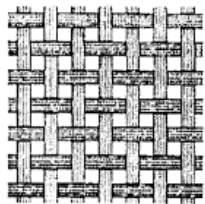
**Inflating**

**Inflating and cooling**

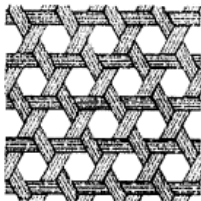
# Resin Transfer Molding (RTM)



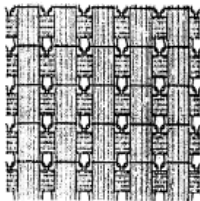
## PREFORM ARCHITECTURES



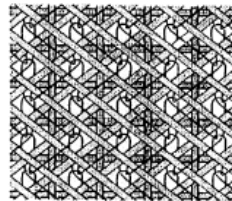
**Biaxial Weave**



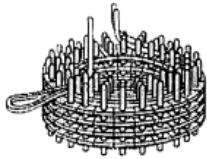
**Triaxial Weave**



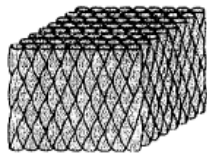
**Knit**



**Multiaxial Multilayer Warp Knit**



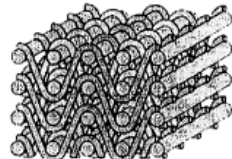
**3-D Cylindrical Construction**



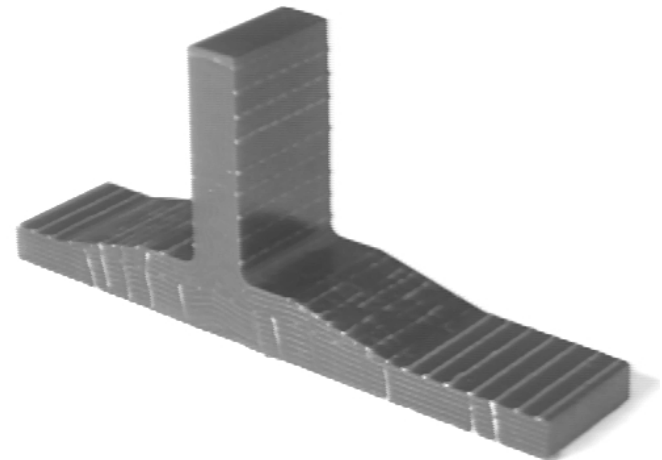
**3-D Braiding**



**3-D Orthogonal Fabric**



**Angle-Interlock Construction**



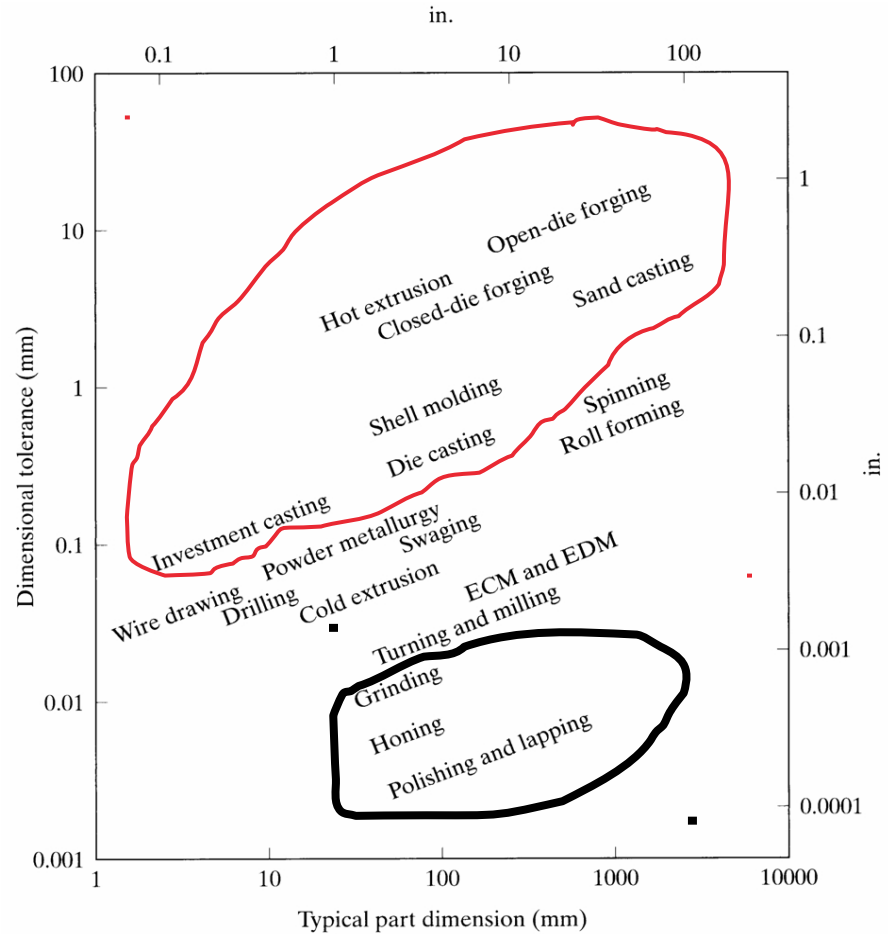
illustrations—Scientific American

# Summary

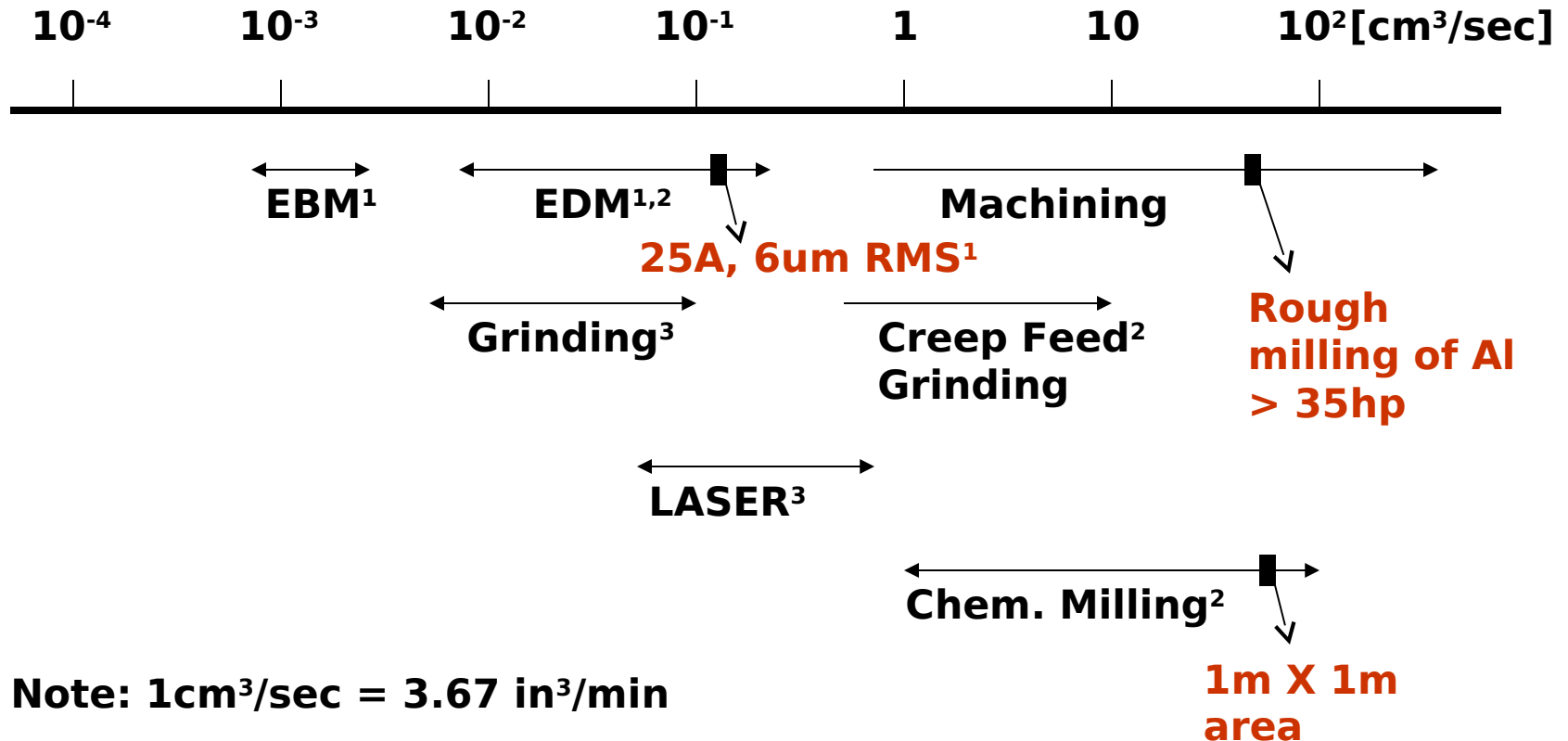
1. Subtractive = large forces
2. Additive = computer controlled
3. Continuous = constant X-section
4. Net shape = Molding

# Next Time

- dimensional tolerance
- rate
- cost
- fixed costs
- materials



# Typical Material Removal Rate



\* References: 1. Advanced Methods of Machining, J.A.McGeough, Chapman and Hall, 1988  
 2. Manufacturing Engineering and Technology, S. Kalpakjian, Addison-Wesley, 1992  
 3. Laser Machining, G. Chryssolouris, Springer-Verlag, 1991



Unit cost:  $C/N = F/N + V$

Serial processes take longer, larger variable costs  
Specialty mat'l add to variable costs

QuickTime™ and a decompressor are needed to see this picture.

Parallel processes require tooling, larger fixed costs, but short cycle time