

# *Manufacturing Processes - Overview*

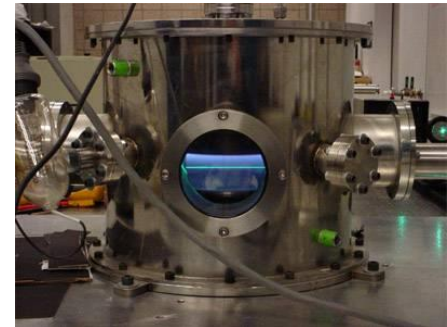
Part 1: mechanisms of geometry formation

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



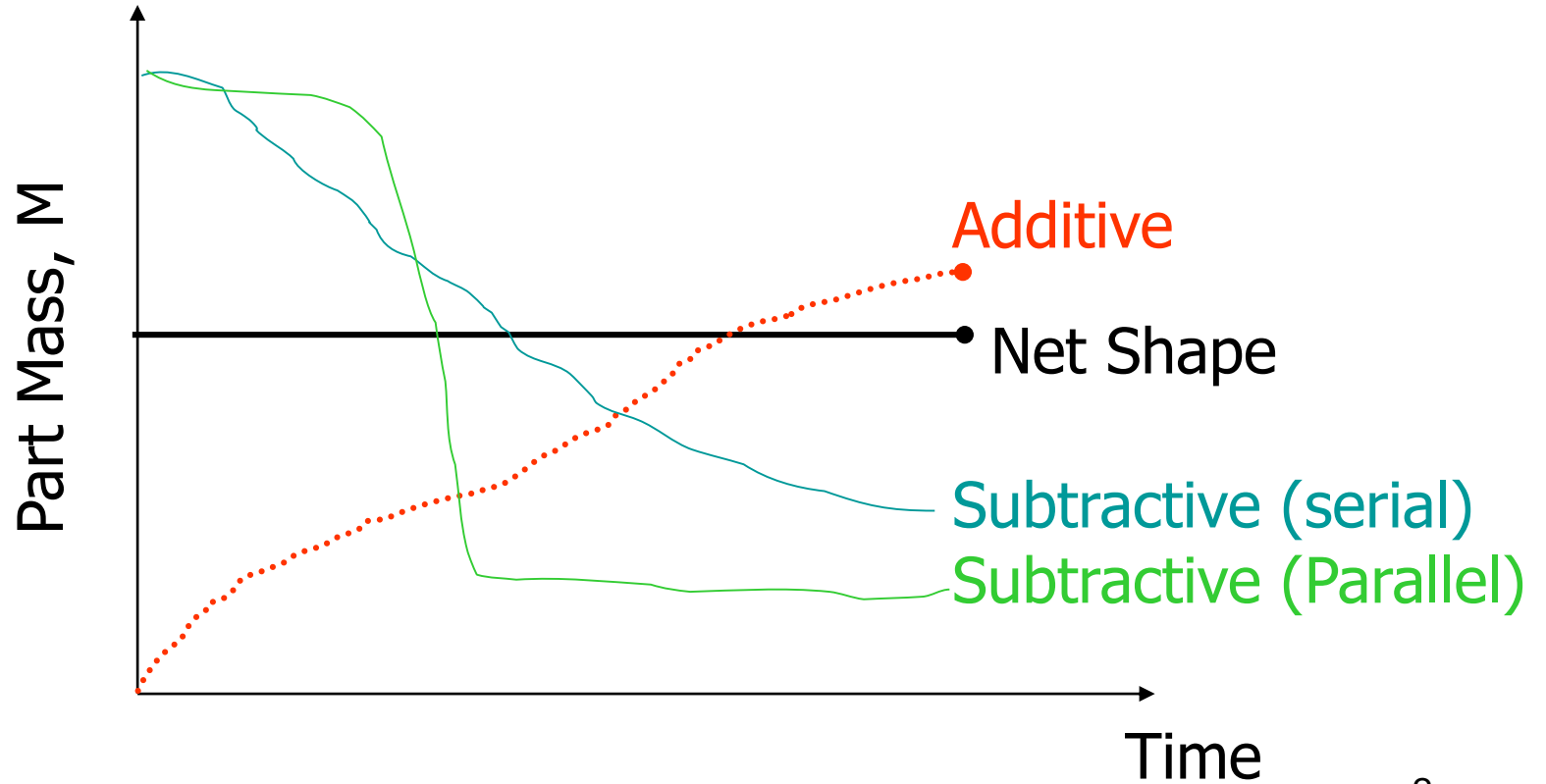
2.810

T. Gutowski



Many of these processes can be found in your text and online

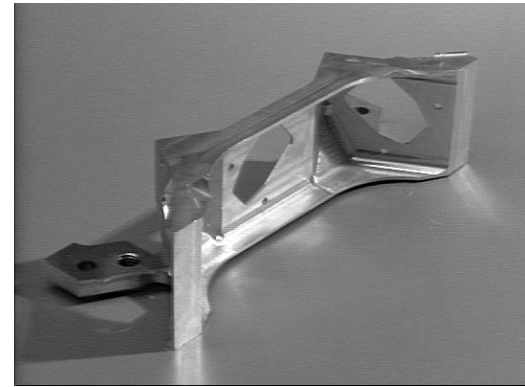
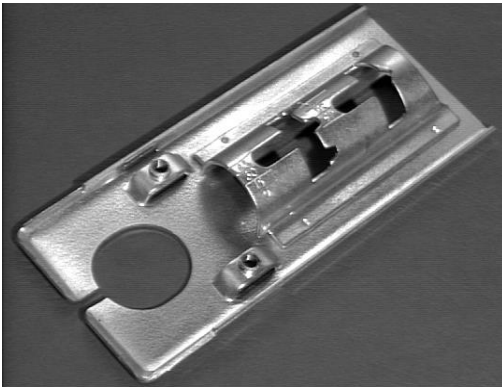
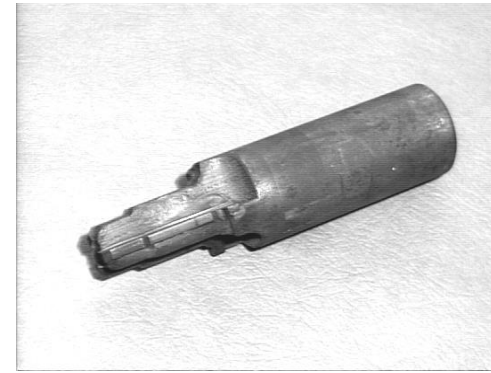
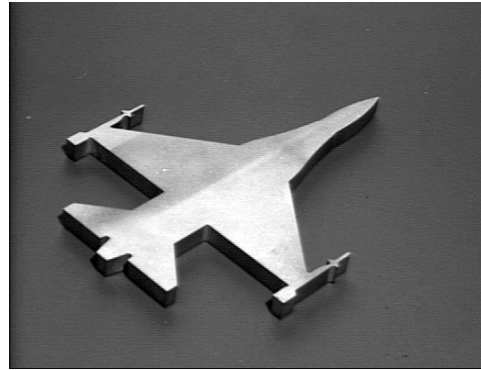
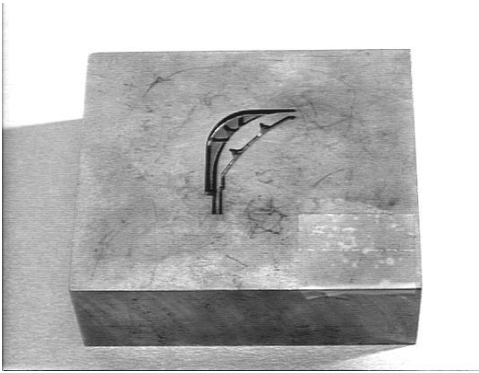
# Geometrical classification



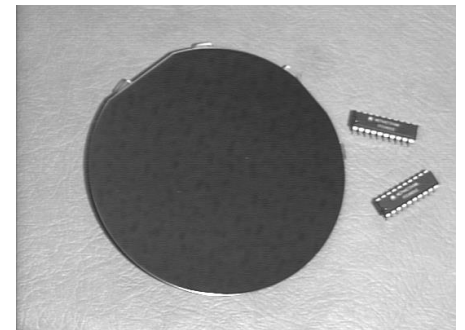
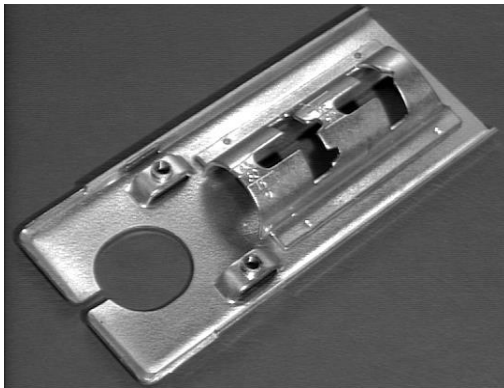
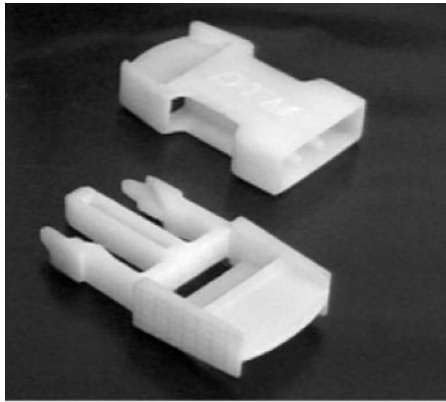
# Mechanisms of Geometry Formation

1. Subtractive
2. Additive
3. “Net shape” (bulk)
4. Net Shape  
(continuous)

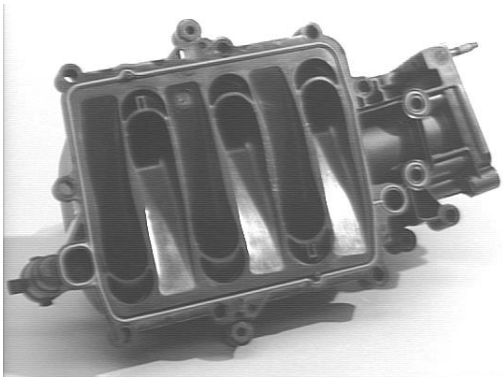
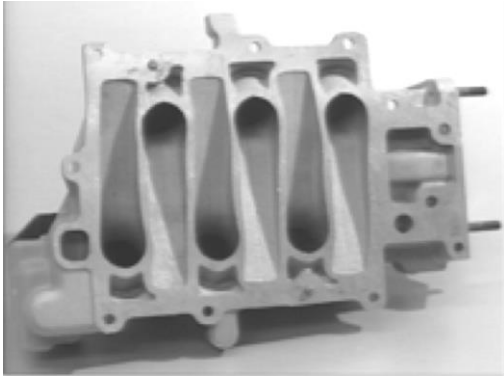
# Examples of Subtractive processes from the parts we saw...



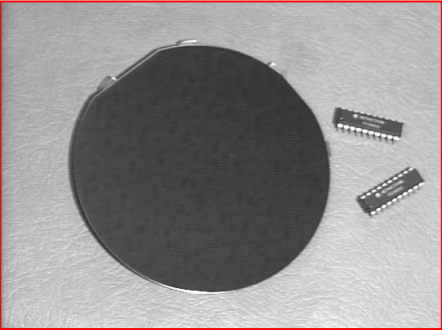
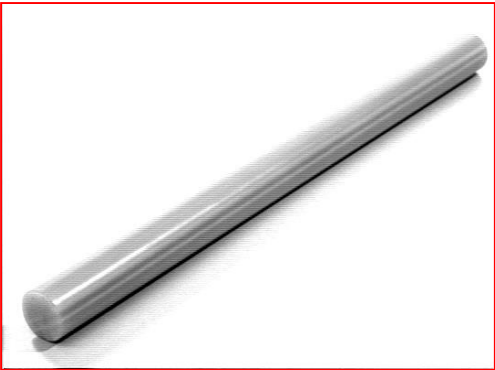
# Examples of Additive parts



## Examples of "Net Shaped" parts we saw last time...



# Examples of Continuous "Net Shaped" parts

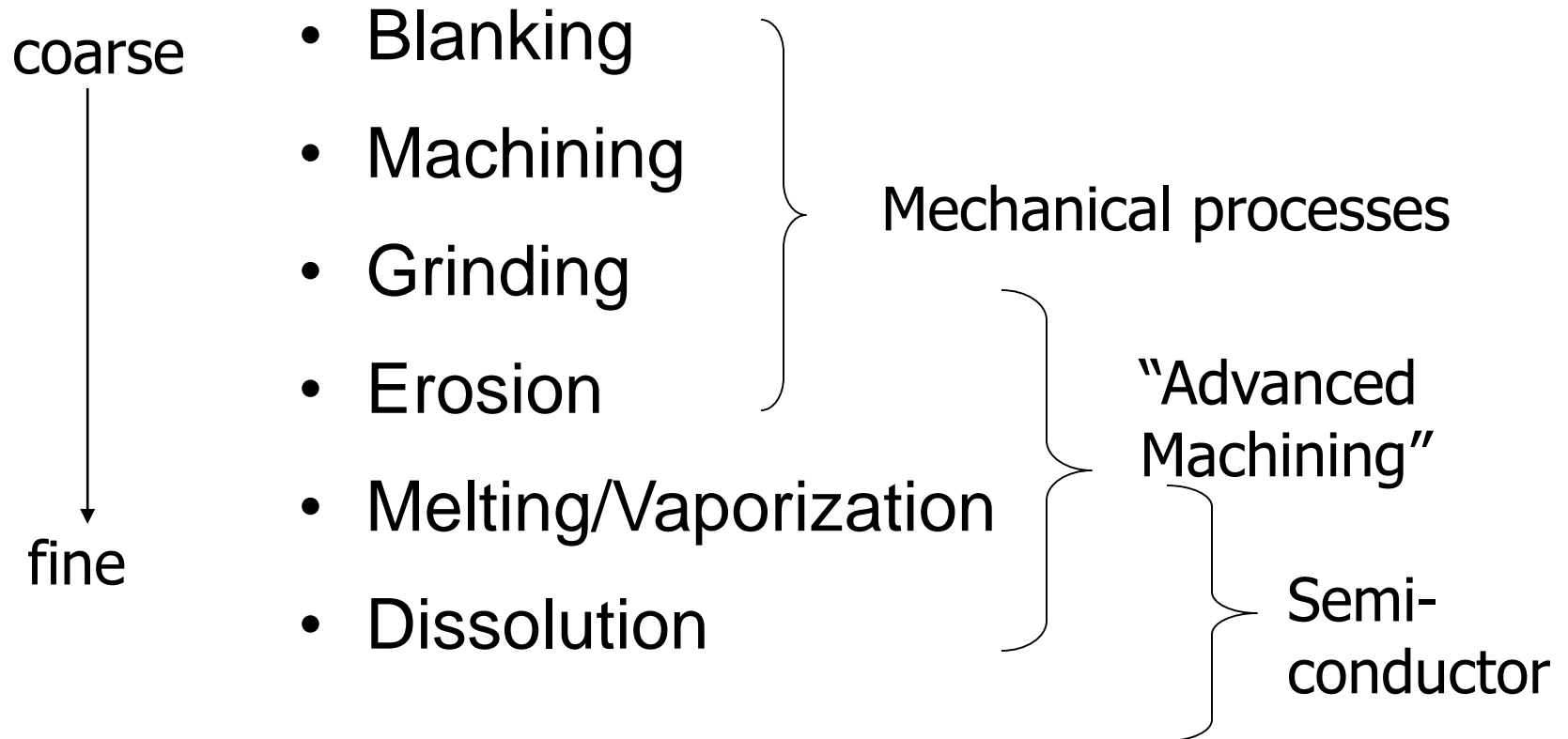


# 1. Subtractive Processes

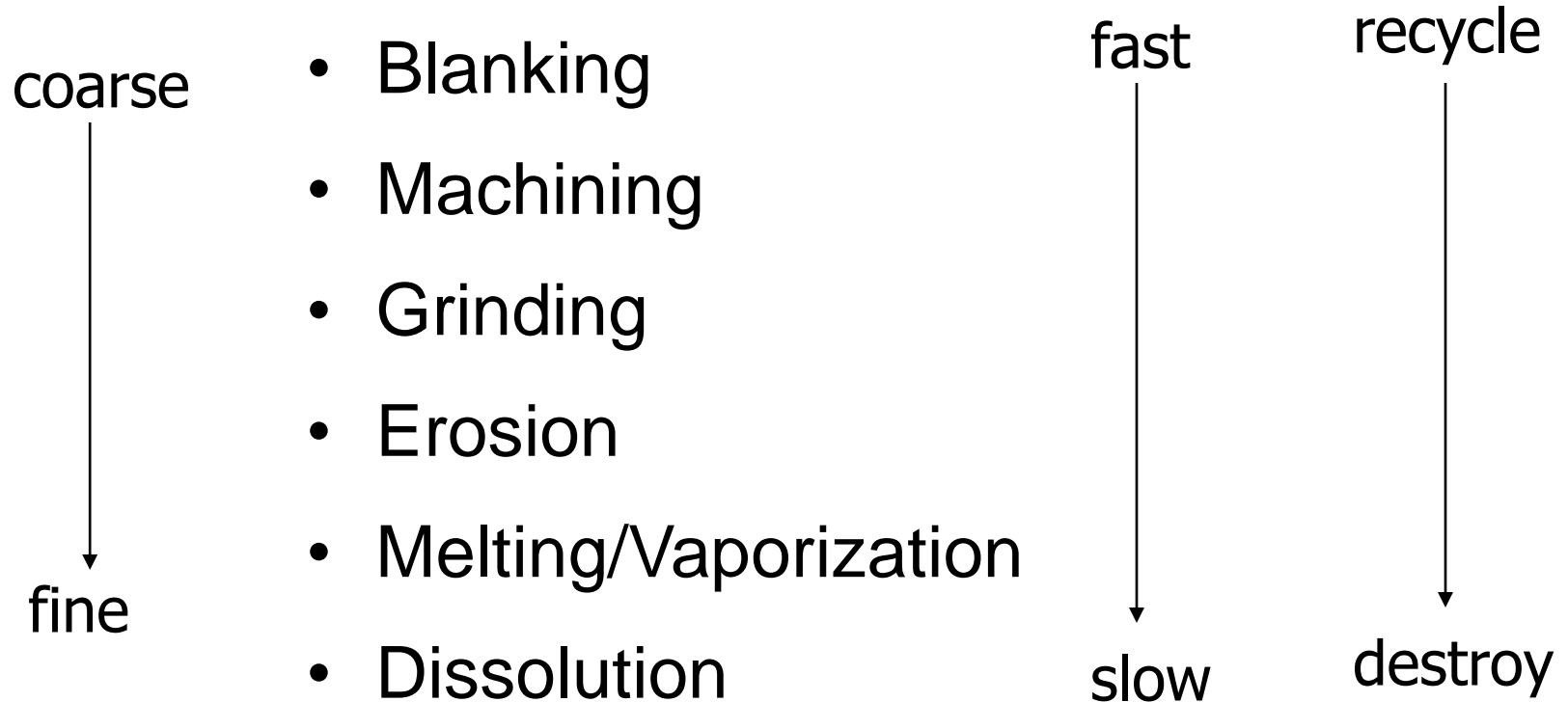
- **Blanking**- shearing, punching..
- **Machining** -turning, milling, boring, reaming...
- **Grinding**- surface, cylindrical, honing,
- **Erosion**- water jet, abrasive water jet, slurries..
- **Melting/Vaporization**- EDM, laser cutting...
- **Dissolution**- plasmas, ECM, solvents...



# 1. Removal Mechanisms



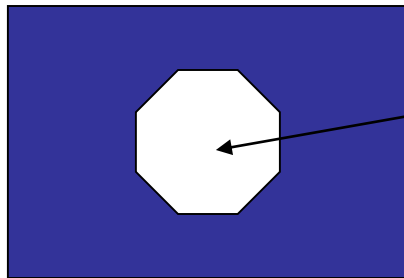
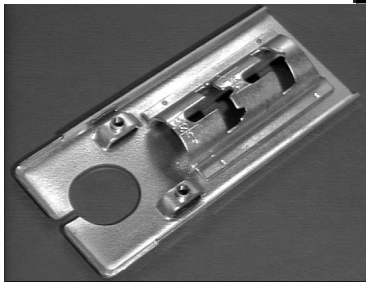
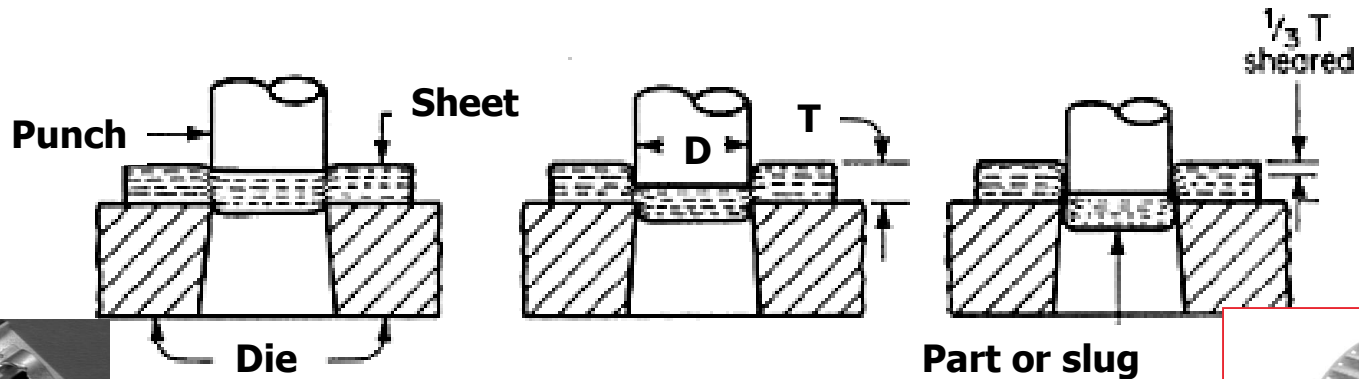
# 1. General Observations\*



\* There are exceptions, e.g. plasma cutting

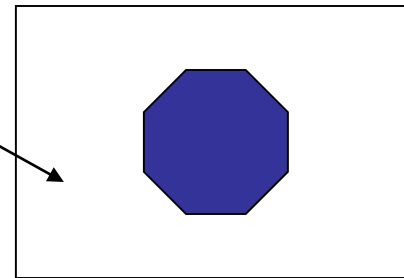
# Blanking and Punching

\*



**Punching**

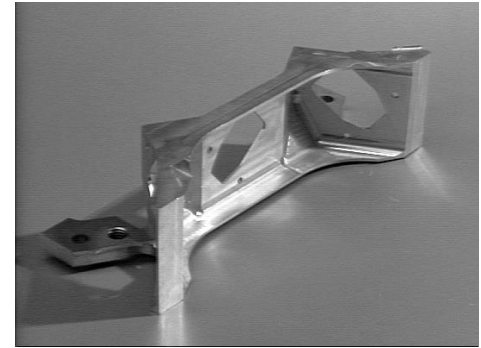
**Discarded**



**Blanking**



# 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

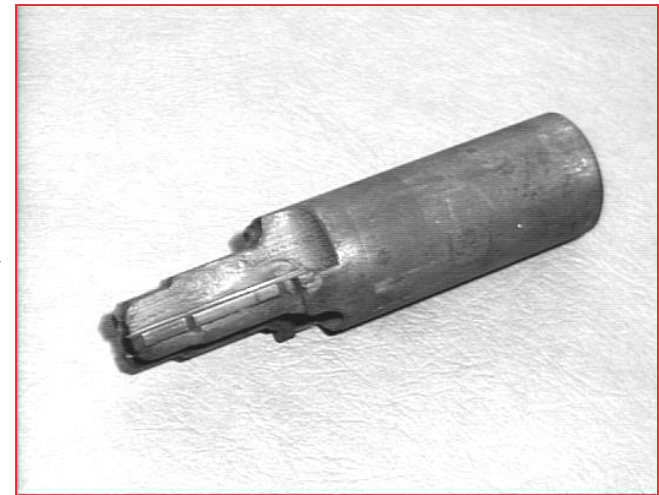


Cylindrical grinding



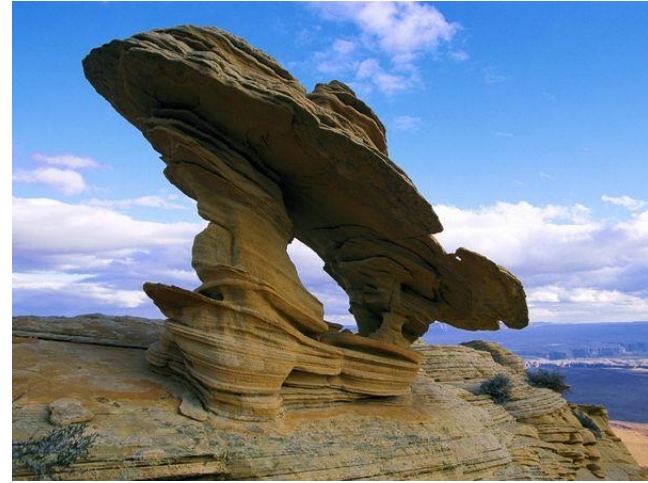
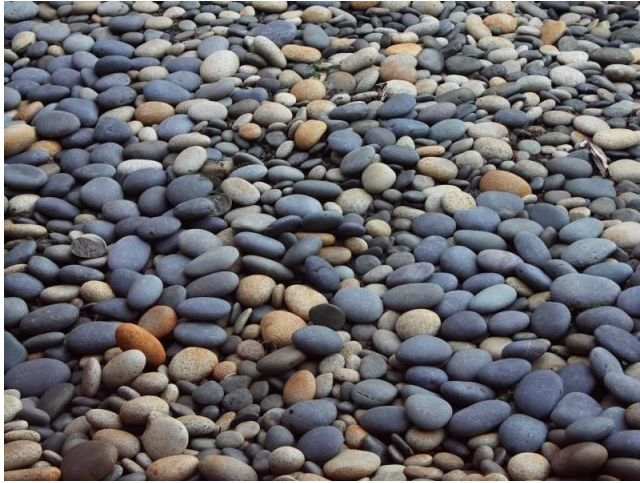
# Variations

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





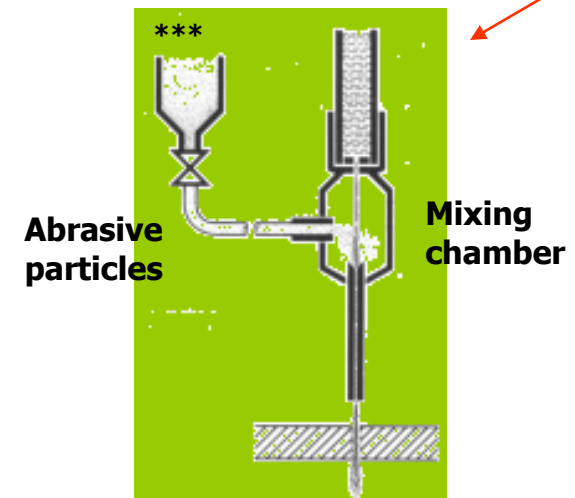
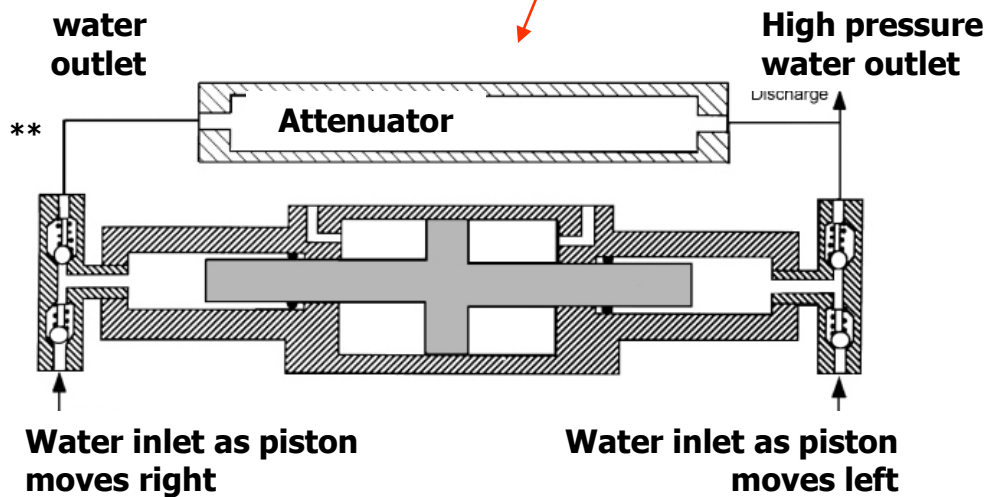
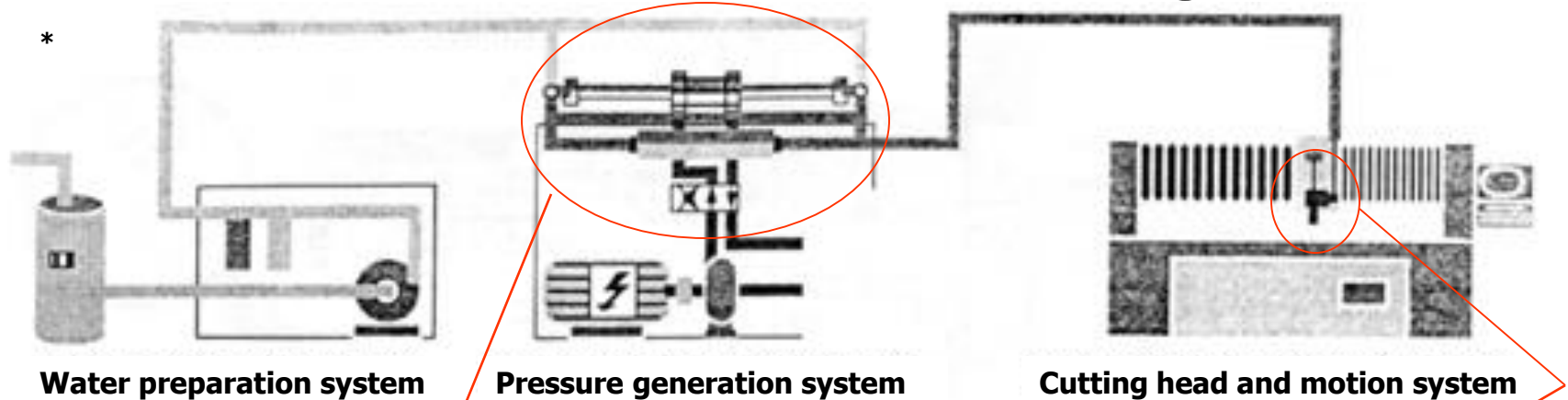
# Removal by erosion



# Water-jet in Bldg 35 Shop



# Waterjet Machining

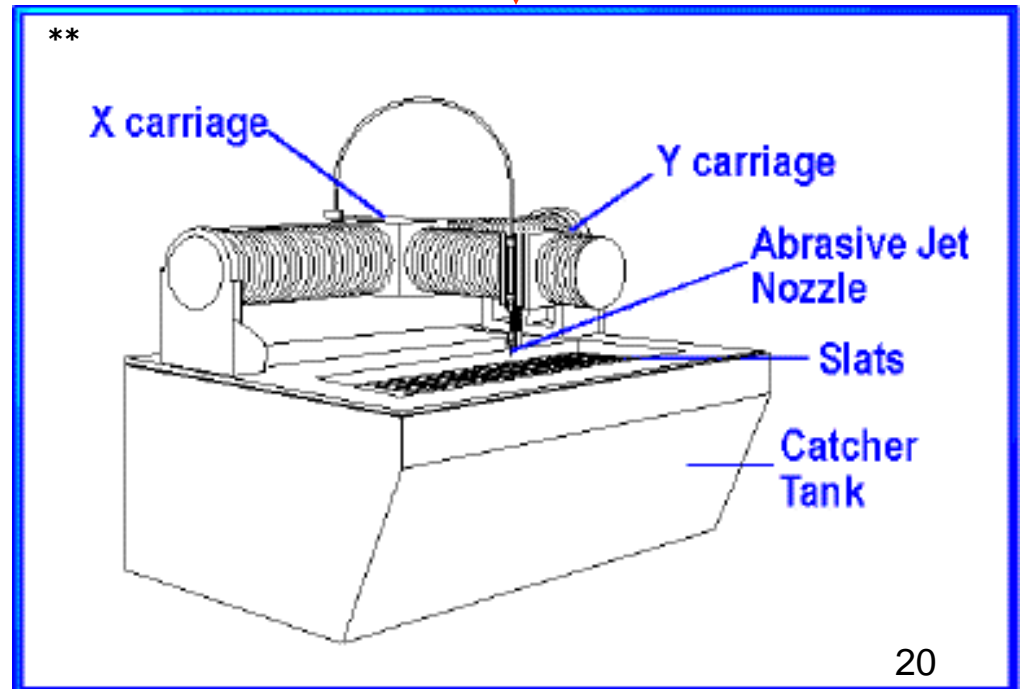
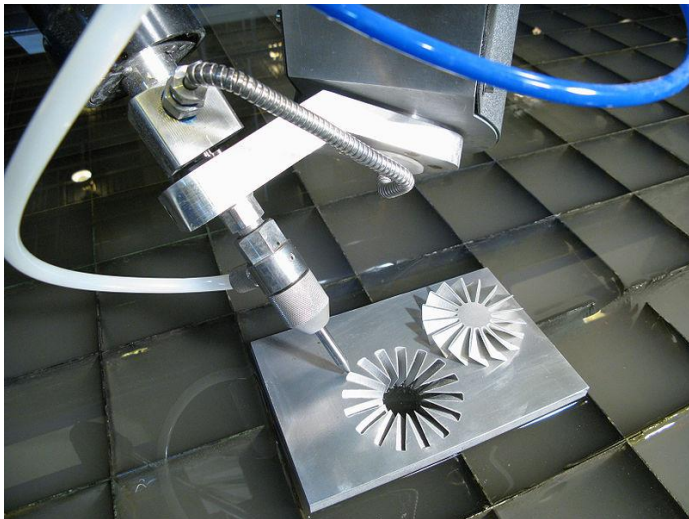
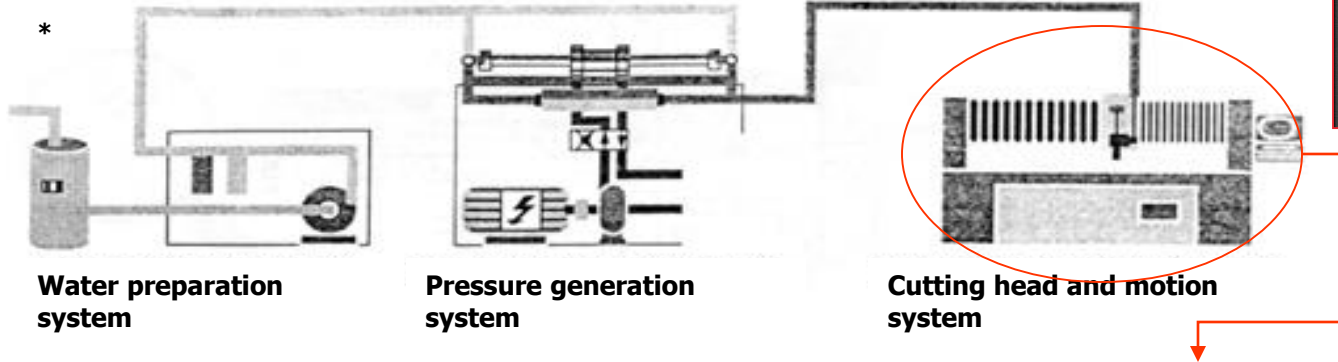
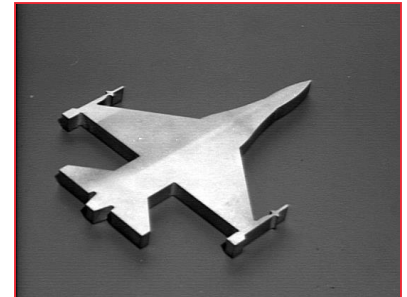


\* Source: <http://www.seas.smu.edu/rcam/research/waterjet/par1.html>; \*\* <http://www.seas.smu.edu/rcam/research/waterjet/par3.html>;  
 \*\*\* <http://kbn.mt.polsl.gliwice.pl/wjm/basics.html>













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

# Waterjet Machining



\* Source: <http://cybercut.berkeley.edu/mas2/html/processes/edm/index.html>; \*\* [http://www.omax.com/components\\_of\\_waterjet.html](http://www.omax.com/components_of_waterjet.html)

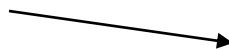
# Mohs Hardness scale

Mohs hardness	Mineral	Chemical formula	Absolute hardness	Image
1	Talc	$Mg_3Si_4O_{10}(OH)_2$	1	
2	Gypsum	$CaSO_4 \cdot 2H_2O$	3	
3	Calcite	$CaCO_3$	9	
4	Fluorite	$CaF_2$	21	
5	Apatite	$Ca_5(PO_4)_3(OH, Cl, F)$	48	
6	Orthoclase Feldspar	$KAlSi_3O_8$	72	
7	Quartz	$SiO_2$	100	
8	Topaz	$Al_2SiO_4(OH, F)_2$	200	
9	Corundum	$Al_2O_3$	400	
10	Diamond	C	1600	



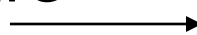
Cushion Garnet Ring with Diamond Halo in 14k White Gold \$1100.00 - Blue Nile

garnet



Cushion-Cut Sapphire and Diamond Halo Ring in 18k White Gold \$14,000

sapphire



# Mohs Hardness scale

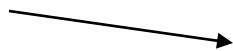


**Garnet Ring with Diamond...**  
\$29.99



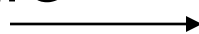
**Cushion Garnet Ring with Diamond Halo in 14k White Gold**  
\$1100.00 - Blue Nile

garnet



**Cushion-Cut Sapphire and Diamond Halo Ring in 18k White Gold**  
\$14,000

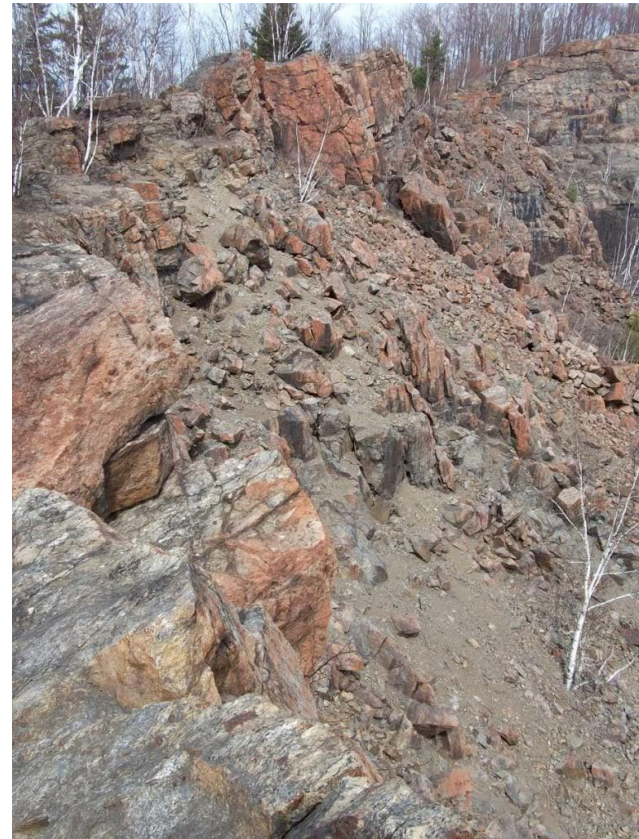
sapphire



Mohs hardness	Mineral	Chemical formula	Absolute hardness	Image
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3	Calcite	$CaCO_3$	9	
4	Fluorite	$CaF_2$	21	
5	Apatite	$Ca_5(PO_4)_3(OH, Cl, F)$	48	
6	Orthoclase Feldspar	$KAlSi_3O_8$	72	
7	Quartz	$SiO_2$	100	
8	Topaz	$Al_2SiO_4(OH, F)_2$	200	
9	Corundum	$Al_2O_3$	400	
10	Diamond	C	1600	



# Gore Mt, New York

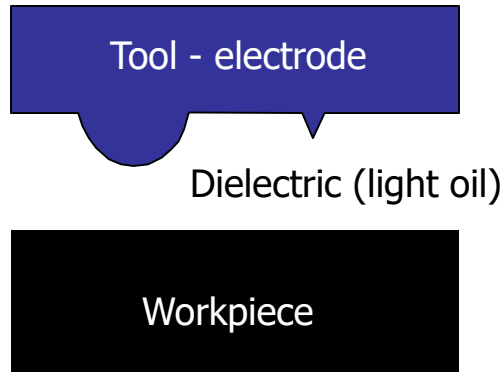


# Waterjet Cleaning Up

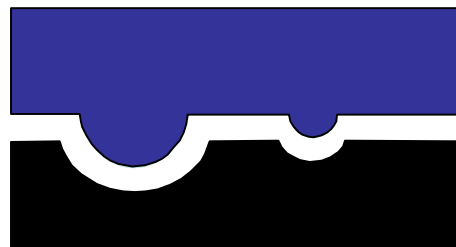




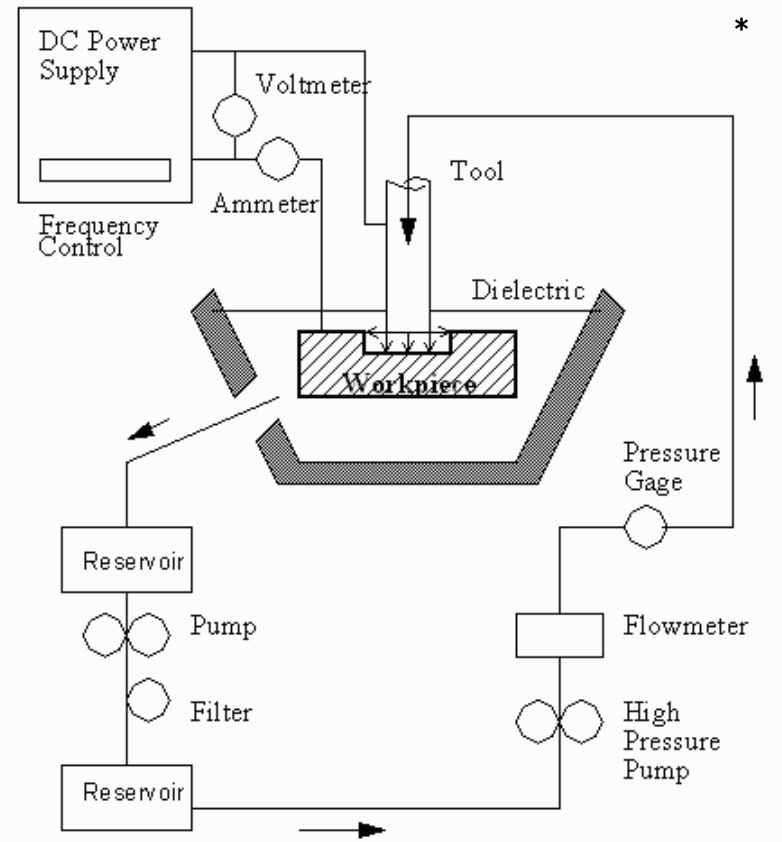
# EDM (Electrical Discharge Machining)



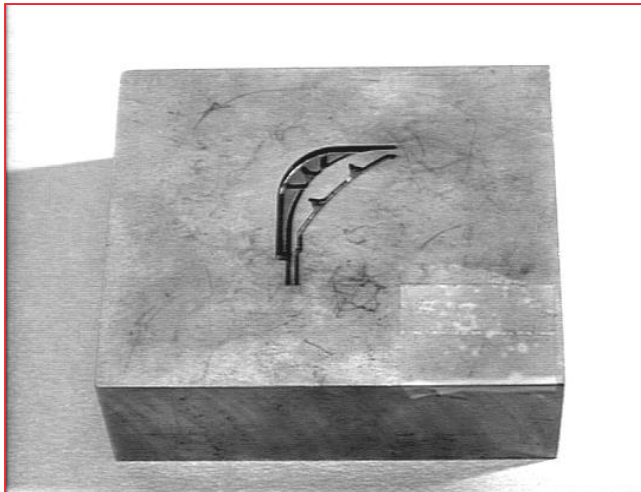
**Initial shapes of electrode and workpiece**



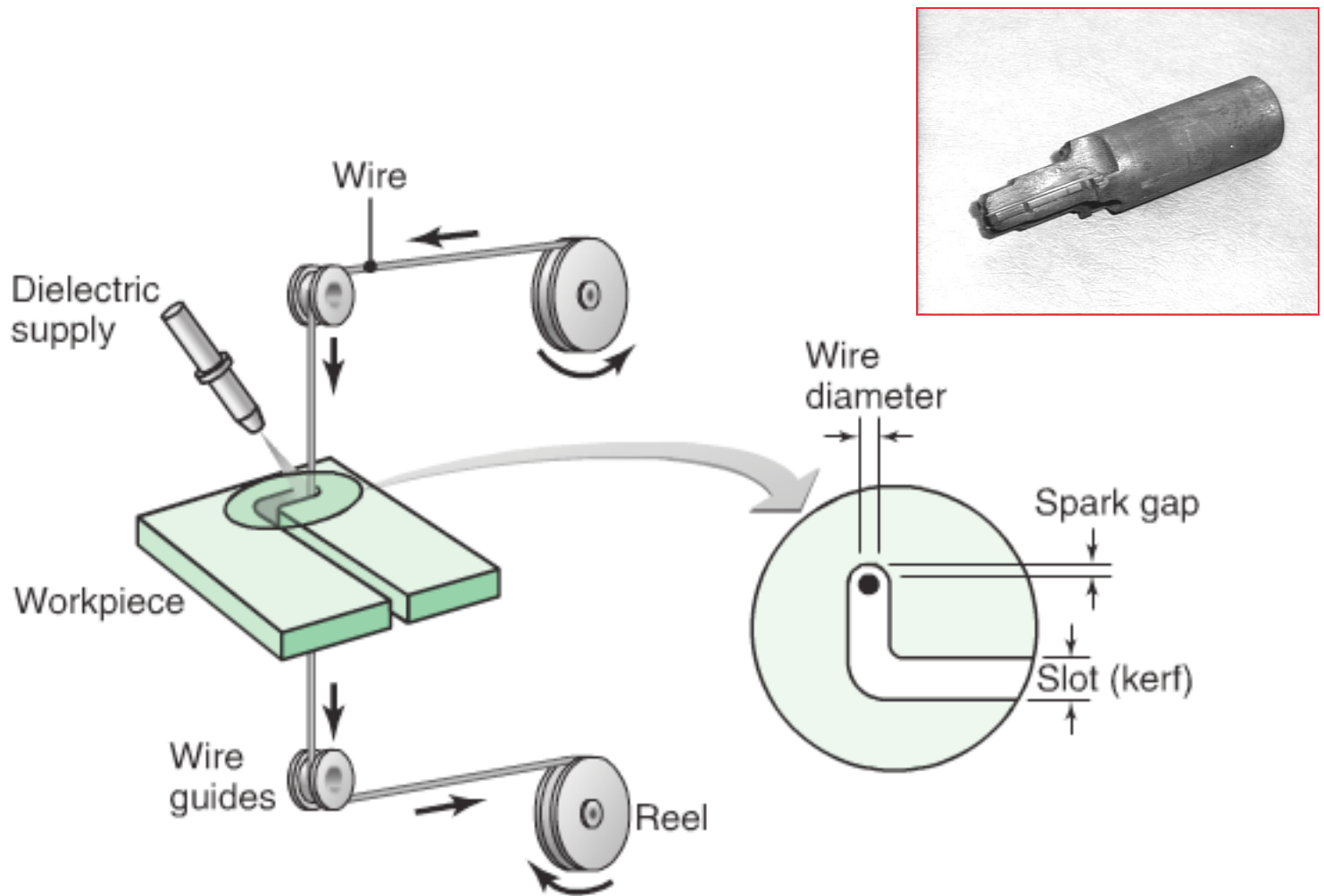
**Final complementary shapes of electrode and workpiece**



# Agitator for top loading washer

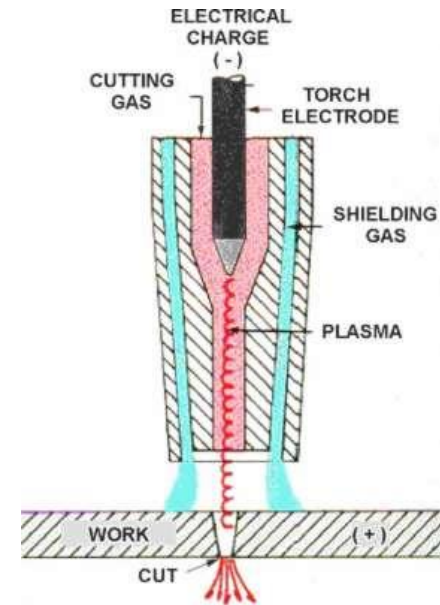


*Mounted Electrode*

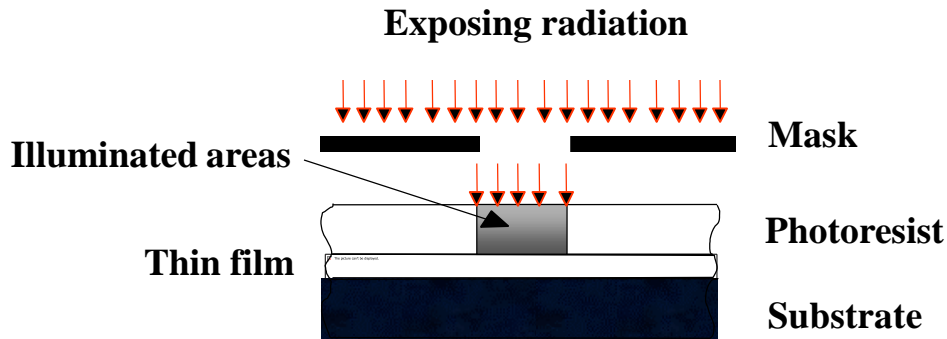


**FIGURE 27.12** Schematic illustration of the wire EDM process. As many as 50 hours of machining can be performed with one reel of wire, which is then discarded.

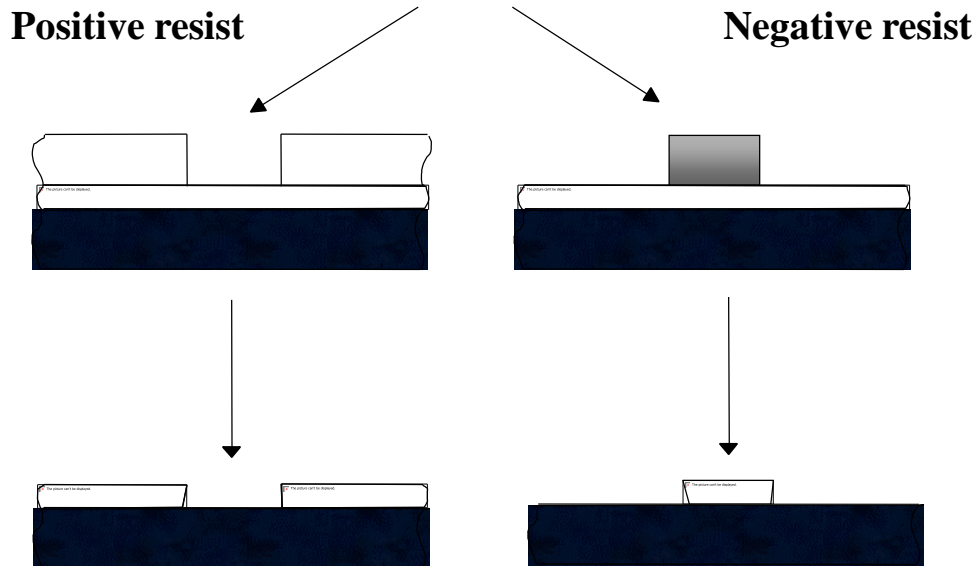
# Plasma arc cutting



# Lithography (additive + subtractive)



**EXPOSURE**



**DEVELOPING**

**ETCHING AND STRIPPING**

# 2. Additive Processes

coarse

**Assembly** - manual, automated, robotic..

**Joining** - mechanical, adhesives, welding, brazing..

**Composites layup**- hand lay-up, tape lay-up, filament winding..

**Additive manufacturing**- 3D printing, stereo lithography...

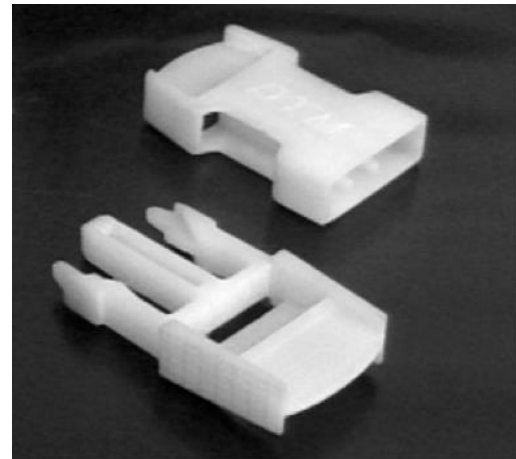
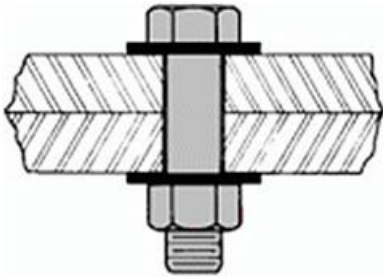
**Surface & Thin Film Processes**-

**liquids** - coatings, painting, printing, plating...

**gases/vapor/atomic scale**- CVD, PVD, sputtering

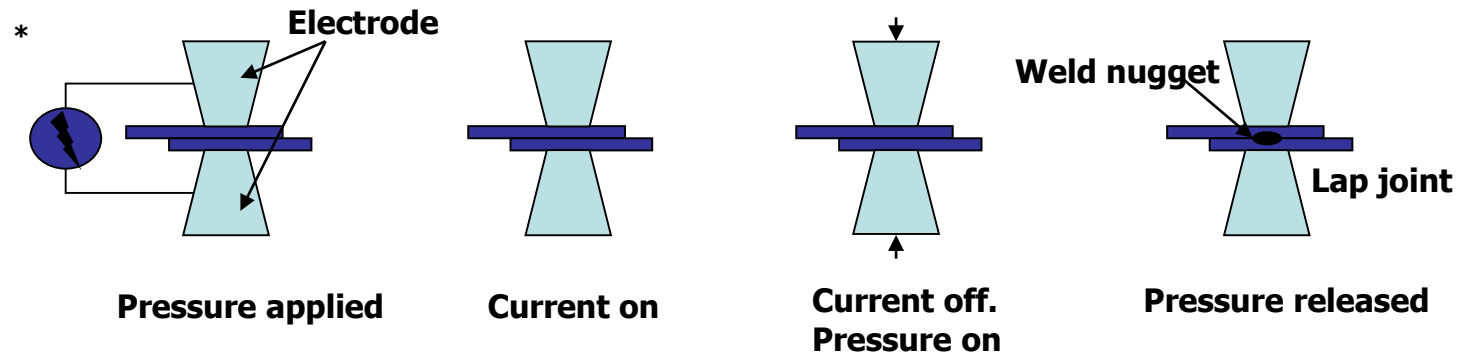
fine

# Mechanical joints



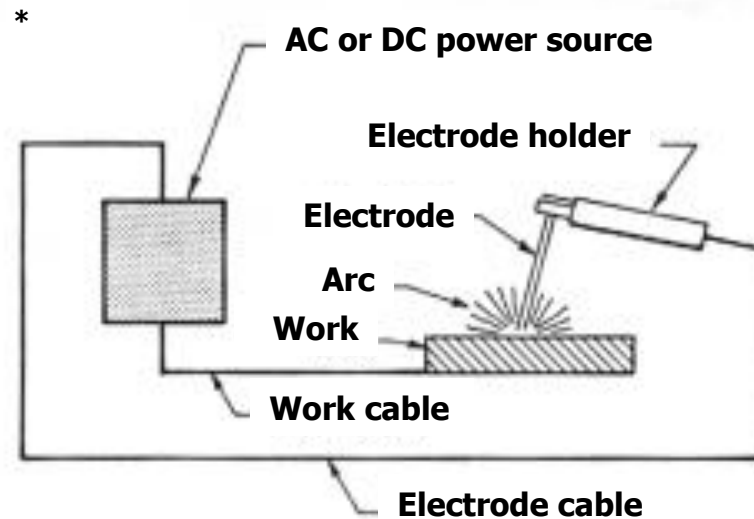


# Welding



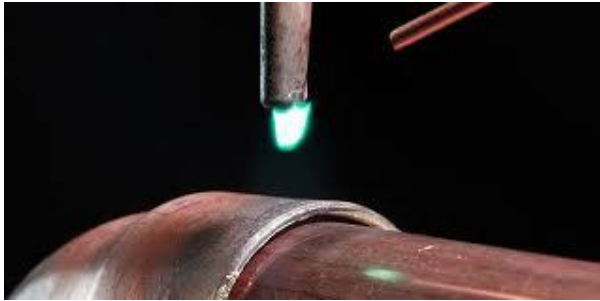
**[Sequence in the resistance spot welding process]**

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





# Brazing



Furnace brazing

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

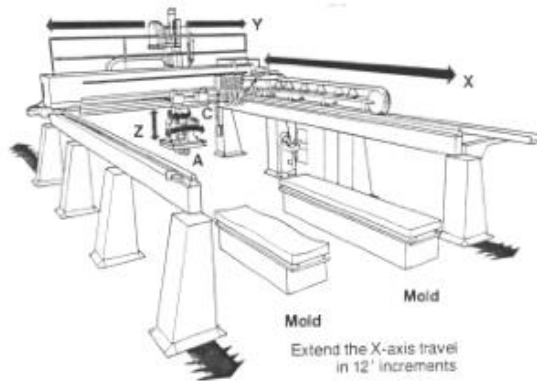
# Lay-Up of Advanced Composites



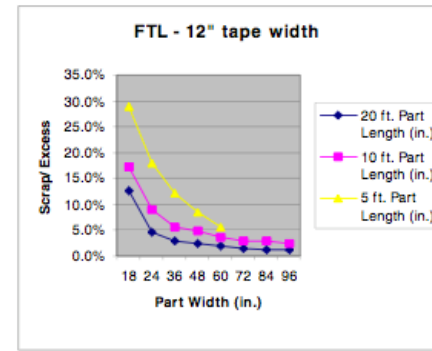
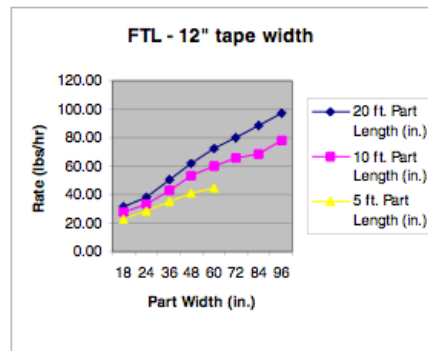
\*



# 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



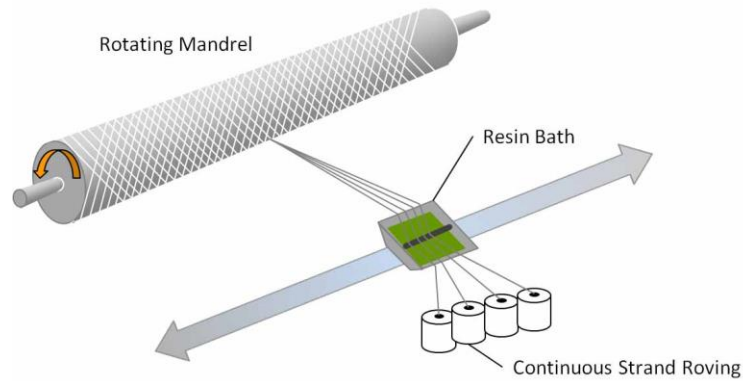
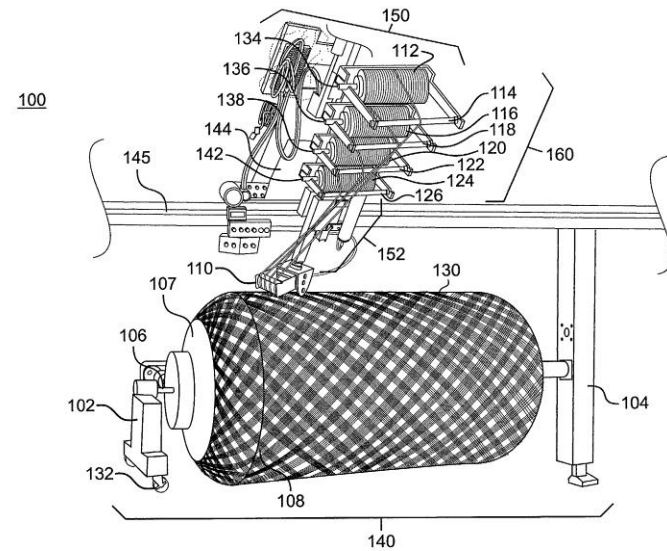
Figure 2. Fiber placement machine.



# Filament Winding



Filament Winding



# braiding

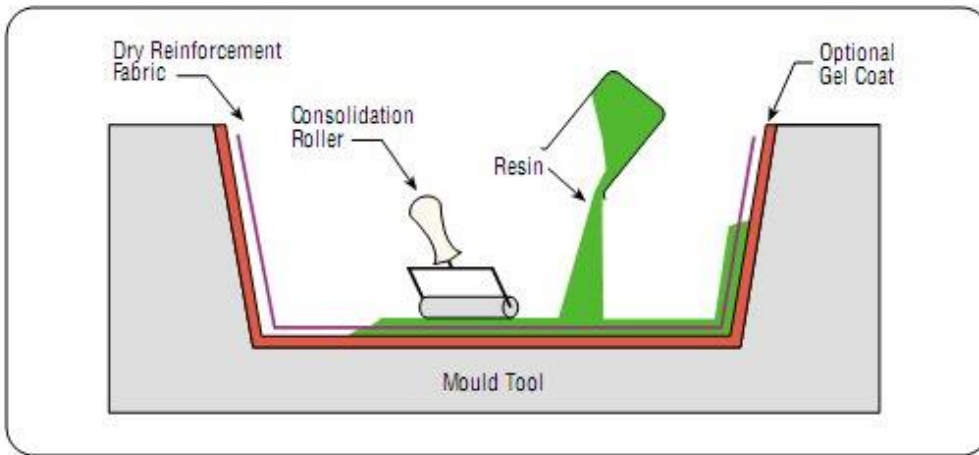


**Braiding  
Videos**

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

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





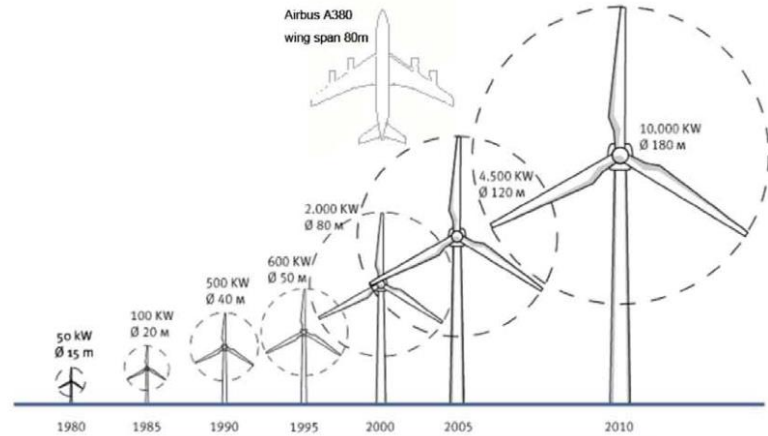
- Hand lay-up
- Spray-up
- Vacuum molding



Vacuum mold video  
Jump to 4 min

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

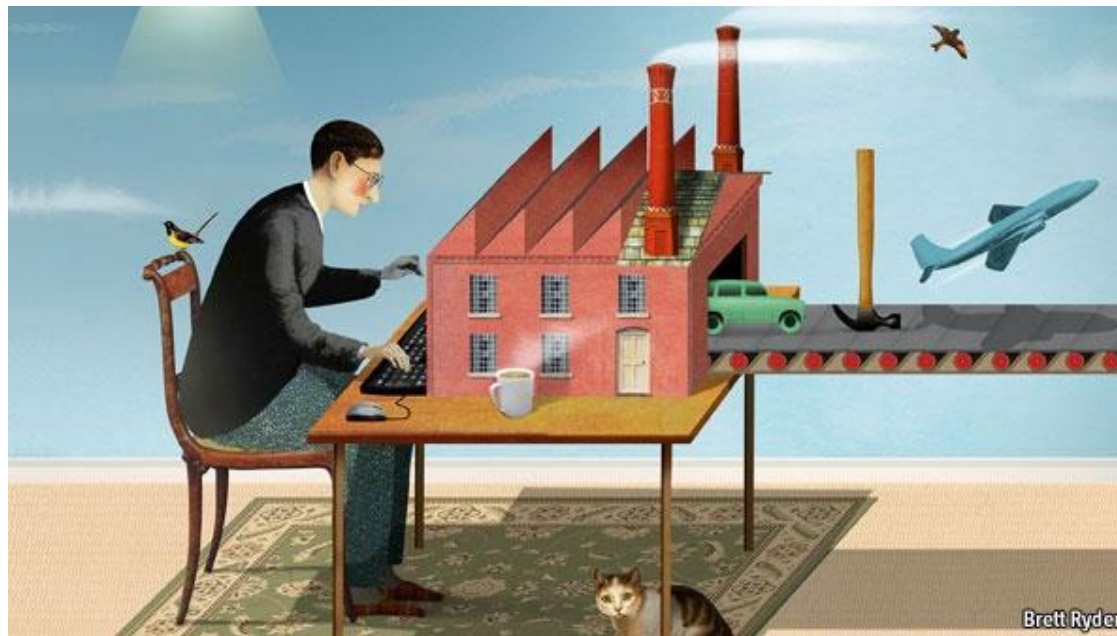
# Growing Wind Turbine Size





# Additive Manufacturing

The  
Economist



# The Third Industrial Revolution?



Additive manufacturing

## Print me a jet engine

Nov 22nd 2012, 12:54 by P.M.

Like 1.5k Tweet 126



GE Aviation

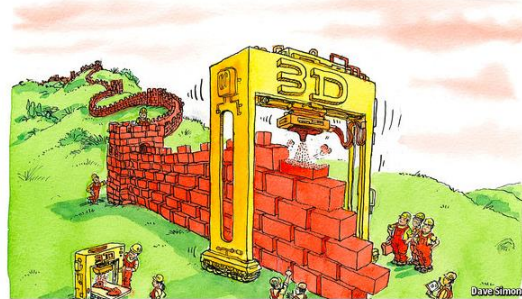
CONFIRMATION as to how seriously some companies are taking additive manufacturing, popularly known as 3D printing, came on November 20th when GE Aviation, part of the

## A new brick in the Great Wall

Additive manufacturing is growing apace in China

Apr 27th 2013 | BEIJING | From the print edition

Like 939 Tweet 155



ALTHOUGH it is the weekend, a small factory in the Haidian district of Beijing is hard at work. Eight machines, the biggest the size of a delivery van, are busy making things. Yet

## Print me a Stradivarius

How a new manufacturing technology will change the world

Feb 10th 2011 | From the print edition

Like 10k Tweet 1,000



EOS/Alamy

THE industrial revolution of the late 18th century made possible the mass production of goods, thereby creating economies of scale which changed the economy—and

Transition from prototypes, to tooling, to parts

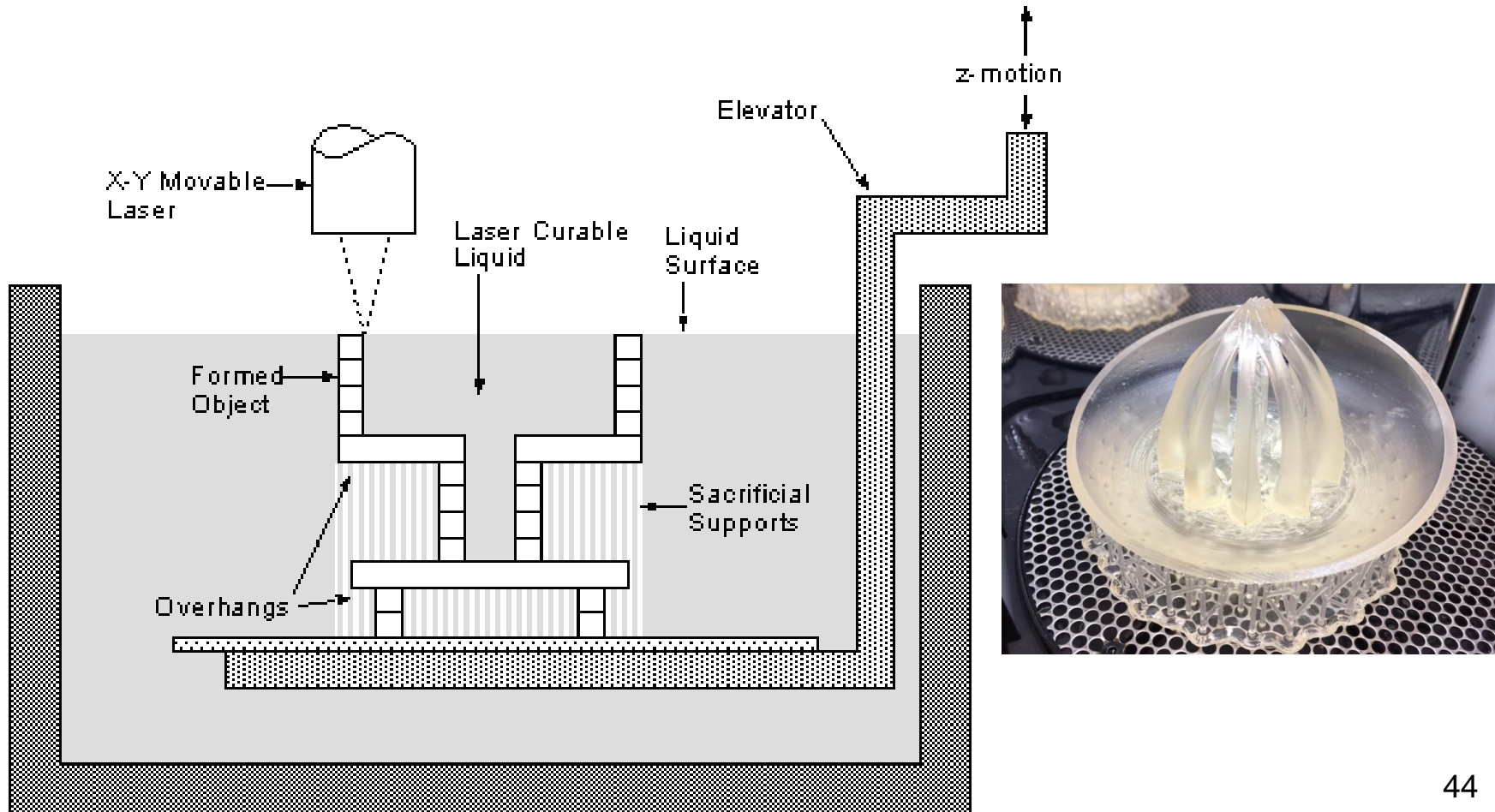
# ADDITIVE MANUFACTURING TECHNOLOGIES



Find out more at [www.3dhubs.com/what-is-3d-printing](http://www.3dhubs.com/what-is-3d-printing)

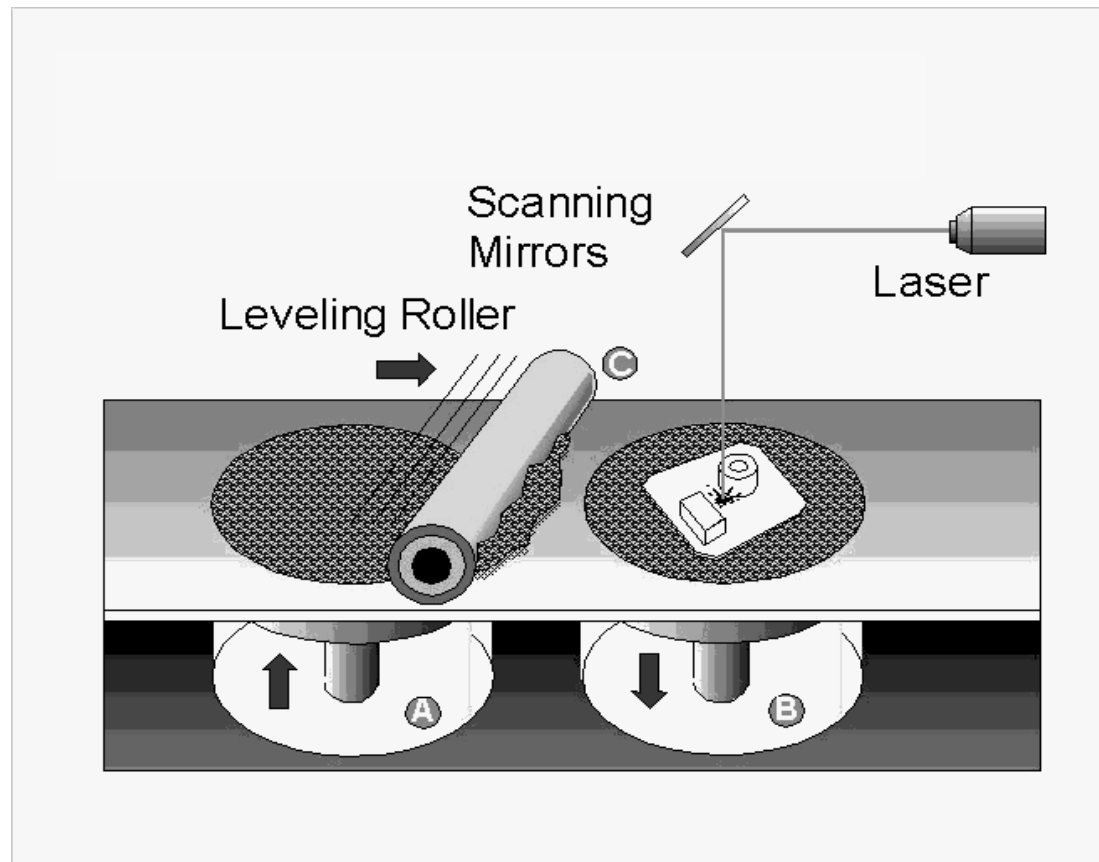
# Stereolithography (SLA)

\*

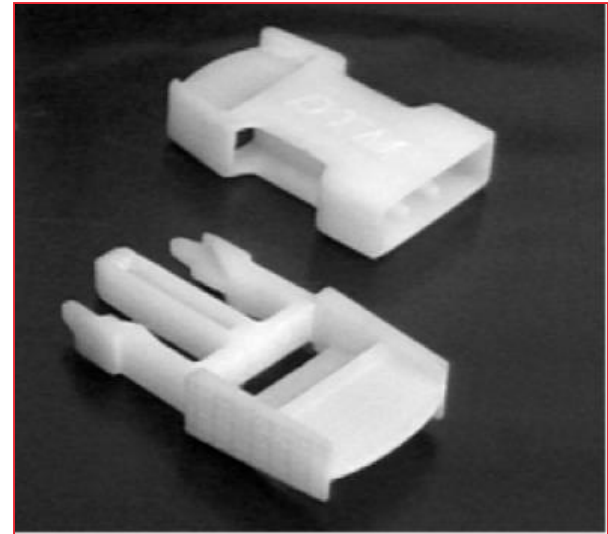


\* Source: <http://cybercut.berkeley.edu/mas2/html/processes/stereolith/more.html>

# Selective Laser Sintering (SLS)



# Selective Laser Sintering (SLS)

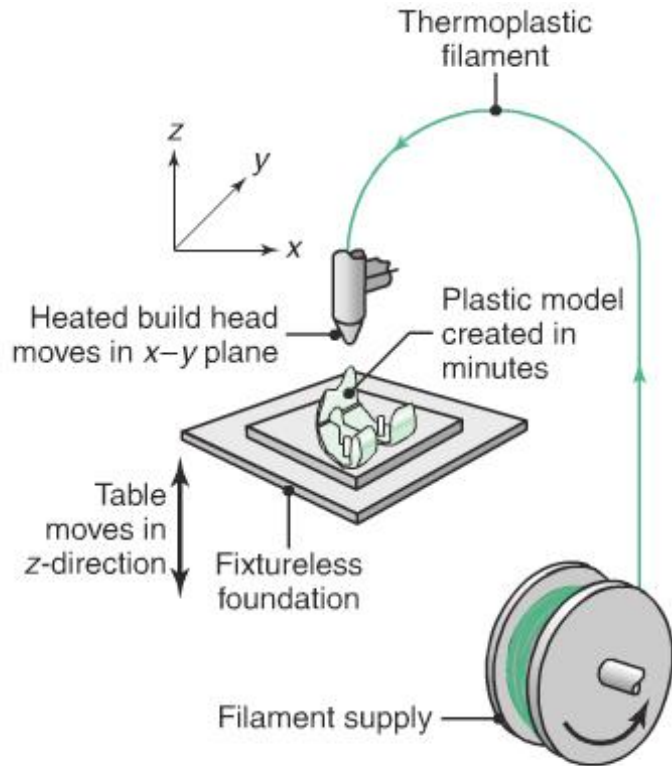


[http://web.mit.edu/2.810/www/lecture/sinter\\_movie.mov](http://web.mit.edu/2.810/www/lecture/sinter_movie.mov)

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

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





(a)



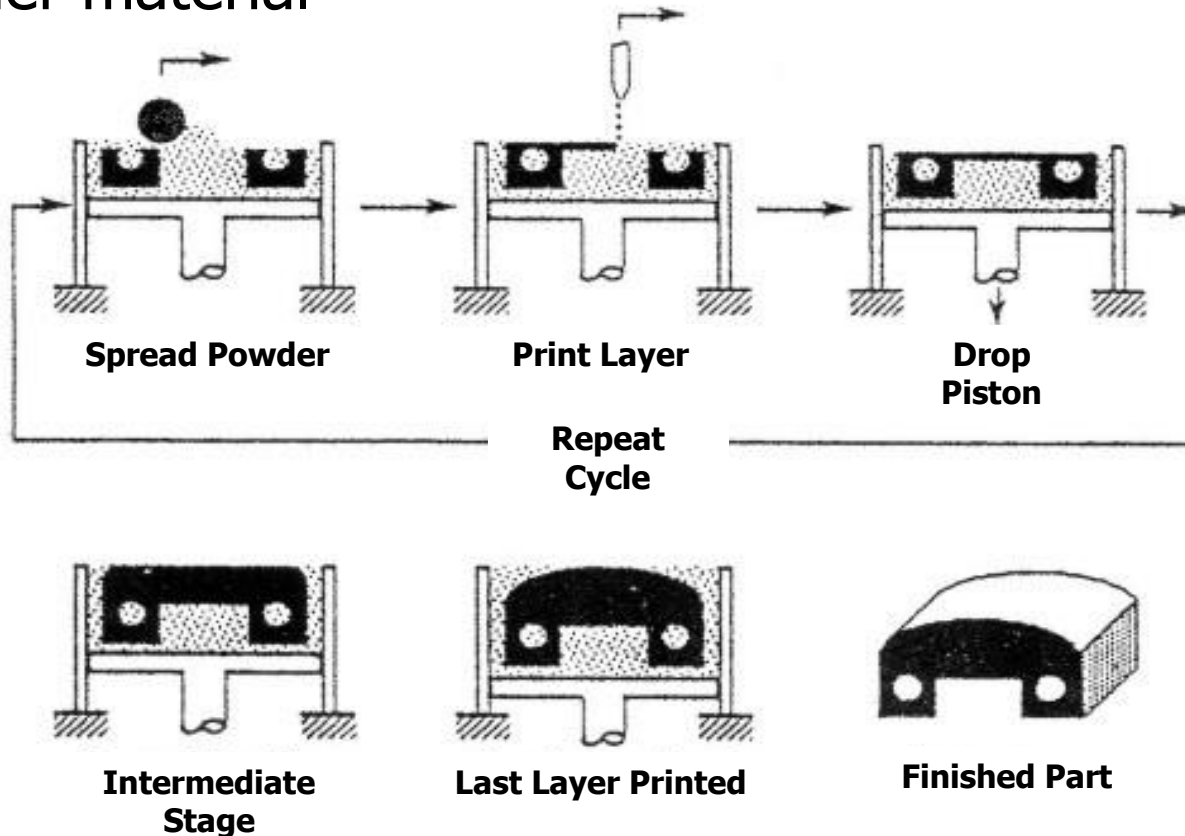
(b)

**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

# 3D Printing

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



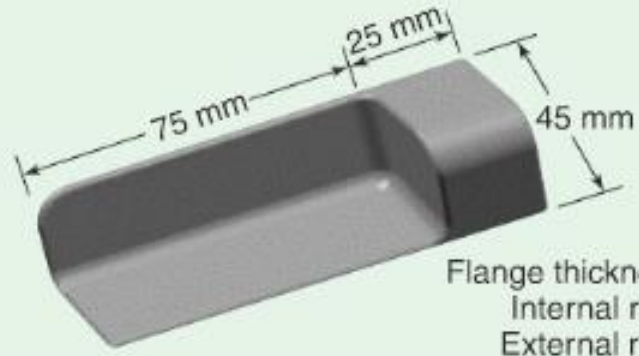
# Direct Printing of Metal Tooling;

ExtrudeHone Corp., Irwin, PA

---

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



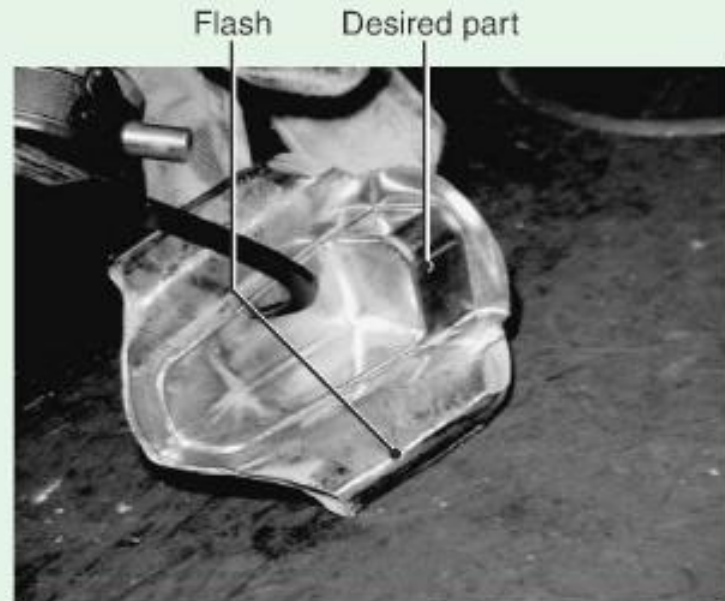


Flange thickness = 3 mm  
Internal radii = 5 mm  
External radii = 10 mm

(a)



(b)

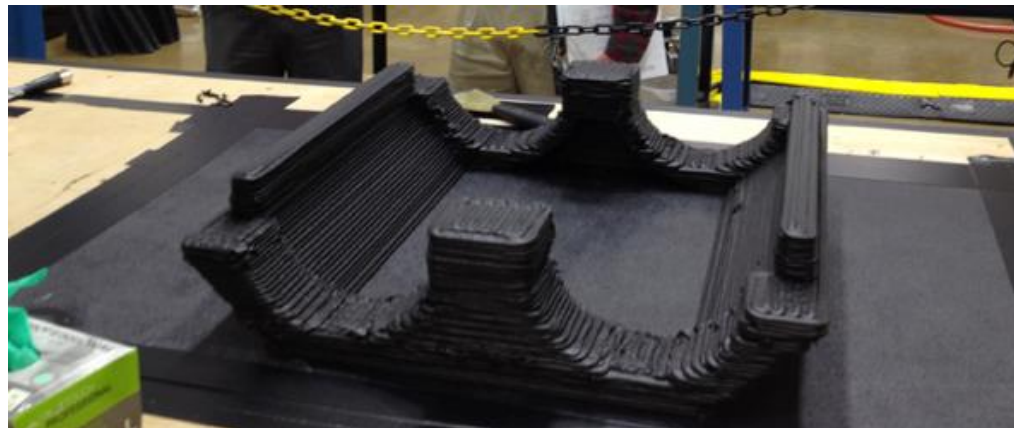


(c)

Forging Die made by 3D printing

# BAAMCI

BIG AREA ADDITIVE MANUFACTURING

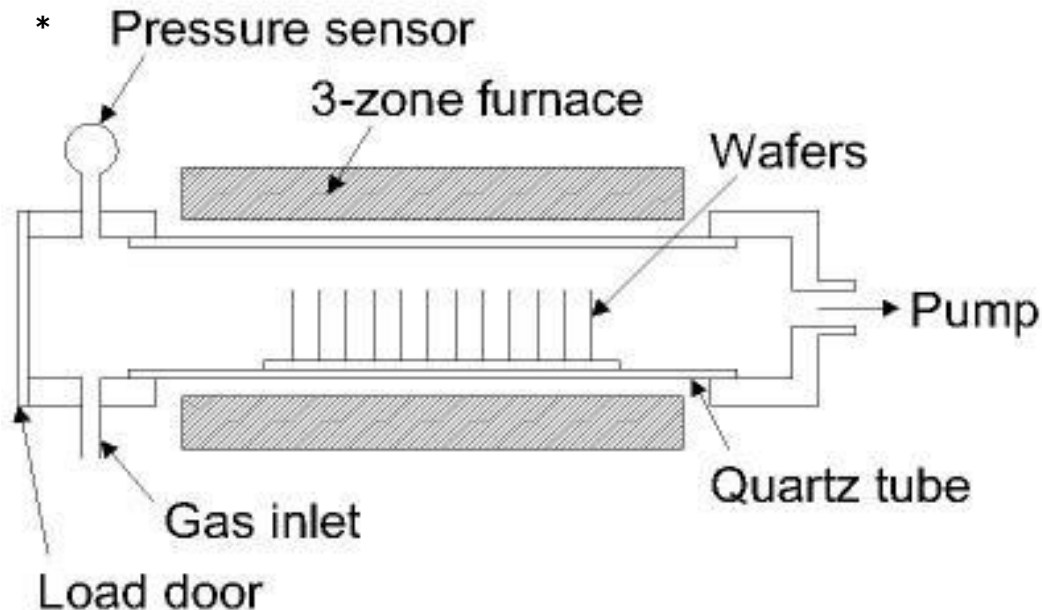




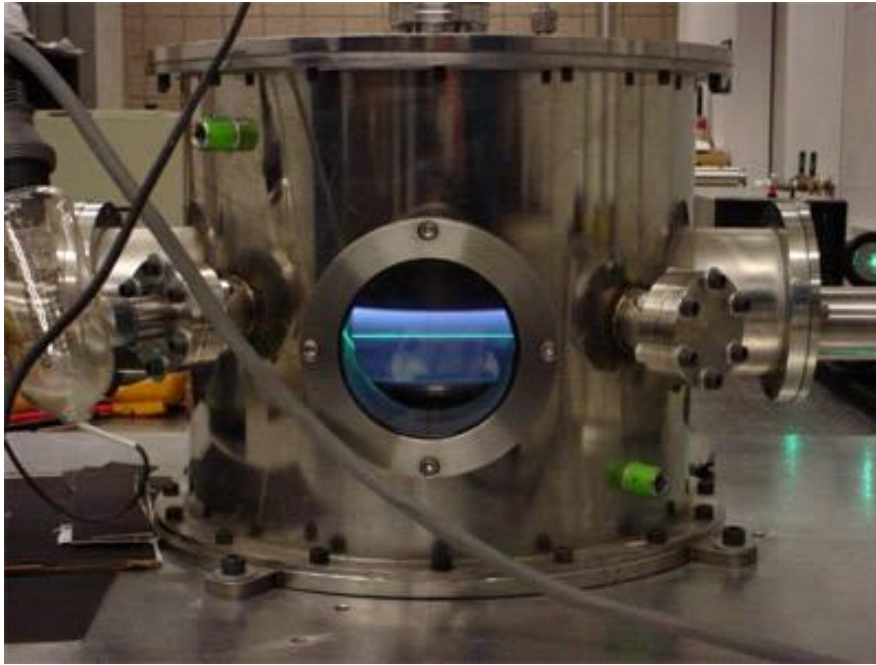
# CVD (Chemical Vapor Deposition)

- 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

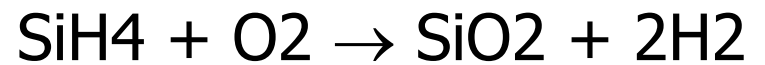
## Typical hot-wall LP(Low Pressure) CVD



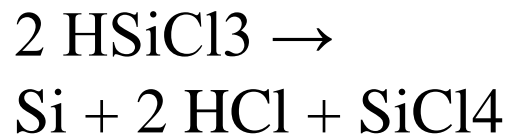




Deposition of SiO<sub>2</sub> from  
Silane gas by PECVD

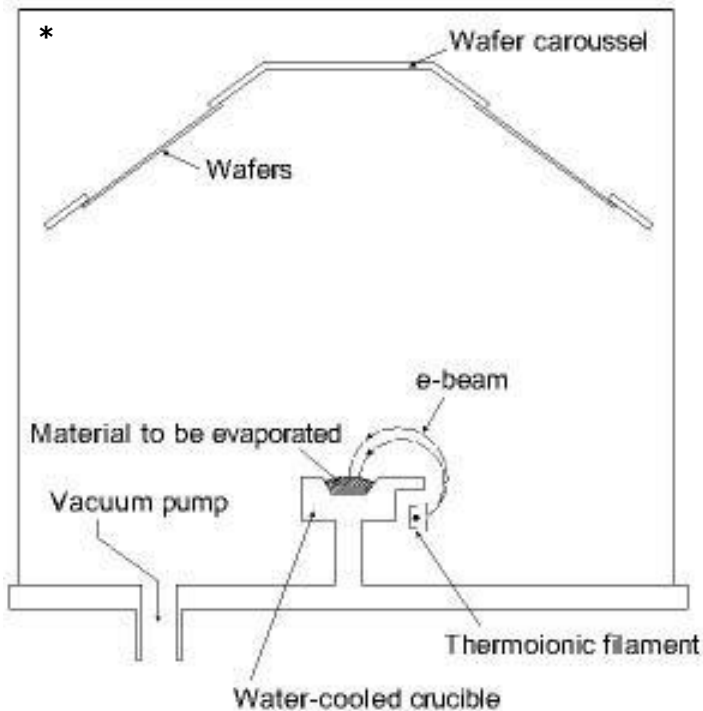


Siemens CVD  
Process for the  
Purification of Si

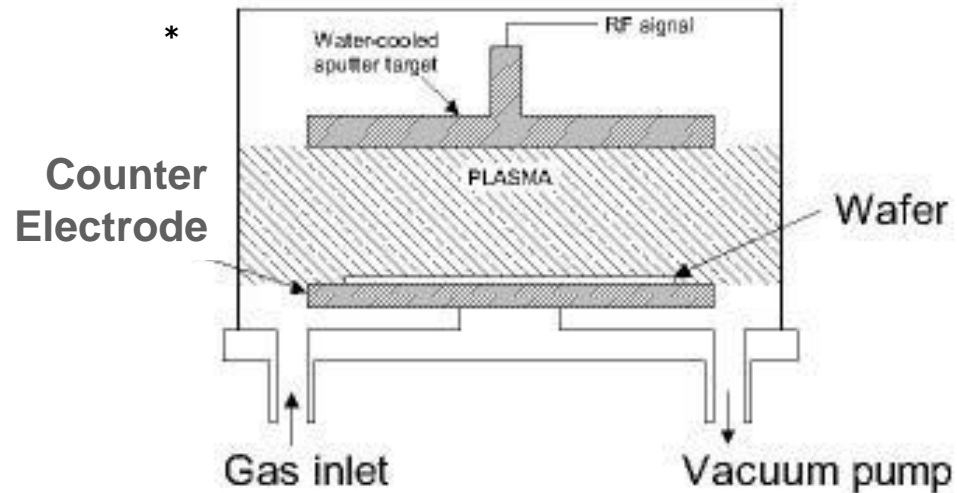


# PVD (Physical Vapor Deposition)

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



**e-beam evaporation system**



**RF sputtering system**

\* Source: <http://www.memsnets.org/mems/beginner/deposition.html>

# Thin film PV cell - CIGS

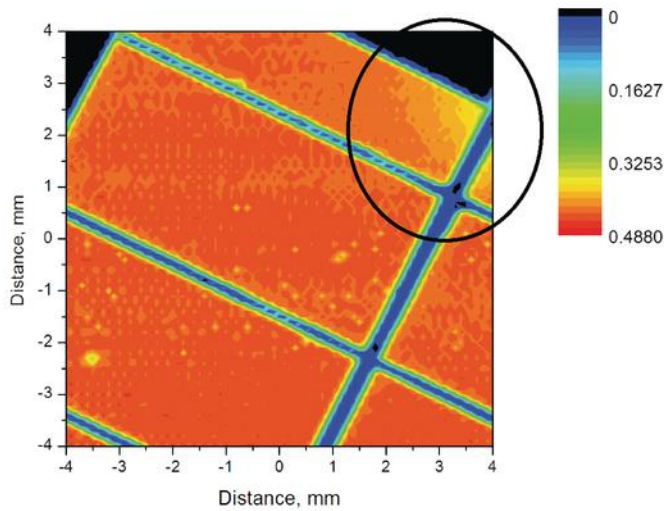
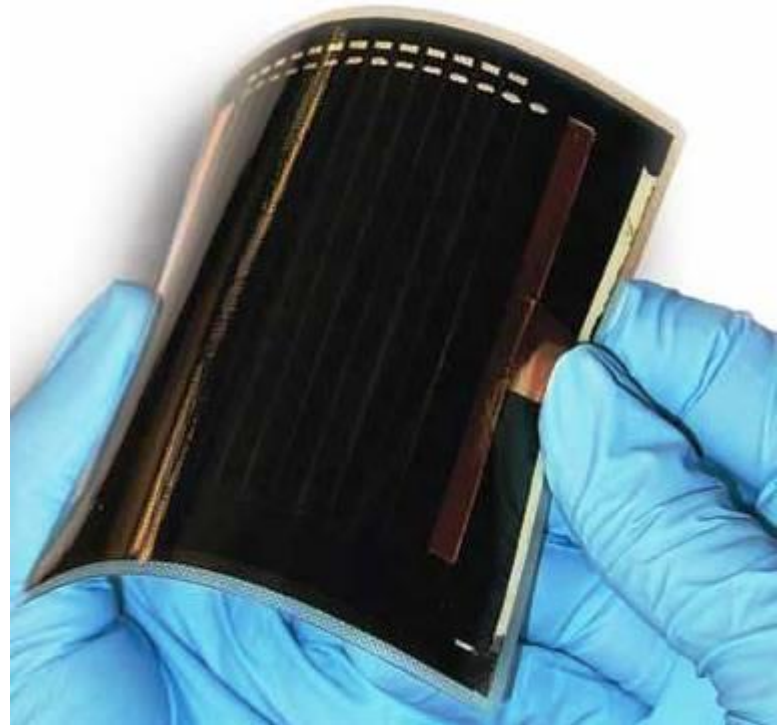


Photo-response mapping  
Of a CIGS cell

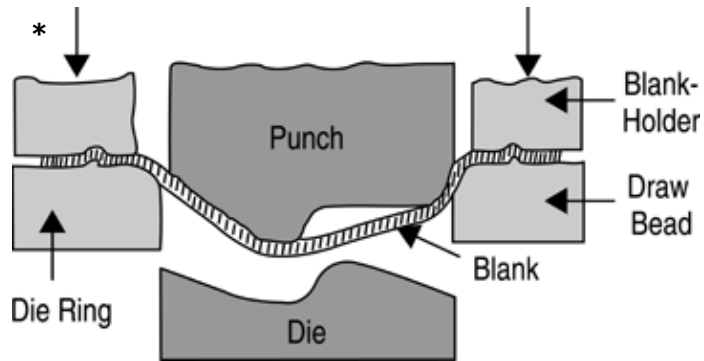


Ascent CIGS Solar Cell

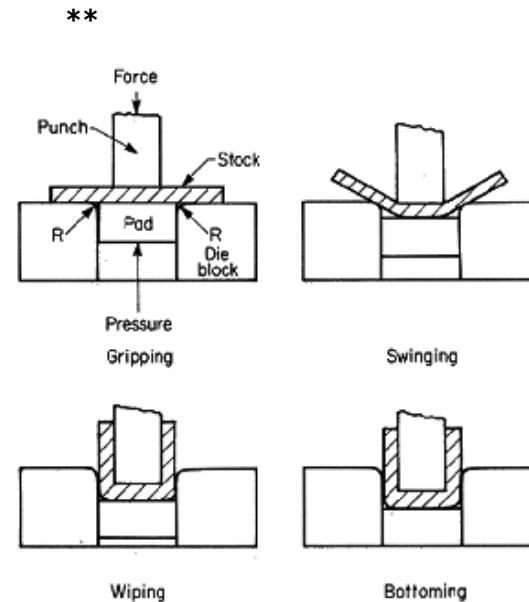
# 3. Net Shape: Molding

- 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**



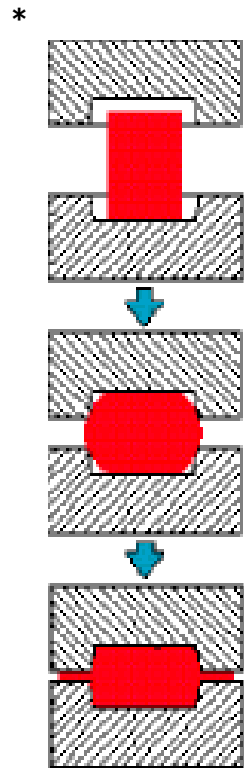
**Drawing**

GM stamping plant go to  
Around 2:39

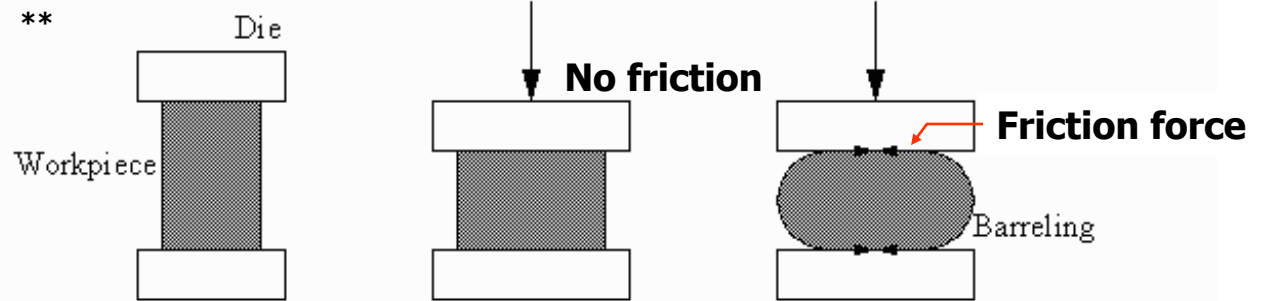
<http://www.youtube.com/watch?v=ixPhogfZTHU&feature=related>



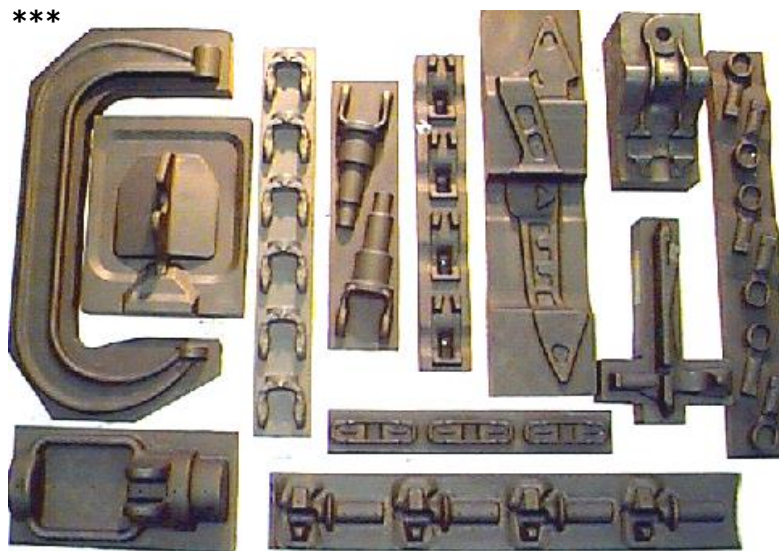
# Forging



**Closed Die Forging**



**Open Die Forging**

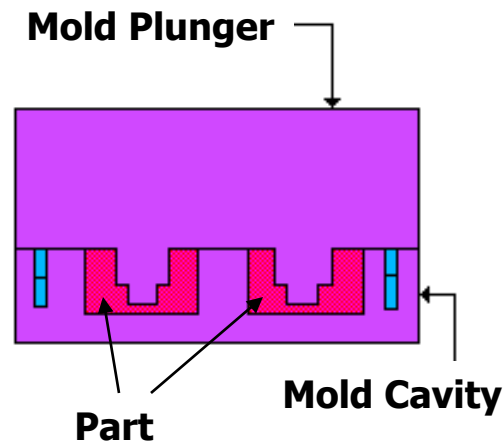
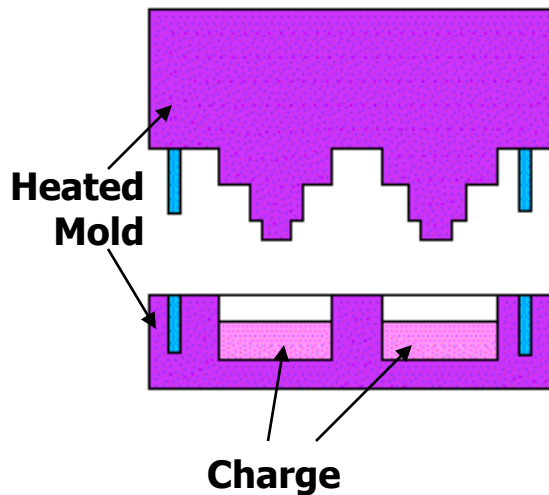


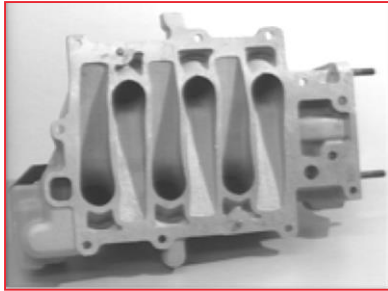




# Compression Molding

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



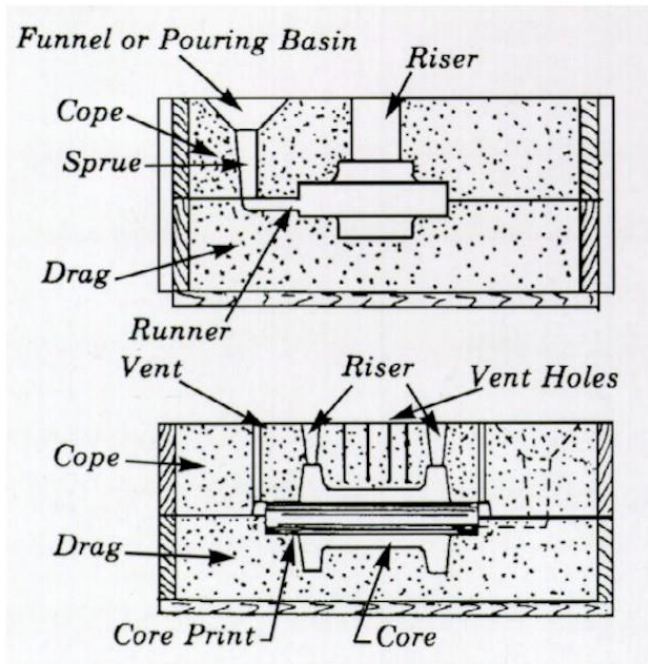


# Metal Casting

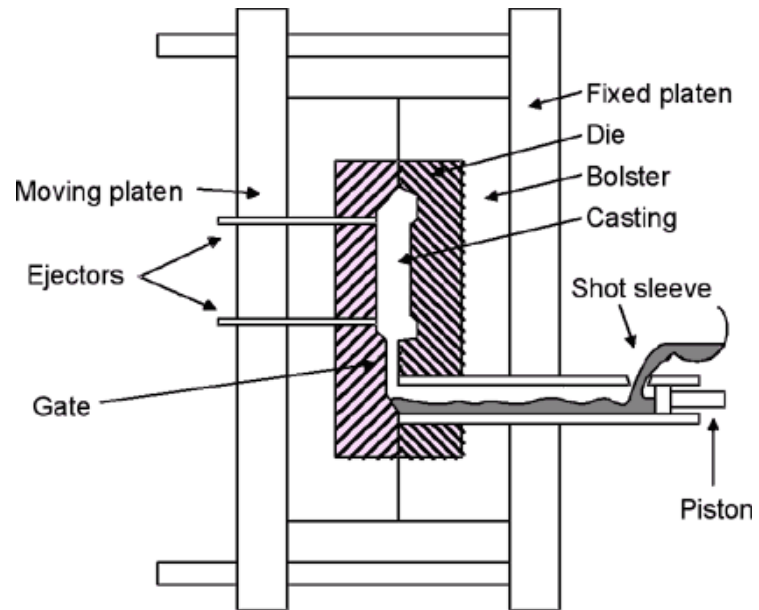


\*

\*\*

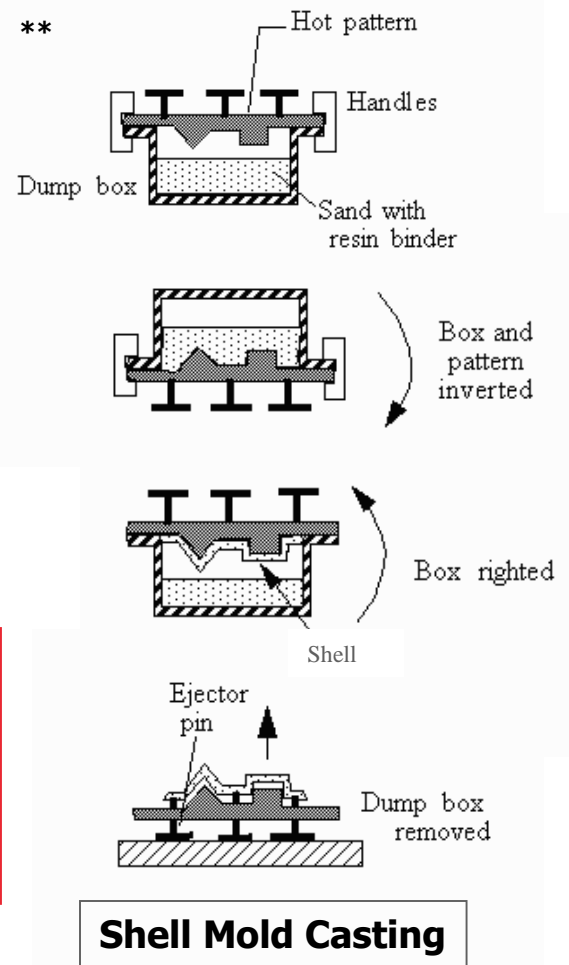
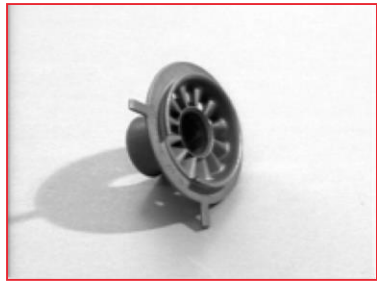
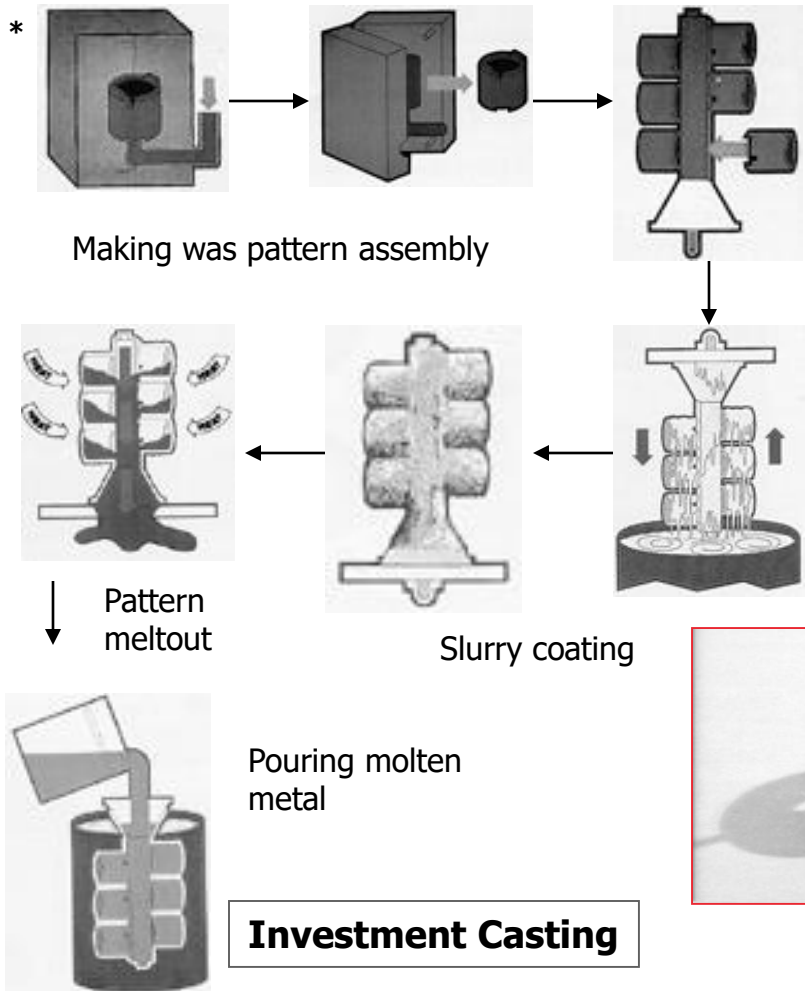


**Sand Casting Mold**



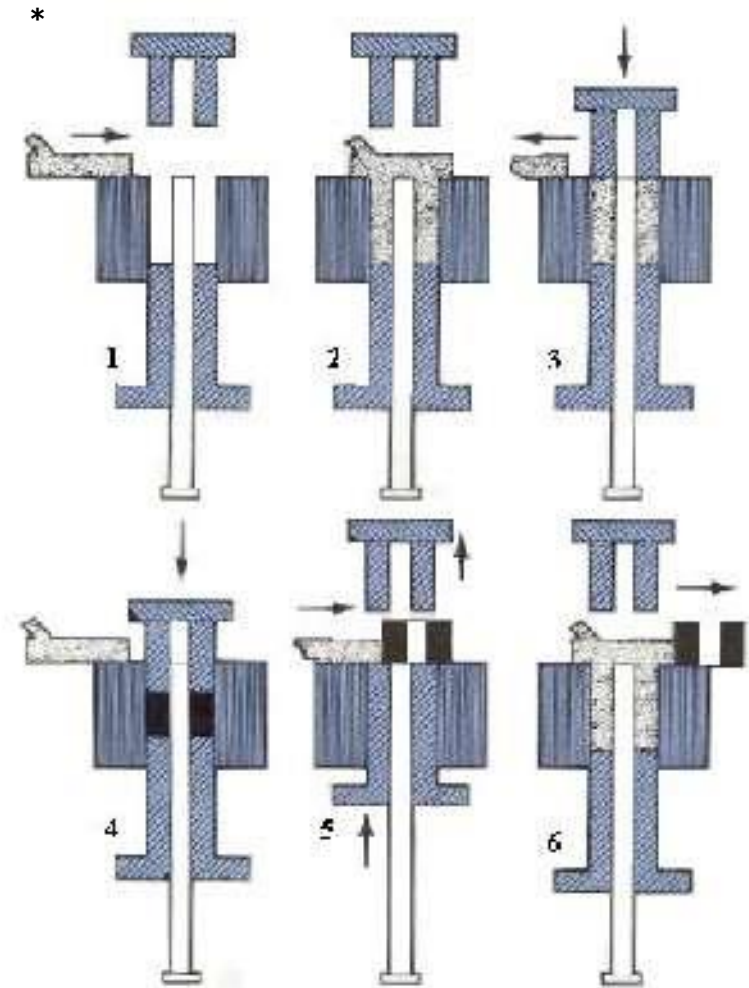
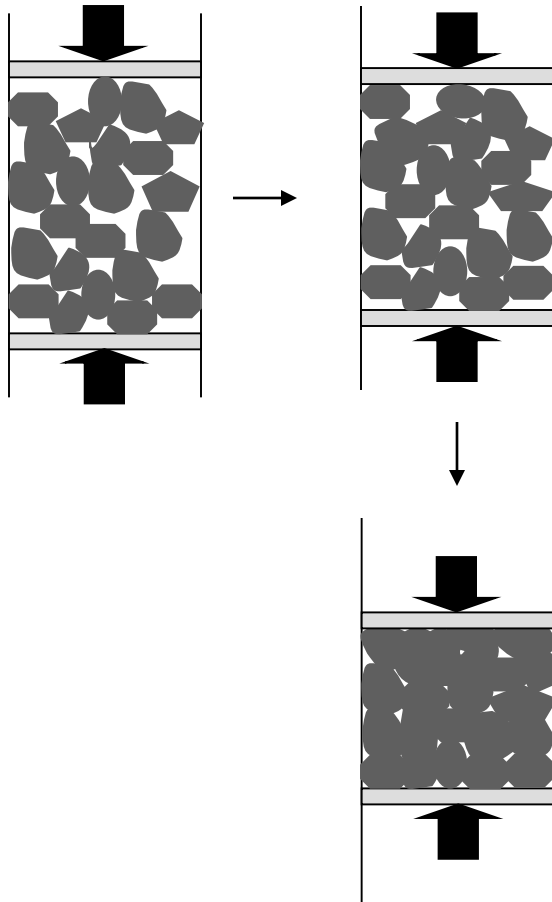
**Die Casting machine**

# Metal Casting

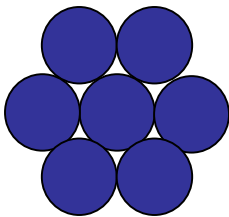
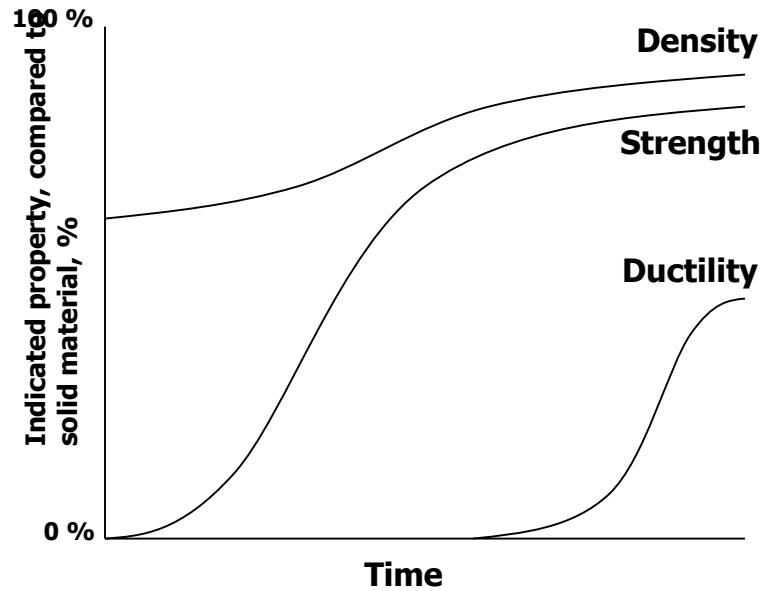




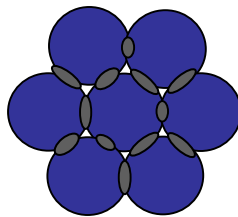
# P/M: Powder Compaction



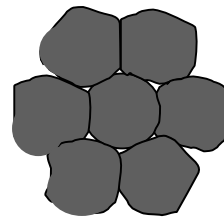
# Sintering



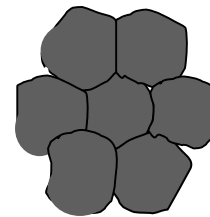
Green compact



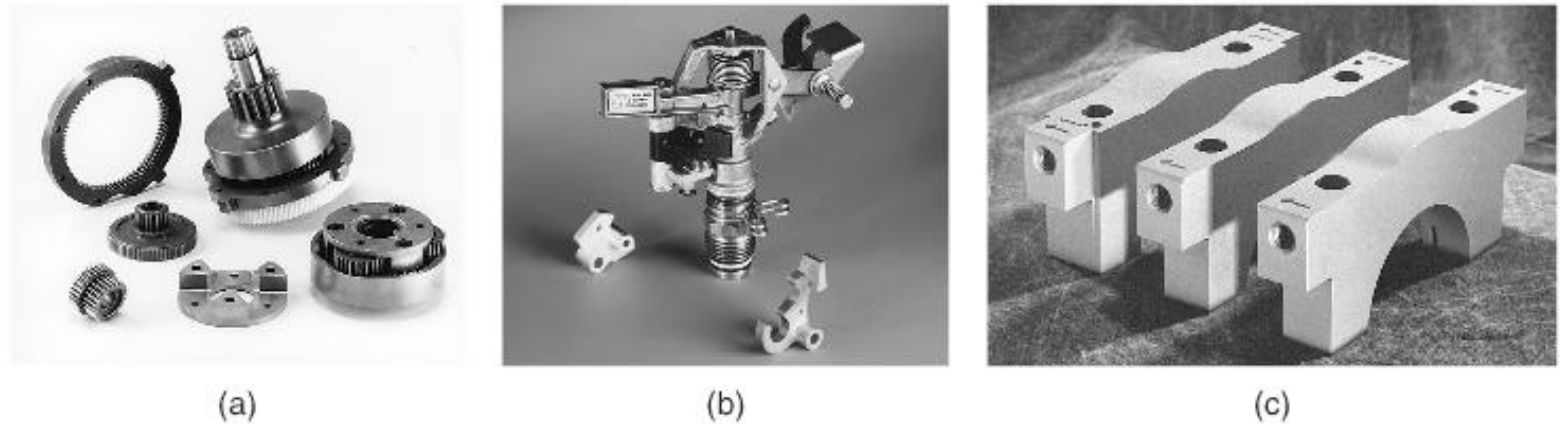
Necks formed



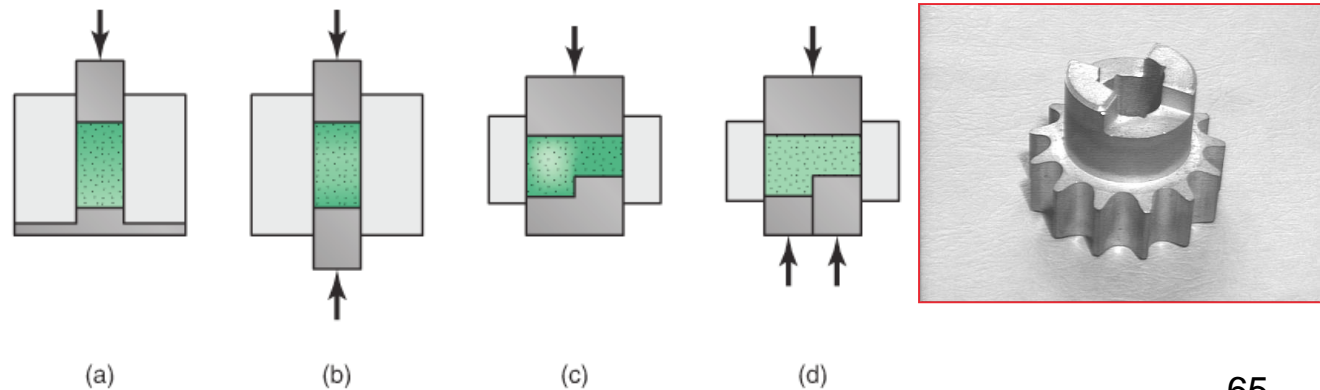
Pore size reduced



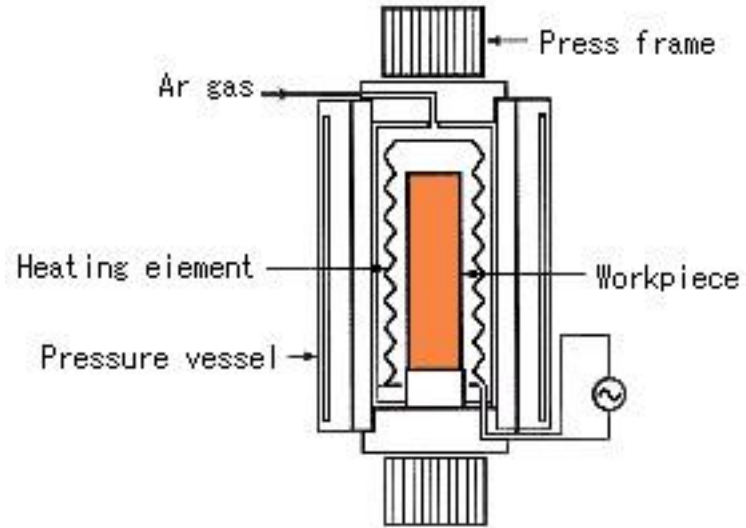
Fully sintered



**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.

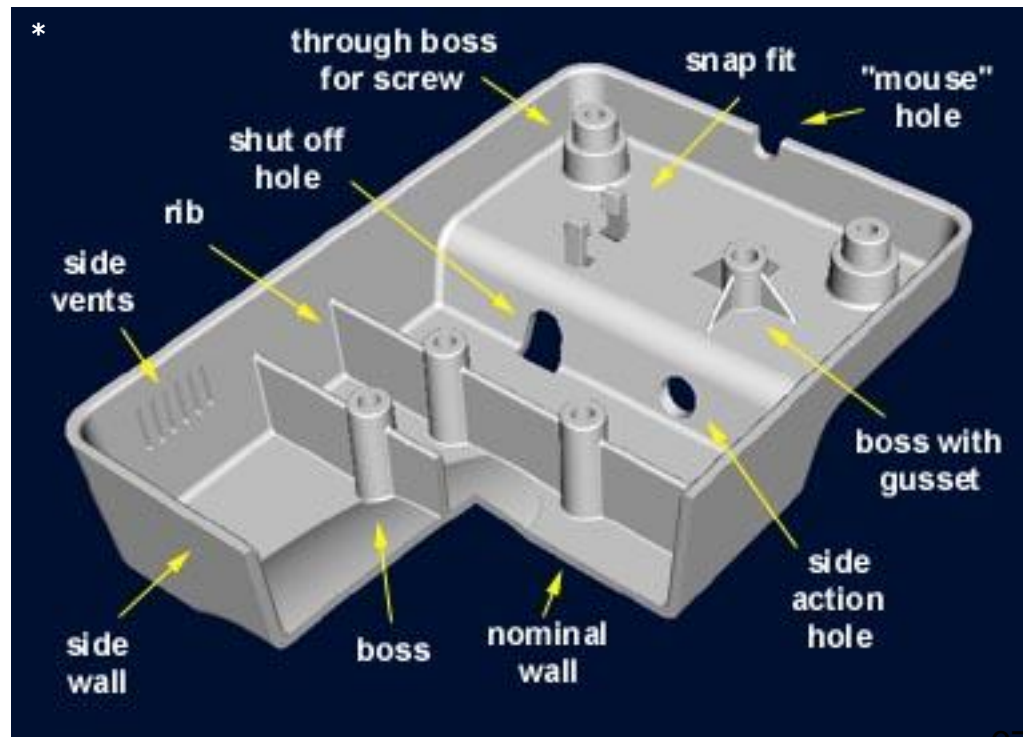
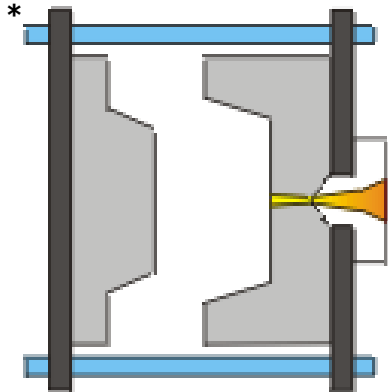


# Hot Isostatic Pressing - HIP



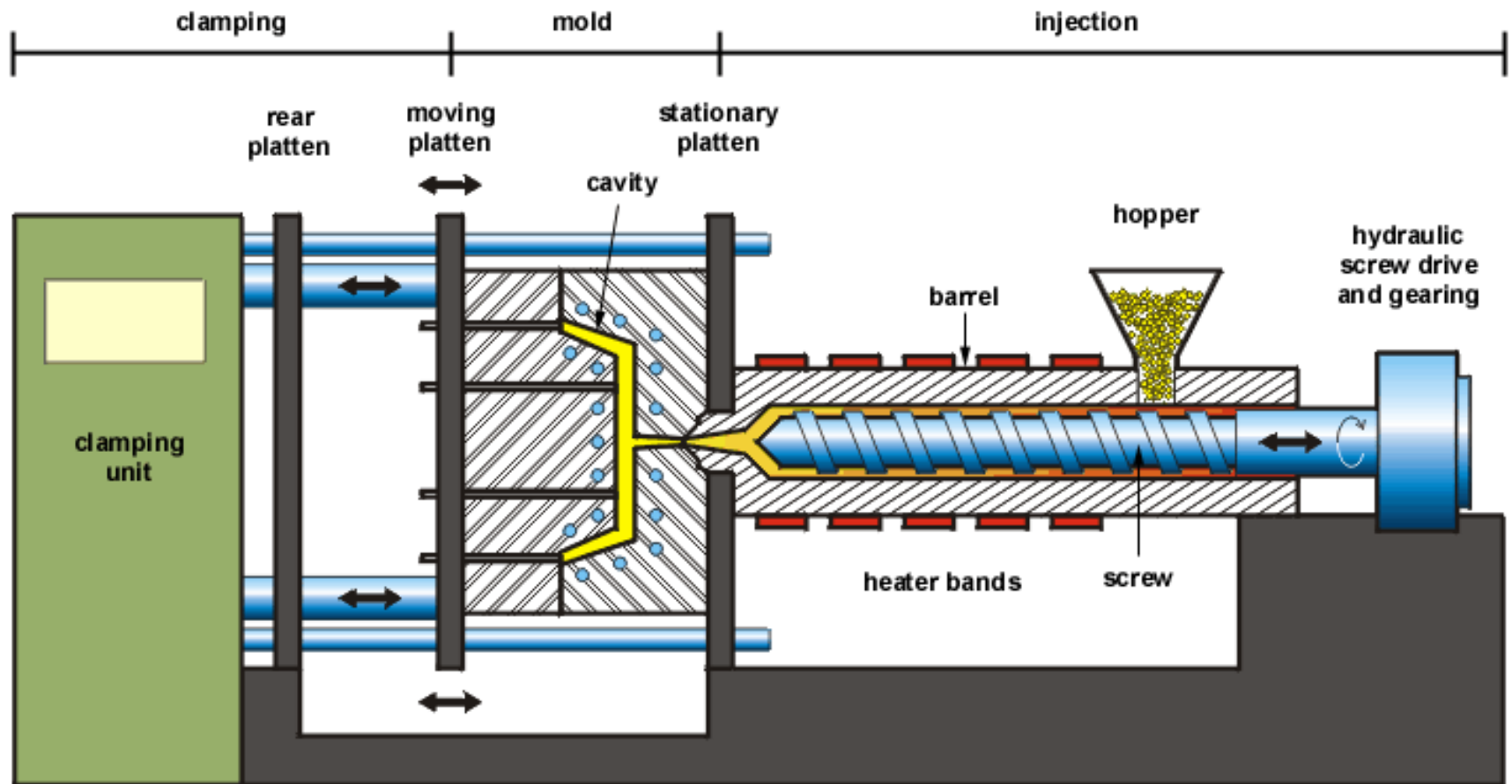
[http://www.youtube.com/watch?v=BsnzgsEXT\\_A](http://www.youtube.com/watch?v=BsnzgsEXT_A)

# Injection Molding



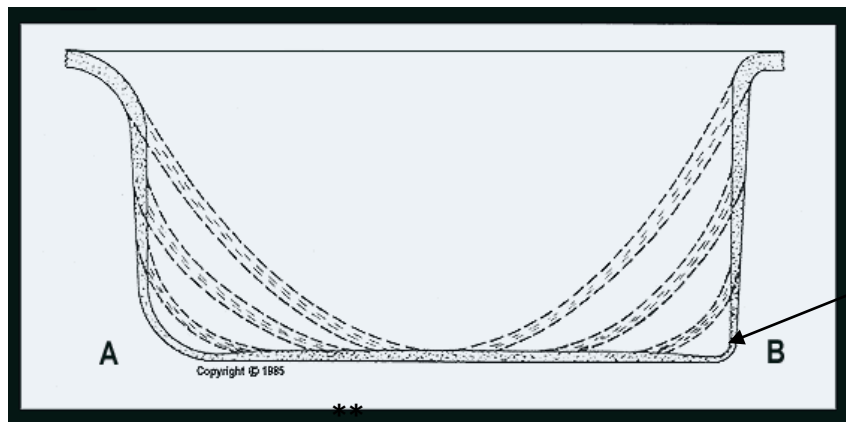
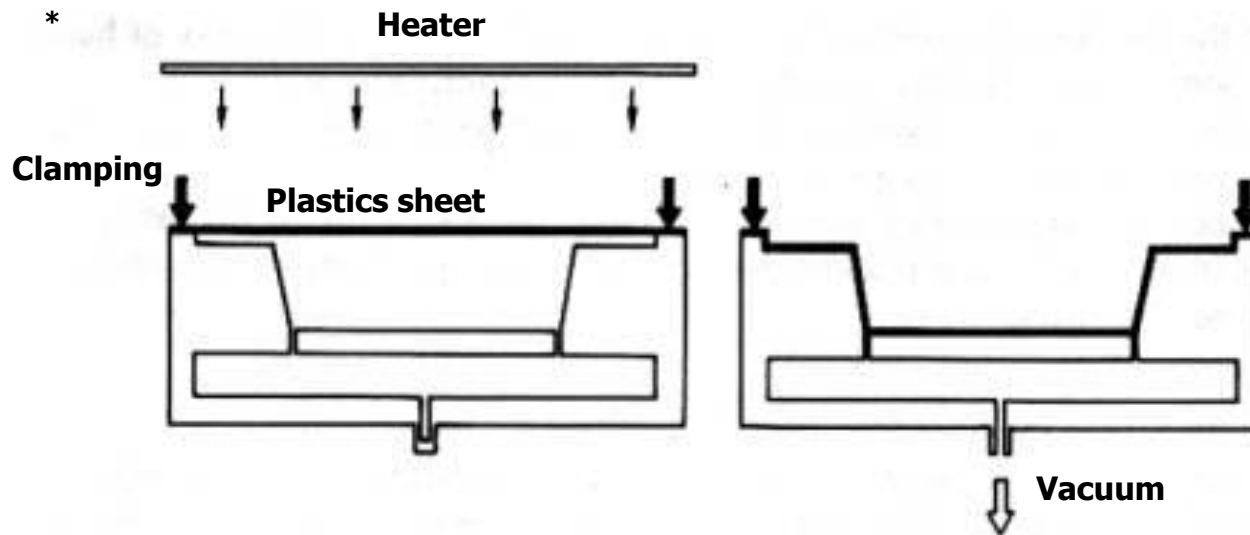


# Injection Molding



schematic of thermoplastic injection molding machine

# Thermofforming



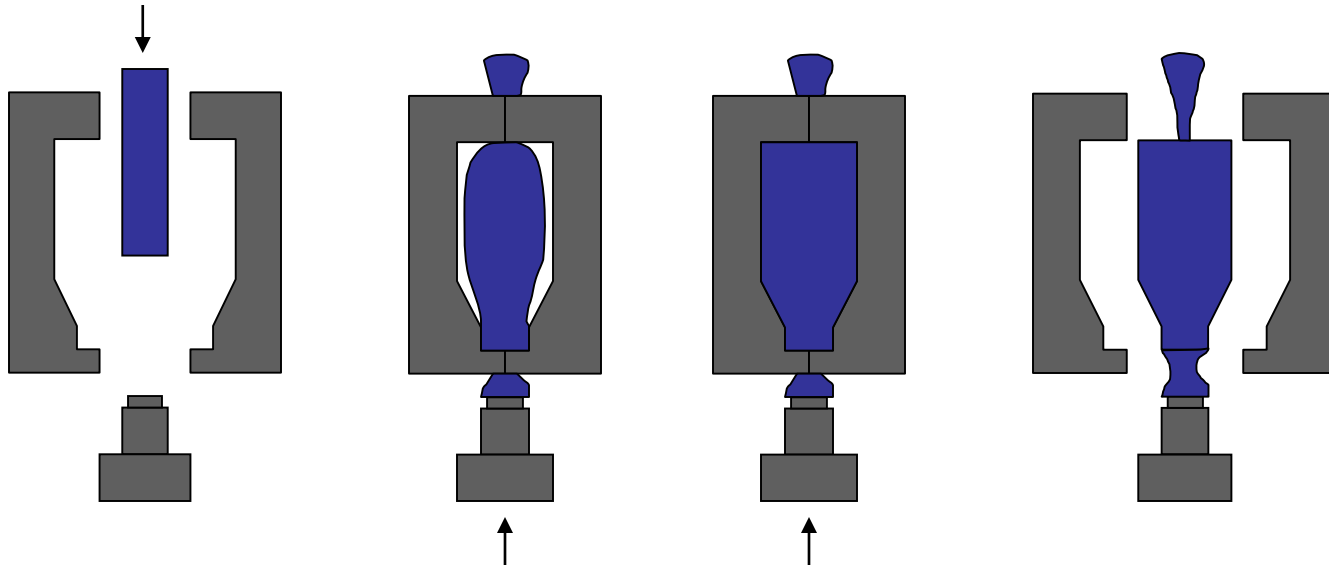
Thin corner



# Blow Molding



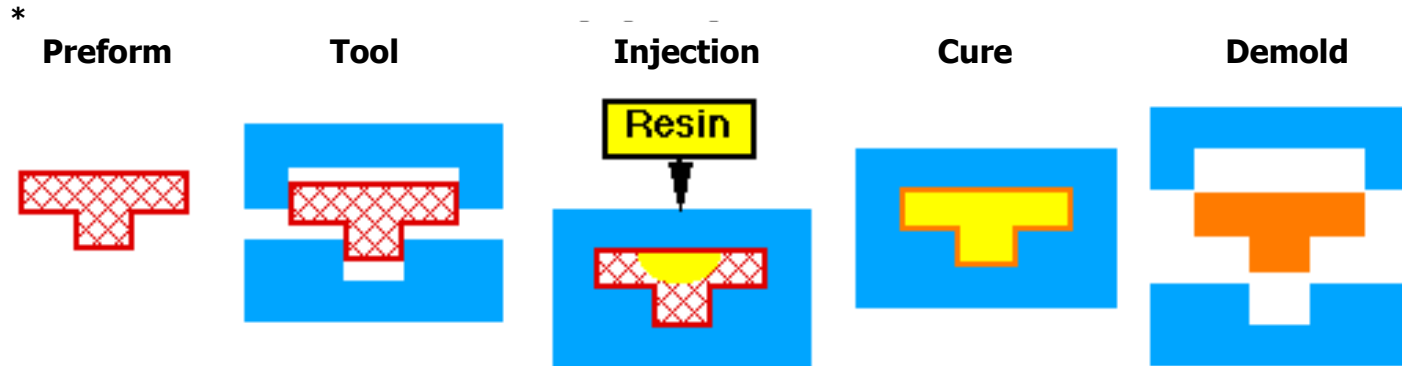
**Descending parison**



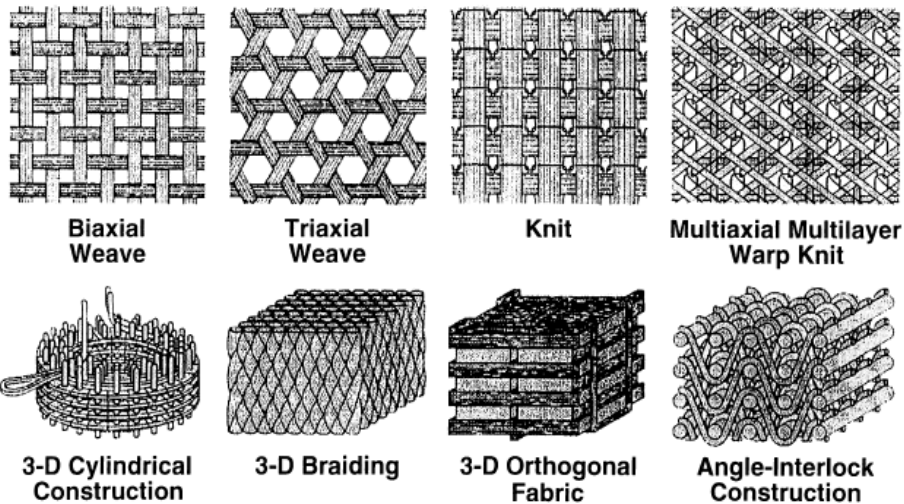
**Inflating**

**Inflating and cooling**

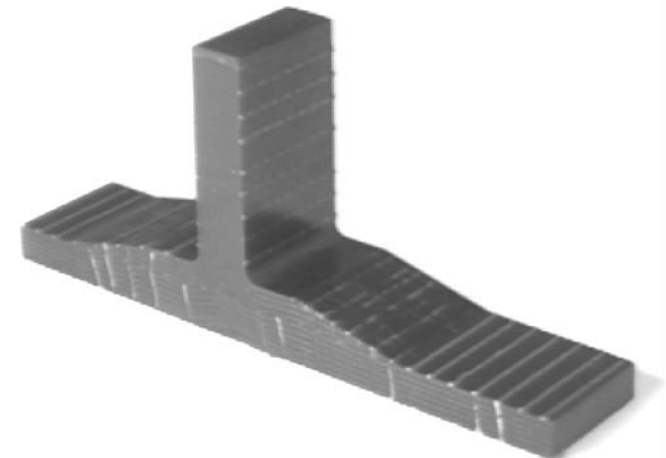
# Resin Transfer Molding (RTM)



## PREFORM ARCHITECTURES



illustrations—Scientific American



# BMW i3 RTM door frame





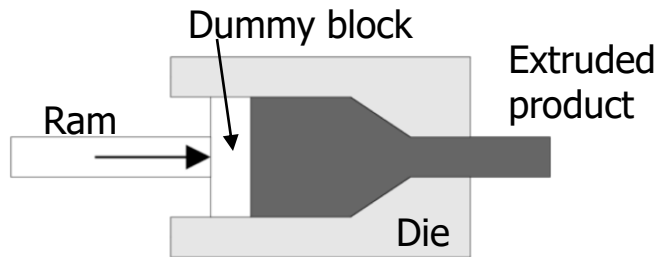
# 4. Continuous Processes

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

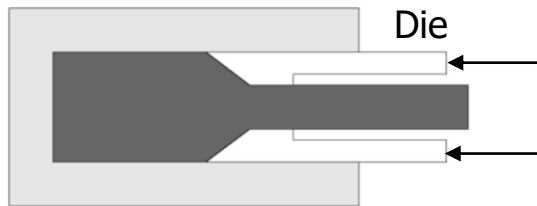
# Pros and Cons

- + 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

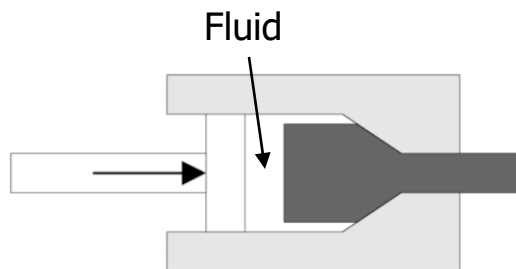
# Metal Extrusion



Direct extrusion process



Indirect extrusion process



Hydrostatic extrusion process

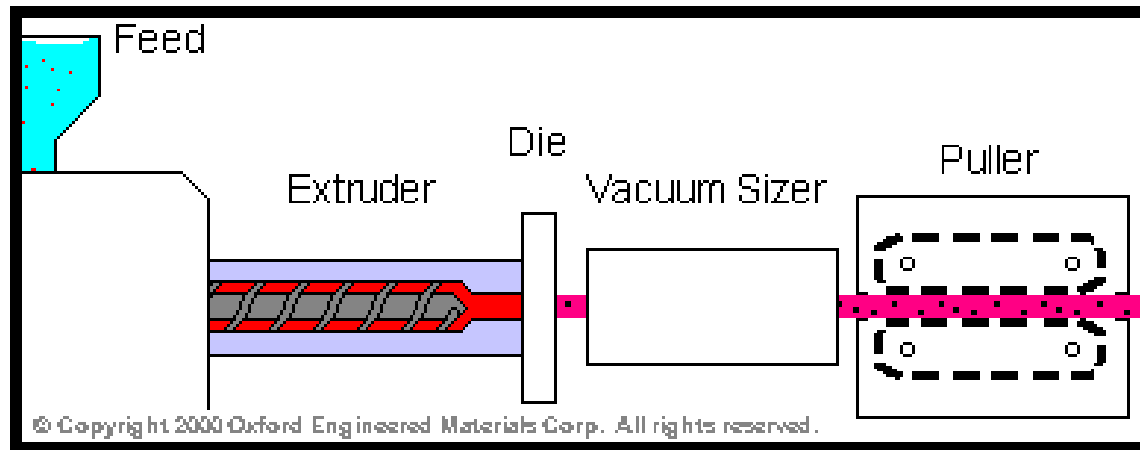


# Aluminum extrusion dies



- Kaiser Aluminum Extrusion
- <https://www.youtube.com/watch?v=s99aSFkV2aY>

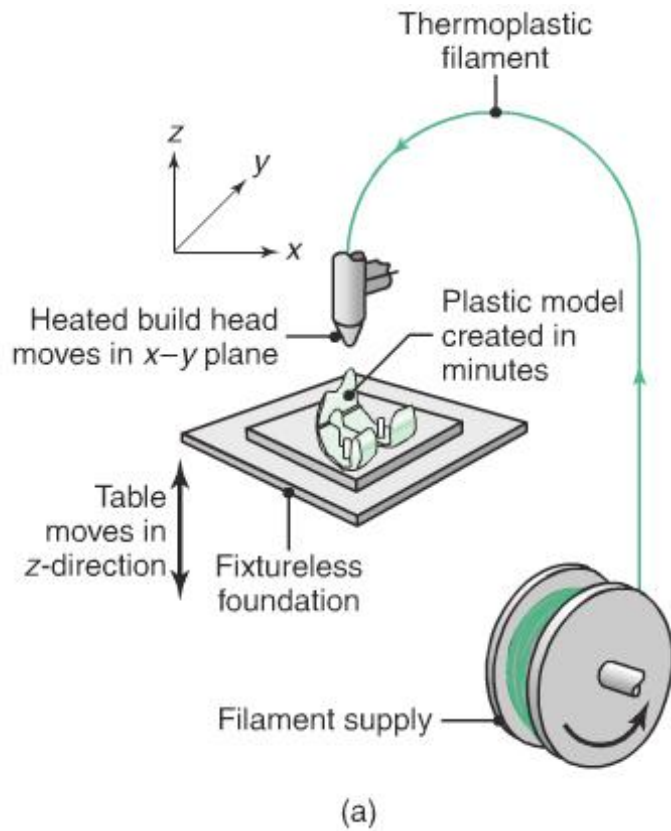
# Plastic Extrusion



**Single Screw  
Plastics Extruder**





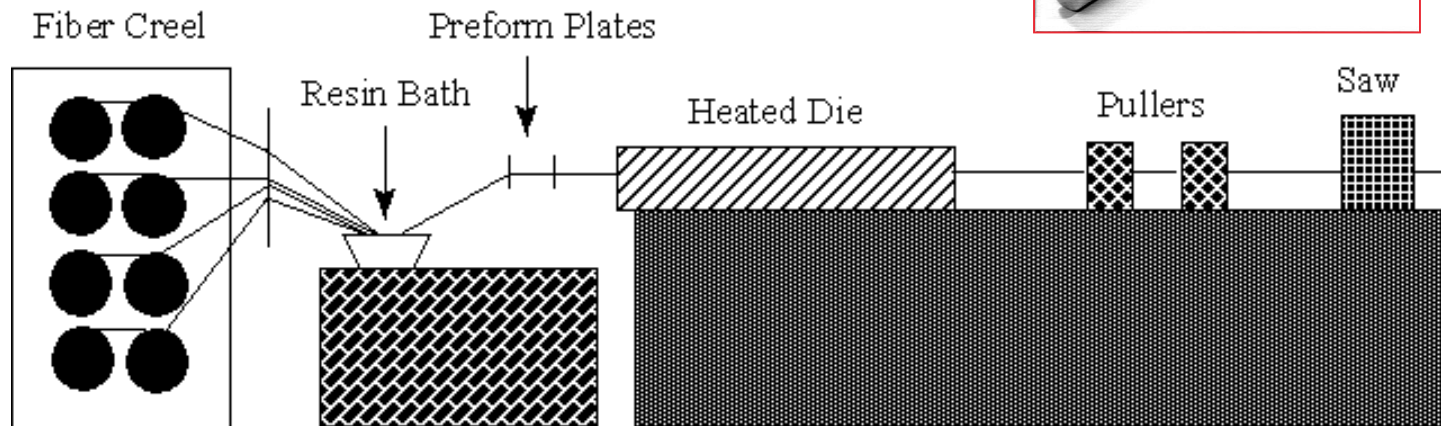
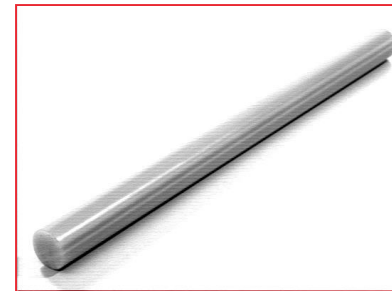


**FIGURE 20.4** (a) Schematic illustration of the fused-deposition-modeling process. (b) The FDM 900mc, a fused-deposition-modeling machine. *Source:* Courtesy of Stratasys, Inc.

## Plastic extrusion used in rapid prototyping

# Pultrusion of Composites

\*

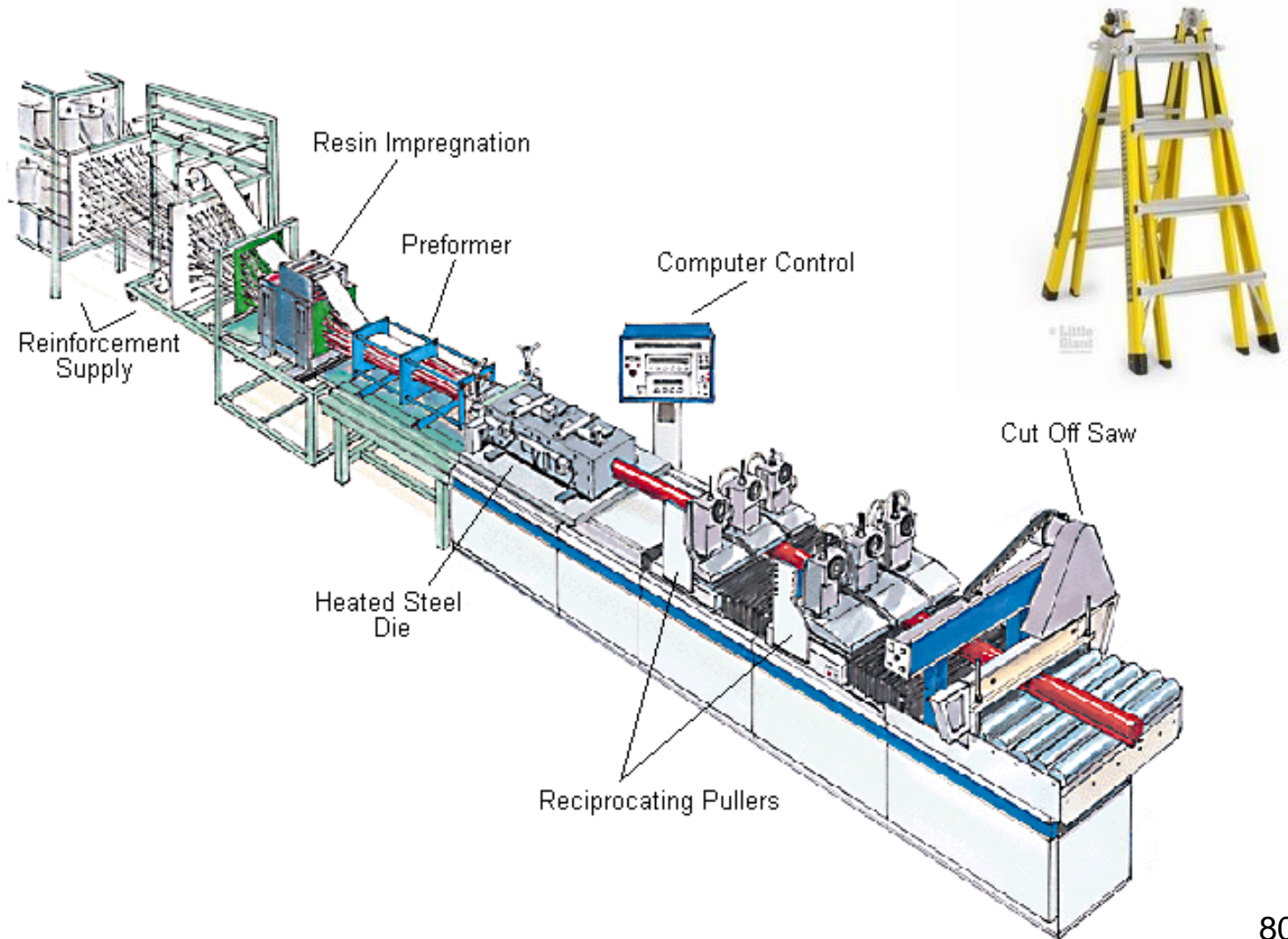


Schematic Diagram of the Pultrusion Process

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

# Pultrusion machine

\*

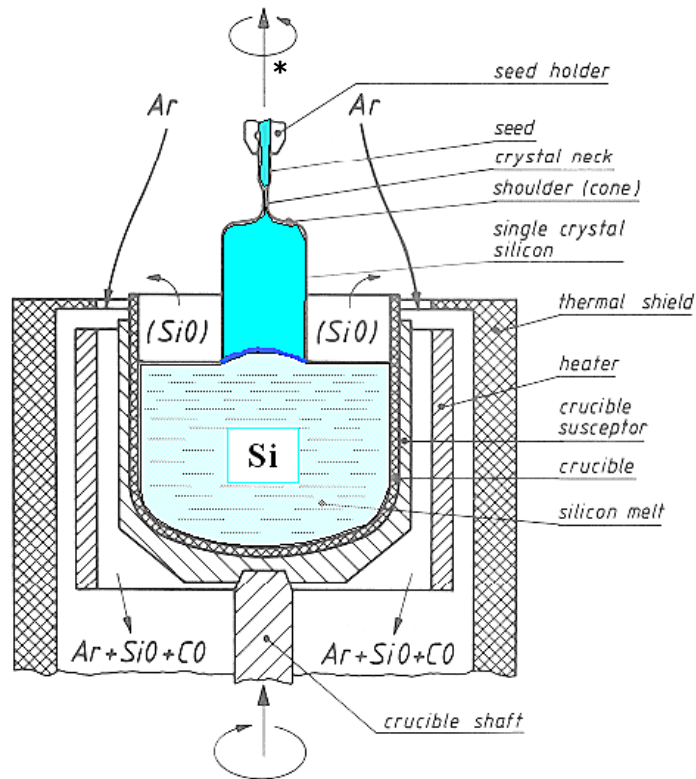


# youtube videos

- Pultrusion
- [https://www.youtube.com/watch?v=4MoHNZB5b\\_Y](https://www.youtube.com/watch?v=4MoHNZB5b_Y)
- <https://www.youtube.com/watch?v=bRjU4na-ol8>

# Czochralski(CZ) Crystal Growth

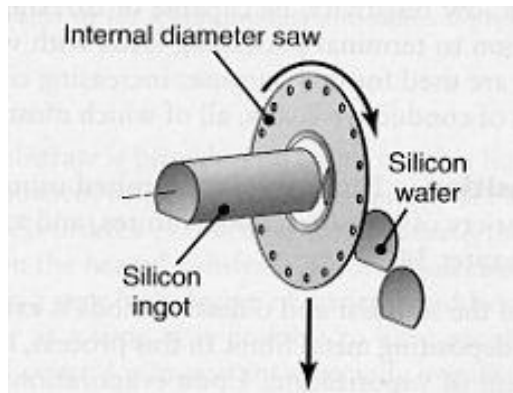
Beginning of crystal growth



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



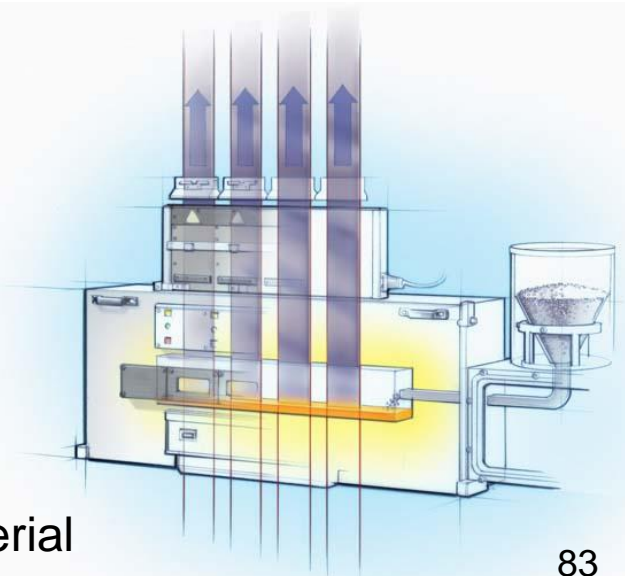
# String Ribbon Process



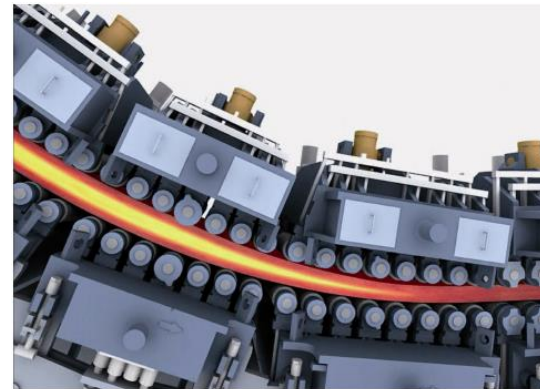
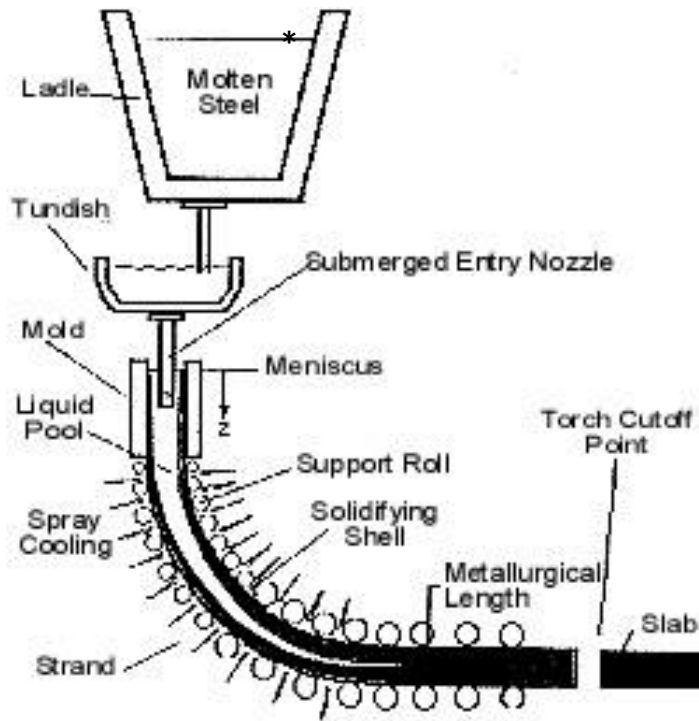
In ID and wire sawing of Si ingots, the kerf material represents lost exergy



String-Ribbon  
Invented by  
Ely Sachs  
saves this material



# Continuous Casting



# Summary

## 1. Additive & subtractive processes

- are mostly serial, potential for real time control
- very flexible in geometry
- But additive is more flexible, with higher degree of automation.
- additive also has the potential to mix materials
- Subtractive usually ensures consistent material properties

# Summary

2. Net Shape are essentially molding processes
  - Tooling requires lead time and high volumes
  - Flow can have significant effect on the material properties both improving them e.g. forging, as well as degrading them e.g brittle behavior of some castings, but mostly causing them to vary

# Summary

## 3. Continuous processes are;

- Generally limited to 2D
- Generally have poorer dimensional control in the long direction (e.g. warping, twisting) compared to other options
- But they are less costly