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

- Additive
- Subtractive (serial)
- Subtractive (Parallel)
- Net Shape
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

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

Mechanical processes

“Advanced Machining”

Semi-conductor
1. General Observations*

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

* There are exceptions, e.g. plasma cutting
Blanking and Punching

* Source: http://bdi-inc.qc.ca/processes/stamping/sp.html
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
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

Water preparation system

Pressure generation system

Cutting head and motion system

Water inlet as piston moves right

Water inlet as piston moves left

High pressure water outlet

Attenuator

**

Water outlet

Abrasive particles

Mixing chamber

***

Waterjet Machining

# Mohs Hardness Scale

<table>
<thead>
<tr>
<th>Mohs hardness</th>
<th>Mineral</th>
<th>Chemical formula</th>
<th>Absolute hardness</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Talc</td>
<td>Mg₃Si₄O₁₀(OH)₂</td>
<td>1</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td>Gypsum</td>
<td>CaSO₄·2H₂O</td>
<td>3</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td>Calcite</td>
<td>CaCO₃</td>
<td>9</td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td>Fluorite</td>
<td>CaF₂</td>
<td>21</td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td>Apatite</td>
<td>Ca₅(PO₄)₃(OH⁺,Cl⁻,F⁻)</td>
<td>48</td>
<td><img src="image5" alt="Image" /></td>
</tr>
<tr>
<td>6</td>
<td>Orthoclase Feldspar</td>
<td>KAlSi₃O₈</td>
<td>72</td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>7</td>
<td>Quartz</td>
<td>SiO₂</td>
<td>100</td>
<td><img src="image7" alt="Image" /></td>
</tr>
<tr>
<td>8</td>
<td>Topaz</td>
<td>Al₂SiO₄(OH⁺,F⁻)₂</td>
<td>200</td>
<td><img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>9</td>
<td>Corundum</td>
<td>Al₂O₃</td>
<td>400</td>
<td><img src="image9" alt="Image" /></td>
</tr>
<tr>
<td>10</td>
<td>Diamond</td>
<td>C</td>
<td>1600</td>
<td><img src="image10" alt="Image" /></td>
</tr>
</tbody>
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- **Garnet**
- **Sapphire**
### Mohs Hardness Scale

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<td>1600</td>
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</table>

- **Garnet Ring with Diamond Halo in 14k White Gold**
  - Price: $29.99

- **Cushion Garnet Ring with Diamond Halo in 14k White Gold**
  - Price: $1100.00

- **Cushion-Cut Sapphire and Diamond Halo Ring in 18k White Gold**
  - Price: $14,000
Gore Mt, New York
Waterjet Cleaning Up
EDM (Electrical Discharge 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
Agitator for top loading washer
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)

Exposing radiation

Illuminated areas

Thin film

Mask

Photoresist

Substrate

EXPOSURE

Positive resist

Negative resist

DEVELOPING

ETCHING AND STRIPPING
2. Additive Processes

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
Mechanical joints
Welding

[Sequence in the resistance spot welding process]

[Sequence in the resistance spot welding process]

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

* Source: Kalpakjian, “Manufacturing Engineering and Technology”
Brazing

Furnace brazing

http://www.youtube.com/watch?v=3UBd1HIXegM
Lay-Up of Advanced Composites
Automated tape layup

![Diagram of Automated Tape Layup and Axis of Movement](image)

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

![Graphs showing FTL - 12° tape width](image)

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

Ref Grimshaw, Grant, Luna-Diaz
More complex shapes
Lay up

Forming
Filament Winding
braiding

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 Third Industrial Revolution?

Transition from prototypes, to tooling, to parts
ADDITIVE MANUFACTURING TECHNOLOGIES

- **SLA** Stereolithography
- **DLP** Digital Light Processing
- **CDLP** Continuous Digital Light Processing
- **FDM** Fused Deposition Modeling
- **MJ** Material Jetting
- **NPJ** NanoParticle Jetting
- **DOO** Drop On Demand
- **BJ** Binder Jetting
- **MJP** Multi Jet Fusion
- **SLS** Selective Laser Sintering
- **DMLS / SLM** Direct Metal Laser Sintering / Selective Laser Melting
- **EBM** Electron Beam Melting
- **LENS** Laser Engineered Net Shaping
- **EBAM** Electron Beam Additive Manufacturing
- **LOM** Layered Object Manufacturing

Find out more at www.3dhubs.com/what-is-3d-printing
Stereolithography (SLA)

* Source: http://cybercut.berkeley.edu/mas2/html/processes/stereolith/more.html
Selective Laser Sintering (SLS)

* Source: Michelle Griffith and John S. Lamancusa, "Rapid Prototyping Technologies," Rapid Prototyping. 1998
Selective Laser Sintering (SLS)

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

* Source: DTM Corporation (3D Systems)
**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
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

* Source: [http://www.memsnet.org/mems/beginner/deposition.html](http://www.memsnet.org/mems/beginner/deposition.html)
Deposition of SiO₂ from Silane gas by PECVD

\[ \text{SiH}_4 + \text{O}_2 \rightarrow \text{SiO}_2 + 2\text{H}_2 \]

Siemens CVD Process for the Purification of Si

\[ 2 \text{HSiCl}_3 \rightarrow \text{Si} + 2\text{HCl} + \text{SiCl}_4 \]
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.memsnet.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**

GM stamping plant go to
Around 2:39

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

**Forming**

Forging

Open Die Forging

Closed Die Forging


http://www.youtube.com/watch?v=mRA6RY2o9Lg
Compression Molding

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

* Source: http://www.mahidol.ac.th/mahidol/eg/em_proj/group7/htm1text.htm
Metal Casting

Sand Casting Mold

Die Casting machine

Metal Casting

* Making was pattern assembly
  * Pattern meltout
  * Slurry coating
  * Pouring molten metal

** Investment Casting

** Shell Mold Casting

* Source: Kalpakjian, “Manufacturing Engineering and Technology”;
  ** [http://cybercut.berkeley.edu/mas2/html/processes/castshell/more.html](http://cybercut.berkeley.edu/mas2/html/processes/castshell/more.html)
P/M: Powder Compaction

* Source: http://www.turkishpm.org/en_tozmetal.htm

http://www.youtube.com/watch?v=1Mjsi2F2MrY&feature=channel
Sintering

Indicated property, compared to solid material, %

100 %

0 %

Density

Strength

Ductility

Time

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
Injection Molding

* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm
Injection Molding

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

Blow Molding

Descending parison

Inflating

Inflating and cooling

* Source: W.A.Holmes Walker, “Polymer Conversion”
Resin Transfer Molding (RTM)

* Source: [http://howard.engr.siu.edu/staff2/abrate/rtm](http://howard.engr.siu.edu/staff2/abrate/rtm)
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
Examples of extruded products

Metal Extrusion

Direct extrusion process

Indirect extrusion process

Hydrostatic extrusion process

* Source: [http://www.eaa.net/pages/material/extruded.html](http://www.eaa.net/pages/material/extruded.html)
Aluminum extrusion dies

• Kaiser Aluminum Extrusion
• https://www.youtube.com/watch?v=s99aSFkV2aY
Plastic Extrusion

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.
Pultrusion of Composites

Schematic Diagram of the Pultrusion Process

http://www.youtube.com/watch?v=4MoHNZB5b_Y

* Source: http://users.techline.com/lord/manu.html
Pultrusion machine

* Source: http://howard.engr.siu.edu/staff2/abrate/NSFATE/camps/pult.htm
youtube videos

• Pultrusion
  • https://www.youtube.com/watch?v=4MoHNZB5b_Y
  • https://www.youtube.com/watch?v=bRjU4na-ol8
Czochralski (CZ) Crystal Growth

http://www.youtube.com/watch?v=cYj_vqcyI78

* Source: http://www.techfak.uni-kiel.de/matwis/amat/elmat_en/kap_5/illustr/i5_1_1.html
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