Overview of Materials Used in Additive Manufacturing

D.L. Bourell
Temple Foundation Professor
The University of Texas at Austin

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Material Demands for AM

- Form Proper Feedstock
- Fabricator Processability
- Post-Processability as Needed
- Acceptable Service Properties
Material for Additive Manufacturing

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Material for Additive Manufacturing

- Composites
- Binders
  - Transient
  - Permanent
- Support Structures
- Graded Structures
- Multi-Materials

Materials Grand Challenge in AM

- Quality
- Process Consistency, Repeatability
- Reliability
- Wide Diversity of Compositions
- Superior Structure and Properties
- Low (Feedstock and Processing) Cost
Materials for Fused Deposition Modeling (Amorphous Thermoplastics)

- ABS [Acrylonitrile Butadiene Styrene] $7-115/lb
- Polycarbonate $113/lb
- PC/ABS Blend
- PLA [Polylactic Acid] $7-25/lb
- Polyetherimide (PEI) [Stratasys ULTEM] $220/lb
- Nylon Co-Polymer (new in 2012)

Source: 2012 Wohlers Report
Materials for Stereolithography and Material Jetting (Proprietary Thermosets, ~$100/lb)

- Acrylics
- Acrylates
- Epoxies
- “ABS-like” (Material Jetting)

Source: 2012 Wohlers Report
Materials for Laser Sintering
(Crystalline/Semi-Crystalline Thermoplastics)

- Polyamide (Nylon) 11 and 12 ~$40/lb
  Neat
  Glass Filled
  Carbon Filled
  Metal (Al) Filled
- Polystyrene (Lost Wax Patterns)
- Polypropylene
- Polyester (“Flex”)
- Polyetheretherkeytone (PEEK) ~$200/lb
- Thermoplastic Polyurethane (new in 2012)
- Nylon 6 (new in 2012)

Source: 2012 Wohlers Report
Metals for AM (BJ, DED, PBF, SL)

- Tool Steel ~$50/lb
- Stainless Steel ~$50/lb
- Aluminum Alloys ~$50/lb
- Co-Cr Alloys ~$55-250/lb
- Nickel Alloys ~$95-125/lb
- CP Titanium ~$150-400/lb
- Ti-6Al-4V ~$150-400/lb
- Gold
- Silver

**Most Popular:**
- SLM
- EBM
- BJ (ExOne)
- DED (LENS, POM, etc.)
- LOM (UAM)

Source: 2012 Wohlers Report
### AM Materials/Properties Summary

<table>
<thead>
<tr>
<th>Property</th>
<th>AM Parts Compared to Conventional Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness</td>
<td>Equal</td>
</tr>
<tr>
<td>Strength</td>
<td>As Strong or Stronger</td>
</tr>
<tr>
<td>Hardness</td>
<td>Harder or as Hard</td>
</tr>
<tr>
<td>Ductility</td>
<td>Less Ductile</td>
</tr>
<tr>
<td>Fatigue (Cyclic)</td>
<td>Weaker</td>
</tr>
<tr>
<td>Toughness</td>
<td>Less Tough</td>
</tr>
</tbody>
</table>

Post-processing to remove porosity (e.g., hot isostatic pressing) restores all properties if the interfaces are properly destroyed.
<table>
<thead>
<tr>
<th></th>
<th>Metals</th>
<th>Polymers</th>
<th>Non-Metallics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity</td>
<td>Porosity Driven (Power Law)</td>
<td>Porosity Driven (Power Law)</td>
<td>Porosity Driven</td>
</tr>
<tr>
<td>Strength/Ductility</td>
<td>Porosity Driven Isotropic (High $\Delta$)</td>
<td>Porosity Driven Anisotropic (Ductility)</td>
<td>Porosity Driven Weibull Mod.</td>
</tr>
<tr>
<td>Fatigue</td>
<td>$\sigma_e &lt; 0.5$UTS or no $\sigma_e$</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>Less or equal to bulk</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

$$\Delta = \frac{\rho}{\rho_{th}} = 1 - \varepsilon$$
Processing Effects on Porosity in SLM Processed 17-4 Stainless Steel

Power = 190 W
$V_{\text{scan}} = 1.30 \text{ m/s}$
$T_{\text{layer}} = 50 \mu \text{m}$

Power = 190 W
$V_{\text{scan}} = 0.80 \text{ m/s}$
$T_{\text{layer}} = 30 \mu \text{m}$

Examples of Porosity in EBM Ti-6Al-4V

Modulus of Elasticity

C.E. Majewski and N. Hopkinson, “Effect of section thickness and build orientation on tensile properties and material characteristics of Laser Sintered nylon-12 parts”, SFF Symposium Proceedings, Univ. Texas at Austin, 2010, pp. 422-34.
Strength

316L Stainless Steel
SLM, As Processed

66Co-28Cr-6Mo
EBM, HIP, Homogenized

**Mechanical Behavior of LS Nylon**

<table>
<thead>
<tr>
<th></th>
<th>LS</th>
<th>Bulk*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (MPa)</td>
<td>22.6</td>
<td>57.9</td>
</tr>
<tr>
<td>Tensile (MPa)</td>
<td>50.0</td>
<td>61.0</td>
</tr>
<tr>
<td>% Elongation</td>
<td>27</td>
<td>350</td>
</tr>
</tbody>
</table>

*CES Edupack Matl Selector, Version 7.0.0, Granta Ltd., 2011

D.K. Leigh, Harvest Technologies, priv. comm., 2011
Strength

\[ \sigma = K \sigma_0 (\Delta)^m \]


\[ H = 1.11(77)(\Delta)^{2.3} \]

Rockwell A Scale

Room-Temperature Tensile Strength of Pre-Mixed SLS (90Cu-10Sn) Bronze and Commercially Pure Nickel Powder as a Function of Relative Density $\Delta = 1-\varepsilon$. (a) As SLS Processed, (b) SLS Processed and Sintered at 900-1100°C for 1 to 10 hr.

Mechanical Properties of AM Parts

Ductility

\[
\frac{Ductility(\varepsilon \neq 0)}{Ductility(\varepsilon = 0)} = \frac{(1 - \varepsilon)^{3/2}}{(1 + C\varepsilon^2)^{1/2}}
\]

Ductility

$$\frac{Ductility(\text{Porous})}{Ductility(\text{Bulk})} = \frac{(1 - \epsilon)^{3/2}}{\sqrt{1 + C\epsilon^2}}$$


Reid, Fatigue of Fused Deposition Modeled (FDM) Acrylonitrile Butadiene Styrene (ABS) Stage Three individual Project MEC 3098, Newcastle University School of Mechanical and Systems Engineering 2011.
Fatigue

LENS Processed Ti-6Al-4V, Stress Relieved or HIPped

Fracture Toughness

LENS Processed Ti-6Al-4V, Stress Relieved or HIPped

S = Probability of Survival
\( \sigma = \) Applied Stress
\( \bar{\sigma}_f = \) Average Fracture Stress
\( \Gamma(x) = \) Gamma Function
\( \approx 0.6 \)
\( S_c = \) Effective Surface Area of a Component
\( S_s = \) Effective Surface Area of the Test Specimen
\( m = \) Weibull Modulus
Ceramics AM Processing
Weibull Behavior

\[ S = \exp \left[ -\left( \frac{\sigma}{\bar{\sigma}_f} \right)^m \left( \Gamma \left( \frac{1 + m}{m} \right) \right)^m \left( \frac{S_c}{S_s} \right) \right] \]

\[ \frac{1}{S} = \exp \left[ +\left( \frac{\sigma}{\bar{\sigma}_f} \right)^m \left( \Gamma \left( \frac{1 + m}{m} \right) \right)^m \left( \frac{S_c}{S_s} \right) \right] \]

\[ \text{LnLn} \left( \frac{1}{S} \right) = \text{Ln} \left[ +\left( \frac{\sigma}{\bar{\sigma}_f} \right)^m \left( \Gamma \left( \frac{1 + m}{m} \right) \right)^m \left( \frac{S_c}{S_s} \right) \right] \]

\[ \text{LnLn} \left( \frac{1}{S} \right) = m \text{Ln}(\sigma) + \left[ -m \text{Ln}(\bar{\sigma}_f) + \text{Ln}(C) \right] \]
Weibull Plot and Modulus

High Weibull Modulus

Low Weibull Modulus
Al₂O₃ powder, 0.4 μm
Freeform Extruded
Freeze-dried
Sintered at 1,550°C for 2 h
Weibull Modulus = 5

Weibull Plot, Sintered Alumina

\( \ln (\ln (1/S)) \) vs. \( \ln \sigma_F \)

S = 10%
S = 50%
S = 90%

150 MPa 300 MPa

Weibull Plot, Sintered FDM Silicon Nitride

Less than 1 micron Si$_3$N$_4$
FDM
Binder Burnout and non-disclosed HT sinter

Vintage 1 – Starting Control
Vintage 2 – After processing quality improvements to minimize large porosity

Weibull Modulus, LOM Silicon Carbide

<table>
<thead>
<tr>
<th>LOM Run #</th>
<th># specimens</th>
<th>Displacement rate (cm/min)</th>
<th>Flexure Strength (MPa)</th>
<th>σ (MPa)</th>
<th>Weibull Modulus</th>
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</thead>
<tbody>
<tr>
<td>1, 2, &amp; 3</td>
<td>10 each run</td>
<td>0.5</td>
<td>158</td>
<td>34</td>
<td>5.2</td>
</tr>
<tr>
<td>4, 5, &amp; 6</td>
<td>10 each run</td>
<td>0.5</td>
<td>152</td>
<td>25</td>
<td>5.7</td>
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<tr>
<td>1</td>
<td>23</td>
<td>0.5</td>
<td>157</td>
<td>22</td>
<td>10.4</td>
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<tr>
<td>2</td>
<td>22</td>
<td>0.5</td>
<td>151</td>
<td>22</td>
<td>8.3</td>
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<tr>
<td>3</td>
<td>24</td>
<td>0.5</td>
<td>158</td>
<td>18</td>
<td>9.0</td>
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<tr>
<td>4</td>
<td>25</td>
<td>0.05</td>
<td>142</td>
<td>23</td>
<td>6.6</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>0.05</td>
<td>142</td>
<td>20</td>
<td>8.2</td>
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<tr>
<td>6</td>
<td>8</td>
<td>0.05</td>
<td>154</td>
<td>10</td>
<td>17.5</td>
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<tr>
<td>5</td>
<td>22</td>
<td>0.005</td>
<td>152</td>
<td>21</td>
<td>8.7</td>
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<tr>
<td>6</td>
<td>21</td>
<td>0.005</td>
<td>165</td>
<td>23</td>
<td>7.6</td>
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</tbody>
</table>

Weibull Modulus
EFF Alumino-Silicate/Fused Silica

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Mixing Time (min)</th>
<th>Alumino-Silicate/Fused Silica (g)</th>
<th>Binder (mL)</th>
<th>Catalyst (mL)</th>
<th>Solid Loading (vol.%)</th>
<th>Average breaking strength (MPa)</th>
<th>Standard deviation (Mpa)</th>
<th>Weibull modulus</th>
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<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>350/0</td>
<td>130</td>
<td>7</td>
<td>49.18</td>
<td>0.370</td>
<td>0.086</td>
<td>4.49</td>
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<tr>
<td>2</td>
<td>1.5</td>
<td>325/25</td>
<td>140</td>
<td>8</td>
<td>47.24</td>
<td>0.382</td>
<td>0.052</td>
<td>7.62</td>
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<tr>
<td>3</td>
<td>1.5</td>
<td>325/50</td>
<td>150</td>
<td>9</td>
<td>47.17</td>
<td>0.533</td>
<td>0.136</td>
<td>4.03</td>
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<tr>
<td>4</td>
<td>1.5</td>
<td>325/75</td>
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<td>10</td>
<td>47.11</td>
<td>0.459</td>
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<tr>
<td>5</td>
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<td>140</td>
<td>9</td>
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<td>6</td>
<td>2</td>
<td>325/25</td>
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<tr>
<td>10</td>
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<td>325/25</td>
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<td>8.53</td>
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<tr>
<td>11</td>
<td>3</td>
<td>325/50</td>
<td>130</td>
<td>8</td>
<td>50.71</td>
<td>0.341</td>
<td>0.030</td>
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<tr>
<td>12</td>
<td>3</td>
<td>325/75</td>
<td>140</td>
<td>7</td>
<td>50.74</td>
<td>0.408</td>
<td>0.073</td>
<td>6.00</td>
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<tr>
<td>13</td>
<td>4</td>
<td>350/0</td>
<td>160</td>
<td>8</td>
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<td>0.246</td>
<td>0.031</td>
<td>8.28</td>
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<tr>
<td>14</td>
<td>4</td>
<td>325/25</td>
<td>150</td>
<td>7</td>
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<td>0.307</td>
<td>0.054</td>
<td>5.96</td>
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<tr>
<td>15</td>
<td>4</td>
<td>325/50</td>
<td>140</td>
<td>10</td>
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<td>0.354</td>
<td>0.030</td>
<td>12.55</td>
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<tr>
<td>16</td>
<td>4</td>
<td>325/75</td>
<td>130</td>
<td>9</td>
<td>52.14</td>
<td>0.511</td>
<td>0.116</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Materials Forecast

• Materials will be demanded in a quantity to justify volume production with concomitant reduction in unit cost for the user. Material cost will drop.

• Lower cost will increase usage, engendering greater demand,…

• Several “mini-suppliers” or niche product companies have appeared in the last 5-10 years and seem to be surviving.
Materials Perspectives

- Common 3DP materials are generally not patent protected

- Material cost is high for consumers, but new suppliers do not seem to be entering the marketplace

- Perhaps the price will come down as material usage volume increases due to adoption

- My impression is that there is little consumer loyalty to a specific brand of material
Summary of AM Mechanical Behavior

• Mechanical behavior is predictable based on the traditional understanding of microstructure and processing.
• Porosity and inter-layer interfaces have a strong influence on the mechanical behavior.
• Anisotropy is not generally an issue if parts are built with low porosity and good layer interface.
• As processed parts are stronger than conventionally processed material but have lower elongation and poorer dynamic properties.
• Polymers produced using best practice have isotropic strength and anisotropic ductility.
Thank you