Materials Testing and Cost Modeling for Composite Parts Through Additive Manufacturing

Eric S. Holm
Vhance V. Valencia
Alfred E. Thal, Jr.
Jason K. Freels
Adedeji B. Badiru

Additive Manufacturing Benefits

- Avoid tools, dies, and material waste associated with conventional manufacturing (Morrow et al., 2007; Serres et al., 2011)
- Produce small quantities of customized items at relatively low average unit cost (Baumers et al., 2011)
- Geometric constraints typical of formative and subtractive processes eliminated (Tuck et al., 2008; Baumers et al., 2011)
- Advanced freeform fabrication (Meteyer et al., 2014)
- Geometrically complex and novel items (Horn and Harrysson, 2012; Mani et al., 2014)
- Environmental benefits and performance improvements
  - 12:1 to 25:1 “buy-to-fly” ratio (ORNL, 2010; Huang et al., 2015)
  - Aircraft industry … $3,000 annual fuel savings per kilogram reduction in mass (Lindemann et al., 2013) and 6.4% reduction in fuel consumption (Huang et al., 2015)

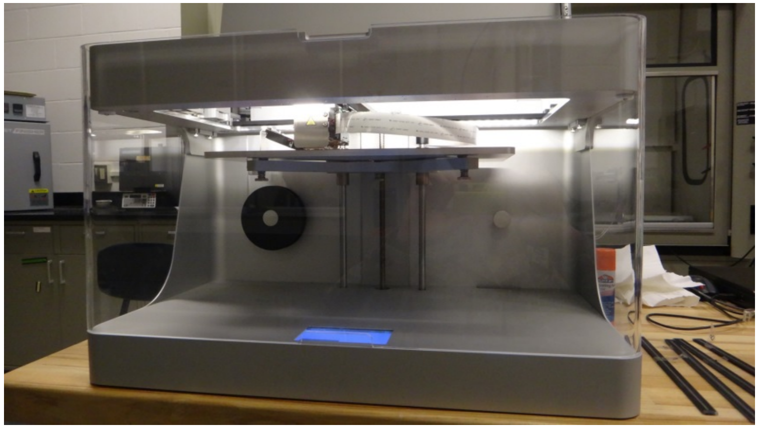
Additive Manufacturing Limitations

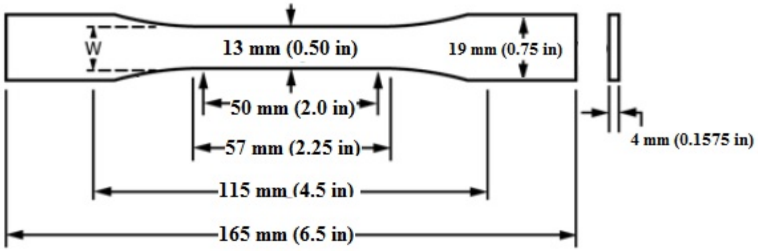
- Ruffo and Hague (2007)
  - Material selection and characteristics
  - Process productivity
  - Accuracy of product dimensions
  - Surface quality
  - Repeatability
  - Unit cost at medium and high volumes
- Huang et al., (2015)
  - Low throughput
  - Geometric repeatability
  - Residual stresses
  - Precision
  - Fatigue resistance
  - Surface quality and high surface roughness
- Schroeder et al. (2015)
  - High rejection rates (operator or machine failures)
  - Industry standard for product quality rarely achieved

Research Purpose

- Primary: address material characteristics
  - How do variations in layer height and raster angle orientation affect mechanical properties?
- Secondary: broadly review cost modeling issues
  - How is energy consumption affected by different types of additive manufacturing processes?
- Fused deposition modeling (FDM) trademarked by Stratasys
  - Fused filament modeling (FFM) and fused filament fabrication (FFF)

Mark One 3D Printer





Experimental Factors

- Layer height and raster angle

Treatment	1	2	3	4	5	6
Raster Angle Orientation	0/90	0/90	0/90	±45	±45	±45
Layer Height (mm)	0.1	0.15	0.2	0.1	0.15	0.2

- Fixed parameters
  - Nylon fill density set to 100%
  - Roof, floor, and wall layers set to one
- Mechanical properties of finished part (quality characteristics)
  - Tensile modulus (secant modulus at 0.5% strain)
  - Yield stress (0.2% strain offset)
  - Percent strain at yield
  - Ultimate tensile strength
  - Percent elongation after break

Material Testing Comparisons

	Tensile Strength at Yield (MPa)	Tensile Strength at break (MPa)	Elongation at break (%)	Elongation at Yield (%)	Tensile Modulus (GPa)
Arkema Group Rilsan® AMN D Nylon-12, Rigid, Injection Grade (Dry)	42.00	not listed	$\geq$ 50	8.0	1.45
Arkema Group Rilsan® AMIN D Nylon-12, Rigid, Injection Grade (Conditioned)	39	not listed	$\geq$ 50	10.0	1.17
ALM PA 650 Nylon-12 Selective Laser Sintering (SLS) Prototyping Polymer	Not listed	48.0	24	not listed	1.70
Polyram PlusTek PD104 Nylon-12, Injection Molding	35	not listed	300	not listed	0.70
Average Experimental Data	12.32	36.5	71	1.28	1.15
Average Experimental Data at 10% Strain	31.2	n/a	n/a	10	n/a

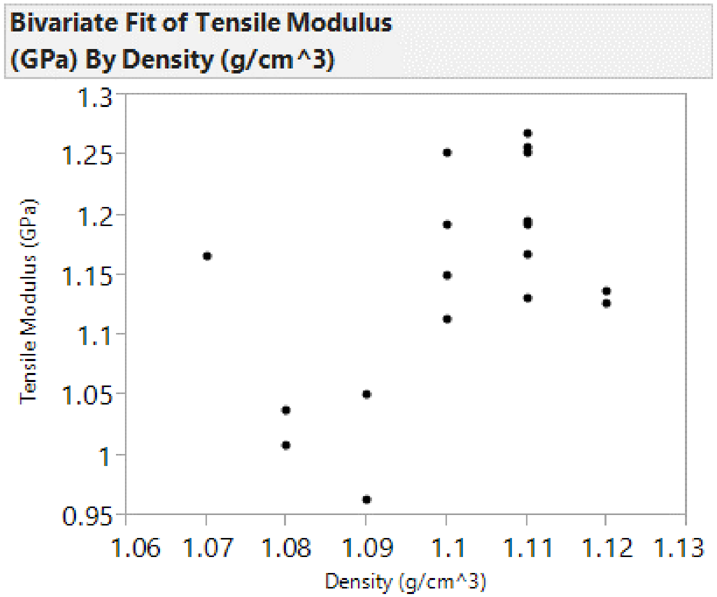
Summary of Material Testing Results

Material Property	Statistically Significant		
	Layer Height	Raster Angle Orientation	Interaction
Mean Tensile Modulus (GPa)	Yes	Yes	No
Mean Yield Stress (MPa)	No	Yes	Yes
Mean % Strain at Yield Stress	No	Yes	No
Mean Ultimate Tensile Strength (MPa)	Yes	No	No
% Elongation at break	No	Yes	No

- As layer height decreases … tensile modulus and ultimate strength increase
- ±45 angle orientation compared to 0/90 angle orientation
  - Greater tensile modulus
  - Greater percent elongation after break
  - Lower yield stress
  - Lower strain at yield

Effect of Material Density

- Material properties evaluated for range of density values … plots were similar
- Based on visual observation of plots, density classified as either low (< 1.095 g/cm^3) or high (> 1.095 g/cm^3)
- Statistically significant differences
  - Tensile modulus
  - Percent strain at yield
  - Ultimate tensile strength
  - Percent strain at break



Specific Energy Consumption (SEC)
(Yoon et al., 2014)

- For one-off items, SEC lower for additive … as number of items increase, SEC of bulk-forming and subtractive decrease significantly
- Bulk-forming cost greater than additive when three or fewer items being produced … above three, additive cost increases sharply
- Found no significant difference between plastic and metal AM processes
- Conclusion: both energy consumption and production cost are related to production quantities

Bulk-forming processes	0.11-5.82 kWh/kg for injection molding 0.62-7.78 kWh/kg for metal casting
Subtractive processes	2.3-188 J/mm^3 for milling 2.7-36.2 J/mm^3 for turning 9-65 J/mm^3 for drilling 343.4-1982.6 J/mm^3 for grinding
Additive processes	14.5-66.02 kWh/kg for Selective Laser Sintering (SLS) 23.08-346.4 kWh/kg for Fused Deposition Modeling (FDM) 14.7-163.33 kWh/kg for other processes

Cost Modeling

- Baumers et al. (2010) compared electricity consumption for selective laser melting and electron beam melting
  - Differences between maximizing capacity utilization and one-off items
  - Energy consumption affected by material selection and layer thickness
  - Proposed summary metrics … kWh/cm^3 or kWh/g
- Baumers et al. (2011) categorized energy consumption
  - Job, time, geometry, and *Z*-height
  - Time-dependent activities consumed 56-61% of energy
- Lindemann (2012) … machine time accounts for 73% of costs
- Bottom line … capacity utilization is critical to energy efficient processes (Baumers et al., 2011)
  - Energy savings ranged from 3.2% for FDM to 97.8% for LS
  - Full capacity operation uses less energy per mass of material deposited for all operating scenarios and materials they tested

Cost Modeling

- Baumers et al. (2012)
  - Energy consumption and production costs not dependent on production quantity
  - Capacity utilization is primary factor affecting process efficiency
- Developed model using speed, energy consumption, and production cost

$$C_{Build} = (C_{Indirect})(T_{Build}) + (w)(P_{Raw\ material}) + (E_{Build})(P_{Energy})$$

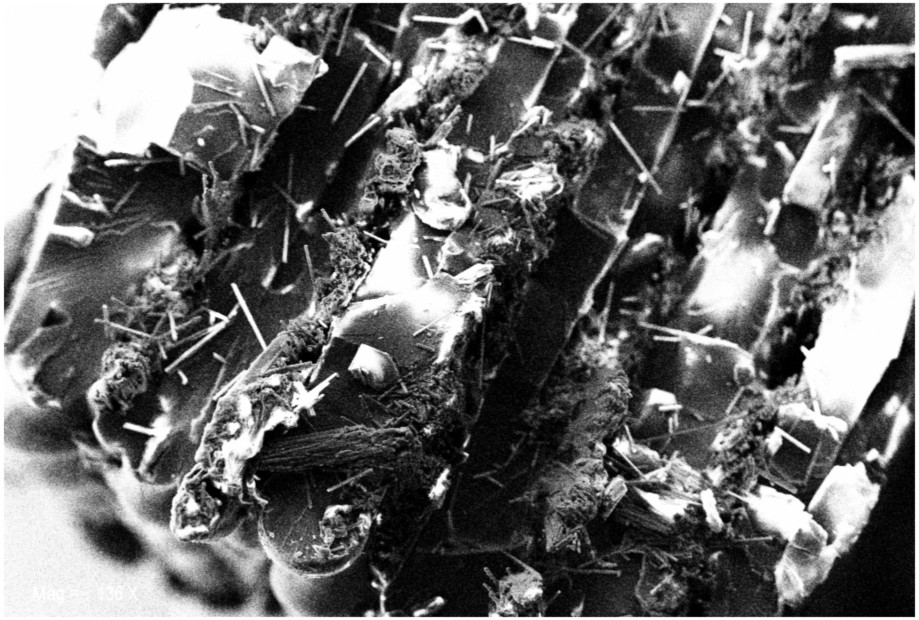
$$E_{Build} = E_{Job} + (E_{Time})(\mathrm{T}_{Build}) + (\alpha_{Energy})(l) + \sum_{z=1}^{z}\sum_{y=1}^{y}\sum_{x=1}^{x} E_{Voxel\,xyz}$$

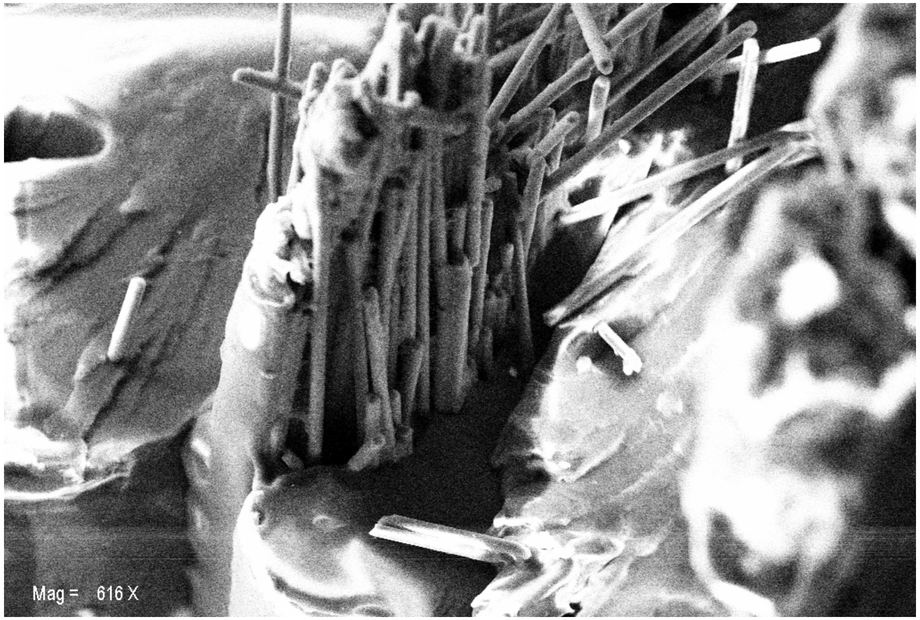
$$T_{Build} = T_{Job} + (\alpha_{Time})(l) + \sum_{z=1}^{z}\sum_{y=1}^{y}\sum_{x=1}^{x} T_{Voxel\,xyz}$$

Final Cost Thoughts

- Baumers et al. (2012) concluded that quantity and variety of items, along with utilizing available machine capacity, affect process efficiency for both energy and cost
- Lindemann et al. (2012) showed that AM more attractive for batch production that can maximize capacity utilization
- Costs and energy consumption must be allocated in an equitable manner … which means that summary metrics like kWh/cm^3 or kWh/g must be used

SEM Photographs





Questions?