Kyle G. Rowe, Robert Bedsole, Charles Hill

Breaking Tradition: Additive Manufacturing for the Advancement of the Automotive Industry
Soft, Biological Systems

High Performance Metals

Polymeric Structures

(Bhattacharjee et al. 2015)

(TCT Magazine)

(Trumpf)

(GE Passport Engine)
What is Large Scale Additive Manufacturing?

- Velocity: \( v \approx 25-300 \text{ mm/s} \)
- Mass flow rate: \( \dot{m} \approx 36 \text{ kg/hr} \)
- Nozzle temperature: \( T_{\text{nozzle}} \approx 120 \text{ °C} \)
- Extruder temperature: \( T_{\text{extruder}} \approx 500 \text{ °C} \)

![Diagram of additive manufacturing process]

- Electric motor
- Feed throat
- Heated zone
- Nozzle
- Printed part
- Heated printer bed with vertical translation

![Cross section of double wall thickness]

- 15 mm

![Time-lapse of layer deposition]

- Layer 60
- Layer 120
- Layer 224
Why Large Scale Additive Manufacturing?

- complex part geometries
- dynamic and flexible designs
- minimal infrastructure cost
- recyclable
- energy efficient

Big area additive manufacturing (BAAM) is one of the most energy efficient manufacturing processes.

The projected amount of money that will be spent on automotive tooling will reach $15.2 billion dollars by 2018, an increase of 64%.

Energy required to produce a car: \(~ 34,000\) MJ
Amount of CO\(_2\) to produce a car: \(~ 2,000\) kg

\(~ 21,000\) MJ (38% reduction)
\(~ 960\) kg (52% reduction)
Challenges and Limitations

Effects of Fiber Reinforcement

delamination during printing due to thermal stresses

Current understanding of fused deposition modeling (FDM) material properties is limited and the large format FDM process remains, relatively, unexplored.
Materials and Mechanical Properties

Material Property Data
- tension, shear, and bending
- fatigue and dynamic properties
- creep
- U.V. and chemical resistance
- residual stresses

B-basis design allowables

Typical Mechanical Test Specimen
Modified ASTM D-638 Specimen

ALL DIMENSIONS IN MILLIMETERS

Cyclic Fatigue
5 Hz stress cycle rate
Tension - tension loading

R = \frac{\sigma_{min}}{\sigma_{max}} = 0.1
Mechanical Properties of Large Scale Additive Manufactured Parts: ABS/20 wt.% Carbon Fiber
Fatigue Properties of Large Scale Additive Manufactured Parts: ABS/20 wt.% Carbon Fiber

**Fatigue Testing**

- **Testing Conditions**
  - Load control
  - 5 Hz
  - tension - tension, \( R = 0.1 \)
  - laboratory conditions

**Specific Performance**

- pronounced whitening at edges in areas of fatigue crack nucleation and growth

- **X - direction**
  - failed in grip
  - did not fail

- **Y - direction**
  - 2024-T6 Al
  - Nylon 6.6/33% GF
  - 1045 Steel
  - CF/ABS - X
  - CF/ABS - Y
  - CF/ABS - Z
  - failed in grip
  - did not fail

- **Z - direction**

---

**Graphs**

- Graph A: Maximum stress vs. cycles
- Graph B: Maximum specific stress vs. cycles for various materials
Fiber Alignment and Distribution in Printed Bead

Optical microscope image of fractured bead edge

μ-CT scan of printed interface

Blue = fibers, red = pores, green = matrix

μ-CT scans show a high degree of fiber alignment near the perimeter of the bead.

Pores or voids are highly prevalent near the interior of the printed bead but very sparse near the interface.
Materials and Mechanical Properties

Form

light transmission

color matching/ surface finish

Function

printed sandwich composite

structural nylon composites

Ultimate-stress (psi)

Reinforced Nylons

Other Reinforced Polymers/ Blends/ Alloys

Reinforced ABS

Z-Direction
DDM Reinforcement Techniques and Opportunities

DDM structures provide an ideal platform for incorporating traditional composites for improved structural reinforcement.

Simple Printed Structure for Multi-Material Composites

- foam filled
- double wall thickness
- printed infill
- inserted reinforcement
- carbon fiber reinforcement
Multi-material component testing using additive manufacturing as a core:

- Combination shear, torsion, and bending for the mechanical testing of multi-material, structural, sub-elements
- Provides real-world performance data for element level designs
- Hydraulic actuation, electronic data acquisition, capable of forces \( \sim 445 \text{ kN} = 100,000 \text{ lbf} \).
3D Digital Image Correlation of Composite Structures – 4 Point Bend

change in z-direction displacement, \( w \)

1st principal strain

force-displacement
Lighter Weight Structures Using DDM and Multi-Material Composites

Specific Stiffness

- lighter, stiffer structures (better for design)
- no fill (SW)
- CF overwrap
- 32 kg/m³ foam (SW)
- 2 ply, 2x2 twill fabric, 3K, ASA Carbon Fiber

 torsional stiffness, $K_t \sim \frac{T}{\phi} = \frac{JG}{L} = \text{slope of curve}

- $T$ - torque (Nm)
- $\phi$ - rotation (radians)
- $J$ - geometry factor (m$^4$)
- $G$ - shear modulus (Pa)
- $L$ - sample length (m)

Estimated Weight Savings

- original strati = ~977 lbs.
- strati using multi-materials approach = ~508 lbs.

48% weight reduction

Further Improvement
- carbon fiber reinforced additive parts

Z-Direction Specimen

CF/ABS

3-Point Bend Test Data

max stress in CF overwrap

machined, Z-direction CF/ABS

- 9.6 MPa

max stress in CF/ABS core

The PMMA, thermoplastic, infusion resin can be recycled along with the carbon fiber over-wrap and the DDM material base
Optimizing Performance with Polymer Composites

**Tensile Stresses in Face Sheets**

![Graph showing tensile stresses in face sheets](image)

**Tensile Stresses in Printed ABS Core**

![Graph showing tensile stresses in printed ABS core](image)

**Stress Distribution and Discontinuity**

![Diagram showing stress distribution and discontinuity](image)
Research Meets Application
· Additive manufacturing offers greatly decreased design to manufacturing times
· Reduces energy consumption and carbon emissions
· Materials and process developments will soon enable mechanical performance comparable to common metallic alloys
· Provides a core for other advanced composite materials to form optimized structures
· May be used to make reusable and recyclable tooling for low volume part production
· Material properties and process improvements are necessary to bring large format additive manufacturing into the commercial manufacturing sector