Tribology of Polymer Matrix Composites (PMCs) Fabricated by Additive Manufacturing (AM)

S. Gupta¹, R. Dunnigan¹, A. Salem², L. Kuentz³, M. C. Halbig⁴, and M. Singh⁵

¹Department of Mechanical Engineering
University of North Dakota, Grand Forks, ND 58201
²Hawken School, Gates Mills OH 44040
³Lake Ridge Academy, North Ridgeville, OH 44039
⁴NASA Glenn Research Center, Cleveland, OH 44135
⁵Ohio Aerospace Institute, Cleveland, OH 44142
Brief Overview of Collaborative Research

Advanced Materials Processing

**Novel Processes**

**Fundamentals**

Engineer Novel Microstructures

Properties and Applications

**Aerospace**

**Automobile**

**Electronics**

**Biomaterials**

**High Temperature**

**Environment**

Fundamental and applied research

Study of Surfaces and Interfaces

Adaptive Coatings  Oxide Whiskers  In Globles on Zr_2InC

A nascent area for fundamental research
University of North Dakota

Grand Forks, North Dakota, United States

Map of the United States showing North Dakota and Grand Forks.

Flowers and landscape images related to North Dakota.
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9TH INTERNATIONAL CONFERENCE ON HIGH TEMPERATURE CERAMIC MATRIX COMPOSITES – HTCMC 9

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JUNE 26 – 30, 2016
Outline

• Background and Introduction
  - Additive Manufacturing Technologies

• Objectives

• Materials and Procedures

• Results and Discussion
  - Starting Materials
  - Printing Parameters
  - Reinforcements
  - Tribological Behavior

• Summary and Conclusions

• Future Work
Additive Manufacturing/3-D Printing (Schematic)

Successive layers of material are formed under computer control to create an object.
3D Printers used for Research

- Afinia H480 3D Printer
- Flashforge Creator Pro 3D Printer
- Form 1+ 3D Printer
Filabot Extruder

• Uses pellets/powders to create filament for FDM 3D printing
• Materials extruded include PLA, MDPE, and HIP

<table>
<thead>
<tr>
<th>Material</th>
<th>Extrusion Temperature</th>
<th>Temperature</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLA</td>
<td>175</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>MDPE</td>
<td>105</td>
<td>115</td>
<td>N/A</td>
</tr>
<tr>
<td>HIP</td>
<td>200</td>
<td>230</td>
<td>266</td>
</tr>
</tbody>
</table>
Fused Deposition Modeling (FDM) Based Additive Manufacturing/3-D Printing

Industrial scale FDM systems (Stratasys)

Process Schematic

MakerBot Replicator 2X

Orion Delta 3D Printer

“RepRap is humanity’s first general-purpose self-replicating manufacturing machine”. www.reprap.org
Objective

To Compare the tribological properties of composite ABS and PLA materials to the pure ABS and PLA:

- Microstructure-Properties-Performance
- Tribological Performance
- Wear Rates
- Friction Coefficients
- Effect of Print Layer Heights
ABS and PLA

ABS (Acrylonitrile Butadiene Styrene)

- **PLA Benefits:**
  - Environmentally friendly
  - Does not release toxic fumes/safe for people

- **ABS Benefits**
  - Have impact resistance and toughness
  - Resistant to aqueous acids, alkalis etc.

Polylactic Acid (PLA)
Following Materials were Studied

- Color Fab, bronze fill metal, PLA
- GMASS, Tungsten, ABS
- Proto Pasta, Magnetic iron, PLA
- 3DXTech, premium red, ABS
- 3DXNano ESD (CNT) black, ABS
- Color Fab, copper fill metal, PLA
- GMASS, Bismuth, ABS
- Proto Pasta, Stainless Steel, PLA
- 3DXTech, black, ABS
- Carbon Fiber 5 wt%, ABS
Types of Composites

- Particle-reinforced
  - Large-particle
  - Dispersion-strengthened

- Fiber-reinforced
  - Continuous (aligned)
  - Discontinuous (short)

- Structural
  - Laminates
  - Sandwich panels

- Aligned
- Randomly oriented
Background

COMPOSITE SURVEY: Particle

- Particle-reinforced
  - Fiber-reinforced
  - Structural

Examples:
- Spherodite steel
  - Matrix: ferrite (\(\alpha\)) (ductile)
  - Particles: cementite (Fe₃C) (brittle)
  - Mean particle size: 60 \(\mu\)m
- WC/Co cemented carbide
  - Matrix: cobalt (ductile)
  - Particles: WC (brittle, hard)
  - Mean particle size: 500 \(\mu\)m
- Automobile tires
  - Matrix: rubber (compliant)
  - Particles: C (stiffer)
  - Mean particle size: 0.75 \(\mu\)m

![Composite materials diagram](image)

**Modulus of elasticity (GPa)**

\[ E_c(u) = E_m V_m + E_p V_p \]
3-D Printing of Multi-Functional Materials

Color Fab, copper fill metal, PLA
Proto Pasta, Magnetic iron, PLA
GMASS, Tungsten, ABS
GMASS, Bismuth, ABS

Highest strength and modulus in CNT reinforced coupons
Pure ABS Coupons – less porosity for lower print heights
Measurement of Friction Coefficient (μ) and Wear Rate (WR)

- Tab on disc method
- Sample shape: 4 mm x 4 mm x (1.5-1.7) mm (MAX phases)
- Dynamic partner: Alumina
- Load: 5 N
- Rotation speed: 31 cm/s
- Temperature: RT Tested in ambient air

CSM TRIBOMETER
PLA and PLA Composites
Mechanical Behavior of PLA and PLA Composites

PLA shows the greatest strength:

- PLA
- Stainless (18%)
- Magnetic Iron (11%)
- Copper and Brass (36%)
Mechanical Behavior of PLA and PLA Composites

• Metal filled PLA show an effect of layer height:

• Lower strength and strain to failure.
Friction Coefficient of PLA and PLA Composite Materials

![Friction Coefficient Graph]

- PLA 0.3 mm
- PLA 0.1 mm
- Cu 0.1 mm
- Cu 0.3 mm
- Bronze 0.1 mm
- Bronze 0.3 mm

I  II (Steady State)
Variation of Wear Rate vs Print Layer Height in PLA and PLA Composites

![Graph showing wear rate vs layer thickness for PLA and composite materials](image)
Variation of Friction Coefficient vs Print Layer Height in PLA and PLA Composites
ABS and ABS Composites
Variation of Friction Coefficient in ABS and ABS Composite Materials

![Graph showing the variation of friction coefficient with distance for different materials.](image)
Variation of Wear Rate vs Print Layer Height in ABS and ABS Composite Materials
Variation of Friction Coefficient vs Print Layer Height in ABS and ABS Composites
Wear Track Analysis

Alumina-ABS Tribocouple

Alumina-PLA Tribocouple

The Wear is Driven by the Formation of Tribofilms
Wear Track Analysis

Alumina-ABS-Bi Tribocouple

The Wear is Driven by the Formation of Tribofilms
Summary and Conclusions

• This study shows that the tribological behavior of PLA and ABS are dependent on layer thickness and particulate additives.
• PLA showed the lowest WR and µ as compared to the composites when the layer thickness was 0.1 mm.
• As the layer thickness was gradually increased, the WR of the composites decreased as compared to PLA samples, and µ remained similar for all the samples.
• Similarly, ABS also showed the lowest WR and µ as compared to the composites when the layer thickness was 0.1 mm.
• As the layer thickness was gradually increased, the WR of the composites were similar to ABS samples, and µ of ABS and ABS-Bi became similar.
• Interestingly, CNT-ABS showed higher µ as compared to the ABS and Bi-ABS composites.
• Preliminary studies showed that the wear mechanisms are driven by the formation of tribofilms. More fundamental studies are needed to understand the intricate mechanism for the formation of tribofilms.
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