Additive Manufacturing: From Rapid Prototyping to Flight

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About Me

B.S. Physics from Eastern Kentucky University
M.S., Ph.D. Mechanical Engineering from Vanderbilt

Previously worked as a materials engineer at United Launch Alliance (ULA)

currently an aerospace engineer in the Materials and Processes Laboratory at NASA Marshall Spaceflight Center
Then.....
NASA Field Centers

- Ames Research Center, Moffett Field, CA
- Dryden Flight Research Center, Edwards, CA
- Glenn Research Center, Cleveland, OH
- Jet Propulsion Laboratory, Pasadena, CA
- Goddard Space Flight Center, Greenbelt, MD
- NASA Headquarters, Washington, DC
- Langley Research Center, Hampton, VA
- Johnson Space Center, Houston, TX
- NASA Shared Services Center, SSC, MS
- Stennis Space Center, SSC, MS
- Marshall Space Flight Center, MSFC, AL
- Kennedy Space Center, KSC, FL
NASA’s Four Core Mission Areas

Science

Space Technology

Human Exploration and Operations

Aeronautics
Current Human Spaceflight Architecture

Commercial support for ISS in low-Earth orbit

SLS for reaching new destinations beyond low-Earth orbit
Space Launch System (SLS)

- Initial lift capacity of 70 MT, evolvable to 130 MT
- Carries the Orion Multipurpose Crew Vehicle (MPCV)
- First flight of SLS in 2018
What is Additive Manufacturing?

- ASTM F42 defines AM as “the process of joining materials to make objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies”

- AM machine software slices a CAD model file into layers

- Base material can be metallic, plastic, ceramic, composite, or biological

- 2.2 billion dollar industry and U.S. is the world leader in industrial AM systems

- AM encompasses a broad range of processes

- Distinguished by techniques used to deposit layers and the way in which the deposited layers are bonded together
What is Additive Manufacturing?

Additive Manufacturing

- Sheet Lamination
- Directed Energy Deposition
- Laser Engineered Net Shaping (LENS)
- Multi-jet Modeling (MJM)
- Material Jetting
- Stereolithography
- Selective Laser Melting (SLM)
- Powder Bed Fusion
- Electron Beam Melting (EBM)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Binder Jetting
- Material Extrusion
- Fused Deposition Modeling (FDM)
Why Additive Manufacturing?

- Aerospace components have complex geometries and are made from advanced materials

- Components are difficult, costly, and time-consuming to manufacture using conventional processes

- Aerospace hardware represents small batch, low-rate production
Why Additive Manufacturing?

**Affordability**
- reduced part count
- fewer critical welds and brazes
- reduced tooling
- schedule and cost savings

**Performance**
- optimized internal flow passages
- minimized leak paths
- lower mass

Design for Manufacturing Manufacturing for Design
History of Additive Manufacturing at NASA MSFC

-NASA MSFC has 20+ years of experience with AM technologies

-initial focus in early 1990s on rapid prototyping

-National Center for Manufacturing Sciences (NCMS)

-first metallic system: laser engineered net shape parts

-currently focused on Electron Beam Melting (EBM) and Powder Bed Fusion (PBF) technology for production of propulsion hardware

-also focused on using AM to build parts in-space
Additive Manufacturing at MSFC

For space

Short term

In space

Long term
The 3D Print project will deliver the first 3D printer on the ISS and will investigate the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.

Melt deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

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<th>3D Print Specifications</th>
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<tr>
<td>Print Volume</td>
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<tr>
<td>Mass</td>
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<td>Est. Accuracy</td>
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<tr>
<td>Software</td>
</tr>
<tr>
<td>Traverse</td>
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<td>Feedstock</td>
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A Vision of In-Space Manufacturing

- In-space fabrication and repair of plastics using 3D printing
- Qualification/inspection of on-orbit parts using structured light scanning
- Printable small satellite technologies
- On-orbit plastic feedstock recycling
- In-space metals manufacturing process demonstration
- Welding in space
- Additive construction using regolith
Additive Manufacturing at MSFC

For space

Short term

Long term

In space
Additive Manufacturing at MSFC

- Primary focus on for-space AM is powder bed fusion processes
- Electron beam melting (EBM) machine for Titanium
- Concept Laser M1 and M2 for Selective Laser Melting (SLM) of Inconel 718 and Inconel 625 in addition to Copper alloys
- Addition of Xline expands build volume by a factor of 6
Selective Laser Melting (SLM) Process Flow

1. 3D CAD model of part sliced into layers
2. Laser scan path is calculated which defines the boundary contour and the fill sequence
3. Powder is fed uniformly onto build plate by a wiper
4. Laser melts the deposited powder layer
5. Melted particles fuse and solidify to form a layer of the component
6. Build table is lowered and additional powder is fed onto plate
7. After part is complete, it undergoes stress relief and EDM is used to separate it from the build plate
8. Part may be subject to additional post-processing (Hot Isostatic Press and/or heat treatment)
**Selective Laser Melting (SLM)**

**SLM process development for AM propulsion hardware is a manufacturing optimization problem.** Build parameters must be optimized to ensure production of a material that will be able to perform in its intended use environment.

<table>
<thead>
<tr>
<th>Controlled Process Variables</th>
<th>Material properties</th>
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<td>Powder characteristics</td>
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<td>Laser scan speed</td>
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<tr>
<td>Post-build material conditioning</td>
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| Yield strength                                |                                        |
| Ultimate strength                             |                                        |
| Elongation                                    |                                        |
| Reduction in area                             |                                        |
| Plastic strain                                |                                        |
| Modulus                                       |                                        |
| Density                                       |                                        |
| Fracture toughness                            |                                        |
Recent AM Builds at MSFC

- F1 engine reconstruction
- In718 1200 lb thrust injector
- Two In718 main combustion chambers
- In625 nozzle for Morpheus project
- 100 lb injector and fin set for NanoLaunch
- Multiple turbomachinery parts
NASA MSFC’s role in the broader aerospace additive manufacturing community is three-fold:

1) Smart buyer
2) Tech transfer
3) Anomaly resolution
Challenges in Additive Manufacturing

Materials Characterization

Process Modeling, Monitoring, and Control

Standard Design Practices

Flight Certification
Development of an AM database will provide a single source data repository that can be used to:

- Characterize materials
- Explore relationships between process variables and material properties
- Disseminate validated materials property data to the modeling, simulation, and design community
- Aid in the development of materials standards and protocols
Certification: the affirmation by the program, project, or other reviewing authority that the verification and validation process is complete and has adequately assured the design and as-built hardware meet the established requirements to safely and reliably complete the intended mission.
Additive Manufacturing: The Path to Flight

- **Develop** part classification approach based on consequences of failure

- **Understand** process failure modes

- **Characterize** process variability

- **Verify** individual build lot quality (lot acceptance testing)

- **Develop** guidelines and specifications for AM materials, processes, and design
  
  - **Provide** recommendations to vendors on allowable practices and certification limits

- **Incorporate** AM materials and processes into existing NASA standards
Summary

- Additive manufacturing (AM) offers tremendous promise for the rocket propulsion community.
- Foundational work must be performed to ensure the safe performance of AM parts.
- Government, industry, and academia must collaborate in the characterization, design, modeling, and process control to accelerate the certification of AM parts for human-rated flight.
Questions

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