Metal Additive Manufacturing for Spaceflight

Paul Gradl
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The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%

- Complexity is inherent in liquid rocket engines and AM provides new designs, part consolidation, and performance opportunities.

- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.
A rocket combustion chamber case study for AM

As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered.

<table>
<thead>
<tr>
<th>Category</th>
<th>Traditional Manufacturing</th>
<th>Initial AM Development</th>
<th>Evolving AM Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and Manufacturing Approach</td>
<td>Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly</td>
<td>Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket</td>
<td>Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and Inconel 625 LP-DED jacket</td>
</tr>
<tr>
<td>Schedule (Reduction)</td>
<td>18 months</td>
<td>8 months (56%)</td>
<td>5 months (72%)</td>
</tr>
<tr>
<td>Cost (Reduction)</td>
<td>$310,000</td>
<td>$200,000 (35%)</td>
<td>$125,000 (60%)</td>
</tr>
</tbody>
</table>

*Low volume production*
Additive Manufacturing in use on NASA Space Launch System (SLS)

Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25 RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from 127 welds to 4 welds

Ref: Andy Hardin, Steve Wofford/ NASA MSFC
AM Processes for various applications


*Not inclusive of all metal AM processes

Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

Directed Energy Deposition

L-PBF of complex components, new alloy developments for harsh environment
Methodical AM Process Selection

- What is the alloy required for the application?
- What is the overall part size?
- What is the feature resolution and internal complexities?
- Is it a single alloy or multiple?
- What are programmatic requirements such as cost, schedule, risk tolerance?
- What are the end-use environments and properties required?
- What is the qualification/certification path for the application/process?
Criteria and Comparison Various Metal AM Processes

Build/Deposition Rate

Multi-alloys

Feature Resolution

EB-PBF

L-PBF

Cold Spray

AFS-D

Gradl, et al JMEP

EBW-DED

AW-DED

LW-DED

LW-DED

UAM

Gradl, et al JMEP

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Various criteria for selecting AM techniques

- Complexity of Features
- Scale of Hardware
- Material Physics
- Cost
- Material Efficiency
- Speed of Process
- Material Properties
- Internal Geometry
- Availability
- Post Processing

Laser Powder Directed Energy Deposition (DED)
LP-DED Large Scale Nozzle Development

60” (1.52 m) diameter and 70” (1.78 m) height with integral channels
90 day deposition

95” (2.41 m) dia and 111” (2.82 m) height
Near Net Shape Forging Replacement

Proper AM process selection requires an integrated evaluation of all process lifecycle steps.
Enabling New Alloy Development using Additive Manufacturing

**GRCop-42**, High conductivity and strength for high heat flux applications

**NASA HR-1**, high strength superalloy for hydrogen environments

**GRX-810**, high strength, low creep rupture and oxidation at extreme temperatures

Ref: Tim Smith, Christopher Kantzos / NASA GRC
Industrial Maturity and TRL of AM Processes

- L-PBF
- LP-DED
- Cold spray
- AW-DED
- LW-DED
- L-PBF
- EBW-DED
• Maturing each of the AM processes and understanding of microstructure, properties, build limitations, and methods for design and post-processing.

• Ongoing development for large scale AM using DED and other processes.

• Continuous hot-fire and component testing to advance various combustion chambers, injectors, nozzles, ignition systems, turbomachinery, valves, lines, ducts, in-space thrusters.

• Polishing (surface enhancements internally) and post-processing development.

• Combining various AM processes for multi-alloy solutions or additional design options.

• Advancement of commercial supply chain for unique alloys (GRCop-42, NASA HR-1, JBK-75).

• New alloy development (Refractory, Ox-rich environments, AM-specific alloys).

• Material database of metal AM properties to allow for conceptual design – tensile, fatigue and thermophysical.

• Design complexity using lattices and thin-wall structures.

• Standards and certification of metal AM are evolving for human spaceflight.
Summary

• Various AM processes have matured for rocket propulsion applications each with unique advantages and disadvantages.
• AM is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense.
• Complete understanding of the design process, build-process, feedstock, and post-processing is critical to take full advantage of AM.
• Additive manufacturing takes practice!
• Standards and certification of the AM processes are in-work.
• AM is evolving and imagination is the limit.
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Photo: NASA/Ben Smegelsky
Bimetallic AM for combustion chambers

- LP-DED Jacket
- Cold spray Jacket
- Direct deposit LP-DED nozzle (Axial Bimetallic)
- EBW-DED Jacket
Example of LP-DED with small features
Microstructure of Various AM Processes  
Alloy 625

As-built microstructure of Alloy 625 => Requires proper post-processing heat treatments

A) Laser Powder Bed Fusion  
B) Electron Beam Powder Bed Fusion  
C) Laser Powder DED (1070 W)  
D) Laser Wire DED  
E) Arc Wire DED

F) Electron Beam Wire DED  
G) Cold Spray  
H) Additive Friction Stir Deposition  
I) Ultrasonic Additive Manufacturing

Each AM process results in different grain structures, which ultimately influence properties

- Image from Mark Norfolk, Fabrisonic
Material Properties for Various AM Processes

- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build.
- Each AM process results in different grain distributions, precipitates, and porosity, all of which influence final properties.
- Heat treatments should be developed based on the requirements and environment of the end component use.
- Process, parameters, and feedstock should all be stable before property development.

**Alloy 625 – Room Temperature UTS**

*Not design data and provided as an example only*
Large-scale Thin Wall Deposition of Nozzles
NASA HR-1 Components Fabricated using LP-DED

RS-25 Powerhead liner

40k-lbf nozzle manifold

RS-25 Powerhead Halfshell (LOX side)

RS-25 Powerhead Halfshell (Fuel side)

40k-lbf Integral Channel Nozzle

2.5k-lbf spiral tube-like DED nozzle
• **NASA HR-1** is an Fe-Ni-Cr alloy developed for high pressure hydrogen environments.
• Derived from JBK-75 and designed for higher strength and improved weldability.
• Reformulated for AM LP-DED to reduce Titanium segregation.
• Advanced using LP-DED at different deposition rates to allow for variations in wall thickness and deposition time as well as L-PBF.
• Optimization of heat treatment for H2 embrittlement and required properties.
GRCop-42 and GRCop-84 for Combustion Chambers

- Oxidation and blanching resistance during thermal and oxidation-reduction cycling.
- Maximum use temperature $\sim 800^\circ C$, depending upon strength and creep requirements.
- Excellent mechanical properties at high use temperatures (2x of typical copper).
- Lower thermal expansion to reduce thermally induced stresses and low cycle fatigue (LCF).
- Established powder supply chain and commercial supply chain for L-PBF and LP-DED.
- Significant maturity in characterization and hot-fire testing (high TRL).
Comparison of GRCop-84 and GRCop-42

GRCop-42 and GRCop-84 for different applications:
• GRCop-42 has improved thermal conductivity (20-30%).
• GRCop-84 has slightly higher strength and improved LCF properties.
• GRCop-42 has matured supply chain and lower cost.
• Both require only Hot Isostatic Pressing (HIP) post-build.

<table>
<thead>
<tr>
<th>Element</th>
<th>GRCop-42 Wt %</th>
<th>GRCop-84 Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Balance</td>
<td>Balance</td>
</tr>
<tr>
<td>Cr</td>
<td>3.1 – 3.4</td>
<td>6.2 – 6.8</td>
</tr>
<tr>
<td>Nb</td>
<td>2.7 – 3.0</td>
<td>5.4 – 6.0</td>
</tr>
<tr>
<td>Fe</td>
<td>Target &lt;50 ppm</td>
<td>Target &lt;50 ppm</td>
</tr>
<tr>
<td>O</td>
<td>Target &lt;250 ppm</td>
<td>Target &lt;250 ppm</td>
</tr>
<tr>
<td>Al</td>
<td>Target &lt;100 ppm</td>
<td>Target &lt;100 ppm</td>
</tr>
<tr>
<td>Si</td>
<td>Target &lt;100 ppm</td>
<td>Target &lt;100 ppm</td>
</tr>
<tr>
<td>Cr:Nb Ratio, %wt</td>
<td>1.13 – 1.18</td>
<td>1.13 – 1.18</td>
</tr>
</tbody>
</table>
• High TRL and maturity of mechanical and thermophysical properties, component application, and supply chain.
• Over 41,033 seconds of hot-fire time and 1,015 starts on >30 chambers.
• Single L-PBF chamber unit achieved 296 starts and >10,600 seconds.
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## Various Metal AM Processes

<table>
<thead>
<tr>
<th>State of Material</th>
<th>Fusion Technique</th>
<th>Feedstock</th>
<th>AM Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Melted</td>
<td>Powder Bed Fusion</td>
<td>Powder</td>
<td>Laser PBF (L-PBF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electron Beam PBF (EB-PBF)</td>
</tr>
<tr>
<td></td>
<td>Directed Energy Deposition</td>
<td>Powder</td>
<td>Laser Powder DED (LP-DED)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wire</td>
<td>Arc-Wire DED (AW-DED)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Laser-Wire DED (LW-DED)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electron Beam Wire DED (EBW-DED)</td>
</tr>
<tr>
<td>No Melting</td>
<td>Solid State</td>
<td>Foil</td>
<td>Ultrasonic AM (UAM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barstock</td>
<td>Additive Friction Stir Deposition (AFS-D)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Powder</td>
<td>Cold Spray (CS)</td>
</tr>
</tbody>
</table>

Many AM processes exist and must be traded (along with traditional techniques) to optimize.


