GRCop-42 Development and Hot-fire Testing Using Additive Manufacturing Powder Bed Fusion for Channel-Cooled Combustion Chambers

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Background and Motivations

• Since 2014 NASA has been developing and maturing additive manufacturing (AM) techniques for GRCop-alloys
  – Specifically Selective Laser Melting (SLM) or Laser-Powder Bed Fusion (L-PBF)
  – Focused on GRCop-84 (Cu-8%Cr-4%Nb)
  – Previous research presented at AIAA Propulsion and Energy 2017 (GRCop-84)
• Several NASA programs have and are making use of additive manufactured SLM chambers and NASA has accumulated significant development time (>18,000 sec and 370 starts and counting)
• The GRCop-84 SLM process has since been transitioned to AM service (printing) vendors and readily available
• NASA sought an opportunity to expand on success of the GRCop-84 material and evolve the GRCop-42 for enhanced performance including increased thermal conductivity
Why GRCop-42?

- Improved thermal conductivity over GRCop-84 (5-8%)
- Oxidation and blanching resistance with thermal and oxidation-reduction cycling
- High use temperatures to ~1400 °F, depending upon strength and creep requirements, for sustained durations
- Adequate material strength at high use temperatures
- Established powder supply chain and simplified over GRCop-84
- Initial database for wrought GRCop-42 to baseline against

*Wrought Data Shown for comparison*
There are several characteristics that were considered and worked in parallel for the development of the GRCop-42 material for component applications:

1. Establishing and controlling the powder supply chain
2. Scalability and transfer of the SLM process to various machines and various sizes machine
3. Improving the work flow and processing time of GRCop-42 compared to GRCop-84 to reduce build times
4. Characterizing the material and establishing a database for designers
5. Understanding property and microstructural sensitivities to powder supply, print parameters, and design features
6. Demonstrating component hardware in a relevant environment and testing at aggressive conditions
7. Dissemination of data to industry partners and commercial vendors

Many of these objectives leading toward cost reduction and performance improvements
Summary of SLM Process Development

• A material powder layer is spread over a build plate. A laser then sinters the component design cross section. The build plate is lowered and a new powder layer is distributed over the previous layer. The process repeats until component completion.

• SLM (or L-PBF) has limited build volumes
  – Currently 15.6 x 15.6 x 15.6 inches max (EOS M400)

• Larger build volumes, such as EOS M400, require larger load volumes of powder to fill build chamber
  – 1,100 lbs of powder (assuming packing factor 1.0)
Summary of SLM Process Development

- Composition derived from wrought alloy chemistry development
- Composition makeup comparison with GRCop-84
- Powder made using inert gas spray atomization (argon)
- Lower Cr and Nb content easier and cheaper for powder vendors to atomize
- Build plate adherence was leveraged from GRCop-84 development
  - Nickel superalloy intermittent layer
- Developed in GE Concept Laser M2 proven to be “copper friendly” when building GRCop parts (same machine as GRCop-84)
  - Inert atmosphere glove box
  - 400 W laser
  - Ergonomic build chamber/glove box design

<table>
<thead>
<tr>
<th>Element</th>
<th>GRCop-42 Wt %</th>
<th>GRCop-84 Wt %</th>
</tr>
</thead>
<tbody>
<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;400 ppm</td>
<td>Target &lt;400 ppm</td>
</tr>
<tr>
<td>Al</td>
<td>&lt;50 ppm</td>
<td>&lt;50 ppm</td>
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<tr>
<td>Si</td>
<td>&lt;50 ppm</td>
<td>&lt;50 ppm</td>
</tr>
<tr>
<td>Cu</td>
<td>Balance</td>
<td>Balance</td>
</tr>
<tr>
<td>Cr:Nb Ratio</td>
<td>1.12 – 1.15</td>
<td>1.12 – 1.15</td>
</tr>
</tbody>
</table>
GRCop-42 Material Property Development

- GRCop-42 & -84 AM samples compared to wrought extruded
- GRCop-42 demonstrated Increased thermal conductivity compared to GRCop-84
- Power and speed build parameters were varied on material samples and evaluated to determine optimal properties for given set of parameters
- Inclusion of the finer particles below the preferred (typical SLM) mesh size resulted in better density and material properties
- Stability of GRCop weld pools allowed 50% thicker layers of powder to be deposited to facilitate (~20%) faster build times
- Similar build feature resolution and standard AM SLM build “rules of thumb”
GRCop-42 Material Property Development

- Additional GRCop-42 development on various AM machines at MSFC and industry service vendors
  - Mechanical test data aligned well on small and large AM platforms
- GRCop-42 HIP similar to GRCop-84 and only required heat treatment
- HIP reduces strength but increases elongation to desired values
- Surface roughness studies completed
- Repeatability of the data was also shown in material sample testing
- Ongoing material testing and data available to government and industry
Hot-fire Testing Evaluation

- Hot-fire Testing conducted at NASA MSFC Test Stand 115
  - Conducted in April-June 2019
- Liquid Oxygen / Gaseous Hydrogen Additive Manufactured Coaxial Injector
  - Spark Ignition (PI100 test program)
  - TEA/TEB Ignition (PJ038 test program)
- Chamber liners are assembled in a slip jacket that allows for easy interchangeable liners between tests
- 2,100 lb₉ thrust class thrust chamber assembly
- Performance parameters evaluated
  - Heat load
  - Pressure drop / Resistance
  - Surface finish and post-processing
Hardware Test Results

- 188 tests, 8,030 sec of hot fire time on (2) different liners
- Higher MR (8.0) conditions conducted at the end of tests
- Maintained consistent conditions throughout cycle testing
- Completed long duration (180 sec) and cycle testing (6 cycles @ 30/sec)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Peak Pc (psig)</th>
<th>Peak MR</th>
<th>Total Starts</th>
<th>Accumulated Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner 1</td>
<td>1,224</td>
<td>6.99</td>
<td>168</td>
<td>7,400</td>
</tr>
<tr>
<td>Liner 2</td>
<td>1,091</td>
<td>8.01</td>
<td>20</td>
<td>630</td>
</tr>
</tbody>
</table>
Hot-fire Testing
Performance Results from Hot-fire Testing

- Each liner was kept in the same or as similar as possible test conditions during cycle testing; instrumentation kept constant
  - Removed liners only for seal replacement or chamber change-out
- Observed stable operation conditions
  - Resistance remained stable during testing – very similar between both liners
  - Initial long duration testing to characterize different conditions
  - Cycle testing completed to thermally cycle the liners
  - No large combustion amplitude or combustion modes
- TEA/TEB ash affect on heat load observed on both liners

![Graph showing performance results](image)

**Cycle Testing (7 cycles @ 30/sec cycle)**

**Total Heat Load for test series (PI100 + PJ038)**
Chamber Inspection Results

• Analytically determined and anchored peak wall temperatures at 1340°F
• Inspected liner after each test and set of cycles
• No blanching observed
• No erosion
• No anomalies in plume signature from video
• Pre and post-test leak checks confirmed no leakage

Liner #1, 168 tests and 7,400 sec (Peak MR=6.99)

Liner #1, 168 tests and 7,400 sec (Peak MR=6.99)

Liner #2, 20 tests and 630 sec (Peak MR=8.01)
Summary and Future Development

• NASA has completed development and hot-fire testing of the Additively Manufactured (AM) Selective Laser Melting (SLM) GRCop-42 material
• Improvements in conductivity and material properties as expected
• Completed hot-fire testing at high Pc and high MR accumulating 188 starts and 8,030 seconds – performed as expected
• Completed series of builds in larger scale (15” dia)
• Continuing to advanced process and working with various industry service vendors to provide material
  – Data available to government and industry partners
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Various MSFC engineering and technician support
Additive Manufacturing (AM) Overview

- Additive Manufacturing (AM) is an emerging technology with a focus on complex metallic component fabrication
  - Enables complex shapes and internal features that were not possibly with traditional manufacturing techniques
  - Significant schedule and overall lifecycle cost reductions

- To date at the NASA Marshall Space Flight Center (MSFC), combustion devices component hardware ranging in size from 100 - 35,000 lbf has been designed and manufactured using AM and many of these pieces have been hot-fire tested.

References


References