Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications

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Objectives

Develop AM Processes to Reduce Costs/Schedules for Liquid Engine Components

- Reduce Overall Mission Costs
- Transfer Technologies to Industry to Enable Long Term Supply Chains

Techniques Evaluated:

- Additive Manufacturing (AM) / Selective Laser Melting (SLM) GRCop-84 (Cu-8Cr-4Nb)
  - Also evaluating C-18150 (CuCrZr) and Glidcop
- Direct Metal Laser Sintering (DMLS) Copper & Nickel Alloys
- Bimetallic AM Chambers
  - Laser Cladding
    - Direct Metal Deposition (DMD)
  - Electron Beam Freeform Fabrication (EBF³)
  - Arc-based Deposition
  - Freeform Blown Powder Deposition/Directed Energy Deposition

Approach:

- Fabricate Various Thrust Chamber Designs with Multiple Techniques
  - Develop Process Parameters with Samples & Components
  - Characterize Material Properties
  - Proof Test Samples & Components
  - Apply Lessons Learned for Timely Design Mods
- Hot-fire Test Chambers in Relevant Environments
Development of SLM GRCop-84 Material Processing

- Challenges in SLM processing for copper-alloys
  - Copper is highly reflective in red and near-IR spectrums
  - High conductivity so heat is rapidly conducted away from melt pool
- GRCop-84 was easily melted using SLM (14 vol.% Cr$_2$Nb)
  - SLM process did not result in segregation of Cr$_2$Nb precipitates
  - Cr$_2$Nb appears to have been refined in size

HIP process developed, well above annealing temperature (600°C / 1112°F)
Mechanical Properties of SLM GRCop-84

- Strength values similar to extruded GRCop-84, elongation increased significantly with HIP cycle
  - Differences observed in horizontal and vertical build orientations
- LCF testing completed in as-built condition (simulated channel)
  - Cracking initiated in as-built surface
  - LCF of as-built surface is lower than extruded, not unexpected

Avg. Stress-Strain curves of SLM GRCop-84, AS-built and HIP’ed

LCF of as-built SLM GRCop-84, RT

LCF Fracture surface
Additively Manufactured SLM Material is Unique

SLM GRCop-84 Copper-alloy in the as-built condition (ASTS, Huntsville)
Low Cost Upper Stage Propulsion (LCUSP) Program

Multi-Center NASA Program under NASA STMD Game Changing

**MSFC**
- Project Management
- Component Design
- SLM GRCop-84 Chamber Liner
- C-C Nozzle Development

**GRC**
Material Property & Characterization for SLM GRCop-84 & EBF³ Inconel

**LaRC**
EBF³ development to direct deposit Inconel jacket onto SLM GRCop-84 Liner

**Program Goal**
Advance select technologies by fabricating & hot-fire testing a 35K lbₜ Regeneratively Cooled LOX/H₂ Thrust Chamber Assembly (TCA)
Print samples evaluated
- Hot wall thicknesses – successfully printed & proof tested
- Channel sizes as small as 0.030” with +/- .001” print tolerances

Mechanical evaluation samples
- Developed process using Electron Beam Freeform fabrication (EBF³) to deposit Inco 625 directly onto SLM GRCop-84
LCUSP Chamber Fabrication

SLM GRCop-84 – Concept Laser M2 at MSFC

Wedge trial printed first – demo complex geometry
Structured light scan to compare print to model

Mid-section EB Weld

Sections Stacked; Mid-section weld & EBF³ Applied
AM GRCop-84 Regen (LCH4) Cooled Chamber

- SLM GRCop-84 at NASA-MSFC (Concept Laser M2)
- Multiple prints and design modifications required to produce successful part
  - Reshaping open volume manifold with proper angles
  - Developing support features
- Printed structure includes:
  - Inlet/exit manifold volumes, inlet boss for threaded interface
  - Integral instrumentation for discrete thermal and performance
  - Forward flange welded post-SLM processing

As-printed methane chamber

Final machined methane chamber
AM GRCop-84 LCH4 Cooled Chamber - Testing

Hot-fire testing with LCH4 cooling – Chambers in excellent condition post-test

Initial testing of throat section; data used to optimize full length chamber

Full length – 4K-lbf thrust methane chamber
1.2K Additive Chamber Development

Designed to replace vintage subscale thrust chamber used for development testing since 1960’s at MSFC.

Nominal Pc ~ 750 psig; Water cooled design supports LOX/H2, LOX/LCH4, LOX/RP1 injector testing.

Overall size allows for one piece build in available SLM machines.
1.2K AM Chamber Development – Hybrid Design

AM used to create GRCop-84 liner to slip into SS housing

Hybrid Chamber with AM Liner Installed at MSFC TS115

AM GRCop-84 Liner

During Subscale Nozzle Testing at MSFC
AM GRCop-84 liner accumulated 2365 seconds (23 starts) of LOX/H2 hot-fire exposure

Hot-fire tested with Carbon-Carbon Extension
1.2K AM 1-piece chamber design transitioned to 2-piece

Allowed for easier removal of powder, simplified design, easier inspections, and reduced overall processing time

Designs will evolve with additive through print trials, testing and design and analysis tools
Video of AM GRCop-84 Chamber Hot-fire Testing

Photo Credit: David Olive / NASA MSFC ET10
Generic Flow for AM Chamber Fabrication Process

1. **Adjust Model / Redesign**
2. **Design of Chambers for SLM**
3. **3D Printing of Plastic Setup parts and SLM Wedges**
4. **Process Model and Digital Compare to Original Model**
5. **SLM of Chamber**
6. **Remove from SLM Chamber and Initial Powder Removal**
7. **Tapping of Ports and Final Powder Removal**
8. **Computed Tomography (CT) Scan**
9. **HIP of Chamber on Build Plate**
10. **EB Weld of Halves (if needed)**
11. **Cladding of Jacket and Manifold Weld Preparations (if needed)**
12. **Welding Operations for Manifolds, Repairs**
13. **Final Machine and Inspections**
AM Chamber Lessons Learned – Design and Build

► Features maintain maximum 45° from vertical, less angle enables more successful builds
► Optimized AM design may not be single-piece
  ▪ Welding multiple AM pieces
    reduces risk, eases powder removal, allows inspection of unique features
  ▪ Inlet/outlet ports can easily be welded on;
    protruding features often experienced print failures
► Coolant channels –
  ▪ Leave access for powder removal
  ▪ Increase effective area to account for rough surfaces...
    600-800 μin are possible, although 200-300 μin is being demonstrated
  ▪ Maintain access for interior powder removal
► Design copper EB weld joints for excess penetration and material heating
► Minimize thick areas to eliminate residual stresses (thick flanges can lift off the build plates)
► Part orientation is critical for coater blade, so optimize design to minimize potential damage
► Include enough stock for secondary bonding ops, run-outs, &/or final machining
► Builds can deform as vertical height increases further from the build plate
► Compare exported CAD files back to original model
► Structured Light (3D scanning) continuously throughout process
AM Chamber Lessons Learned – Design and Build

- Powder dose factor is critical as parts get taller.
- Design for Powder Removal
  - Physical efforts for powder removal can cause stress on the part.
    - Mallet blows created microcracks in some components prior to HIP
  - High pressure (>500 psi) air/GN2 aided in powder removal
  - Alcohol evaporates and helped remove powder from select channels
    (although residual powder might clump when exposed to this fluid).
  - Include threaded ports that can be blocked off during powder removal to seal air flow properly (dry state/no oils).
  - CT scan continuously to verify powder removal.
  - Removing prior to HIP is ideal, but it can be removed after, since it does not all consolidate.
- Build direction is critical and overhangs may fail; 45 deg max build angles appear possible.
- Creating plastic models or building small wedges/slices to demonstrate parameters prior to metal designs can be helpful; identify potential issues prior to actual component builds.
- TIG braze repairs for debonds worked well; identical filler material is ideal.
  
  *Include weld wire within SLML builds.*
- Design for shrinkage/deformation in all process steps, such as welding and metal deposition.
Summary and Future Work for AM Copper Chambers

- NASA has successfully demonstrated additive manufacturing of copper-alloy combustion chambers for liquid rocket engines
  - Processing time and cost reductions have been demonstrated
- NASA has completed parameter development for GRCop-84 using additive manufacturing / selective laser melting
  - Parameters are available for industry use
  - Property development complete and reports will be available
- Design for additive manufacturing techniques have advanced with development of AM copper-alloys
- NASA has completed hot-fire testing of chambers in LOX/H2 and LOX/CH4
  - 2365+ seconds accumulated on LOX/H2 chambers
  - 35K LCUSP chamber tested in 2017
  - Methane chambers being continuously hot-fire tested
- Additional development to evaluate C-18150 and Glidcop
  - Increase scale available for chamber fabrication
GRCop-84 3D printing process developed at NASA and infused into industry

GRCop-84 AM Chamber Accumulated **2365 sec**
hot-fire time at full power with no issues

LOX/Methane Testing of 3D-Printed Chamber
Methane Cooled, tested full power
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