Additively Manufactured
Rocket Engine Combustion Chamber
Structural Analysis

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SLaMS Young Professional Forum
September 1-3, 2015
Outline

- Project Background
- Manufacturing Background
- Material Properties
- Combustion Chamber Background
- Thermal Analysis Background
- Structural Analysis
- Finite Element Model
- Structural Analysis Results
Low Cost Upper Stage Propulsion (LCUSP)

LCUSP is a multi-center partnered project funded by the Space Technology Mission Directorate Game Changing Development Program with the goal of making liquid engine chambers more affordable.

The Technical Approach

- Develop materials properties and characterization for SLM manufactured GRCop-84. [GRC]
- Develop and optimize Selective Laser Melting (SLM) manufacturing process for a full component GRCop-84 chamber and nozzle. [MSFC]
- Develop and optimize the Electron Beam Freeform Fabrication (EBF³) manufacturing process to direct deposit a nickel alloy structural jacket and manifolds onto an SLM manufactured GRCop-84 chamber and nozzle. [LaRC]
- Hot Fire Test at MSFC
Selective Laser Melting (SLM)

- Layer additive manufacturing process where geometry is built up layer by layer by sintering powder material using a high power laser
- Process is sensitive to powder size, powder contaminates, layer thickness, laser speed, and laser power
- Parts are typically HIPed after to reduce porosity
- Geometry volume size is limited to build box
- Smallest printable feature size around .020”
- Geometry tolerance is around +/- .005”
Electron Beam Freeform Fabrication (EBF³)

- Layer additive manufacturing process where geometry is built up by depositing wired material onto a substrate using an electron beam to fuse the materials together.
- Process is done in a high vacuum chamber.
- Geometry volume size is limited to vacuum chamber size.
- Smallest printable feature size is dictated by size of wire used.
- Geometry tolerance is dictated by size of wire used.

Figure: Schematic of the EBF³ process.\[6\]

EBF³ Inconel 625 deposited onto copper plate substrate.\[2\]
Sintered Hot Isotactic Pressured (HIPed) GRCop-84

- Sintered materials are anisotropic by nature, due to the layer additive manufacturing process
- Due to the lack of test data, assumed isotropic GRCop-84 HIPed properties
  - Ref. Aerospace Structural Metals Handbook
- Layer thickness is 30 microns
- Tensile, low cycle fatigue, high cycle fatigue, and creep tests are scheduled

SLM GRCop-84 bottom half chamber on build plate

GRCop-84 HIPed yield strength, ultimate strength, and stress strain curves.[1]
**Material Properties**

**Bond between EBF$^3$ Inconel 625 and GRCop-84**

- Due to the lack of test data, bond properties are assumed to take on the weaker material properties
- The EBF$^3$ material penetrates the substrate
- A copper Inconel alloy layer is created
- Tensile, low cycle fatigue, high cycle fatigue, and creep tests are scheduled

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Magnified cross section of EBF$^3$ Inconel 625 deposited onto copper plate substrate.[8]

Composition plot of EBF$^3$ Inconel 625 deposited onto copper plate substrate analyzed near bond layer showing copper particulates.[2]
**EBF³ Inconel 625**

- Due to layer additive manufacturing process, anisotropy is observed in initial testing.
- Due to the lack of test data, properties are a combination of current test data and annealed Inconel 625.
- Compared to annealed Inconel 625:
  - Modulus is slightly lower – 25-27 vs 30 [Msi]
  - Yield is comparable
  - Ultimate is slightly lower - 110 vs 120 [ksi]
- Tensile, low cycle fatigue, high cycle fatigue, and creep testing is scheduled.

**High magnification of fracture surface.**

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<th>Sample</th>
<th>$E$, Msi</th>
<th>0.2% YS, ksi</th>
<th>UTS, ksi</th>
<th>$\varepsilon_f$, %</th>
<th>RA, %</th>
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<td>109.5</td>
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<td>35.29</td>
<td>39.8</td>
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<table>
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<th>Specification</th>
<th>0.2% YS, ksi</th>
<th>UTS, ksi</th>
<th>$\varepsilon_f$, %</th>
<th>RA, %</th>
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<tr>
<td></td>
<td>60-95</td>
<td>120-150</td>
<td>30-60</td>
<td>40-60</td>
</tr>
</tbody>
</table>

Longitudinal and transverse tensile tests of EBF³ Inconel 625 deposited onto cooper plate substrate. [3]
**Key SLM Features and Limitations**
- Ability to print closed-out integral coolant passages thus simplifying the manufacturing process
- Ability to vary shape, size and direction of channel
- Due to size of current build box, chamber had to be printed in two pieces and joined

**Key EBF³ Features**
- Ability to directly deposit onto liner and achieve net shape geometry
- Ability to combine jacket and manifolds
- No deposit around channel openings - risk of deforming or collapsing
  - Drove stringer design in manifolds
LCUSP manufacturing flow removes many machining and joining steps present in conventional chamber manufacturing.

Combustion Chamber Background

- SLM GRCop-84 Liner Halves
- HIP
- EB Weld Liner Halves
- EBF$^3$ Inconel 625 Jacket and Manifold Deposition
- Final Machine
- Stress Relieve
Combustion Chamber Background

Physics of a Regeneratively Cooled Combustion Chamber

- **Oxidizer - LOX**
- **Fuel - LH2**
- **Outlet Manifold**
  - GH2 200F
  - 1600 psi
- **Structural Jacket**
  - Inconel 625
- **Liner**
  - GRCop-84
- **Inlet Manifold**
  - LH2 -400F
  - 2000 psi
- **Injector**
- **Combustion**
  - 4000F-6000F
  - 1400 psi
- **Convection and Conduction**
- **Radiation and Convection**
Thermal Analysis Background

- Modes of Heat Transfer
  - Convection and radiation from combustion gases
  - Coolant convection
  - Conduction within the liner walls
- Two Dimensional Kinetics (TDK) and empirical methods are used to predict gas side heat flux
- FEA is used to solve for the temperature
- Variables effecting coolant convection
  - Channel contraction/expansion
  - Entrance effect
  - Curvature effect
  - Surface roughness
  - Pressure drop

Figure: Heat transfer schematic for regenerative cooling.\[7\]
Project Requirement

- Demonstrate the capability of these manufacturing processes in a hot fire environment.

Structural Requirements

- NASA-STD-5012
  - FOS Yield = 1.10 (Mechanical loads only)
  - FOS Ultimate = 1.40 (Mechanical loads only)
  - Fatigue Analysis Factor = 1.15 (Non-rotating components)
  - Low Cycle Fatigue Service Life Factor = 4.0

Modes of Failure

- Debonding EBF$^3$ Jacket from GRCop Liner
- Liner hot wall thinning/cracking due to low cycle fatigue and creep

Figure: Throat section of SSME MCC showing hot wall thinning.[4]
Finite Element Model

- **Geometry**
  - 4.5° axisymmetric model

- **Materials**
  - HIPed GRCop-84 – Isotropic properties
  - EBF\(^3\) Inconel 625
    - Linear elastic - Transversely isotropic properties
    - Elastic plastic – Isotropic properties

- **Boundary Conditions**
  - Cyclic symmetric boundary constraint
  - Axial and hoop DOF fixed at washer diameter area to simulate injector mount
  - Bonded at GRCop EB weld
  - Bonded between EBF\(^3\) Inconel jacket and GRCop liner

- **Mesh**
  - ~1.2 million high order tetrahedron elements
Finite Element Model

- Steady State Loads
  - Gas side pressure profile
  - Coolant side pressure profile
  - Temperature profile
Constitutive Equations for EBF\(^3\) Inconel 625

- EBF\(^3\) is assumed to behave as a fibrous material; where the fiber direction corresponds to the deposition direction
- Assume symmetry about the \(i_3\) axis

Hybrid Transversely Isotropic
3 Independent Constants

\[
\begin{bmatrix}
E_1 & E_1 & 0 \\
E_1 & E_3 & 0 \\
0 & 0 & G_{13}
\end{bmatrix}
\]

Transversely Isotropic
5 Independent Constants

\[
\begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{13}}{E_1} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\
\frac{\nu_{13}}{E_1} & \frac{1}{E_1} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{13}}{E_3} & \frac{\nu_{13}}{E_3} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{2G_{13}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{2G_{13}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1+\nu_{13}}{E_1}
\end{bmatrix}
\]

\(\nu_{13} = \nu_{1} = \nu, \ G_{13} = \frac{E_1}{2(1+\nu)}\)
Linear Elastic
- Temperature dependent elastic modulus
- No thermal strain effects
- No nonlinear effects
- Temperature contour applied
- Mechanical loads are applied in one step
Steady State – Linear Elastic – Deformation

- The chamber experiences bulging due to chamber pressure; primarily noticed in the barrel section.
- Due to the converging diverging geometry, the chamber experiences a blow off force above the throat and a thrust force after the throat.
- The forward manifold experiences bending/rotation due to blow off load.

Radial Direction Deformation Plot

Axial Direction Deformation Plot
Steady State – Linear Elastic – Liner

- Bulging at the barrel section causing moderate stress on the channels (Section D)
- Local yielding occurs at the channel fillets in the middle manifold (Detail B)
  - Investigate in nonlinear analysis for strain levels
**Steady State – Linear Elastic – Jacket**

- The structural jacket seems to be of appropriate thickness to contain the chamber pressure.
- The manifolds seem to be of appropriate thickness to contain the coolant pressure.
- The MCC injector flange seams to be of appropriate thickness to carry the bending load (Detail A).
- High local stress occurs in forward manifold stringers due to chamber axial blow off load (Detail A,C).
  - Possibly life limited
  - Investigate in nonlinear analysis for strain levels.

Barrel Section Stress Check:

$$\sigma = \frac{Pr}{t} = \frac{(1400 \text{ psi})(3.75''\text{)}}{0.25''\text{}} = 21 \text{ ksi}$$

*FEA = 18 ksi*
Steady State – Linear Elastic – Bond Stress

a. Axial stress in stringers due to blow off load
b. Hoop stress due to chamber pressure
c. Axial stress due to blow off load
d. Normal and shear stresses due to jacket discontinuity
e. Radial stress due to boundary constraint
Elastic Plastic

- Temperature dependent bilinear and multi-linear stress-strain curve
- Thermal strain effects included
- Mechanical and thermal loads are applied in one step and unloaded the next step
- The strain range is calculated for the cycle

\[
\Delta \varepsilon = \frac{1}{\sqrt{2(1+v')}} \sqrt{(\Delta \varepsilon_x - \Delta \varepsilon_y)^2 + (\Delta \varepsilon_y - \Delta \varepsilon_z)^2 + (\Delta \varepsilon_z - \Delta \varepsilon_x)^2 + \frac{3}{2} (\Delta \varepsilon_{xy}^2 + \Delta \varepsilon_{yz}^2 + \Delta \varepsilon_{zx}^2)}
\]

\[
v' = \frac{\Delta \varepsilon_{elastic} \Delta \varepsilon_{elastic} + \Delta \varepsilon_{plastic} (0.5)}{\Delta \varepsilon_{total}}
\]

- Three consecutive cycles are ran to verify shake down effects
Steady State – Elastic Plastic – Deformation

- The chamber experiences bulging due to chamber pressure; primarily noticed in the barrel section
- Due to the converging diverging geometry, the chamber experiences a blow of force above the throat and a thrust force after the throat
- The forward manifold experiences bending due to blow off load
- The aft end contracts due to the cyro coolant inlet and the forward end expands due to the warm coolant outlet; driven by thermal strain, therefore not seen in the linear elastic analysis
Steady State – Elastic Plastic – Liner

- Typical high strain occurs at the cold/hot wall due to extreme thermal gradients (Section B).
- There is a local high strain region where the channels diverge into the middle manifold leaving an area uncooled, causing extreme thermal gradients and high thermal strain; not typical since conventional chamber coolant channels are continuous (Detail A, Section C).

**Strain Range**

**Detail A - Strain Range**

**Temperature (°F)**

Relatively low strain in middle manifold where high stresses occurred in linear elastic analysis.

\[ \Delta \varepsilon_{\text{range}} = 1.95\% \]
Steady State – Elastic Plastic – Jacket

- Due to low strain levels, the life of the chamber is not limited by the jacket
- Only place of concern is the forward manifold stringers (Detail A, D)
  - Recommendation: Need to control the geometry attaching the stringers to the jacket/manifold

\[\Delta \varepsilon_{\text{range}} = (1.15)(0.21\%) = 0.24\%\]

\[\text{Life}_{\text{LCF}} = \frac{1.0 \times 10^4}{4.0} = 2500 \text{ cycles}\]
Structural Analysis Results

**Steady State – Elastic Plastic– Bond Stress**

- **a.** Axial stress in stringers due to blow off load
- **b.** Hoop stress due to chamber pressure
- **c.** Axial stress due to blow off load
- **d.** Normal and shear stresses due to jacket discontinuity
- **e.** Radial stress due to boundary constraint
Creep
- Temperature dependent bilinear and multi-linear stress-strain curve
- Thermal strain effects included
- Creep effects included
- Mechanical and thermal loads are applied in one step and held for desired duration
- Norton Creep Law

$$\dot{\varepsilon}_c = C_1 \sigma^C e^{\frac{-C_3}{T}}$$
Steady State – Creep – Liner

- Analysis evaluated for 30 seconds
- Due to GRCop-84’s good creep resistance, creep is not a significant contributor to overall strain
- Maximum strain occurs on cold wall in the channels diverging into the middle manifold; consistent with the low cycle fatigue analysis (Section A)
- Ultimate creep failure is small relative to LCF strain range, therefore negligible

Structural Analysis Results

Creep Strain

Section A – Creep Strain

Section B – Creep Strain

Creep Strain vs Time

$\varepsilon_{\text{creep}} = 0.13\%$
Chamber Life Allowable

- The life of the chamber is limited by the LCF life of the liner
  - Maximum strain range occurs on cold wall in the channels diverging into the middle manifold
- Note: Due to limited resources, no transient cases were analyzed
- For conservative value use 95% confidence interval

\[
\Delta \varepsilon_{\text{range}} = (1.15)(1.95\%) = 2.24\%
\]

\[
\text{Life} = \frac{100}{4.0} = 25 \text{ cycles}
\]
1. Aerospace Structural Metals Handbook
3. Carter, B., Lerch, B., NASA Glenn Research Center, *Tensile Test Results of IN625 Buildup*
5. Ellis, D., Lerch, B., Locci, I., NASA Glenn Research Center, *Microstructure of IN625 Tensile Samples Deposited on Cu*
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8. Taminger, K., NASA Langley Research Center, *PEA Quarterly Review*
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