



# Material Characterization of Additively Manufactured Components for Rocket Propulsion

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# GRC's Roles in Additive Manufacturing of Rocket Components

## GRC Technical Strengths:

- Research, test, and development of rocket engine technology
- Materials for extreme environments

## GRC Partnerships with other NASA Centers, industry and other Government agencies have enabled:

- Characterization additively manufactured space propulsion components
- In Depth understanding of additive manufacturing processes

## Recent Accomplishments:

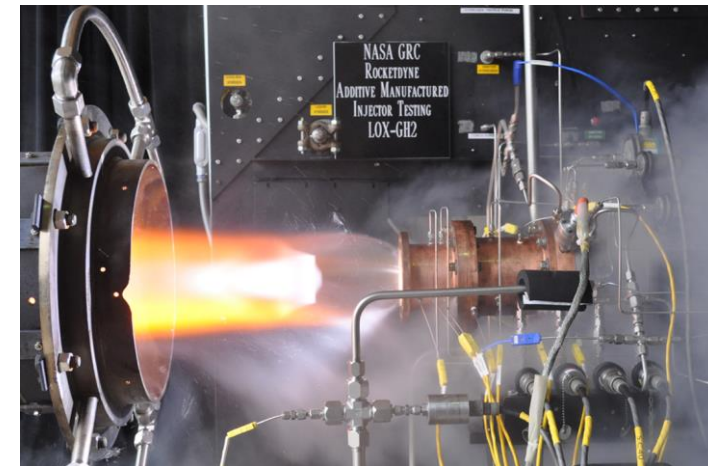
1. Materials Characterization of Electron Beam Melted Ti-6Al-4V for gimbal
2. Additively Manufacturing of Rocket Engine Combustion Chamber
3. GRC Hot Fire Test of Aerojet Rocketdyne Copper Thrust Chamber Assembly
4. RL10 Additive Manufacturing System Study with Aerojet Rocketdyne/GRC



Ti-6Al-4V gimbal



GRCop-84 Liner



Hot Fire Testing

# Materials Characterization of Electron Beam Melted Ti-6Al-4V

**Work performed in support of the Air Force Research Lab, and in consort with Aerojet Rocketdyne.**

Justification: Additive Manufacturing can reduce part count, welding, and touch labor required to manufacture the gimbal cone for the RL10 rocket engine.

Objective: Generate materials characterization database on additively manufactured (AM) Ti-6Al-4V to facilitate the design and implementation.

Process: Electron Beam Melting (EBM)

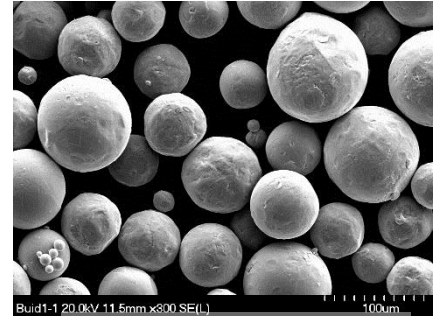
- Electron beam energy source melts powder in a vacuum (~10<sup>-5</sup> torr)

Characterization Data Obtained:

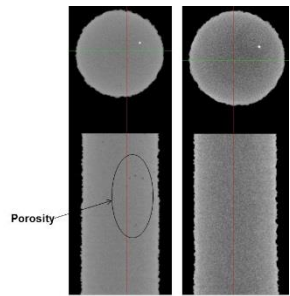
- Chemistry, microstructure of powder and manufactured samples.
- Non-Destructive Evaluation (NDE).
- Thermal properties and dynamic modulus.
- Tensile, Low Cycle Fatigue, High Cycle Fatigue, Fatigue crack growth, fracture toughness from cryogenic to 300 °F temperatures from 2 lots of material.



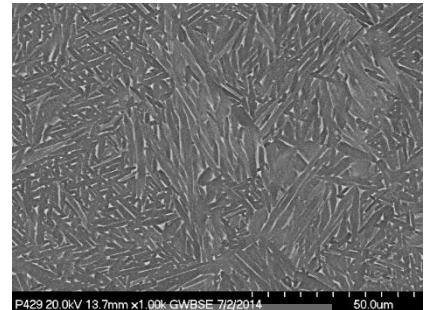
Full Scale Component



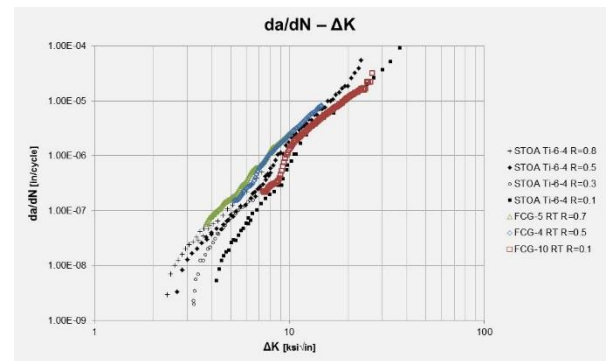
Powder Characterization



CT of pre and post HIP'd builds



Microscopy

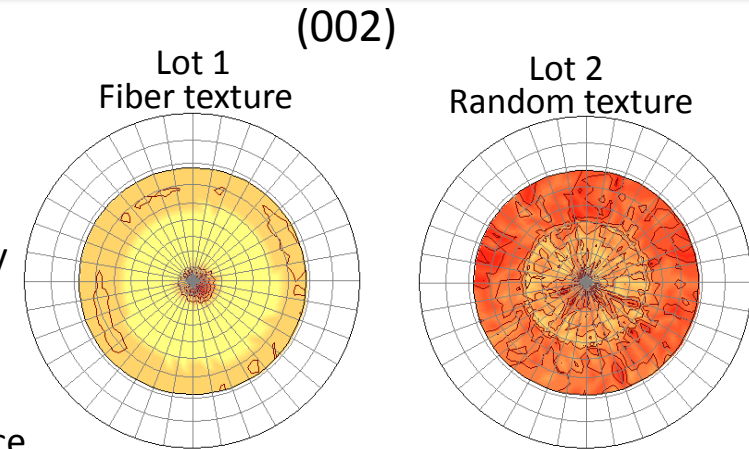


Fatigue Testing

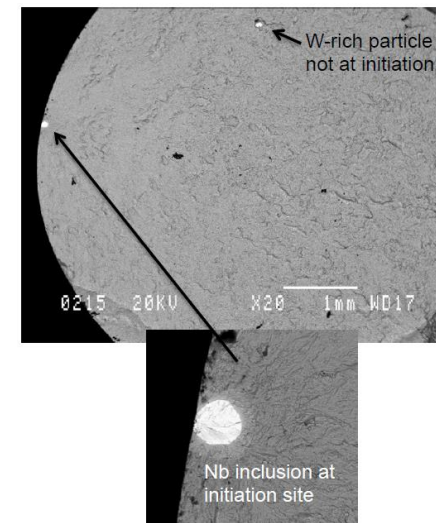
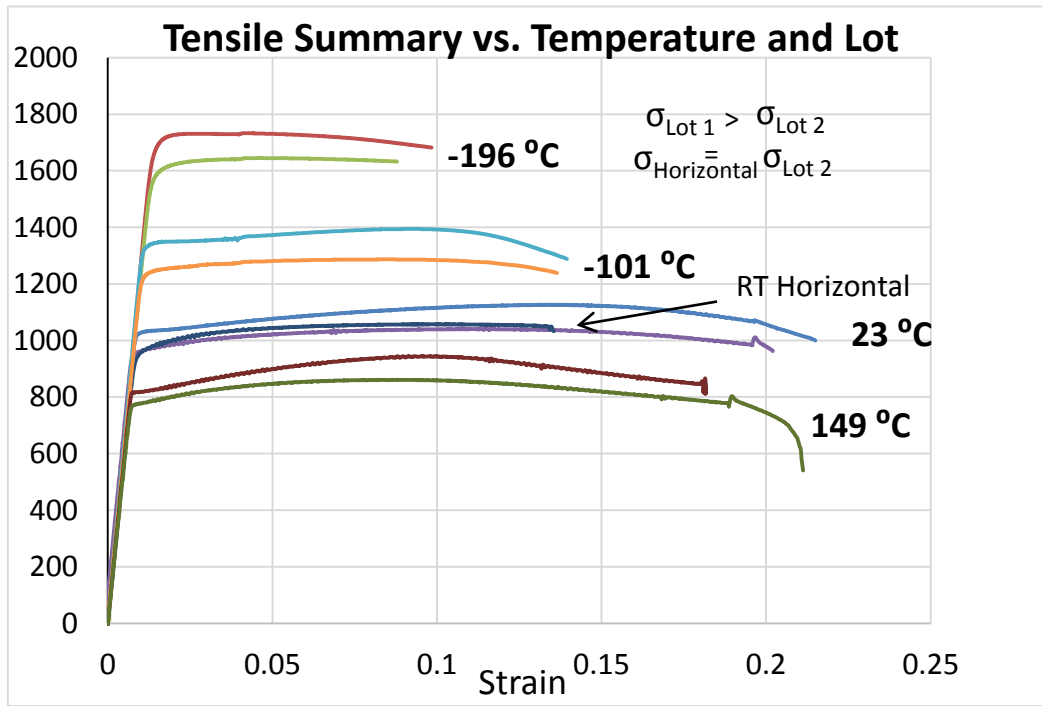
# Materials Characterization of Electron Beam Melted Ti-6Al-4V

## Significant Findings:

- Mechanical properties of EBM Ti-6Al-4V equivalent or superior to handbook data on conventionally manufactured Ti-6Al-4V.
- Lot 1 and Lot 2 (different “builds”) showed different mechanical strengths. Correlated with fiber texture variation observed by x-ray diffraction. Results illustrate that varying AM build parameters can affect materials strength.
- Elemental Nb particles were at a few fatigue failure initiation sites. Nb likely came from feedstock powder. Results illustrate importance of powder quality.



Pole Figure showing Fiber texture in (002) direction responsible for higher tensile and fatigue strength for lot 1.



Some fatigue specimens failed at elemental Nb inclusions. Inclusion likely came from powder.

# Low Cost Upper Stage Propulsion – AM Combustion Chamber

**Multi-Center Project funded by NASA Game Changing Development Program.**

**Objective:**

- Fully additively manufactured rocket engine combustion chamber.
- Reduced cost and schedule to fabricate, also enables design features not conventionally possible.

**Processes:**

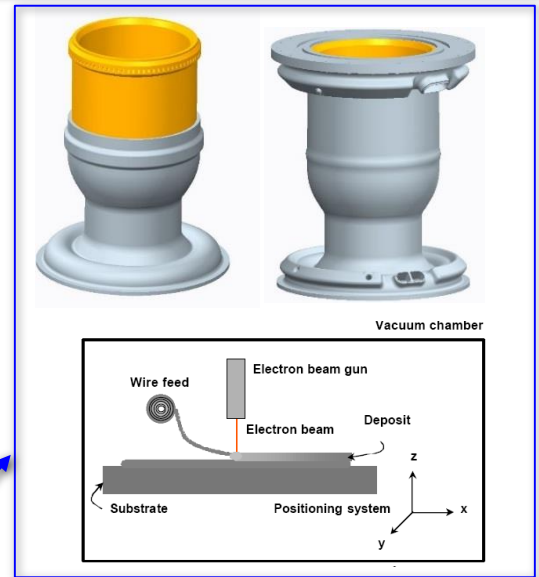
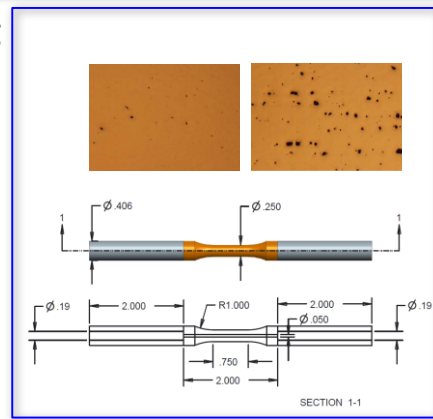
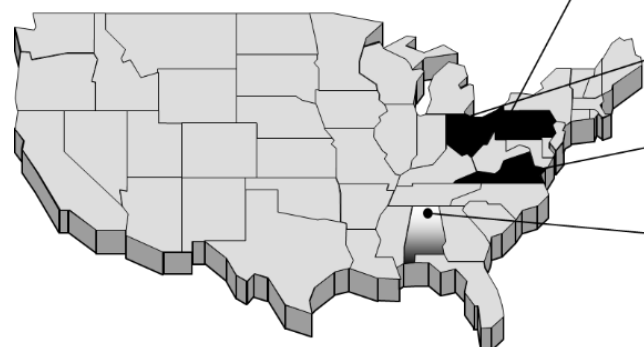
- GRCo-84 Combustion Chamber Liner produced at MSFC using Selective Laser Melting (SLM)
- Inconel 625 structural jacket applied to the liner using EB Free Form Fabrication (EBF<sup>3</sup>) at LaRC

Allegheny Technologies Incorporated  
GRCo powder

NASA GRC

NASA LaRC

NASA MSFC



# Low Cost Upper Stage Propulsion – AM Combustion Chamber

- **Three Sets of Material properties / Material characterizations are being performed at GRC:**

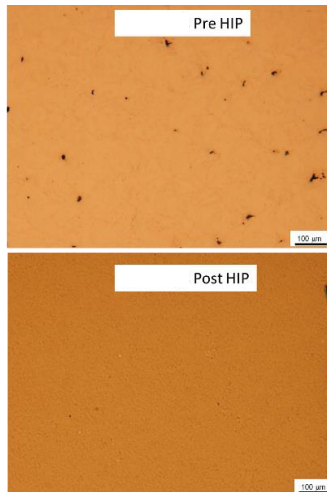
1. SLM GRCo-84 Liner
2. EBF<sup>3</sup> Alloy 625 Jacket
3. Joint between GRCo-84 and Alloy 625

- **Characterization:**

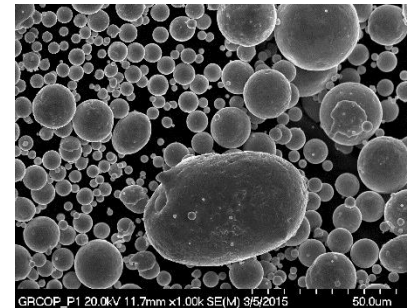
- Powder Characterization (Chemistry, Size Distribution, Porosity)
- Post-fabrication chemistry
- Computed Tomography
- Porosity pre- and post- Hot Isostatic Press (HIP)
- Microstructure
- Mechanical Testing (Tensile, Fatigue, Creep, Stress Rupture, Toughness)



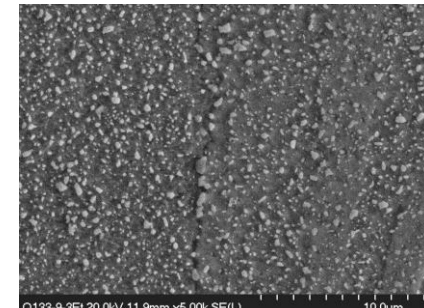
GRCop-84 Liners produced by SLM



Pre and Post-HIP optical metallography  
The dark area on the right of the lower images is the edge of the sample, not porosity.



SEM Powder Characterization



SEM Characterization of builds

## Hot Fire Test of an Aerojet Rocketdyne Copper Thrust Chamber Assembly

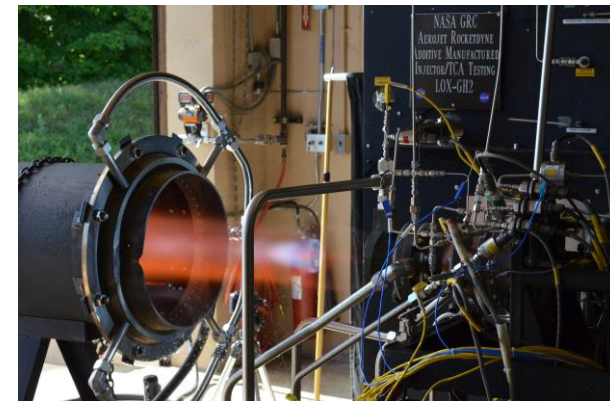
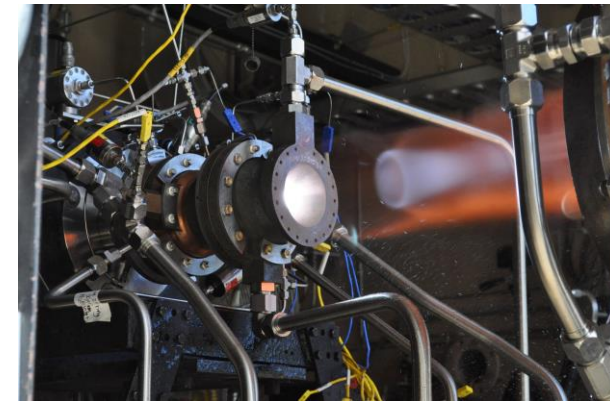
- Funded by NASA Game Changing Development Program
- Objective: Hot fire test an Additively Manufactured (AM) sub-scale rocket engine thrust chamber assembly with RL10 full-scale features

### Key Accomplishments:

- 19 successful ignitions across four different engine configurations
- >35 seconds of total hot fire time
- The targeted flow rates and chamber pressures were achieved on each run and were in-line with pre-test predictions

### Significance:

- Successful ignitions with Inconel AM injector
- First ever hot fire test of an AM copper component
- Identification of potential for improved performance and cost savings
- Enabled verification of AM component functional requirements, validated AM design tools and paved the way for RL10 full scale infusion



## RL10 Additive Manufacturing System Study with Aerojet Rocketdyne

- Down select of high payback parts of the RL10 engine to be manufactured by additive manufacturing process
- Engineering and verification effort to certify the selected components are ready for production transition.
- High payback parts include
  - Injector inter propellant plate,
  - Injector fuel manifold,
  - Turbopump Mount Brackets

### Work in Progress:

- AM all-inclusive RL10 injectors
- AM injector core
- NDE testing of AM components at AR and GRC
- Full-scale RL10 testing with AM components
- Structural testing of gimbal with AM attach brackets

### Significance:

- RL10 cost savings due to AM infusion will save NASA/DOD millions of dollars over the next 20 years







- At GRC we are leveraging our core competencies in materials and propulsion to further the development and implementation of Additive Manufacturing for rocket engine applications.
- We have developed a characterization database for Electron Beam Melted Ti-6Al-4V, which includes tensile, fatigue, and fracture data at temperatures relevant to the engine operating environment.
- We are in the process of developing a similar database for Selective Laser Melted copper alloy GRCop-84 for combustion chamber liner applications.
- We have successfully performed hot fire testing to demonstrate the performance of additively manufactured components.