



Additive Manufacturing Research and Development at the NASA Glenn Research Center

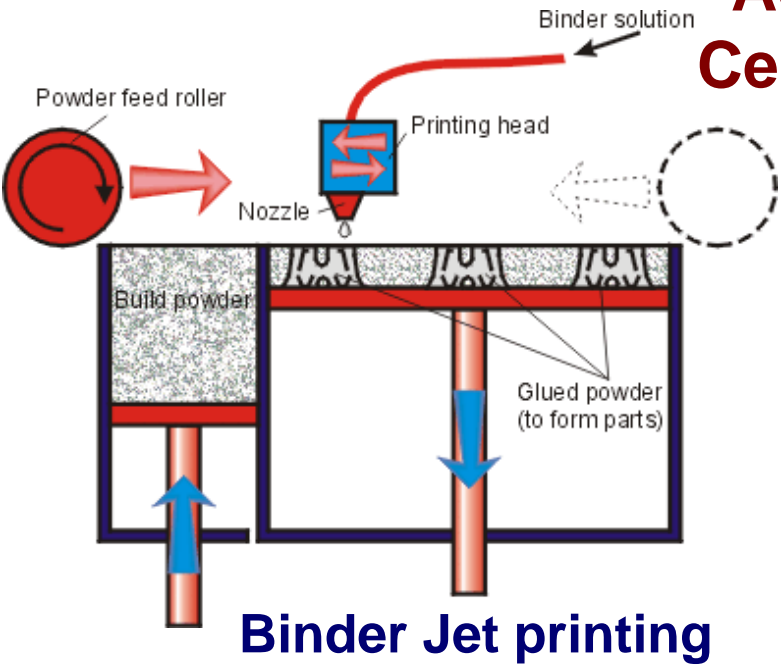
Robert Carter
NASA GRC



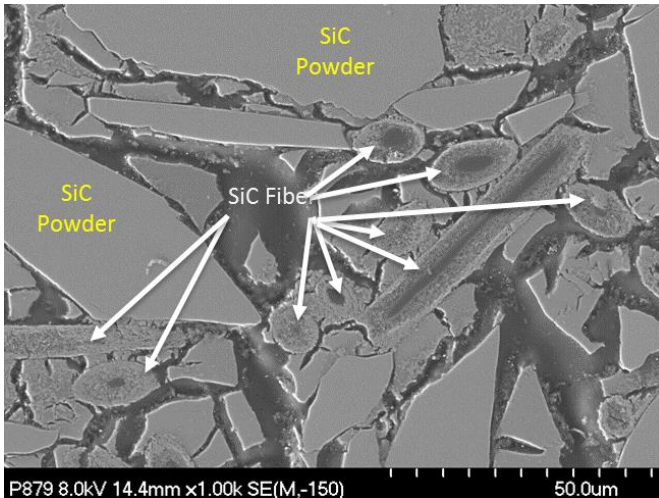
GRC AM Background

- Focus on High Temperature Materials for Power and Propulsion
- We have extensive materials development and characterization capabilities, and are gradually increasing our in-house AM capability
- We are working with other Centers and Agencies on the development of standards and specifications

Additive Manufacturing of SiC-Based Ceramics Using the Binder Jet Process



ExOne's Innovent and M-Flex print machines



Chopped Fiber Reinforced Ceramic Matrix Composite



High pressure turbine nozzle segments: cooled doublet vane sections.

Direct Printing for Innovative Stator Designs for Electric Motors

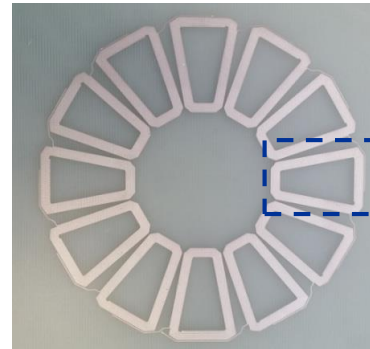
Objective: Utilize additive manufacturing methods to achieve new motor designs that have significantly higher power densities and/or efficiency.



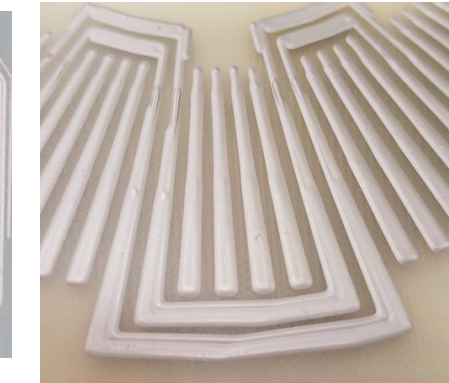
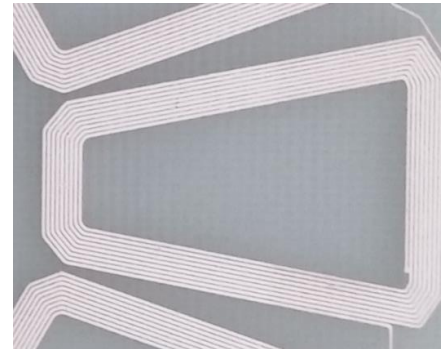
Axial Flux Machines – pancake motors



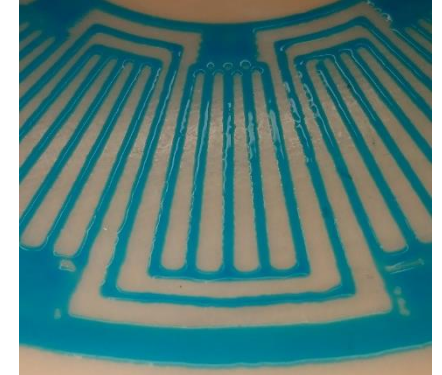
NScript Machine and SmartPump



NASA GRC Direct Printed Concentrated Windings



Silver Conductor Print Layer



Dielectric Print Layer

Supported by the Compact Additively Manufactured Innovative Electric Motor (CAMIEM) Sub-Project under the NASA CAS Project

RL10 Additive Manufacturing Study



RL10 Additive Manufacturing Study (RAMS) between NASA Glenn and Aerojet-Rocketdyne sponsored by USAF

- 3-Year task to characterize AM parts for the RL10 engine and execute an engineering and verification effort to transition selected parts to production

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

Process: Electron Beam Melting (EBM) performed at the NNSA's National Security Campus in Kansas City

Characterization Data Obtained:

- Chemistry, microstructure of powder and manufactured samples
- Non-Destructive Evaluation
- Thermo-physical properties
- ~360 mechanical tests performed including tensile, LCF, HCF, Fatigue crack growth, fracture toughness from cryogenic to 300 °F temperatures from 2 lots of material

NASA/TM—2016-219136



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

*Susan L. Draper, Bradley A. Lerch, and Jack Telesman
Glenn Research Center, Cleveland, Ohio*

*Richard E. Martin
Cleveland State University, Cleveland, Ohio*

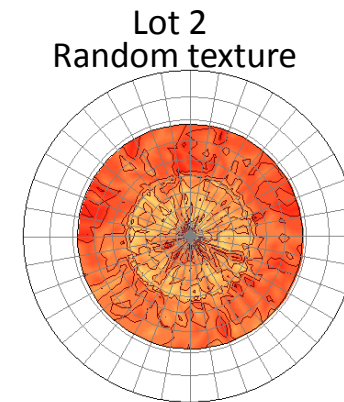
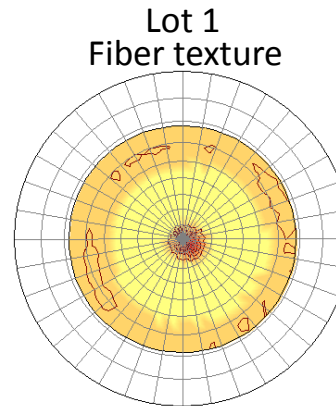
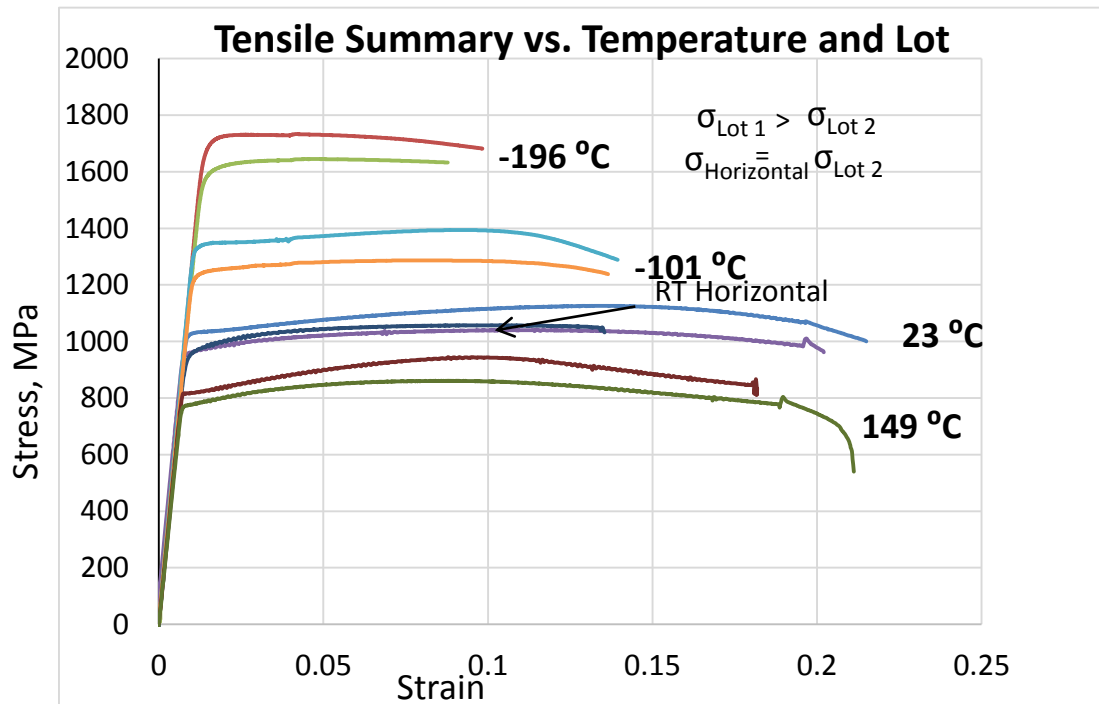
*Ivan E. Locci and Anita Garg
University of Toledo, Toledo, Ohio*

*Andrew J. Ring
Ohio Aerospace Institute, Brook Park, Ohio*



September 2016

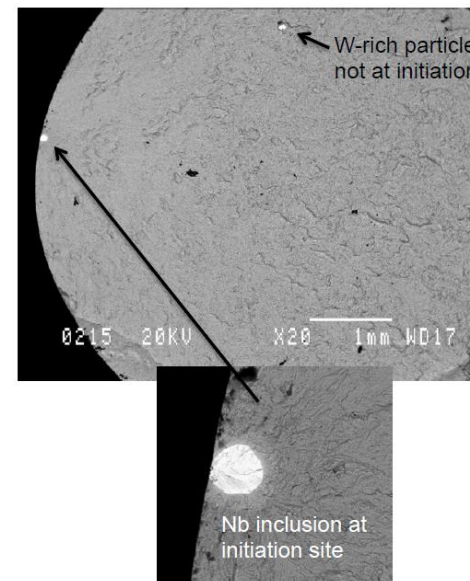
RL10 Additive Manufacturing Study



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

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 material texture, and therefore strength.
- Elemental Nb particles found at fatigue failure initiation sites. Nb likely came from feedstock powder. Results illustrate importance of powder quality.



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

Low Cost Upper Stage Propulsion



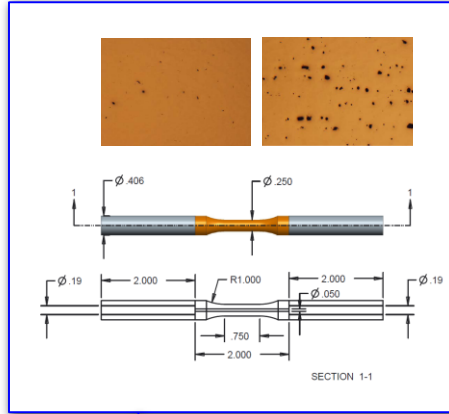
NASA Multi-Center Project funded by STMD's Game Changing Development Program.

Objectives:

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

Processes:

- GRCop-84 Combustion Chamber Liner produced at MSFC using Selective Laser Melting (SLM)
- Alloy 625 structural jacket applied to the liner using EB Free Form Fabrication (EBF³) at LaRC



66th International Astronautical Congress, Jerusalem, Israel. Copyright ©2015 by the International Astronautical Federation. All rights reserved. One or more authors of this work are employees of the government of United States, which may preclude the work from being subject to copyright in United States, in which event no copyright is asserted in that country.

IAC-15-C2.9.3

MATERIALS CHARACTERIZATION OF ADDITIVELY MANUFACTURED COMPONENTS FOR ROCKET PROPULSION

Robert Carter
National Aeronautics and Space Administration, Glenn Research Center, U.S.A., robert.carter@nasa.gov

Susan Draper, Ivan Locci, Bradley Lerch, David Ellis, Paul Senick, Michael Meyer, James Free
National Aeronautics and Space Administration, Glenn Research Center, U.S.A.

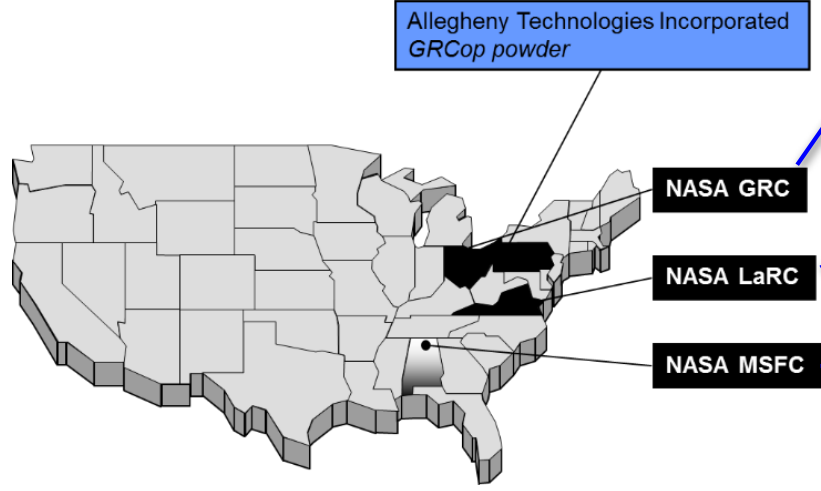
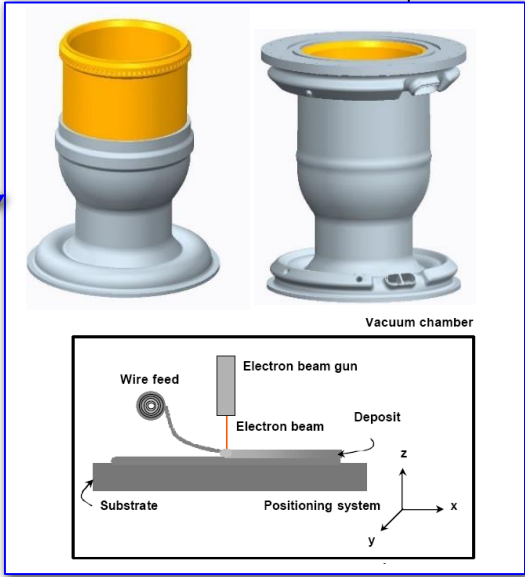
Ken Cooper, Zachary Jones
National Aeronautics and Space Administration, Marshall Space Flight Center, U.S.A.

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

Paul R. Gradl¹, Sandy Elam Greene², Dr. Christopher S. Protz³
NASA Marshall Space Flight Center, Huntsville, AL 35812

Dr. David L. Ellis⁴, Dr. Bradley A. Lerch⁵
NASA Glenn Research Center, Cleveland, OH 44135

Dr. Ivan E. Locci⁶
University of Toledo, Cleveland, OH



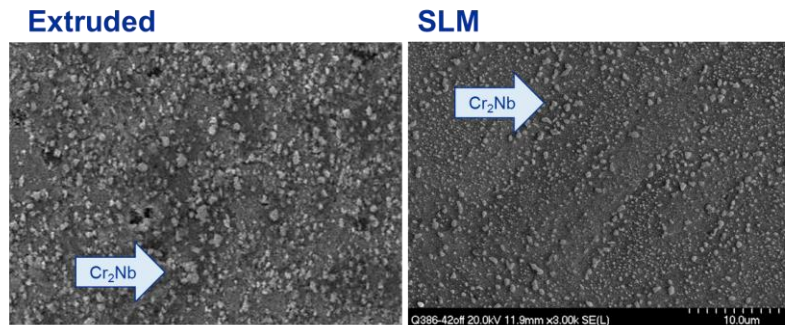
Low Cost Upper Stage Propulsion

Three Sets of Material properties / Material characterizations are being performed at NASA Glenn:

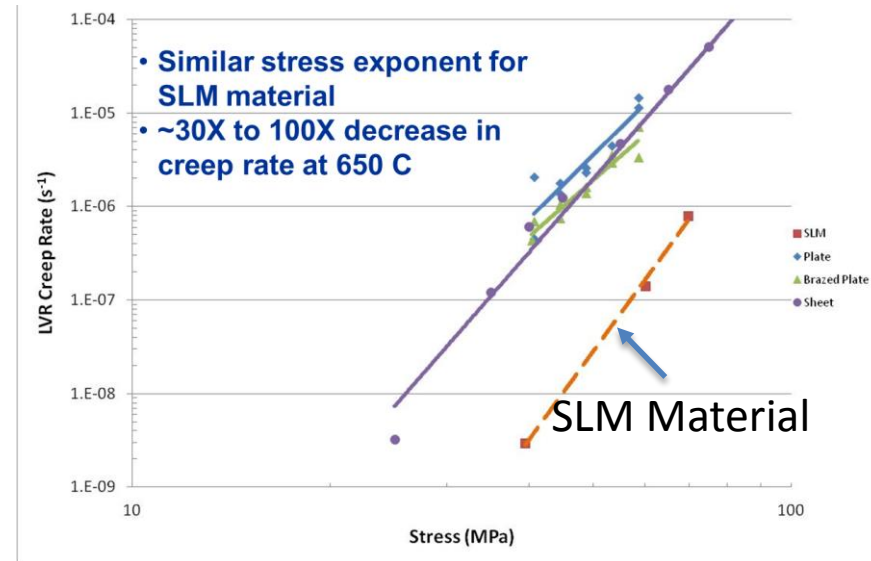
1. SLM GRCo-84 Liner
2. EBF³ Alloy 625 Jacket
3. Joint between GRCo-84 and Alloy 625

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)



- Images reveal fine, uniform distribution of Cr₂Nb plus some Cr precipitates
 - Better dispersion than baseline extruded GRCo-84
 - Should improve mechanical properties



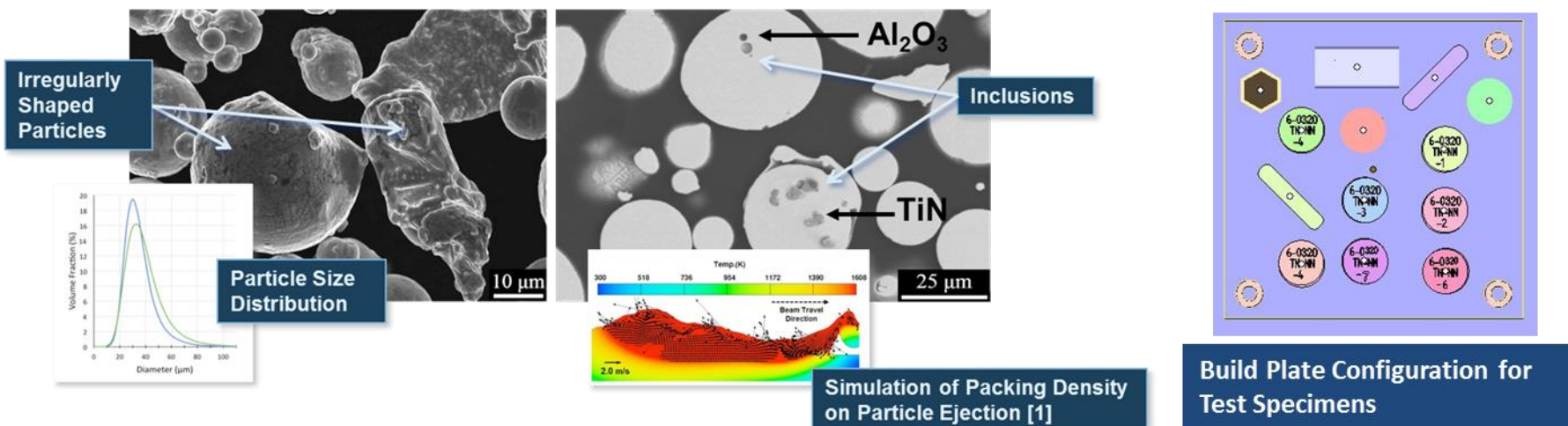
Creep Testing

Significant Finding – SLM breaks up and disperses agglomerated strengthening particles. This improves mechanical properties, and could be significant for other dispersion strengthened alloys or carbide strengthened alloys like Haynes 230.

Description: Multi-Center project to provide technical data to support certification of additively manufactured rocket propulsion components

NASA Glenn's Role:

- Obtain a comprehensive understanding of feedstock controls for SLM 718
 - From powder to processing to properties
- Ascertain acceptable ranges for these controls to inform NASA standards
- Determine and make recommendations for maximum powder recyclability limits





AM Standards for Manned Spaceflight

- NASA and its partners in human spaceflight (Commercial Crew, Space Launch System, and Orion Multi-Purpose Crew Vehicle Programs) are actively developing additively manufactured parts for flight as early as 2018.
- To bridge the standards gap, NASA Marshall Space Flight Center (MSFC) has authored a Center-level standard to establish standard practices for the Laser Powder Bed Fusion (L-PBF) process.
- In its draft form, the MSFC standard has been used as a basis for L-PBF process implementation for each of the human spaceflight programs.

About the MSFC Standard



- Originally drafted a Center-level MSFC requirement (Jul 2015)
- Peer Review (Aug – Oct 2015)
- Revised version in two parts: standard and specification
- Final versions currently in release cycle
- Watching progress of standards organizations and other certifying Agencies (ongoing)
- Incorporate AM requirements at an appropriate level in Agency specifications (later)



Questions