Development and Hotfire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications

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NASA and industry partners are working towards fabrication process development to reduce costs and schedules associated with manufacturing liquid rocket engine components with the goal of reducing overall mission costs. One such technique being evaluated is powder-bed fusion or selective laser melting (SLM), commonly referred to as additive manufacturing (AM). The NASA Low Cost Upper Stage Propulsion (LCUSP) program was designed to develop processes and material characterization for GRCop-84 (a NASA Glenn Research Center-developed copper, chrome, niobium alloy) commensurate with powder bed AM, evaluate bimetallic deposition, and complete testing of a full scale combustion chamber. As part of this development, the process has been transferred to industry partners to enable a long-term supply chain of monolithic copper combustion chambers. To advance the processes further and allow for optimization with multiple materials, NASA is also investigating the feasibility of bimetallic AM chambers. In addition to the LCUSP program, NASA's Marshall Space Flight Center (MSFC) has completed a series of development programs and hot-fire tests to demonstrate SLM GRCop-84 and other AM techniques. MSFC's efforts include a 4K lb_f thrust liquid oxygen/methane (LOX/CH4) combustion chamber. Small thrust chambers for 1.2K lb_f LOX/hydrogen (H2) applications have also been designed and fabricated with SLM GRCop-84. Similar chambers have also completed development with an Inconel 625 jacket bonded to the GRCop-84 material, evaluating direct metal deposition (DMD) laser and arc-based techniques. The same technologies for these lower thrust applications are being applied to 25-35K lb_f main combustion chamber (MCC) designs. This paper describes the design, development, manufacturing and testing of these numerous combustion chambers, and the associated lessons learned throughout their design and development processes.

I. Introduction

Additive Manufacturing (AM) technologies continue to evolve and mature creating opportunities for application to liquid rocket propulsion systems. Several new individual techniques and combinations of techniques appear to offer options to mitigate production time and significantly reduce cost and schedule in liquid rocket chambers and nozzles, if the enabling technology challenges can be solved. Specifically, high pressure/high temperature combustion chambers and nozzles must be regeneratively cooled to survive their operating environment, causing their design fabrication to be costly and time consuming, due to the number of individual steps and different processes required. Traditional cooled chambers and nozzles require either the closeout of milled passages or the bonding of tubes together.

For closeouts, the techniques of electrodepositing or Hot Isostatic Pressing (HIP) braze operations are typically used. Selective Laser Melting (SLM) offers a new approach to fabricate pre-closeout coolant passages and makes alternate processes viable for creating a structural jacket, and these new processes can significantly reduce fabrication costs and schedules. For nozzles, additive techniques such as SLM, directed energy deposition (DED) and direct metal deposition offer the opportunity to "print" one-piece units as opposed to joining hundreds of tubes together or closing out milled passages. NASA has been investigating several of the new additive manufacturing techniques to determine their viability and to better understand the available savings offered. These techniques include:

- Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS)
- Laser Cladding such as Directed Energy Deposition and Direct Metal Deposition

- Freeform Blown Powder Deposition
- Direct metal Deposition
- Arc-based Deposition
- Electron Bear Freeform Fabrication

NASA LOW COST UPPER STAGE PROPULSION (LCUSP) PROGRAM

Over the past three years NASA's LCUSP program has developed AM technologies and design tools aimed at reducing the costs and manufacturing time of regeneratively cooled rocket engine components. LCUSP is a multi-center project with the project management and design leads at the Marshall Space Flight Center (MSFC). MSFC is also the lead in developing and optimizing the SLM manufacturing process for GRCop-84 (a copper, chrome, niobium alloy). Langley Research Center (LaRC) is the lead in developing and optimizing the EBF^3 manufacturing process to direct deposit a nickel alloy structural jacket and manifolds onto an SLM manufactured GRCop-84 chamber. Glenn Research Center (GRC) is the lead in developing and characterizing materials properties and characterization for both the SLM manufactured GRCop-84 and the EBF^3 Inconel.

One of LCUSP's goals is to advance these technologies to the level that can then be used to fabricate a test article that can be used to advance the technology readiness level (TRL) of the techniques [1]. Testing of a 4K lb_f thrust class methane cooled chamber printed from GRCop-84 has been completed, as discussed below, advancing the TRL of printed GRCop-84 in these applications. A 35K lb_f thrust chamber assembly (TCA) as shown in Figure 1 is under fabrication to demonstrate the bi-metallic technology of EBF^3 jacketing applied to SLM GRCop-84. In addition, this TCA will include an integrated nozzle / film coolant ring (INFCR) designed and procured by LCUSP to advance one-piece SLM Inconel nozzle technology. And finally, testing will conclude with the addition of a Carbon-Carbon (C-C) nozzle extension as a pathfinder test to evaluate high temperature domestically produced C-C radiatively-cooled extensions for upper stage engines [2]. The LCUSP TCA is to be tested at MSFC with a previously demonstrated SLM injector at a chamber pressure of 1400 psia [3,4].

Under LCUSP, AM technologies in SLM GRCop-84 and EBF^3 Inconel 625 have been significantly advanced. The SLM development of the process for GRCop-84 and the resulting material properties data collected to date has been described in references [5] and [6]. In general, properties are in family with traditionally manufactured GRCop-84 with the exception of High Cycle Fatigue (HCF) life. This reduction in life is likely due to the inherent surface roughness of the SLM process, and it is believed that in applications where surface finishing operations can be applied, this life would be comparable to traditional GRCop-84, as well. A fully printed 2-piece chamber is also shown in Figure 2.

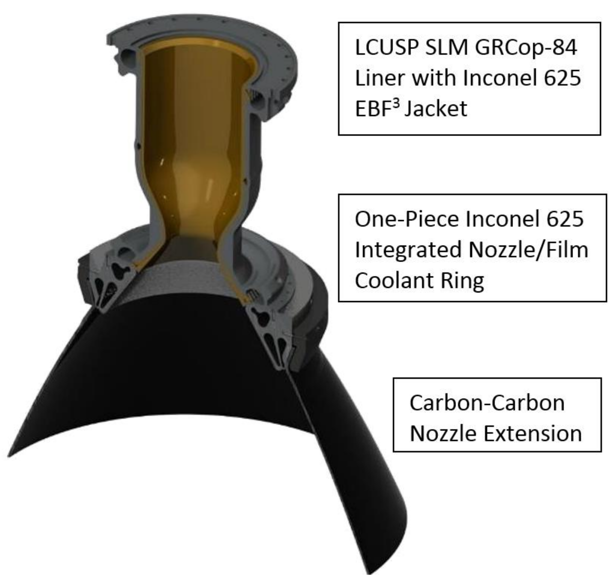

Figure 1. LCUSP Thrust Chamber Assembly.

Figure 2. 3D Printed Chamber Sections for LCUSP.

Methane Cooled 3D Printed Chambers

Since 2005, MSFC has been designing, fabricating, and hot-fire testing thruster components for LOX/methane applications at thrust levels up to 7000 lb_f [7,8,9,10]. Along with injectors and igniters, a variety of chamber designs have been evaluated. Recently, MSFC has been designing chambers for regenerative cooling with methane. The initial unit was fabricated with AM using Inconel 718, and after it was successfully hot-fire tested, a similar unit was fabricated at MSFC with SLM using GRCop-84. Hotfire testing was completed on this unit at MSFC Test Stand 115 in July 2016. Figure 3 shows the unit installed on the facility, along with an image of a hot-fire test.

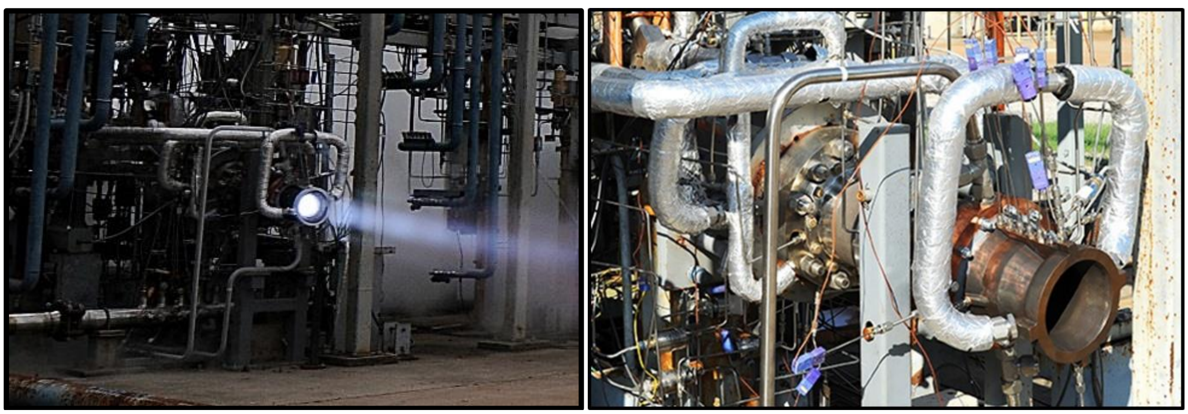

Figure 3. Methane Cooled SLM GRCop-84 Chamber Mounted & Hot-fire Tested at MSFC TS115

1.2K CHAMBER DEVELOPMENT

A 1.2K-lb_f thrust LOX/H2 chamber was designed to replace a heritage chamber (vintage 1960's design) for use as a new workhorse unit for TS115 subscale component testing. Due to the overall size of this chamber, it was a prime candidate to use the additive manufacturing GRCop-84 process developed under LCUSP. The chamber was designed as a one-piece unit to fit within the standard 250x250x250mm build boxes for the Concept Laser M2 at MSFC and ASRC Federal. The size of this hardware was also ideal for lower-cost fabrication and validation through hot-fire testing. An alternate design to the one-piece unit was considered that used the same hot wall contour and coolant channels, but focused on developing various processes for a bimetallic jacket and manifold interfaces. A slip jacket additively manufactured chamber is shown in Figure 4.

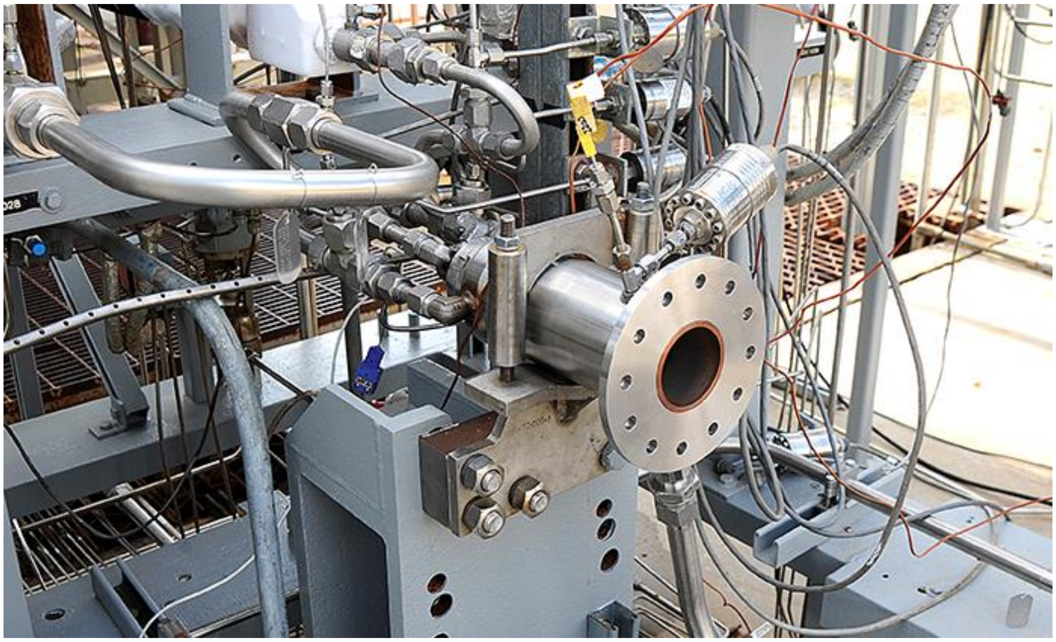

Figure 4. Chamber MER01446 with SLM GRCop-84 Liner Installed at TS115.

[1] Protz, C., Bowman, R., Cooper, K., Fikes, J., Taminger, K., Wright, B. **Additive Manufacturing of Low Cost Upper Stage Propulsion Components**. Joint Army-Navy-NASA-Air Force (JANNAF) Liquid Propulsion Subcommittee (LPS) Advanced Materials Panel (AMP) Additive Manufacturing for Propulsion Applications Technical Interchange Meeting (TIM); 3-5 Sept. (2014.)

[2] Gradl, P.R., Greene, S.E., Valentine, P., Crisanti, M. **Subscale Carbon-Carbon Nozzle Extension Development and Hot Fire Testing in Support of Upper Stage Liquid Rocket Engines**.
Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

[3] Barnett, G., Bullard, B. **Summary of Liquid Oxygen/Hydrogen, Direct Metal Laser Sintering Injector Testing and Evaluation Effort at Marshall Space Flight Center**, 62nd JANNAF Propulsion Meeting and Joint Meeting of the 10th Modeling & Simulation Subcommittee (MSS) / 8th Liquid Propulsion Subcommittee (LPS) / 7th Spacecraft Propulsion Subcommittee (SPS), Nashville, TN, June 1-5, 2015

[4] Bullard, B. **Design, Fabrication and Hot-fire Test of an Additively Manufactured Liquid Oxygen/Hydrogen 35-klbf Swirl Coaxial Element Injector**. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

[5] Carter, R. W., Ellis, D.L., Locci, I.E., Evans, L.J., Lerch, B., Jones, Z.C., Cooper, K. G. **Evaluation of GRCop-84 Produced Using Selective Laser Melting,** 62nd JANNAF Propulsion Meeting and Joint Meeting of the 10th Modeling & Simulation Subcommittee (MSS) / 8th Liquid Propulsion Subcommittee (LPS) / 7th Spacecraft Propulsion Subcommittee (SPS), Nashville, TN, June 1-5, 2015

[6] D. L. Ellis, B. A. Lerch, and R. W. Carter, I.E. Locci, **Microstructure and Properties of Additively Manufactured GRCop-84,** Joint Army-Navy-NASA-Air Force (JANNAF) Liquid Propulsion Subcommittee (LPS) Advanced Materials Panel Additive Manufacturing for Propulsion Applications TIM, Huntsville, AL, August 23-25, 2016.

[7] Elam, S.K; and Sprader, C.L: **Test Summary Report for Test Program P2514-Six-Inch Liquid Oxygen/Liquid Methane Injector Demonstration**. NASA TM 2008-215470. August 2008.

[8] Elam, S.K; and Sprader: **LOX/LCH4 Technology Demonstration - P8006A**, NASA TM2009-216268, December 2009.

[9] Elam, S.K.; Protz, C.; and Reynolds, D: **Design and Demonstration of a Liquid Oxygen/Liquid Methane (LOX/LCH4) Impinging Injector**. 54th JANNAF Propulsion Meeting, Denver, Colorado, May 2007.

[10] Klem, M., Smith, T., Wadel, M., Meyer, M., Free, J., Cikanek, H.A.., III. **Liquid Oxygen/Liquid Methane Propulsion and Cryogenic Advanced Development**. IAC-11-C4.1.5, E-17931. 62nd International Aeronautical Congress; Cape Town; South Africa. 3-7 Oct. (2011).