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

Paul R. Gradl[1], *Sandy Elam Greene*[2], *Dr. Christopher S. Protz*[3]
NASA Marshall Space Flight Center, Huntsville, AL 35812

Dr. David L. Ellis[4], *Dr. Bradley A. Lerch*[5]
NASA Glenn Research Center, Cleveland, OH 44135

Dr. Ivan E. Locci[6]
University of Toledo, Cleveland, OH

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 has completed a series of development programs and hot-fire tests to demonstrate SLM GRCop-84 and other AM techniques. NASA's efforts include a 4K lb_f thrust liquid oxygen/methane (LOX/CH4) combustion chamber and subscale thrust chambers for 1.2K lb_f LOX/hydrogen (H2) applications that have been designed and fabricated with SLM GRCop-84. 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.

Nomenclature

AM	=	Additive Manufacturing
BSE	=	Backscatter Electron
CT	=	Computer Tomography
DED	=	Directed Energy Deposition
DMD	=	Direct Metal Deposition
DMLS	=	Direct Metal Laser Sintering
EB	=	Electron Beam welding

[1] Combustion Devices Engineer, NASA Marshall Space Flight Center, Huntsville, AL 35812
[2] Combustion Devices Engineer, NASA Marshall Space Flight Center, Huntsville, AL 35812
[3] Combustion Devices Engineer, NASA Marshall Space Flight Center, Huntsville, AL 35812
[4] Materials Research Engineer, NASA Glenn Research Center, Cleveland, OH 44135
[5] Materials Research Engineer, NASA Glenn Research Center, Cleveland, OH 44135
[6] Principle Researcher, University of Toledo, Toledo, OH 43606

EBM	=	Electron Beam Melting
EBF^3	=	Electron Beam Freeform Fabrication
GH2	=	Gaseous hydrogen
GRC	=	Glenn Research Center
GRCop-84	=	NASA GRC Copper-alloy (Cu-8 at.% Cr-4 at.% Nb)
H2	=	Hydrogen
HCF	=	High Cycle Fatigue
HIP	=	Hot Isostatic Pressing
INFCR	=	Integrated Nozzle / Film Coolant Ring
K lb_f	=	thousand pounds of force (thrust)
LaRC	=	NASA Langley Research Center
LCUSP	=	Low Cost Upper Stage Propulsion
LCF	=	Low Cycle Fatigue
LOX	=	Liquid Oxygen
MCC	=	Main Combustion Chamber
META-4	=	Methane Engine Thrust Assembly for 4K-lb_f thrust
MSFC	=	Marshall Space Flight Center
PBF	=	Powder-bed Fusion
SEM	=	Scanning Electron Microscope
SLM	=	Selective Laser Melting
TCA	=	Thrust Chamber Assembly
TIG	=	Tungsten Inert Gas

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 (regen) 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. AM offers the design and fabrication options not previously possible with other manufacturing techniques including complex internal and integral design features. This allows for an overall reduction in the assembly and elimination of joints. Additive manufacturing is not a process that will replace all traditional processes, but it does provide significant advantages, and NASA is exploring the use of AM for chambers and nozzles through design, development and hot-fire testing.

While AM processes, specifically powder bed fusion (PBF) or selective laser melting (SLM), have matured over the last decade for a variety of materials, a limited number of metals are available using this process. SLM for aerospace components has primarily focused on superalloys. NASA, under the Low Cost Upper Stage Propulsion (LCUSP) program has advanced the printing process for copper alloys, specifically the NASA Glenn Research Center (GRC) developed GRCop-84 (Cu-8 at.% Cr-4 at.% Nb). This NASA-led project has matured the process significantly and also made process parameters and characterization data available to industry to enable commercial supply chains. Several industry partners have continued to advance the GRCop-84 material in addition to exploring other copper-alloys such as C-18150, C-18200, C-18000 and Glidcop.

The design focus for the SLM process of the GRCop-84 material has been on combustion chambers, where high-strength and higher thermal conductivity are required. GRCop-84 was developed at GRC as a non-heat treatable copper-alloy for reusable combustion chambers that increases strain and fatigue capabilities over traditional copper-alloys. GRCop-84 has been an ideal material suited for the SLM processing. Through a variety of complementary projects to the LCUSP program, NASA has designed, developed and tested combustion chambers using the SLM process and captured significant lessons learned.

Combustion chambers provide an ideal component for AM to contain the high pressure coolant and route the inlet and outlet manifold distributions. AM replaces several traditional processes into a single build step, but does require several post-processing operations, which will be discussed later in this paper. Traditional channel wall combustion chambers have been fabricated using a vacuum-casted and subsequent spun-formed or near net shape forged copper liner[1]. The liner is then final machined and slotted to form the coolant channels and required hotwall thicknesses. Closeout processes for the channels have included electrodeposition of copper and nickel or various methods of furnace and vacuum brazing, including pressure-assisted or Hot Isostatic Pressing (HIP) brazing[2,3,4].

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 (DMD) offer the opportunity to "print" one-piece units. NASA has been investigating several of the new AM techniques to determine their viability and to better understand the available savings offered. These techniques include:

- SLM or Powder-bed fusion, also known as Direct Metal Laser Sintering (DMLS)
- Laser Cladding such as Directed Energy Deposition and Direct Metal Deposition
- Freeform Blown Powder Deposition
- Arc-based Deposition
- Electron Beam Freeform Fabrication
- Cold Spray Deposition
- Hybrid techniques using a combination of the above techniques and also hybrid additive /subtractive technologies

While LCUSP was the primary development program, the benefit of the AM GRCop-84 process was realized early and several other programs were spun-off to enable further lessons learned of the process. NASA has completed a series of development projects to advance the technology readiness level (TRL) and manufacturing readiness level (MRL) for the GRCop-84 additive manufacturing process as well as downstream processing techniques. These design, development, manufacturing and test projects have enabled various lessons learned. They include lessons in the design process, processing of SLM supply chain from powder to complete part, post-processing, bimetallic deposition, and test operations of the AM components. These projects took place over 3 years from 2014 through 2017 and development work continues to improve upon the existing design and manufacturing processes being applied to other programs. Additionally, industry vendors have picked up much of the development work to continue the longer-term supply chain. The projects that will be discussed in this paper include the following:

1) Low Cost Upper Stage Propulsion (LCUSP) Program for 35K lb_f Engines
2) Thrusters for Liquid Oxygen (LOX)/Methane In-Space engine applications
3) 1.2K-lb_f Subscale Workhorse Test Chambers
    a) One-Piece workhorse
    b) Two-Piece workhorse
    c) Interchangeable Additive Liner Slip Jacket Chamber

Each of these programs had varying objectives to advance the AM technology. This included detailed design and analysis tools relative to the GRCop-84 AM process (design-for-AM), optimization of the AM build process, determining build feature limitations, post-processing (including powder removal, inspections, HIP, plate removal), assembly operations using welding techniques, machining strategies, and gathering hot-fire test data and build time on the AM material. The additive process provided the opportunity to complete builds of several chambers and feedback into the design cycle. Much of this learning was accomplished through build failures. The most common build failures observed were gross and micro-cracking resulting from residual stresses and material lifts caused by the re-coater arm/blade catching and often combined with short powder feeds. These build failures have led to redesigns of the chambers. The generic design changes to eliminate future failures often included thinning of material, addition of varying support features, or changing angles of walls and overhangs.

II. Overview of SLM GRCop-84 Processing and Material

A variety of copper-based alloys such as NARloy-Z (Cu-3 wt.% Ag-0.5 wt.% Zr) and C-18150 have been used for combustion chambers in prior and current programs[5]. Development work of GRCop-84 under the LCUSP program has advanced additive manufacturing of GRCop-84. Work is ongoing with plans to hot fire test at least one such section in the Fall of 2017 as discussed below, but some preliminary material properties have been generated on SLM processed GRCop-84 that indicate that the liners will have properties consistent with conventional wrought product tested under the Reusable Launch Vehicle - Second Generation (RLV 2nd Gen) program[6].

In SLM, a layer of powder tens of microns thick is spread on a flat plate. A laser melts the powder where solid material is desired to turn the loose powder into solid metal. Additional layers of powder are spread and selectively melted to form the desired shape. Loose powder is subsequently removed when the part is removed from the powder bed.

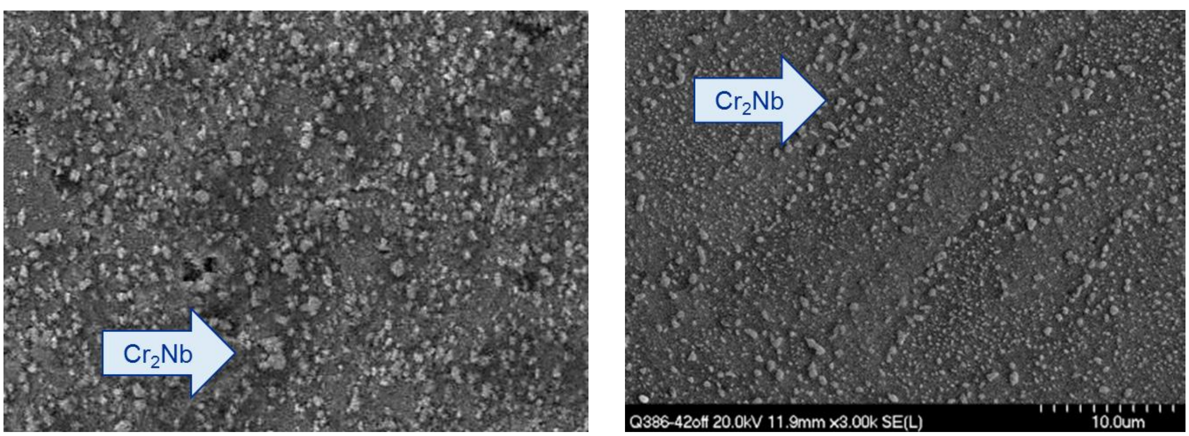
Several challenges exist in attempting to consolidate copper-based alloys using SLM. The first is that copper is highly reflective in the red and near infrared portions of the spectrum where many SLM machine lasers operate. The second is that the alloys are highly conductive, so any heat put into the powder bed is rapidly conducted away from the melt pool. These two issues can limit the ability of an SLM laser to effectively melt copper-based alloys and form a fully dense part with no unmelted powder incorporated into it.

GRCop and GlidCop, two alloys that have been considered for rocket engines in the past[7], have the unique problem that both are dispersion strengthened by a high melting point phase, Cr_2Nb and Al_2O_3, respectively. Both of these phases are less dense than copper and could float to the surface of the melt pool and segregate during SLM processing. Neither will be melted during normal SLM processing where the temperature of the melt pool is likely only a bit above the melting point of copper.

Finally, SLM processing leaves a surface finish roughly equivalent to the diameter of the powder used. Typically a powder cut in the -325 mesh (<40 micron) range is used for SLM. Using the powder diameter as an approximation of the surface finish, the as built surface would have the rough equivalent of a 63 microinch machined surface. While the exposed surfaces can be machined to a smoother finish, it is very difficult and more likely impossible to machine the interior cooling channels of liners and other SLM parts. The rough surface will increase turbulent flow during engine operation. This will increase the pressure drop but also increase the heat transfer to the coolant. Whether the increased benefits of greater heat transfer outweigh the increased pressure drop are likely going to be specific to each design, but designers do need to address the issue.

It was rapidly discovered that GRCop-84 was easily melted in the SLM process. Most likely, the 14 vol.% Cr_2Nb phase is partially responsible for a higher absorption of laser energy than pure copper and results in easier heating initially. The reflectivity of copper rapidly decreases with temperature, and the powder should absorb more energy from the laser and heat readily[8].

The microstructure of the SLM GRCop-84 was examined by sectioning witness samples made at the same time as the liner section. A typical micrograph is shown in Figure 1. For purposes of comparison, a micrograph of extruded GRCop-84 is also presented in Figure 1. In Figure 1, the Cr_2Nb is the lighter phase disperse in the darker copper matric.



(a) As-Extruded GRCop-84 **(b) SLM GRCop-84**

Figure 1. Backscattered Electron (BSE) Scanning Electron Microscope (SEM) Images of (a) Extruded and (b) SLM GRCop-84.

Two observations were made. First, the SLM process did not result in segregation of the Cr2Nb precipitates. This is likely due to turbulence in the melt pool mixing the molten and solid particles. Once the laser moves away, the liquid-solid mixture would be rapidly solidified by the conduction of heat out of the material through the GRCop-84 substrate. This apparently did not allow sufficient time for buoyancy effects to segregate the Cr_2Nb to the surface of the molten copper. The results was a very uniform distribution of Cr_2Nb throughout the sample.

The second observation was that the Cr_2Nb appears to have been refined in size. The Cr_2Nb present in the as-extruded material is actually an agglomeration of finer Cr_2Nb particles formed in liquid copper during the gas atomization process. It appears that thermal and perhaps mechanical forces acting upon the agglomerations break them up and form the finer particles seen in the SLM sample. This is important because basic strengthening mechanisms such as Ashby-Orowan strengthening predict that the strength of a material will be increased as the average diameter of the particles is decreased[9].

Room tensile testing was conducted on a limited number of as-built specimens and samples that underwent a Hot Isostatic Pressing (HIPing or HIP) to close the fine porosity in the samples. The HIPing temperature was well above the normal 600 °C (1112 °F) annealing temperature of GRCop-84. The average stress-strain curves are shown in Figure 2.

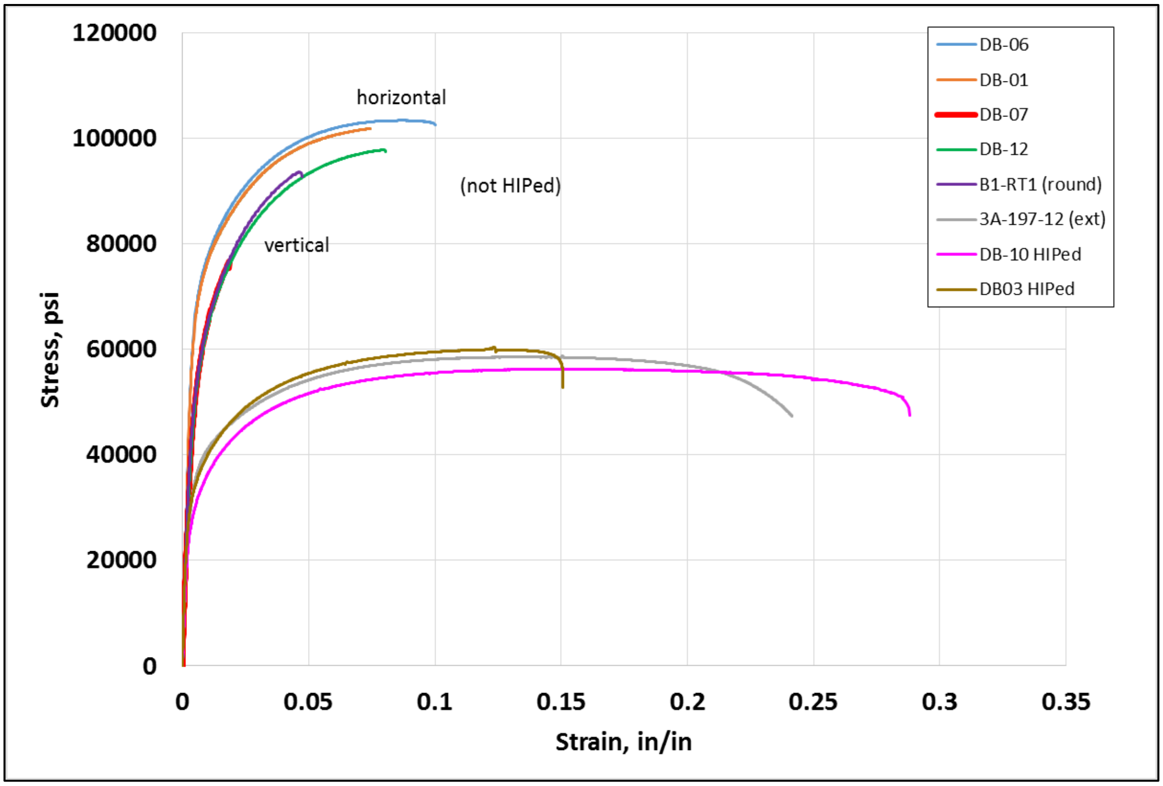


Figure 2. Average Room Temperature Stress-Strain Curves for SLM GRCop-84 in the As-Built and HIPed Conditions.

Three things were immediately apparent. The first observation was that there was significant anisotropy in the as-built samples between the vertical or Z direction (parallel to the build direction) and the horizontal direction (in the plane of the powder layers). The horizontal direction was almost 10% stronger, on average than the vertical direction.

The second observation was that the as-built samples were much stronger than the HIPed samples and had lower ductility as measured by the tensile elongation. These indicate that large compressive residual stresses were present in the as-built samples. After HIPing, the material, the strengths returned to values similar to those of extruded GRCop-84, and the elongations increased. This was taken to indicate that there was a full anneal of the GRCop-84 during HIPing.

The third observation was that the tensile elongations of the HIPed SLM GRCop-84 were much greater than those of the baseline extruded material. It is unclear why the elongations increased, but it is most likely due to the finer Cr_2Nb particles being more effective at strengthening the copper matrix and allowing the matrix to strain more before failure.

Not shown in Figure 2 but documented elsewhere, HIPing and other high temperature thermal excursions will decrease the strength of GRCop-84 relative to the baseline extruded material. In this case, the finer Cr_2Nb particles resulted in additional strengthening and raised the strengths to be equivalent to that of the extruded material. This improvement indicates a potential benefit to using SLM and similar AM processes to consolidate GRCop alloys.

Creep testing also revealed that the material retains information from the SLM process. Figure 3 shows a backscattered electron image of a creep sample fracture surface. Parallel lines were observed on the surface that appear to correspond to the hatch pattern. These regions normally did not have microvoids that are typical of GRCop-84 failures. While there does not appear to have been a severe problem with lack of fusion, these patterns may indicate that there are further improvements possible through improved bonding between layers.

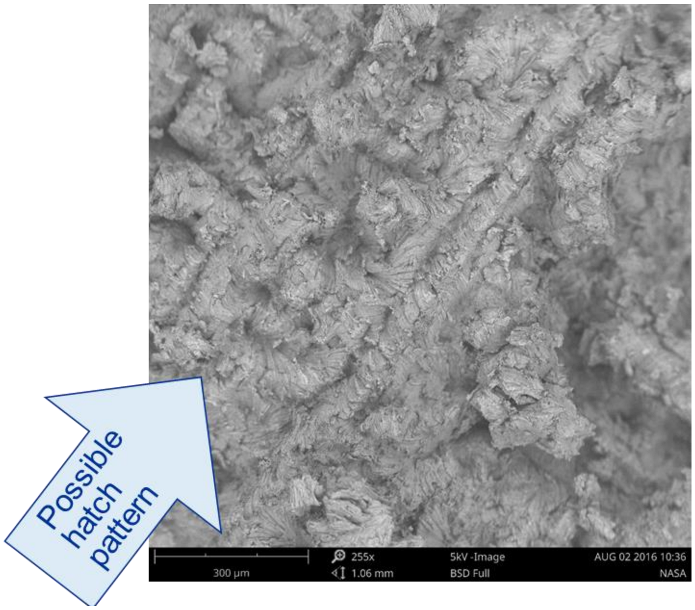


Figure 3. Fracture Surface Of Creep Sample. (Photos courtesy of Phenom).

Low Cycle Fatigue (LCF) occurs in rocket engine liners due to thermally induced stresses when the interior of the liner attempts to expand when heated by the combustion of the fuel while the exterior is both cooled and restrained by the jacket. Strains can easily exceed 1%.

As noted earlier, the cooling channel walls could not be machined to a smooth surface. To test the combined effects of both the surface roughness and the SLM processing on the room temperature LCF properties, an LCF sample was additively manufactured that had the conventional polished exterior surface but also had a circular channel extending the length of the sample. The channel was not machined and retained the as-built surface finish.

As can be seen in Figure 4, the LCF samples initiated cracking on the rough interior surface at multiple locations as expected. The cracks appeared to grow in a manner consistent with prior LCF testing of GRCop-84. The LCF lives of SLM GRCop-84 are compared to results for prior LCF testing of GRCop-84 consolidated by HIPing using the same parameters as the SLM material in Figure 5. Not unexpectedly, the lives were reduced, but the reduction was relatively small, given the extremely rough interior surface. While not tested yet, it is likely that conventional smooth LCF samples will have as good or better properties than the conventionally processed materials tested previously.

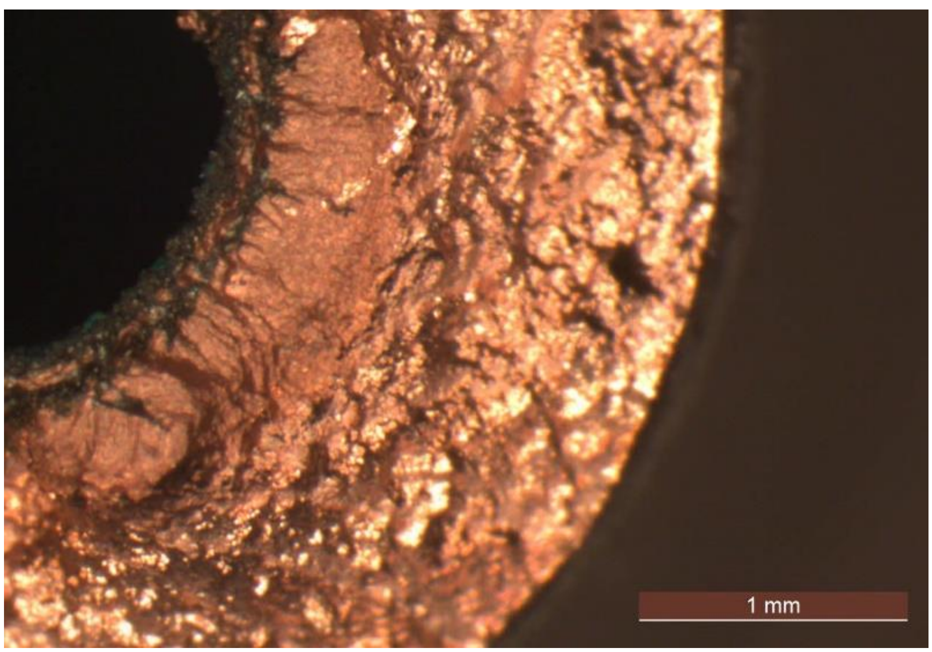


Figure 4. Fracture Surface of LCF Specimen Showing Multiple Initiation Sites and Cracks Emanating from the Rough Interior Surface.

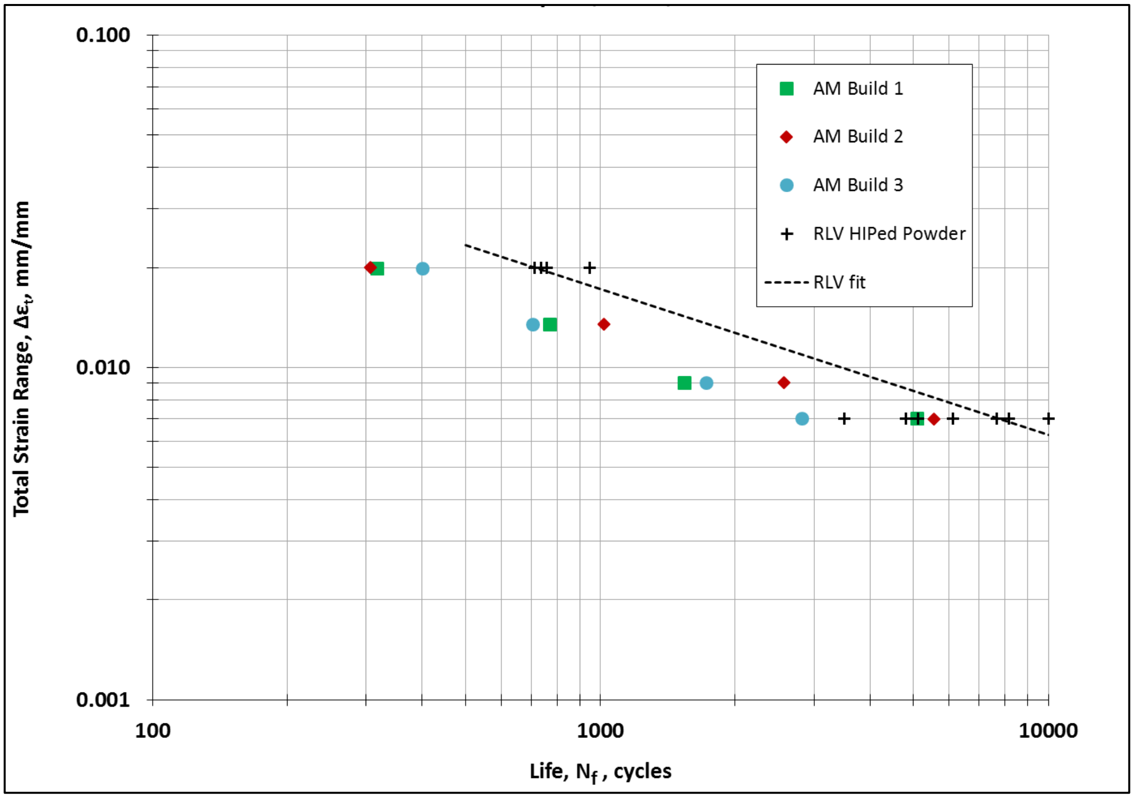


Figure 5. Room Temperature Low Cycle Fatigue Lives of HIP Consolidated and SLM Processed GRCop-84.

For reusable rocket engines, creep and other time dependent properties become a concern. The SLM GRCop-84 was tested at 500 °C, 650 °C and 800 °C (932 °F, 120 °F and 1472 °F) at various stresses. The strain was measured using an optical measurement system. Both the steady-state creep rate and rupture life were determined. Creep rate results for the 650 °C testing are shown in Figure 6. Compared to conventionally processed GRCop-84 samples, the SLM GRCop-84 samples have a much lower creep rates and longer creep lives. The slope of the creep rate curve is equivalent, which means that the creep stress exponent remains the same. The consistency between the two data sets indicates that the creep mechanism remains constant. Most likely, the finer Cr_2Nb particles act as more efficient pinners of grain boundaries and dislocations, thereby strengthening the SLM GRCop84 better and increasing the creep properties.

It has been noted in the past that GRCop-84 has significant scatter in creep testing. That can be seen in the conventional material results shown in Figure 6. In contrast, the SLM results fall almost perfectly on a straight line, and where repeats have been done in the testing, excellent repeatability is observed. The cause of this improvement must lie with the SLM process since the test rigs and the material remains otherwise constant. Regardless of the cause, S-basis minimum creep properties are improved due to the lack of variability.

Overall, the properties of SLM GRCop-84 are equal to or exceed the properties of conventionally processed GRCop-84 with the exception of the LCF lives. The LCF lives are shortened by the multitude of crack initiation sites that result in premature failure of the sample.

The benefits of SLM processing may extend to some other additive manufacturing processes. Electron Beam Melting (EBM), which also has a turbulent melt pool, likely will have similar results. Other processes such as binder jet printing where there is no mechanism to refine the Cr_2Nb particles will likely not result in improved properties. More likely, the mechanical properties will remain similar to the HIPed or extruded and thermally cycled conventional GRCop-84.

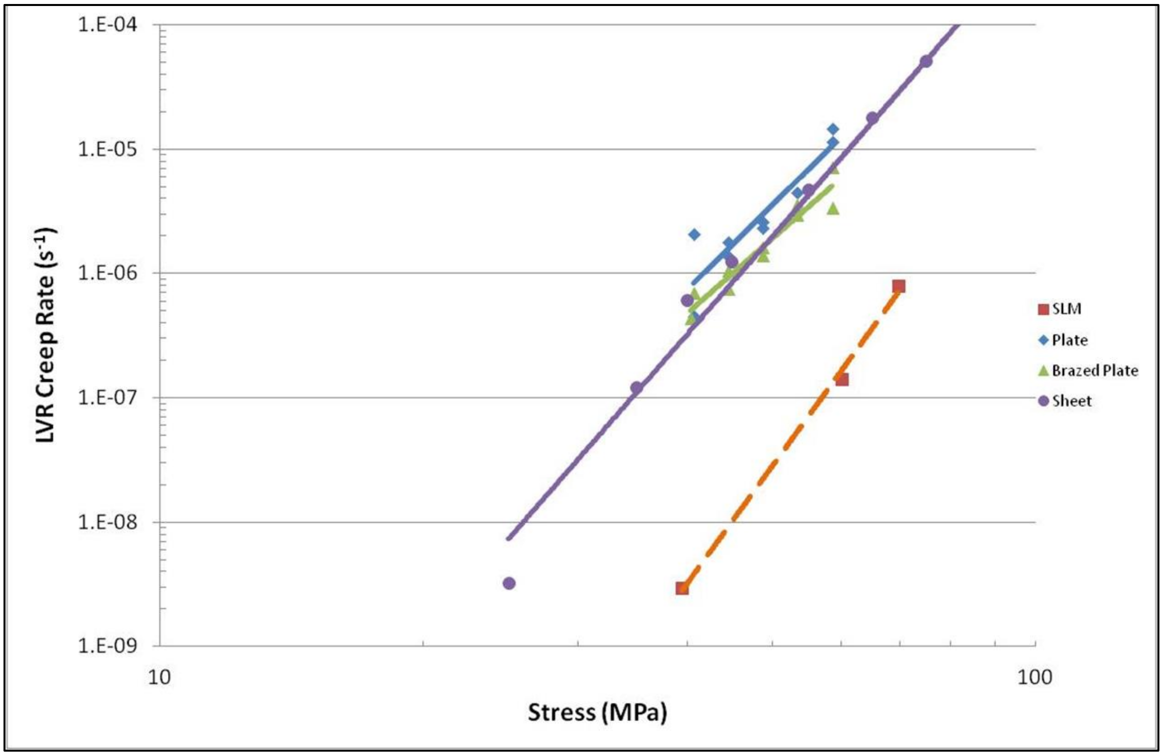


Figure 6. 650 °C (1472 °F) Creep Rate of Conventionally Processed and SLM GRCop-84.

III. Low Cost Upper Stage Propulsion (LCUSP) Program

Starting in 2014, 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 LOX/hydrogen (H2) systems. 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. Langley Research Center (LaRC) is the lead in developing and optimizing the Electron Beam Freeform Fabrication (EBF^3) manufacturing process to direct deposit a nickel alloy structural jacket and manifold preparation regions onto an SLM manufactured GRCop-84 chamber. GRC is the lead in developing and characterizing materials properties and characterization for both the SLM manufactured GRCop-84 and the EBF^3 Inconel and the joint between the two.

One of LCUSP's goals is to advance these technologies to the level that can then be used to fabricate a test article to advance the TRL of the techniques[10]. 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 7, is under fabrication to demonstrate the bi-metallic technology of EBF^3 jacketing applied to SLM GRCop-84. In addition, this thrust chamber assembly (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 to evaluate high temperature, domestically produced, C-C radiatively-cooled extensions for upper stage engines[11]. The LCUSP TCA is to be tested at MSFC with a previously demonstrated SLM injector at a chamber pressure of approximately 1400 psi[12,13].

Under LCUSP, AM technologies in SLM GRCop-84 and EBF^3 Inconel 625 have been significantly advanced. In general, properties are in family with traditionally manufactured GRCop-84 with the exception of High Cycle Fatigue (HCF) life as previously described. 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. Sections for a fully printed 2-piece chamber are shown in Figure 8, and the LCUSP unit that is planned for hot-fire testing is shown in Figure 7b.

Figure 7.(a) LCUSP Thrust Chamber Assembly and (b)Hot Fire Test Article after joining and EBF^3 Deposition – Image (b) Courtesy Karen Taminger

Figure 8. 3D Printed Chamber Sections for LCUSP.

Figure 9 shows an example of the low porosity that can be achieved when SLM processing GRCop-84. As the process was developed it became clear that faster laser scan speeds produced more porosity in general, however trials also showed that porosity could be reduced with a HIP cycle. In the baseline process selection, a trade was made to accept some porosity in the un-HIPed state in order to speed the fabrication of parts, having demonstrated that the HIP cycle could produce results like shown below. In addition to the material properties characterization of the SLM GRCop-84, one sample with a hot wall thickness characteristic of liquid rocket combustion devices, with characteristic coolant passage dimensions over a 1” length, has been proof pressure tested to 2000 psia with no signs of leakage, and a 4K lb_f thrust class methane cooled chamber has been hot-fire tested after the successful repair of one layer-to–layer non-lamination.

There are several areas that future GRCop can improve upon the aforementioned process. The core parameters can be optimized for a higher production rate by increasing the space of hatching before density degradation is observed. The contours can be further optimized for small improvements in the surface finish. However, these are marginal improvements on what has proven to be a very robust and successful process development[14].

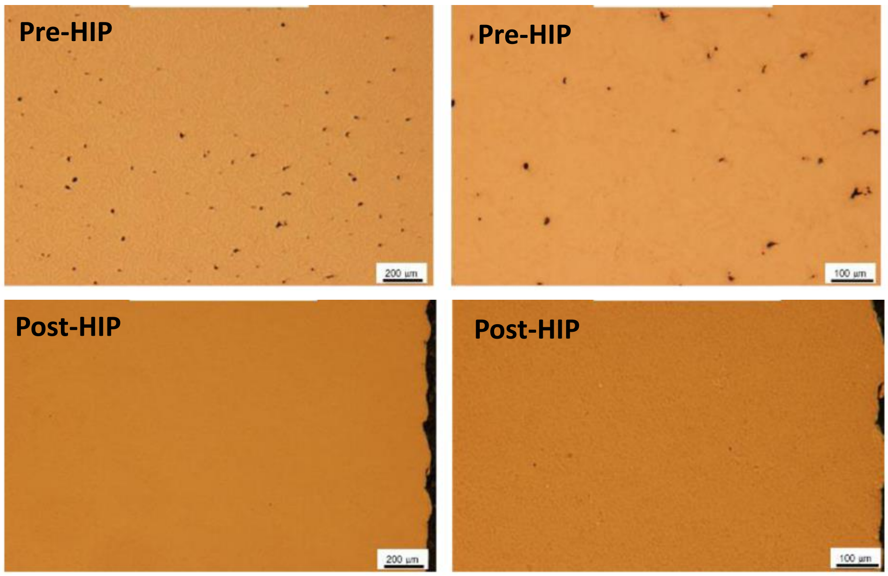


Figure 9. Pre and Post-HIP optical metallography of samples produced in GRCop-84 process development. Note – The dark area on the right of the lower image is the edge of the sample, not porosity.

The EBF^3 process used for bimetallic deposition in LCUSP utilizes a wire, fed in combination with an electron beam gun, to deposit material in an additive fashion and can be seen in Figure 10a [15,16]. Under the LCUSP project, LaRC has been developing processes to join Inconel 625 to SLM GRCop-84. Results to-date are promising, and samples have been shown to produce bond strengths in family with GRCop-84 parent material strength. Further process refinement has been performed in the last several months to address issues related to geometry and heat loading in the fabrication of a large combustion chamber, and the result is the unit shown in Figure 7b that is expected to undergo hot-fire tests. An example of the specimen failure can be seen in Figure 10b within the GRCop material.

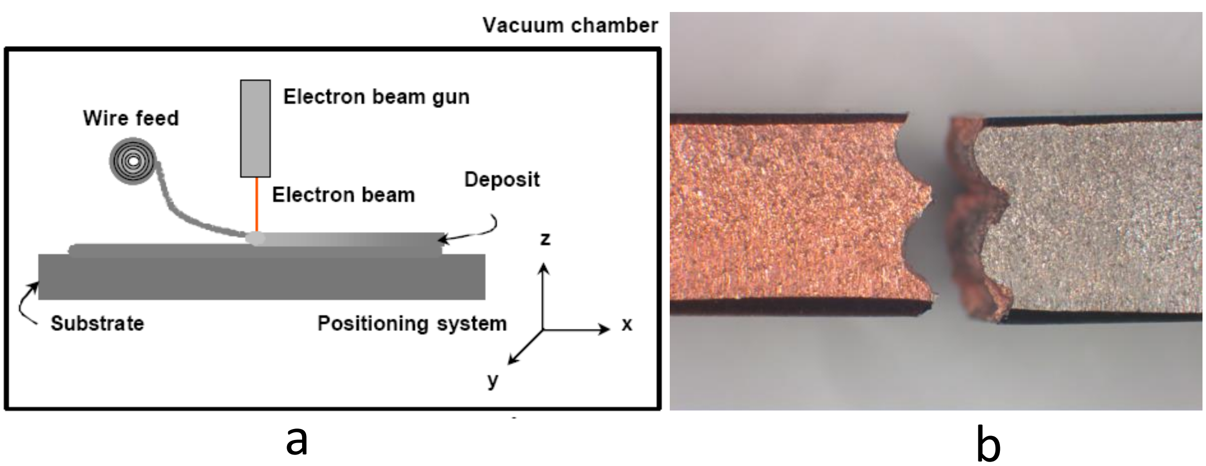


Figure 10. (a) EBF^3 Process and (b) Pull test specimen after test to failure on the GRCop-84 to EBF^3 Inconel 625 bond interface.

A. LESSONS LEARNED UNDER LCUSP

As the initial design was underway, the team was aware of historical lessons learned from SLM fabrication. Therefore, early builds consisted of wedges of the more complex geometries that would need to be printed. These wedges, like the one shown in Figure 11, demonstrated that features were printable before the team committed to full builds of chamber halves. Additional trial pieces were also printed to characterize the coolant passage feature sizes that would result from a certain model geometry. These articles were structured light scanned as shown in Figure 11 and demonstrated that for channel sizes down to 0.030", no model corrections were needed and the channels could be expected to be held to +/- 0.001".

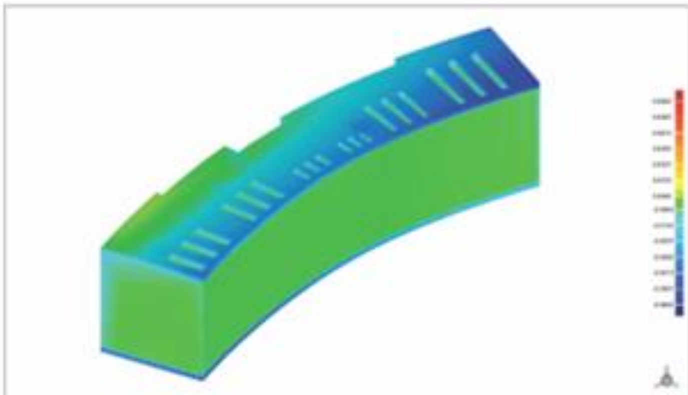


Figure 11.Structured light scan of a channel sizing part used to confirm model to as-built channel sizing.

Structured light scanning was also used as the parts flowed through the entire processes. One result of these scans, like the ones shown in Figure 12a, was to show that the SLM chamber halves held to <0.005" near the build plate and about 0.010" at the opposite ends of the build (maximum Z-height). Other scans later in the process flow show how the liner I.D. moved as further processes (HIP and EBF^3) were completed. HIP of the SLM liners resulted in nearly no movement, while the EBF^3 process had two interesting results. The first that the inner radius of the liner shrank on order of 0.070" and second that the exit diameter of the throat spool expanded outward [see Figure 12b]. This second result was mitigated later builds as the process flow was changed to reduce the amount of Inconel that will be deposited to the part and replace that with a forged close-out for the manifolds.

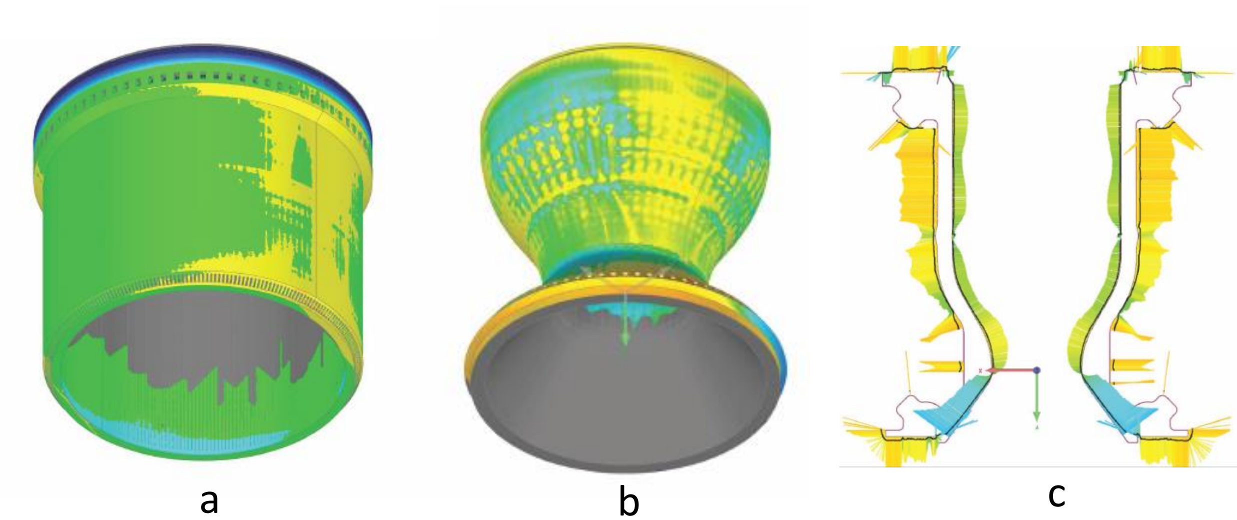


Figure 12. (a) Structured light scans of post SLM, post HIP chamber halves, (b) post-EBF3 deposition and post HIP joined unit and (c) 2D cross section of post-EBF3 deposition.

As SLM parts are typically printed in a full bed of powder, the powder must be removed from internal passages after the build completes. While this was considered a risk early on, because of the two-piece design of the LCUSP chamber, powder clearing was accomplished in 2 days. Pressurized air and sharp blows to the build plate were the primary methods utilized. Because all individual passages were exposed at the mid-chamber joint, it could be confirmed that each passage was clear. Water flow testing (see Figure 13) was performed to visually confirm that all channels were cleared by the gas flow, and it was discovered that one of the channels was partially blocked. Water pressure and sharp blows cleared this passage also. Later designs for other parts included SLM printed manifolds, and powder removal in these cases was more difficult as discussed later in this paper.

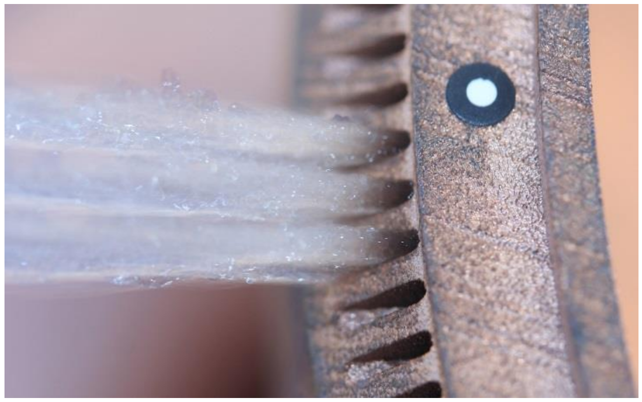


Figure 13. Water flow testing to confirm all channels were clear. In the LCUSP chamber design, one inlet feeds three channels, as illustrated by the flow shown.

As the required chamber length exceeded the build box dimensions of the SLM machine utilized for fabrication of these parts, a method of joining the two chamber halves had to be developed. An EB weld was selected, as the parts would be in LaRC's EBF^3 machine for deposition. The LaRC developed process parameters for the EB weld of SLM GRCop-84 and demonstrated it on SLM trial rings as shown in Figure 14. This also resulted in process efficiencies as the parts were then already on the mandrel and ready for the next phase, Inconel jacket deposition, as soon as the EB beam weld was complete at the halves. While the initial attempt on this joint was successful, in order to further ease fabrication the joint has been further refined to create a continuous copper alloy substrate for the Inconel deposition.

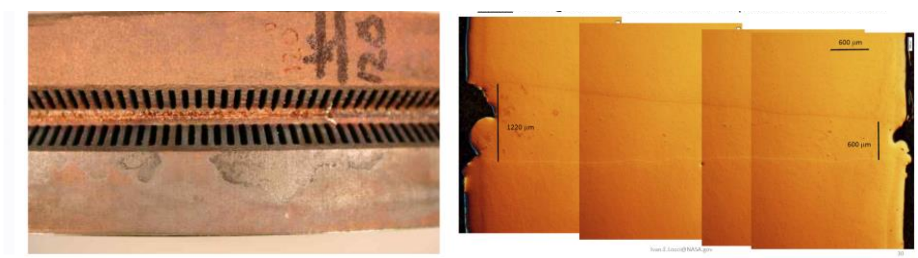


Figure 14. Chamber Halves Joint Trial EB Weld.

Structured Light Scanning was found to be a highly effective tool for characterization of the results of these additive processes. Scanning provided data relative to positional tolerance and feature sizes of SLM parts, data about movement of the materials as they were subjected to these additive processes and data that could be used to compare the as-modeled parts with the as-deposited state post deposition. Figure 15 shows an example of the scan data compared to the model data for an early manufacturing demonstrator unit. The green is the scan data and the black line is the model. Several features become clear. First, the green line is inside of the black line on the top of the figure below, showing how the part compressed toward the centerline. The top black line is the SLM GRCop-84 substrate and did not have Inconel deposited in that region, so the movement represented movement of the substrate. Second, regions where the process limitations prevented deposition of the minimum required material are shown as regions where the green line is far outboard of the black line.

This information is useful for iterating on future redesigns and serves to quantify the limits of the types of features that can be deposited. Note that more material deposition is not an unrecoverable flaw as it can be machined away, but it does add cost and the potential for additional residual stresses to build up as compared to a minimal deposition. And finally, regions where the green line is in board of the black line show regions where not enough material went onto the part. With additive processes, it is possible to end up with too little material on a part if the process does not feed material at the right time. This is compared to subtractive machining, in which the tool must make contact in an undesired region in order to have more material removed than planned. Part scanning and comparisons likes these serve as relatively quick checks to confirm the additive process deposited enough material.

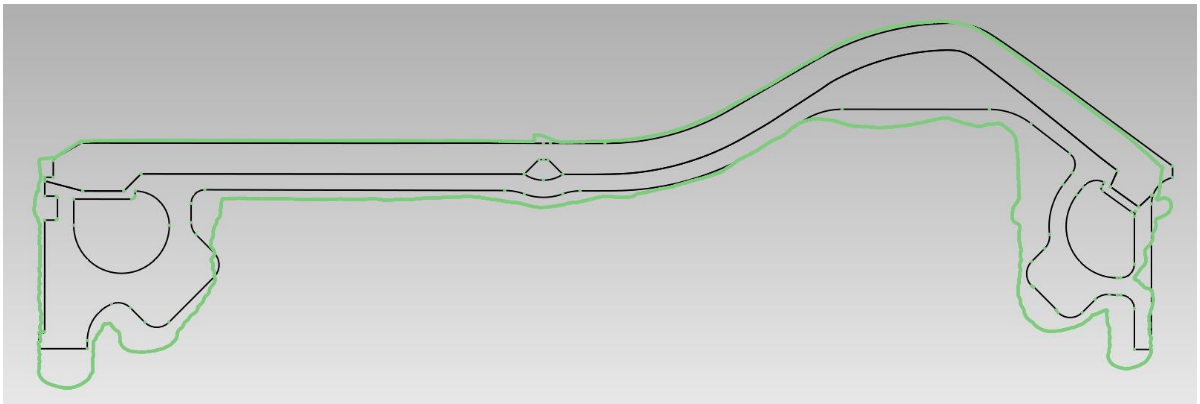


Figure 15. Comparison of Design Model (CAD) and post EBF3 Structured Light Scan Data Outer Mold Lines to Check for Minimum Material in All Locations. [Courtesy of Will Brandsmeier, NASA MSFC].

A technique utilizing the combination of structured light scanning with CT information and the design model were utilized together proved very valuable in these additive processes, as well. Figure 16 shows how the structured light scan, the CT scan, and the model can be overlaid to provide a rapid assessment of both the external feature characteristics of the AM part as well as the internal feature characteristics as compared to the model also. In Figure 16 it can be seen that the inside of the manifold contours did not match the curve of the design. This information can be utilized to estimate knock-down factors for use in revised structural modeling of the as-built geometry.

Figure 16. Overlay of Design (CAD), Structured Light Scan (3D Scan) and CT Scan Information. [Courtesy of Will Brandsmeier and EM20, NASA MSFC].

Finally, CT scans in comparison to the model geometry were found to be very useful for disposition discrepancies. On demonstrator unit, it was evident that some EBF^3 Inconel 625 had collected in the region of the coolant passage inlets and outlets, but external visual inspections were indeterminate as to whether the passages were blocked. CT scans were taken. Overlaying these scans with the model served to orient the viewer as to what the CT slice in that region should look like. When coolant passages are built in to the part and turn back to allow for manifolding, it creates some potentially confusing slices that contain multiple sets of passages. The overlay of the model showed that in this case clearly that the passages were blocked. This information was critical in order to disposition the part and to help make an informed decision as to whether repair or rebuild would be a more effective go-forward solution.

To date, development units have been fabricated and destructively evaluated to understand the full process development. A final printed and cladded unit is currently in fabrication. The LCUSP project will begin hot-fire testing at MSFC Test Stand 116 in Summer 2017 after the final unit has been produced.

IV. GRCop-84 Methane Engine Thrusters At MSFC

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[17,18,19,20]. Along with injectors and igniters, a variety of chamber designs have been evaluated. Recently, MSFC has been designing chambers for regenerative cooling with methane[21,22]. The initial unit was fabricated as a throat section with AM using Inconel 718, and after it was successfully hot-fire tested, a similar throat section unit was fabricated at MSFC with SLM using GRCop-84.

Shown in Figure 17, the coolant channels were printed into this first GRCop-84 design, so that no separate closeout layer was required. Since the operating pressures were low enough, this unit did not require a separate structural jacket – the thickness of the copper was sufficient for containing pressure. The design included unique features to gather discrete data for evaluating performance and anchoring thermal models for methane cooled systems. Additional printed features included the inlet and exit manifold volumes, along with an inlet boss for a threaded interface. The only welding required was to attach the forward flange. This flange, which provided the bolt hole pattern to mate the chamber with adjacent hardware, had to be welded on since its diameter would not fit in the print volume available with the Concept Laser M2 unit at MSFC. The only machining required was tapping threads for each port and polishing for the mating seal surface.

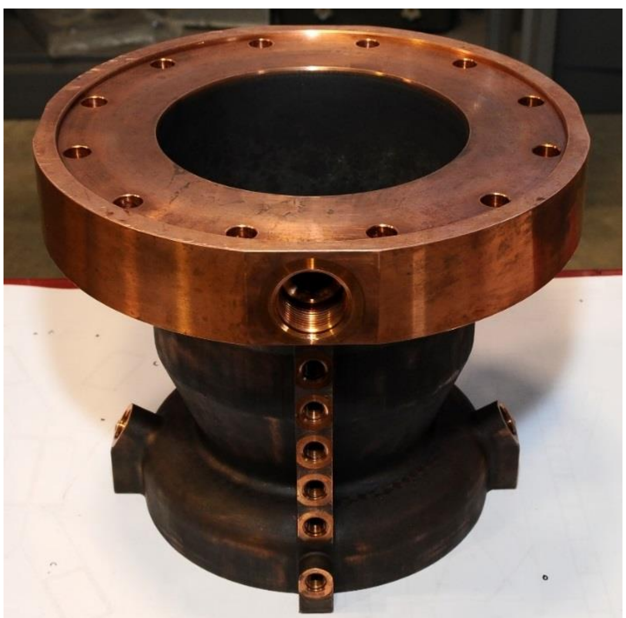


Figure 17. Methane Cooled SLM GRCop-84 Throat Section Chamber.

This unit required multiple print attempts and design changes were made after each to produce a successful part. Figure 18 shows the unit on its build plate. In early attempts, printing failed in the open volume of the inlet manifold. The open volume had to be reshaped with proper angles and varying support features to achieve success. Similar angles were included in the exit manifold volume. Also in the upper portion of the chamber, additional material had to be printed in to properly support the upper edge.

Figure 18. Methane Cooled GRCop-84 Throat Section on Build Plate.

Hot-fire testing was completed on this throat section chamber at MSFC Test Stand 115 (TS115) in July 2016. Figure 19 shows the unit installed on the facility, along with an image of a hot-fire test.

Figure 19. Methane Cooled SLM GRCop-84 Throat Section Chamber Mounted & Hot-fire Tested at MSFC TS115. [Photo credit: David Olive/MSFC]

The data from this methane cooled throat section chamber was used to optimize the design for the full length chamber used in MSFC's Methane Engine Thrust Assembly for 4K lb_f (META4). META4 includes a LOX/methane injector and igniter, previously developed and demonstrated at MSFC, mated with a full length, regeneratively cooled, GRCop-84 chamber fabricated with SLM.

Due to its overall length, the chamber is printed in two sections to fit in the print envelope in the available Concept Laser M1 and M2 machines. Chamber sections for the first unit were printed at MSFC, while those for the second unit are being printed at Arctic Slope Technical Services (ASTS) in Huntsville, AL.

Liquid methane is provided to the inlet manifold at the aft end. An open volume for this manifold is printed in, but the complete volume is created by welding on the closeout of the manifold. While the entire manifold structure could have been printed, MSFC intentionally left the printed portion of the manifold open to allow for easier powder removal and channel inspections. The closeout portion of the manifold was machined from a traditional copper alloy.

At the forward end, the open manifold allows the fuel to be directed into the fuel side of the mating injector. This open area of the printed structure also allowed for easy powder removal. A forward copper flange was welded on to create the bolt patterns required for the injector assembly and facility mounting.

Using SLM allowed unique coolant channel features to be included, since for this design, the methane coolant operates in subcritical conditions, with a phase change occurring just upstream of the throat.

Hot-fire testing on the first META4 unit was successfully performed in March 2017. Figure 20 shows the completed assembly installed at MSFC's TS115 and an image of one of the hot-fire tests. Test conditions challenged the GRCop-84 chamber at high mixture ratio (MR) conditions, and the chamber remained well overcooled, showing high performance margins for potential throttle conditions. The results for this initial META4 chamber were used to determine design changes required for the second unit to make fabrication and assembly efforts easier, while still maintaining high performance. The second META4 chamber unit is expected to be completed and available for testing at MSFC in October 2017.

An alternate version of META4 has been designed to create a smaller thruster for potential engine applications. The inner diameter (I.D.) of the META4 chamber at the injector end is close to 6", in order to use an available, high performance injector developed under previous LOX/methane technology programs at MSFC. META4x4 uses an injector end I.D. of 4" to create the same design and operational features as META4, but packaged with a smaller injector that still allows 4000 lb_f thrust at a slightly higher chamber pressure. The first unit of META4x4 is expected to be available in late 2017.

A smaller version of META4 is also being developed as MET1 – Methane Engine Thruster for 1000 lb_f. This unit can be used for engines that require lower thrust, or it can be clustered for higher thrust applications. The MET1 assembly will use an injector printed with SLM Inconel 625, along with an SLM GRCop-84 chamber. Its smaller, regeneratively cooled chamber requires a shorter length that can be printed in one-piece, instead of the two piece design for META4 and META4x4. Figure 21 shows a conceptual image of MET1. Its chamber and injector are currently being printed at MSFC, and the first completed MET1 assembly is expected to be available for testing at MSFC later in 2017.

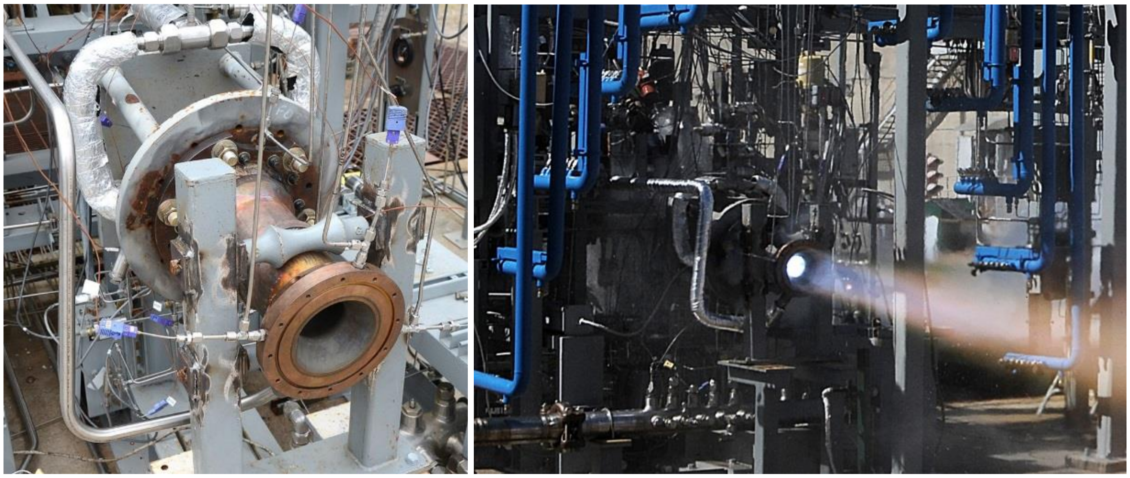


Figure 20. META4 Mounted & Hot-fire Tested at MSFC TS115. [Photo credit: David Olive/MSFC]

Figure 21. MET1 Concept Unit.

V. 1.2K Chamber GRCop-84 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 MSFC TS115 subscale component testing. Due to the overall size of this chamber, it was a prime candidate to use the AM GRCop-84 process. The chamber was designed as an integral one-piece unit to fit within the standard 250x250x250mm build boxes for the Concept Laser M2 at MSFC and various vendors. The size of this hardware was also ideal for lower-cost fabrication and validation through hot-fire testing. A series of these workhorse chambers were designed that allowed for varying configurations as the process was being developed and lessons learned. The development 3D printed chambers included: 1) One-piece combustion chambers, 2) Two-piece chambers, 3) bimetallic chambers and, 4) Slip-Jacket chambers. The objectives of these chambers were to allow iterations of design changes while understanding the process and minimize test cost to prove the technology in a relevant environment.

These new workhorse chambers were designed to meet chamber pressure up to 1100 psia and a range of MR requirements, in addition to 2000 psig coolant pressure for both water-cooling and gaseous hydrogen cooling. The nozzle contour aft of the throat was modified for full expansion of the flow to allow for longer nozzles to be tested, such as composite nozzle extensions and regeneratively-cooled channel wall nozzles[23]. The channels were optimized to minimize wall temperatures with pressure drop being a secondary consideration since it is used as a development workhorse unit. This enabled a rapid design process and minimized material for additive manufacturing. The baseline SLM chamber design channels had varying cross sectional area in the barrel, throat and nozzle sections. The SLM design allowed a smooth transition design between varying aspect ratios to minimize pressure drop in these regions. A constant hot wall thickness was maintained. The maximum wall temperatures are shown in Figure 22 and they are within previous test experience for the GRCop-84 material[24].

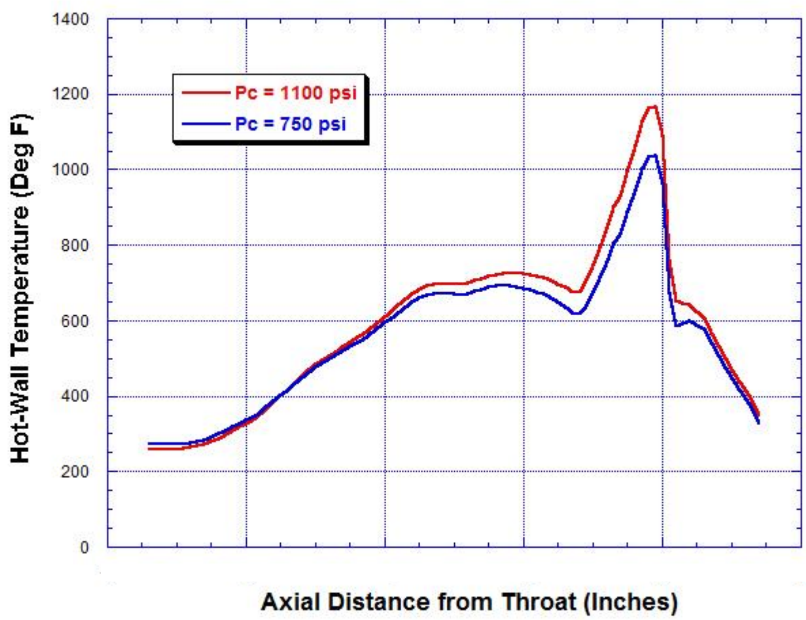


Figure 22. Thermal Analysis of 3D Printed GRCop-84 1.2K-lbf chamber (Ref. Van Luong/MSFC).

A. One-Piece Chamber Development

The design of the one-piece chamber shown in Figure 23 included integral features such as the liner and coolant channels, inlet and outlet manifolds and associated ports, as well as the forward and aft attachment flanges. All features were designed to meet the maximum 45-degree overhang rule with the exception of the small features such as the channels[25].

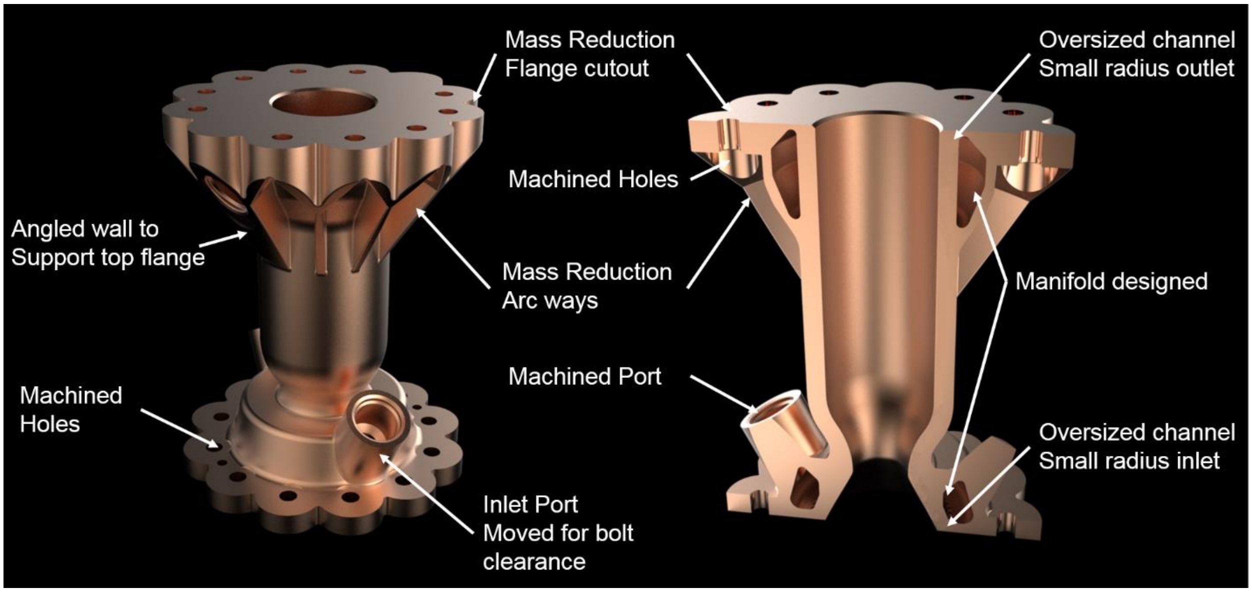


Figure 23. Additive design features in the 1.2K LOX/GH2 Combustion Chamber.

The initial SLM build of the one-piece chamber was completed at the MSFC materials lab. This build used a mix of virgin and recycled GRCop-84 powder, although exact mixing was unknown. The total build time for the chamber was approximately 14 days. Following completion of the build and removal from the build box, a start-stop knit line could be observed and also an area on the outer surface where some slight material curls were present. An initial attempt was made to remove powder from the chamber using a series of dead blows to the build plate and within thickened areas of the additive chamber. The chamber was then sent for Computer Tomography (CT) scanning to verify powder removal from the channels and manifolds. The first CT scan revealed a significant amount of powder was present with >60% of the channels still blocked, as shown in Figure 24. It was determined the best method to continue with powder removal was to drill and tap the ports to allow for pressurized air to help with powder removal. The chamber remained on the build plate for this operation.

The ports were each tapped manually using the port top surface as a primary datum and the outer circumference as the secondary datum for centerline alignment. A lesson learned has been to set up the ports manually (individually) for tapping instead of an automated computer numerical control (CNC) setup due to potential distortions from the build process. At this stage of fabrication small cracks were observed in the thinner regions of the ribs. These cracks were likely due to several conditions: 1) A stress riser as an artifact of the design, 2) Microcracks during solidification from the build, 3) A low cycle fatigue (LCF) or HCF condition present during the mallet blows from powder removal and machining of the ports, and 4) Brittleness of the material prior to the HIP conditioning[26]. These cracks were monitored and saw some slight growth during continued powder removal operations.

Following the port tapping, additional attempts were made at powder removal but continued to be a challenge. There was no visible powder emanating from the chamber after continued rotation and mallet impacts. It was determined that the build plate would dampen the mallet blows and not much of that energy was being imparted into the areas needed. The chamber was then removed from the build plate with a band saw; the build plate removal would have typically been completed following HIP. Several attempts were made to remove the powder including high pressure gaseous nitrogen (GN2) purges in conjunction with mallet impacts. A fair amount of powder was observed emanating from the part during these operations. However, an additional CT scan was run showing that 40% of the channels were still blocked. Several more attempts were made at powder removal, and it was finally decided to cut a groove in the outer diameter (OD) to allow direct access to the channels.

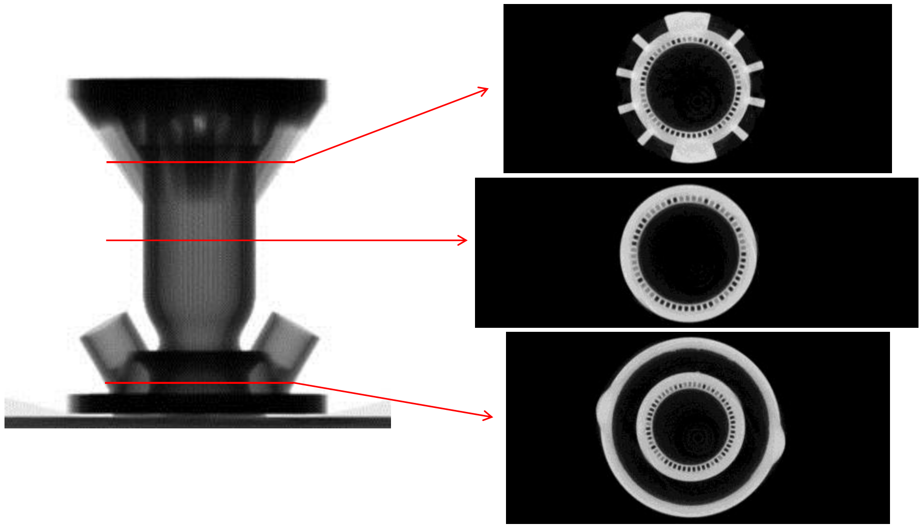


Figure 24. Computed Tomography (CT) scan data of One-piece 1.2K chamber with channel blockage.

The OD groove allowed for small diameter wire to be traversed up and down each one of the channels to help loosen and remove the powder. Several passes were made using this technique in addition to allowing the chamber (channels) to soak in alcohol for more than 12 hours and the use of alternating shop air within each of the channels. These techniques finally cleared a majority of the powder. A water flow test was conducted from the forward and aft end of the chamber revealing that each of the channels were flowing. A final CT scan was not conducted based on the visual evidence from the water flow test. A GN2 purge was maintained on the chamber to dry prior to HIP operations.

It was suspected that some of the recycled powder, most of which is sieved, may have caused some clumps to form due to the finer powder sizes. Other sources of contamination, such as moisture could have also been present - although that was unlikely since the powder was trapped within the channels. These channel sizes were very similar and, in most cross sections, larger than the LOX/Methane chambers described earlier in this paper.

The chamber was sent for a HIP cycle. A split ring was machined to match the groove to closeout the channels. The ring was machined from GRCop-84 billet stock as a cylinder and then electro-discharge machined (EDM) to provide the split. The first ring was fit for welding and observed to have a significant gap. A visual and caliper inspection revealed that the initial groove, cut prior to HIP, had deformed slightly after the HIP, causing the gap. The OD groove on the chamber was skim cut on both sides on the lathe and a second split ring manufactured to precisely fit.

The split ring was EB welded using a root penetration pass and a secondary cosmetic EB final pass. Initial development work demonstrated approximately the appropriate depth of penetration for the chamber weld, which required elevated EB weld parameters as typical with copper. The axial splits in the split ring were also initially EB welded and then cleaned up using a manual tungsten inert gas (TIG) repair. Several new cracks were also observed following the HIP cycle in the same location of the flange support ribs. Some of the cracks were observed in the area of one of the forward end outlet ports. All of these cracks were repaired using TIG and compatible filler material.

This initial chamber was proof tested after all welding, but several hot wall pinhole leaks were discovered at low pressures. The completed chamber and subsequent leaks can be seen in Figure 25. Initial EB weld setup demonstrated that consistent depth of penetration could be maintained with room temperature welding operations. However, as the copper heated up during welding of the full chamber, the depth of penetration increased by 2-3x that of the room temperature samples. The hot wall leaks were evident in the areas of the channels and not in the area of lands. This would support the increased penetration due to the increased heating of the material.

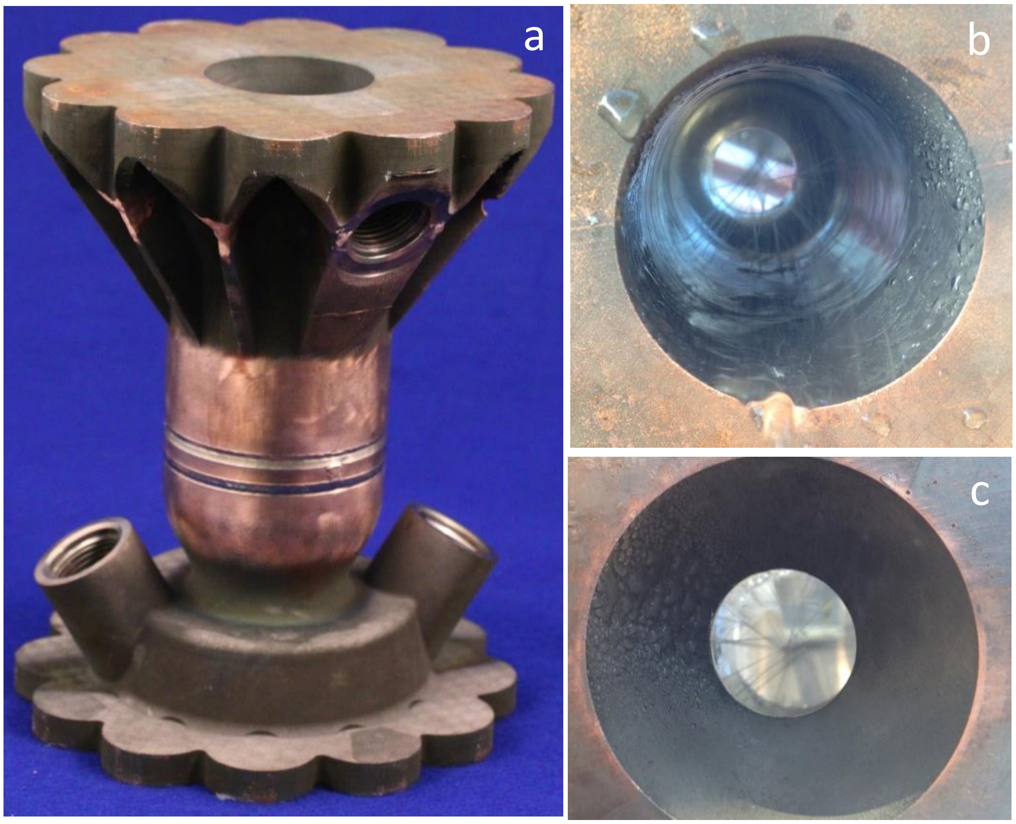


Figure 25. Completed 1.2K One-piece chamber: a) Completed chamber with EB weld of split ring and repairs of cracks, b) pinhole leaks during water flow from forward end, c) Pinhole leaks as seen from aft end in the area of the EB weld split ring.

Although this one-piece chamber was not tested, it provided several lessons learned during the design and development of AM GRCop-84-based combustion chambers. Several features have been modified to mitigate potential cracking during builds or during post-processing operations. Welding operations for the GRCop-84 were also developed that allows for future chambers to be welded using EB or TIG. Other design approaches were also learned during this one-piece chamber to aid with powder removal and other post-processing to reduce overall development cycle time.

B. Two-piece chamber development

Due to many of the issues discovered with the one-piece chamber assembly, a two-piece chamber assembly was designed that incorporated the lessons learned from the one-piece. Although the development process for the first unit of the one-piece chamber was described above, several additional units were attempted and found build failures during the SLM process following several design changes. These build failures included damaging the coater arm/recoater blade, which led to subsequent non-uniform material sintering and ultimately a unrecoverable build failure. Another build failure frequently discovered was curling of the material due to unsupported regions of excessive heat sinks. Based on the series of failures, the two-piece chamber was designed and fabricated.

The design of the two-piece was nearly identical to that of the one-piece including variable channels and integral manifolds and inlet and outlet ports. However, the two-piece chamber incorporates two (2) EB welds at the forward end of the chamber to fully close out the manifold area for distribution of the coolant. This two-piece chamber simplifies the powder removal since each of the channels can be directly pressurized following AM of the initial chamber portion. The forward manifold closeout is printed in a second print with the flange attached to the build plate. There is minor post-processing of this part. The design and AM fabricated two-piece GRCop-84 chamber can be seen in Figure 26.

The SLM process for GRCop-84 has gone through significant development to produce desirable surface finishes. The surface finishes do vary per machine and per vendor. The surface finishes are dependent on a number of variables including sintering and coater arm (powder-refresh) speeds, starting powder size, mix of virgin and recycled powder, oxidation, features, sintering pattern, and post-processing techniques. These factors are further complicated by the machine and the vendor being used for AM. Sample pieces were measured during development for the two-piece chamber and produced a surface finish of 400 µ-in. Other development work being completed has produced surface finishes ranging from 200-500 µ-in. Surface finish can affect several factors including mechanical properties, heat transfer, and hydraulic pressure drops, but the required surface finish is dependent on the final application. The as-produced surface finish was found to be acceptable, except for high cycle fatigue (based on properties), for the two-piece and other chambers discussed in this paper.

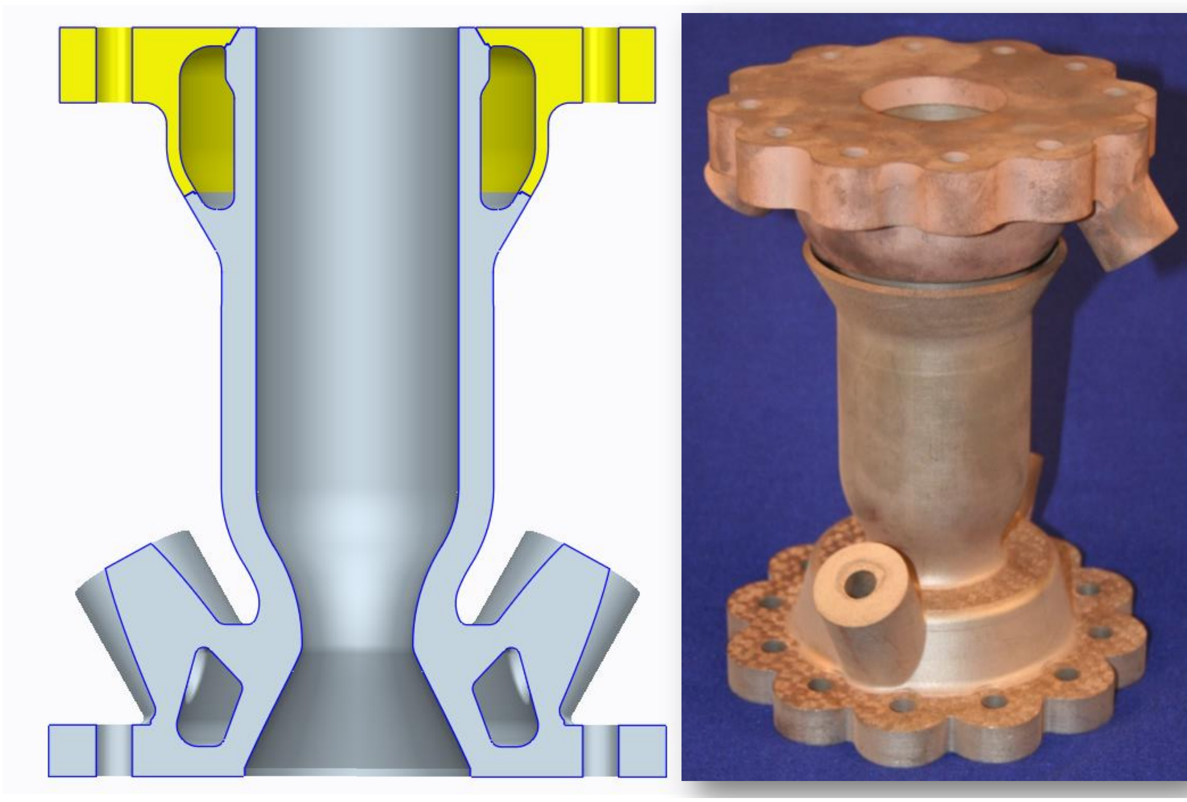


Figure 26. Two-piece regen-cooled AM chamber design and fabrication. Fabricated chamber on the right is shown prior to manifold machining and welding. AM GRCop-84 chamber printed at ASTS.

C. Interchangeable Hybrid Additive Liner Slip Jacket Chamber Design

Additional AM chamber development is being completed at MSFC using copper-alloy liners within a stainless steel 304 slip jacket. This design uses a variant of the liners from the one-piece and two-piece chambers without the attachments of the manifold plenums. This simplified design used a series of rubber O-rings providing radial and face seals at the forward and aft ends. The jacket incorporated the O-ring grooves and a threaded aft capture ring was used to hold the liner in place within the jacket. This design allows for a quick change-out to test various geometries of channels or changes in materials. The TCA of the AM-liner with slip jacket and injector is shown in Figure 27.

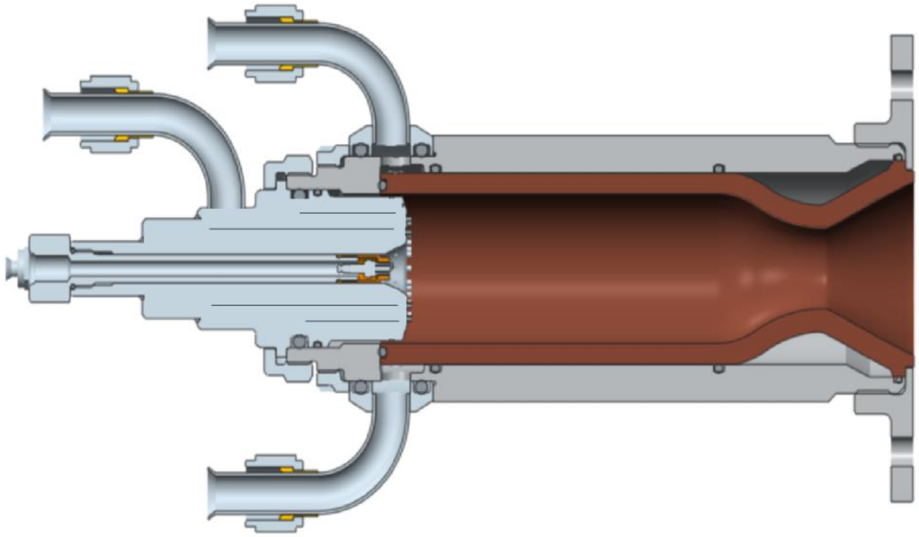


Figure 27. 1.2K SLM Printed Regen Chamber with Slip Jacket and O-Ring Design.

The hybrid additive slip jacket chamber completed hot-fire testing in November 2016 at MSFC TS115 using a GRCop-84 liner. The chamber was hot-fire tested in the as-built condition with no post-processing of the internal coolant channels and minor machining of the external surfaces. The only machining completed on the external surfaces were mating surfaces. The surface finishes were acceptable in the as-built condition for this chamber configuration. The GRCop-84 liner accumulated 2,365 seconds of hot-fire time and 23 starts. The chamber installed in the test stand can be seen in Figure 28 and hot-fire testing of this chamber seen in Figure 29. The chamber was removed from the test stand and inspected; no signs or erosion were observed and there was only slight discoloration near the injector. Based on the condition of the liner, it will be used for additional testing at MSFC.

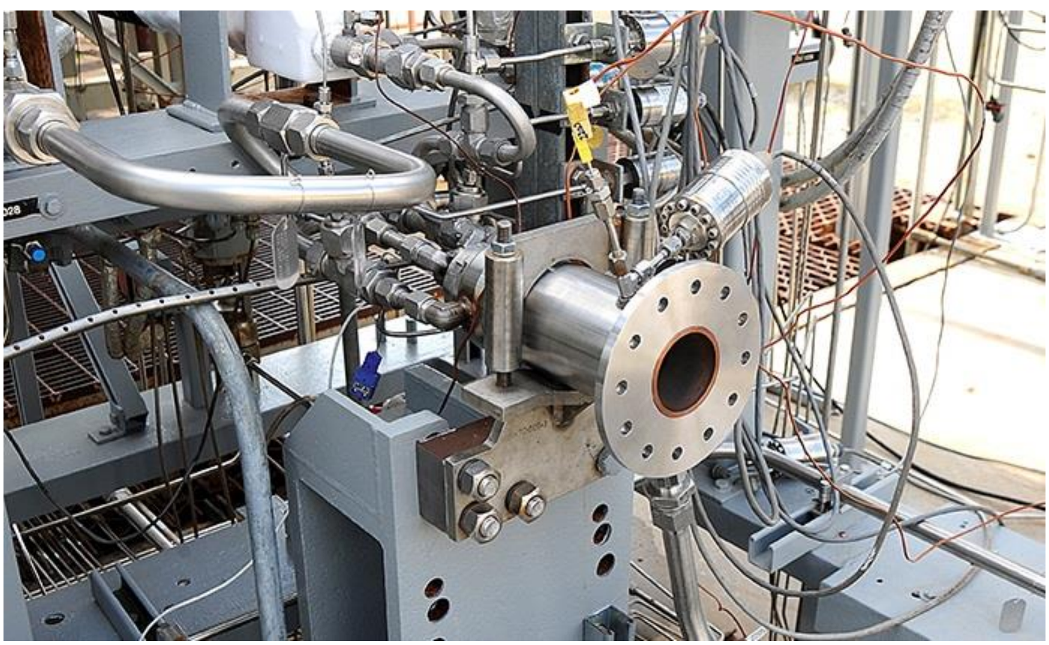


Figure 28. Slip-jacket Chamber with SLM GRCop-84 Liner Installed at TS115.

Figure 29. Hot-fire testing of the GRCop-84 additively manufactured liner with the stainless slip jacket and Carbon-Carbon nozzle extension[27]. The chamber accumulated a total of 2,365 seconds of hot-fire time. [Photo credit: David Olive/MSFC]

A series of additional AM copper-alloy liners was fabricated that mate with the stainless steel hybrid slip jacket. These liners were fabricated from GRCop-84 and also C-18150 (Copper-Chrome-Zirconium). The GRCop-84 material has exhibited reusability for extended duration testing during this initial program and previous programs with the vacuum plasma sprayed GRCop-84 material[28]. Although the powder can be recycled during the SLM build process, it is still a significant cost. The C-18150 material is a solution and aged material and provides a significant cost savings for the raw material. The C-18150 does have an increased thermal conductivity over the GRCop-84 but with reduced strength at operating temperature. Another alloy being evaluated is Glidcop using the SLM process. These alloys are being considered as alternate AM materials for chambers and nozzles to enable reduced cost with SLM process scale-up. NASA will complete hot-fire testing on a series of GRCop-84 liners and also C-18150 liners produced at MSFC and commercial industry partners.

VI. Lessons Learned

Several chambers for various thrust classes have been designed, developed and fabricated at MSFC. Each chamber SLM build has offered opportunities to develop lessons learned during the lifecycle and incorporate these into future builds. A generic process flow has been developed that incorporates some of the lessons learned for the GRCop-84 design and fabrication process. This process flow can be seen in Figure 30.

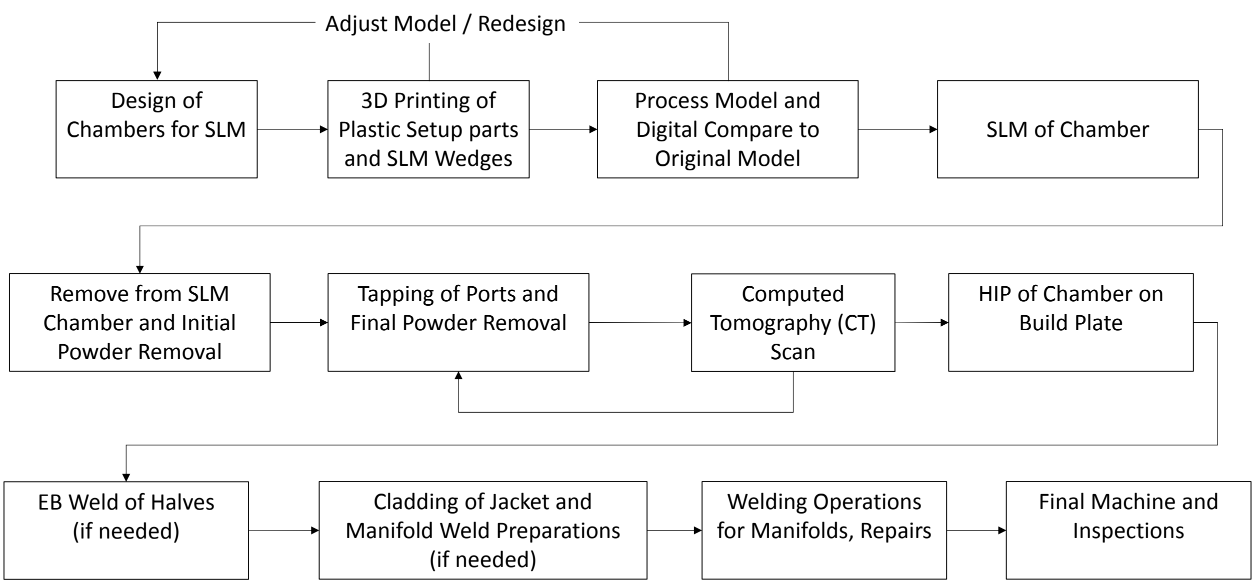


Figure 30. Generic process flow for Design and Fabrication of SLM GRCop-84 chambers.

If a designer does not have internal access to the SLM machines and process, it should be noted that one should be familiar with the post-processing of the part to allow for design features to be incorporated. Many SLM builds are being contracted out, and in turn the full processing is being pushed onto the vendor. This includes model preparation, SLM fabrication, powder removal, removal from build plate, support removal, surface preparation, local grinding, heat treatments and final machining. These pre-processing steps such as model preparation and post-processing steps can have a significant impact on the final quality of the component being built, so one should be familiar or provide specific requirements relative to these. Although not meant to be an inclusive list, here were some lessons learned during the development of the copper-alloy combustion chambers.

A. Design of Chambers

- For the GRCop-84 AM material, all features must maintain a maximum 45° surface or feature from vertical as common in SLM components.
- Multi-piece additive chambers may allow for a more optimized design in all processing operations as opposed to a single piece chamber.
  - Welding can be successful if it simplifies operations such as powder removal and access to internal features for inspection
  - Chambers should leave one set of channels open to allow for full access to aid in powder removal. Blocked channels can result in scrapped hardware. This is not a critical lesson learned, but access to channels has been employed for many successful chambers and caused difficulties on several one-piece chambers.
- Design should accommodate features to allow for proper powder removal.
- Inlet and outlet ports do not have to be integral to the build and can easily be welded during a final operation to simply the build.
  - Protruding features were generally where SLM build failures were experienced.
- Design EB weld joints for excess penetration during the process.
  - Welding of copper requires excessive heat and penetration varies with temperature, so it changed with longer duration welds.
- Increase the effective area for channel inlet and outlets to account for rougher surfaces or drop-down.
  - Overhangs in printing is often required to allow flow at channel inlets and outlets.
- Thick areas should be minimized to eliminate residual stresses
  - Several SLM builds experienced failures due to the thicker flanges lifting off the build plate.
- Part orientation is critical during the build (for the coater arm), thus the design should be optimized based on minimizing potential damage of the coater arm/re-coater blade.
  - Features that can create knife edges should avoid facing normal to the coater arm/blade.
- Account for accurate channel roughness in thermal analyses. Surface finishes vary depending on the type of material and also vendors.
- Include adequate stock for post-processing and secondary bonding operations, run-outs, and/or machining clean-up required.
- The native CAD files should be compared back to the original model to determine actual build geometry.
- SLM component builds can deform as Z-height increases further from the plate.
- Design of ports to be tapped during powder removal process to obtain good seals for flowing air can help aid with powder removal processes.

B. Processing of Chambers

- Model preparation can have a significant impact on the resolution of features being built.
- Structured light or dimensional full surface scanning should be used continuously throughout all steps of the fabrication cycle to determine and adjust final geometry.
- The as-produced surface finish was found to be generally acceptable for chambers discussed in this paper.
  - Surface finishes are dependent on a number of variables including sintering and coater arm (powder-refresh) speeds, starting powder size, mix of virgin and recycled powder, oxidation, features, sintering pattern, and post-processing.
- Powder dose factor is critical as parts get taller to ensure proper lubrication of the coater arm and adequate powder to fill any voids.
- Material density can vary with the height of the build and should be evaluated during development.

- Starts and stops during builds can be accommodated with proper pre-heating before build continuation.
- Alcohol aided with powder removal from channels and subsequently evaporated from select channels.
- High pressure air or GN2 aided (>500 psia) with powder removal, but requires appropriate ports to be tapped.
- Continuous scans using CT was employed to properly verify powder removal.
- Tapping of ports should be completed in a dry state, without the use of any oils prior to verification of full powder removal.
- Powder removal techniques can cause additional stresses on the component and should be considered during design and analysis of component.
    - Mallet blows for powder removal enabled crack growth and created microcracks in some components prior to HIP operations.
- Build direction is very important in how parts may fail with overhangs; 45-degrees max build angle.
    - Use of plastic parts or short build wedges/slices to demonstrate build parameters for metal designs can be helpful by pinpointing potential problem areas prior to actual component build.

C. Post-Processing Techniques

- TIG braze repair of unbonded SLM parts worked very well; using identical filler material was ideal for successful repairs.
    - Include weld wire within SLM builds for use during repairs; this allows for compatible material.
- While removing powder prior to HIP is ideal, it can still be removed after HIP, since all powder may not consolidate. A high pressure, high flow rate flush can aid with powder removal. It is recommended to remove as much as possible prior to HIP though.
- Water flow testing should be completed as early as possible in process after powder removal.
- Design for shrinkage and deformation within all processing steps, such as welding and deposition processes.

VII. Conclusions

A process for SLM fabrication for combustion chambers using GRCop-84 copper-alloy has been developed and shown to be feasible for liquid rocket engine applications. Several chambers in various thrust classes have been designed, developed and fabricated at MSFC. Each SLM build in all thrust classes has offered opportunities to develop lessons learned and incorporate them into future builds. GRC has completed significant characterization of the SLM AM GRCop-84 material and data will be available in further reports.

NASA has completed hot-fire testing of several chamber units as of the publication of this paper in LOX/H2 and LOX/methane environments. The chambers were hot-fire tested in the as-built condition with no post-process of internal coolant channels and only minor machining on external surfaces. All AM GRCop-84 chambers tested to date have performed extremely well and have met all performance requirements. Hot-fire testing will be completed on several future units including the LCUSP Chamber, META4, MET1 and additional 1.2K workhorse units.

A thorough understanding of the entire SLM process from model generation to end application should be understood to make use of lessons learned in processing of copper alloys. Many SLM builds are being contracted out, which in turn the full processing is being pushed onto the vendor. This includes model preparation, SLM fabrication, powder removal, removal from build plate, support removal, surface preparation, local grinding, heat treatments and final machining. These pre-processing steps such as model preparation and post-processing steps can have a significant impact on the final quality of the component being built, so one should have an understanding of and provide specific requirements relative to these.

NASA is continuing to design, fabricate and hot-fire test chambers and combustion devices using GRCop-84, Glidcop and C-18150 copper-alloys. The LCUSP AM and META4 chambers have been fabricated that maximize the current build limitation of 9.8" diameter with axial welds to maximize the length of the chamber. NASA is working projects with industry to increase this scale to larger diameters and also evaluating concepts for multi-piece to enable larger scale AM technologies.

Additive manufacturing of GRCop-84 using SLM has been developed, characterized and shown to meet intended material properties, and validated through hot-fire testing in relevant environments. This process has the potential to significantly reduce fabrication times for liquid rocket engine combustion chambers over traditional fabrication techniques.

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