Lightweight Thrust Chamber Assemblies using Multi-Alloy Additive Manufacturing and Composite Overwrap

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Additive Manufacturing (AM) has brought significant design and fabrication opportunities for complex components with internal features such as liquid rocket engine thrust chambers not previously possible. This technology allows for significant cost savings and schedule reductions in addition to new performance optimization through weight reduction and increased margins. Specific to regeneratively-cooled combustion chambers and nozzles for liquid rocket engines, additive manufacturing offers the ability to form the complex internal coolant channels and the closeout of the channels to contain the high pressure liquid propellants with a single operation. Much of additive manufacturing development has focused on monolithic alloys using Laser Powder Bed Fusion (L-PBF), which do not allow for complete optimization of the structure. The National Aeronautics and Space Administration (NASA) completed feasibility of an AM bimetallic L-PBF GRCop-84 copper-alloy combustion chamber with an AM electron beam freeform Inconel 625 structural jacket under the Low Cost Upper Stage Propulsion (LCUSP) Project. A follow-on project called Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) is under development to further expand large-scale multi-alloy thrust chambers while maturing composite overwrap technology for significant weight savings opportunities. The RAMPT project has three primary objectives: 1) Advancing blown powder Directed Energy Deposition (DED) to fabricate integral-channel large scale nozzles, 2) Develop composite overwrap technology to reduce weight and provide structural capability for thrust chamber assemblies, and 3) Develop bimetallic and multi-metallic additively manufactured radial and axial joints to optimize material performance. In addition to these primary manufacturing developments, analytical modeling efforts compliment the process development to simulate the AM processes to reduce build failures and distortions. The RAMPT project is also maturing the supply chain for various manufacturing processes described above in addition to L-PBF of GRCop-42. This paper will present an overview of the RAMPT project, the process development and hardware progress to date, material and hot-fire testing results, along with planned future developments.

Nomenclature

AM	=	Additive Manufacturing
BMI	=	Bismaleimide

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BP-DED	=	Blown Powder Directed Energy Deposition
DED	=	Directed Energy Deposition
EBF^3	=	Electron Beam Freeform Fabrication
GCD	=	Game Changing Development
GRC	=	NASA Glenn Research Center
GRCop-42	=	NASA GRC Copper-alloy (Cu-4 at.% Cr-2 at.% Nb)
GRCop-84	=	NASA GRC Copper-alloy (Cu-8 at.% Cr-4 at.% Nb)
HIP	=	Hot Isostatic Pressing
$K\text{-}lb_f$	=	thousand pound-force (thrust)
L-PBF	=	Laser Powder Bed Fusion
LaRC	=	NASA Langley Research Center
LCUSP	=	Low Cost Upper Stage Propulsion
LCH4	=	Liquid Methane
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
MSFC	=	NASA Marshall Space Flight Center
NASA HR-1	=	Hydrogen-resistant Superalloy (Fe-Ni-Cr-Co-Ti)
Pc	=	Chamber Pressure (psig)
RP-1	=	Rocket Propellant-1
RAMPT	=	Rapid Analysis and Manufacturing Propulsion Technology
STMD	=	Space Technology Mission Directorate
TCA	=	Thrust Chamber Assembly
UTS	=	Ultimate tensile strength

I. Introduction

The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project is maturing novel design and manufacturing technologies to increase scale, significantly reduce cost, and improve performance for regeneratively-cooled thrust chamber assemblies (TCA), specifically the combustion chamber and nozzle for government and industry programs. This project addresses some of the largest, longest lead, highest cost, and heaviest components in the liquid rocket engine system. While additive manufacturing (AM) has changed how parts are fabricated for rocket engines, this project seeks to expand upon the prior work and provide additional solutions. An additional outcome of RAMPT is to create a domestic supply chain and develop specialized technology vendors available for all interested industry partners and government agencies. RAMPT's purpose is to evolve an integrated multi-alloy light-weight thrust chamber assembly that significantly increases scale over current additive manufacturing technologies, reduce associated cost and schedule, and provide design options not previously possible. This project is taking advantage of government and industry investments through public-private partnerships to provide process development data and technology improvements across propulsion and related industries.

RAMPT is focusing on maturation and integration of the following key technology areas:

1. Blown Powder Directed Energy Deposition (DED) freeform additive manufacturing techniques to fabricate an integrated regen-cooled channel wall nozzle structure.
2. Composite overwrap techniques to significantly reduce weight and provide structural capability for a large Thrust Chamber Assembly (TCA), applied to both the combustion chamber and nozzle.
3. Bimetallic and multi-metallic additive manufacturing and deposition techniques, including copper-alloy to superalloy transitions to optimize component and material performance.
4. Advance modeling and simulations of large-scale deposition techniques to obtain optimal property predictions, material designs, and develop "smart" tool-paths to reduce distortion and provide acceptable components.
5. Development of integrated regeneratively-cooled combustion chamber and nozzle design tools to significantly reduce design cycles and take full advantage of additive technologies.

RAMPT is partnering with industry through a public-private partnership to design, characterize, and manufacture component parts of the thrust chamber assembly[1]. This allows NASA and industry to co-invest in the technology, allowing publicly available government data to aid with design and development of the processes, while process-

specific data can reside at the specialty manufacturing vendors. The RAMPT project is funded under NASA's Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program. It is a joint effort across NASA Marshall Space Flight Center (MSFC), Glenn Research Center (GRC), Langley Research Center (LaRC), and Ames Research Center (ARC). The public private partnerships are managed through Auburn University under an agreement with NASA. The overall RAMPT technology concepts can be seen in Figure 1. The concept and development under the RAMPT project is to amalgamate and evolve several advanced manufacturing techniques to allow for a full integrated thrust chamber assembly. The overall concept starts with the GRCop copper-alloy combustion chamber as the core with integral channels fabricated using Laser Powder Bed Fusion (L-PBF). DED technology is then used to deposit manifold weld land preparations so that a forward manifold can be welded to the chamber. Following interim machining, a blown powder DED integral channel nozzle is deposited onto the aft end of the chamber. Following this operation and heat treatments, the TCA is composite overwrapped using a carbon-fiber polymeric matrix composite (PMC) overwrap[2,3,4]. Development, fabrication, and test of this hardware along with future hardware and test plans in RAMPT are discussed in this paper.

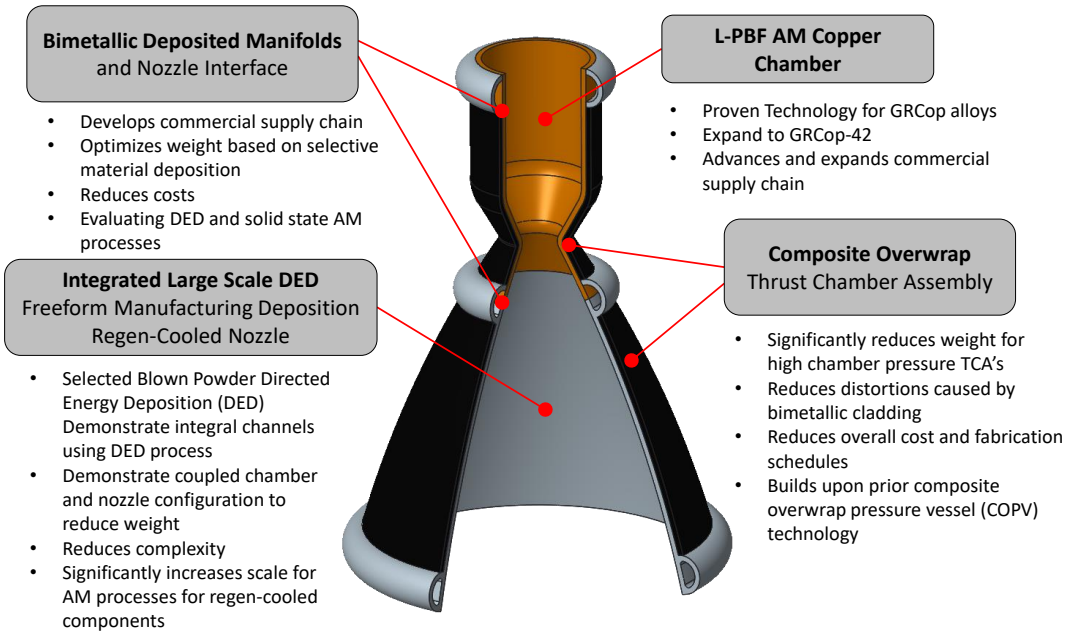

Figure 1: RAMPT Technology Overview.

The RAMPT project is improving upon manufacturing technologies for propulsion components, and it builds on the technologies developed under NASA's GCD Program's Low Cost Upper Stage Propulsion (LCUSP) project as well as on other technology development projects[5]. LCUSP developed L-PBF of GRCop-84 (Cu-8 at.% Cr-4 at.% Nb) and Electron Beam Free Form Fabrication (EBF^3) with Nickel Alloy Inconel 625 manufacturing technologies to produce a rocket combustion chamber within a shorter schedule and at a lower cost than conventionally manufactured components[6,7,8]. The LCUSP technology elements and a picture from hot-fire testing are shown in Figure 2. The initial LCUSP chamber completed hot-fire testing at 35K-lb_f thrust class using Liquid Oxygen/Liquid Hydrogen (LOX/LH2). The LCUSP program successfully completed process development, characterization, and hot-fire testing of various additively manufactured bimetallic chambers at chamber pressures over 1,400 psig. Additionally, the LCUSP chamber demonstrated greater than 50% reduction in fabrication schedule and substantial cost savings over traditional manufacturing techniques. Further costs and schedule improvements are being shown under the RAMPT project.

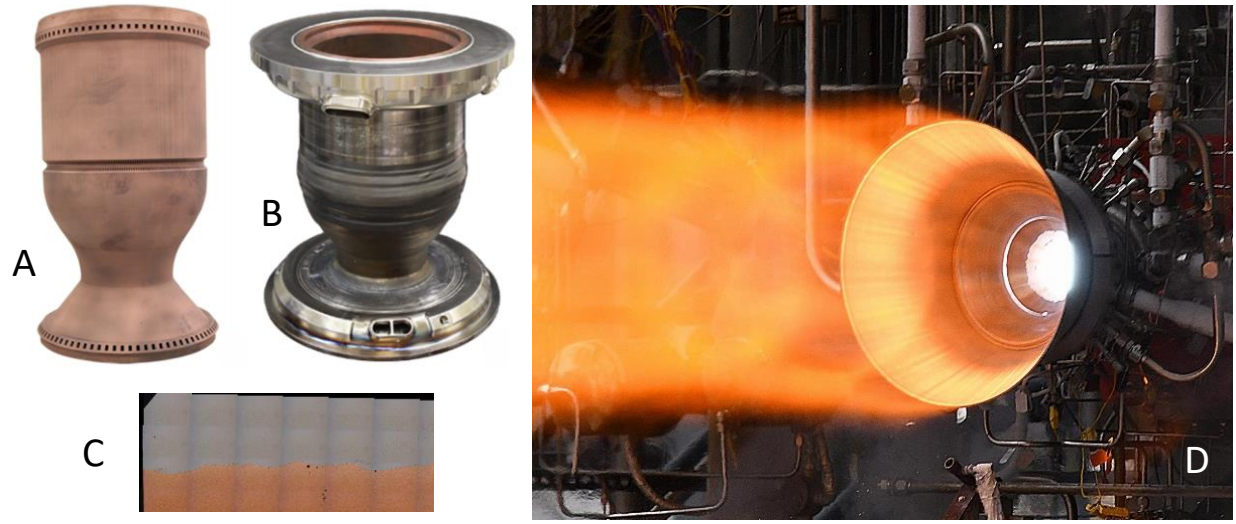

Figure 2: LCUSP Technology and Hot-fire Testing. A) L-PBF of GRCop-84 2-piece chamber, B) L-PBF GRCop-84 Chamber with EBF[3] Inconel 625 Jacket, C) Bimetallic Joint, D) Hot-fire testing of LCUSP.

While LCUSP demonstrated all technical manufacturing and test objectives, there were several lessons learned that indicated potential for improvements to be made. A challenge in the bimetallic alloy deposition for chambers was the shrinkage experienced through distortion in the axial and radial directions. This was about 3-4% on overall length and about 7-10% in the throat region. This shrinkage from bimetallic cladding was also observed in smaller chambers and repeatable. An image of this shrinkage observed can be seen in Figure 3 comparing it directly to a composite overwrap chamber being developed under RAMPT. Both chambers shown in the figure were GRCop-84 L-PBF liners with integral coolant channels. They were identical designs that started off at identical heights, thus the need to develop a jacket process that minimizes distortion is visually compelling. While the recent development efforts to fabricate chambers with AM techniques have shown that, while the techniques are faster and function in relevant environments, current capabilities have effects on chamber geometry and leave residual stresses.

Another reason to improve upon the LCUSP development is the need to reduce weight. At the start of LCUSP, the material properties and printing feasibility of GRCop alloys were uncertain. Since the AM development has since been proven that copper-alloys could be fabricated using L-PBF with channels that are fully closed out, this provides the case for new supplemental technology. The composite overwrap does not need to close-out the coolant channels independently and only needs to provide structural support to react various thrust chamber loads. This provides a significant weight savings opportunity using a higher strength to weight material such as the carbon-fiber composite. A composite overwrap for weight savings has been studied in several U.S. and international programs for rocket thrust chamber assemblies[9,10]. Many of these studies did not provide any further information regarding successful application in a test environment. Overwraps were applied successfully on the NASA Marshall Space Flight Center Fastrac (MC-1) engine over an ablative chamber assembly and hot-fire tested[11,12]. Other subscale TCA's have demonstrated heritage composite materials including Metal Matrix Composite (MMC) and Ceramic Matrix Composites (CMC) for use as a jacket[13].

Under the RAMPT project, composite overwrap is being advanced as the structural support/jacket of the chamber liner. The copper liner with coolant channels remain as a fully AM L-PBF part. Additional developments have been made with the L-PBF GRCop-alloys though with the advancement of GRCop-42 (Cu-4 at.% Cr-2 at.% Nb) as a higher conductivity high strength alloy. Copper alloys are desirable for chamber liners for their high thermal conductivity, which allows for effective wall cooling to keep the chamber hot wall in a high strength temperature region. Composites offer much higher strength-to-weight than the traditional metals utilized for structural support jackets in chambers. The LCUSP project developed the ability to produce closed wall copper alloy liners. Composite formulations that can sustain temperatures spanning from cryogenic upwards of 450 °F make composites a viable and desirable choice for chamber jackets.

Figure 3: (Left) Composite overwrap chamber compared to (Right) DED bimetallic jacket chamber showing shrinkage. Both liners started off at the same height with identical GRCop-84 liners.

While composite overwrap trades well for a structural jacket, the RAMPT project has continued to maintain focus on AM bimetallic development as it is still necessary for materials transitions for the welded manifolds. This enables optimized material selection using high strength-to-weight metals for manifolding that can be machined easily for inlets and instrumentation. The manifolds are ideally made from a non-copper alloy such as a Superalloy or stainless material. This bimetallic AM allows for local deposition using various alloys should a combination of multi-alloys and composite overwrap help react all the structural and dynamic loads in a TCA. The bimetallic development is being developed for both radial and axial directions in the TCA to further optimize the weight by using the most appropriate alloy in discrete locations[14]. The axial bimetallic joint enables a channel-cooled nozzle to be incorporated for a material that is non-copper as heat fluxes are significantly reduced and a higher strength-to-weight material can be accommodated. In some applications, this also permits continuous coolant channels between the chamber and the nozzle, which further reduces weight by eliminating manifolds.

The blown powder DED (BP-DED) is one of the key technologies being evaluated under RAMPT as it has been proven in early studies for rapid fabrication of integrated channel wall nozzles[15]. The L-PBF AM technique has been shown to be limited in scale for use on many liquid engine components for larger thrust class engines. The BP-DED has a much larger build volume and only limited by the robotic arm or gantry system available. The specific developments using BP-DED under RAMPT is to demonstrate integrated channel deposition at large scales. This allows for the entire nozzle to be formed with all channels eliminating the need for closeout operations such as brazing, plating, laser welding, or laser wire direct closeout[16,17,18,19,20]. The advantages of this are numerous since it demonstrates the potential for significantly reduced parts and operations to form a regeneratively-cooled nozzle. A secondary objective is to provide a new AM material for use on channel-cooled nozzles and other components, which is NASA HR-1. NASA HR-1 is a high strength hydrogen resistant alloy for higher temperature operations such as liquid rocket nozzles and is suitable for use with several AM techniques.

The RAMPT project is maturing the manufacturing technologies and the integration of these technologies with various scales of hardware. This allows for early lessons to be learned on subscale hardware and progressing towards larger scale and increased chamber pressures as thermal and structural loads become more challenging. RAMPT is demonstrating hardware as both a coupled configuration, integrally manufactured AM chamber and nozzle, and de-coupled, which is a bolted configuration that allows for early lessons learned. While the ultimate goal of RAMPT is to evolve the fully integrated AM designs, it is recognized that many future applications could make use of the technologies independently as well. The variations in scale of hardware under RAMPT demonstrate different test objectives. The RAMPT thrust-class hardware is shown in Figure 4 and progress of components will be shown throughout this paper. Early hot-fire testing was completed on de-coupled hardware, which included composite overwrap chambers and a BP-DED nozzle with integral channels. This demonstrated feasibility with temperatures approaching 250 °F on the composite overwrap. De-coupled hardware is also being developed for the 7K-lb_f and 40K-lb_f thrust-classes and will undergo hot-fire testing with a bolted joint between the L-PBF chamber and BP-DED nozzle.

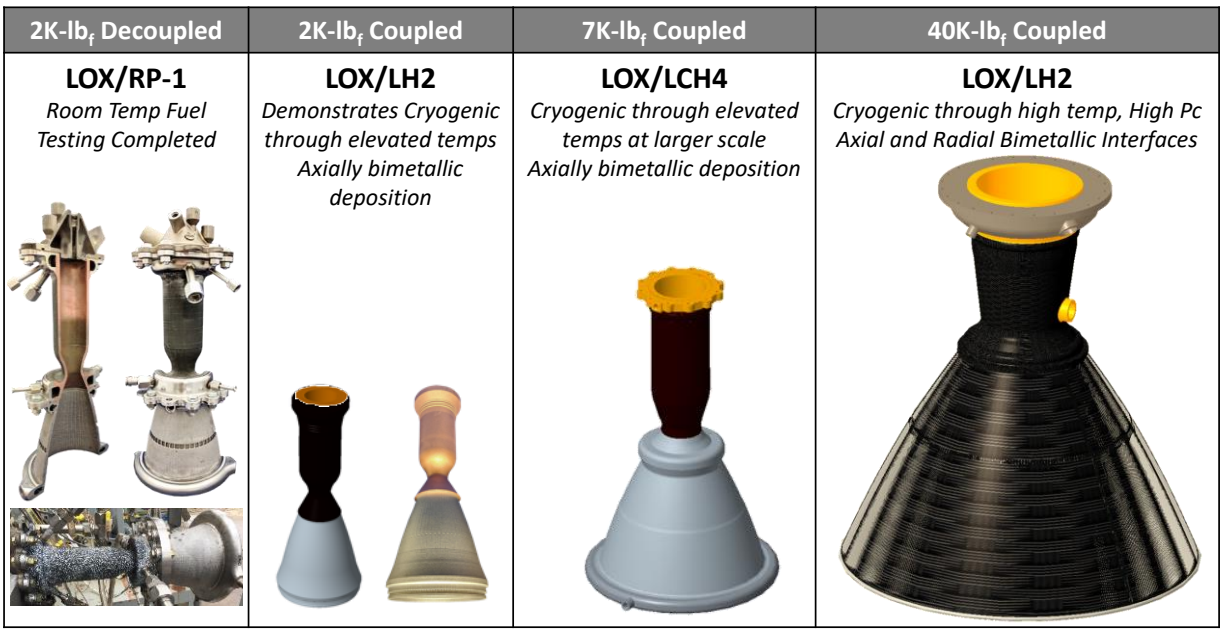

Figure 4. Various thrust classes of RAMPT hardware being developed.

II. Manufacturing Process Development

Several manufacturing technologies have advanced over the last few decades that are enabling RAMPT to further mature and integrate these into an integrated TCA. The manufacturing technologies being developed are:

1. Freeform BP-DED with integral coolant channels
2. Composite overwrap
3. Bimetallic additive manufacturing
4. L-PBF of copper-alloys, specifically GRCop-42 and GRCop-84

While various thrust-class chambers are being fabricated, the general manufacturing sequence is similar for all the TCA's being developed and tested. A generic manufacturing flow can be seen in Figure 5. The core of the RAMPT TCA starts with a L-PBF GRCop copper-alloy combustion chamber. This allows all other features to be fabricated and integrated onto the combustion chamber. While the LCUSP project developed GRCop-84, the RAMPT project has invested in GRCop-42, allowing for higher conductivity[21]. The chamber is fabricated with integral channels that are fully closed-out to a thickness determined for each thrust-class of design. After successful fabrication and post-processing of the L-PBF chamber, it is prepared for deposition of a radial bimetallic interface. This radial bimetallic interface is not required on all chambers and mostly being demonstrated on the 40K-lb_f TCA. DED technology is then used to deposit manifold weld land preparations to allow for welding of a forward manifold to the chamber. Following interim machining and processing operations, a blown powder DED integral channel-cooled nozzle is deposited onto the aft end of the GRCop-42 chamber. The nozzle deposition creates a bimetallic axial joint between the nozzle and the chamber. In some of the configurations the channels are aligned between the chamber and nozzle allowing for continuous cooling, which solves some design challenges and interface issues with bolted designs. Following this operation and subsequent post-processing, the TCA is composite overwrapped using a carbon-fiber polymer matrix composite (PMC) overwrap.

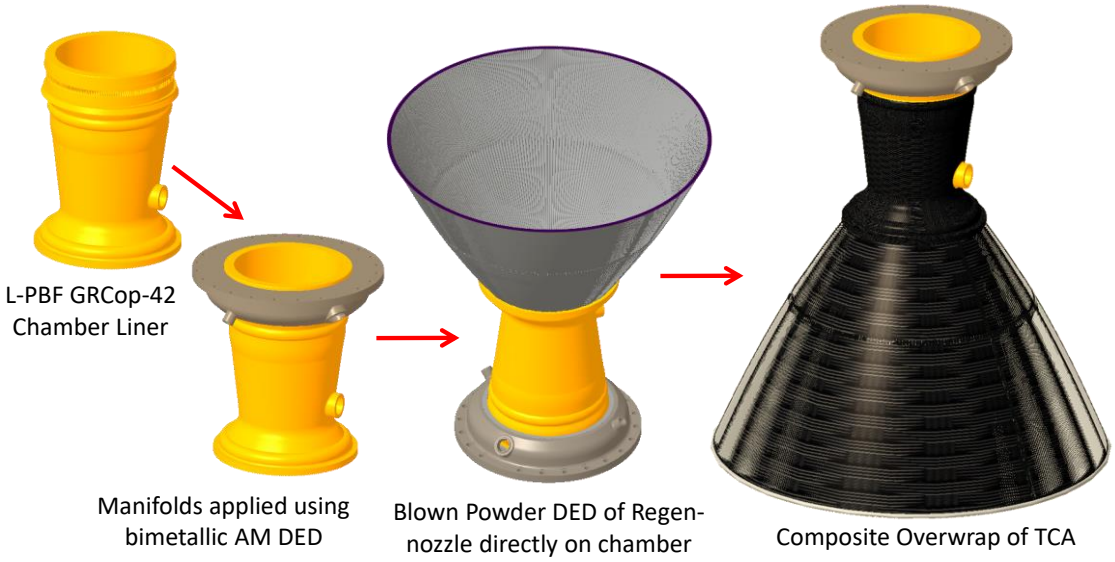

Figure 5. Generic manufacturing process flow of the RAMPT thrust chambers.

Process development has been completed in each of these areas and continues to progress rapidly. The GRCop-42 L-PBF alloy has sufficient maturity and significant materials characterization and hot-fire testing. Several U.S. domestic suppliers have developed the material build parameters using L-PBF and have abilities to fabricate parts up to 15.6 inch (400mm) diameter. The maturity of the GRCop-alloys was an enabling core technology for RAMPT since it requires a high density material with fully closed-out internal coolant channels. The maturity of the GRCop-42 L-PBF also allowed for further development of the multi-alloy deposition processes providing a reasonable backer material for radial and axial depositions or cladding. The development and evaluation of the GRCop alloys using L-PBF has been discussed in prior papers[6,7,8,21].

The various thrust-class RAMPT chambers fabricated with GRCop-42 L-PBF have been completed (Figure 6). These chambers were fabricated across various suppliers, while obtaining additional material properties. Many of the prior challenges with powder removal and post-processing has improved with the GRCop-alloys as the powder and fabrication supply chain has evolved. While the GRCop-alloys have been considered the most mature in the process, there were several new design features attempted under RAMPT that proved to be successful providing additional performance benefits.

Figure 6. GRCop-42 RAMPT chambers following AM L-PBF, prior to machining.
[Chambers fabricated at 3DMT, AME, and Elementum 3D]

Several challenges exist in the integration of the various processes and often competing requirements and trades must be made in the designs. For instance, the optimal heat treatments (namely homogenization and solutioning) for the manifold weld preparations using superalloys require a higher temperature than the GRCop-42 is capable of. This requires some impact to the material properties. Other challenges experienced in the integration is the sequence of operations, where the composites are limited in temperature and most welding and machining operations must be done prior to the overwrap to avoid any damage. The process developments continue in these areas and lessons being captured along with proper risk management.

A. Large-Scale Directed Energy Deposition

BP-DED was selected for RAMPT since it traded well in resolution of features, deposition rates, and ability to scale. However, each of these attributes needed many improvements to be able to demonstrate the large scale channel wall nozzle fabrication and integral nozzle deposition. While BP-DED cannot compete with the resolution of L-PBF, it has demonstrated the ability to build the channel sizes necessary for engine applications.

The BP-DED fabrication technique uses a coaxial or multiple nozzle deposition head and centered laser energy source. The powder is injected with an inert carrier gas into a melt pool at a focal plane on the part or substrate. The melt pool is created by the central laser energy source causing a bead of material to be deposited. The powder is accelerated, or blown, into the melt pool using an inert carrier gas and a central inert gas is also supplied to minimize oxidation. The deposition head system, with integrated focus optics and blown powder nozzle is attached to a gantry system that controls a toolpath defined by the CAD model. A gantry system is necessary to fabricate the resolution of features for integrated nozzles that a robotic arm cannot achieve. The BP-DED head can be contained in an inert gas chamber or operated with the local central purge. The blown powder and gantry system allows for complex freeform structures to be built with small integral features, such as thin-walls and channels. An example of the BP-DED fabrication can be observed in Figure 7 along with a 40k-lb_f de-coupled nozzle fabricated from JBK-75.

Figure 7. (Left) Example of BP-DED process fabricating integral channels, and (Right) 40k-lb_f nozzle fabricated using BP-DED. [Fabricated at RPM Innovations]

NASA along with industry partners have developed the process to enable the thin-walled channels. Some examples of channels demonstrated in BP-DED can be seen in Figure 8. These channels demonstrated possible design options, various toolpath strategies, and determined geometry limitations of the process. Another focus of the early process development was to demonstrate fabrication of the material NASA HR-1. The NASA HR-1 material was ultimately selected as the best option across several applications, although initial trials were completed with Inconel 625 and JBK-75, which had immediate availability in powder. Details of the BP-DED process for nozzles and subscale testing was discussed in prior publications for the Inconel 625 and JBK-75 materials[15,31].

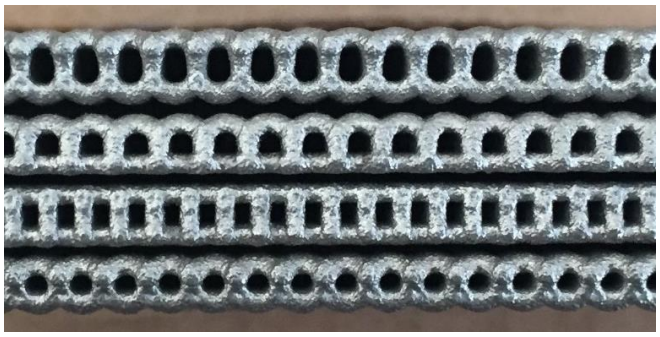

Figure 8. Examples of various integrated channel wall structures.

Under the RAMPT project, NASA traded and eventually selected development with the NASA HR-1 material. The NASA HR-1 material provides a good trade between thermal conductivity, high yield strength, low cycle fatigue, elongation, density, and hydrogen resistance over other superalloys[22]. It provides advantages over several alternate materials when traded amongst these key nozzle requirements. Additive manufacturing technologies provided a critical method for fabrication of the NASA HR-1 affordably and a simplified powder and fabrication supply chain compared to the prior processing required using Vacuum Induction Melting (VIM) and Vacuum Arc Remelt (VAR) methods. This material has been discussed in more detail in prior publications by Katsarelis and Chen[23, 24].

Under the RAMPT project, NASA and industry partners completed parameter development and optimization for the NASA HR-1 material demonstrating high density deposits in thin-wall geometry. A series of metallography, mechanical test coupons, harvest boxes and other witness samples have been produced for characterization, heat treatment optimization, and mechanical and thermophysical testing. As previously discussed in the NASA HR-1 paper by Katsarelis, the deposition rate, based on spot size and laser power, has a strong influence on the grain size and response to heat treatments[23]. Based on this, the witness samples and mechanical test data should match closely the geometry of the actual part. Early process development work completed nozzle structures sans channels and transitioned to the integral channels. In addition to the integrated channel development work, the blown powder DED process is being used for other components across RAMPT including manifolds. This has further demonstrated the scale and the reduction of many process steps. This replaces the need for a casting or forging and significantly reduces the final machining time required.

An integrated manufacturing demonstrator chamber was completed with a direct JBK-75 BP-DED nozzle applied to the aft end of a GRCop-84 L-PBF chamber. GRCop-84 and JBK-75 were used at the time of this demonstration due to availability of these materials, namely powder. The chamber included a bimetallic joint produced with L-PBF based on the layer of Inconel 625 required for the GRCop-42 to adhere to the build plate[7,21]. This manufacturing demonstrator showed the feasibility of combining these processes with a complex joint. Several lessons were learned that required some redesign of the joint to allow for adequate stock material and avoid excess heating. Following this manufacturing demonstrator and hardware fabrication for monolithic (de-coupled) NASA HR-1 nozzles, the team moved to the development for the coupled bimetallic thrust chamber assembly. This hardware can be seen in Figure 9 with the 2K-lb_f coupled NASA HR-1 nozzle to a GRCop-42 L-PBF chamber. This design incorporated continuous coolant channels in the nozzle and chamber and eliminated the manifold at the joint. This was designed to optimize the weight based on appropriate material selection based on heat flux. The project is continuing to develop and fabricate the 7K-lb_f and 40K-lb_f larger scale coupled nozzle and chambers at the time of this publication.

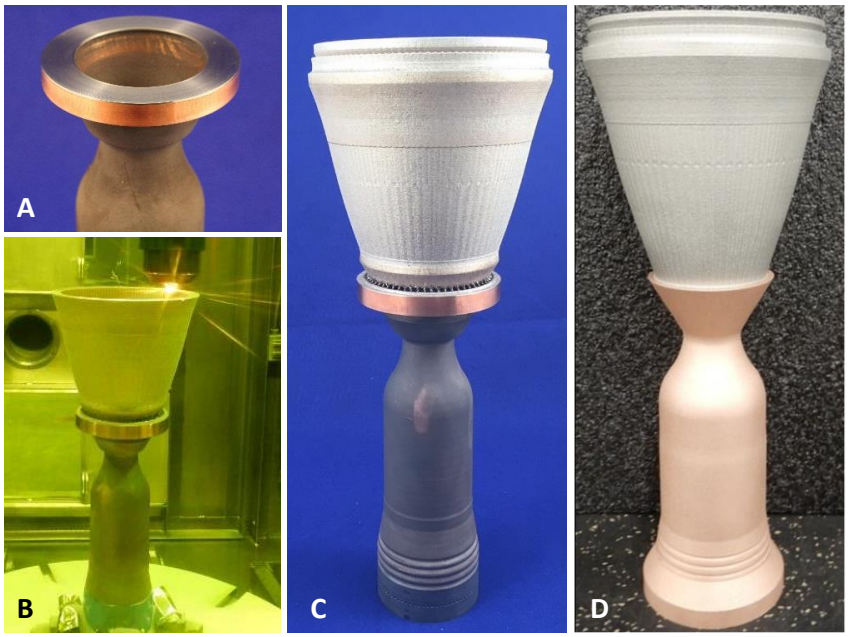

Figure 9. Coupled BP-DED nozzle with L-PBF chamber development. A) GRCop chamber with bimetallic joint prepared for BP-DED, B) BP-DED process of coupled manufacturing demonstrator, C) Completed coupled BP-DED/L-PBF bimetallic demonstrator, D) 2K-lb_f coupled hardware for hot-fire testing.

Another objective of the RAMPT project was to demonstrate the scale of the BP-DED process for integral channel nozzles. A series of manufacturing demonstrators and de-coupled (bolted) test articles were fabricated at the 7K-lb_f and 40K-lb_f thrust-classes. These nozzles all demonstrated successful fabrication meeting the geometric tolerances, ability to remove any excess powder, minimal distortion, and a developed the build and toolpath strategies. The team decided based on these successes to move to a large scale technology demonstrator about 12 months ahead of schedule. The large scale BP-DED integral channel demonstrator was designed with various size channels and transitions at 40 in (1016 mm) diameter and 38 in (965 mm) length (Figure 10). The nozzle deposition time was approximately 30 days, which is a greater than ten times schedule reduction compared to a traditionally manufactured nozzle of this scale. Following deposition and post-processing, the nozzle completed 3D scanning that showed less than 0.02 in (0.5 mm) deviations from the nominal geometry. This integral channel configuration significantly reduces the number of operations and parts compared to a traditionally manufactured assembly.

The BP-DED process has demonstrated a series of manufacturing demonstrators and test hardware under the RAMPT project for integral channel nozzles. Additionally, the process has shown feasibility for bimetallic and multi-alloy deposition for fully integral thrust chamber assemblies. Subscale and full scale hardware has been fabricated and continuing to be fabricated at evolving scales. BP-DED has demonstrated a significant reduction in build schedules and a feasible technology for channel-cooled nozzles. Additional development work is required at larger scale, which NASA is currently working with industry partners under supplemental funding through the NASA Space Launch System (SLS) program. There are some challenges that remain with the BP-DED process including higher than desired surface roughness. Research is being conducted to evaluate polishing techniques for the channels and DED materials. Characterization work continues on the BP-DED NASA HR-1 material to optimize the heat treatment and collect mechanical and thermophysical properties.

Figure 10. Integral channel NASA HR-1 BP-DED nozzle at 40 in (1016 mm) diameter and 38 in (965 mm) length. [Fabricated at RPM Innovations]

B. Composite Overwrap

The second key technology is the composite overwrap, which mainly focused on the combustion chamber as a light-weight structural jacket. Since the channels are already closed out using the L-PBF process, the overwrap is used to react loads during hot-fire. The composite overwrap was filament wound at MSFC and GRC with surface preparation and base plies performed at MSFC, GRC, and LaRC. Filament winding at MSFC employed a resin bath and doctor blade for fabrication whereas GRC utilized brush application of resin onto dry carbon fiber as it was wound over the chamber. Multiple resins, wind patterns and bonding approaches were evaluated. Process developments and testing was completed for the decoupled 2K-lb_f chambers and further overwrap development completed on the 2K-lb_f and 7K-lb_f coupled chambers. There are several areas of the composite processing that require development including surface preparation, resin selection and application, and overwrap manufacturing process steps.

1. Surface Preparation

Initial designs required a strong bond between the thrust chamber and composite. The chamber surface was inherently rough due to the additive manufacturing process, however to encourage bonding with the composite the part was grit blasted, washed in a mild (3-5%) phosphoric acid solution, then rinsed with ethanol, as shown in Figure 11. Two film adhesives were evaluated, AF121 from 3M® and EA9696 from Hysol®. The adhesive was applied to a subset of test chambers prior to filament winding (Figure 11). Alternatively, fiber/resin was applied directly to the remaining chambers following surface preparation. Since these initial tests, it has been determined that an unbounded surface is more beneficial. Meaning, the fiber will be wound directly over the copper chamber with a mold release agent applied.

Figure 11. (Left) Decoupled 2K-lb_f Chamber following Surface Preparation, (Right) Film Adhesive was Applied to the Chamber Surface (prior to filament winding)

2. Resin

The thermal requirements of the composite material and resin vary by chamber design configuration for the 2K-lb_f, 7K-lb_f, and 40K-lb_f. The initial development on the 2K-lb_f decoupled chamber ranged from room temperature through 250°F (121°C). The continued development at larger scales, 7K-lb_f, and 40K-lb_f, are based on the regenerative cooling propellant fuel temperatures from cryogenic through elevated up to 450°F (232 °C), based on the application. To accommodate both the elevated and lower temperature extremes, the resins evaluated included, 5250-4 toughened bismaleimide (BMI) and EP2400 toughened epoxy, both from Solvay®.

A quantity of resin calculated to equal 40 wt.% of the total composite weight was applied to the dry fiber throughout the wind. To reduce viscosity throughout the manufacturing process, the resin was heated on a hotplate and the chamber was kept warm with mounted hot-air guns to maintain a reduced resin viscosity during fabrication (Figure 12). The resin temperature was selected based on vendor provided rheology curves.

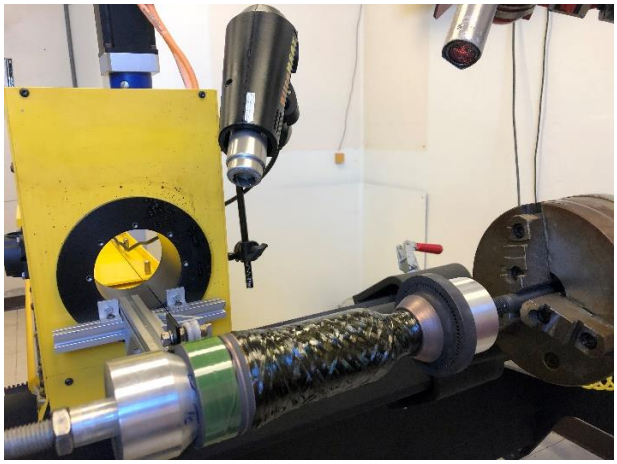

Figure 12. Heat guns used at GRC to maintain proper viscosity.

3. Composite Fabrication

The composite overwrap was manufactured using IM7, 6K tow carbon fiber from Hexcel® with candidate resin materials in a filament winder. The carbon fiber was wound on a McClean Anderson®, 4-axis filament winder with a small amount of tension applied. The wind pattern followed a helical orientation with an approximately 40-degree fiber angle relative to the chamber axis as seen in Figure 13A. Figure 13B shows closers to a 35-degree fiber angle being used as the wind pattern. The helical tows covered the chamber as a first ply. The chamber was hoop wound over the helical (Figure 13C and D) and this pattern was repeated to yield a total of four plies.

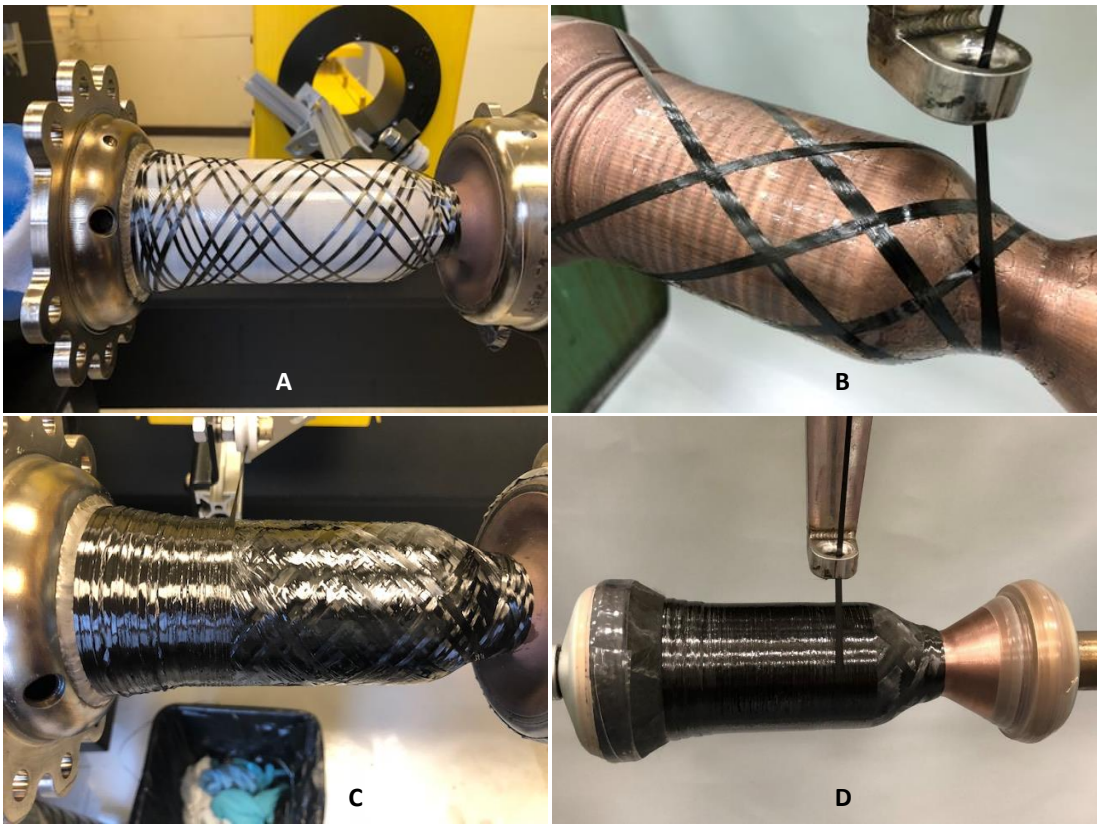

Figure 13. Overwrap of 2K-lb_f chambers. A) Helical tows wound over the chamber with adhesive (GRC), B) Helical tows wound over chamber without adhesive or base plies (MSFC), C) Hoop layer wound over a layer of helical fibers (GRC), D) Hoop layer of helical fibers (MSFC).

There were some variations of the baseline helical-hoop fiber architecture evaluated. In-service compressive loads on the part drove fiber orientation parallel to the chamber axis and pressure loads required the hoop wind. Chambers were wound which included (1) first layer of Hexcel® IM7/8552 uni-directional tape (Figure 14) and (2) first ply of Hexcel® SGP196P/8552 woven fabric (Figure 14). These initial layers were over-wrapped according to the helical-hoop profile outlined above. The dry fiber of those helical-hoop layers were impregnated with EP2400 toughened epoxy.

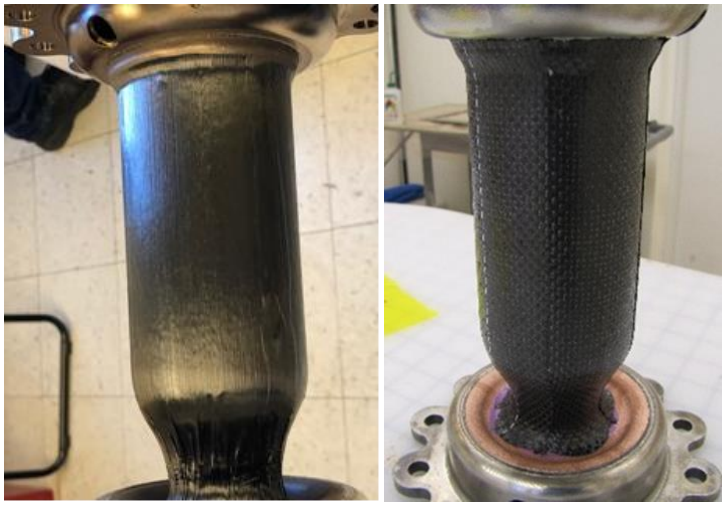

Figure 14. (Left) Uni-directional tape and (Right) plain-weave prepreg fabric.

The curing process on the chambers varied at each of the NASA centers and was based upon available facilities. The GRC procedure included an initial application of shrink-wrap to the uncured composite, to ensure a smooth surface finish (Figure 15). The part was vacuum bagged and autoclave cured according to the vendor recommended cure cycle. The 5250-4 BMI required a free-standing post cure to increase glass-transition temperature.

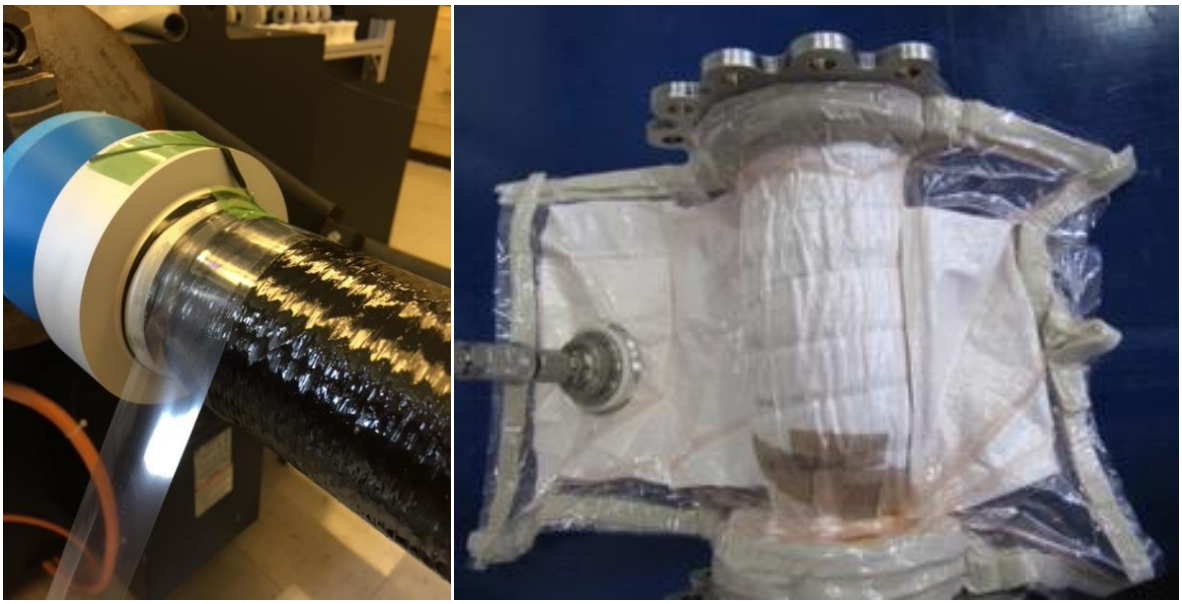

Figure 15. Shrink wrap was wound over the part prior to vacuum bagging to ensure a smooth part surface.

MSFC utilized an oven rotisserie cure, as seen in Figure 16 (left). After cure, each part was visually inspected for dry spots or resin pooling. Figure 16 (right) shows a fully cured composite overwrapped combustion chamber.

Figure 16. (Left) 2k-lb_f chamber being placed in oven for rotisserie cure and (Right) cured composite overwrap of a 2K-lb_f thrust chamber.

Plastic 3D printed models have been a significant part of the composite overwrap process development. These low-cost versions of the surface profile provided a realistic practice mandrel to wind over before getting the metal chamber in the lab. One of the main challenges facing the composite overwrap is the manifolds. This model allows the team to evaluate many different winding patterns on the chamber without risk of damage to the real part. Figure 17 show the 7K-lb_f thrust chamber plastic model with a helical and hoop pattern.

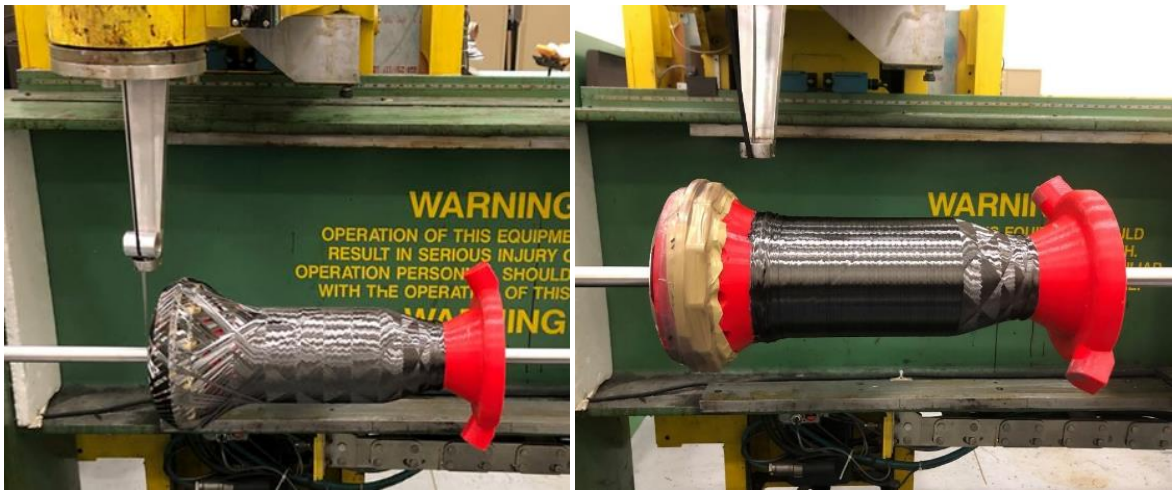

Figure 17. (Left) 7K-lb_f plastic thrust chamber helical dry fiber layer (MSFC) and (Right) 7K-lb_f plastic thrust chamber hoop and helical dry fiber layer (MSFC).

C. Bimetallic Development

The third key technology development of the RAMPT project is bimetallic additive manufacturing. This allows for materials to be added locally for weight optimization based on component requirements. The bimetallic development is focused on the joining of copper-alloys, specifically GRCop-42 or GRCop-84, and a superalloy. While this was demonstrated under the LCUSP project using the EBF[3] process, additional development was deemed necessary to further evaluate alternatives and also develop a commercial supply chain. The bimetallic development is focused on radial deposition for application of manifold weld preparations, while this could also be used for deposition of a fully deposited metal AM structural jacket. The second aspect of the bimetallic deposition development is the axial joint between the chamber and BP-DED nozzle. While the process for the nozzle is baselined, some alternatives are being considered how to create this joint, such as the discussion in the BP-DED section and shown in Figure 9. The main objective of the axial deposition development is characterization and defining proper interface materials, as needed.

Several techniques are being evaluated for the bimetallic deposition with the GRCop-alloys and superalloys. These techniques include gas cold spray, blown powder DED, and laser hot wire cladding. These techniques all have different advantages and disadvantages including heat input and potential for distortion, ability to deposit on complex surfaces, material overspray/usage, bonding strength, supply chain, and feedstock availability. These characteristics must be traded for the particular thrust chamber application and post-processing requirements to determine the most optimal process. Analysis of the bimetallic joint in the LCUSP program demonstrated the formation of deleterious intermetallics at the interface, and techniques investigated under RAMPT are being tuned to mitigate these effects. Computational modeling has also been performed to predict intermetallics at the interfaces formed at high temperatures[25]. Model predictions of deleterious intermetallics at the GRCop and superalloy interface necessitated investigations into a variety of interlayer materials to prevent formation of potential weakening phases.

Cold spray is a high-energy solid-state coating and powder consolidation process. The technique uses a compressed high velocity supersonic gas to accelerate unmelted powder onto a substrate[26]. Material deforms and is built up on the surface upon impact through kinetic energy and creates a bond of solid material. The cold spray bonding mechanism is a combination of mechanical interlocking and metallurgical bonding from re-crystallization at highly strained particle interfaces[27]. Cold spray has an advantage since it is not melting material, so reduces potential for thermal residual stresses, intermetallic formation, oxidation, and distortion from heat input compared to the other processes. The high-pressure carrier gas used to accelerate the powder can also be pre-heated as necessary for certain applications[28]. The lack of heat input from melting may limit the full fusion with the base material that some of the other processes can provide: further experiments are planned to fully evaluate the bond integrity via materials testing and characterization. The source powder, cold spray, and substrate preparation parameters are tuned to achieve pure optimized interfaces, surfaces, and feature build-up. Figure 18 demonstrates early trials of cold sprayed NASA HR-1 and Nickel onto L-PBF GRCop surfaces.

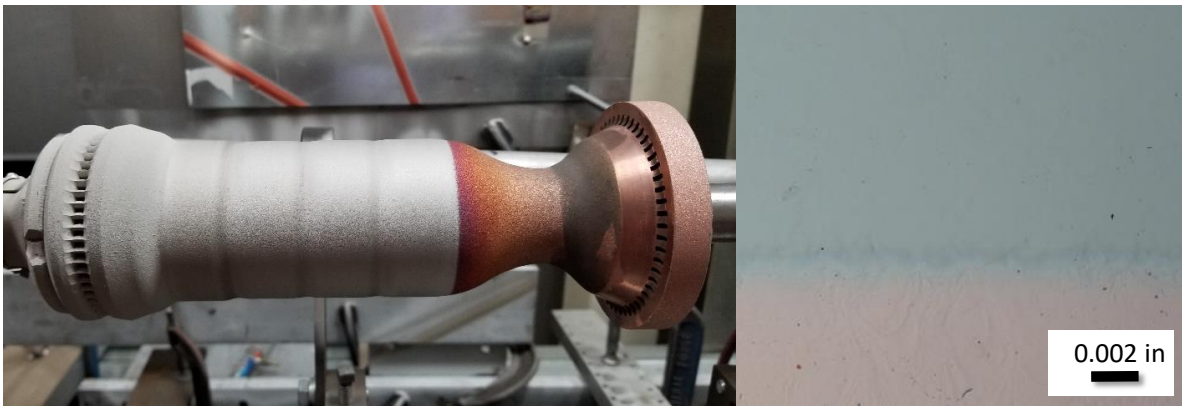

Figure 18. (left) Cold spray of NASA HR-1 onto a L-PBF GRCop-84 subscale chamber. (right) Cold spray and heat treated nickel intermetallic onto a L-PBF GRCop-42 substrate [fabricated at ASB Industries]

The BP-DED process was previously described and has advantages for bimetallic since it is being applied for the integrated channel nozzle and provides the opportunity to minimize setup and operations. This process does have higher heat though and distortions can occur. The BP-DED process is not 100% efficient in powder usage, so overspray powder could become lodged in channels, although early developments have shown this is not a significant concern. Initial experiments have successfully joined a variety of superalloys to GRCop utilizing BP-DED. Further experiments are planned to fully evaluate the bond integrity via materials testing and characterization. Some of the initial development trials with and without intermediate interface materials is shown in Figure 19.

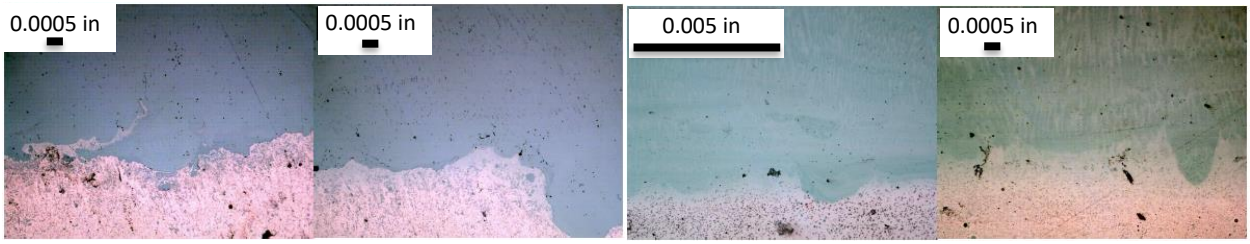

Figure 19. (left) BP-DED IN625 onto a L-PBF GRCop-42 substrate. (right) BP-DED CuNi intermetallic onto a L-PBF GRCop-42 substrate. [Fabricated at RPM Innovations]

The laser hot wire process uses an off-axis wire feed where the wire is preheated to an elevated temperature just below melting point and fed into a melt pool on the substrate, or part, created by a laser[29]. Advantages include complete utilization of the source wire as well as less heat going into the part directly since less thermal energy is required with the wire being at elevated temperatures. This has advantages for reduced distortion over the BP-DED process, but does still impart heat into the part. Laser hot wire can provide high deposition rates, low dilution, thermal stability, and general metallurgical control in additive manufacturing applications[30]. Early experiments have successfully joined and mechanically tested a variety of superalloys to GRCop utilizing laser hot wire. Some examples of the bimetallic interfaces can be seen in Figure 20.

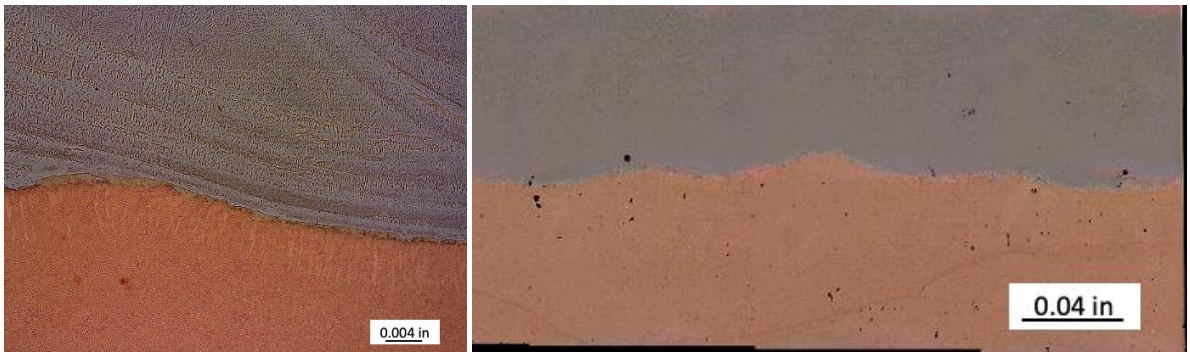

Figure 20. (left) Laser hot wire IN625 onto a GRCop-84 substrate. (right) Laser hot wire Techalloy-99 intermetallic onto a L-PBF GRCop-84 substrate. [Fabricated at Lincoln Electric Holdings, Inc.]

Initial bimetallic characterization was performed through microtensile testing of the GRCop-84 and superalloy joints (Figure 21). Joints are considered of sufficient strength if failures occur in the weaker GRCop or at an average ultimate tensile strength (UTS) consistent in magnitude with wrought and L-PBF GRCop-84 [~430 MPa (62 ksi)]. Fracture surfaces should also exhibit clear evidence of ductile failure, with cup and cone correlation. Preliminary laser hot wire and BP-DED interfaces have been mechanically tested and evaluated. Even with the presence of brittle facets of intermetallics, tested samples had an average UTS as expected. Samples with failures at the interface revealed a combination of brittle facets and Cu-rich ductile regions, while samples that failed in the GRCop demonstrated ductile cup-and-cone failure and microvoid coalescence. Further development of the bimetallic interface is underway to determine an optimum additive technique, interlayer, and heat treatments for consistent failure away from the interface in standard tensile samples. It should be noted that different bimetallic AM techniques may be utilized based on the component application.

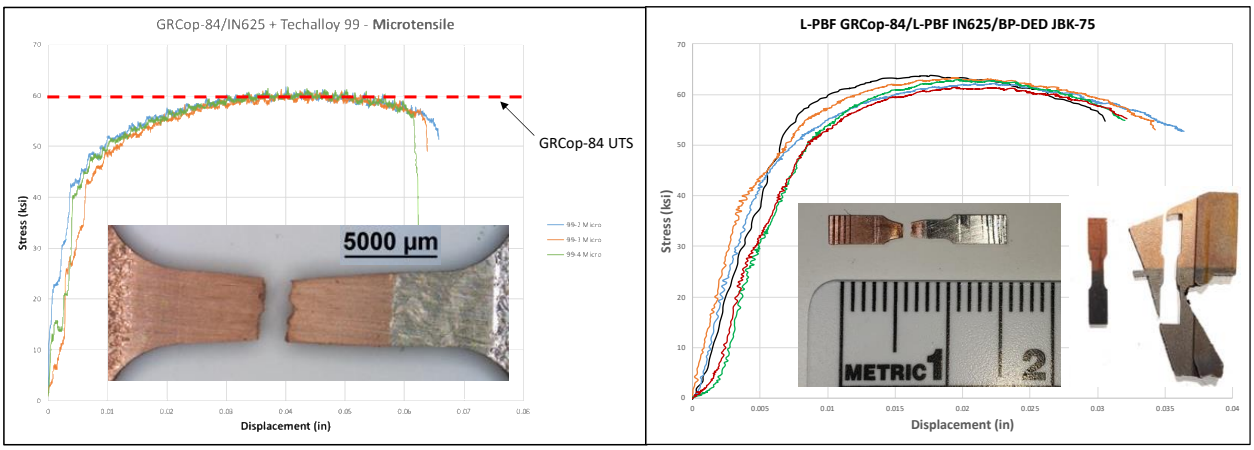

Figure 21. (left) Laser hot wire IN625/Techalloy 99/GRCop-84 microtensile data (right) BP-DED JBK-75/L-PBF IN625/L-PBF GRCop-84 microtensile data.

Following initial bimetallic development, further evaluations were completed to baseline radial deposition on a full scale component. A 40K-lb_f combustion chamber was fully cladded using Inconel 625. Shrinkage was observed in this chamber, similar to the prior subscale and LCUSP chamber. This deposition had fairly significant build up including in the areas for the manifolds and structural jacket throat support to fully react loads from testing. While this is not the final goal of the RAMPT project, it provided an intermediate step for the bimetallic development. This chamber also provided a baseline for weight comparisons with the composite overwrap chamber. Based on the fully cladded chamber with the design for the 40K-lb_f composite overwrap chamber, a weight savings of approximately 50% is possible. The cladded chamber can be seen in Figure 22.

Figure 22. Bimetallic chamber cladding. (Left) 40K-lb_f L-PBF GRCop-42 chamber, B) Chamber after BP-DED Inconel 625 jacket was applied. [Fabricated at DM3D]

III. Hot-fire Testing

NASA has completed several hot-fire test series that demonstrate some of the key technologies under the RAMPT project. These early development tests established feasibility to continue to the fully integrated multi-alloy and composite overwrap chambers. There were three test series that included the key technologies of a composite overwrap combustion chamber and an integral channel BP-DED nozzle. All testing was completed at NASA MSFC Test Stand 115 (TS115) at chamber pressures above 1,100 psig generating approximately 2,000 lb_f of thrust at the highest pressure. The propellants used in these test series were Liquid Oxygen/Kerosene (LOX/RP-1) and Liquid Oxygen/Gaseous Hydrogen (LOX/GH2). The testing initially used water cooling to characterize the total heat load of the chamber and nozzles and eventually transitioned to full regenerative cooling using GH2 or RP-1, depending on the test series. A DED JBK-75 nozzle was tested in LOX/GH2 and a DED Inconel 625 was tested in both LOX/GH2 and LOX/RP-1. The nozzle configurations and test statistics for these can be seen in Table 1.

Table 1. Summary of Hardware Configuration and Accumulated Test Time.

Propellant	Chamber & Material	Nozzle	Material	Starts	Time (sec)
LOX/GH2	GRCop-42 L-PBF w/ Slip Jacket	BP-DED	JBK-75	114	4,170
LOX/GH2	GRCop-42 L-PBF w/ Slip Jacket	BP-DED	Inco 625	1	15
LOX/RP-1	GRCop-84 L-PBF w/ Composite Overwrap	BP-DED	Inco 625	17	617
LOX/RP-1	GRCop-84 L-PBF w/ Bimetallic Jacket	BP-DED	Inco 625	10	440

Initial testing was conducted using Inconel 625 and JBK-75 superalloy DED nozzles with fully integral channels in LOX/GH2. This was prior to development of the NASA HR-1 alloy. The thrust chamber assembly used a L-PBF additively manufactured shear coaxial injector and L-PBF additive manufactured GRCop-alloy combustion chamber liner, specifically GRCop-42. This data was presented in prior publications[15, 31]. The testing used water as cooling to initially characterize the heat load and then switched to full regenerative cooling with GH2 and showed good performance. The conditions included chamber pressures (Pc) up to 1,140 psig and mixture ratios (MR) up to 6.5 on the JBK-75 BP-DED. An image of the BP-DED nozzle and testing can be seen in Figure 23.

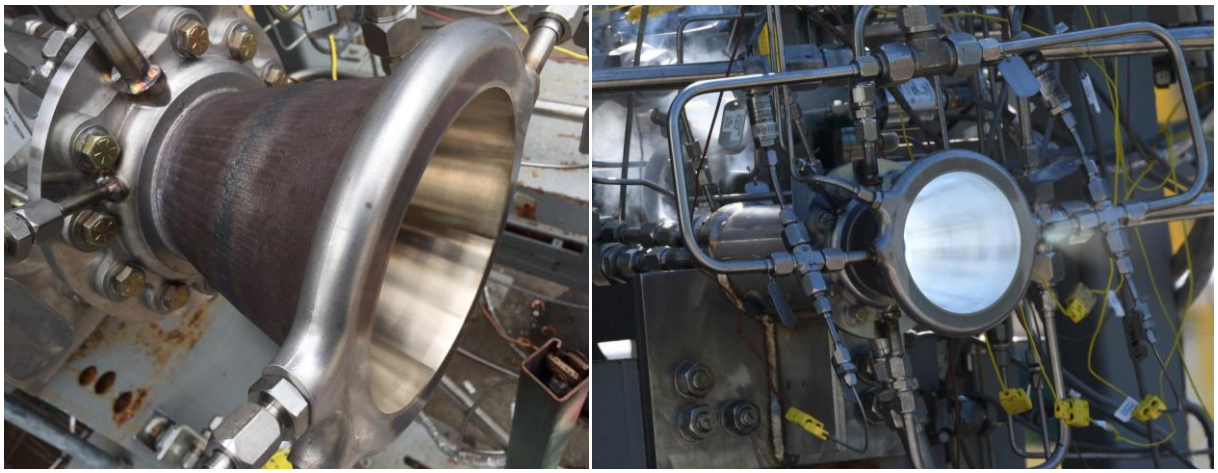

Figure 23. Development testing of integrated channel BP-DED nozzle in LOX/GH2[15, 31].

A further test series was conducted with an Inconel 625 integrated channel BP-DED nozzle and several carbon-fiber composite overwrap chambers using LOX/RP-1 propellants. This test campaign started under MSFC test campaign PI084-1 with water-cooling and continued testing under PJ024 and PI084-2 with full regen RP-1 cooling. These programs for LOX/RP-1 used an additively manufactured impinging injector and operated at chamber pressures (Pc) up to 1,240 psig and mixture ratios (MR) of 2.8 to challenge wall temperatures and loading of the nozzle and resin temperatures of the composite. The primary focus of the testing was the composite overwrap testing in the PI084 program. The nozzle was a decoupled (bolted) configuration. Details of the BP-DED integrated channel wall nozzles were previously presented in a paper with manufacturing process and hot-fire test results[31].

Initial testing with water cooling and RP-1 cooling subjected the backside of the composite overwrap to temperatures approaching 250 °F (121 °C), and later testing under the RAMPT project will push the lower and upper temperature limits of the composite material during steady operation. Overwrapped chambers fabricated at GRC, LaRC, and MSFC were all hot fire tested from December 2018 to February 2019. The chambers used multiple fabrication and resin variants including filament winding, hand-layup, and tape wrapping as previously described. Eighteen (18) hot-fire tests were completed on the various chambers and all performed well at the tested conditions. An example of a hand-layup chamber prior to the tape wrapping overwrap chamber is shown in Figure 24. A filament wound overwrap chamber with stochastic speckle pattern is shown in Figure 25. A Digital Image Correlation (DIC) technique was used to obtain strain measurements during hotfire testing and also during burst testing following the test series[32].

Figure 24. Composite overwrap chamber at MSFC with hand-layup prior to tape wrapping.

Figure 25. Hot-fire setup of composite overwrapped chamber with speckling for Digital Image Correlation (DIC), along with BP-DED Inconel 625 nozzle.

Testing utilized pressurized propellant tanks with flows controlled by cavitating venturis. Water coolant flow was also pressure fed and was controlled by a specifically sized orifice at the coolant water outlet. Ignition was achieved by a LOX lead with Triethylaluminum-Triethylborane (TEA/TEB) injection into the chamber. Mainstage tests were completed at chamber pressures ranging from 750 to 1,240 psia at mixture ratios from 2.2 to 2.8 with LOX/RP-1 propellants. Chamber pressures were driven from a legacy 750 psia case utilized on similar chambers. Chambers accumulated from 80 to 180 seconds of duration and multiple starts, with coolant outlet temperatures and skin temperatures peaking about 250°F. The skin temperatures of the composite were measured with contact type-K thermocouples and no detrimental effects were observed on the composite overwrap during post-test inspections.

Hotfire testing began in November, 2018 with an all metal chamber to prove out the entire start and mainstage sequencing. Testing details were presented in Protz et al[33]. All data was as expected in both the chamber and in the additively manufactured nozzle utilized, and minor sequence changes were made to reduce RP-1 left in the chamber post-test. The hardware was all in good condition with a thick coating of soot on the inner diameter (ID) walls and TEA ash on the lower surface of the chamber and nozzle. Testing then proceeded to the overwrapped chambers, with the main objectives to demonstrate the capabilities in terms of chamber pressure and in terms of liner to overwrap interface temperature. An image from hot-fire testing of the composite overwrap is shown in Figure 26.

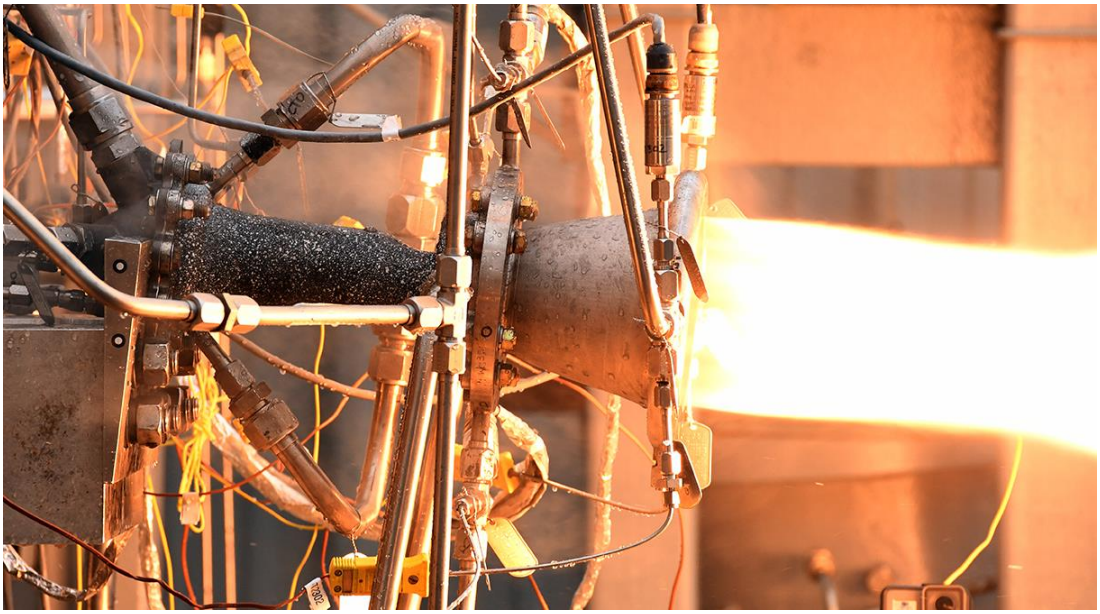

Figure 26. Mainstage hot-Fire testing of filament wound chamber and Inconel 625 BP-DED under PI084-2.

All data was summarized and performance calculated for the specific set of conditions from test data. Post-test analysis predictions were also completed to anchor models to actual hardware measurements, including hotwall temperatures and applied stresses. The nozzle wall temperatures for the integrated channel DED nozzles were previously reported for the RP-1 (Inconel 625) testing at ~1,350°F, and the hydrogen cooled testing (JBK-75) reached a peak near 1,300°F. The wall temperatures peak near the forward end of the nozzle, where the heat flux is highest. Test conditions were intentionally chosen to provide aggressive wall temperatures in order to include large thermal strains in the coolant passage walls. The aggressive testing conditions also demonstrated survivability of the composite resins in this dynamic environment. An image from a composite overwrap chamber post-test can be seen in Figure 27.

Figure 27. Post-test image of the a filament wound chamber - no damage was observed.

IV. Future Developments

The RAMPT project is making significant progress and has several test programs planned in 2020 and 2021 along with the supporting hardware development. Several key milestones have been met, including the large scale blown powder DED nozzle previously shown. Coupled hardware is currently under development and evidenced throughout this publication along with hardware demonstrations of decoupled (bolted) hardware as seen in Figure 28. The chambers for the various scale hardware, which will be used for the integral (bimetallic) nozzle BP-DED were shown previously in Figure 6, and the integrated 2K-lb_f chamber in Figure 9.

In order to develop and demonstrate the composite overwrap onto the L-PBF copper liner technology and the scaling of DED nozzle technologies, three phases of hardware build and tests are in progress. These builds progress in size and thrust levels (2K-lb_f, 7K-lb_f, 40K-lb_f) and will utilize liquid hydrogen (LH2) with regenerative cooling, liquid methane (LCH4) with regenerative cooling as fuels, and LH2, respectively. All test series will use LOX as the oxidizer. The cryogenic fuels are relevant to landers applications and provide the opportunity to demonstrate the composite interface at temperatures from liquid hydrogen temperature (~-390 °F up to the elevated outlet temperatures up to (~450 °F). Fabrication and testing of the increasing size and cooling schemes allows for development efforts to address risks individually and progressively.

The bimetallic development with integral BP-DED nozzle onto the L-PBF chamber was completed for the 2K-lb_f TCA and is actively being fabricated for the 7K-lb_f, 40K-lb_f TCA's. There is simulation modeling to help inform build strategies to control distortion during fabrication. Many of these simulations are limited to monolithic materials, although bimetallic is being studied, but will require additional future development efforts to fully evolve.

The composite overwrap has been demonstrated at the 2K-lb_f scale and fabrication demonstrator completed at the 7K-lb_f scale. There is ongoing work to evaluate new resins that allow for a wider temperature range, focusing on the higher temperatures up to 450 °F (232°C).

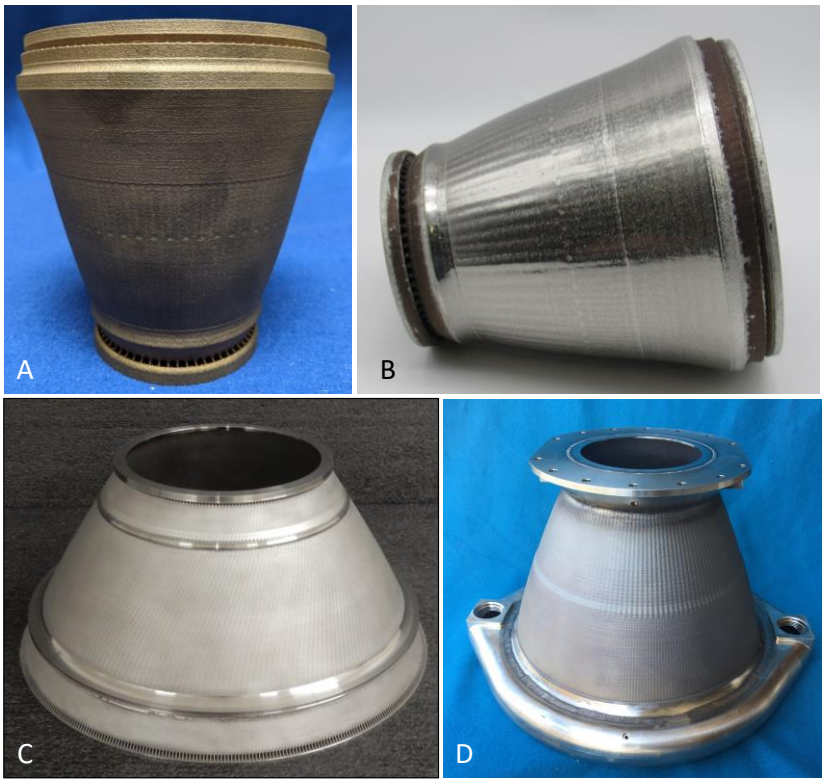

Figure 28. Decoupled integrated channel nozzle fabrication using BP-DED. A) NASA HR-1 2K-lbf nozzle, B) 2K-lbf NASA HR-1 nozzle after polishing, C) 40K-lbf nozzle prior to manifold welding, D) 7K-lbf NASA HR-1 completed prior to polishing.

V. Conclusions

In order to address some of the longest lead, highest cost, and largest mass contributors to liquid rocket engines, NASA is maturing novel design and manufacturing technologies for regeneratively-cooled thrust chamber assemblies (TCA) under the RAMPT project. This project is maturing these technologies to increase scale of additive manufacturing for TCA's, significantly reduce cost and fabrication timelines, and improve performance. RAMPT is improving upon manufacturing technologies for propulsion components, and it builds on the technologies developed under NASA's GCD LCUSP project as well as on other technology development projects[34]. RAMPT has three primary objectives: 1) Advancing blown powder directed energy deposition (BP-DED) to fabricate integral-channel large scale nozzles, 2) Develop composite overwrap technology to reduce weight and provide structural capability for thrust chamber assemblies, and 3) Develop bimetallic and multi-metallic additively manufactured radial and axial joints to optimize material performance. RAMPT is partnering with industry through a public-private partnership to design, characterize, and manufacture component parts of the thrust chamber assembly.

The BP-DED process has completed a series of manufacturing demonstrators and test hardware under the RAMPT project for integral channel nozzles. Additionally, the process has shown feasibility for bimetallic and multi-alloy deposition for fully integral thrust chamber assemblies. Subscale and full scale hardware have and are continuing to be fabricated. BP-DED has demonstrated a significant reduction in build schedules and a feasible technology for integral channel wall nozzles. Under the RAMPT project, NASA selected to perform this development with the NASA HR-1 material. The NASA HR-1 material provides a good trade between thermal conductivity, high yield strength, low cycle fatigue, elongation, density, and hydrogen resistance over other superalloys. It provides advantages over several alternate materials when traded amongst these key nozzle requirements.

Composite overwrap structural jackets provide a significant weight savings opportunity due to the high strength to weight ratio of the carbon-fiber composite. The advances in composite formulations can sustain temperatures spanning from cryogenic upwards of 450 °F. This combined with the L-PBF GRCop-alloy liner technologies allow fully closed out regenerative cooling channels to be built with high conductivity alloys and maintain low weight.

Composites are a viable and desirable choice for chamber jackets. Various overwrap chamber configurations were hot fire tested from December 2018 to February 2019. Eighteen hot-fire tests were completed at chamber pressures up to 1,240 psia. Liner to composite interface temperature of up to 250°F was achieved. Selection of composite material systems and winding/overwrapping strategies for the 7K-lb_f and 40K-lb_f thrust class hardware is continuing under RAMPT.

While composite overwrap trades well for a structural jacket, the RAMPT project is continuing to develop AM bimetallic development as it is still necessary for materials transitions for the welded manifolds. This enables optimized material selection using high strength-to-weight metals for manifolding that can be machined easily for inlets and instrumentation. The bimetallic technology is being developed for both radial and axial directions in the TCA to further optimize the weight by using the most appropriate alloy in discrete locations. Several techniques are being evaluated for the bimetallic deposition with the GRCop-alloys and superalloys. These techniques include gas coldspray, blown powder DED, and laser hotwire cladding. These techniques all have different advantages and disadvantages including heat input and potential for distortion, ability to deposit on complex surfaces, material overspray/usage, bonding strength, supply chain, and feedstock availability. These characteristics must be traded for the particular thrust chamber application and post-processing requirements to determine the most optimal process. A 40k-lb_f bimetallic combustion chamber completed process development using BP-DED to provide a baseline of radial deposition.

The RAMPT project is demonstrating novel manufacturing technologies and integration of these technologies using various scales of hardware. This allows for early lessons to be learned on subscale hardware and progressing towards larger scale and increasing chamber pressures as thermal and structural loads become more challenging. Early hot-fire testing was completed on de-coupled hardware, which included composite overwrap chambers and a BP-DED nozzle with integral channels. This demonstrated feasibility with temperatures approaching 250 °F on the composite overwrap. Testing was also completed on integrated-channel BP-DED nozzles accumulating a total of 142 tests and over 5,242 seconds. Nozzles and overwrapped chambers tested to-date have met most predictions with aggressive test conditions. Hot-fire testing of the completed 7K-lb_f and 40K-lb_f chambers will be performed upon completion of fabrication.

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