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Advancing GRCop-based Bimetallic Additive Manufacturing to Optimize Component Design and Applications for Liquid Rocket Engines

Paul R. Gradl[1], Thomas Teasley[2], Chris Protz[3], Marissa Garcia[4]
NASA Marshall Space Flight Center, Huntsville, AL 35812

Christopher Kantzos[5], *David Ellis*[6]
NASA Glenn Research Center, Cleveland, OH 44135

Additive manufacturing (AM) is advancing many applications of component design for liquid rocket engines. The ability to rapidly design and manufacture components has provided significant opportunities for development and flight programs across the propulsion industry. AM has demonstrated significant advantages that include cost and schedule savings in addition to performance improvements through new design opportunities. While these performance advantages can be in the characteristics of complex design features, they can also be in the form of new materials. AM has been demonstrated in these various component applications using a variety of metal alloys, many of which are traditional alloys for extreme environments. Additional developments were completed using AM to provide new alloys and maturing these material uses for high performance applications. Almost all of the prior developments across component applications have focused on single-alloys in these AM processes. NASA and industry partners have focused in recent years to advance processing to create bimetallic and multicomponent AM processes and materials. The role of multi-alloy AM offers advantages since it can further optimize weight, optimize reliability and performance by increasing the strength to weight ratio of a component, and can optimize materials for various engineering requirements. This is particularly important in liquid rocket engine combustion devices that must reject heat in high heat flux environments yet maintain adequate structural margins under high operational pressure. NASA has been exploring several AM processes, materials, and applications for combustion devices, specifically combustion chambers, injectors, nozzles, and ignition systems. These components require fine geometric features for internal flow or cooling functionality. They experience high thermal gradients across thin-walls and must survive high pressures and temperatures from propellants and the combustion process. A copper-based alloy is normally used to provide high thermal conductivity, but at the detriment of increased weight if used as a single alloy in an AM chamber. Various AM processes were demonstrated on these components using a copper-based alloy/superalloy bimetallic solution. The AM processes being explored individually and in combination for bimetallic applications include Laser Powder Bed Fusion (L-PBF), Laser Powder Directed Energy Deposition (LP-DED), and cold spray. The combination of bimetallic material combinations explored in this research include copper-based material primarily and superalloys, Inconel 625 or NASA HR-1. The various aspects of the additive manufacturing processes and challenges, materials characterization, and the testing of bimetallic components in a relevant environment will be discussed.

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[1] Senior Combustion Devices Engineer, Component Technology Branch, Associate Fellow, AIAA
[2] Combustion Devices Engineer, Component Technology Branch
[3] Team Lead, , Component Technology Branch
[4] Combustion Devices Engineer, Component Technology Branch
[5] Materials Research Engineer, High Temperature and Smart Alloys Branch
[6] Materials Research Engineer, High Temperature and Smart Alloys Branch

Nomenclature

AM	=	Additive Manufacturing or Additively Manufactured
ALPACA	=	Advanced Lander Propulsion using Additive Cold spray Assembly
AW-DED	=	Arc Wire Directed Energy Deposition
CT	=	Computerized Tomography
DED	=	Directed Energy Deposition
EB	=	Electron Beam
EB-DED	=	Electron Beam Directed Energy Deposition
EBF^3	=	Electron Beam Freeform Fabrication
GRC	=	Glenn Research Center
GRCop-84	=	NASA GRC Copper-based alloy (Cu-8%Cr-4%Nb)
GRCop-42	=	NASA GRC Copper-based alloy (Cu-4%Cr-2%Nb)
HIP	=	Hot Isostatic Pressing
K-lb_f	=	thousand pound-force (thrust)
MSFC	=	George C. Marshall Space Flight Center
L-PBF	=	Laser Powder Bed Fusion
LCUSP	=	Low Cost Upper Stage Propulsion
LEMMINGS	=	LEO Mid-scale Main Chamber and Integrated Nozzle Ground Testing
LOX	=	Liquid Oxygen
LP-DED	=	Laser Powder Directed Energy Deposition
Pc	=	Chamber Pressure (psig)
psig	=	Pounds Per Square Inch, gage pressure
RP-1	=	Rocket Propellant 1, Kerosene
TCA	=	Thrust Chamber Assembly

I. Introduction

Combustion device components on liquid rocket engines operate in extreme environments that challenge the functional design, materials, and fabrication that must be integrated into the entire rocket engine system. These components include combustion chambers, nozzles, injectors, gas generators, and igniter systems. Each of these components serve different functions, but have commonality in requirements. They must endure high-pressure propellants and high-temperature gases while maintaining positive structural margins. At the same time, they must be as light-weight as possible to fulfill the needs of the engine system and launch vehicle. Many of these components include complex internal features in the form of flow passages, orifices, and small restrictions. The design of these components often requires thin-walls and a combination of metal alloys that must survive in these environments for multiple reuses.

The materials used in these applications must be selected for propellant compatibility, resisting oxidation, hydrogen embrittlement, hydrocarbon coking, high pressures, high thermal gradients, low- and high-cycle fatigue, and high-static and -dynamic loads in these harsh environments. The component must show repeatable performance and achieve leak-free fabrication. These requirements translate into a material that requires high conductivity, high strength, high ductility, and high-fracture toughness. A single alloy does not fit all these requirements. Various alloys are often used as part of the design to optimize for the environment and minimize weight. This allows the engine system to be optimized and meet performance requirements for the vehicle mission. While many of these requirements are part of the designer's desire, the requirements must be translated into materials selection and manufacturing processes and are not always practical or even possible.

Manufacturing of these components is where many of the challenges remain in providing reliable and repeatable performance. In conventional manufacturing, the use of multiple materials and the complexity of the parts requires multiple joining operations. Integration of these manufacturing, fabrication, and joining techniques, stack up tolerances, and design complexity combine to form the assembly, but also have inherent risks and issues. Improper bonding or assembly can reduce performance from leakage, off-nominal geometry or other manufacturing and joining challenges. Common traditional processes used in the fabrication and assembly of combustion chambers, nozzles, injectors, and igniter subsystems include brazing and welding. This includes furnace and pressure assisted brazing to join multiple parts together. These pieces are often fabricated from multiple alloys. Other joining operations include welding such as tungsten inert gas (TIG) or electron beam (EB) welding to close out manifolds, attach flanges and ports, and provide seals to flow high-pressure propellants or hot gases. Other processes such as subtractive machining, forming, plating, cleaning, inspection, and heat treatments make the overall fabrication process more challenging and cause additional opportunities for the component to have non-conformances against the intended design. It should be noted that many of these processes are also used with AM parts, but the overall goal is to reduce the joining operations and processing as much as possible.

Many technologies have been developed over the last several decades to solve these challenges. The closeout of the coolant channels remains a significant challenge among combustion chambers and nozzles. The two primary configurations for combustion chamber thrust cells are the tube-wall and channel wall configurations. This research focuses on combustion chamber and nozzle components for the channel wall configuration. Prior techniques developed for fabrication of chambers and nozzles include laser welding, pressure assisted brazing, diffusion bonding, platelets, vacuum plasma spray, and explosive bonding. Some companies are highly experienced in these traditional techniques, other techniques exist at vendors as a commercial service, and many new operations have limited and even no commercial expertise in these traditional manufacturing processes.

While significant challenges exist in the closeout of a chamber or nozzle, the upstream and downstream operations are just as important to make a component that meets the intended performance. For traditional manufacturing of chambers, the fabrication is generally broken down into four major steps for a channel wall configuration that can be seen in Figure 1 and was previously discussed in a prior publication [1]. This includes the liner fabrication, channel forming or slotting, closeout of the channels and structural jacketing, and joining of the distribution manifolds. Each of these major operations has numerous sub-operations and steps. Figure 1 does not capture the major demands of specialty assembly and joining tooling that is often necessary to maintain tolerances during assembly and joining operations. These operations are further complicated with the use of multiple alloys. For chambers, the material generally used for the liner is a copper-based alloy. For nozzles, the liner material can vary based on the heat load environment but is normally a stainless steel or superalloy, not a copper-based alloy. The closeout and jacket are generally fabricated from a high strength to weight material to react the component and engine mass.

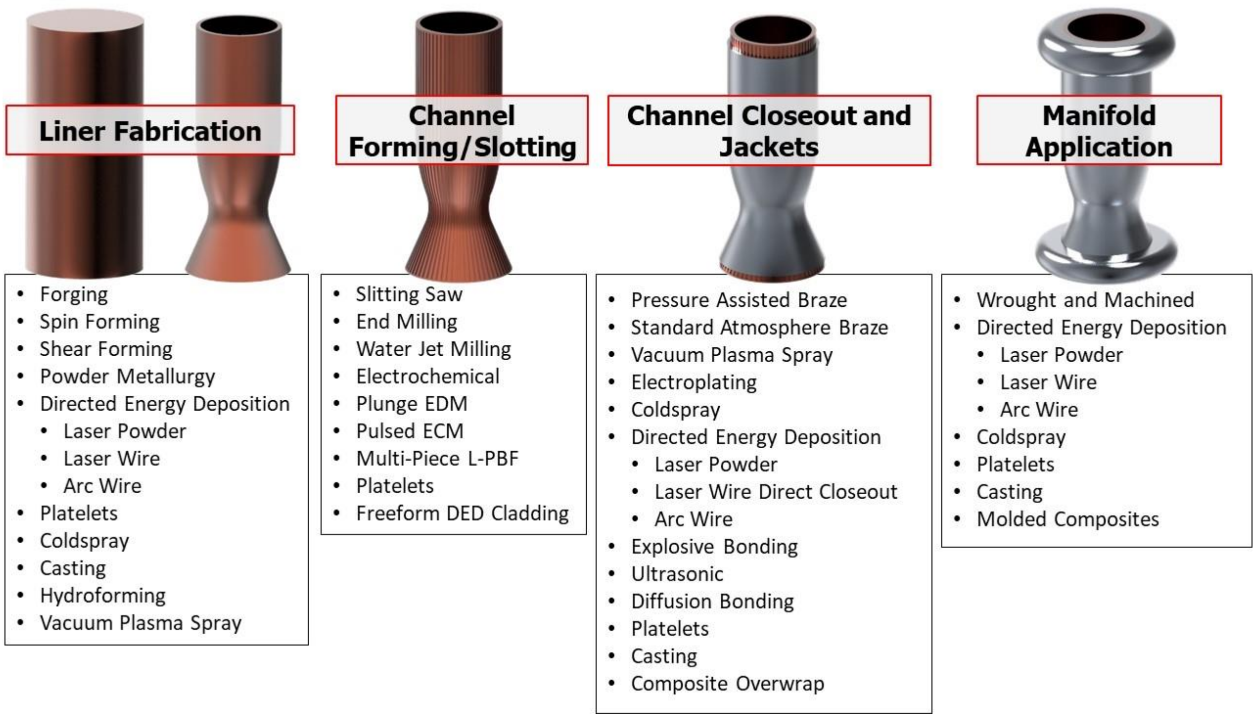


Figure 1. Overview of various manufacturing processes for combustion chambers [2].

Injectors are assembled from many piece parts and have similar fabrication challenges. These components must be held to very tight tolerances for integration into the final assembly. Multiple materials are used in these designs. Various alloys are often used with different requirements for heat transfer and pressure load capabilities. The manifolds and fuel and oxidizer flow passages serve different functions from that of the faceplate that is exposed to the hot gas environment.

Traditional injector fabrication can be broken down into three major operations as can be seen in Figure 2. They are the manufacturing of the elements and/or faceplate, manufacturing of the manifolds and other subassemblies, and the final assembly. Each of these major operations has numerous sub-operations that may include machining, forming, plating, etching, grinding, polishing, cleaning, inspection, and heat treatments. Many of these manufacturing techniques can be seen in use across various flight engines. Some of the fabrication techniques are heavily dependent on the specified design, the company, supply base, and expertise. Figure 2 does not capture the added complexities and design required in specialty tooling required for the assembly operations.

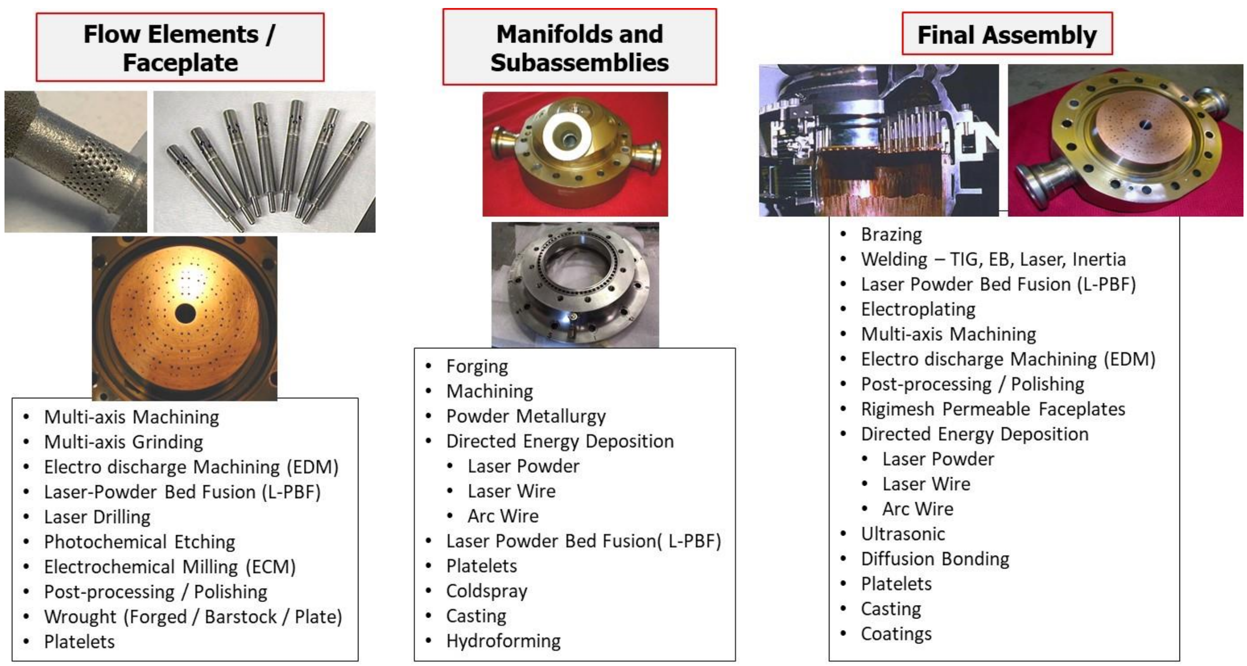


Figure 2. Overview of various manufacturing technologies for injectors [2].

The prior discussion focused on the traditional fabrication methods for chambers, nozzles, and injectors. Additive manufacturing (AM) has removed barriers for fabrication of these components. Notably, it can compress the four major operations of the chamber into a single operation with a few sub-operations. The three major operations for manufacturing the injector can also be reduced to a single operation with a few sub-operations. AM provides a significant advantage for component fabrication by reducing operations while allowing increased design complexity. It solves many of the manufacturing and fabrication issues while reducing the risk associated with joining operations. AM reduces the need for unique manufacturing expertise and specialty processes. It also eliminates most or all the tooling for joining operations.

While AM does offer significant advantages and is in heavy use across the propulsion industry for chambers, nozzles, and injectors, the optimization of the total process has been limited. A majority of the applications using AM are using a single alloy to make one component. Those components may require additional joining operations if multiple alloys are used. Further performance improvements could be made through an AM processing of a second material that has different functional properties to meet local thermal and mechanical loads. Building material radially and axially – to create such features as integral nozzles, manifolds, and flanges – can improve the thrust chamber assembly's performance by optimizing load paths or heat transfer characteristics.

This paper focuses on the process development, material characterization, and component manufacturing of various AM thrust cell assemblies. It includes bench evaluation and hot-fire testing of these bimetallic AM components. The development efforts concentrate on bimetallic AM joints using GRCop-42 (Cu-4 Cr-2 Nb by at.%) and GRCop-84 (Cu-8 Cr-4 Nb by at.%) for the liner material [3]. The GRCop-alloys were then joined to superalloys used for jackets, nozzles, manifolds, etc. The superalloys of interest in this development were Inconel 625 (Ni-21.5 Cr-9 Mo-3.65 Nb-5 Fe (max)) and NASA HR-1 (Fe-34 Ni-14.5 Cr-3.7 Co-2.3 Ti). The intent of using bimetallic AM is to mimic the traditional design when high performance has been proven but takes advantage of AM to reduce the fabrication time and cost. In some designs, performance improvements can be made to help optimize the fluid flow or decrease weight.

II. Materials and Bimetallic AM Processes

Several researchers have evaluated development of bimetallic AM using copper-based alloys and superalloys. Anderson et al., completed evaluation of discrete bimetallic interfaces with C18150 (Cu-1 Cr-0.15 Zr in wt.%) copper-based alloy and Inconel 625 with DED processes, specifically laser wire DED, arc wire DED, and laser powder DED [4]. The results demonstrated complete bonding at the interfaces with the degree of mechanical mixing and diffusion bonding dependent upon the process energy density. Several channel-cooled nozzles were fabricated using C18150 and Monel 400 and hot-fire tested using laser wire DED, also referred to as Laser Wire Direct Closeout (LWDC). These nozzles demonstrated multiple hot-fire tests and repeat cycle testing [5].

Another study was completed using functional gradient compositions of Inconel 718 and GRCop-84 for bimetallic samples to increase thermal diffusivity [6]. Karnati et al. also studied the use of LP-DED for a copper-nickel functional gradient interface with low porosity [7]. Pan et al. completed further research using LP-DED of Inconel 625 onto Copper 110 (C11000, Electrolytic Tough Pitch (ETP) Copper, 99.9% min. Cu) and observed high tensile strength of interface, which demonstrated successful bonding [8]. Other examples of depositing copper using LP-DED to a base material such as a tool steel or Titanium (TA15) to Inconel using a copper interlayer has been demonstrated [9,10].

This prior research provided some of the foundational understanding of bimetallic AM joints, but limited research has been done on the practical application of bimetallic AM for aerospace component applications. The practical application of bimetallic AM uses a base component manufactured from one material and a second material is added with the same or a different AM process. An interfacial layer may be added to prevent mixing and formation of deleterious phases as well. In the process development described in this paper, the base component was always manufactured from L-PBF. This allowed for the small features and tight tolerances of the liner to be met while gross features such as nozzles and manifolds that are too large for L-PBF could be built using another process. Material selection is paramount for these applications, but the AM process selection is just as critical. The deposition process determines the thermal history and mixing of the material at the interface, which in turn determines the stress state and phases formed.

The processes being explored for bimetallic AM include a combination of L-PBF, LP-DED, Electron Beam Wire Directed Energy Deposition (EBW-DED), Arc Wire- Directed Energy Deposition (AW-DED), and cold spray. The materials advanced using these processes include copper-based alloys GRCop-84, GRCop-42 and superalloys Inconel 625 and NASA HR-1. From these materials, the material combinations demonstrated using the processes include:

- GRCop-42 to Inconel 625
- GRCop-42 to NASA HR-1
- GRCop-84 to Inconel 625

The processes used to create each bimetallic combination are shown in Figure 3.

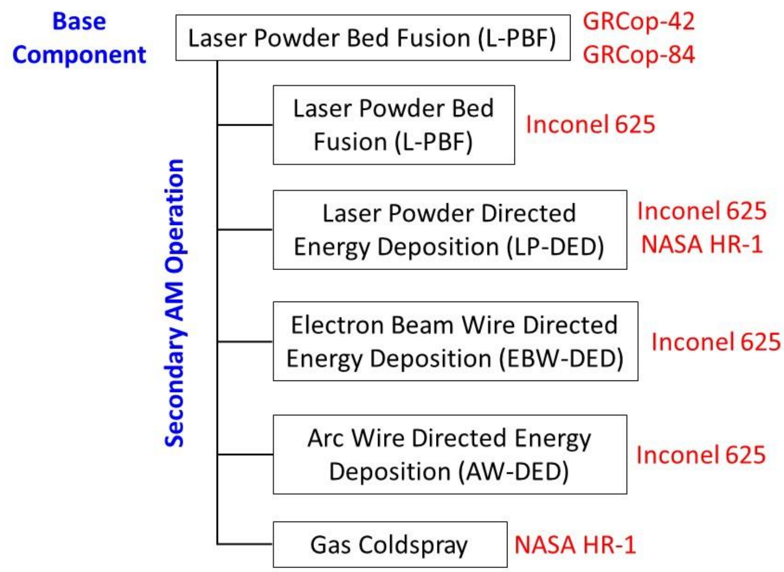


Figure 3. Processes and Materials applied to Bimetallic AM components.

For the application of these bimetallic joints, different configurations were considered along with different processes. The transition from a high-conductivity material like GRCop-alloys to a superalloy can be challenging and the local thermal history is critical to understand. In particular, the copper-based alloys act as excellent heat sinks and make it difficult to transition to the lower thermal conductivity nickel- and iron-based superalloys. As the superalloy layers are added to the liner, the thermal conductivity also changes and can force changes in processing parameters such as lowering the energy density to avoid keyholing.

Each material used in a combustion chamber and the injector serve different functions. The GRCop-alloys have high-conductivity to allow for proper cooling and heat rejection. The superalloy provides high-strength to contain the pressure and support thrust loads. The joint between the two types of materials must meet unique design requirements that include not only functional application but also material compatibility, thermophysical properties, and mechanical properties. This can lead to different joint configurations that include a discrete transition, continuous gradient, or interface material (Figure 4).

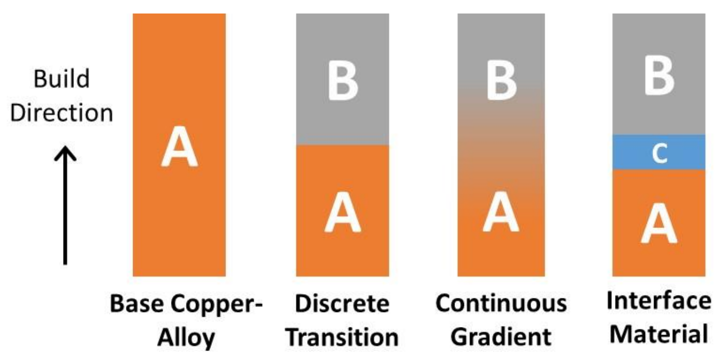


Figure 4. Types of joint configurations for Copper-alloys to Superalloys.

The preferred joint is compliant and accounts for the structural and thermo-mechanical loads. The joint strength is ideally equivalent to the weaker of the two alloys, the GRCop-alloy in this case. To accomplish this requires proper process selection, which can vary based on the application, process development, and available material properties. There are trades between each of the processes and joint configurations that come with varying risks. AM bimetallic joints are challenging in general because the copper-based alloy requires high heat input for proper melting and dilution at the interface. For example, the DED processes each have varying levels of heat required for proper mechanical mixing of the superalloy with the GRCop-alloy. The GRCop-alloy is high CTE, while the Superalloy is lower, so during deposition, the copper expands and then cools and the Superalloy has less expansion, which can cause shrinkage and high residual stresses. This is a highly complex joint with the high plasticity of the GRCop-alloy and does require an appropriate deposition strategy and understanding of the thermal history. Prior publications for bimetallic joints reported as much as 10% radial and axial shrinkage on combustion chamber development hardware [11]. Cold spray joints can largely eliminate this shrinkage problem since lower temperatures are experienced in processing, but the joint strength may be lower because there is only mechanical bonding at the interface. The high residual stresses from the cold spray process can setup some shrinkage based on the design. Examples of different bimetallic joints with varying degrees of diffusion can be seen in Figure 5.

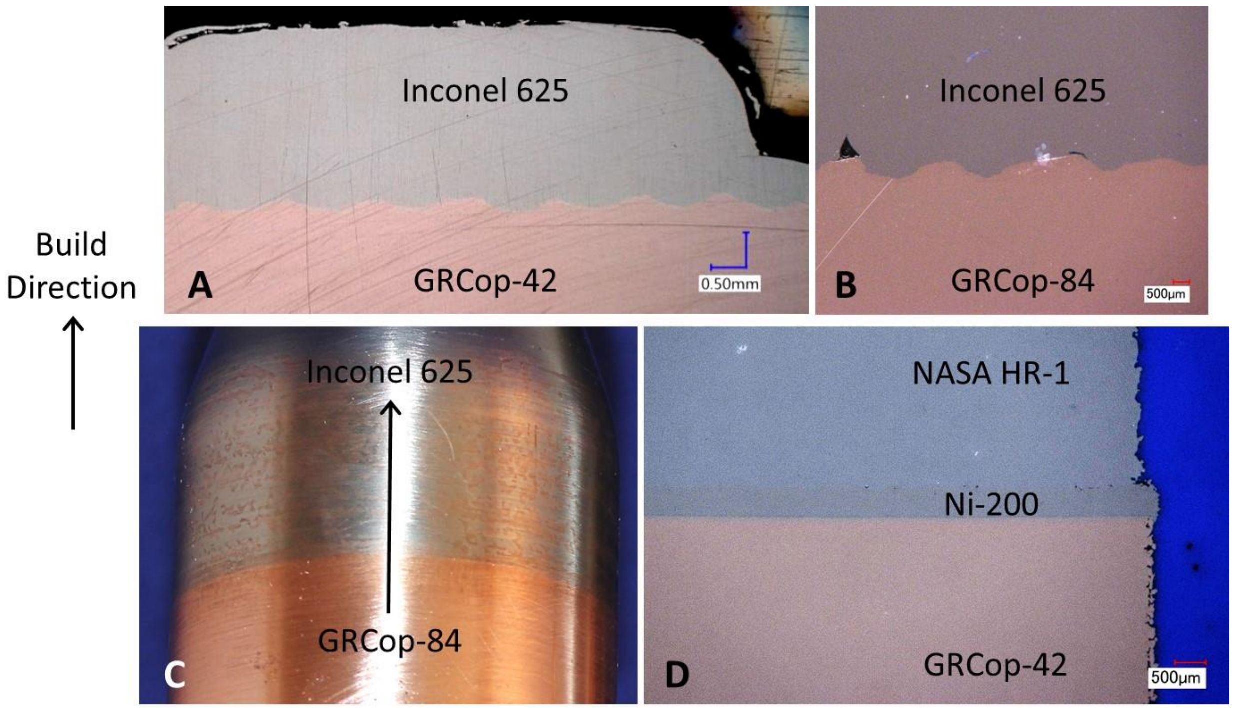


Figure 5. Bimetallic or multi-metallic joint examples. A) Laser Powder DED with Inconel 625 to GRCop-42, B) Arc Wire DED with Inconel 625 to GRCop-84, C) Gradient transition from GRCop-84 to Inconel 625, D) Interface metal using cold spray Nickel followed by Laser Powder DED of NASA HR-1.

A. Laser Powder Bed Fusion (L-PBF)

The L-PBF process is a layer-by-layer AM process within a bed of powder. The process is initiated with a 3D-CAD model that is sliced into discrete 2D layers that provide definition of the laser toolpath for melting each layer of the part. A thin layer of metal powder, typically 20-45 microns, is spread across the build area using a recoater arm. A fine-focus laser rasters across the powder layer and melts the area that defines the part cross-section at that particular layer [12,13]. A build plate is required to initiate the process so the material has something to support the first layer. After a layer is completed, the build plate is lowered an amount equal to the desired layer thickness, a new layer of powder is spread, and the process is repeated. Sufficient power is used to penetrate into previous build layers allowing proper bonding between layers. The process is repeated thousands or even tens of thousands of times for a large piece such as a liner until the part is fully fabricated or grown. This allows complex internal features like cooling channels in liners to be manufactured and fully closed-out in a single manufacturing step. Different parameters are used for the infill (internal material) and the contouring (surfaces inboard or outboard) for a component. The intent of the contour pass is to provide a fine surface finish while the infill parameters are optimized for speed.

Most L-PBF machines use a single powder. It currently has not been demonstrated to be feasible to build rocket engine combustion chambers with a second alloy in the same operation. There are references for bimetallic alloy L-PBF processing, but still under development [14]. To perform bimetallic L-PBF for this study, a secondary machine was used with a different alloy. There are challenges with this process that includes proper cleaning of the base part, alignment of the build plate to ensure proper geometry, and interface melting and bonding by the new material to the existing build.

To accomplish printing Inconel 625 onto GRCop-42 to make a component, the base part was fabricated first with GRCop-42 onto the build plate. The part was them removed from the machine and gross powder removed along with precision cleaning of any excess residual powder. The build plate with the GRCop-42 part was then bolted into a secondary machine and aligned to ensure the new build would start at the interface location. The builds were aligned using crosshair datum features fabricated on the build plate separate from the component. The bed then filled with Inconel 625 powder to the determined height. Several initial preheating operations were conducted before powder was fully melted to create the Inconel 625 to GRCop-42 bimetallic interface.

Mechanical test samples were manufactured prior to the bimetallic component builds. However, a fundamental difference with these samples was the reverse of alloy printing order. The Inconel 625 was fabricated first and then the GRCop-42. This was due to parallel development that was ongoing at the time to evaluate using a bond layer of Inconel 625 to secure the GRCop-42 to the build steel plate better [15]. These samples went through identical cleaning, alignment, and preheating operations as component development builds. Following L-PBF the samples were hot isostatic pressing (HIP) using the standard GRCop HIP parameters. The samples were machined and tensile tested per ASTM E8 [16]. The typical ultimate tensile strength (UTS) and yield strength (YS) are shown in Figure 6 along with average UTS and YS of HIP'd L-PBF GRCop-42. The six interface samples tested at room temperature and five interface samples tested at each of the elevated temperatures showed good repeatability. The GRCop-42 data set is much larger. It was observed that the results were similar with the bimetallic samples being slightly stronger at all test temperatures. This indicated that the interface was as strong or stronger than the parent, GRCop-42. There was also considerable plastic deformation in the GRCop-42. While elongation data was collected and exceeded 20% based on extensometer data, a biaxial stress state is created at the interface and no plastic deformation is observed in the Inconel 625. Similar results were presented using bimetallic microtensile specimens with GRCop-84 and JBK-75 (UNS S66285, Fe-15 Cr-20 Ni-2.5 Ti-0.5 V-0.5 Al-2 Mn-1 Si in wt.%). The fracture again occurred in the GRCop-42 [11].

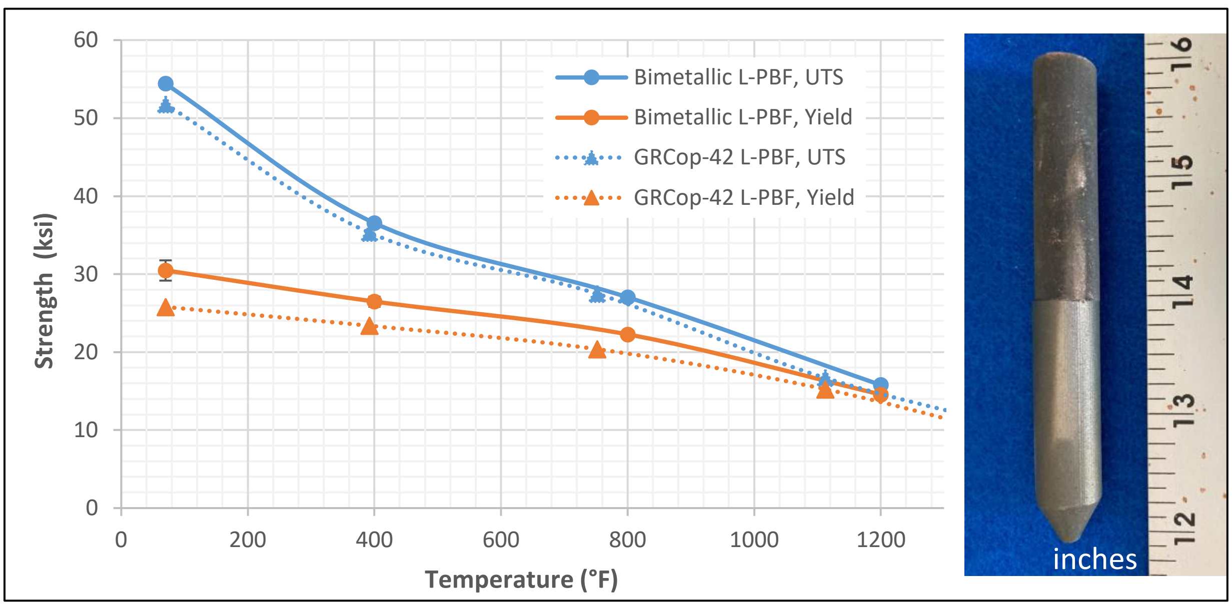


Figure 6. Typical Tensile and Yield Strength of HIP'd GRCop-42 to Inconel 625 bimetallic samples using L-PBF. Test results are compared with typical monolithic L-PBF GRCop-42 HIP'd material.

B. Laser Powder Directed Energy Deposition (LP-DED)

The laser blown powder DED (LP-DED) fabrication technique uses a coaxial nozzle with a central laser source with one or more powder nozzles or an annular nozzle. The desired powder is injected into a gas stream in the nozzle and blown into the focus of the laser beam. The melt pool is created on a base plate or part and material is deposited. The powder is blown into the melt pool using an inert carrier gas. Much like various inert gas welding techniques, the inert gas shields the molten metal from the air and minimizes oxidation. This head system, with integrated focus optics and blown powder nozzle(s), is attached to a robotic arm or gantry system that follows a toolpath defined from the CAD model. Various optics can be used to vary the spot size, which control the size of features that can be built. The blown powder head can be contained in an inert gas chamber or operated with a local purge. The blown powder system and robot allows for large, complex freeform structures to be built. The method also avoids the need to fill a large build volume with powder as in a powder bed process.

Various developments have been completed with LP-DED application of superalloys onto GRCop-42 L-PBF. These developments include deposition at multiple vendors. So far, both a direct deposition using Inconel 625 and deposition o NASA HR-1 with an intermediate Cu-Ni layer have been completed.

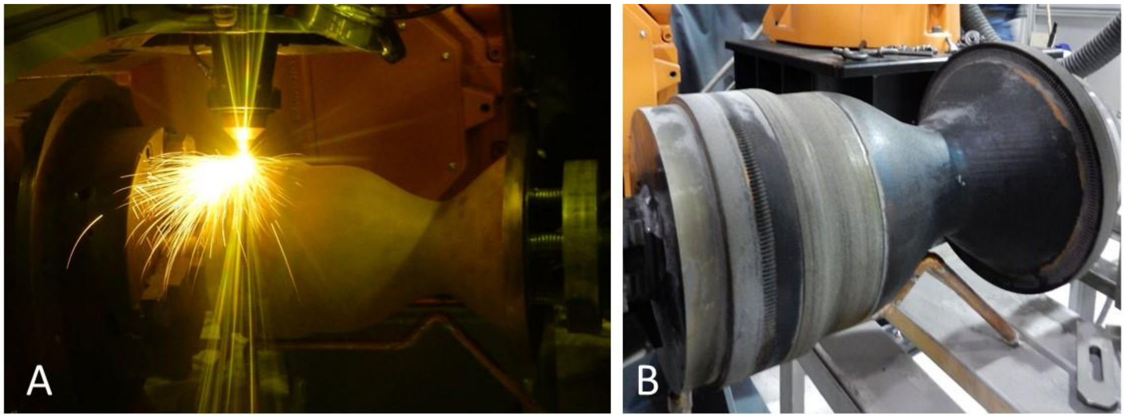


Figure 7. LP-DED cladding of bimetallic structural jacket using Inconel 625 onto GRCop-42.

C. Cold Spray

Cold spray is a solid-state deposition technique that can create bimetallic joints and build up material for welding of manifolds or other parts onto components. It is often commercially used for repair applications as well.

The process injects a stream of powder into an inert carrier gas like the LP-DED process. In this process, the carrier gas is supersonic, typically in the range of 500-900 m/s [17] and imparts high energy to the powder particles. The nozzle creates a tight stream of particles that is directed to the top of a plate, mandrel, liner, etc. When the metal powder hits a surface, such as the component, it plastically deforms. In addition to mechanical bonding, the intimate contact between clean metal surfaces created by the deformation develops a metallurgical bond without mixing the two materials. The entire process occurs near room temperature and does not create residual thermal stresses observed in most AM processes.

The cold spray deposition head is integrated with a robotic arm. The system allows multi-axis coordinated motion to deposit material where required. Cold spray has been used for various superalloys and copper-based alloys [18]. It has been demonstrated with copper-based alloys C18150, GRCop-84 and GRCop-42 with near-wrought properties [19,20,21]. Cold spray has also been used as a replacement for casting or forging to make the combustion chamber liner. In this application, the liner was later machined and slotted with channels. The cold spray process was demonstrated for closeout of the copper liner and application of the structural jacket as seen in Figure 8.

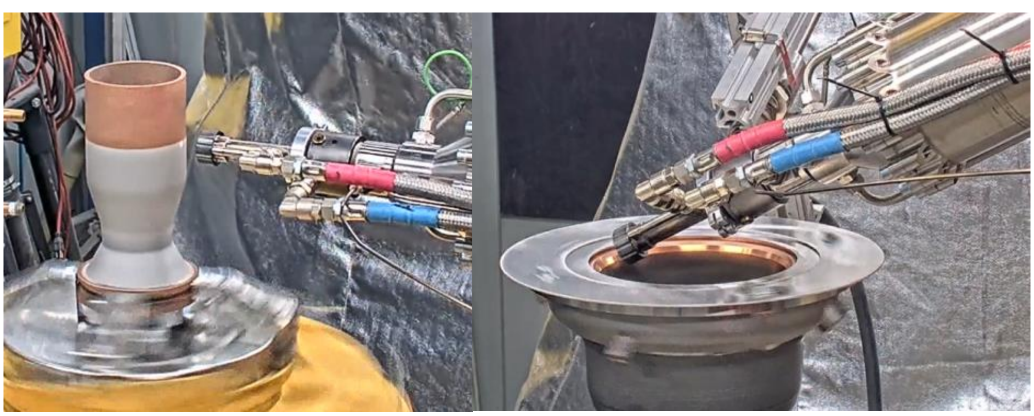


Figure 8. Cold spray of bimetallic chamber structural jacket (left) and cold spray repair of bimetallic chamber (right).

D. Electron Beam Wire Directed Energy Deposition (EBW-DED)

The EBW-DED process uses an electron beam energy source and off-axis wire feed as the material feedstock. A melt pool is created using the electron beam on the substrate while a wire is fed into the molten pool at a controlled rate. The part and wire feed traverses using a kinematic robotic arm or Cartesian gantry system. This is coordinated with a tilt and turn trunnion table. The entire build process takes place within a vacuum, which is required for the electron beam. This build process allows high deposition rate, layer-by-layer manufacturing to complete a freeform components or bimetallic features. Two wire feeders can be used independently or simultaneously. This enables increased deposition rates or material gradients to create bimetallic or multi-metallic structures. NASA demonstrated the EBW-DED for deposition of an Inconel 625 structural jacket onto the GRCop-84 L-PBF combustion chamber seen in Figure 9. The EBW-DED process is typically higher heat input and can impart high residual stresses and distortion if not properly accounted for during manufacturing. The minimum feature size is controlled by the wire diameter and is much larger than powder AM processes (millimeters versus micrometers).

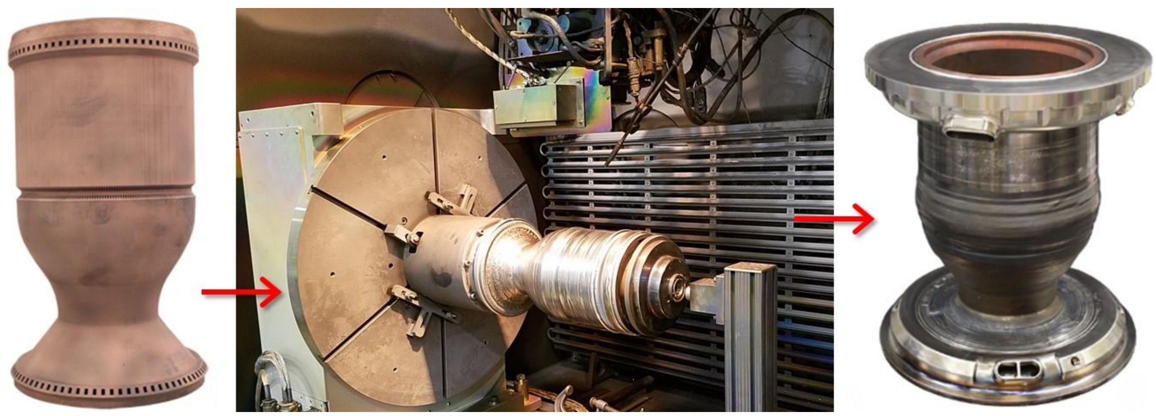


Figure 9. Inconel 625 jacket deposition using Electron Beam Wire Directed Energy Deposition (EBW-DED) at NASA Langley.

E. Arc Wire Directed Energy Deposition (AW-DED)

AW-DED uses a metal inert gas (MIG) welding process where electric current is applied to a central feedstock wire surrounded by inert gas. An arc is created between the wire and substrate, and the wire is continuously fed into the melt pool. The MIG power supply and wire feed is typically a pulsed-wire system and can vary voltage for a stable arc. Like the EBW-DED systems, the MIG deposition head is attached to a kinematic robotic arm and integrated with a tilt and turn trunnion table for multiple degrees of freedom. This allows for creation of freeform parts or cladding operations such as depositing a jacket on a liner. The AW-DED process, similar to EBW-DED, creates a coarse bead and does not allow for feature resolution below 2-3 mm [22]. The AW-DED process can be seen in Figure 10 along with a jacket applied to a L-PBF GRCop-84 liner.

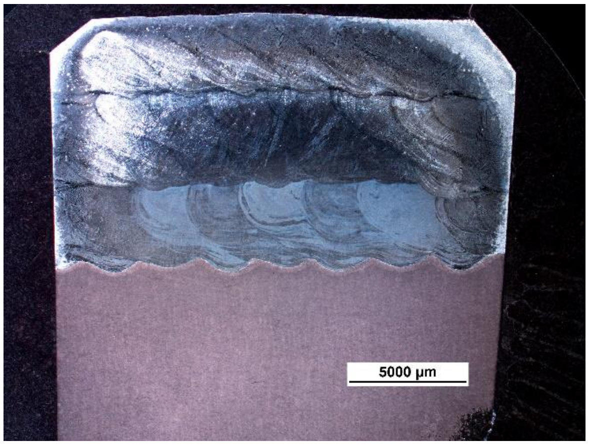
Figure 10. Arc Wire DED (AW-DED) process. A) Process demonstration of monolithic chamber, B) Inconel 625 jacket applied to GRCop-84 L-PBF liner, C) Finished bimetallic chamber using AW-DED jacket.

F. Bimetallic Joint Evaluation and Testing

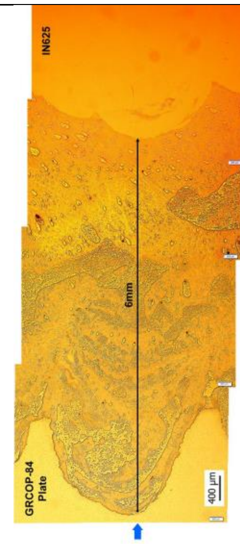
Evaluation of bimetallic processing for combustion chamber assemblies at NASA began under the Low Cost Upper Stage Program (LCUSP). One of the main goals of the program was to apply an Alloy 625 structural jacket to a GRCop-84 liner using AM techniques. The liner was first made using L-PBF. Inconel Alloy 625 was added by Electron Beam Freeform Fabrication (EBF^3), a form of EBW-DED processing. The resulting as-manufactured chamber is shown in Figure 9.

Several lessons were learned during the LCUSP program. The first was that the stresses imparted during the EBF^3 deposition were much greater than anticipated. No modeling was done beforehand, but the similarity of the coefficient of thermal expansion (CTE) of Inconel Alloy 625 [23] and GRCop-84 [24] led to the selection of it to minimize thermally induced stresses. Instead, the liner was compressed by up to 10% in the axial direction [25]. Reductions in diameter were also noted. Residual stress testing of a chamber section also showed that the residual stresses were similar to the yield strength of GRCop-84. The implications were that there would be dimensional changes during deposition of a second material that could result in a part no longer being within dimensional tolerances. Design of a chamber or other part to account for these changes would mitigate that potential risk.

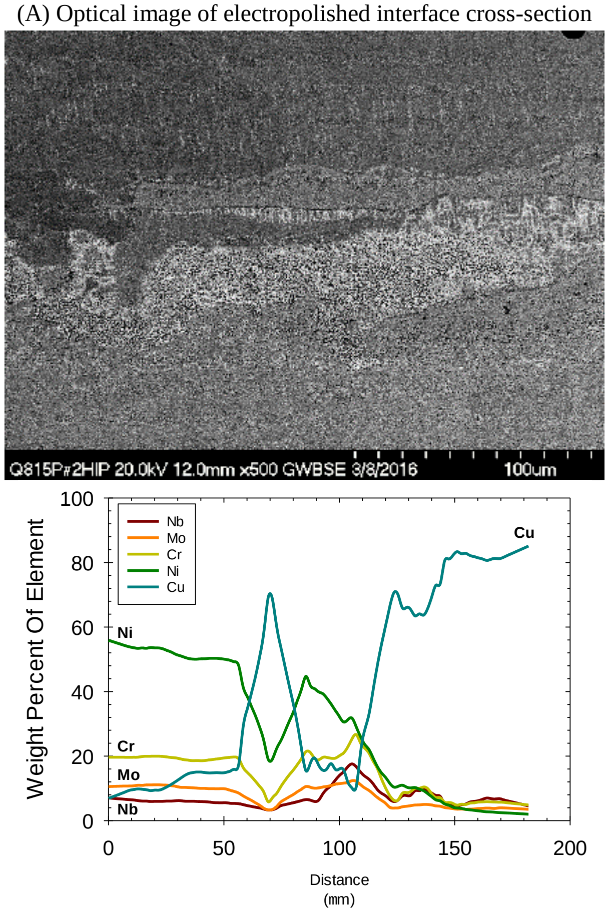
The second discovery was that the dilution of GRCop-84 into the Inconel Alloy 625 deposit was greater than anticipated. As seen in Figure 11, there were clearly visible differences in the look of the deposit near the interface (Figure 11A and Figure 11B). Using Energy Dispersive Spectroscopy (EDS), Cu not only was observed in the first bead as expected but was easily detectable in the second bead as well. This created alloys with different properties and potentially new phases. These could create potential issues at and near the interface. The new alloys can have vastly different mechanical properties. New phases such as eta (η), delta (δ) and Laves phases could embrittle the material and result in loss of tensile strength or fatigue life. Proper selection of the second alloy through Calculated Phase Diagrams (CALPHAD) and similar techniques can identify when such phases may be created.



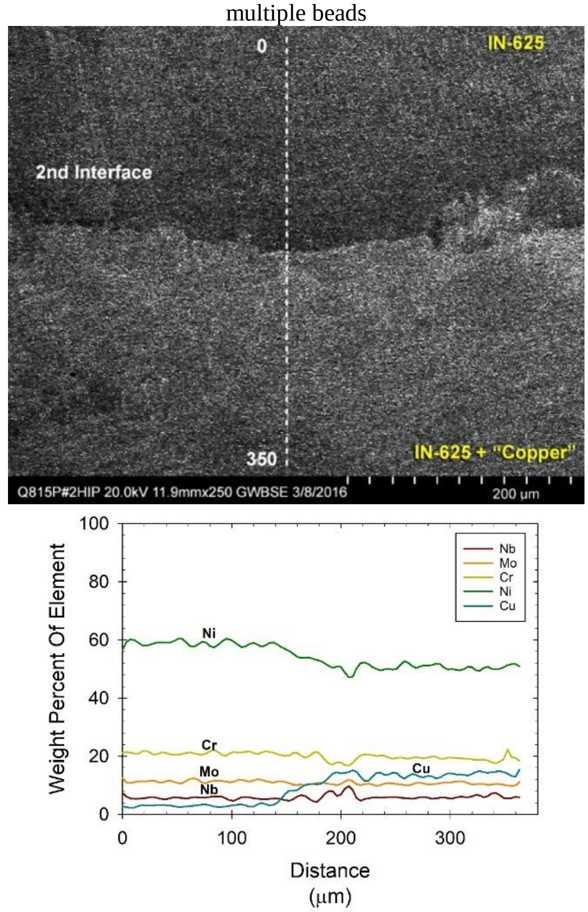
(A) Optical image of electropolished interface cross-section



(B) Composite optical image showing dilution across multiple beads



(C) SEM image and EDS line scan of the primary Inconel Alloy 625 interface. Note physical inclusion of GRCop-84 particle.



(D) SEM image and EDS line scan of the secondary Inconel Alloy 625 interface between the first and second layers. Note persistence of Cu in second layer.

Figure 11. Bimetallic EBW-DED to L-PBF. (A,B) Images of GRCp-84/Inconel Alloy 625 interface and (C,D) SEM and Energy Dispersive Spectroscopy (EDS) line scan across the interface.

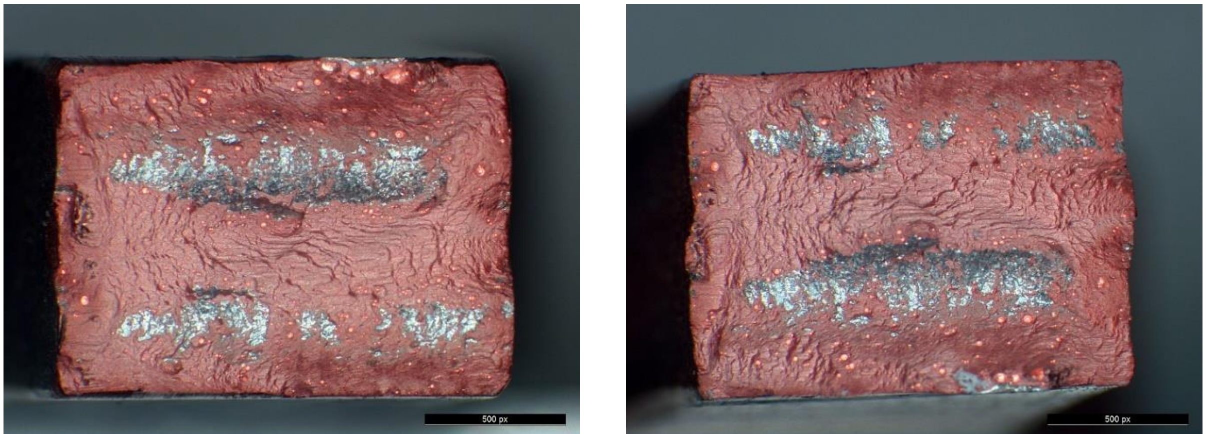
The third observation was that there was cracking present at the interface between the GRCop-84 substrate and the first Inconel Alloy 625 layer. There were also cracks observed between the first and second Inconel Alloy 625 layers as seen in Figure 12. In some samples, cracking in the Inconel Alloy 625 deposit was greater than at the interface. It was unclear if this was a residual stress or processing issue, but both were identified for consideration in future efforts.

Figure 12. Macrophotograph of crack in Inconel Alloy 625/GRCop-42 sample used for interface bond strength testing of EBW-DED. Crack is between the first and second Inconel Alloy layers.

The fourth major finding was that the bond across the interface had a strength similar to that of the underlying GRCop-84 material as seen in Table 1. This showed excellent bond strength between the substrate and deposit when cracks were not present. While the joint was the location of the failure, the interface itself remained intact. Figure 13 further supports this as there was easily observed transfer of GRCop-84 to the Inconel Alloy 625 half of the failure surface. This demonstrated that excellent bond strengths are possible for bimetallic joints.

Table 1. L-PBF GRCop-84/EBW-DED Inconel Alloy 625 interface bond strength Summary

Condition		**0.2% Offset Yield Strength, ksi (MPa)**	**Ultimate Tensile Strength (UTS), ksi (MPa)**
As-Deposited	Average	31.4 (216.7)	55.3 (381.5)
	Lower 95% Confidence Value	30.5 (210.3)	54.3 (374.7)
HIP'd	Average	29.0 (200.0)	27.4 (327.1)
	Lower 95% Confidence Value	27.9 (192.6)	46.3 (319.3)



(a) Inconel Alloy 625 half (b) GRCop-84 half

Figure 13. Typical interface failure surfaces from EBW-DED Inconel 625 to L-PBF GRCop-84.

Under the RAMPT program, the work begun under LCUSP has been continued. One of the first studies completed was a series of CALPHAD simulations to analyze the phases that should be present in the GRCop-42/Inconel Alloy 625 interfacial region. These simulations are sensitive to two major factors: the percentage of mixing, equivalent to dilution, between alloys and the temperature used to calculate equilibrium. The effective temperature and extent of mixing change considerably based on the deposition process (e.g. cold spray versus laser hot wire deposition). They also vary within each sample based upon its position (e.g., the differences in beads shown in

Figure 11 above). Thus, a variety of mixture ratios and temperatures were considered in the simulations. Table 2. CALPHAD Summary shows the calculated phases of concern that were predicted in CALPHAD models for a number of alloys mixing with GRCop alloys. The table shows the compositions of these phases, whether or not these phases are known to be deleterious, and if they have been observed in our analysis.

Table 2. CALPHAD Summary

	Ni		**Inconel Alloy 625**				**JBK-75**				**NASA HR-1**				
Phase	δ	Cr	δ	σ	Laves	Cr	δ	Laves	η	Cr	δ	Laves	η	Cr	σ
Composition	Ni_3Nb	Cr	Ni_3Nb	FeCr	$(Ni,Cr)_2$ (Nb,Mo)	Cr	Ni_3Nb	$(Fe,Cr)_2$ (Mo,W)	Ni_3Ti	Cr	Ni_3Nb	$(Fe,Cr)_2$ (Mo,W)	Ni_3Ti	Cr	FeCr
Potnetially deleterious?	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes
Observed	Maybe (Could be γ")	Yes	Yes	No	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes

Because of the undesired phases that were observed in the CALPHAD simulations, as well as initial metallography results, a barrier layer was explored to transition from the GRCop alloys to the superalloy. Table 2 shows how pure Ni does not contain any of the elements that form potentially harmful phases, namely Fe, Mo, W, and Cr. Initially, a Ni-Cu interlayer was chosen as a more gradual transition between the Ni-based superalloys and Cu-based GRCop alloys.

Based upon these analyses, a first attempt was made to build two nozzles made of NASA HR-1 onto two GRCop-42 liners using LP-DED. One nozzle was built directly onto the liner while the second had a Cu-30 Ni (Cu- 30 wt.% Ni) interface layer. A sufficiently good bond was established to allow removal and testing of interface samples, though some interface cracking and separation was observed with both the Cu-30 Ni interlayer and the direct NASA HR-1 deposition. An area at the aft end of the GRCop-42 liner that was also between nozzle channels (Figure 14) was selected. The microtensile design allowed several samples to be extracted. The samples were heat treated using the NASA MSFC-developed heat treatment steps for AM NASA HR-1. The ultimate tensile strength (UTS) of the interface at each heat treat step is shown in Table 3. With a few exceptions, the results are similar to the UTS of the L-PBF GRCop-42. The low strength samples were likely the result of partial cracking at the interface, leading to a decreased cross-sectional area. Some decrease in the strength of GRCop-42 occurs during the high temperature solution heat treatment for the NASA HR-1 due to coarsening of the Cr_2Nb precipitates that give GRCop alloys their strength. This results in a corresponding decrease in the interface UTS.

Table 3. Summary of average tensile strengths of interfaces.

Thermal History	**No Interlayer, ksi (MPa)**		**Cu-30 Ni Interlayer, ksi (MPa)**	
-	54 (372.6)	52 (358.8)	50 (345.0)	44 (303.6)
Stress Relief	50 (345.0)	47 (324.3)	48 (331.2)	46 (317.4)
Solution Treatment	41 (282.9)	49 (338.1)	44 (303.6)	37 (255.3)
Aged (Full HT)	49 (338.1)	48 (331.2)	*25 (172.5)*	46 (317.4)

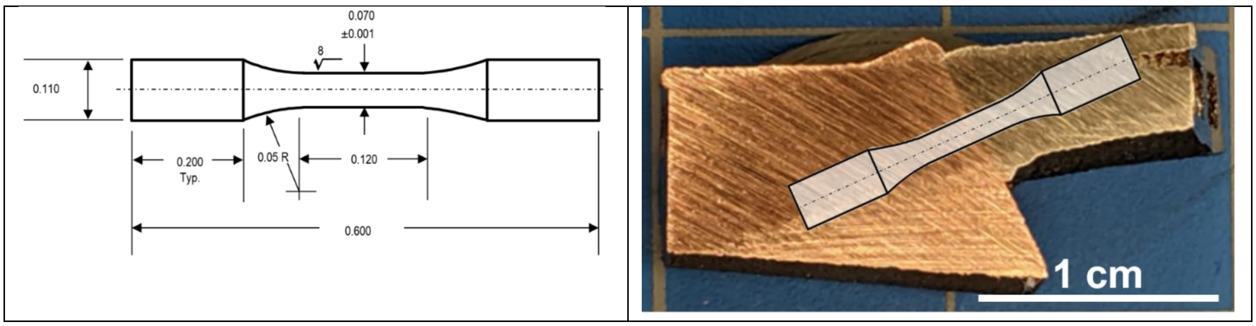


Figure 14. Microtensile specimen design and location selected for sample extraction.

Figure 15 shows a cross-section of the interface. During LP-DED, the laser will melt the substrate and mix the alloys together much like was observed in EBF^3 during LCUSP but on a much finer scale (microns versus millimeters). When deposited directly onto GRCop-42, this can create embrittling phases as noted previously. A potential method to eliminate this mixing and formation of undesired phases is to use a solid-state process such as cold spray. Because there is no mixing, the elements are physically separated. There also is no melting, so there is no dilution and no energy or heat to drive diffusion and reactions.

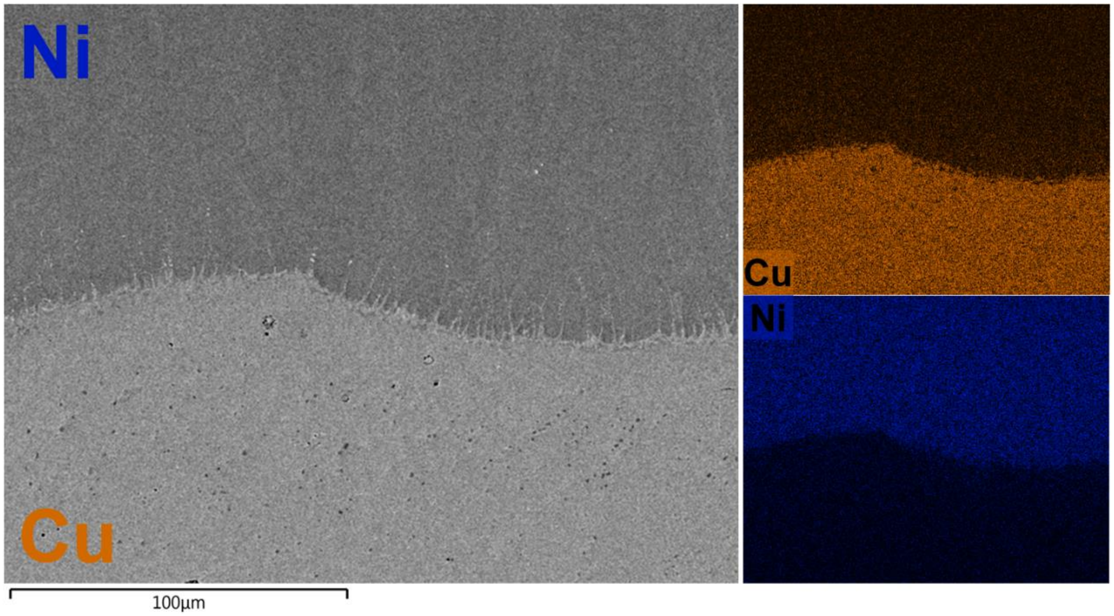
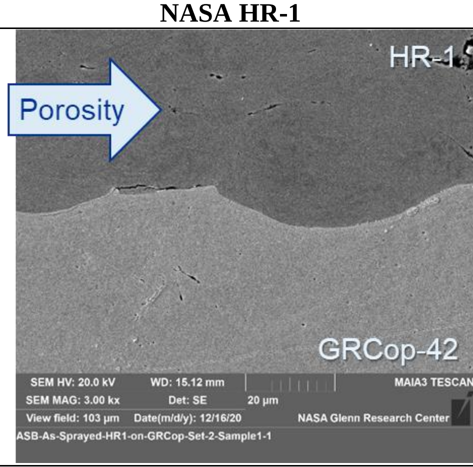
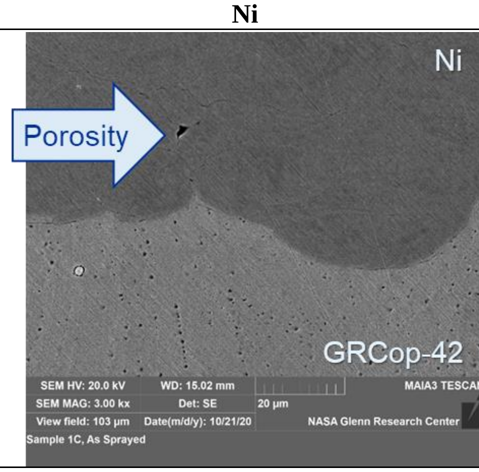


Figure 15. Secondary Electron (SE) image (left) of the interface of LP-DED deposited Ni-Cu with a full heat treatment. EDS x-ray maps of Ni (upper right) and Cu (lower right) of the interface of LP-DED deposited Ni-Cu with a full heat treatment.

Cold spray was selected as the solid-state processing method. Pure Ni was selected as a first attempt to improve the interface with a cold sprayed boundary layer. Samples were prepared with Ni and NASA HR-1 cold sprayed onto a GRCop-42 substrate. Half of the samples were HIP'd using the standard GRCop-42 HIP cycle that exposed the interfaces to elevated temperatures for several hours. The resulting microstructures are summarized in Figure 16.

	NASA HR-1	**Ni**
As-Deposited		

HIP'd

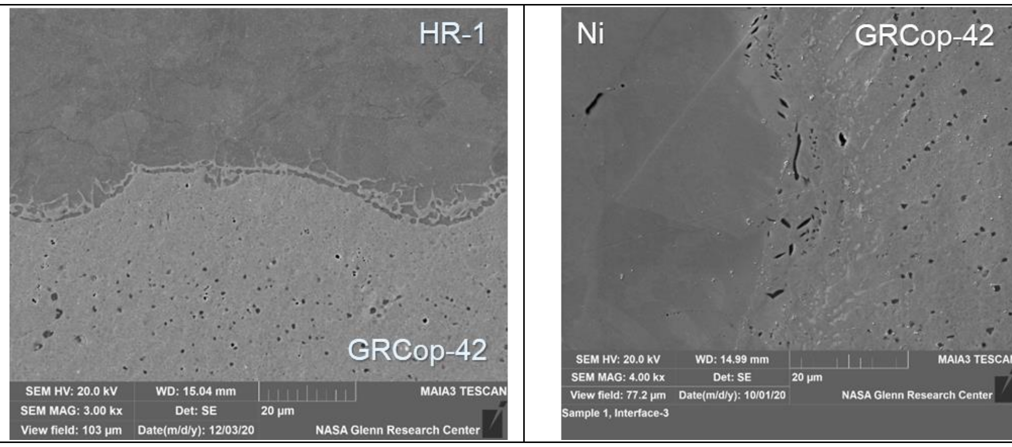


Figure 16. Interfaces in the as- cold sprayed and after HIP'd conditions

In both cases, the as-sprayed interfaces were cleaned and degreased with minimal roughening. The original surface finish was not measured, but peak-to-valley depths for the interface were around 20 μm, which is similar to a medium finish turned surface. The interfaces have minimal porosity, but the coatings have very little to a few percent depending upon the spraying parameters.

During the HIP process, the temperature and time allowed the elements in each metal to diffuse. This creates compositional gradients and new phases. Table 4 provides a summary of the detected phases. The high Fe content in NASA HR-1 combines with Cr from both the NASA HR-1 and GRCop-42 to form a nearly continuous layer of σ FeCr, a known embrittling phase in stainless steels. While awaiting test results, it is expected that this interface will be brittle and fail easily. Any fatigue crack should propagate easily along the interface as well. In contrast, the Ni produces a diffuse interface with only phases that general strengthen materials present.

Table 4. Phases present in cold sprayed samples following HIP cycle.

Cold Spray Deposit	Major Phases Detected
NASA HR-1	Fe-Ni-Cr solid solution (NASA HR-1) Cu (GRCop-42 matrix) Cr_2Nb (GRCop-42 strengthening phase Cr (GRCop-42 strengthening phase) σ FeCr
Ni	Ni Cu (GRCop-42 matrix) Cr_2Nb (GRCop-42 strengthening phase Cr (GRCop-42 strengthening phase) T (Ni-stabilized hexagonal Cr_2Nb transition phase) γ" or δ Ni_3Nb

Based upon the cold spray HIP'd sample results, it is suggested that a Ni layer be tried as a boundary layer. The thickness should be sufficient to prevent the bottom of the melt pool reaching the GRCop-42. It should also have enough additional material to prevent diffusion of elements from NASA HR-1 into the GRCop-42 to form σ FeCr. The first dimension is dependent upon the AM process but should be between 100 and 300 micrometers for a laser-based process. Assuming a standard GRCop-42 HIP cycle after deposition, the diffusion distance for GRCop-42 and NASA HR-1 into the Ni layer will be about 50 μm each for a total of 100 μm. Ideally, the melting and diffusion of the alloys into the Ni will completely consume the Ni layer and leave behind a smooth transition from GRCop-42 to NASA HR-1 and a strong, tough interface.

III. Application, Design, and Fabrication of Bimetallic GRCop-alloy AM Components

Additive manufacturing has significantly advanced the design opportunities to use bimetallic or multi-metallic solutions. The various AM processes must work collectively using the L-PBF for unique features and the DED or cold spray processes for their advantages. For this study, liners were made using L-PBF so that coolant channels, internal passages, or internal features could be closed-out [26]. This allowed the use of DED or cold spray processes to create the structural portions of the combustion chamber assemblies. There are several intended design applications using bimetallic AM that offer advantages over the traditional techniques. The AM bimetallic techniques can be applied in both a radial configuration, such as a jacket for the chamber, and in an axial arrangement such as a nozzle built on the aft end of a liner. These specific applications included the following, and examples are shown in Figure 3 below:

1. Superalloy structural jacket to a copper-based alloy combustion chamber liner with coolant channels
2. Superalloy injector elements, body, and manifolds to a copper-based alloy faceplate
3. Superalloy channel cooled nozzle or radiatively-cooled nozzle to a combustion chamber

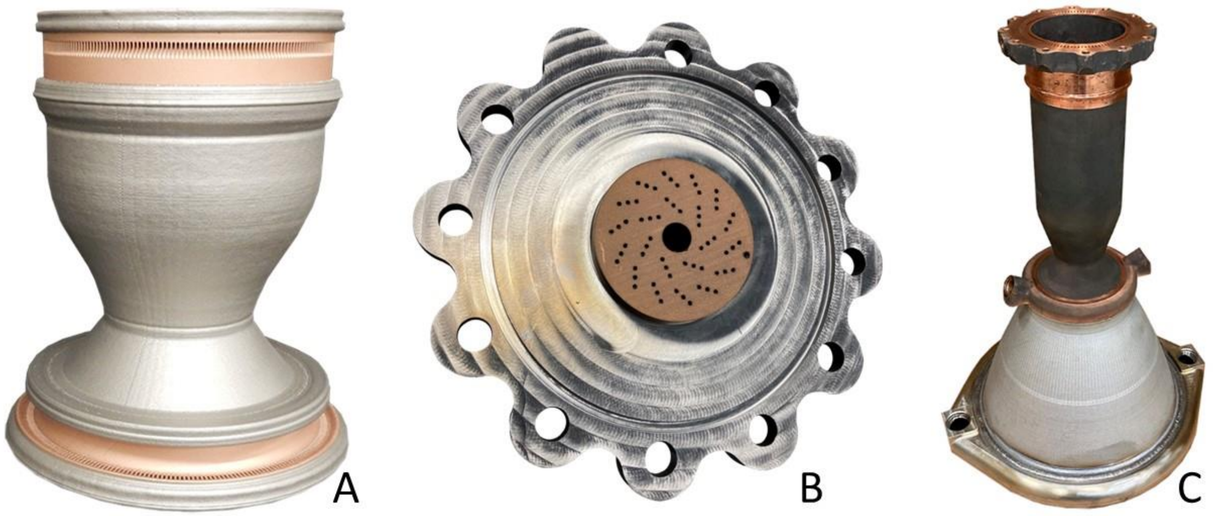


Figure 17. Examples of Component Configurations using GRCop-Superalloy Bimetallic AM Interfaces. A) Combustion chamber with radial bimetallic deposition using LP-DED, B) Injector using axial bimetallic using L-PBF, C) Coupled chamber and nozzle with axial bimetallic using LP-DED.

NASA first demonstrated the use of bimetallic AM under the Low-Cost Upper Stage Propulsion (LCUSP) project with successful hot-fire testing in 2018. LCUSP was the first successful use of L-PBF for the GRCop-84 (Cu-8 at.% Cr-4 at.% Nb) alloy. After the liner with all cooling channels was fabricated using L-PBF, an Inconel 625 structural jacket was added at NASA Langley Research Center using EB-DED, also known as Electron Beam Freeform Fabrication (EBF^3). The bimetallic joint was a GRCop-84 to Inconel 625 transition to form the bimetallic combustion chamber. A conventionally forged and machined Inconel manifold assembly was Electron Beam (EB) welded to the AM EBF^3 jacket to complete the chamber assembly. This project demonstrated the successful use of bimetallic AM culminating in over 147 seconds of hot-fire time and 9 starts at 100% design conditions in Liquid Oxygen/Liquid Hydrogen (LOX/LH2). The LCUSP project transferred the AM process using GRCop-84 developed at MSFC and the materials property data collected by GRC to industry. As a direct result, L-PBF GRCop-42 and GRCop-84 liners are now available commercially from multiple vendors, although many lessons are still being learned on the application of bimetallic chambers with various design configurations. A follow-on project, Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) is further characterizing and advancing bimetallic chamber applications using AM.

Based on the success of LCUSP, a project under the NASA Space Technology Mission Directorate (STMD) Announcement for Collaborative Opportunity (ACO) Program was established between NASA and Virgin Orbit. The ACO program was launched to promote public private partnerships and industry to use of NASA-developed technologies and utilize NASA facilities and engineering expertise. The core of the ACO partnership was to develop and test various copper-based alloys and integrate them into a bimetallic combustion chamber assembly using hybrid AM technologies. The outcome of the program fabricated several bimetallic combustion chambers and completed hot-fire testing to determine performance. The NASA contributions were L-PBF AM processes for GRCop-84, C18150

(Cu-1 Cr-0.1 Zr), and GRCop-42 copper-based alloys; materials testing and characterization; chamber design' and hot-fire testing [27]. Virgin Orbit's contribution was design and fabrication of the bimetallic Inconel 625 structural jacket using their hybrid AM and subtractive LP-DED technology, integration of the chamber assembly, and hot-fire testing. This project successfully completed fabrication and testing of multiple bimetallic chambers and accumulated 20 tests totaling 880 seconds. All tests were completed with LOX/RP-1 at chamber pressures up to 750 psig. NASA also fabricated a series of similar sized chambers using several commercial vendors and completed hot-fire testing.

NASA had previously reported the bimetallic LP-DED fabrication and testing of an augmented spark igniter (ASI) ignition system [28]. While this application was a wrought C18150 base with a LP-DED Inconel 625, it provided the early feasibility of the bimetallic joints between copper-based alloys and superalloys [29,30]. This also demonstrated both radial and axial joints using bimetallic and accumulated over 100 starts under relevant test conditions on LOX/ Gaseous Hydrogen (GH2) [31].

NASA also evaluated and hot-fire testing a series of bimetallic nozzles using C18150 for the liner and Monel 400 for closeout of the coolant channels. Three nozzles were fabricated and accumulated 72 starts and over 3,500 seconds of hot-fire test time in LOX/GH2 [31].

With the success of L-PBF GRCop-42 development and infusion into the commercial supply chain, NASA has continued developments. A recent application of GRCop-42 was use for injector faces with L-PBF processing combining GRCop-42 and Inconel 625. This design could allow for a one-piece injector with multiple metal alloys for specific requirements. This would include a high conductivity injector face to dissipate heat and eliminate coatings in high heat flux testing. The manifolds and injector body were fabricated with Inconel 625 to reduce overall mass and allow high operating pressures.

This process was demonstrated at NASA MSFC first by printing the impinging injector face using GRCop-42. The print was paused at a predetermined height, and the powder and build plate with the injector removed. The entire sample was precision cleaned. The build plate and injector were placed in a second machine and aligned carefully for a printing the Inconel 625 from the faceplate using L-PBF. An overview schematic is shown in Figure 18. The GRCop-42/Inconel 625 joint had some dilution (Figure 19) but less than observed with the DED techniques.

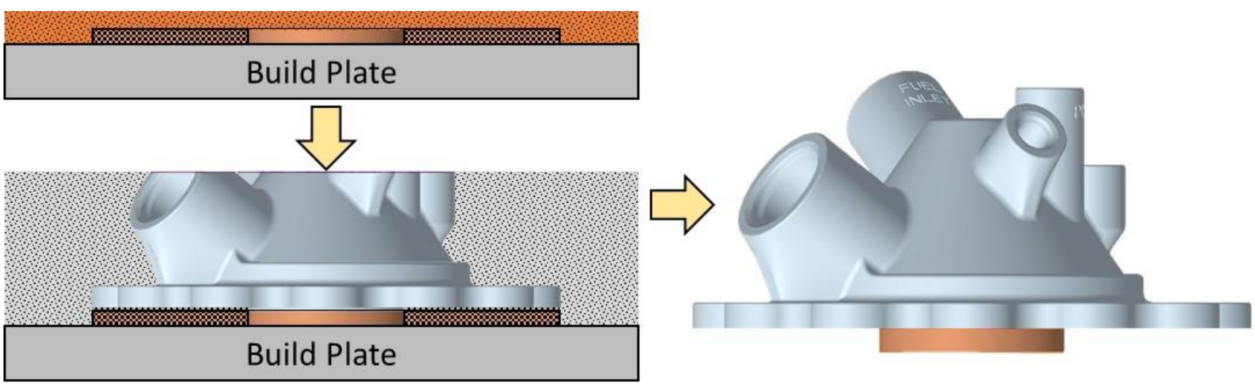


Figure 18. L-PBF Build Process strategy for bimetallic injector.

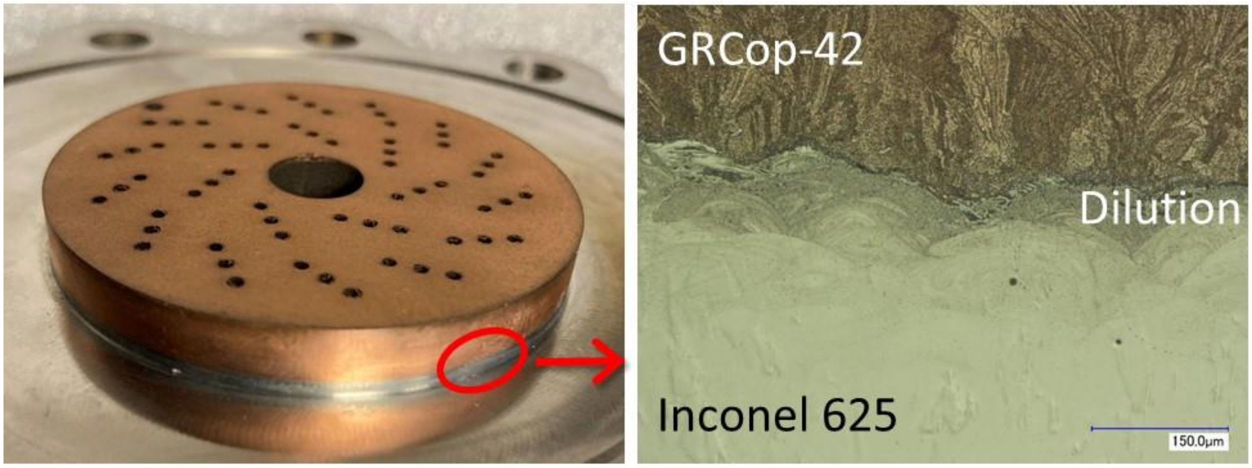


Figure 19. Bimetallic L-PBF Injector face using GRCop-42/Inconel 625 and the interface diffusion between these alloys.

One of the primary uses of bimetallic AM is for structural jackets of combustion chambers. The L-PBF is enabling since the GRCop-alloy liner with integral coolant channels is completely closed-out. This provides various options using the DED techniques, cold spray, or other techniques to apply a superalloy or alternate alloy structural jacket. NASA has completed several recent chambers in both the 7K-lbf and 40K-lbf thrust classes.

The LEO Mid-scale Main Chamber and Integrated Nozzle Ground Testing (LEMMINGS) was produced using a structural LP-DED jacket on a L-PBF GRCop-42 liner. LEMMINGS is a 40K-lb_f regenerative chamber and its purpose is to prove bimetallic technology and to evaluate the performance of several channel-wall cooled nozzles. The chamber assembly includes a liner, a structural jacket, a forward manifold, and an aft manifold. The L-PBF GRCop-42 liner was printed, verified for powder removal, underwent HIP, structure light scanning, interim machining for cladding, and cleaned. The liner was then cladded with LP-DED Inconel 625 to create the structural jacket as seen in the images furthest right in Figure 20. A post-cladded AM chamber with NASA HR-1 alloy, as seen in the center, left image, underwent HIP, CT scanning to check for blocked channels, and machined for weld preparations. The Inconel 625 manifolds were EB welded to the chamber and final machined to create the chamber assembly as seen in the center, right image in Figure 20. Hot-fire testing for LEMMINGS has not been conducted as of this publication.

Figure 20. Bimetallic Jacket using LP-DED Process. (Left) GRCop-42 L-PBF liner cladded at RPMI with NASA HR-1 Jacket using an interface alloy; (Right) GRCop-42 L-PBF liner cladded at DM3D with Inconel 625 Jacket.

The Advanced Lander Propulsion Additive Cold spray Assembly (ALPACA) project was conducted under a partnership with Aerojet Rocketdyne under the Announcement of Collaboration Opportunity (ACO) program with NASA Space and Technology Mission Directorate (STMD) [32]. The ALPACA chamber configuration was produced using a structural cold spray closeout of NASA HR-1 in collaboration with GE Research. This jacket application process with cold spray is shown in Figure 8 (left). This chamber was L-PBF produced using GRCop-42, HIP'd, final machined, EB welding of the inlet manifold, and water flow tested before finally applying the cold spray jacket. Images of this development process are shown in Figure 21.

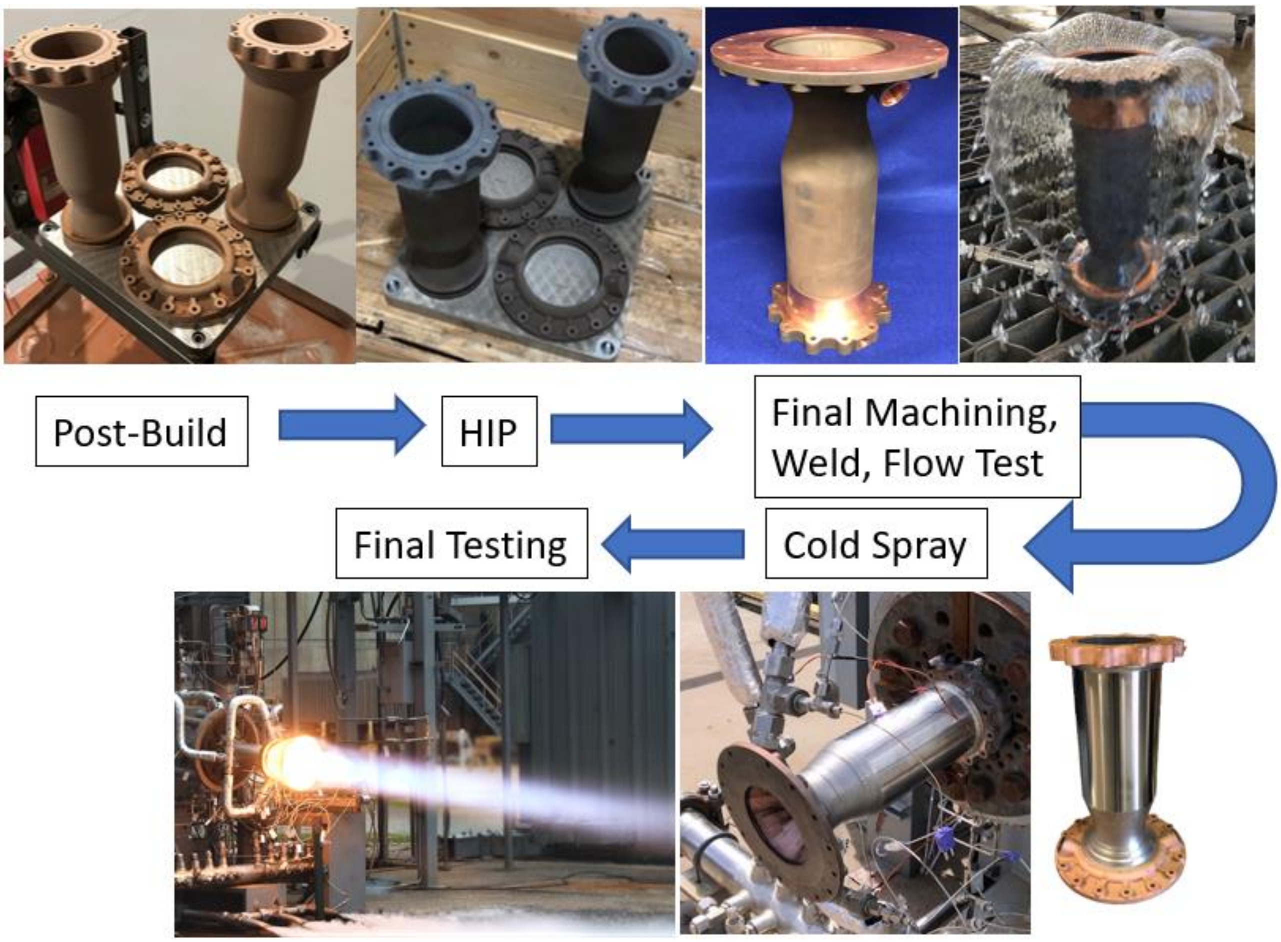


Figure 21. Flow path of ALPACA development process.

IV. AM Bimetallic Component Testing

NASA has completed fabrication of a various bimetallic and multi-metallic AM hardware and successfully hot-fire testing these components. This testing was conducted at NASA Marshall Test Stands 115 and 116 on hardware ranging from 2,000 lb_f to 30,000 lb_f thrust. Testing was completed with various propellants including LOX/LH2, LOX/RP-1, and LOX/CH4. A summary of this testing can be seen in Table 6. A total of 41 starts and 1,459 seconds have been accumulated on AM bimetallic chambers since 2018 under the LCUSP, STMD ACO, RAMPT, and NASA internal development projects.

Table 6. Summary of Hot-fire testing using bimetallic AM chamber configurations.

Project	Propellants	Thrust (lb_f)	Metal Alloys	Jacket Process	Starts	Seconds
PF086	LOX/LH2	30,000	GRCop-84 / Inconel 625	EB-DED	9	147
PJ024	LOX/RP-1	2,400	GRCop-84 / Inconel 625	LP-DED	11	475
PJ024	LOX/RP-1	2,000	C18150 / Inconel 625	LP-DED	9	405
PI043	LOX/LCH4	2,200	GRCop-84 / Inconel 625	LP-DED	6	76
PK076	LOX/LCH4	7,000	GRCop-42 / NASA HR-1	Coldspray	6	356
PJ051	LOX/LH2	40,000	GRCop-42 / Inconel 625 GRCop-42 / NASA HR-1	LP-DED	--	--

The first test project that initiated both the development of GRCop-84 L-PBF and the application of bimetallic AM EBW-DED Inconel 625 jacket at NASA was LCUSP. This project was the highest thrust class tested as of this publication. This project was previously discussed in prior publications [33, 34]. Building upon the success of LCUSP, two test projects were initiated to advance bimetallic AM and other advanced manufacturing technologies that included PJ024 and PI043. The PJ024 project was in partnership with Virgin Orbit and also discussed in prior publications [27,35]. The PI043 test project used LO_X/Methane (LO_X/LCH_4) to develop and characterize high temperature composite nozzles. A bimetallic AM chamber for this testing used LP-DED on a hybrid DMG Mori Seiki machine. The chamber was GRCop-84 L-PBF with channels built integrally. An Inconel 625 structural jacket was applied using the hybrid process with integral subtractive machining. Stainless steel 304L manifolds were machined and the manifold joints weld-deposited using the DMG hybrid LP-DED process. The general processing and testing of this bimetallic AM chamber can be seen in Figure 22.

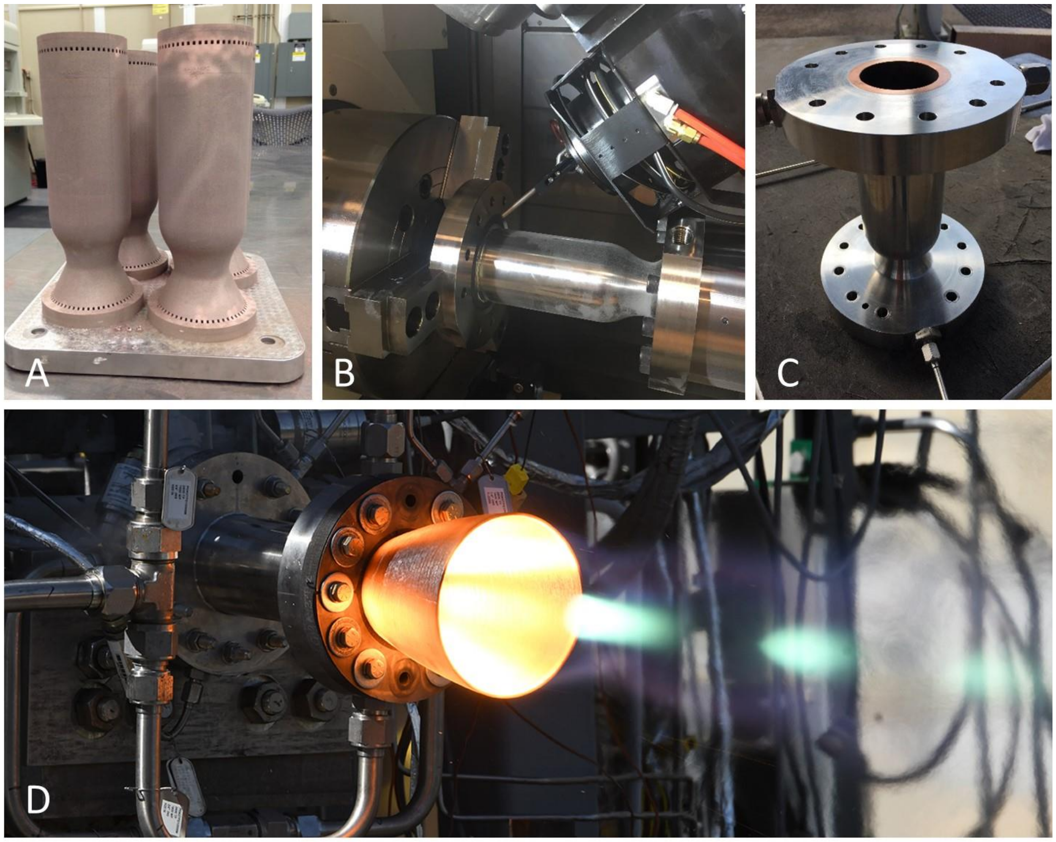


Figure 22. Bimetallic AM chamber under PI043. A) GRCop-84 L-PBF chambers, B) Hybrid LP-DED machine following jacket deposition and manifolds setup for welding on hybrid machine, C) AM bimetallic chamber during proof testing, D) AM bimetallic chamber with C-C nozzle extension during testing.

Hot fire testing of the bimetallic ALPACA chamber was conducted in February of 2021 at NASA Marshalls Test Stand 115. Testing achieved 6 starts at over 356 seconds of cumulative mainstage duration. A single long duration burn of 110 seconds was also achieved to successfully demonstrate chamber endurance and assess impacts on the cold spray/L-PBF interface. Testing was conducted using LOX/LCH_4 with the cryogenic liquid methane used for regenerative cooling circuit in the L-PBF GRCop-42 coolant channels. Mixture ratios of 2.37 to 3.08 were achieved with mean chamber pressures of 737 psia.

In post-test evaluation of hardware, test engineers noted that there were no observable alterations to the bimetallic jacket. Typically, some form of discoloration is observed on the closeout of fully L-PBF produced GRCop-alloy chambers, though none were seen in this case. Further evaluation of future iterations of ALPACA chambers with minimal material applied to the closeout will be assessed to further reduce chamber mass, build costs, and processing time.

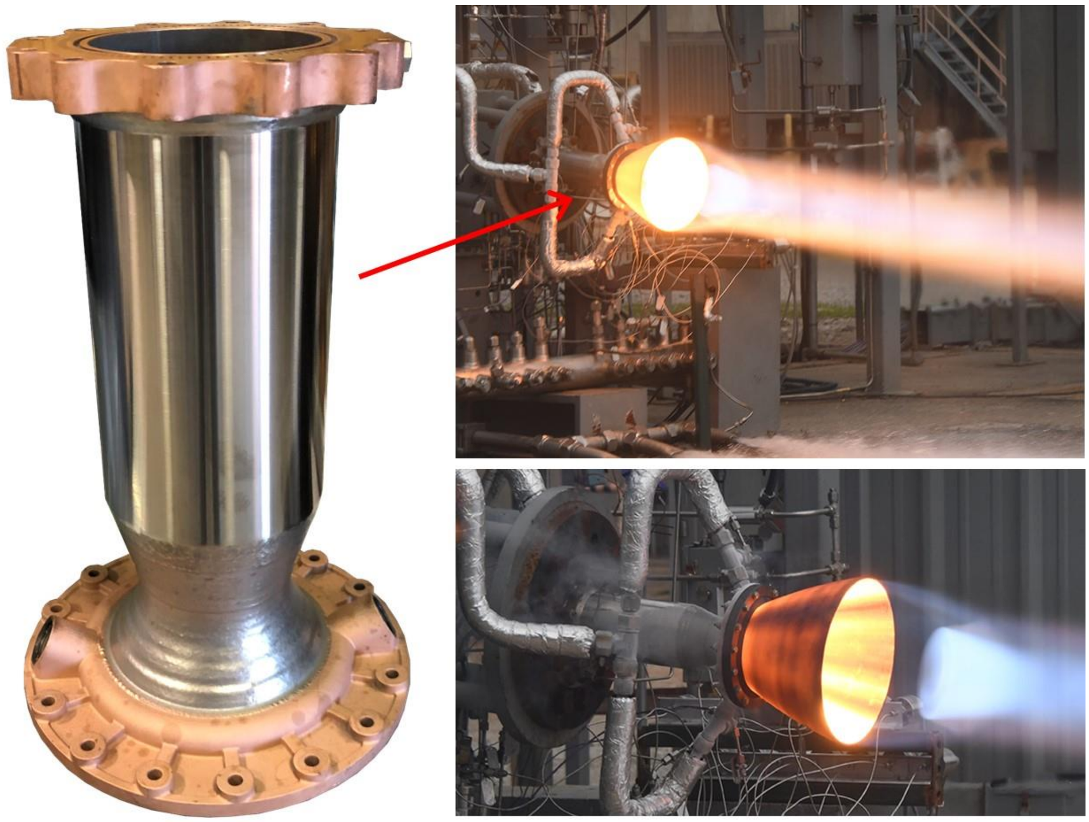


Figure 23. ALPACA (PK076) bimetallic AM L-PBF and coldspray following fabrication and tested at MSFC TS115 with a Carbon-Carbon and CMC nozzle extensions.

Most forms and testing of the bimetallic AM were GRCop-alloy combustion chambers with superalloy structural jackets. As described in the fabrication section, a bimetallic L-PBF injector also completed development. This was a development component and not intended for hot-fire testing. It did however complete water flow testing of the fuel and oxidizer circuits and revealed that each of the impingement orifices were fully clear and flowed as expected. The water flow testing can be seen in Figure 24. There was some non-uniform flow observed due to slight misalignment and an issue with the contour passes of the GRCop-42 flow passages. Additional NDE inspections were completed and the development unit was sectioned for evaluation (single image shown in Figure 19).

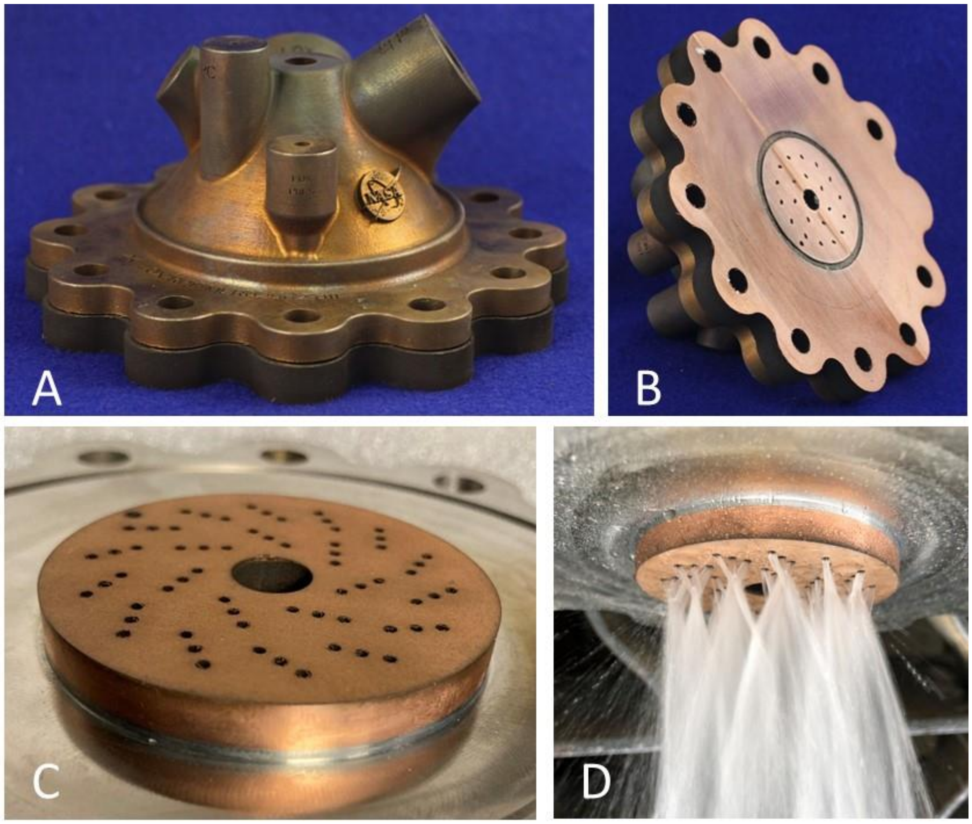


Figure 24. Bimetallic L-PBF Injector processing. A) Printed and HIP'd injector, B) Injector face with solid GRCop-42 material, C) Post-machining of the L-PBF Injector face, D) Combined Fuel and LOX circuit flow testing of the axial bimetallic injector.

V. Conclusions

NASA has advanced state-of-the-art bimetallic and multi-alloy GRCop-alloy to superalloy AM for liquid rocket engine components. These advancements were made through evaluations of various multi-alloy AM processes, material characterization, and successful component manufacturing and hot-fire testing for various combustion devices. This includes the evaluation and hot-fire testing of bimetallic AM components including combustion chambers, injectors, and nozzles. A total of 41 starts and over 1,459 seconds of hot-fire time has been accumulated on various bimetallic AM components at the time of this publication. These bimetallic and multi-alloy systems allow for the advantages of AM processes to be realized and enable further optimization of designs through reduced weight and increased performance for future liquid rocket engines.

The series of bimetallic AM processes evaluated include: Laser Powder Bed Fusion (L-PBF), Laser Powder Directed Energy Deposition (LP-DED), Coldspray, Electron Beam Wire Directed Energy Deposition (EBW-DED), and Arc Wire Directed Energy Deposition (AW-DED). All these approaches were advanced for either creating a bimetallic liner or jacket for combustion chambers. GRCop-42 and GRCop-84 were used for the chamber liner application and NASA HR-1 and Inconel 625 were used for the structural jacket. Intermediate transitional materials such as Copper-Nickel and pure Nickel were also used. The L-PBF process was used to create the liner with GRCop-alloys and either LP-DED, Coldspray, EBW-DED, or AW-DED were used to manufacture the superalloy structural jacket. A bimetallic injector using L-PBF with a GRCop-42 face and Inconel 625 body and manifolds was also demonstrated.

There have been several observations and lessons learned about bimetallic joints including:

- Each AM process has different heating and cooling characteristics
- Considering dimensional adjustments for the secondary material (jacket) to mitigate possible compressive stresses on the base material (liner).

- Predicting phases in the interface using CALPHAD modeling;
    - Both HR-1 and Ni have a couple of strengthening phases when used in the Cold Spray process; however, a high Fe content in an HR-1 joint will cause embrittlement.
    - Modeling can assist in secondary material selection.
- Observed greater cracking in the Inconel layer compared to the interface layer, possibly due to residual stresses (further investigation needed).
- Interface bond strength between secondary material and GRCop-84 showed similar strength compared to the GRCop-84. This proves that excellent bonds are possible for bimetallic AM.
- Investigating potential interface barrier material, such a Ni, with Coldspray.

This bimetallic AM technology has been utilized for combustion devices from 2K-lb_f to 40K-lb_f thrust classes. Under the 40K-lb_f regenerative chamber LEMMINGS project, two chambers were produced with LP-DED Inconel 625 and NASA jackets on a L-PBF GRCop-42 liner. ALPACA, a 7K-lb_f chamber, demonstrated a NASA HR-1 Coldspray jacket on a L-PBF GRCop-42 liner. In test program PK076, the bimetallic AM ALPACA was hot-fire tested with LOX/LCH4 for the propellants. It accumulated 6 starts and 356 seconds of hot-fire time.

NASA has current and future development tasks in process that expand on the bimetallic and multi-alloy AM techniques in this paper, including modeling to understand the complex bimetallic joints. The mechanical and hot-fire data is being made available to industry partners and NASA is working to actively mature the supply chain.

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