# Bimetallic Channel Wall Nozzle Development and Hot-fire Testing using Additively Manufactured Laser Wire Direct Closeout Technology

*Paul R. Gradl[1], Sandy Elam Greene[2], Tal Wammen[3]*
NASA Marshall Space Flight Center, Huntsville, AL 35812

NASA has been developing and advancing regeneratively-cooled channel wall nozzle technology for liquid rocket engines to reduce cost and schedules associated with fabrication. One of the primary methods being advanced is Laser Wire Direct Closeout (LWDC). LWDC was developed to provide an additively manufactured laser deposited closeout of the coolant channels that also forms the structural jacket in-situ. This technique has been previously demonstrated through process development and hot-fire testing on a series of subscale nozzles at NASA Marshall Space Flight Center. The hot-fire test articles were fabricated using monolithic alloys to simplify the fabrication process. Ongoing research is being conducted to further expand use of this process for increased scale and bimetallic or multi-alloy options. The use of multi-alloys is desired to fully optimize the combination of materials in the radial and axial directions to reduce overall weight of the nozzle and allow for higher thermal and structural margins on the channel wall nozzle. NASA recently completed process development and hot-fire testing of a series of channel wall nozzles that incorporate a copper-alloy as the hotwall liner material and a superalloy and combination thereof for the structural jacket using the LWDC technique. The fabrication process was further advanced by using a multi-alloy axial joint using explosive bonding integrating a copper-alloy at the forward end of the nozzle hotwall and a stainless-alloy for the remaining length. A third alloy was then used for the channel closeout using the LWDC process. This paper will describe the process development using the LWDC process for channel closeout utilizing the multi-alloys, hardware design and results from hot-fire testing on subscale multi-alloy LWDC channel cooled nozzles.

## Nomenclature

| | | |
|---|---|---|
| AM | = | Additive Manufacturing or Additively Manufactured |
| CTE | = | Coefficient of Thermal Expansion |
| CWN | = | Channel Wall Nozzle |
| DED | = | Direct Energy Deposition |
| EB | = | Electron Beam (welding) |
| GH2 | = | Gaseous hydrogen |
| GRCop-42 | = | NASA Glenn Research Center (GRC) Copper-alloy (Cu-4Cr-2Nb) |
| H | = | Enthalpy, BTU |
| ID | = | Internal Diameter |
| $K\text{-}lb_f$ | = | thousand pound-force (thrust) |
| LWDC | = | Laser Wire Direct Closeout |
| LOX | = | Liquid Oxygen |
| $\dot{m}$ | = | Mass flow rate, lbm/second |
| MR | = | Mixture Ratio, measured as LOX/GH2 |
| MSFC | = | NASA George C. Marshall Space Flight Center |
| OD | = | Outer Diameter |
| PBF | = | Powder Bed Fusion (or Selective Laser Melting) |
| $\rho$ | = | Density, $lbm/ft^3$ |

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[1] Senior Combustion Devices Engineer, Component Technology Branch, Senior Member, AIAA
[2] Senior Combustion Devices Engineer, Component Technology Branch
[3] Test Engineer, Flight Systems Test Branch

P           =  Pressure, psia (or psid when $\Delta P$)
Pc          =  Chamber Pressure (psig)
psig        =  Pounds Per Square Inch, gage pressure
Q           =  Heat load, BTU/s
R           =  Resistance
Regen       =  Regeneratively-cooled nozzle
T           =  Temperature, °F (or $\Delta T$, °F)
TEA/TEB     =  Triethylaluminium / Triethylborane
TCA         =  Thrust Chamber Assembly
TIG         =  Tungsten Inert Gas

## I. Introduction

Regeneratively-cooled (regen) nozzles are a critical component of a liquid rocket engine system to allow optimal expansion of the hot-gas and increase temperature of the propellants for turbine drives or injector performance. Nozzles are very challenging to fabricate due to their large size and the tight tolerances required to maintain proper performance. An actively-cooled regen nozzle uses one of the propellants as a coolant to ensure that the hotwall remains cool enough to maintain the structural margins of the material being used. A channel wall nozzle uses an internal liner with machined coolant passages that are closed-out using a variety of fabrication techniques[1].

Figure 1 illustrates a section of a channel wall nozzle that incorporates integral coolant channels, within an internal copper liner using a bimetallic structure. The channel wall configuration requires that the thickness of the hotwall be tightly controlled during the machining of the coolant channels. These channels are then closed out by bonding a closeout or structural jacket to the lands of the channels within the inner liner to contain the pressurized coolant within each individual channel. Inlet and outlet manifolds are fabricated separately and joined by a welding or brazing process to complete the nozzle. Channel wall nozzles offer cost and schedule savings due to fewer manufacturing steps and less manual labor, as compared the tube-wall nozzles[2].
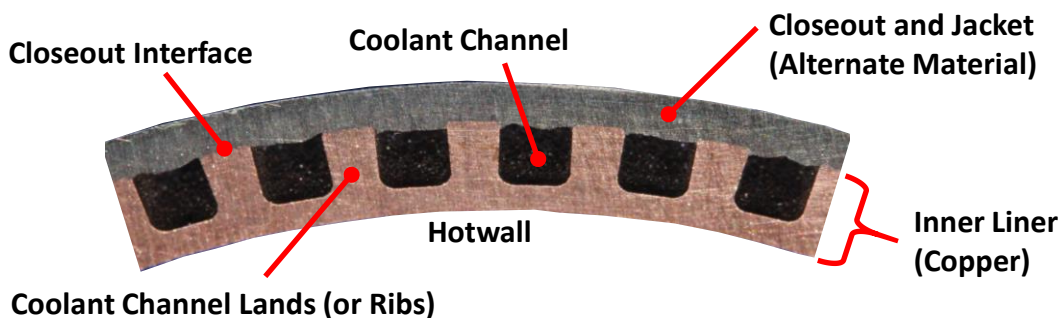


**Figure 1. Configuration of Bimetallic Channel Wall Nozzle.**

Channel wall nozzles have been demonstrated in a variety of materials, but have typically used monolithic materials – stainless-based or superalloys for fabrication due to reduced joining complexity during manufacturing. A bimetallic or multi-metallic channel wall nozzle structure generally incorporates a copper liner and can vary the materials radially and axially for weight optimization and increased thermal and subsequent structural margins. The radial bimetallic configuration will use a copper-alloy liner for the entire length and use an alternate material (stainless-based or superalloy) as the closeout layer or structural jacket. An axial bimetallic nozzle integrates a copper-alloy at the forward end of the nozzle with the highest heat flux region and transitions to a lower-density material as heat flux is reduced enough to make use of a non-copper alloy. The closeout for this axial bimetallic will often use a stainless-based or superalloy material. An illustration of the radial and axial bimetallic and multi-metallic split can be seen in Figure 2. Bimetallic channel wall nozzles and chambers have been demonstrated under several programs using a copper-alloy liner with a stainless or superalloy-based structural jacket and manifolds using brazing or alternate fabrication techniques such as cladding[3]. Limited fabrication techniques are available to form bimetallic structures with a reliable bond, and as the size of the nozzle increases, the challenges for available techniques become even greater[4].

Bimetallic and multi-metallic channel wall nozzles with radial and axial joints have some advantages over monolithic configurations depending on the engine and subsequent component requirements. The use of a copper liner

can significantly reduce the wall temperatures with the high thermal conductivity of the copper-alloys[5]. This can provide significant structural margins and the ability to operate at much higher heat fluxes or move manifold joints forward reducing overall system weight. However, copper-alloys are higher density than stainless or superalloys, so a monolithic copper-alloy channel wall nozzle is not ideal for overall system weight optimization. A bimetallic closeout or structural jacket can be employed to allow for a higher strength, lower density material on the outer surface of the copper-alloy liner.

Another advantage of the copper-alloy for the liner over the monolithic configuration is reduced manufacturing tolerances for the slotting and subsequent hotwall thickness. The use of a copper-alloy allows for a softer material to be used in the liner (compared to stainless or superalloy) and significantly increases the slotting and machining time required. The copper-alloy liners also tend to have a thicker hotwall due to reduce material strength, but the higher conductivity material allows for reduced wall temperatures. The increased thickness and reduced sensitivity to wall thickness variations for hotwall temperatures also improves manufacturing by allowing for a wider range on the tolerance (i.e., overall wall thickness). However, part of the increased hotwall thickness in the copper-alloys is because the yield and ultimate strength is reduced compared to the stainless or superalloys. With the increased thickness of the higher density liner material, the overall nozzle weight increases. The overall nozzle and system weight must be balanced with the increased margin on hotwall temperatures with the copper liner design.



**Figure 2. (Left) Example of radial bimetallic configuration and (Right) Axial/Radial Bimetallic/Multi-metallic CWN Configuration.**

The stainless or superalloy-based nozzles are designed to run a higher wall temperatures and thinner walls, particularly at the forward end or joint with the combustion chamber. They can fail in this region due to high thermal fatigue and oxidation, depending on the gas species. While the copper-alloys are not immune from this same failure, the margins are much higher in the higher heat flux regions. The high elongation in copper-alloys does help with thermal fatigue and ratcheting effects.

There are several advantages to the multi-metallic (multi-alloy) nozzles being developed with an axial split on the hotwall. This design solution is important because the materials are fully optimized in the axial and radial locations as needed to provide margins and reduce overall component weight. This configuration incorporates a high conductivity material necessary for high heat load region at the forward end, while maintaining a high strength material for structural loads in the jacket. The materials were varied in this application radially to optimize for the environment and subsequent loads. This design solution allows for much higher wall temperatures than with a purely monolithic material and balances weight. A similar coefficient of thermal expansion (CTE) material is used for the axial split to limit stresses at the axial joint.

NASA Marshall Space Flight Center (MSFC) has been investigating a variety of fabrication techniques for channel wall nozzles to reduce the overall fabrication time and to offer new design opportunities and performance increases. One of the techniques that has been matured through manufacturing process development and hot-fire testing is the Laser Wire Direct Closeout (LWDC). While previously, the maturation of the technology has been focused on monolithic materials such as Inconel 625, Haynes 230, JBK-75, and Stainless Steel 347, easy demonstrations of the process showed the feasibility of using it for bimetallic applications with a copper-alloy. More recent process developments were completed to demonstrate the bimetallic application of the LWDC technology for a direct closeout of a slotted copper-alloy liner. A description of the LWDC bimetallic closeout process will be provided including an overview of supporting test hardware with various configurations. These nozzles also completed hot-fire testing at MSFC Test Stand 115 in early 2019 and the results will be presented.

## II. LWDC Process Overview

The LWDC technology was developed by MSFC and industry partners, Keystone Synergistic Enterprises and Laser Technology Associates. The process deposits a filler wire material that bridges the span of the coolant channels without any internal channel fillers needed. An independent wire feed and offset inert gas-purged laser beam melts the feedstock wire using an area of material prior to the start of the coolant channels (generally progressing aft end to the forward). While the nozzle is rotated about the center axis, the wire is deposited - penetrating and joining to the previously deposited layer (or area of stock) with a minor amount of laser energy being used to fuse the wire to the backside of the channel lands (or ribs). This process is repeated along the wall of the nozzle at continuously varying angles until the required area is closed out[6]. LWDC is used for the direct closeout of the coolant channels and application of the structural jacket. Examples of the LWDC process can be seen in Figure 3. The individual layers of closeout can be observed traversing axial along the channel lands.
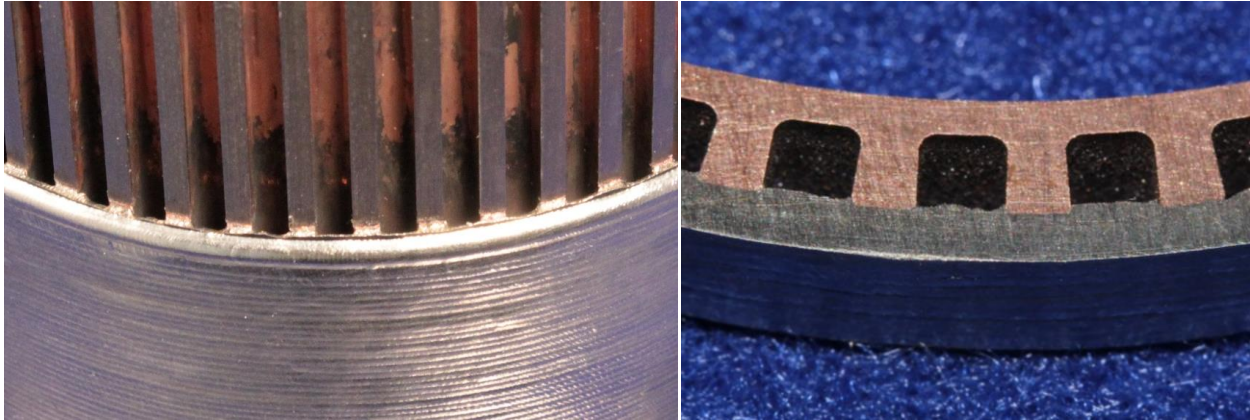


**Figure 3. Examples of Bimetallic LWDC Technology.**

LWDC is additive manufacturing (AM) wire-fed laser deposition process that eliminates the need for a tight tolerance structural jacket and plating operations compared to traditional manufacturing. This process provides a direct closeout of the coolant channels and forms the jacket integral in the same process. A small diameter wire is used and the low heat flux freeform wire-deposition process provides the ability to form the jacket in place while maintaining the geometry of the thin-walled channel lands or ribs, minimizing overall distortion.

The LWDC process is initiated by depositing material in the stock on the aft end of the channel wall nozzle liner. Several passes are deposited in this region of stock prior to the axial stations where the coolant channels begin. This deposition in the starting region of stock provides for a starting "step" for subsequent layers. For the closeout of the coolant channels, an off-axis laser beam and off-axis wire-fed system is used at angles defined relative to the nozzle wall half angle and rotated about a center axis. A majority of the laser energy is focused (spot size) on the previously deposited "step" of material, while the remaining energy is focused on the channel land[7]. This allows the material to penetrate into the previous layer while material is also bonded to the lands without burning through the lands or material dropping into the channels[8]. An example of the LWDC process can be seen in Fig. 4. The angles of the laser and wire-feed are continuously varied as a function of the nozzle outer wall to prevent drop through and maintain the proper bonds. Overheating can cause deformation of the liner wall or potential blow-through of the hotwall, so a mandrel can be used [9].

The primary advantage of the LWDC process is the jacket and channel closeout are integrally formed, so tolerances are much looser compared to brazing or other laser welded closeout processes. A continuous bond is created at each of the ribs to ensure structural margins are met. Eliminating the need for channel fillers reduces post-processing time. The process does use small wire for deposition to control heat input into the part, and deposition rates are much slower compared to other direct energy deposition (DED) processes; a comparison of deposition rates is shown in Ref. 10. However, this time is offset by the elimination of a closeout jacket and subsequent bonding operations. The LWDC process employed on bimetallic nozzles is shown Figure 5.
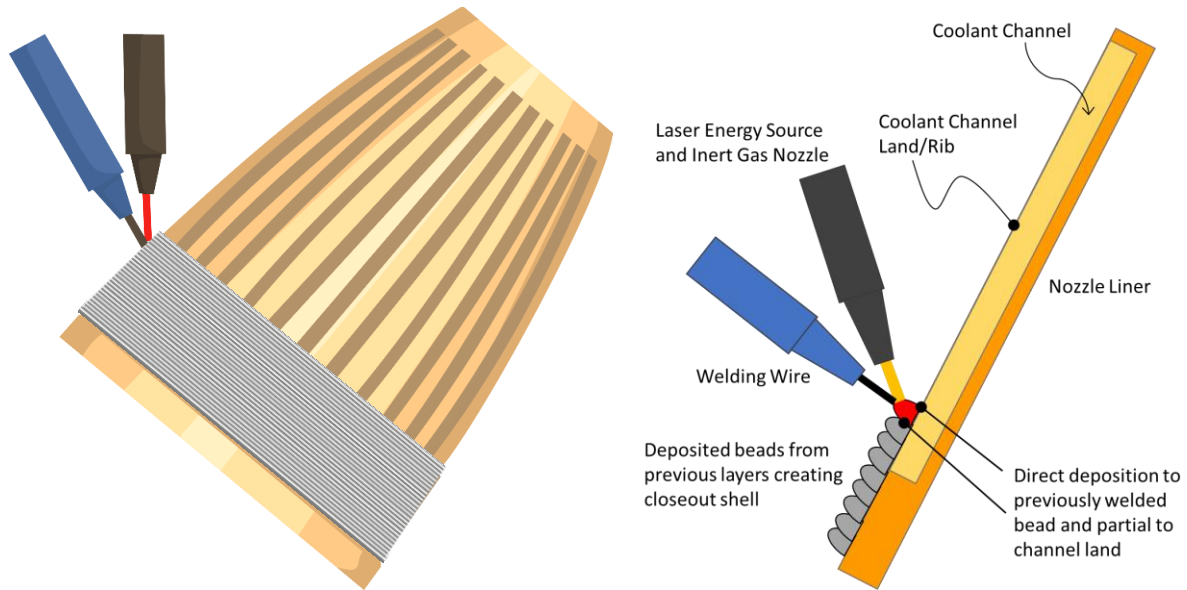
**Figure 4. LWDC Process Overview.**

While previous developments and hot-fire testing on various monolithic materials, including CRES 347/Inconel 625/ Haynes 230, have been completed, a current focus on the LWDC process has been bimetallic and multi-metallic materials[11]. The bimetallic configuration uses the copper-alloy liner and an alternate material for closeout. The initial development and testing effort used C-18150 (Cu-Cr-Zr). The final closeout material selected was Monel 400. Various alloys, including Inconel 625 and CRES 347 in combination with the C-18150, were attempted, but they did not exhibit good joining during LWDC process development. The Monel 400 provided a similar CTE to the C-18150 and material compatibility. One challenge with the Monel 400 is the potential for hydrogen embrittlement in the appropriate environment, but it was still selected to move forward with hardware development. While Inconel 625 has been shown to successfully bond using the blown powder directed energy deposition (DED) process, it was not successful with the laser wire and channel geometry[12]. The blown powder DED process is providing higher mixing and diffusion at the interface and the LWDC is limited in energy due to heat input with the channel ribs.
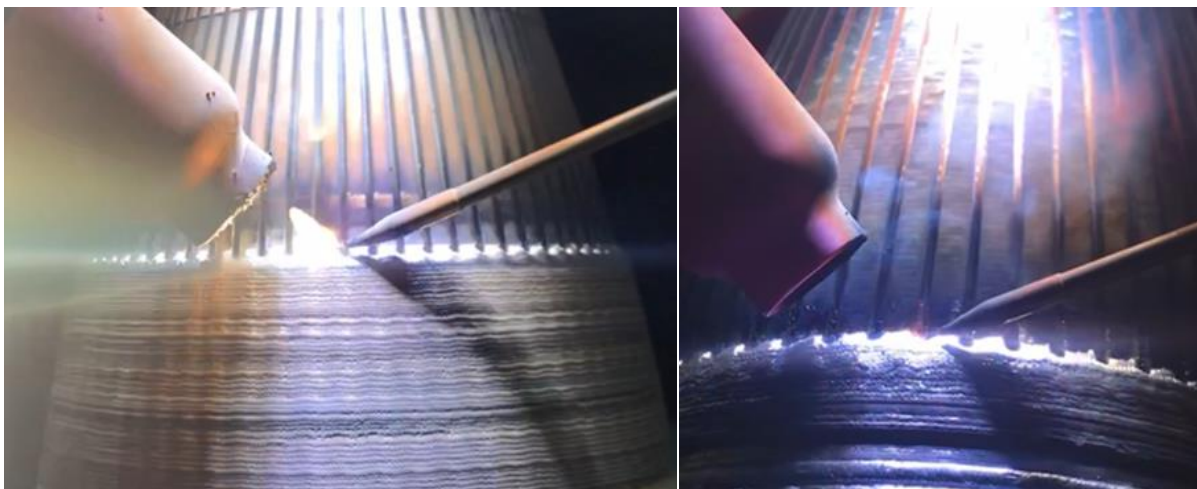


**Figure 5. Nozzle Closeout being completed with LWDC.**

### III. Hardware Overview Fabrication

To advance the LWDC bimetallic and multi-metallic process, a series of subscale nozzles were fabricated for hot-fire testing. Table 1 summarizes the nozzle configurations and materials that were fabricated. Nozzle units #1-4 were monolithic configurations previously tested and presented[8,9]. The current configurations, with radial and axial bimetallic and multi-metallic joints, included:

1. Radial bimetallic structure with a full C-18150 liner with LWDC Monel 400 closeout and structural jacket
    a. Direct LWDC of the C-18150 liner
    b. Multi-metallic intermediate transition alloy LWDC of the C-18150 liner
2. Axial split multi-metallic liner that allows copper-based materials at the forward end where high heat flux environments must be mitigated. This then incorporated LWDC closeout of the axial split with a 3rd multi-alloy as the closeout and jacket.

**Table 1. Configuration and Materials of Bimetallic and Multi-metallic Nozzles.**

| Nozzle Unit | Configuration | Liner | LWDC Closeout | Heat Treatment |
|---|---|---|---|---|
| Nozzle #6 | Radial Bimetallic, Intermediate Alloy | C-18150 | Monel 400 | Solution and Age |
| Nozzle #7 | Axial Multi-alloy | C-18150 / CRES 347 | Monel 400 | Solution and Age |
| Nozzle #8 | Radial Bimetallic, Direct | C-18150 | Monel 400 | Solution and Age |
| Nozzle #9 | Radial Bimetallic, Direct | C-18150 | Monel 400 | None |

In addition to the LWDC process, other fabrication processes were developed in parallel. The blown powder directed energy deposition (DED) process was used for cladding of the manifold preparations and explosive bonding, or explosive welding, for the axial bimetallic joint development.

Blown powder DED was used as a fabrication process to clad the manifolds in a freeform build-up on the outer diameter (OD) surface of the LWDC deposited closeout. The blown powder DED uses a co-axial laser energy source creating a melt pool in which powder is blown into, providing a weld bead. The powder is accelerated, or blown, into the melt pool using an inert carrier gas to allow for minimal or reduced oxidation in the high temperature deposition/weld. This system is attached to a robot that controls a toolpath defined by the CAD model. The blown powder DED system and robot allows for complex features or cladding of multi-alloys, or fabrication of freeform structures, such as the manifold offsets (weld preparations) shown in Figure 6.
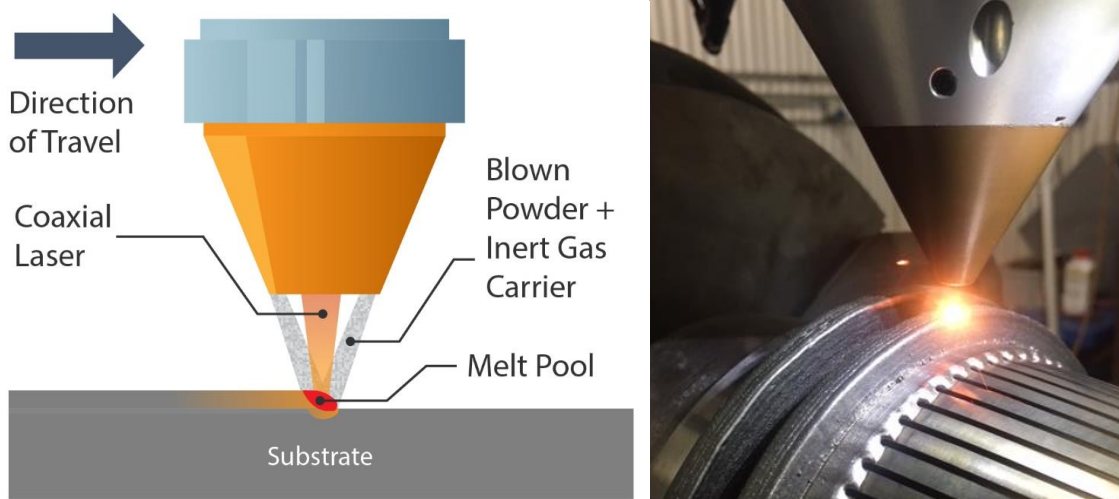


**Figure 6. Overview of Blown Powder DED Process.**

Explosive bonding is a solid-state process used to create a metallurgical joint, often in two or more alloys. For the nozzle application, the axial transition from C-18150 to SS347 bimetallic joint was created using this process. Explosive bonding uses controlled high energy explosives to accelerate a flyer metal into a backer metal[13]. This is most often flat plates or other simple geometries. The force in which the materials collide causes a plasma to be created and cleans the preceding contact region, which is trailed by the bonding of the metals. The pressure at the collision point is high enough to cause the metals to act like viscous fluids, creating an interlinking bond of the two metals[14]. This process was previously investigated for the closeout layer on channel wall nozzles[15]. The process creates a clean solid state bond that can easily join incompatible materials without causing intermetallic or brittle phases.

## A. Nozzle #6 with Radial LWDC Closeout and Intermediate Alloy

Nozzle #6 was fabricated using a bimetallic liner: with C-18150 copper-alloy for the hot wall and channels, and a closeout using Monel 400 with an intermediate interface material. The C-18150 liner material provided much lower predicted hotwall temperatures to significantly reduce these temperatures compared to the monolithic, particularly at the forward end in the high flux region. The Inconel 625 interface material, specific to this nozzle configuration, was used to enable increased bonding with the copper. This configuration was desired prior to the full development of the direct (sans interface alloy) LWDC process. Since the LWDC process has intermittent heat sinks with the alternating channel ribs and span (width) of the channel geometry, the energy required varies compared to monolithic LWDC processing. The intent of this configuration was to use an intermediate alloy such as Inconel 625 providing a bond with each of the ribs prior to the full closeout spanning the channels.

C-18150 barstock was used as the starting material and the nozzle OD was final machined. The OD surface was then cladded using a layer of Inconel 625 and the coolant channels were then slotted and machined through the Inconel 625 layer and C-18150 material, creating the desired hotwall. This left a layer of Inconel 625 on each of the lands to aid with the LWDC closeout. The intent was that less heat input would be required for the LWDC process where the Monel 400 would bond directly to the Inconel 625. A general process flow for Nozzle #6 can be seen in Figure 7.
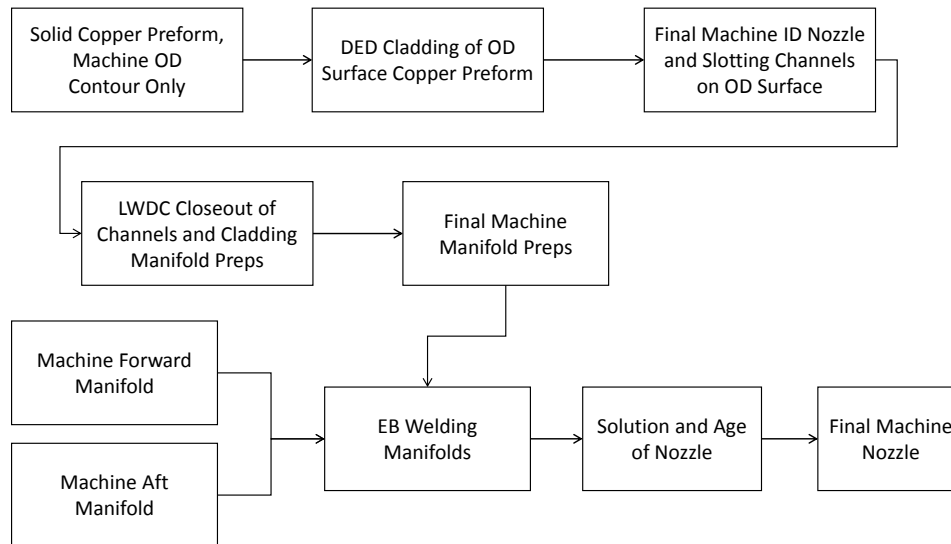


**Figure 7. High-level process flow of the intermediate-bonded bimetallic LWDC nozzle.**

The LWDC process was developed in parallel on the C-18150 with Inco 625 interface and also without any intermediate alloy on the C-18150 channel ribs. It was determined that Monel 400 exhibited the best results so it was used as the closeout material, as previously described. The Inconel 625 interface material provided some advantage with slightly lower heat input during processing. There were no issues noted during the LWDC process of Nozzle #6. The manifold weld preparations were applied using blown powder Inconel 625 DED as a cladding operation with Inconel 625. Examples of the process development are shown Figure 8.
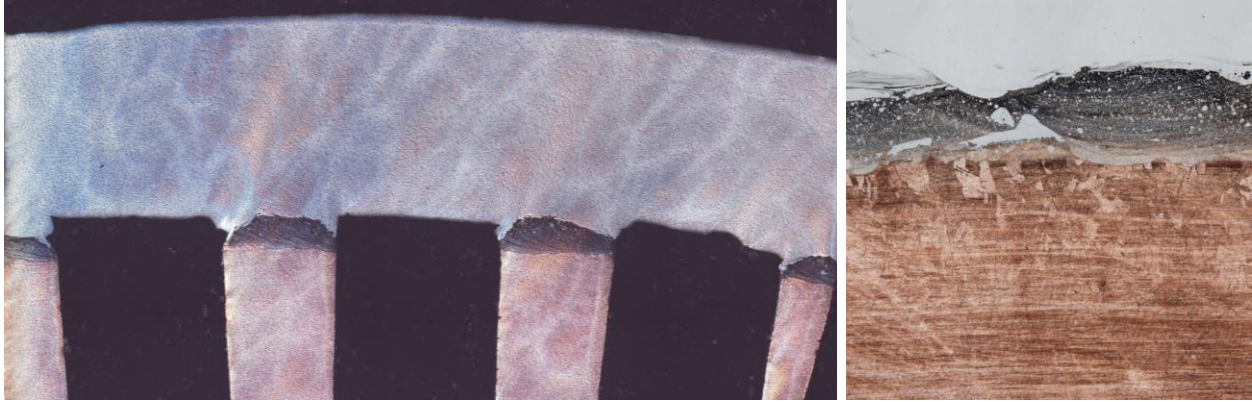
**Figure 8. Process development samples of Interface using the intermediate alloy for Nozzle #6.**

The weld preps for Nozzle #6 were final machined to accommodate the forward and aft manifolds, which were attached with Electron Beam (EB) welding. After EB welding, the nozzle completed a solution and aging cycle in vacuum. The nozzle was final machined on the forward flange mating interface and the inlet and outlet tubes were welded onto the manifolds. The nozzle was hydro-proof tested at over 2,000 psig and no issues were observed. Figure 9 shows images of Nozzle #6 after LWDC closeout.
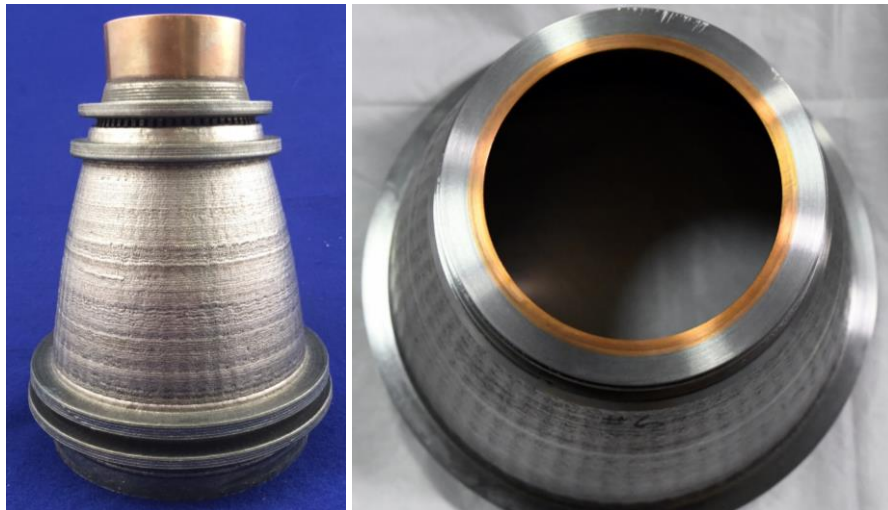


**Figure 9. Nozzle #6 following LWDC closeout and prior to EB welding.**

### B. Nozzle #7 Axial Multi-metallic LWDC Closeout

Nozzle #7 was designed using various manufacturing processes providing an axial bimetallic interface. Explosive bonding was developed to provide the starting stock blank for the axial bimetallic interface. The channels were traditionally slotted and the LWDC process was used for closeout. The significant advantage of Nozzle #7 was the reduction in wall temperatures at the high heat flux region at the forward end. If the SS347 were to be used in this region, it would be reaching the margin of the material at which oxidation and reduced properties could cause issues. This also provided weight optimization by using the lower density SS347 along the rest of the length. With the high conductivity of the copper being used at the forward end a 4x reduction in wall temperatures could be achieved as seen in Figure 10.
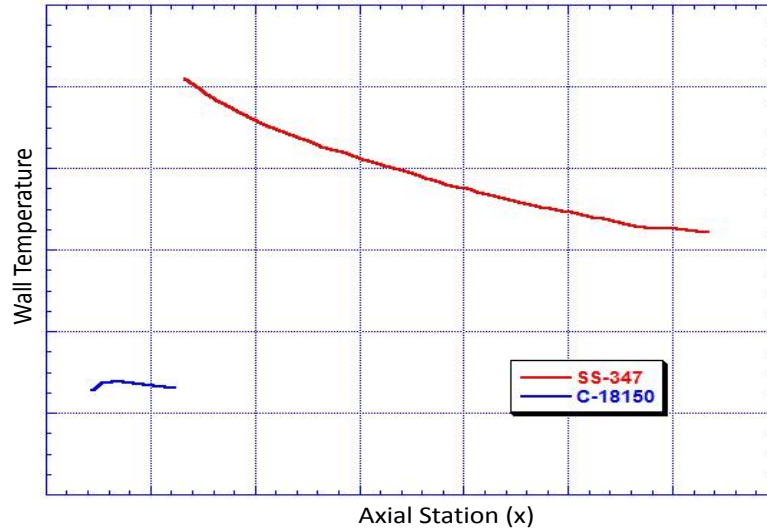
**Figure 10. Example of 2D Simulated Wall Temperatures using the Bimetallic Axial Split.**

The starting stock for Nozzle #7 used a Stainless Steel 347 thick plate. Thinner C-18150 plate was then explosively bonded to the SS347, providing a solid state joint [16,17]. A second C-18150 plate was then explosively bonded to the first C-18150 plate to form the axial section of the C-18150. There were some areas of debond on the overall bimetallic stock assembly mapped by ultrasonic scans around the perimeter, but the gross acreage had excellent bonding. A series of round plugs were then water jet cut from the bimetallic stock. These plugs were used as the starting stock to machine the nozzle and test specimens.

The joint for the bimetallic was used as an approximate datum to provide the axial location where the interface was to be located and other datums could be established. The ID of the nozzle was then final machined and placed on a mandrel. Speeds and feeds were constant and optimized to provide a good finish on both units. The nozzle was then placed on a mandrel and the OD was final machined. The channels were machined with an endmill to a final wall thickness. Figure 11 provides images of the initial bond stock and the final machined unit.
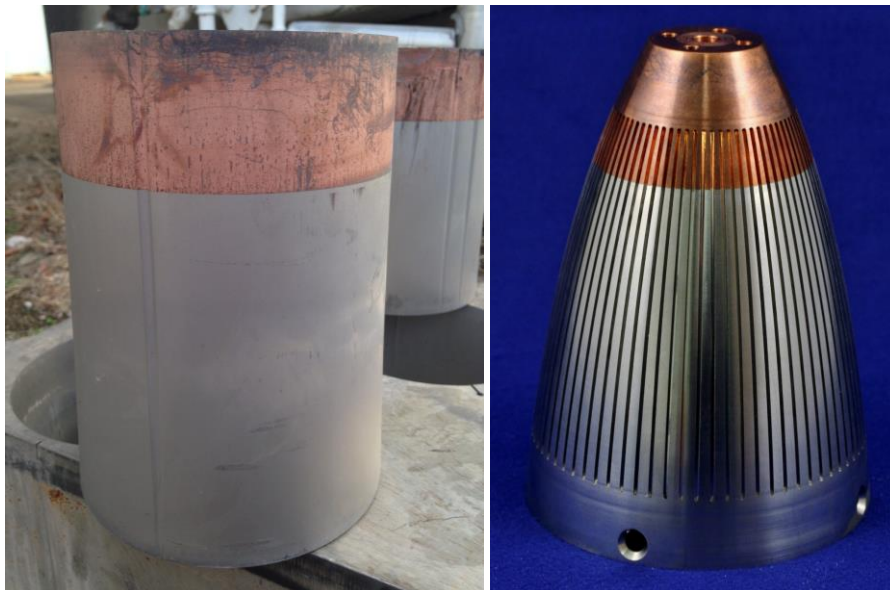


**Figure 11. (Left) Bimetallic "Plug" Stock Cut from Explosive Bonded Plates and,
(Right) Final Machined Axial Bimetallic Nozzle.**

Following machining of the slots, the nozzle was closed out using the LWDC process. Prior nozzles fabricated in SS347 were closed out with SS347. However, with the C-18150 copper at the forward end, the SS347 would not work.

It was decided to use Monel 400 for the entire closeout of the axial bimetallic nozzle. The Monel closeout worked well with no major issues noted with the SS347 or the C-18150. On future units, the SS347 (or alternate alloy) would be closed out with the matching alloy and then the LWDC process would transition to the Monel 400 (or alternate). The manifold weld preparations were cladded using blown powder DED with Inconel 625. The weld preparations on Nozzle #7 were final machined to mate with the manifolds and EB welded. This nozzle also went through a solution and aging process. Following solution and age, the forward flange interface surface was final machined and the tubes were welded to the manifolds. The nozzle was then hydrostatically proof tested.

At pressure of about 50 psig, there was significant blowing leaks at the forward end at the very forward tip and within a few channels in the copper. The leaks were present in the channels and not within the explosive bonded joint. A manual tungsten inert gas (TIG) braze repair was attempted in this area and the surrounding area. A 2nd proof test was conducted and taken to a pressure of about 500 psig, but several blower leaks were still observed and the pressure would drop quickly. The TIG braze did repair most of the gross leakage though.

A further repair was conducted using Loctite, which had been successfully used for previous nozzles. A 3rd proof test was conducted and several blowing leaks still existed. It was decided not to test this nozzle in this test series. The hotwall of this nozzle for the C-18150 was machined much thinner than typical designs. A modified hotwall design would likely resolve the leaks on future units. Nozzle #7 during process development and proof testing can be seen in Figure 12.
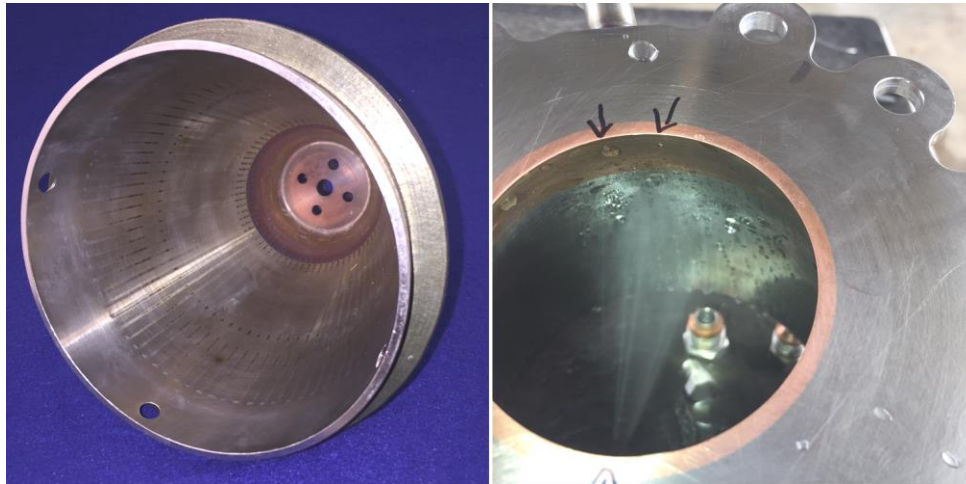


**Figure 12. Nozzle #7 with axial bimetallic: (Left) ID after LWDC and (Right) Leaks during final proof test.**

## C. Nozzle #8 and #9 LWDC Direct Closeout of Copper Liner

Nozzle #8 and #9 were fabricated using the LWDC technology, but demonstrated the C-18150 liner and closeout using Monel 400 directly to the C-18150. Based on the initial development work with the bimetallic LWDC, the Monel was selected since it did not crack at the interface. C-18150 barstock was used as the starting material and the nozzle ID and OD surfaces were final machined, including the slots. The direct interface did reduce several steps in the process, including the interim cladding, and increased machining time with the elimination of the Inconel intermediate material. Characteristic interfaces of the C-18150 to direct Monel 400 LWDC can be seen in Figure 13. Some porosity was observed at the interface during development, but did not cause any issues observed during testing.

The LWDC for Nozzles #8 and 9 processed very similar and there were no issues noted. The overall process was identical to that shown in Figure 7, but did not include the application of the intermediate layer. The manifold weld preparations were applied using blown powder Inconel 625 DED as a cladding operation with Inconel 625. Nozzle #8 was solution and aged in vacuum, while Nozzle #9 remained in the as-built condition. Both nozzles were final machined on the forward flange mating interface and the tubes were welded onto the manifolds. The nozzles were proof tested at 2,000 psig and no issues were noted. Nozzle #9 saw an additional 18 proof cycles prior to hot-fire testing.

**Figure 13. Characteristic Interfaces of the Monel 400 direct to C-18150 using LWDC during development. (Left) Etched Micrograph and (Right) Unetched.**

## IV. Hot-fire Testing and Results

MSFC completed two hot-fire test series, PI100 and PJ038, to evaluate the bimetallic and multi-metallic nozzles in relevant test conditions. The testing was conducted on a Liquid Oxygen /Gaseous Hydrogen (LOX/GH2) thrust chamber assembly[18,19]. The thrust chamber assembly used a Powder Bed Fusion (PBF) additively manufactured coaxial injector and PBF additive manufactured GRCop-42 combustion chamber liner. This testing was similar to previous testing to evaluate these advanced fabrication channel wall nozzle technologies to gather performance data in a relevant environment[20]. These nozzles were tested at MSFC Test Stand 115 (TS115) in a thrust chamber assembly (TCA) that is approximately 2K-lb$_f$ thrust class. The testing initially used water cooling to characterize the total heat load of the thrust chamber assembly and eventually transitioned to full regenerative cooling using GH2.

The injector was previously tested and characterized under several similar test programs[21]. The chamber configuration was also previously demonstrated with a slip-jacket liner, allowing for quick change-over of the liners[22]. The integrally-cooled liner that was tested as part of the PI100 and PJ038 series was a PBF GRCop-42 material, recently developed at MSFC and Glenn Research Center (GRC)[23,24]. The liner's coolant channels were printed into the structure, so that no channel closeout was necessary. Each nozzle test unit was bolted to the aft end of the chamber adapter ring. The injector included a center port for the igniter. The TCA configuration with the bimetallic LWDC nozzle can be seen in Figure 14.

The PI100 program was setup to provide initial performance characterization of various channel wall nozzles[25]. Follow-on testing under PJ038 performed cyclic testing to achieve high duty cycles to understand performance and durability of the hardware. The PI100 test series provided single cycle tests with up to 180 seconds of mainstage duration. The PJ038 testing that followed completed a series of cyclic tests with up to 7 full hot-fire and purge cycles per test. The latter test series allowed for fully reversal strains and cycling for fatigue conditions to challenge the hardware under these conditions.

A total of 72 tests were completed on the bimetallic LWDC hardware and accumulated over 3,500 seconds of mainstage test time. The conditions included chamber pressures (Pc) up to 1,225 psig and mixture ratios (MR) up to 8.0. The high mixture ratio testing was completed at the end of the series to fully demonstrate hardware durability on the chamber and nozzles. An image of a hot-fire test during mainstage is shown in Figure 15. Table 2 summarizes the number and type of tests on each unit.

While overall the nozzle hardware performed as expected, there were several observations were made about the test series relative to the different nozzle configurations. A summary of comparison tests with similar MR and Pc is shown below in Table 3. For each test, the performance of the nozzles was tabulated before setting conditions of the subsequent testing. Instrumentation included inlet and outlet temperatures and pressures within the manifolds as well as tubing. Additional backside (coldwall) thermocouples were tack welded to the nozzle jacket.

**Figure 14. Test configuration with LWDC Bimetallic Nozzle shown at MSFC TS115.**
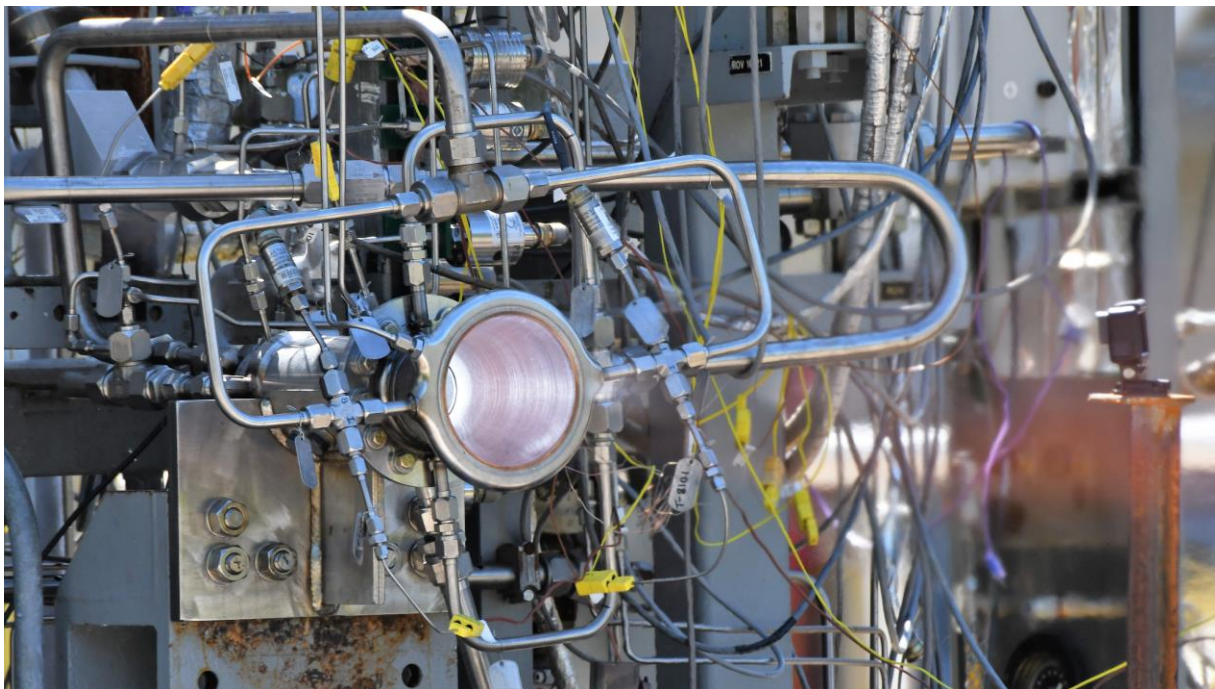


**Figure 15. Mainstage hot-fire testing with bimetallic LWDC channel wall nozzle #9.**

**Table 2. Summary of Bimetallic LWDC Nozzle Hot-fire Test Results.**

| Nozzle | Configuration | Coolant | Peak Chamber Pressure (psig) | Peak MR | Starts | Accumulated Time (sec) |
|---|---|---|---|---|---|---|
| Nozzle #6 | Radial Bimetallic, Intermediate Alloy | GH2 | 1,122 | 6.2 | 3 | 540 |
| Nozzle #7 | Axial Multi-alloy | N/A | N/A | N/A | N/A | N/A |
| Nozzle #8 | Radial Bimetallic, Direct | GH2 | 1,139 | 6.2 - 8.0 | 60 | 1,830 |
| Nozzle #9 | Radial Bimetallic, Direct | Water / GH2 | 1,225 | 6.2 | 9 | 1,130 |

**Table 3. Summary of Nozzle Performance with comparable test conditions.**

| Nozzle | Test | Pc (psig) | MR | ΔP (psid) | ΔT (F) | Total Q (BTU/s) | R |
|---|---|---|---|---|---|---|---|
| Nozzle #6 | PI100-013 | 1,122 | 6.13 | 86 | 111 | 295 | 129 |
| Nozzle #8 | PJ038-026A | 1,118 | 6.14 | 142 | 112 | 295 | 218 |
| Nozzle #9 | PJ038-001 | 1,109 | 6.11 | 128 | 104 | 279 | 192 |

The ΔP across the nozzle was measured within the inlet and outlet manifolds. The ΔT was measured using an average of outlet temperatures and inlet temperatures to account for any flow non-uniformity. The lower ΔT seen in Nozzle #9 could have been due to a difference in insertion depth of the probe. As noted in the table above, Nozzle #9 was originally tested with water cooling to characterize the heat load and then switched to GH2 cooling. All data analysis was with the GH2 condition. The test conditions did not change otherwise. The total heat absorbed, Q, was calculated based on the change in enthalpy according to equation (1), where the fuel flow rate, $\dot{m}$, was calculated via the sonic venturi in the facility feed system.

$$\text{Total Q} = \Delta H \times \dot{m} \qquad (1)$$

The resistance, R, of the nozzle was calculated based on equation (2).

$$R = \frac{\Delta P \times \rho}{\dot{m}^2} \qquad (2)$$

The measured resistance provided a relative comparison of the nozzles independent of flow rate. There was some changes noted between the nozzle configurations, but generally within family. Nozzle #6 with the intermediate bond layer had a lower resistance compared to the other direct LWDC configuration. There was an approximate 10% increase in flow area with the intermediate bond, but this did not account for the full reduction in pressure drop. Figure 16 provides a plot of the observed nozzle resistance during the cycle testing.

Another observation during the testing was the backside temperature of the nozzles. Three thermocouples, T1, T2, T3 were tack welded along with a strain relief at the 3 o'clock position onto each nozzle being tested. This allowed for a coldwall temperature measurement to help anchor models and provide a relative comparison of performance. For similar test conditions, the backside thermocouples were compared for the three nozzles that completed the test series. Nozzle #6 with the intermediate Inconel 625 bond layer saw much higher temperatures on the backside compared to the direct LWDC for Nozzles #8 and 9. A comparison of this data is observed in Figure 17. The temperatures remained very consistent from test to test for a particular nozzle including the temperature during a particular test. The mainstage conditions for Nozzle #6 at MR=6.3 and Pc=1,098 psig can be seen in Figure 18. This was the 3rd test of Nozzle #6 under similar conditions and the data remained consistent.
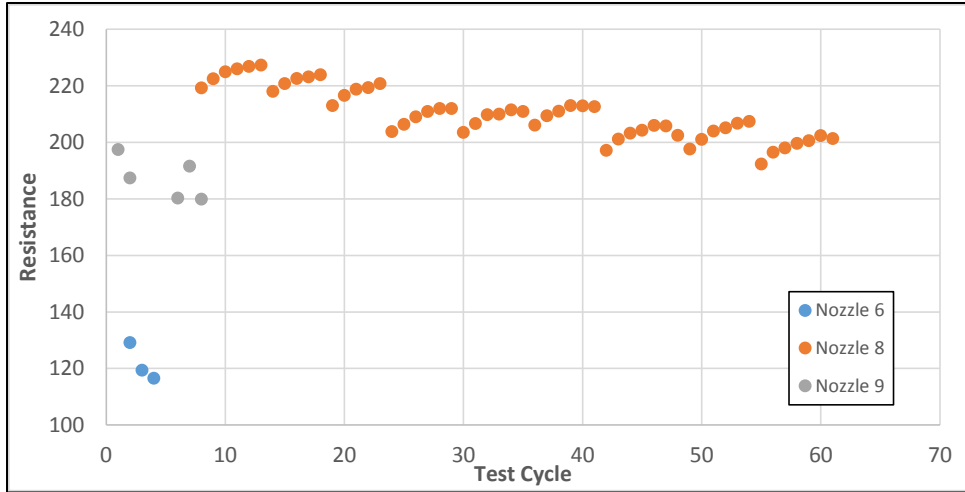
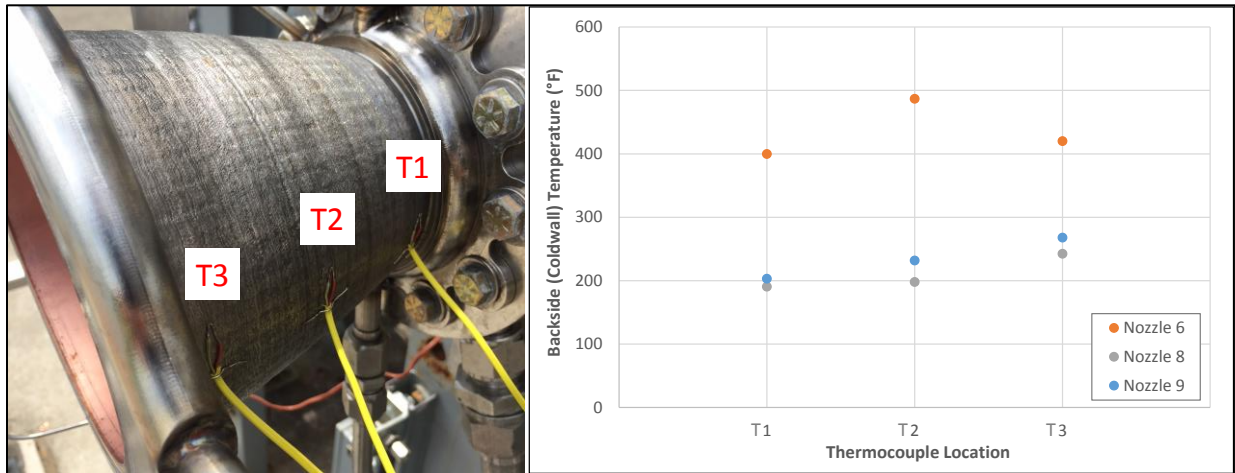**Figure 16. Comparison of Nozzle Resistance during mainstage.**



**Figure 17. (Left) Location of backside thermocouples and (Right) Comparison of thermocouples with similar test conditions.**
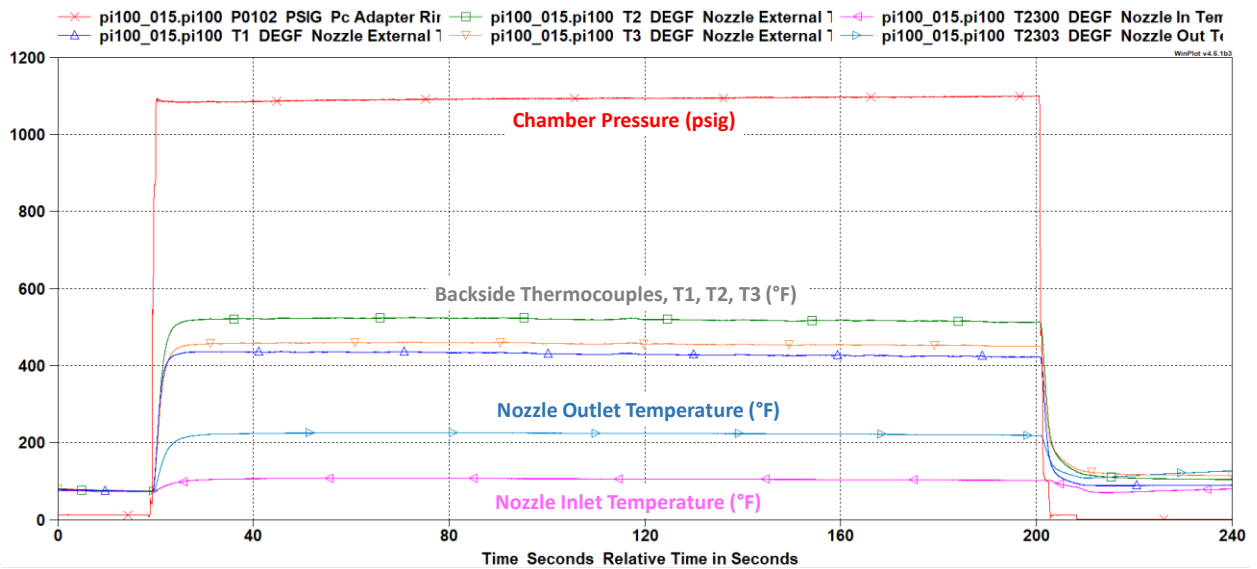


**Figure 18. Typical Mainstage Conditions for Nozzle #6 with MR=6.5 and Pc=1,098 psig (PI100-015 shown).**

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Following the initial testing in PI100, cycle testing was completed on additional nozzles including Nozzle #8 with the direct LWDC and, solution and aging. The intent of this testing was to thermally cycle the chamber and nozzle with fully reversal thermal and structural loading. After an initial cycle of 30 seconds, a purge sequence was completed for 25 seconds, lowering the temperatures to the starting condition. The nozzle was inspected after each test (series of cycles) and repeated. Nozzle #8 performed well during this cyclic testing and no significant changes to the hardware were observed. A summary of the cycles performed on Nozzle #8 can be seen in Table 4.

**Table 4. Summary of Cycle Testing on Nozzle #8.**

| Test | Avg Pc (psig) | Avg MR | # Cycles | Total Time (sec) |
|---|---|---|---|---|
| PJ038-024 | 1,136 | 6.07 | 6 | 180 |
| PJ038-025 | 1,134 | 6.03 | 6 | 180 |
| PJ038-026 | 1,125 | 6.08 | 5 | 150 |
| PJ038-027 | 1,120 | 6.17 | 5 | 150 |
| PJ038-028 | 1,103 | 6.50 | 6 | 180 |
| PJ038-029 | 1,096 | 6.66 | 6 | 180 |
| PJ038-030 | 1,071 | 6.95 | 6 | 180 |
| PJ038-031 | 1,083 | 6.96 | 6 | 180 |
| PJ038-032 | 1,076 | 7.00 | 1 | 60 |
| PJ038-033 | 1,081 | 6.94 | 6 | 180 |
| PJ038-034 | 1,021 | 7.96 | 7 | 210 |
| **Total** | | | 60 | 1,830 |

The plot in Figure 19 shows the final test on Nozzle #8 with an average MR=7.96 and Pc=1,021 psig. A total of 7 cycles were completed in the last test (PJ038-034) and the plot shows the chamber pressure, outlet manifold pressure and temperature remained constant for each of the cycles. Nozzle #8 demonstrated repeatable performance during the cycle testing and no physical changes noted.
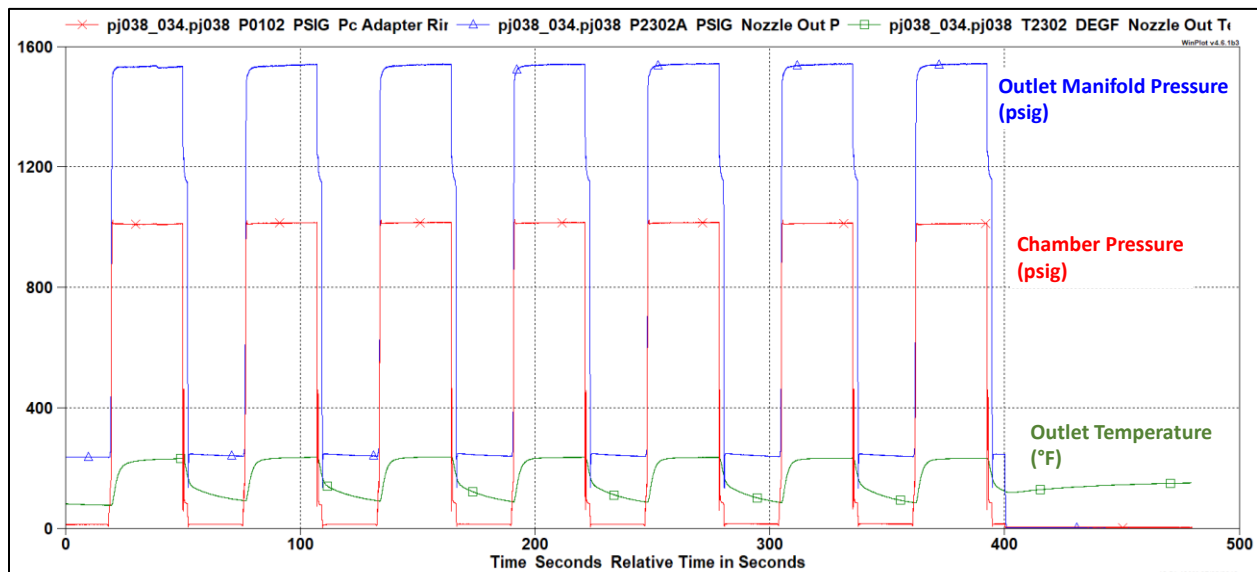


**Figure 19. Hot-fire cycle testing of Nozzle #8 with MR=7.96 and Pc=1,021 psig.**

Nozzle #8 completed a total of 60 tests and no major changes to the hardware were noted. There was some discoloration and minor wall waviness noted at the forward end, which can be seen in Figure 20. This change at the

forward end was course waviness and the surface did not roughen in a manner typically characteristic of blanching. This was only observed on Nozzle #8 and the waviness was seen after the initial test on this unit (PJ038-024). The waviness was very minor and primarily observed visually. It could barely be felt to the touch.

All nozzles performed well during testing with no visual geometric changes. There were varying levels of steaking and some surface oxidation as expected. Following cycle testing, the nozzles were sectioned for metallography to understand the various joint configurations under the loading conditions. A series of sections were cut to observe the joints across the channel ribs, axially along the ribs, and down the channel centerline. Some microcracks were observed on a few pieces, but it was uncertain if this was part of the initial process or cauased from hot-fire testing. Nozzle #6 saw some porosity at the interface and some minor cracking in the Monel to Inconel 625 interface. Nozzle #8 also saw some cracking at the interface and ongoing metallography being performed. One other observations was the roughness of the channel backside, which can be seen in Figure 21. These nozzles were the first units NASA developed using the bimetallic LWDC process, so there are several improvements that could be made to help performance on future units.
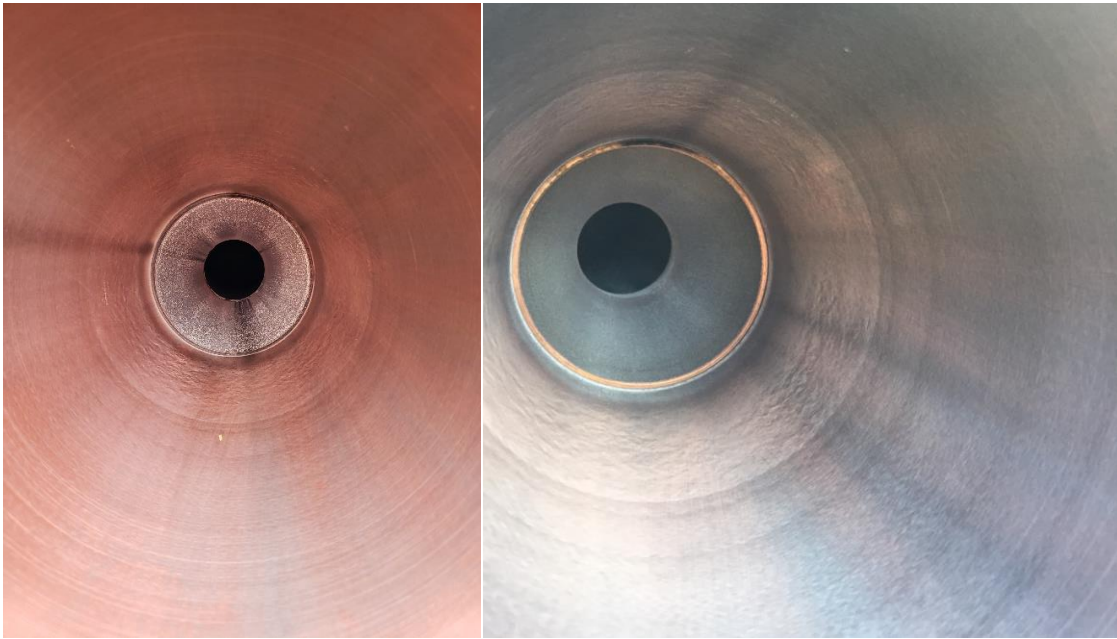


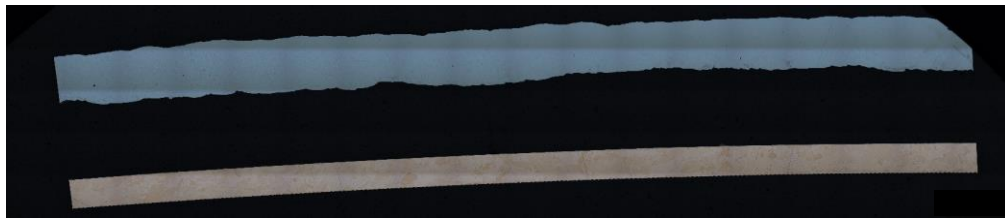**Figure 20. Nozzle #8: (Left) After initial 6 cycles and (Right) After 60 accumulated cycles and 1,830 sec.**



**Figure 21. Coldwall surface roughness observed on Nozzle #8 post-test (Unetched).**

## V. Conclusions

NASA and industry partners completed process development and hot-fire testing using the LWDC technology for bimetallic channel wall nozzles. LWDC offers an AM wire-fed laser deposition process that eliminates the need for a tight tolerance structural jacket and plating operations compared to traditional manufacturing. The process provides a direct closeout of the coolant channels and forms the jacket integral in the same process. A series of bimetallic nozzles completed development with various LWDC approaches for the channel closeout. The research builds upon the prior development for monolithic nozzle hardware. The hardware demonstrated the feasibility of using it for bimetallic applications with a copper-alloy and completed hot-fire testing in a relevant environment.

Several bimetallic configurations were fabricated and tested. Three nozzles (Nozzles #6, 8, 9) were fabricated using the LWDC on a C-18150 copper-alloy liner and Monel 400 jacket with radial deposition. Monel was chosen

due to the material compatibility and providing the best results during the process development. An alternate material may be considered for future development. The radial deposition liners had some variations in how the process was applied including direct application of Monel 400 to C-18150. An intermediate transition layer, Inconel 625, was also used prior to the Monel 400 closeout. Nozzle #6 used the intermediate alloy, while Nozzle #8 and 9 had a direct bimetallic closeout with the Monel. A fourth nozzle (#7) was fabricated using an explosive bonding that provided an axial bimetallic joint to reduce peak temperatures at the forward end in the high heat flux region. Nozzle #7 was then closed out using the LWDC process and failed leak checks during the final proof test. It did not continue with hot-fire testing. Future development using this process could include a modified hotwall design solution.

Hot-fire testing was completed on Nozzles #6, 8, 9 and accumulated 3,500 seconds and 72 starts on the various configurations. Testing was conducted using a PBF GRCop-42 chamber liner and PBF Inconel 718 injector with LOX/GH2. Nozzle #8 completed cycle testing and accumulated 60 starts and 1,830 seconds at mixture ratio up to 8.0 and chamber pressure up to 1,139 psig. All nozzles performed well during testing with no visual geometric changes. There were varying levels of streaking and some surface oxidation as expected. Following hot-fire testing the Nozzle units were sectioned and the joints and material structure characterized. There were varying levels of porosity observed in the joints with the channel ribs, although did not manifest in testing. Sections through the ribs and along the length were taken. The surface roughness of the LWDC process was higher than expected in these nozzle units resulting in higher than expected pressure drop.

Improvements to the LWDC process for future units would include an evaluation of alternate materials chosen specific to the operating environments. The surface roughness of the LWDC could also be improved to reduce any impacts to performance. Process control is also being evaluated to minimize or mitigate any of the porosity or microcracks observed, which could be a result of improper feed location of the wire when depositing. The intermediate alloy prior to the LWDC process did not appear to provide an immediate benefit and increased processing time. There was a significant increase in the backside wall temperature of this configuration during testing. The final configuration with direct or intermediate alloy should be evaluated based on the application.

The LWDC process was demonstrated from development through hot-fire testing on a bimetallic channel wall nozzle application. Significant test time and starts demonstrated the process is feasible for future applications to nozzles. MSFC also developed a new test capability for high duty cycle testing of liquid rocket engine component hardware at MSFC Test Stand 115. The ability to conduct a 7 cycles at 30 seconds per cycle provided the capability to accumulate significant starts and time on hardware to demonstrate feasibility.

## Acknowledgements

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