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Channel Wall Nozzle Manufacturing Technology Advancements for Liquid Rocket Engines

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Abstract

A regeneratively-cooled nozzle is a critical component for expansion of the hot gases to enable high temperature and performance liquid rocket engines systems. Channel wall nozzles are a design solution used across the propulsion industry as a simplified method to fabricate the nozzle structure with internal coolant passages. The scale and complexity of the channel wall nozzle (CWN) design is challenging to fabricate leading to extended lead times and higher costs. Some of these challenges include: 1) unique and high temperature materials, 2) Tight tolerances during manufacturing and assembly to contain high pressure propellants, 3) thin-walled features to maintain adequate wall temperatures, and 4) Unique manufacturing process operations and tooling. The United States (U.S.) National Aeronautics and Space Administration (NASA) along with U.S. specialty manufacturing vendors are maturing modern fabrication techniques to reduce complexity and decrease costs associated with channel wall nozzle manufacturing technology. Additive Manufacturing (AM) is one of the key technology advancements being evaluated for channel wall nozzles. Much of additive manufacturing for propulsion components has focused on powder bed fusion, but the scale is not yet feasible for application to large scale nozzles. NASA is evolving directed energy deposition (DED) techniques for nozzles including arc-based deposition, blown powder deposition, and Laser Wire Direct Closeout (LWDC). There are different approaches being considered for fabrication of the nozzle and each of these DED processes offer unique process steps for rapid fabrication. The arc-based and blown powder deposition techniques are being used for the forming of the CWN liner. A variety of materials are being demonstrated including Inconel 625, Haynes 230, JBK-75, and NASA HR-1. The blown powder DED process is also being demonstrated for forming an integral channel nozzle in a single operation in similar materials. The LWDC process is a method for closing out the channels within the liner and forming the structural jacket using a localized laser wire deposition technique. Identical materials mentioned above have been used for this process in addition to bimetallic closeout (C-18150–SS347, and C-18150–Inconel 625). NASA has completed process development, material characterization, and hot-fire testing on a variety of these channel wall nozzle fabrication techniques. This paper will present an overview of the various processes and materials being evaluated and the results from the hot-fire testing. Future development and technology focus areas will also be discussed relative to channel wall nozzle manufacturing.

Keywords: Additive Manufacturing, Channel Wall Nozzles, Liquid Rocket Engine Nozzle, Regeneratively Cooled Nozzles, Channel Cooled Nozzles, Directed Energy Deposition, Laser Wire Direct Closeout, LWDC, DED, NASA HR-1, JBK-75, Thrust Chamber Assembly, Advanced Manufacturing

Acronyms/Abbreviations

Additive Manufacturing (AM), Channel Wall Nozzle (CWN), Direct Energy Deposition (DED), Explosive Welding (EXW), Gaseous hydrogen (GH2), Kerosene (RP-1), Liquid Oxygen (LOX), Metal Inert Gas (MIG), Mixture Ratio (MR), Marshall Space Flight Center (MSFC), Laser Powder Bed Fusion (L-PBF), Laser Wire Direct Closeout (LWDC), Chamber Pressure (Pc), Rapid Analysis and Manufacturing Propulsion Technology (RAMPT), Regeneratively-cooled nozzle (Regen), Thrust Chamber Assembly (TCA), Water Jet Milling (WJM)

1. Introduction

A regeneratively-cooled nozzle for liquid rocket engine applications is a significant cost of the overall engine due to the complexities of manufacturing a large thin-walled structure that must operate in extreme temperature and pressure environments. The United States (U.S.) National Aeronautics and Space Administration (NASA) has been investigating methods for fabrication of liquid rocket engine regeneratively-cooled channel wall nozzles (CWN) to realize further cost and schedule improvements over traditional techniques. Regeneratively-cooled (regen) nozzles make use of a large area ratio contour to provide expansion of hot gases coupled with active cooling of the hotwall to maintain adequate structural margins. The complexities of nozzles are numerous since these are often large scale component structures that require very thin-walls for the channels and extreme environments providing challenging thermal and structural loads. A cross section of a channel wall nozzle can be seen in Fig 1, demonstrating the thin-wall and series of channels that make up the wall structure.

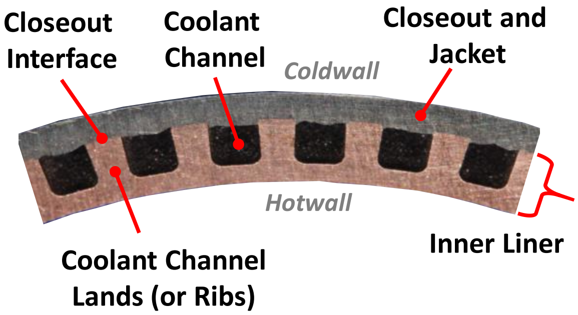

Fig. 1. Channel Wall Nozzle Configuration (Bimetallic liner shown).

Nozzle designs are continually being stretched to deliver additional performance to the liquid rocket engine. This drives the increase in size which must be balanced with the ability to be manufactured at lower costs in higher volumes. To meet this demand, the limitations of the material properties must be balanced with the ability to fabricate complex geometric features that still perform in extreme environments where large thermal gradients exist in addition to high dynamic loading. Examples of design considerations for nozzles include:

- Thinner hotwalls to balance cooling with increased heat fluxes
- Balancing coolant channel dimensions with pressure drop profiles
- Ability to produce robust joints at increased bond joint temperatures
- Ability to inspect the bonding of the closeout to the channel lands
- Reduction in assembly build hours and manual processing
- Reduction in lead time for materials or processes
- Various options for materials and combinations (i.e. monolithic, bimetallic and multi-metallic)
- Direct build and/or simplified attachment of manifolds
- Increased system performance through nozzle weight reduction or hydraulic performance

To address many of these design challenges NASA has been evaluating modern manufacturing techniques, including various additive manufacturing (AM) technologies, focused on reduced tooling, inspections, and maturing these new manufacturing technologies for their application to regen-cooled nozzles. The advanced manufacturing development efforts for nozzles started around 2012, although many of the core technologies started well before that time. These techniques offer further cost savings and reduction in fabrication time that have the potential for scale-up to the sizes needed for modern channel wall nozzle applications. The goal of this development is to demonstrate manufacturing process feasibility to the application of channel wall nozzles, to develop basic material properties, to demonstrate application within the nozzle environment, and enable a domestic supply chain for government and commercial companies to make use of. Several of these techniques were discussed in further detail in prior research [1]. Independent from a single-piece integrated-channel wall using additive manufacturing, the general steps described in the fabrication of a channel wall nozzles include the liner perform, formation of the coolant channels, closeout of the coolant channels, and assembly of the fluid distribution manifolds. Several manufacturing processes were evaluated, some based on prior research and other industry benchmarks, and then several down selected for further evaluation.

The manufacturing techniques are traded based on the engine and subsequent nozzle requirements and many can be coupled to provide the optimal manufacturing solution. The primary purpose of these coupled manufacturing process steps is to properly control the geometry for the actively-cooled channels. Variations in these coolant channel features can cause local hot spots and off-nominal operating conditions which can lead to failures. These local features of the coolant channels combined with the scale at which the entire nozzle must be fabricated further complicate the complexity of manufacturing. The tolerances must be controlled throughout all processing steps of fabrication including machining, heat treatments, brazing, welding, deposition, and closeout to achieve the desired dimensions [2]. These operations can affect the roundness of the part, variation in the final hotwall contour, variation in the outer surface (coldwall) of the nozzle, and thickness of the liner. In addition, the stack-up of tolerances of each processing step has an impact on the final geometry of the channels.

Liner Forming
- Forging
- Spin Forming
- Shear Forming
- Powder Metallurgy
- Directed Energy Deposition
    - Blown Powder Laser
    - Wire-based Laser
    - Arc-based Wire
- Multi-Piece L-PBF
- Platelets
- Explosive Forming
- Coldspray
- Casting
- Vacuum Plasma Spray

Slotting
- Slitting Saw
- End Milling
- Water Jet Milling
- Electrochemical
- Plunge EDM
- Multi-Piece L-PBF
- Platelets
- Freeform DED Cladding

Closeout and Jackets
- Pressure Assisted Braze
- Standard Atmosphere Braze
- Multi-Piece L-PBF
- Vacuum Plasma Spray
- Electroplating
- Coldspray
- Directed Energy Deposition
    - Blown Powder Laser
    - Laser Wire Direct Closeout
    - Arc-based Wire
- Explosive Bonding
- Ultrasonic
- Laser Welding
- Diffusion Bonding
- Platelets
- Casting
- Composite Overwrap

Manifolds
- Forged and Machined
- Directed Energy Deposition
    - Blown Powder Laser
    - Wire-based Laser
    - Arc-based Wire
- L-PBF (single or multi piece)
- Platelets
- Casting
- Molded Composites

Fig. 2. Various Manufacturing Technologies considered for Channel Wall Nozzle Fabrication.

While a variety of fabrication techniques were initially evaluated as shown in Fig. 2, NASA focused recent development on five (5) major technologies of interest. Many of these technologies are focused on large scale additive manufacturing using varying deposition techniques. Each technique has limitations that requires considerations and trades within the design. Other manufacturing techniques are still being evaluated, just not discussed in this paper. The technologies that will be further discussed are:

1. Laser Wire Direct Closeout (LWDC), for channel closeout and structural jackets
2. Directed Energy Deposition (DED), specifically Blown Powder DED, for monolithic nozzles with integral channels
3. DED Deposition for liners and jacket preforms, such as Arc-based DED and blown powder DED
4. Water Jet Milling, for channel forming
5. Explosive Bonding, for coolant channel closeout and structural jackets, and bimetallic transitions

Several of the processes being evaluated and down selected involve forms of metallic AM, and this is one of the enabling technologies for cost and schedule reductions. Much of additive manufacturing for propulsion components has focused on laser powder bed fusion (L-PBF), but that current scale is not yet feasible for application to large nozzle components. NASA is evolving several directed energy deposition (DED) based techniques for nozzles including arc-based deposition, blown powder deposition, and Laser Wire Direct Closeout (LWDC). There are different approaches being considered for fabrication of the nozzles for different engine requirements. Each of these DED processes offer unique process steps for rapid fabrication. The arc-based and blown powder deposition techniques are being used for the forming of the CWN liner. A variety of materials have been demonstrated including Inconel 625, Haynes 230, JBK-75, and NASA HR-1. The blown powder DED process is also being demonstrated for forming an integral channel nozzle in a single operation in similar materials. The LWDC process is a method for closing out the channels of a slotted liner and forming the structural jacket using a localized laser wire deposition technique. Identical materials mentioned above have been used for this process in addition to bimetallic closeout (C-18150–SS347, and C-18150–Inconel 625).

To fully mature these processes NASA has completed process development with samples and subscale hardware, material characterization, and hot-fire testing on a variety of these nozzle fabrication techniques. This paper will present an overview of the various processes and materials being evaluated and the results from the hot-fire testing. Future development and technology focus areas will also be discussed relative to channel wall nozzle manufacturing including the increased scale development currently being conducted.

2. Manufacturing Process Development

The manufacturing processes that are continuing development include LWDC, Blown Powder DED for thick-walled nozzle liners and integral channel nozzles, and advanced manufacturing techniques such as water jet milling and explosive bonding.

2.1 Laser Wire Direct Closeout (LWDC)

The LWDC process was developed by MSFC and industry partners, Keystone Synergistic Enterprises and Laser Technology Associates, to provide a channel closeout method for monolithic and bimetallic nozzles. While a monolithic material is feasible for most channel wall applications, some engine applications may require a bimetallic design solution with a copper liner for higher heat flux environment. A bimetallic, or multi-metallic, 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 channel closeout 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 conductivity but higher strength-to-weight material as heat flux is reduced enough to make use of a lower conducting alloy. The closeout for this axial bimetallic will often use a stainless-based or superalloy material.

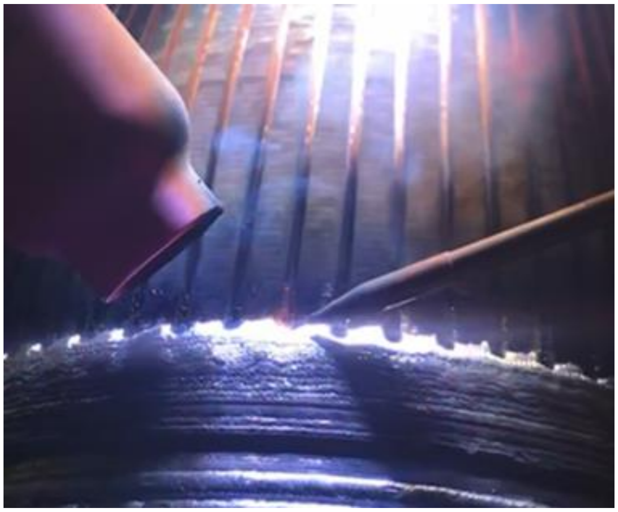

Figure 3. Bimetallic Nozzle Closeout being completed with LWDC.

The LWDC process deposits a welding wire that bridges the span of the coolant channels without any internal channel filler material needed. An independent wire feed and offset inert gas-purged laser beam melts the feedstock wire using an area of stock material prior to the start of the coolant channels (generally progressing aft end to the forward). While the nozzle is rotated about the central 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 [3]. LWDC is used for the direct closeout of the coolant channels and application of the structural jacket. The individual layers of closeout can be observed traversing axial along the channel lands.

Figure 4. LWDC Closeout of Monolithic, Inco 625.

LWDC is an AM-based wire-fed laser deposition process that eliminates the need for a tight tolerance structural jacket and additional operations compared to traditional manufacturing, such as brazing or structural plating closeout [4]. The LWDC process provides a direct closeout of the coolant channels and forms the integral jacket in the same process. A small diameter wire is used to reduce heat load to the part. Thus, the 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 [5]. An overview of the LWDC process can be seen in Fig. 5. 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 [6].

The primary advantage of the LWDC process is the jacket and channel closeout are integrally formed, so tolerances can be reduced 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

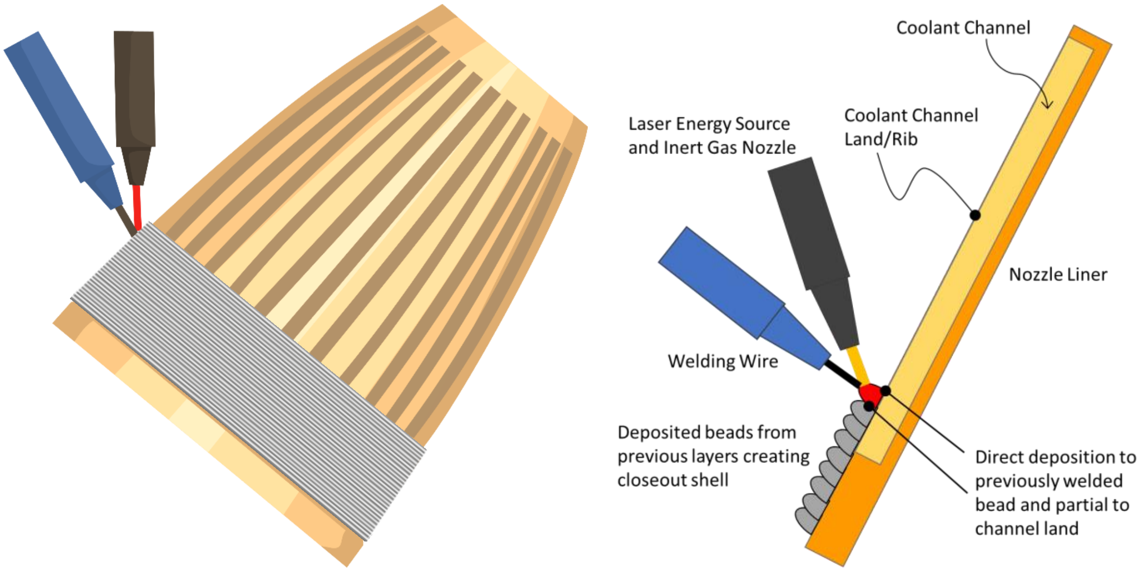

Fig. 5. Diagram of the Laser Wire Direct Closeout (LWDC) Process.

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 DED processes; a comparison of deposition rates is shown in Ref. [7]. However, this time is offset by the elimination of a closeout jacket and subsequent bonding operations.

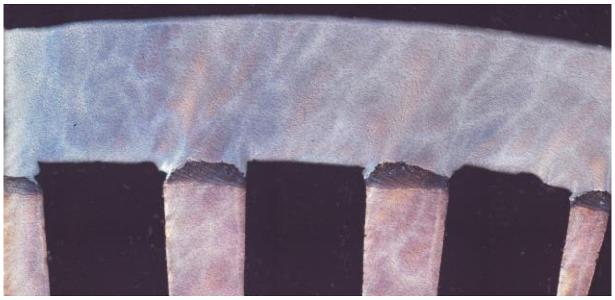

Fig. 6. Cross Section of Bimetallic LWDC Process.

Several material combinations have been evaluated using the LWDC process. These include a variety of monolithic materials and bimetallic or multi-metallic. The primary monolithic materials that have been evaluated include Inconel 625, Haynes 230, Stainless Steel CRES 347, JBK-75, and NASA HR-1 [8]. Some of the bimetallic materials include C-18150 (Cu-Cr-Zr) with a Monel 400 and Inconel 625 closeout. These materials were selected for various engine applications and discussed in more detail in a later section.

2.2 Blown Powder Directed Energy Deposition

The Blown powder directed energy deposition (DED) process is being studied for several applications of regen-cooled nozzles. This includes forming near-final shape components such as liners, manifolds, and an integrated-channel configuration to minimize part count. A significant advantage of the DED processes is the ability to adapt to a robotic or gantry CNC system with a localized purge or purge chamber, allowing unlimited build volume. Much of the current focus of the DED is being explored to form the entire channel wall nozzle with integral coolant channels within a single AM build. This relies on the DED-fabrication of complex and thin-walled features. Characterization of the material properties produced with this technique is required in order to evolve this process [9].

The blown powder DED fabrication technique uses a coaxial nozzle with a central laser source and powder injected (or blown) into the laser focus. The melt pool is created by the co-axial laser energy source causing a weld bead to be deposited. 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 head system, with integrated focus optics and blown powder nozzle(s), is attached to a robot or gantry system that controls a toolpath defined by the CAD model. 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 complex freeform structures to be built with small integral features, such as thin-walls and channels. Various optics can be used to vary the spot size, which control the size of features that can be built. A picture of the process can be seen in Fig 7.

Prior publications [Ref 7, 9] discussed specific design details of the blown powder DED process for nozzles and application of the technology to nozzles. A majority of the early blown powder DED evolved the process as a forging or casting replacement technology, such as forming nozzle liners, manifolds, and bimetallic jackets for combustion chambers [10]. This was shown by fabricating large structures and machining to final dimensions. This process has shown a viable option is feasible with acceptable properties.

Fig. 7. Blown Powder DED process applying nozzle manifold preparations.

The current focus of the Blown powder DED is on integrated- channel nozzles that can significantly reduce part count and may only require a few post-processing operations to complete an assembly. During this development, several lessons learned were collected on the design process as it relates to DED (compared to previous lessons on L-PBF). Some of the primary differences of DED compared to L-PBF are the inability to use break-away supports, minimum feature size results in thicker as-built walls, feature resolution is more coarse, higher surface roughness, and higher heat input. The integral channel nozzle fabrication process (Fig. 8 and 9) has rapidly evolved and NASA along with industry partners have demonstrated a variety of initial hardware, including hot-fire testing later discussed.

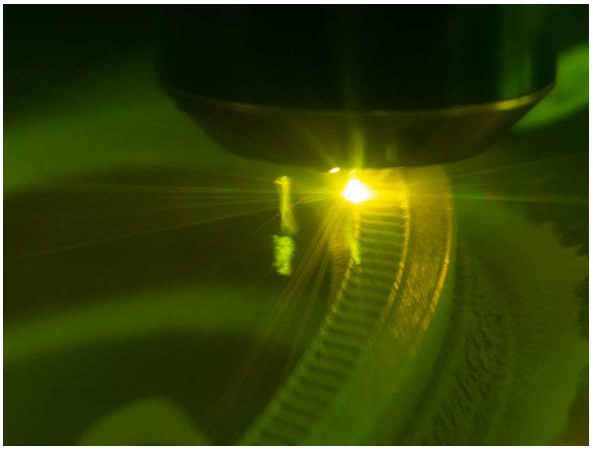

Fig. 8. Blown Powder DED fabrication with integrated channels (RPM Innovations).

Fig. 9. Examples of Blown Powder DED integral channel nozzles (RPMI).

2.3 Supporting Technologies for CWN Advanced Manufacturing

Arc-based additive manufacturing deposition technology uses a pulsed-wire metal inert gas (MIG) welding process to create near net shape components. The deposition head is integrated with a robot and turntable to freeform components from a derived toolpath. The toolpaths are developed to minimize porosity and allow for optimal properties. A series of integral sensor packages to determine material temperature, build geometry, and melt pool are integrated into the deposition system to allow for real-time inspection of the preforms as they are fabricated. The arc-based deposition process does not have the ability to fabricate precise features since it uses a larger deposited bead, so coarse features are typical of this type of deposition. This process is capable of high deposition rates with high density and acceptable material properties. A variety of arc-deposited nozzles liners have been fabricated in Inconel 625, Haynes 230, and JBK-75. This process also allows for large scale since it is only limited by the manipulation robot.

Water jet milling (WJM) is a technique that NASA has been advancing with industry partner Ormond, LLC for precision milling of coolant channels. WJM is a blind milling process using a high pressure water jet and abrasive material with a specialized nozzle and toolpath strategy to selectively mill channels from a preform nozzle liner. Prior process developments for WJM of coolant channels resulted in a taper of the channel sidewalls with the thinner channel width nearing the hotwall. This presented concerns with proper cooling of the hotwall due to the increased material volume. Further process improvements have been completed to square the channels, providing wall perpendicularity, to replicate the slotting process to maximize cooling to the hotwall. These process developments also improved repeatability of the channel depth.

WJM provides several advantages over traditional slotting of channels, particularly for difficult to machine materials such as superalloys. The first being channel complexity and the ability to form a variety of channel shapes using multi-axis WJM. This allows for various designs such as bifurcated channels, dove tail channels for bonding enhancement, integral instrumentation ports, multi-pass channels and integral turnaround, undercuts, and several other features [ref. 1]. The second advantage is a low load process resulting in the ability to create thin-walled channels over traditional slotting. The third advantage is a time savings associated with superalloys, allowing for higher milling rates in selected materials. One final advantage is the process inherently creates squared channels at the ends of the nozzle liner. Traditional slotting processes create a radius of the slitting saw; a secondary process is required using an end mill to square the ends of the channels. This allows for proper cooling to the ends of the liner where designs can be particularly challenging. An example of a mid-scale WJM nozzle liner and channel is provided in Fig. 10.

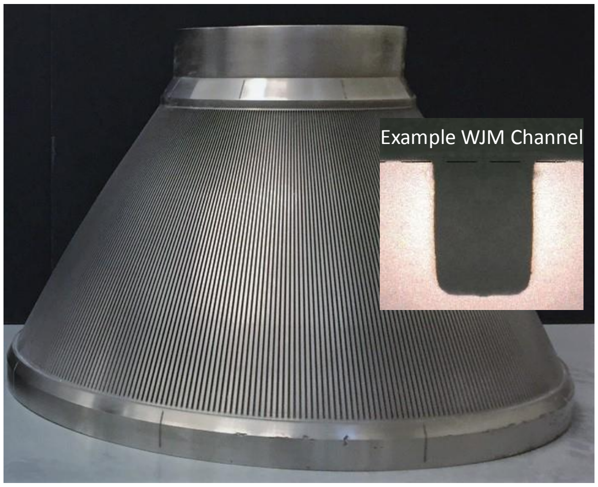

Fig. 10. Water Jet Milling (WJM) of mid-scale (~22” diameter) Haynes 230 Liner and channel example.

Explosive bonding or explosive welding (EXW) is a solid state bonding process that has been used for joining similar and dissimilar metals for many decades. It is often been used for simple geometries such as flat plate and cylindrical components. The process uses explosive powder to accelerate a flyer into a backer component and the kinetic energy permanently bonds the components together. As part of the process the rapid movement of the flyer plate ionizes the surface of the metals creating a plasma jet that strips the oxides from the surface of the components to allow for a clean joint. This process was shown to have some advantages, including ability to bond dissimilar metals and also be cost effective. The tooling and processing is relatively inexpensive. The tolerances for the closeout shell can be much lower than traditional processes such as brazing. The process is also scalable to large conical nozzle shapes. Explosive bonding has been evaluated for nozzles including dissimilar material joining providing an axial hotwall joint and also closeout of the coolant channels. An example of an explosive bonded axial joint on a nozzle can be seen in Fig. 11.

Fig. 11. Explosive bonded axial bimetallic liner.

2.4 Material Selection

A variety of materials have been evaluated during the processes discussed above. The materials were selected based on maturity for the process and also compatibility with the propellant combination. These materials are shown in Table 1. The Inconel 625, SS347, and Haynes 230 were materials selected based on industry experience and higher maturity for additive manufacturing processes. JBK-75 is a high-strength hydrogen resistant material derived from A-286 with good weldability characteristics desired for additive manufacturing [11, 12, 13]. Additive manufacturing using the DED blown powder and LWDC manufacturing provided new opportunities to overcome historical processing challenges [14]. The use and availability of JBK-75 in the wrought powder form provided significant opportunity for additive manufacturing processes to be matured. NASA HR-1 is a material that is an alternative to JBK-75 providing some further advantages for better hydrogen resistance, weldability for an additive process, and high strength. The NASA HR-1 material was derived from the JBK-

75. The Inconel 625, JBK-75, and NASA HR-1 have and are being developed in the blown powder DED process with integral channels. Several materials including Inconel 625, Haynes 230, CRES 347, JBK-75, and NASA HR-1 have all been developed with the LWDC process.

Table 1. Material Selection for CWN.

Material	**Nozzle Use [15,16,17,18,19]**
Alloy 625 or Inconel 625	High strength, easily weldable for non-hydrogen applications
Haynes 230	High temperature and strength, oxidation resistance
SS347	Good hydrogen resistance, lower strength, lower cost
JBK-75	Good hydrogen resistance, lower density, and high strength
NASA HR-1	Excellent hydrogen resistance, high strength, and readily weldable
C-18150	High heat flux application, lower strength-to-weight compared to non-copper

The bimetallic development made use of a copper alloy for the entire or partial length of the inner liner (hotwall). The material selected at the time for development was C-18150 (Cu-Cr-Zr) due to maturity in industry and readily available supply chain for large scale [20]. The closeout material selected for bimetallic LWDC Monel 400. Various alloys, including Inconel 625 and CRES 347 in combination with the C-18150, were attempted using bimetallic LWDC, but they did not exhibit good joining during LWDC process development. 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 [21].

3. Hot-fire Testing and Results

NASA completed several hot-fire test series to evaluate the LWDC and DED regeneratively-cooled nozzles in relevant test conditions. The testing was conducted on a Liquid Oxygen /Gaseous Hydrogen (LOX/GH2) and LOX/Kerosene (LOX/RP-1) thrust chamber assembly (TCA) that used an identical chamber contour and attach area ratio for all programs [22,23,24]. The thrust chamber assembly used a Laser Powder Bed Fusion (L-PBF) additively manufactured shear coaxial injector and L-PBF additive manufactured GRCop-alloy combustion chamber liner, specifically GRCop-84 and GRCop-42 [25]. These nozzles were tested at NASA 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 chamber and nozzles and eventually transitioned to full regenerative cooling using GH2 or RP-1, depending on the test series.

The injector was previously tested and characterized under several similar test programs [26]. The combustion chamber configuration was also previously demonstrated with a slip-jacket chamber liner, allowing for quick change-over of the liners [27]. Each nozzle test unit was bolted to the aft end of the chamber adapter ring. The injector included a center port for a direct spark igniter or TEA-TEB pin, depending on the configuration. The setup can be seen in Fig 12, with the all-additive manufacturing TCA. This configuration allowed for quick hardware changes during test. Depending on the propellants being used, continuous durations of 180 seconds were completed in LOX/GH2 and 60 seconds in LOX/RP-1. Cyclic multi-start testing was also conducted on the LOX/GH2 nozzles with 30 second cycles followed by a 25 second full purge and repeated for a total of 7 starts. This accumulated significant time and allowed for fully reversal strains and cycling of fatigue conditions to challenge the hardware.

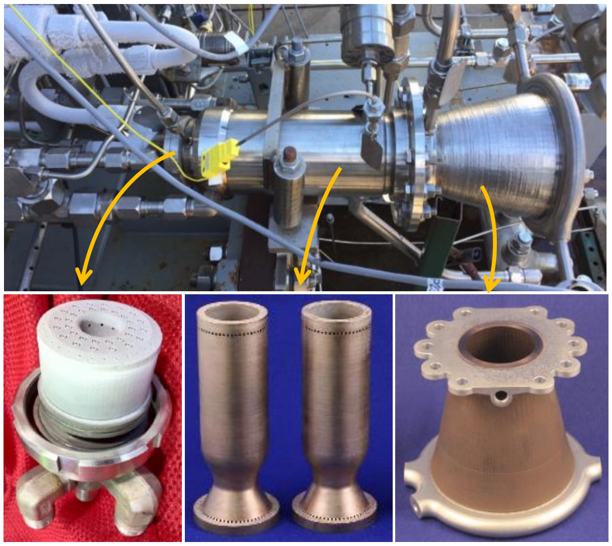

Fig. 12. Thrust Chamber Assembly for LWDC and DED subscale testing. The bottom shows the AM coaxial injector, GRCop-84 liners, and DED nozzle.

A total of nine (9) nozzles were fabricated with a various processes previously described. These nozzle configurations and test statistics can be seen in Table 2.

The LWDC SS347 nozzle was fabricated from a forging and final machined including water jet milled channels. This nozzle was then closed out using LWDC. The Inconel 625 and Haynes 230 liners used an arc-deposition process for the starting material. The Inconel 625 channels was cut using WJM and closed out using LWDC, which the Haynes 230 used traditional machining for the channels and LWDC. A series of bimetallic liners using LWDC were also completed with a C-18150 liner and various direct and intermediate LWDC configurations previously described in prior publications [9]. Two different integral-channel DED nozzles were fabricated and tested. The first nozzle was fabricated from Inconel 625 and used a bifurcated channel design as the diameter increased. This nozzle was initially water-cooled and tested in LOX/GH2 and then later tested with regenerative cooling with RP-1. The second nozzle used a similar design, but was fabricated from JBK-75.

Table 2. Summary of Nozzle Configuration and Accumulated Test Time.

Propellant	Process	Material	Starts	Time (sec)
LOX/GH2	LWDC	SS347	4	160
LOX/GH2	LWDC	Inco 625	10	1060
LOX/GH2	LWDC	Haynes 230	1	180
LOX/GH2	LWDC	C-18150-Inco/Monel	3	540
LOX/GH2	LWDC	C-18150-Monel 400	60	1830
LOX/GH2	LWDC	C-18150-Monel 400	9	1130
LOX/GH2	DED	JBK-75	114	4170
LOX/GH2	DED	Inco 625	1	15
LOX/RP-1	DED	Inco 625	27	1057

The DED subscale nozzles were fabricated in three (3) pieces which included the DED integral channel liner, the forward manifold, and the aft manifold. The subscale nozzles used a design approach to optimize the build process and considered a weight-optimized approach for future applications. The LWDC nozzles also included 3-piece assembly including the liner with LWDC closeout, forward manifold, and aft manifold. The manifolds were all EB welded and interfaces final machined. An image of a bimetallic LWDC nozzle on the stand can be seen in Fig 13.

Fig 13. Bimetallic LWDC nozzle at MSFC TS115.

Several test series were completed to evaluate the channel-cooled nozzles including PH034, PI084-1, PJ024, PI084-2, PI100, and PJ038. Hot-fire testing was completed from December 2017 through June 2019. Cooling with deionized water was completed for each propellant combination to characterize and validate the heat flux curves used for the thermal analysis for each of the nozzles. The first test series, PH034, completed a single hot-fire test on the Inconel 625 DED nozzle and the monolithic LWDC nozzles to show initial feasibility in LOX/GH2. An image from the SS347 nozzle can be seen in Fig 14. Testing with chamber pressures up to 805 psig and mixture ratio to 6.6 was completed in this initial series.

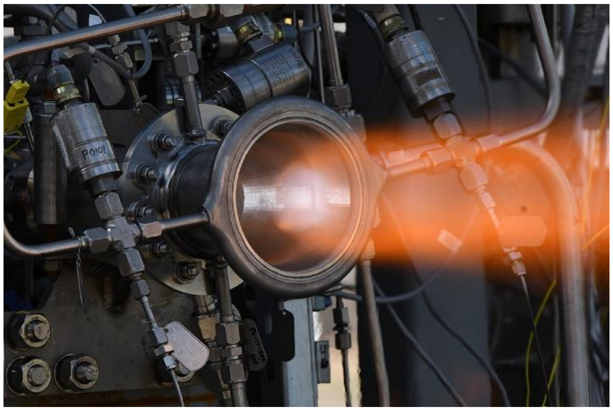

Fig. 14. Monolithic LWDC SS347 nozzle with Water Jet Milled Channels during hot-fire start-up.

Following this test series the Inconel 625 DED nozzle completed more extensive testing in LOX/RP-1. There were several programs with a variety of conditions that this was tested under. It started initial testing under PI084-1 with water-cooling and continued testing under PJ024 and PI084-2. These programs for LOX/RP-1 used an additively manufactured impinging injector and operated at a chamber pressures (Pc) up to 1,240 psig and mixture ratios (MR) of 2.8. Full regenerative-cooling using RP-1 of the DED Inconel 625 nozzle was also completed during these follow-on testing (Fig 15). This test program also incorporated a carbon-fiber composite overwrap combustion chamber under the Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project.

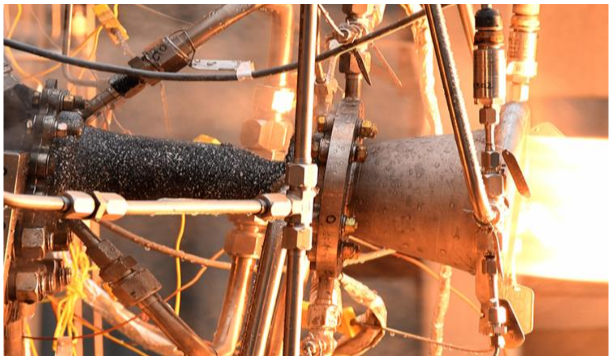

Fig 15. Composite overwrap L-PBF GRCop-84 liner and Inconel 625 DED nozzle.

A later test series was conducted to complete testing on the bimetallic LWDC nozzles and the JBK-75 integral-channel DED nozzle. This test series provided single cycle tests with up to 180 seconds of mainstage duration. Multi-start hot-fire testing that followed completed a series of cyclic tests with up to 7 full hot-fire and purge cycles per test. 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.

For each test conducted, all data was summarized and performance determined for the specific conditions. Post-test analysis predictions were also completed to anchor to actual hardware measurements, including hotwall temperatures and applied stresses. Shown in Fig 16 is an example of the hotwall temperatures for the DED Inconel 625 and JB-75 DED integral-channel nozzles. Wall temperatures for the RP-1 cooled case (shown in blue) reached a peak of ~1,350°F, and for the hydrogen cooled case reached a peak near 1,300°F. The wall temperatures peak near the forward end of the nozzle, where the heat flux is highest. Test conditions were intentionally chosen to provide aggressive wall temperatures in order to include large thermal strains in the coolant passage walls. Testing in this manner demonstrates the capability of nozzles produced in this manner to withstand cyclic loading experienced in regeneratively cooled nozzle applications. Similar data anchoring was completed for all the LWDC nozzles to compare performance.

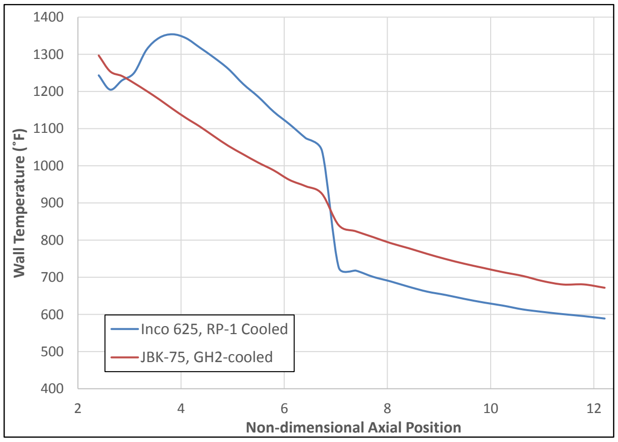

Fig 16. Hotwall temperatures for the integrated channel DED nozzles, Inconel 625 and JBK-75.

NASA completed testing on 9 different channel wall nozzles with a variety of fabrication techniques incorporated. A total of 229 tests were completed on the LWDC and integrated-channel DED nozzles accumulating 10,142 seconds. Specific to the integrated channel DED nozzles, a total of 142 tests and over 5,242 seconds were accumulated. The JBK-75 DED nozzle completed a total of 114 hot-fire tests and 4,170 seconds in LOX/GH2. The Inconel 625 nozzle completed a series of hot-fire tests in LOX/RP-1 and accumulated 28 starts and 1,072 seconds. The respective test series demonstrated chamber pressures exceeding 1,200 psig and high mixture ratios. The nozzles were inspected after each hot-fire tests and remained in good condition and leak-free. The successful tests with no nozzle damage show that the nozzle survived the aggressive thermal loads induced by testing, and demonstrate the value in further pursuing these materials with the DED process for nozzles. The LWDC nozzles also performed well and accumulated 15 starts and 1,400 seconds on the monolithic configurations and 72 starts and 3,500 seconds on the bimetallic configurations. Several lessons learned and design improvements were determined from the test data including reduction in pressure drop for some designs. Overall, the nozzles met most predictions with aggressive test conditions.

4. Current and Future Development

NASA along with industry partners are continuing to mature the advanced manufacturing technologies applied to channel wall nozzles using a variety of techniques. The subscale nozzle hot-fire testing was successfully completed and provided some performance metrics for process improvements to apply these manufacturing techniques to larger scale designs. NASA is currently planning for fabrication and hot-fire testing of mid-scale hardware at approximately 35K-lb_f thrust in LOX/Hydrogen. A series of nozzles using the

LWDC and integrated channel DED process are completing fabrication. Early manufacturing technology demonstrators were completed using similar materials to the subscale nozzles. An Inconel 625 nozzle can be seen in Fig 17. This liner for this nozzle was deposited using the arc-based DED process, final machined, and then channels formed using water jet milling. The nozzle was then closed out using LWDC with Inconel 625. Some additional lessons were learned on the increased scale hardware including sensitivity to the LWDC angles and tooling design. Additional nozzles are in fabrication using JBK-75 and NASA HR-1.

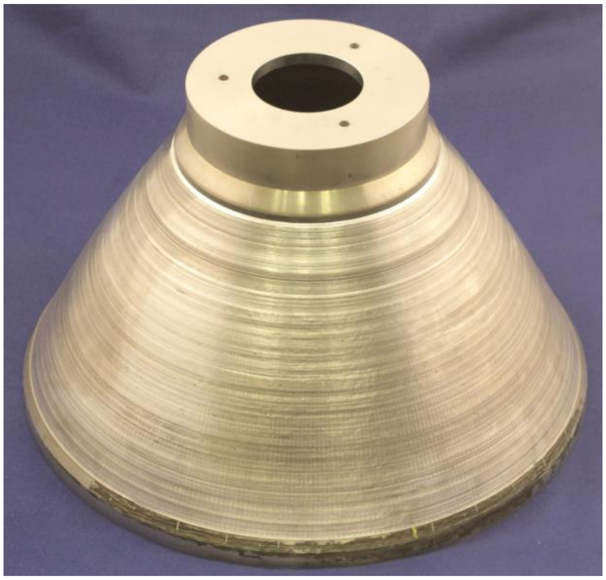

Fig 17. LWDC mid-scale nozzle with Inconel 625 (approx. 23” diameter)

NASA is continuing to advance the blown powder DED technology with increased scale hardware fabrication. A 1/2-scale RS25 liner (~44” diameter and ~48” length) was recently completed using JBK-75 at DM3D (Auburn Hills, MI) without any integral channels. As the scale increased additional lessons were learned about distortion during the build and heat treatment cycles. This 1/2-scale did demonstrate a significant reduction in fabrication time for the liner preform and machining was partially machined (Fig. 18). Additional development is being completed on Non-Destructive Evaluation (NDE) techniques for the large scale hardware in additional to full metallurgical evaluations, material testing, and heat treatment optimization for these new processes and materials. NASA is continuing to scale up these manufacturing techniques

Fig 18. 1/2-Scale RS25 Nozzle Liner fabrication with Blown Powder DED, No channels. (approx. ~44” dia and ~48” tall)

The integral-channel DED nozzles have also significantly progressed with further process development. A series of nozzles were completed at the same 35K-lb$_f$ scale using JBK-75 and NASA HR-1 materials at RPM Innovations (Rapid City, SD). These nozzle designs were completed to advance the capabilities of the DED methods and allowed for new channel designs to be fabricated in a single piece and a significant reduction in fabrication time compared to traditional techniques. NASA is fabricating a series of DED nozzles under the RAMPT project and internal research and development (IRAD) under the Liquid Engines Office to characterize properties of the JBK-75 and NASA HR-1 materials. This includes database development and data dissemination of mechanical and thermophysical properties, heat treatment optimization, build process optimization, and best practices for DED nozzle design, in addition to significant scale-up. An example of a 35K-lbf JBK-75 integral channel nozzle can be seen in Fig. 19.

Fig 19. JBK-75 Integral-channel DED 35K-lb$_f$ nozzle fabricated at RPMI.

5. Conclusions

NASA has completed development on a variety of advanced manufacturing technologies for fabrication of channel-cooled nozzles. These technologies offer the potential to realize cost and schedule improvements over traditional techniques. Fabrication technologies include Laser Wire Direct Closeout (LWDC), for channel closeout and structural jackets, Directed Energy Deposition (DED), specifically Blown Powder DED, for monolithic nozzles with integral channels, and DED Deposition for liners and jacket preforms, such as Arc-based DED and blown powder DED. In addition manufacturing technologies to support these techniques include Water Jet Milling for channel forming, and Explosive Bonding for coolant channel closeout and structural jackets, and bimetallic transitions. NASA has completed process development with samples and subscale hardware, material characterization, and hot-fire testing on a variety of these nozzle fabrication techniques.

NASA completed fabrication of two (9) different subscale nozzles using the LWDC and integrated-channel additive manufacturing DED process. These subscale nozzles were designed to be tested in Liquid Oxygen/Hydrogen (LOX/GH2) and LOX/Kerosene (LOX/RP-1) environments. Hot-fire testing was completed from December 2017 through June 2019. A total of 229 tests were completed on the LWDC and integrated-channel DED nozzles accumulating 10,142 seconds. Cooling with water was completed for each propellant combination to characterize and validate the heat flux curves used for the thermal analysis for each of the nozzles, followed by regenerative cooling with the respective propellants. Wall temperatures were modeled for the tested conditions.

Specific to the integrated channel DED nozzles, a total of 142 tests and over 5,242 seconds were accumulated. The initial materials that were evaluated during this testing were high-strength nickel-based Inconel 625 and JBK-75. The JBK-75 DED nozzle completed a total of 114 hot-fire tests and 4,170 seconds in LOX/GH2. The Inconel 625 nozzle completed a series of hot-fire tests in LOX/RP-1 and accumulated 28 starts and 1,072 seconds. The respective test series demonstrated chamber pressures exceeding 1,200 psig and high mixture ratios. The nozzles were inspected after each hot-fire tests and remained in good condition and leak-free. The successful tests with no nozzle damage show that the nozzle survived the aggressive thermal loads induced by testing, and demonstrate the value in further pursuing these materials with the DED process for nozzles.

Process development, manufacture, and hot-fire testing were completed on nozzles utilizing LWCD. The LWDC technique was used to close out coolant passages without filler material in the channels while reducing the tolerances needed for traditional closeout and jacketing techniques. This technique also creates the structural jacket at the same time the coolant passages were closed out. Monolithic and Bimetallic channel wall nozzles were fabricated with various techniques and tested. A total of 1,400 seconds and 15 starts were accumulated on LWDC monolithic nozzles using Inconel 625, Haynes 230, and SS347. Bimetallic LWDC nozzles also completed testing using a Copper-alloy C-18150 liner with Monel 400 closeout and accumulated 72 starts and 3,500 seconds.

The LWDC process and DED integral-channel process have been shown to be feasible as demonstrated during development testing. A series of larger LWDC nozzles focused on JBK-75, Haynes 230, and NASA HR-1 are being fabricated and will be hot-fire tested in the future. Significant development work continues on the DED integral-channel technique in NASA's Game Changing Development (GCD) Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project. This actively-funded project aims to significantly increase scale for DED CWN, significantly reduce cost, and improve performance for regeneratively-cooled thrust chamber assemblies, specifically the combustion chamber and nozzle for government and industry programs. The process development work detailed here will be carried into RAMPT and transferred to the NASA HR-1 alloy from the initial JBK-75 work in order to develop regen-cooled channel wall nozzle structures at large scale. Additional scale-up and process development is also being pursued under technology development for the Liquid Engines Office to demonstrate channel-cooled nozzles with the JBK-75 material.

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