Channel Wall Nozzle Manufacturing and Hot-Fire Testing using a Laser Wire Direct Closeout Technique for Liquid Rocket Engines

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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 National Aeronautics and Space Administration (NASA) has been investigating and advancing methods for fabrication of liquid rocket engine channel wall nozzles to realize further cost and schedule improvements over traditional techniques. The methods being evaluated are targeting increased scale required for current NASA and commercial space programs. Several advanced rapid fabrication methods are being investigated for forming of the inner liner, producing the coolant channels, closeout of the coolant channels, and fabrication of the manifolds. NASA's Marshall Space Flight Center (MSFC) has completed process development and subscale hot-fire testing of a series of these advanced fabrication channel wall nozzle technologies to gather performance data in a relevant environment. The primary fabrication technique being discussed in this paper is Laser Wire Direct Closeout (LWDC). This process has been developed to significantly reduce the time required for closeouts of regeneratively-cooled slotted liners. It allows for channel closeout to be formed in place in addition to the structural jacket without the need for channel fillers or complex tooling. Additional technologies were also tested as part of this program including water jet milling and arc-based additive manufacturing deposition. Each nozzle included different fabrication features, materials, and methods to demonstrate durability in a hot-fire environment. The results of design, fabrication, and hot-fire testing are discussed in this paper.

Nomenclature

AM	=	Additive Manufacturing
CWN	=	Channel Wall Nozzle
DED	=	Directed Energy Deposition
EB	=	Electron Beam Welding
GH2	=	Gaseous hydrogen
GRCop-84	=	NASA GRC Copper-alloy (Cu-Cr-Nb)
ID	=	Internal Diameter
IPD	=	Integrated Powerhead Demonstrator
K-lb_f	=	thousand pound-force (thrust)
LCUSP	=	Low Cost Upper Stage Propulsion
LOX	=	Liquid Oxygen
LWDC	=	Laser Wire Direct Closeout
MDDM	=	Metal Direct Digital Manufacturing
MIG	=	Metal Inert Gas Arc-welding
MSFC	=	Marshall Space Flight Center
MTD	=	Manufacturing Technology Demonstrator
Pc	=	Chamber Pressure (psig)
psi	=	Pounds Per Square Inch

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Regen	=	Regeneratively-cooled nozzle
SLM	=	Selective Laser Melting
SSME	=	Space Shuttle Main Engine
TCA	=	Thrust Chamber Assembly
TRL	=	Technology Readiness Level
WJM	=	Water Jet Milling

I. Introduction

Regeneratively-cooled (regen) nozzles are a critical component of a liquid rocket engine to allow optimal expansion of the hot-gas and increase temperature of the propellants for 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. Fabrication methods for regen nozzles have focused on tube-wall manufacturing methods and channel wall manufacturing techniques[1]. In a tube-wall configuration the coolant from the manifolds is routed through a series of individual coolant tubes, which are brazed or joined together. A channel wall nozzle uses an internal liner with machined coolant passages that are closed-out using a variety of fabrication techniques. Compared to tube wall designs, channel wall nozzles offer cost and schedule savings due to fewer manufacturing steps and less manual labor[2].

Figure 1 illustrates the design of a section of a channel wall nozzle that incorporates integral coolant channels, within an internal liner. 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.

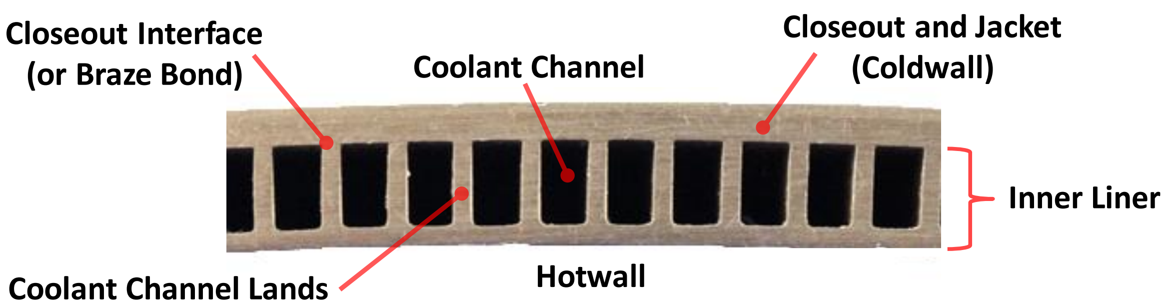

Figure 1. Configuration of a Channel Wall Nozzle.

Although a few variations on the design of a channel wall nozzle exist and are continuing to be developed, the generic fabrication sequence can be broken down into four process categories:

1) Fabrication of the Internal Hot Gas Wall Liner
2) Machining the Coolant Channels/Passages into the liner
3) Closeout of the Coolant Channels integral to the liner
4) Fabrication and bonding of the manifolds

Several methods for fabrication of channel wall nozzles have been evaluated since the 1950's. Most of these fabrication methods focus on the closeout of the coolant channels. The most common method for channel closeout involves brazing an external closeout structural jacket to an internal liner that includes machined or slotted coolant channels. A braze foil or alternate braze alloy application method is applied between the two mating surfaces. Proper material selection, braze alloys and preparation, and a tightly controlled atmosphere, including temperature profiles and pressures for brazing within the furnace, must be maintained for a brazed channel wall nozzle to be successful. Russian technology used this method for most of their engines and applied a pressure-assisted brazing process to ensure a reliable closeout joint[3,4]. This method has also been applied domestically for fabrication of the Space Shuttle Main Engine (SSME) manufacturing technology demonstrator (MTD) 33:1 nozzle in the early 2000's, the Cobra engine program in late 1990's, the Integrated Powerhead Demonstrator (IPD) nozzle in the early 2000's, and flight nozzles for commercial space companies.[5,6,7,8] While brazing has been applied successfully, it requires very tight tolerances for braze gaps, highly specialized tooling, and challenging inspections to evaluate success or failure. Even with all the attention to tooling, tolerances and inspections during the process, brazes are not always 100% successful and voids or debonds are often accepted[9].

A more modern technique for channel wall nozzle fabrication is the sandwich wall nozzle technology developed and fabricated by GKN (formally Volvo). The GKN sandwich wall technology uses laser welding to bond a thin sheet-metal jacket to a machined slotted inner liner that starts as a conical shape. The thin closeout jacket is tightly fit against the inner liner, and X-Ray seam tracker inspection is used to track each one of the channel lands, which is followed by the laser beam to penetrate through the outer jacket, creating a bond at the jacket and underlying land (or rib). An additional X-Ray tracker is used to inspect the joint along the land as it is welded. This is completed for each one of the lands providing 100% coverage. The entire assembly is then formed using an inner mold line (IML) expansion die to form the desired contour. The manifolds and structural support stiffeners are then applied using wire-based additive manufacturing (AM) techniques[10]. GKN has completed hot-fire testing of a full-scale nozzle assembly and certification of the technology for future use on the Ariane 6 [11,12,13].

While AM techniques using Selective Laser Melting (SLM) are providing significant advantages for component fabrication, this technology is still very limited in scale. The current state of the art build volume for SLM is the Concept Laser XLINE at 600mm X 400mm X 500mm, which still limits the scale of nozzles that can be fabricated. Although new SLM machines such as the GE Atlas is being introduced with a 1-meter x 1-meter build platform, it still does not meet the scale for regen-nozzles. NASA has completed development of hot-fire testing on an Inconel nozzle that was fabricated using SLM, but limited to the 400mm (15.7") diameter under the Low Cost Upper Stage Propulsion (LCUSP) project[14]. NASA's Marshall Space Flight Center (MSFC) has investigated the use of assembled SLM panels to fabricate an entire nozzle, but the concept introduces several joints with tolerance complexities, opportunities for leakage, and is still not practical for the large nozzle structures.

Nozzle designs are continually being stretched to deliver additional performance to the liquid rocket engine which drives the increase in size, 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 with the ability to 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 attachment of manifolds
- Increased system performance through nozzle weight reduction or hydraulic performance

To address many of these design challenges MSFC has been evaluating modern manufacturing techniques focused on reduced tooling, inspections, and maturing these new technologies for their application to channel wall nozzles. The advanced manufacturing development efforts for nozzles started around 2012. 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 nozzles. The goal of this development is to demonstrate feasibility - relative to basic material properties and operability within the nozzle environment - and to enable a domestic supply chain for the benefit of government and commercial companies. Several of these techniques were discussed in further detail in prior MSFC research under Ref. 15.

The primary objective of this recent nozzle development and hot-fire testing program was to fabricate subscale channel-cooled nozzle hardware and complete testing in a relevant environment. Using the capabilities at MSFC's Test Stand 115, a variety of subscale nozzles could be hot-fire tested at various conditions, and nozzle change-outs could be accommodated quickly. The tests were all conducted with Liquid Oxygen (LOX)/Gaseous Hydrogen (GH2). An overview of the manufacturing techniques is provided, followed by the nozzle design and approach using each of these manufacturing techniques. Finally, the hot-fire testing and results will be described on the two nozzles fabricated with these new manufacturing techniques.

MSFC has been investigating alternate fabrication techniques for forming the liner, creating the coolant channels and closeout of the coolant channels. Hot-fire testing of two of these advanced fabrication channel wall nozzle technologies was performed to gather performance data in a relevant environment. The method used for the channel closeout fabrication was an additive-based Laser Wire Direct Closeout (LWDC). Additional technologies also being tested as part of this program included water jet milling and arc-based additive manufacturing deposition. Each nozzle included different fabrication features and methods to demonstrate durability in a hot-fire environment.

II. Fabrication Techniques

Although varying methods exists to fabricate channel wall nozzles, there are generally four major steps required to fabricate, closeout the coolant channels and completion of the channel wall nozzle. These include forming the internal liner, producing or machining the coolant channels, closeout of the coolant channels, and incorporating manifolds to complete the entire coolant circuit[14]. Typical fabrication of channel wall technology incorporates an inner liner that is formed from a spin forging or from a series of welded and machine forgings. This inner liner is machined using a slotting or milling operation to remove material to produce the channels on the outer surface of the inner liner. A closeout operation is then completed to contain the fluid under high pressure within each of the coolant channels. Traditional techniques for the closeout include pressure-assisted brazing of a closeout jacket or laser welding a closeout shell. After this process is successfully completed, the manifolds can be welded or brazed to allow distribution of the coolant to each of the channels.

While a variety of fabrication techniques are being evaluated, MSFC focused on three of these techniques for this development and test project. Other advanced manufacturing techniques have been covered in prior papers including Ref. 16 and 17. Many of these technologies are focused on large scale AM using various deposition techniques. Each technique has limitations that requires considerations within the design. The technologies that will be further discussed are:

1. Laser Wire Direct Closeout (LWDC), for channel closeout and structural jackets
2. Arc-based deposition additive manufacturing, for liner and jacket preforms
3. Water Jet Milling, for channel forming

A. Laser Wire Direct Closeout (LWDC)

The Laser Wire Direct Closeout (LWDC) technology was developed by MSFC and industry partners, Keystone Synergistic Enterprises and Laser Technology Associates. The process deposits wire to bridge the coolant channels without the need for any filler within the channels. An independent wire feed and offset inert gas-purged laser beam melts wire in an area of stock prior to coolant channels. While the nozzle is rotated about the center axis, the wire is deposited onto the previous layer with a minor amount of laser energy being used to fuse the wire to the backside of the channel lands. This process is repeated along the wall of the nozzle at continuously varying angles until the required area is closed out[18]. LWDC is used for the direct closeout of the coolant channels and application of the structural jacket. LWDC is an AM wire-fed laser deposition process that eliminates the need for a tight tolerance structural jacket and plating operations. A small diameter wire is generally 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 stock prior to the axial region of the coolant channel. This provides a starting "step" for the full channel closeouts. 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 and rotated about a center axis. A majority of the laser energy is focused (spot size) on the previous "step" of material while the remaining energy is focused on the channel land. This allows the material to penetrate into previous layer while material is also bonded to the lands without burning through the lands or material dropping into the channels. An example of the LWDC process can be seen in Fig. 2. 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 is generally used.

The primary advantage of the LWDC process is the jacket and channel closeout are integrally formed, so tolerances are much more liberal 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 slower compared to the MDDM process; a comparison of deposition rates is shown in Ref. 16. However, this time is offset by the elimination of a closeout jacket and subsequent bonding operations.

Significant process developments have been completed using this closeout technique on a variety of material combinations and geometric configurations, including 300 series stainless steel, Inconel 625, Haynes 230, and Copper-Inconel bimetallic[19]. These improvements have enabled minimal material to be consumed on the backside, minimal to no distortion to the liner, closeout of various channel widths and land widths, and high margins on closeout bond strength. The LWDC process has also been improved to automate and increase speed of the closeout process. Since the laser head and wire feed system are integrated onto a robot or gantry system, the scale is not limited.

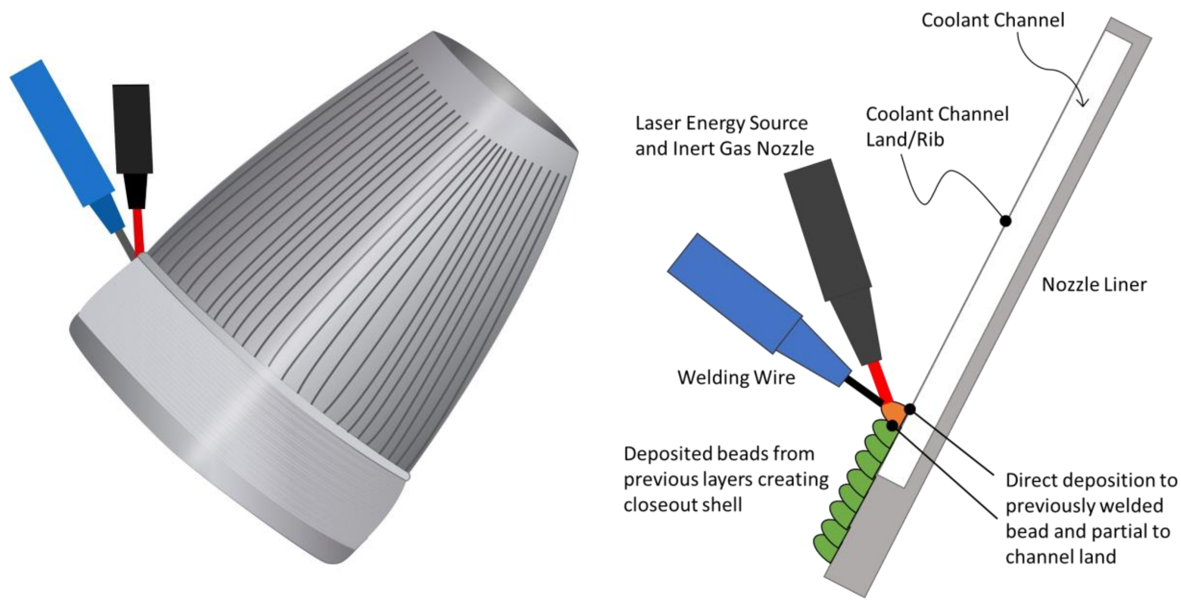

Figure 2. Overview of Laser Wire Direct Closeout method for freeform closeout of channels.

The primary consideration for design using the LWDC process is the channel widths and lands thicknesses. Since the process bridges the channels, an increase in channel width increases the chances of slump into the channel. A channel land that is too thin can be consumed during deposition. A local purge is also used and overall tooling minimized to an internal diameter (ID) mandrel.

B. Arc-based Liner Deposition

Arc-based AM is a directed energy deposition (DED) technology that uses a pulsed-wire metal inert gas (MIG) welding process to create near net shape components. The DED 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 course features on the order of 0.15”+ are typical of this type of deposition. An example of the deposition process can be seen in Fig. 3.

The pulsed-arc deposition process provides some advantages with high material deposition rates (20+ lbs/hour) and also interim cleaning for surface oxides. The wire is pulsed to aid with cleaning of oxides, alternating pulses with deposition of metal droplets. The voltage can also be varied real-time to further produce a uniform and clean deposition (weld). The preform components, such as the nozzle liner, are fabricated in several passes with varying offsets within each pass as height is built to eliminate lack of fusion defects. A build strategy is developed that optimizes density of material, mechanical properties, and designed to meet part dimensions. A build plate is used for the base of the part to allow a ground.

The pulsed-arc process does introduce significant heat into the part during the build so proper stock must be added to allow for distortion or shrinkage during processing. A stress relief process is often necessary after the build, along with other thermal processing to help improve grain structure and associated properties. Keystone Synergistic Enterprises has completed the continued development of the arc-based deposition with their Metal Direct Digital Manufacturing (MDDM) that uses integral sensors to continuously control and monitor the process.

MSFC has been working with Keystone to continuously increase the scale of the process, improve deposition strategies, and obtain material properties for design. Materials that have been demonstrated with this process for liners as of the writing of this paper are Inconel 625 and Haynes 230. Deposition strategies allow for staggered start and stop beads as the height increases, eliminating a continuous seam at any one circumferential location. Distortion control is also considered. A nozzle liner designed for the MDDM process should consider sufficient stock to allow for full final machining cleanup and also consider tooling, which can be fabricated integral to the nozzle liner. An example of increased-scale liners being fabricated in Inconel 625 and Haynes 230 are shown in Fig. 4.

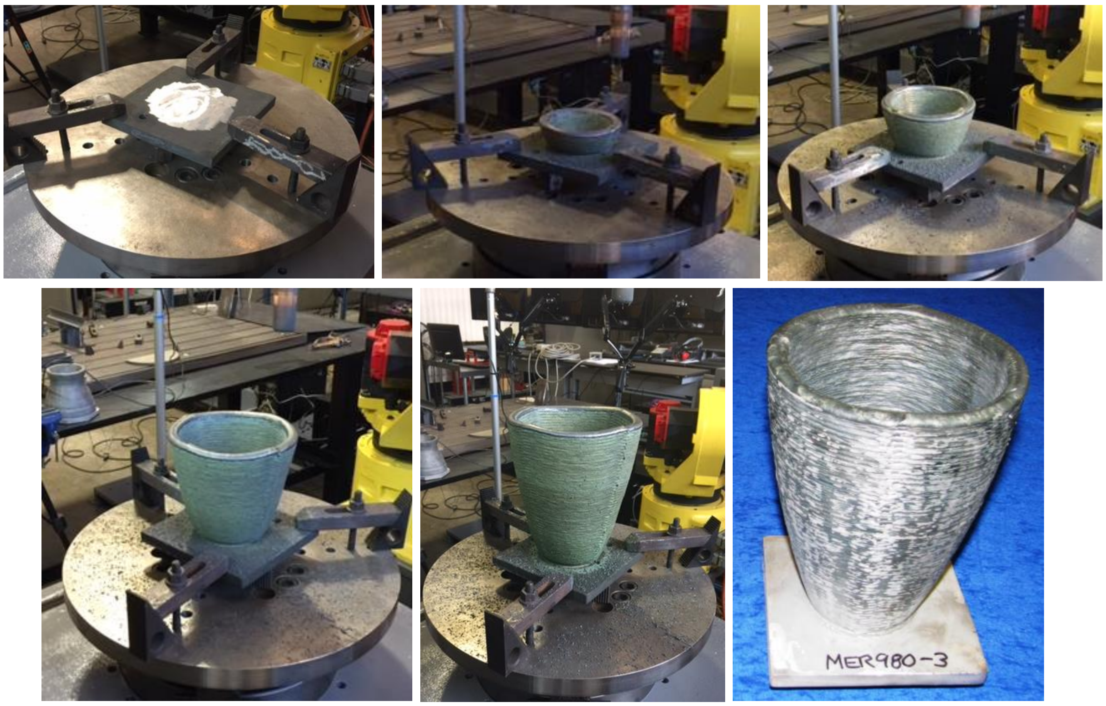

Figure 3. Arc-based Deposition Process for Subscale Nozzle Liner Fabrication.

Figure 4. Nozzle Liner with Arc-based MDDM: A. In-process & B. Prior to heat treat/ final machining.

C. Water Jet Milled Coolant Channels

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 at the hot wall, replicating the traditional slotting process to maximize hotwall cooling. These process developments also improved repeatability of the channel depth to maintain a tolerance of +/-0.002" at the hotwall.

A traditionally slotted liner will generally create movement of the material into the hotwall as the material thins based on tool loads from slotting. WJM is a low load process and eliminates this deformation of the hotwall. This can be observed in Fig. 4. In this example, the hotwall of the traditionally slotted liner was 25% thicker and still experienced this local yielding. An example of the recent WJM channel developments can also be seen in the Fig. 5.

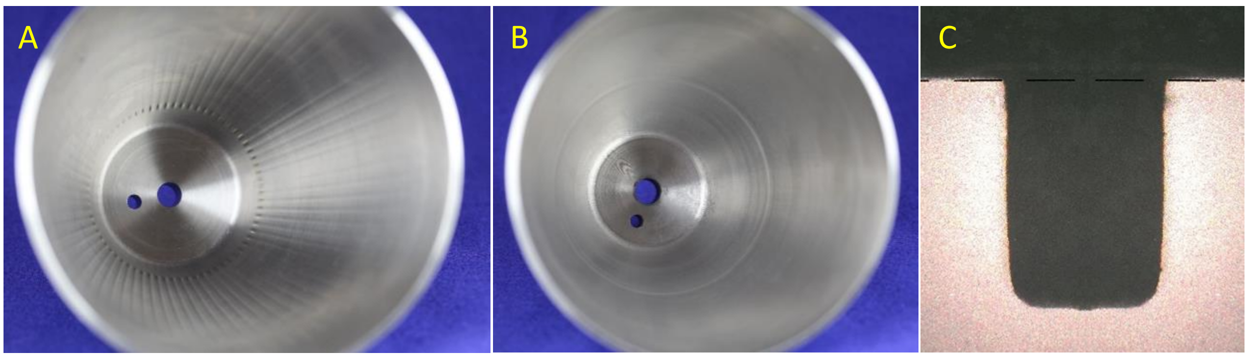

Figure 5. A. Traditionally Machined-Slotted Liner with Deformed Hotwall, B. Water Jet Milled Liner with 25% thinner hotwall than Machined but no Deformation, C. Example of Water Jet Milled Channel.

The component specific tooling is very minimal for water jet milling since minor loads are induced into the part. A mandrel is not required when water jet milling the channels allowing for full access to the hotwall to allow for interim inspections as the part is being milled. Channels are water jet milled to partial depth so interim inspections can be performed prior to full depth, and process adjustments can be made if required. An integrated ultrasonic hotwall inspection technique has been developed as part of the process to determine interim and final hotwall thickness.

There are a few design considerations using the water jet milling process. Channel width and depth can be varied but a single abrasive water jet nozzle is generally used. This requires multiple passes to achieve a varying width along the length of the nozzle. This is akin to an end mill for channel slotting if full width is not accomplished in a single pass. A small radius can be achieved at the bottom of the channel (adjacent to the hotwall) and channels can be squared similar to slotting techniques for channel wall nozzles. There is also some abrasion of the radii leading into the channel that should be accounted for. Surface finish is another consideration. A series of surface roughness measurements were completed and although higher than traditionally machined, values still allow for an acceptable design condition.

III. Fabrication and Hot-fire Testing of Nozzles

A. Nozzle Fabrication Overview

MSFC completed hot-fire testing of a series of these advanced fabrication channel wall nozzle technologies to gather performance data in a relevant environment[20]. Several nozzles were tested, but the focus of this paper will discuss the design and hot-fire testing consisting of the LWDC and associated fabrication technologies described above. Each nozzle included different design features based on fabrication requirements and methods to demonstrate durability in a hot-fire environment.

The nozzles were designed to be water-cooled, but hydrogen cooling could be considered in future test programs. The injector was supplied with LOX/GH2. Each nozzle included common inlet and outlet facility interfaces. An overview of the general nozzle design is provided, which is followed by more details on some unique features for each. The configuration for the nozzles is summarized in Table 1.

The nozzles used very similar fabrication flow processes. The primary differences between the LWDC nozzles tested was the liner: Nozzle #1 used a Stainless 347 forged liner, while Nozzle #2 used an arc-based MDDM liner preform. The overall process flow for Nozzle #2 can be seen in Fig. 6.

The liner was deposited using Inconel 625 MDDM process and an alternating layer deposition strategy as seen in Fig. 7. Following deposition of the liner, a stress relief heat treatment was completed. Final machining of the liner was completed on a lathe and then sent for water jet milling.

Table 1. Configuration of Regen-Cooled Channel Wall Nozzles for PH034.

	Nozzle Unit #1	Nozzle Unit #2
Liner Fabrication Technique	Forged	Arc-based MDDM Additive
Liner Material	CRES 347	Inconel 625
Channel Forming	Water Jet Milling	Water Jet Milling
Closeout Technique	LWDC	LWDC
Closeout Material	CRES 347 Wire	Inconel 625 Wire

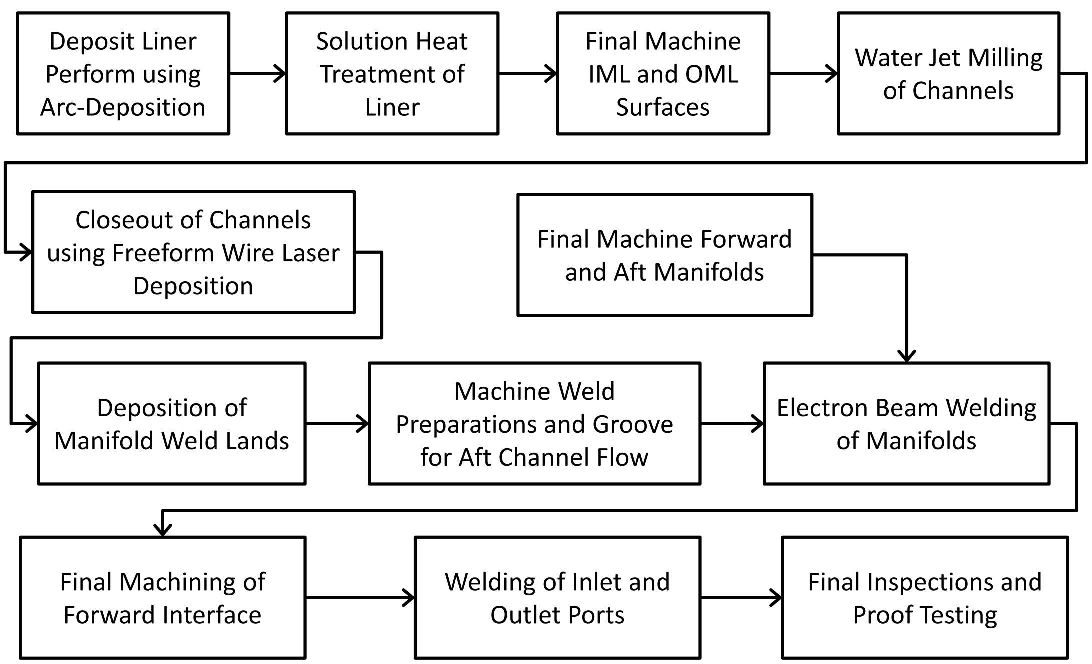

Figure 6. Manufacturing Process Flow for Nozzle #2, Inco 625 LWDC.

Figure 7. Nozzle #2 Arc-deposition Build-up of Liner Shown with Setup Hardware.

The liner was closed-out using the LWDC technique with Inconel 625 wire. The thickness and groove maintained during closeout was very similar to nozzle #1. The manifold lands were also deposited using laser wire with Inconel 625 and then final machined to mate with the manifolds and complete the EB welding. The liner did not complete any additional stress relief or solution to heat treat the material following the deposition closeout and EB welding. The liner was then proof tested over 1,800 psig and held for 30 seconds. No leaks were observed.

Images of the completed nozzle #1 and #2 are provided in Fig. 8. An overview of nozzle #2 interim fabrication steps can be seen in Fig. 9.

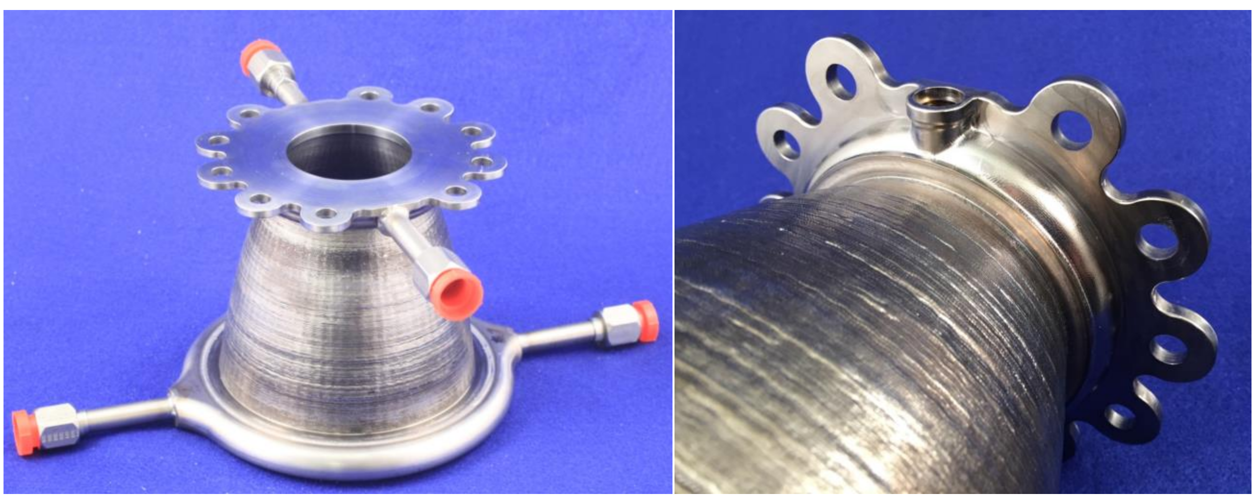

Figure 8. Nozzle #1 and Nozzle #2 prior to hot-fire.

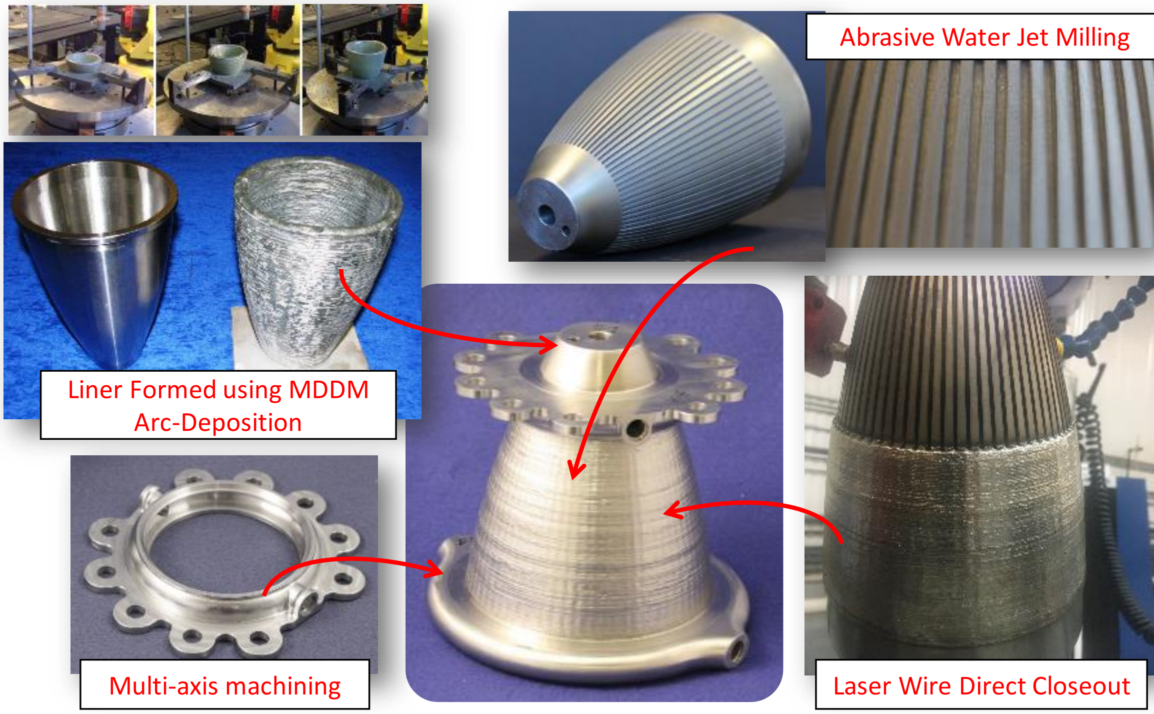

Figure 9. Overview of Nozzle #2 Interim Fabrication Images.

B. Thrust Chamber Assembly

The thrust chamber assembly (TCA) used for this program was similar to that used in previous uncooled Carbon-Carbon nozzle testing. The SLM coaxial injector was threaded on to the water cooled workhorse chamber assembly. The chamber assembly used a stainless 304 housing around an SLM GRCop-84 liner[21,22]. The chamber's coolant channels were printed into the structure, so that no channel closeout was necessary. Each nozzle unit was bolted to the aft end of the chamber ring. The injector included a center port for the direct spark ignition. Fig. 10 shows one of the assemblies installed at MSFC Test Stand 115.

C. Hot-fire Test Results

Hot-fire testing was performed in November 2017. Tests conditions were similar for each nozzle, but mixture ratio and coolant flow rates were varied. Thirteen (13) tests were performed on the LWDC nozzles with durations up to 160 seconds of mainstage. Table 2 provides a summary of the nozzle test time and starts, while Fig. 11 provides images taken during hot-fire testing.

Table 2. Accumulated time and starts on LWDC nozzles.

Nozzle Identifier	Starts	Accumulated Time (seconds)
Nozzle #1 - SS347 LWDC	4	160
Nozzle #1 - Inco 625 Fully AM LWDC	9	880

Chamber pressures, Pc's, ranged from 750-800 psig and mixture ratios ranged from 5.5 to 6.7. Nozzle #1 remained in excellent condition during the test series and no anomalies were noted. Visible radiation could be observed at the forward end of the nozzle during testing (Fig. 11). There was little indication of the Stainless 347 bluing during its tests. The nozzle was cycled at Pc up to 720 psig and mixture ratios up to 6.06. Post-test inspections revealed no issues with the nozzle and performance was as-expected.

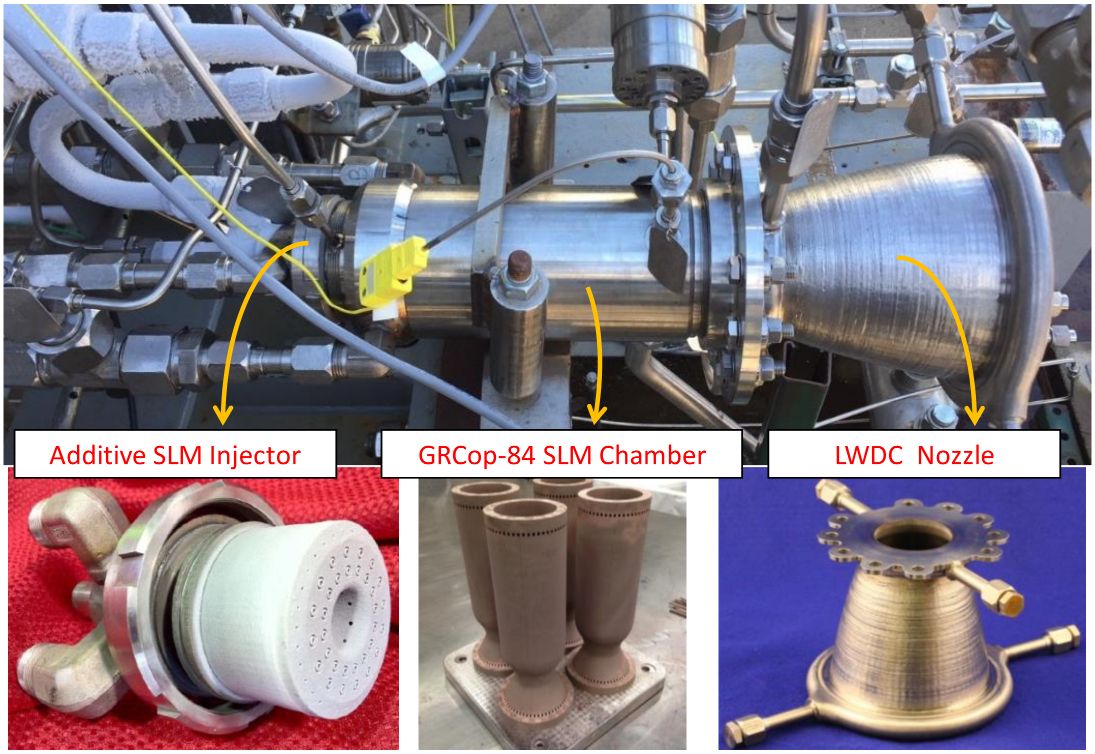

Figure 10. Thrust Chamber Assembly with LWDC Nozzle #1 Installed at MSFC Test Stand 115.

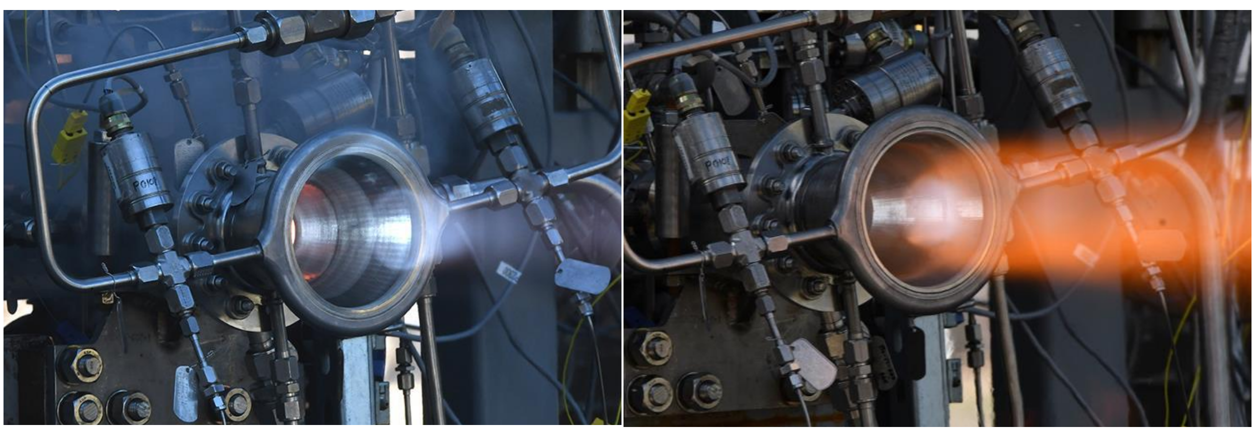

Figure 11. (Left) Mainstage hot-fire testing of SS347 Nozzle #1, (Right) Startup transient image from Inco 625 Nozzle #2.

Nozzle #2 accumulated 880 seconds of hot-fire time over 9 tests. The nozzle remained in excellent condition during the test series and no anomalies were noted. The nozzle was cycled by varying Pc from 723 to 805 psig and MR's ranged from 5.98 to 6.67. Minor discoloration was noted during the test series, but the hotwall and overall nozzle remained in excellent condition. As Pc and MR were increased, there was an increase in bluing at the forward end of the nozzle. There was also a slight tint to some acreage of the nozzle.

The coolant flowrate was reduced by 45% during the test series to allow for continued cycling of the nozzles. The pressure drops met all predictions for the water jet milled channels, and Nozzle #1 and Nozzle #2 showed identical pressure drops, demonstrating repeatability within the process.

IV. Conclusions and Future Work

Hot-fire testing in this program allowed for new channel wall nozzle manufacturing technology to be proven in a relevant environment. The testing was low cost and allowed for significant data and visual information to be collected quickly. A series of chamber pressure and mixture ratio variations were completed while lowering the coolant flow rate on the nozzles to continuously challenge the new manufacturing techniques. Significant data was obtain during this testing and demonstrated a new manufacturing technique that is feasible for fabricating nozzle liners, creating coolant channels, and closeout of the coolant channels. This data is being used to proceed with scale-up of the technology.

Nozzle #1 using LWDC in Stainless 347 accumulated 180 seconds and 4 starts. The hardware remained in excellence condition post-test and the manufacturing technologies performed as expected. Nozzle #2 using the laser wire direct closeout in Inconel 625 and arc-deposition liner accumulated 880 seconds and 9 starts. A total of 13 starts and 1,040 seconds have been accumulated on the LWDC manufacturing technology. The arc-deposited liner demonstrates a new process for large scale fabrication of high temperature thin-walled components such as the liner and a potential replacement for forgings or spin formed liners.

The LWDC process – evaluated with manufacturing technology demonstrators, a series of lab testing, and now subscale hot-fire testing – has successfully increased the corresponding technology readiness level (TRL) for channel closeouts. This technique does not require the use of filler material within the channels and allows the channels and structural jacket to be formed in a single operation. Time for fabrication shows significant advantages over prior techniques.

The 3D printed injector used in this program was one of the original units fabricated and hot-fire tested at MSFC. With the testing performed in this program, along with its previous testing, the injector has accumulated >7,200 seconds of hot-fire testing and remains in excellent condition. The SLM GRCop-84 liner was fabricated by ASRC Federal Astronautics and accumulated a total of 1,055 seconds and 14 starts. The liner showed no indication of blanching, erosion, or bluing and performed well. Due to the improved surface finish available with this liner, it provided significantly reduced pressure drop compared to previous SLM GRCop-84 liners.[22]

These rapid fabrication manufacturing technologies for channel wall nozzles demonstrated that subscale nozzles could be fabricated, and the new processes could produce materials capable of surviving and meeting performance in a relevant hot-fire environment. These techniques are being pursued at a larger scale and further developed for material properties. The arc-deposition, LWDC, and water jet milling and now being considered across industry for use in channel wall nozzles. NASA will continue to pursue development of these techniques and make further data available for industry use.

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