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Channel Wall Nozzle Manufacturing and Hot-Fire Testing using a Laser Wire Deposition 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. NASA has been investigating and advancing methods for fabrication of liquid rocket engine channel wall nozzles to realize further cost and schedule improvements. 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 Marshall Space Flight Center (MSFC) 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 Deposition Closeout (LWDC). This process has been developed to significantly reduce 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 performance is discussed in this paper.

I. Introduction

Nozzles must withstand the extreme temperature and pressure environments in which liquid rocket engines operate to provide expansion of the hot gas generating thrust for the vehicle. Regenerative-cooling is method employed to properly cool the walls of the nozzle to adequately survive the extreme environment and operate within the structural capabilities of the material. A modern method of fabrication employed for a regen-cooled nozzle is channel wall nozzle manufacturing as opposed to a more traditional tube-wall fabrication method.

Although varying methods exists to fabricate channel wall nozzles, there are four major steps required to fabricate and closeout the coolant channels. 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. 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.

NASA has been investigating alternate fabrication techniques for forming the liner, creating the coolant channels and closeout of the coolant channels. An alternate large-scale additive manufacturing process combines all of these processes into significantly reduced operations that forms the channels, closeout, and manifolds lands in the same operation. In test program, PH034, MSFC completed hot-fire testing of a series of these advanced fabrication channel wall nozzle technologies to gather performance data in a relevant environment. A total of two (2) nozzles completed hot-fire testing consisting of two (2) different configurations and material combinations. The method used for the channel closeout fabrication was an additive-based Laser Wire Deposition Closeout (LWDC). Additional technologies also being tested as part of this program include 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.

The main objective of this test program was to fabricate a series of nozzles utilizing new manufacturing technologies for regen-cooled nozzles. These techniques have been in development since 2012 specific to nozzles, while the core technology extends back further for other applications. A brief description of each of the techniques being evaluated includes the following:

1. Water Jet Milling
2. Laser Freeform Deposition Closeout
3. Arc-based Preform Additive Manufacturing

A. Water Jet Milling

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. A small radius at the bottom of the channel as a result of this process. These process developments also improved repeatability of the channel depth to maintain a tolerance of +/-0.002" of the hotwall.

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. 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.

B. Laser Wire Deposition Closeout

A wire-based laser deposition process has been developed to close out the coolant channels called Laser Wire Deposition Closeout (LWDC). 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.

The nozzle is placed on an internal mandrel as the fixture, but also provides some heat sync since the deposition closeout of wire is completed in thin areas of the nozzle. Overheating can cause deformation of the liner wall or potential blow-through of the hotwall. The primary advantage of the LWDC process is the jacket and channel closeout are formed integrally, 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. The elimination of channel fillers during the process also reduced post-processing time. The process does use small wire for deposition to control heat input into the part and can only deposit 10's of inches per hour. 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. These improvements have enabled minimal material to be consumed on the backside, minimal 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.

C. Arc-based Additive Manufacturing Preform Deposition [or Metal Direct Digital Manufacturing (MDDM)]

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 such 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.

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 at a frequency of XX hz with alternating pulses to clean oxides and deposit 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 wide and varying offsets within pass as height is built to reduce porosity. A build strategy is developed that optimizes density of material and optimizes mechanical properties. 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 is often necessary after the build and other thermal processing to help improve grain structure and associated properties.

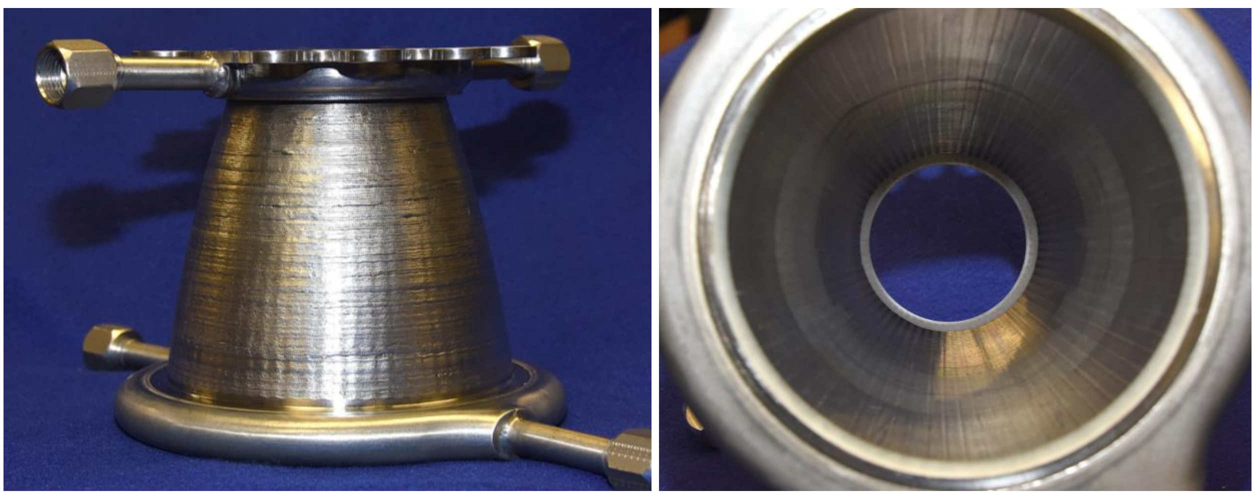

Figure 1. Nozzle #2, Inco 625 Fabrication and Closeout.

HOT-FIRE TESTING

Two nozzles completed hot-fire testing using the laser wire deposition closeout technique. The general process for fabrication of these nozzles is shown in the Figure below.

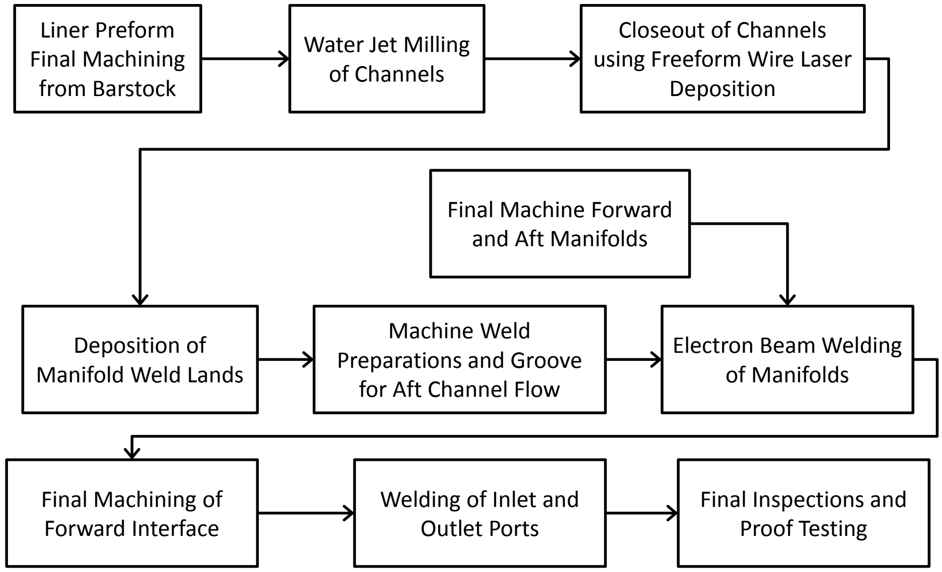

Figure 2. Process Fabrication Flow for Nozzle #1 during hot-fire testing using the Laser Wire Deposition Closeout.

Hot-fire testing was completed in November 2017 accumulating a total of 1,040 seconds and 13 starts on the two nozzles.

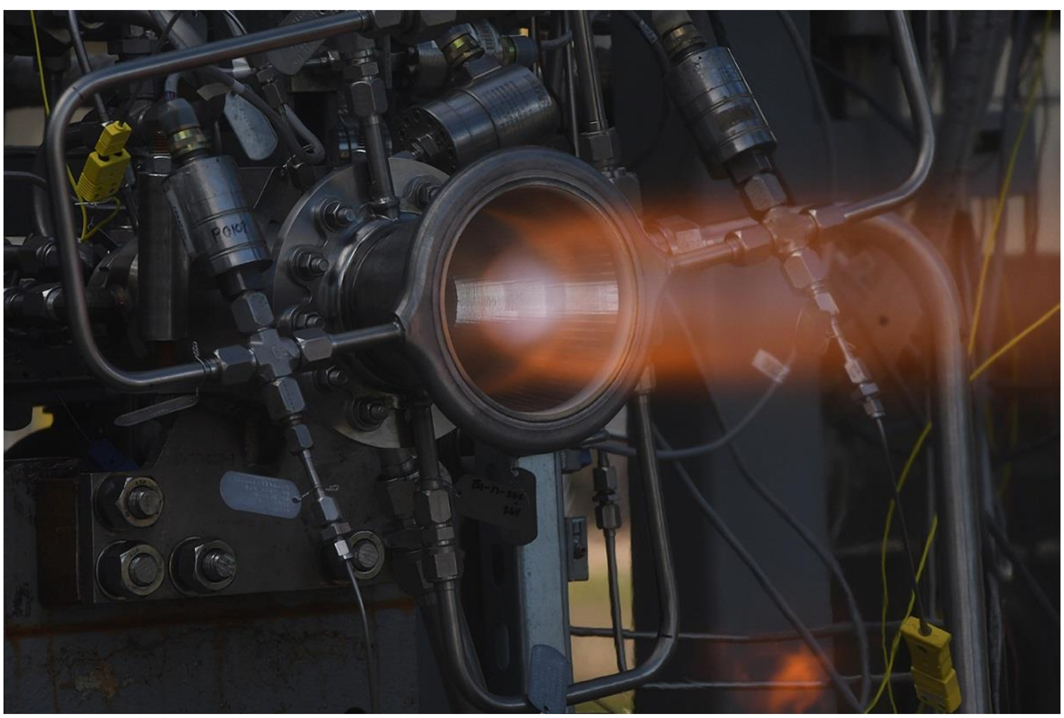

Figure 3. Image at startup from hot-fire testing of Nozzle #2.

CONCLUSIONS

Results will be presented and conclusions regarding hardware fabrication and performance.