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Technology advancements for channel wall nozzle manufacturing in liquid rocket engines

Paul R. Gradl*, Christopher S. Protz

NASA Marshall Space Flight Center, Propulsion Systems Department, Component Technology Development/ER13, Huntsville, AL, 35812, USA

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ABSTRACT

A regeneratively-cooled or dump-cooled nozzle is a critical component for expansion of hot gases to enable high temperature and performance in liquid rocket engines systems. Regeneratively-cooled 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 can be challenging to fabricate which results in extended lead times and higher costs. Some of these challenges include: 1) Unique and high temperature materials, 2) Tight tolerances on large parts 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 complex tooling. The United States (U.S.) National Aeronautics and Space Administration (NASA) and 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 under evaluation for channel wall nozzles. Much of additive manufacturing for propulsion components has focused on laser powder bed fusion (L-PBF), 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 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 technique. This publication presents an overview of the various channel wall nozzle manufacturing processes and materials under evaluation including results from the hot-fire testing. Future development and technology focus areas is also discussed relative to channel wall nozzle manufacturing.

1. Introduction

A regeneratively-cooled, or alternatively dump-cooled, nozzle for a liquid rocket engine application is a significant cost of the overall engine system due to the complexities of manufacturing a large thin-walled structure that must operate in extreme temperature and pressure environments. The 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 cost and schedule improvements over traditional manufacturing techniques. Regeneratively-cooled (regen) or dump-cooled channel wall nozzles make use of a large area ratio contour to provide expansion of

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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; Wire Arc Additive Manufacturing, WAAM; Water Jet Milling, WJM

[*] Corresponding author.

E-mail addresses: Paul.R.Gradl@nasa.gov (P.R. Gradl), Christoper.S.Protz@nasa.gov (C.S. Protz).

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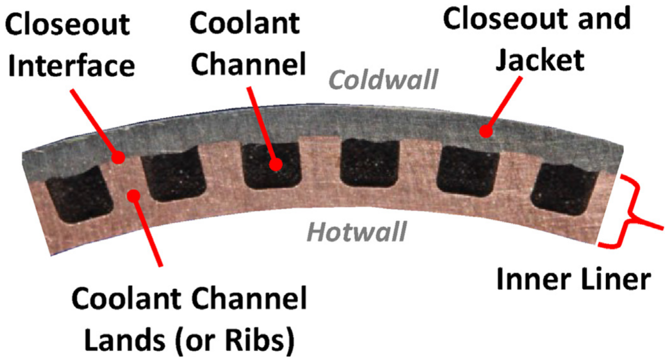

Fig. 1. Channel Wall Nozzle Configuration (Bimetallic liner shown).

hot gases coupled with active cooling of the hotwall to maintain adequate structural margins. The complexities of nozzles are numerous. Large-scale component structures require very thin-walls for the channels and since they must survive 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. Traditional CWN designs and manufacturing used square channels while modern additive manufacturing and advanced techniques can use either square, round or other geometric channel structures.

Nozzle designs are continually being stretched to deliver additional performance to the liquid rocket engine system. 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 combine with 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 (and all internal features)
- Reduction in assembly build hours and manual processing
- Reduction in lead time for materials or processes
- Various and new options for materials and material 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 evaluated modern manufacturing techniques, including various additive manufacturing (AM) technologies, with a focus on reduced tooling, in-process inspections, and maturing these new manufacturing technologies for their application to regen-cooled nozzles. The advanced manufacturing development efforts for regen nozzles at NASA started around 2012, although many of the core technologies have been matured in other industries and were subsequently adopted for aerospace. These techniques offer cost savings and reduction in fabrication time and have the potential for scale-up to the sizes needed for modern channel wall nozzle applications. The goal of these developments 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 to enable a stable and accessible supply chain for government and commercial companies to make use of. Several of these techniques were discussed in further detail in prior research [1].

Several state of the art manufacturing technologies have been evaluated and developed for channel wall nozzles over the last two decades by rocket manufacturing companies such as Aerojet Rocketdyne and GKN, formally Volvo [2,3,4]. These technologies include laser welded sandwich wall, advanced brazing using hot isostatic pressing (HIP) technology and Vacuum Plasma Spray (VPS) [5]. These technologies were focused on the channel closeout, which remains the most challenging manufacturing process due to high rates of failure or leakage. While these technologies provided cost and schedule advantages, there were challenges presented previously described in Ref. 1. The development of these techniques also preceded the advancements in additive manufacturing, which is the primary focus of the research presented in this publication. More traditional manufacturing technologies for closeout operations, such as furnace brazing and electroplating, have had minimal advancements and remain similar to techniques developed in the 1960's [6].

The general steps described in the fabrication of channel wall nozzles include the liner preform, 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 down selected for further evaluation, which are present herein. A further solution that covers all the manufacturing steps into a single operation is an integrated channel wall nozzle using additive manufacturing, later described.

The manufacturing techniques were traded based on the engine and subsequent nozzle requirements. Many of these technologies can be coupled to provide an 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 performance losses or failures. These local features of the coolant channels combined with the scale at which the entire nozzle must be fabricated generate complexities in 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. These joining operations presented some of the prior manufacturing challenges, which later propagated into failure modes as presented by Cheng [7]. These operations can affect the roundness of the part, can cause variation in the final hotwall contour and outer surface (coldwall) of the nozzle, and impact 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 and can lead to undesirable channel geometry leading to overload or develop fatigue failures [8].

While a variety of fabrication techniques were initially evaluated as shown in Fig. 2, NASA focused recent development on five (5) major manufacturing technologies of interest. Many of these technologies are focused on large scale additive manufacturing using varying deposition techniques. Each technique has limitations that require considerations and trade-offs within the design solution. The technologies of further discussion are as follows:

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 fully-integral channels
3. DED for liners, jacket preforms, and manifolds 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, being 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

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
- Hydroforming
- Vacuum Plasma Spray

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

Closeout and Jacket
- 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
- Wrought and Machined
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Multi-Piece L-PBF
- Platelets
- Casting
- Molded Composites

Fig. 2. Various manufacturing technologies for CWN fabrication.

the current scale of L-PBF is not yet feasible for application to large nozzle components. NASA is evolving several direct energy deposition based techniques for nozzles including arc-based deposition, blown powder deposition, and Laser Wire Direct Closeout (LWDC). These techniques have feasibility for and target the large scale required for nozzles. There are different approaches being considered for fabrication of the nozzles based on engine requirements. Each of these DED processes offer unique process steps. The arc-based and blown powder deposition techniques are being used for the forming of the CWN liner. A variety of materials using these techniques 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 with 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 were down selected for continued process development included LWDC, Blown Powder DED for thick-walled nozzle liners and integral channel nozzles, water jet milling for slotting channels, and explosive bonding for closeout.

2.1. Laser Wire Direct Closeout (LWDC)

The LWDC process was developed by NASA 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 require a bimetallic design solution with a copper liner for a higher heat flux environment. A bimetallic, or multi-metallic, nozzle structure incorporates an internal copper liner and can vary the materials radially and axially for weight optimization and increased thermal and subsequent structural margins. The radial bimetallic configuration uses a copper-alloy liner for the entire length and 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.

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 in a region of stock material prior to the start of the coolant channels; generally progressing aft end to the forward (Fig. 3). 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 [9]. 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 (Fig. 4).

LWDC is an AM-based wire-fed laser deposition process that eliminates the need for a tight tolerance structural jacket and additional operations when compared to traditional manufacturing, such as brazing, HIP bonding, or structural electroplating closeout. The LWDC process deposits a full closeout of the coolant channels and forms the integral jacket within the same process eliminating the need to form a separate jacket. A wire less than 1 mm 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. 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 slump into the channels and maintain the proper bonds.

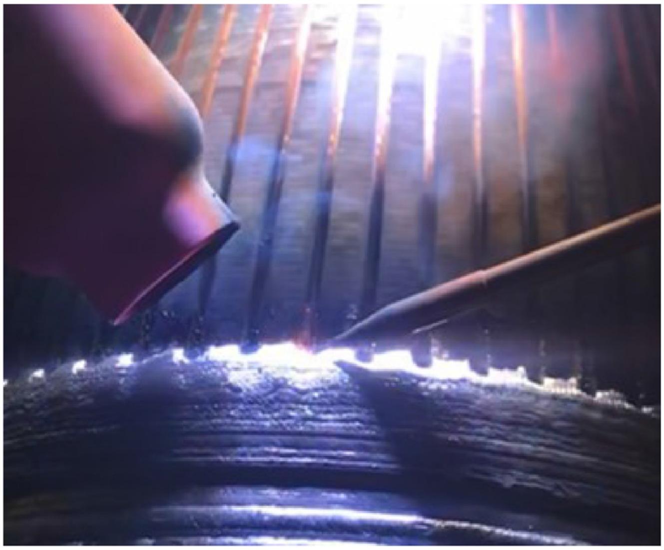

Fig. 3. Bimetallic Nozzle Closeout using LWDC.

Fig. 4. LWDC closeout of monolithic, inco 625.

Overheating can cause deformation of the liner wall or potential blowthrough of the hotwall, so a mandrel is often used.

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 and repeatable bond is created at each of the ribs to ensure structural margins are met (Fig. 6). Eliminating the need for channel fillers reduces post-processing time compared with more traditional manufacturing techniques. Since the process does use small wire for deposition to control heat input into the part, deposition rates are much slower compared to other DED processes. However, this time is offset by the elimination of a precision fit closeout jacket and subsequent bonding operations. A comparison of deposition rates is shown in Ref. 15.

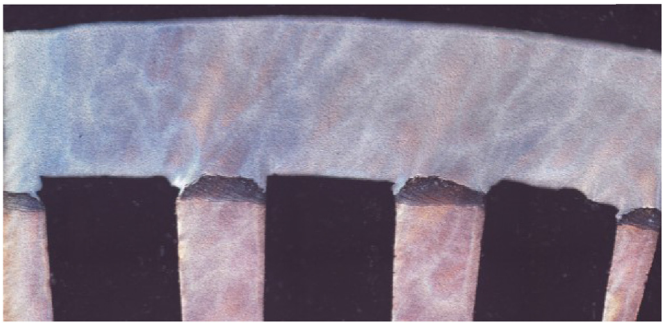

Fig. 6. Cross section of bimetallic LWDC process.

Several material combinations have been evaluated using the LWDC process. These include a variety of monolithic materials and bimetallic or multi-metallic variations. The primary monolithic materials that have been evaluated include Inconel 625, Haynes 230, Stainless Steel 347, JBK-75, and NASA HR-1 [10]. Some of the bimetallic material combinations include C-18150 (Cu–Cr–Zr) with a Monel 400 and Inconel 625 closeout [32]. 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-net shape components such as liners and manifolds, in addition to a near-final shape fully integrated-channel configuration to minimize overall 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, but provides a significant reduction in build schedule

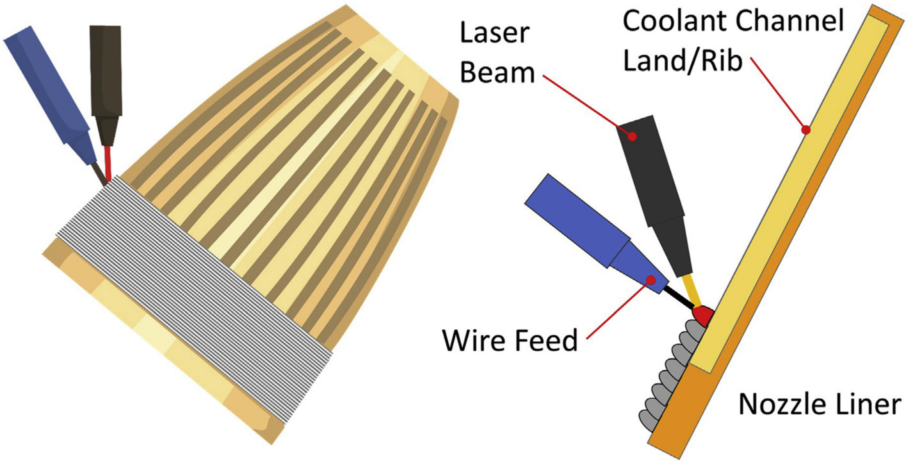

Fig. 5. Diagram of the laser wire direct closeout (LWDC) process.

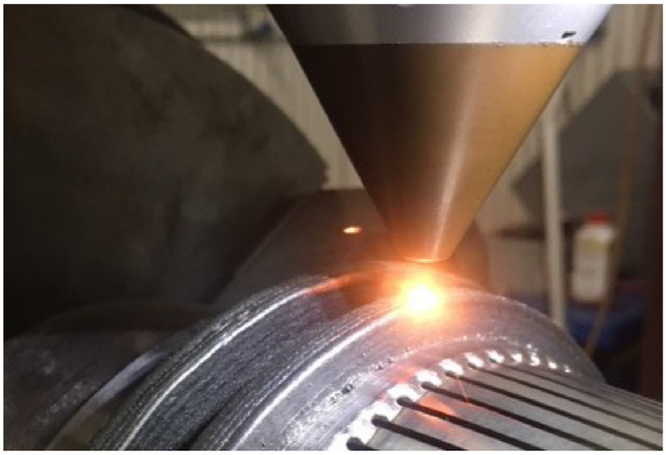

Fig. 7. Blown Powder DED process applying nozzle manifold preparations.

compared to all other fabrication processes. Characterization of the material properties produced with this technique has been shown in prior literature [11,12].

The blown powder DED fabrication technique uses a deposition head with a centered laser energy source and surrounding powder injection nozzles into the laser focus. The melt pool is created by the laser energy source causing a weld bead to be freeform 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 subsequently 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 [1,11] 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 development evolved the process as a forging or casting replacement technology, such as forming nozzle liners, manifolds, and bimetallic jackets for combustion chambers [13]. This was shown by fabricating large structures and machining to final dimensions. This process has shown a viability in this application with acceptable properties.

The current technology focus for 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. This has a significant advantages over other nozzle fabrication technologies through reduction of process steps. During this development, several basic 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: breakaway supports cannot be used, minimum feature size results in thicker as-built walls, feature resolution is coarser, surface roughness is higher, and heat input is higher. The integral channel nozzle fabrication process (Figs. 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.

2.3. Supporting technologies for CWN advanced manufacturing

Arc-based additive manufacturing deposition technology uses a pulsed-wire metal inert gas (MIG) welding deposition process to create near net shape components. The deposition head is integrated with a robot and turntable to freeform components from a derived toolpath.

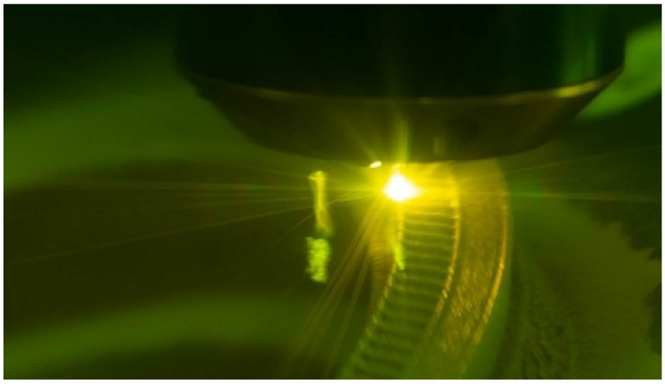

Fig. 8. Blown Powder DED fabrication with integrated channels (RPM Innovations).

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

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 technology [14]. This process, often referred to as Wire Arc Additive Manufacturing (WAAM) is capable of high deposition rates with high density and acceptable material properties [15,16]. A variety of arc-deposited subscale nozzles liners have been fabricated in Inconel 625, Haynes 230, JBK-75, and NASA HR-1. 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, which was undesirable compared to traditional slotting. This presented concerns with proper cooling of the hotwall due to the increased material volume. Further process improvements have evolved 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 advantages over traditional slotting of channels,

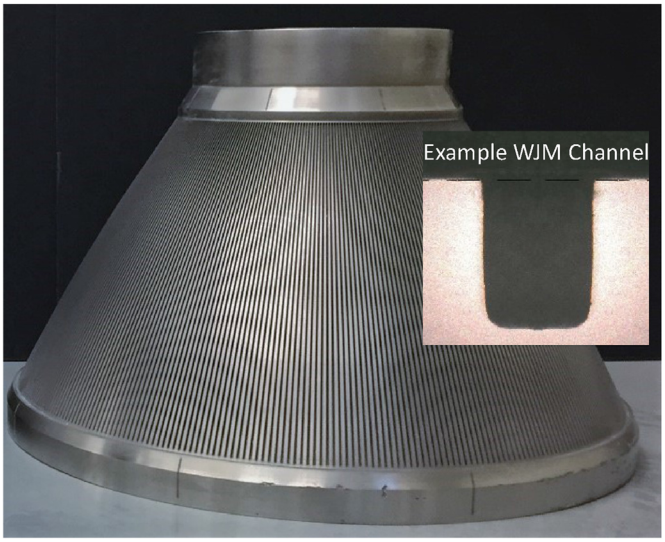

Fig. 10. Water Jet Milling (WJM) of mid-scale (~22″ diameter) Haynes 230 Liner and channel example.

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 turnarounds, undercuts, and several other features [1]. The second advantage is a low load process resulting in the ability to create thinner wall channels over traditional slotting. The third advantage is a potential time savings from higher milling rates in selected materials, such as superalloys. One final advantage is the process inherently creates squared channels at the ends of the nozzle liner. Traditional slotting processes create a large radius along the axial stations from the slitting saw. A secondary process is then 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.

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 [17]. It is often 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 compared to tooling for traditional brazing techniques. The tolerances for the closeout shell can be much lower than traditional processes such as brazing and laser welding. 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.

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 [18,19,20]. Additive manufacturing using the DED blown powder and LWDC manufacturing provided new opportunities to overcome historical processing challenges [21]. 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 higher strength. The NASA HR-1 material was derived from JBK-75 and A-286. 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, SS347, JBK-75, and NASA HR-1 have all been developed with the LWDC process.

Fig. 11. Explosive bonded axial bimetallic liner.

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. GRCop-alloys have also been evaluated, but are not available in large wrought form billets and limited to AM. The closeout material selected for bimetallic LWDC was Monel 400. Various alloys, including Inconel 625 and SS347 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 [27].

3. Hot-fire testing and results

NASA conducted several hot-fire test campaigns to evaluate the LWDC and integral channel 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. The thrust chamber assembly used a

Table 1
Material selection for CWN.

Material	Nozzle Use [22–26]
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

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. These nozzles were tested at NASA Marshall Space Flight Center (MSFC) Test Stand 115 (TS115) in a thrust chamber assembly (TCA) that is approximately 2 K-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 additively manufactured injector and combustion chamber with slip-jacket configuration were previously tested and characterized under several similar test programs [28,29]. 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-additively manufactured TCA. This configuration allowed for quick hardware changes during test. Depending on the propellants being used, continuous durations of 180 s were completed in LOX/GH2 and 60 s in LOX/RP-1. Cyclic multi-start testing was also conducted on the LOX/GH2 nozzles with 30 s cycles followed by a 25 s 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.

A total of nine (9) nozzles were fabricated with the 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 the wire arc additive manufacturing deposition process for the starting liner material. The Inconel 625 channels were cut using WJM and closed out using LWDC, while the Haynes 230 liner used traditional machining for the channels and LWDC. A series of bimetallic liners using LWDC were also evaluated with a C-18150 liner and various direct and intermediate-layer LWDC configurations previously described in prior publications [30]. 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 and tested in LOX/GH2.

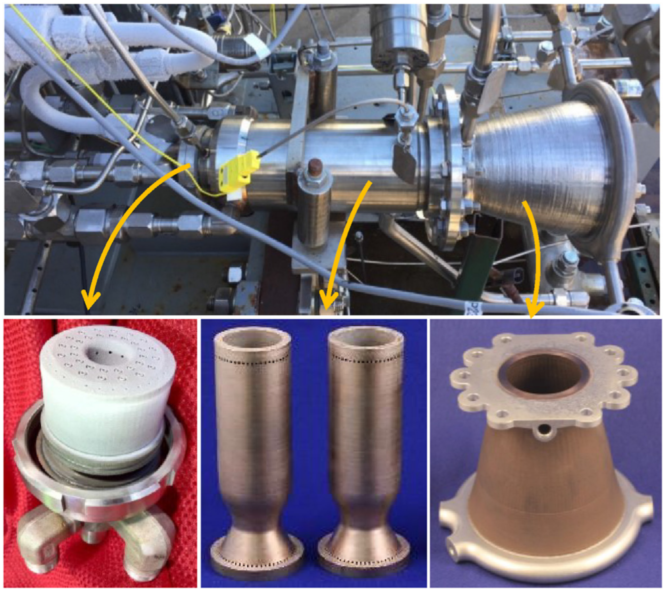

Fig. 12. Thrust Chamber Assembly for LWDC and DED subscale testing. The bottom shows the AM coaxial injector, AM GRCop-84 liner, and DED nozzle.

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 comprising of 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.

Hot-fire testing was conducted from December 2017 through June 2019 and comprised of five different test campaigns. Deionized water was used as the coolant for each propellant combination to characterize and validate the heat flux curves to validate thermal analysis for each of

Fig. 13. Bimetallic LWDC nozzle at NASA Test Stand115.

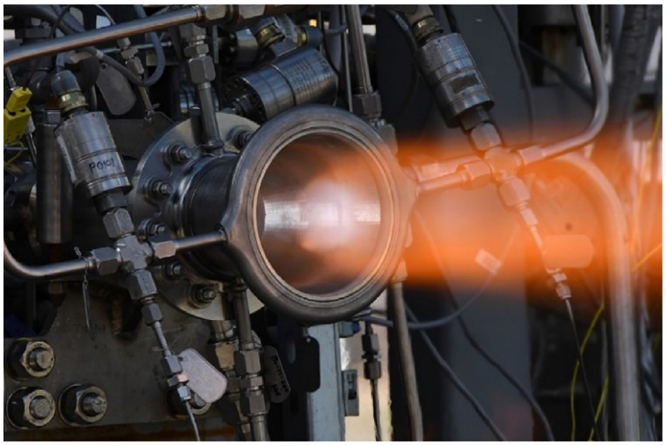

Fig. 14. Monolithic LWDC SS347 nozzle with Water Jet Milled Channels during hot-fire start-up.

the nozzles. The first test series demonstrated a single hot-fire test on the Inconel 625 DED nozzle and several 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 pressure up to 805 psig and mixture ratio to 6.6 was evaluated in this initial series. This test series demonstrated feasibility and expected performance of the manufacturing techniques under combined loading conditions and provided data to continue to evaluate the techniques.

Following the feasibility test series, the Inconel 625 DED nozzle was operated in a more extensive test series using LOX/RP-1. This test series initially used water-cooling to characterize total heat loads in LOX/RP-1 and later changed over to operate with RP-1 regenerative cooling. This test series used an additively manufactured impinging injector and operated at chamber pressure (*Pc*) up to 1240 psig and mixture ratios (MR) of 2.8 (Fig. 15). This test program also incorporated a carbon-fiber composite overwrap combustion chamber under the NASA Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project.

A further hot-fire test campaign was conducted to evaluate performance of the bimetallic LWDC nozzles and the JBK-75 integral-channel DED nozzle. This test series provided single cycle tests with up to 180 s of mainstage duration. This was followed by cyclic tests with up to 7 full hot-fire and purge cycles per test. The conditions included chamber pressure up to 1225 psig and aggressive mixture ratios (MR) up to 8.0. The high mixture ratio testing was conducted at the end of the series to determine hardware durability on the chamber and nozzles. Significant hot-fire time was accumulated on the hardware without failure demonstrating that further evaluations of the processes should proceed.

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 1350 °F, and for the hydrogen cooled case reached a peak near 1300 °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 demonstrated the capability of nozzles produced in this manner to withstand cyclic loading experienced in regeneratively cooled or dump-cooled nozzle applications.

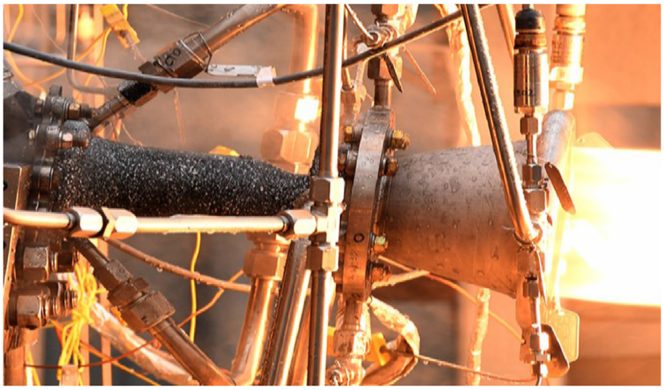

Fig. 15. Composite overwrap L-PBF GRCop-84 liner and Inconel 625 DED nozzle.

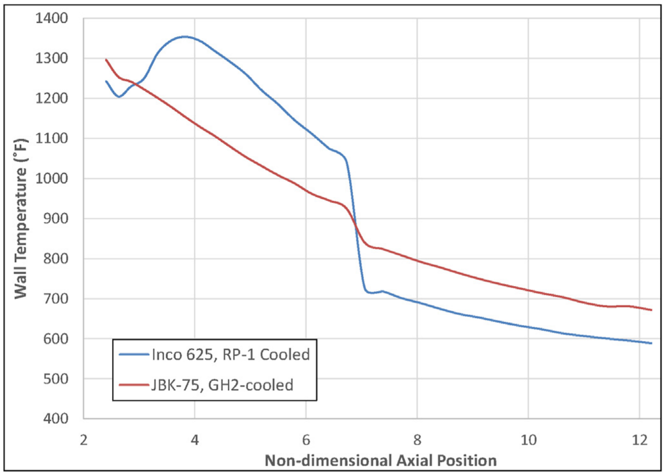

Fig. 16. Hotwall temperatures for the integrated channel DED nozzles, Inconel 625 and JBK-75.

A total of 229 tests were conducted on the LWDC and integrated-channel DED nozzles accumulating 10,142 s. Specific to the integrated channel DED nozzles, a total of 142 tests and over 5242 s were accumulated. The JBK-75 DED nozzle accumulated a total of 114 hot-fire tests and 4170 s in LOX/GH2, validating consistent performance and high durability. The Inconel 625 nozzle completed a series of hot-fire tests in LOX/RP-1 and accumulated 28 starts and 1072 s. The respective test series demonstrated chamber pressures exceeding 1200 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 and excepted performance show that the nozzle survived the aggressive thermal loads induced by testing, and established the significance in further pursuing these materials with the DED process for nozzles. The LWDC nozzles also performed well and accumulated 15 starts and 1400 s on the monolithic configurations and 72 starts and 3500 s on the bimetallic configurations. Several lessons learned and design improvements were determined from the test data including reduction in pressure drop for some designs. These lessons are being incorporated into larger scale development. Overall, the nozzles met most predictions with aggressive test conditions.

4. Current and future development

NASA and industry partners are continuing to mature the advanced manufacturing technologies applied to channel wall nozzles using the various techniques. The successful subscale nozzle hot-fire testing demonstrated feasibility of the technologies. Additional lessons were learned to apply to larger scale designs and fabrication using the technologies described. NASA is currently in process of fabrication and planning hot-fire testing of mid-scale hardware at approximately 40 K-lbf thrust in LOX/Hydrogen. A series of nozzles using the LWDC and

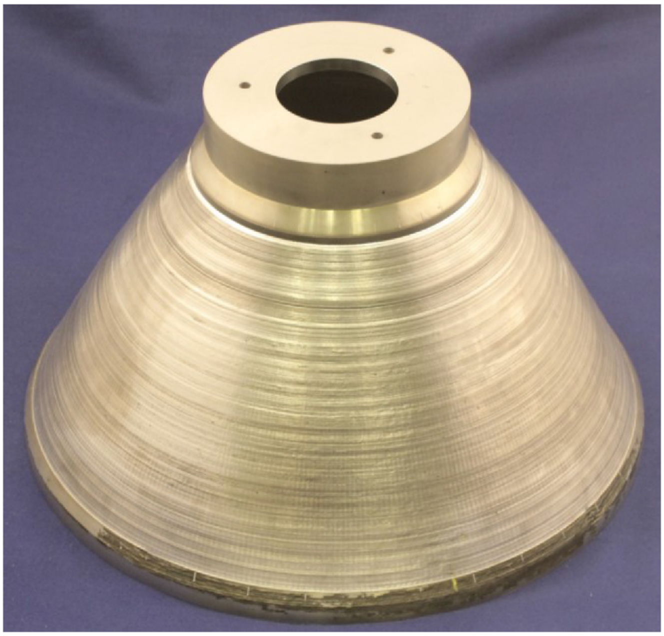

Fig. 17. LWDC mid-scale nozzle with Inconel 625 and WAAM liner. (Approx. 23″ diameter).

fully integrated channel DED process are continuing fabrication. Early manufacturing technology demonstrators were fabricated using materials similar to the ones of the subscale nozzles. An Inconel 625 nozzle can be seen in Fig. 17. The liner for this nozzle was deposited using the WAAM DED process, final machined, and channels were formed using water jet milling. The nozzle was then closed out using LWDC with Inconel 625. Additional lessons from the increased scale hardware include sensitivity to the LWDC angles and tooling design. Additional nozzles are in fabrication using Haynes 230, JBK-75, and NASA HR-1 at the increased scale.

NASA continues to advance the blown powder DED technology with increased scale hardware fabrication. A 1/2-scale RS-25 nozzle liner (44″ diameter and 50" length) was deposited using JBK-75 at DM3D as the liner preform sans integral channels. As the scale increased additional distortion was observed during the deposition and heat treatment processing. This 1/2-scale demonstrated a significant reduction in fabrication time for the liner preform compared to traditional forgings or spin-forming [31]. The liner is shown partially machined in Fig. 18. Additional development is underway on Non-Destructive Evaluation (NDE) techniques for the large scale hardware in addition 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.

The full integral-channel DED nozzles have significantly progressed with additional process development. A series of nozzles were deposited using blown powder DED at the same 40 K-lbf scale using JBK-75 and NASA HR-1 materials at RPM Innovations (RPMI). These nozzle designs demonstrated capabilities of the DED methods with thin-wall and allowed for new channel designs to be fabricated in a single piece, yielding a significant reduction in fabrication time compared to traditional techniques previously mentioned. NASA is fabricating a series of DED nozzles under the RAMPT project and internal research and development (IRAD) under the Liquid Engines Office to fully characterize properties of the JBK-75 and NASA HR-1 materials. This includes material database development and data dissemination of mechanical and thermophysical properties, heat treatment optimization, build process optimization, and best practices for DED nozzle design. Work towards significant scale-up is also underway. An example of a 40 K-lbf JBK-75 integral channel nozzle can be seen in Fig. 19.

Fig. 18. 1/2-Scale RS-25 Nozzle Liner fabrication with Blown Powder DED (~44″ dia and ~50″ tall).

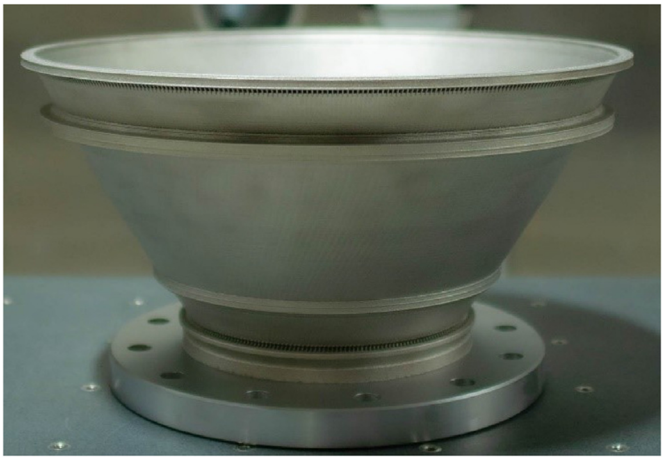

Fig. 19. JBK-75 Integral-channel blown powder DED 40 K-lb$_f$ nozzle.

5. Conclusions

NASA has conducted process development, material and process characterization, subscale hardware fabrication and hot-fire testing on a variety of advanced manufacturing technologies for channel-cooled nozzles, specifically regeneratively-cooled and dump-cooled nozzles. Through the process development and testing, significant cost and schedule improvements over traditional manufacturing techniques significant cost are being realized. 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. NASA fabricated and hot-fire tested nine (9) different subscale nozzles using the additive manufacturing LWDC and integrated-channel blown powder DED processes. A total of 229 tests were achieved accumulating 10,142 s on various monolithic and bimetallic subscale nozzles using these techniques. The following conclusions are presented:

- Channel wall nozzles could be fabricated using LWDC, which offers a robust joining technique to form the closeout and jacket in place. This has advantages through reduced processes and tooling over traditional manufacturing techniques. LWDC has been verified through proof testing, initial material characterization, and hot-fire testing that joints can maintain high pressure, thermal, and dynamic environments through cyclic testing.
- Integrated-channel nozzles using blown powder DED validated a rapid development cycle that can provide a high-density material and components to withstand high duty cycles in aggressive thermal and dynamic hot-fire testing environments. The blown powder DED nozzles have shown a significantly reduced fabrication schedule over the LWDC and traditional processes, considering all nozzle manufacturing sequences.
- Component designs using the LWDC and DED processes must account for process limitations, including proper areas of stock and channel features to take advantage of these new technologies.
- Integral processes such as WAAM, water jet milling, and explosive bonding have demonstrated advantages such as unique channel features, rapid deposition, or bimetallic transitions that would be impractical with traditional machining, forging and casting, or traditional joining techniques.

Based on success and performance of the subscale nozzle manufacturing and test hardware, the development process is continuing on large scale hardware. NASA has invested additional funding to fabricate larger-scale nozzles for hot-fire testing and full scale manufacturing demonstrators. These manufacturing techniques are currently being considered in trade studies for flight applications within NASA programs and with commercial space vendors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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