Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys

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Additive manufacturing (AM) is being investigated at NASA and across much of the rocket propulsion industry as an alternate fabrication technique to create complex geometries for liquid engine components that offers schedule and cost saving opportunities. The geometries that can be created using AM offer a significant advantage over traditional techniques. Internal complexities, such as internal coolant channels for combustion chambers and nozzles that would typically require several operations to manufacture traditionally can be fabricated in one process. Additionally, the coolant channels are closed out as a part of the AM build process, eliminating the complexities of a traditional process like brazing or plating. The primary additive manufacturing technique that has been evaluated is powder bed fusion (PBF), or selective laser melting (SLM), but there is a scale limitation for this technique. There are several alternate additive manufacturing techniques that are being investigated for large-scale nozzles and chambers including directed energy deposition (DED) processes. 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. This paper will discuss the development and hot-fire testing of channel-cooled nozzles fabricated utilizing one form of DED called blown powder deposition. This initial development work using blown powder DED is being explored to form the entire channel wall nozzle with integral coolant channels within a single AM build. Much of this development is focused on the design and DED-fabrication of complex and thin-walled features and on characterization of the materials properties produced with this techniques in order to evolve this process. Subscale nozzles were fabricated using this DED technique and hot-fire tested in Liquid Oxygen/Hydrogen (LOX/GH2) and LOX/Kerosene (LOX/RP-1) environments accumulating significant development time and cycles. The initial materials that were evaluated during this testing were high-strength nickel-based Inconel 625 and JBK-75. Further process development is being completed to increase the scale of this technology for large-scale nozzles. This paper will summarize the general design considerations for DED, specific channel-cooled nozzle design, manufacturing process development, property development, initial hot-fire testing and future developments to mature this technology for regeneratively-cooled nozzles. An overview of future development at NASA will also be discussed.

Nomenclature

AM	=	Additive Manufacturing or Additively Manufactured
CWN	=	Channel Wall Nozzle
DED	=	Direct Energy Deposition
EB	=	Electron Beam
GCD	=	Game Changing Development
GH2	=	Gaseous hydrogen
GRCop-42	=	NASA Glenn Research Center (GRC) Copper-alloy (Cu-4Cr-2Nb)
LOX	=	Liquid Oxygen
$\dot{m}$	=	Mass flow rate, lb-m/second

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MR	=	Mixture Ratio
MSFC	=	Marshall Space Flight Center
PBF	=	Powder Bed Fusion
ρ	=	Density, lbm/ft^3
P	=	Pressure, psia (or psid when ΔP)
Pc	=	Chamber Pressure (psig)
psig	=	Pounds Per Square Inch, gage pressure
Q	=	Heat load, BTU/s
R	=	Resistance
RAMPT	=	Rapid Analysis and Manufacturing Propulsion Technology
RP-1	=	Rocket Propellant-1, Kerosene
Regen	=	Regeneratively-cooled nozzle
SLM	=	Selective Laser Melting
T	=	Temperature, °F (or ΔT, °F)
TEA/TEB	=	Triethylaluminium / Triethylborane
TCA	=	Thrust Chamber Assembly
TRL	=	Technology Readiness Level

I. Background

Liquid rocket engine components require complex manufacturing processes to fabricate the thin-walled large scale features incorporated into the design of a channel-cooled nozzle. These features, primarily the coolant channels are required in order to maintain low enough wall temperatures so structural margins of the material are met and successful during operation. A channel wall nozzle is designed to include a series of integral channels with a thin hotwall, structural ribs that define the width of the channels, and a closeout structure to contain the coolant fluid. The sub-features within these coolant channels including the hotwall thickness and width of the ribs are very sensitive to thickness variations and must be tightly controlled during manufacturing. Prior papers described in detail the manufacturing steps for fabrication of channel wall nozzles including modern techniques being applied for fabrication to reduce associated schedule and cost[1]. The general steps described include fabricating of the liner perform, formation of the coolant channels, closeout of the coolant channels, and assembly of the fluid distribution manifolds.

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

Additive manufacturing has been demonstrated in various government and industry programs as a game changing fabrication method for liquid rocket engine nozzles and combustion chambers. The overall fabrication process is greatly simplified through elimination of several processing steps; this reduces the burden on the manufacturing tolerances and ultimately can provide better performing parts. AM allows the coolant channels to be formed through a layer-by-layer additive technique that are closed out in the same AM operation. NASA Marshall Space Flight Center (MSFC) has been investing significant resources into AM technologies targeting this for use on channel-cooled combustion chambers and nozzles[3]. While powder bed fusion (PBF), or more specifically selective laser melting (SLM), have been one of the primary focuses, the current scale is limited for these techniques. It is often the goal with AM to be able to fabricate components in a single-piece or as few pieces as feasible. Split-lines on the hotwall of combustion devices are not a preferred option, although have been successfully demonstrated on programs such as NASA's Low Cost Upper Stage Propulsion (LCUSP)[4]. SLM is limited in scale to existing machines, currently limited to 15.6" (400mm) diameter parts[5]. Larger machines have been announced such as the GE ATLAS, however at the time of publication for this paper have not been fully demonstrated[6]. This presented a need and desire for techniques to fabricate nozzles using additive manufacturing beyond the scale of current technology.

NASA started exploring an alternate additive manufacturing technology as part of the MSFC Liquid Engines Office (LEO) Technology Development and under the Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project for channel wall nozzles. A technology that provides a much larger build volume than SLM and ability to produce smaller geometric features is blown powder directed energy deposition (DED). The blown powder DED process can form integral channels within components providing the ability to significantly reduce part count and eliminate many of the process steps typically required for forming the liner, channel slotting and closeout of the coolant channels. This alternative technology is very attractive for these reasons, but at a lower technology readiness level (TRL). MSFC's goal was to evaluate the technology and mature the process for integral channel wall nozzles, material characterization and properties, design for DED additive manufacturing, and complete hot-fire testing in relevant environments.

This paper will provide an overview of the blown powder DED process and how it is being applied to regeneratively-cooled channel wall nozzles. An overview of the materials and process development will be presented and rationale for selection of these materials. Results from hot-fire testing will be presented including performance of the nozzles and future development work using the blown powder DED process. The blown powder DED process was shown to be feasible for integral channel wall nozzle structures and demonstrates a rapid fabrication method for fabricating regen-cooled nozzles.

II. Blown Powder Directed Energy Deposition for Nozzles

Directed Energy Deposition (DED) is a family of additive techniques that use a deposition head to locally add material using a powder or wire stock The core technology of this technique has been around for decades and used mostly for cladding operations, to add material to an existing component. More recently, these DED techniques have been applied to freeform structures. NASA has developed the laser-wire DED technique for closeout of channel wall nozzles, however this follows a more traditional fabrication process flow, focused on a simplified closeout operation[7]. Current research is being conducted to evaluate the blown powder DED for forming the integral coolant channels and closeout in a single operation. Since blown powder DED can operate at a much larger scale outside of a build box or inside a large build chamber, the scale for components has radically increased. Parts that were not previously possible in SLM can be built with blown powder DED with a minor sacrifice to feature resolution. An example of a large scale JBK-75 nozzle liner using high-rate course deposition without integral channels can be seen in Figure 1. This part was approximately 44" diameter and 48" in height.

Figure 1. Example of large scale blown powder DED part fabricated in JBK-75 (approx. 44" dia).

The blown powder DED fabrication technique uses a coaxial nozzle with a central laser source and powder injected (or blown) into the laser focus. The melt pool is created by the co-axial laser energy source causing a weld bead to be deposited. The powder is accelerated, or blown, into the melt pool using an inert carrier gas to allow for minimal or reduced oxidation in the high temperature deposition/weld. This head system, with integrated focus optics and blown powder nozzle(s), is attached to a robot or gantry system that controls a toolpath defined by the CAD model. The blown powder head can be contained in an inert gas chamber or operated with a local purge. The blown powder system and robot allows for complex freeform structures to be built. Various optics can be used to vary the spot size, which control the size of features that can be built. A cartoon and picture demonstrating an overview of the blown powder DED process can be seen in Figure 2.

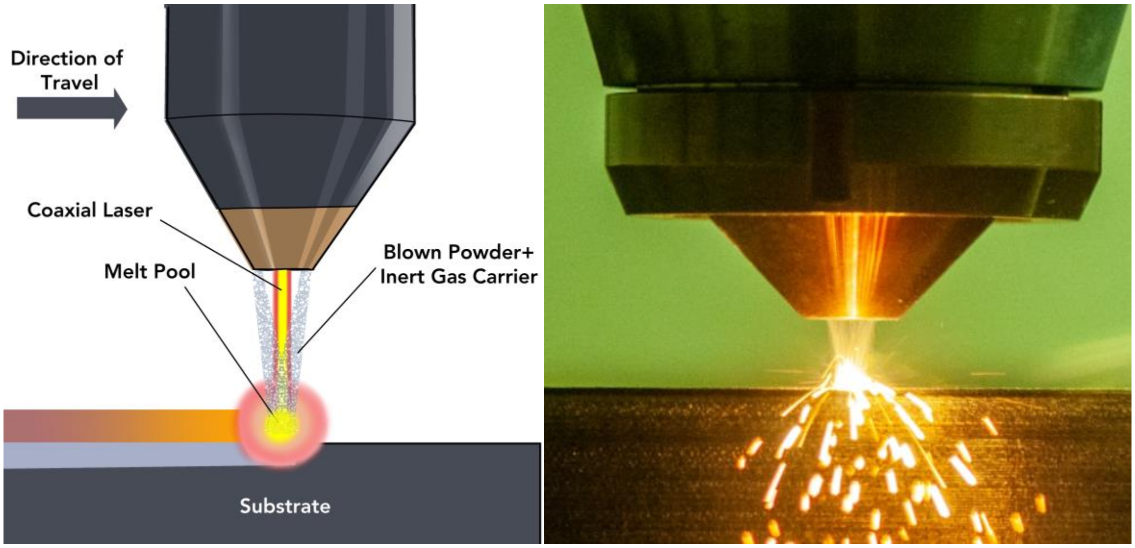

Figure 2. Blown Powder Directed Energy Deposition (DED) process: (Left) Cartoon overview of process and (Right) Image from DED process[8].

The blown powder DED process has several advantages over the SLM process, primarily a much larger build volume. The build volume is dictated by an inert gas chamber (build area) or built using a local purge, which limits scale only to the size of the gantry or robotic system. Powder is only deposited locally and can be fabricated in multi-axis including deposition onto existing features of components. Blown powder is a good trade between high deposition rates and resolution of features, which allows for much higher build rate than SLM[9]. The trade of the higher deposition rate is loss of resolution in features such as small holes, channels, wall thicknesses. There are more materials available to select from using the DED process including the ability to fabricate multi-alloys and/or gradient materials[10,11,12].

Small sintering zones can be achieved by controlling the laser beam spot size thereby increasing the resolution at which features can be built. Although features, including wall thicknesses, of less than 0.03" have been produced, a dimension of 0.04" is more realistic with current technology[13,14]. The blown powder deposition technology also has a much rougher surface finish than the powder bed technology. Because of the impact of surface finish on fatigue life, post-processing may be required [15,16,17].

Blown powder DED presents some new design opportunities and challenges that are unique compared to prior lessons learned with powder bed fusion. While many of these comparisons between DED and SLM have been previously documented, some unique design and manufacturing challenges are being emphasized. Although NASA and industry partners are investing and working to advance upon current feature and DED build limitations, the following was considered during the design and processing of the current DED technology:

- Break-away support structures cannot be used or use of course features to support features
- Limited wall thicknesses to 0.04" and thicker
- A minimum internal feature of 0.06" to avoid bridging across the feature
- A maximum angle of 30-35-degrees from vertical using 2.5D slicing (ability to use multi-axis slicing removes this limitation)[18,19]
- Higher surface roughness than SLM[20]
- Powder removal and access to internal channels
- Higher heat input leading to more distortion than SLM
- Material sampling plan should be representative of hardware geometry

- Powder supply chain providing course-cut and repeatable spherical powder
- Post-processing considerations such as HIP and heat treatments

The blown powder DED process allows for freeform fabrication of material in-place and wall thicknesses is limited using this process since they must be self-supported. Thinner walls have been demonstrated, but still require further development and very limited in the angles that they were fabricated. The powder within the injection nozzle for the DED system must be precisely focused into the laser energy source to be adequately melted, so spot sizes are limited at which thicknesses can be produced. Other process limitations such as step over and build angle must be considered in combination with the wall thickness and limits these features.

The DED process does not allow or is very limited in how support structures integral to the build can be used. Where SLM often uses thin walls or lattice structures that are easily removable, the DED process does not allow for these type of support structures. The features that can be built with DED compared to SLM are much more limiting in this regard. The support structures often built with DED are much more course and cannot be removed using break-away techniques and must be machined.

Features built using DED blown powder are more course compared to features with SLM. There are a few reasons for this. The laser spot size being used for the blown powder deposition is larger than that of SLM. There is also a higher energy density since material is being deposited and melted concurrently; the prior layer of material is required to be melted to join with the current layer being built[21,22]. The layer thickness (often Z-height axis in SLM) is also much thicker (5-25x) in DED blown powder compared to SLM[23,24,25]. Based on experimentation for internal features built using DED, the minimum height or width is approximately 0.06”. This is based on the ability to create a repeatable feature, allowing for removal of potential trapped powder, and also eliminating any bridging across the feature. The bridging effect has been observed where residual powder and heat not immediately in the laser focus build spot can effectively close the channel feature with gaps less than 0.06”. This is dependent upon several parameters including laser energy, tool path strategy, powder flow rate, material, and detailed feature geometry. Examples of fine and course deposition blown powder DED deposition process for nozzles can be seen in Figure 3.

The maximum build (overhang) angles are much less aggressive for DED compared to SLM. SLM can typically fabricate features that are 45 degrees off vertical build height, where DED blown powder is limited to 30 degrees reliably and can be pushed to 35 degrees for some features[26]. This assumes 2.5 axis slicing and not full 5-axis tool path slicing techniques. Where the build angle limits for SLM can also be pushed higher (steep angles and overhangs) for smaller features, this is limited in DED since material must be present on a prior layer to be built upon. This presents further challenges for the channel inlets and outlets and often different build orientations to optimize the channel design.

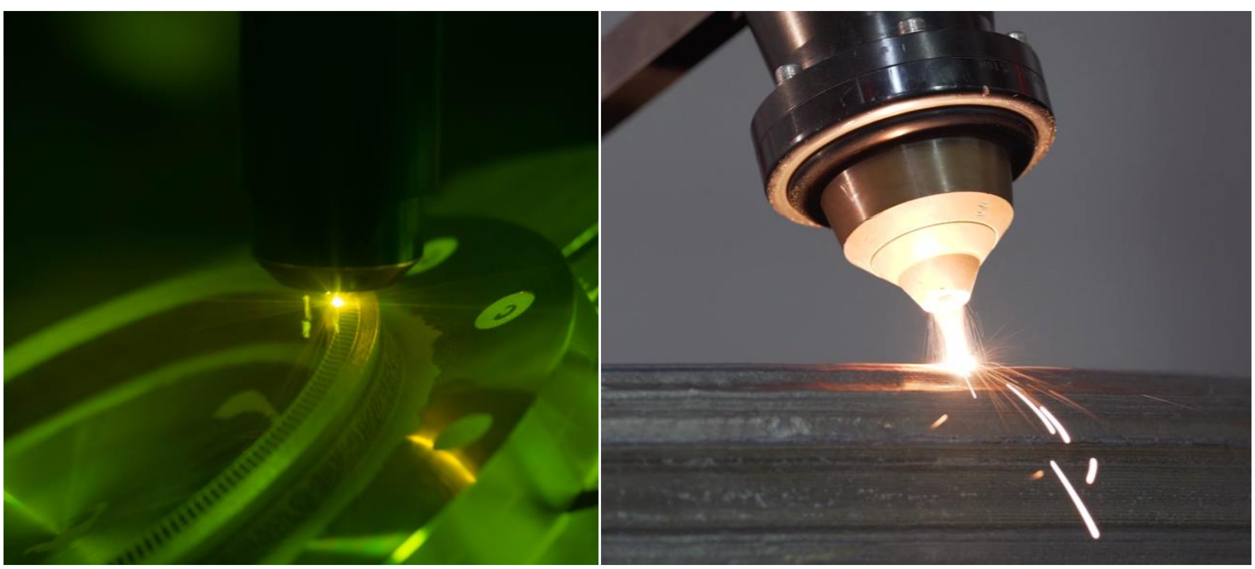

Figure 3. (Left) Image of Blown Powder DED Applied to Thinner-Wall Nozzle. (Right) Blown powder DED with thicker wall nozzle liner.

Surface roughness is a consideration for the coolant circuit performance and also affects heat flux for the internal hotwall flow. Parts fabricated with DED have a higher surface roughness compared to SLM. This is also dependent on the material and build parameters. This also assumes no post-processing considerations of the internal channels or hotwall. As it will be discussed later, the surface finish had minor effect on the performance though when it is properly accounted for in the design.

In SLM of components with internal channels, the removal of the powder is a strong consideration within the design since it must be completely removed. This is still a consideration in the DED blown powder process. Since the powder is being injected into the laser energy focus spot with the carrier gas, there is excess powder not consumed in the process[27]. The powder utilization can range from 20-90% depending on spot size and build rate, so the excess powder can collect within the internal passages[28]. If too much powder is trapped within the internal channel features, it can fuse creating the closed channels and compound the bridging discussed earlier. Powder removal must still be considered as part of the design and build process for DED.

Material quality and post-processing should be considered specific to the process, in this case DED blown powder. Witness specimens such as round tensile bars have typically been used for SLM, but may not be representative of the DED process. In SLM, a similar tool path scanning pattern that is used to build the part is also applied to the witness specimens[29]. However, DED must consider the part being built in respect to tool path strategy, features such as wall thicknesses, and also build angles. A simple tensile bar may have a higher heat input and different material properties than than actual part and not representative. A larger part being built may have thick and thin regions and varying degrees of heating and cooling rates. Witness specimens should fully consider the geometry of the part being built as part of the material characterization and qualification approach. Representative samples (as seen in Figure 4) have included mechanical test dogbones that are harvested from racetracks or box configurations that use similar wall thickness to features on the component.

Other considerations such as hot isostatic pressing (HIP) and heat treatments need to be considered and optimized specific to the DED process. The mechanism of the fusion process in DED is different than SLM and the resultant heating and cooling rates produce a different material that reacts different to heat treatments. Due to the increasing scale for components using the DED process, a thorough review of HIP should also be considered such as HIP furnace size constraints and also if the process is necessary. Other post-processing techniques such as machining, channel polishing should also be evaluated specific to DED since they will react different than SLM, even if the same material.

III. Material Overview and Selection

NASA and industry partners completed a series of manufacturing demonstrator channel wall nozzles using the DED blown powder deposition process. These witness samples, demonstrator parts, and channel-cooled nozzles provided design feedback, material characterization of thin featured sections, minimum features that could be fabricated, build strategy, build parameters, scalability, heat treatments, and post-processing. A variety of propellants are being considered and discussed later, so different materials were considered as part of the initial development. For hydrogen applications, the JBK-75 iron-nickel based superalloy was down selected and Inconel 625 superalloy selected for kerosene and methane-based applications[30,31,32]. JBK-75 is also being considered for the latter applications as well. The composition for Inconel 625 and JBK-75 is shown in Table 1. Additional development under the NASA RAMPT project has baselined the use of NASA HR-1 superalloy as an alternative to the JBK-75 with higher strength and better weldability [33,34].

JBK-75 is a high-strength hydrogen resistant material derived from A-286 with good weldability characteristics desired for additive manufacturing[35,36,37]. Additive manufacturing using the DED blown powder manufacturing provided new opportunities to overcome historical processing challenges[38]. JBK-75 has been previously used for a variety of combustion devices chamber and nozzle applications, but required specialized forging, machining, and joining operations that limited the use due to expense and lead times[39,40]. The use and availability of JBK-75 in the wrought powder form provided significant opportunity for additive manufacturing processes to be matured. JBK-75 also provides higher conductivity and strength at elevated temperatures and was an ideal demonstrator material for early process development.

Inconel 625 is a common material used in additive manufacturing, including DED, due its excellent weldability and availability in a powder form[41]. Inconel 625 was selected for its process development maturity, high strength at temperature, simplified post-processing, and compatibility with other desired alloys. Prior development with blown powder DED Inconel 625 demonstrated the ability to achieve high density material and achieve desired mechanical properties with proper heat treatments[42].

Table 1. Elemental Composition of Inconel 625 and JBK-75 by percent[43,44].

	Inconel 625	JBK-75
Nickel	58.0 min	29.0 - 31.0
Chromium	20.0 - 23.0	13.5 - 16.0
Iron	5.0 max	48.0 - 54.2
Molybdenum	8.0 - 10.0	1.0 - 1.5
Niobium	3.15 - 4.15	-
Carbon	0.10 max.	0.01 - 0.03
Manganese	0.50 max.	0.2 max.
Silicon	0.50 max.	0.1 max.
Phosphorus	0.015 max.	0.006 max.
Sulfur	0.015 max.	0.005 max.
Aluminum	0.40 max.	0.15 - 0.35
Titanium	0.40 max.	2.0 - 2.3
Cobalt	1.0 max.	-
Boron	-	0.0005 - 0.002
Vanadium	-	0.1 - 0.5

NASA completed a series of mechanical test and characterization samples with various industry vendors using the JBK-75 and Inconel 625 materials. This work was to understand the DED fabrication of various features along with mechanical test characterization and powder supply chain. As previously mentioned, one of the challenges in the DED fabrication is to determine mechanical witness samples that are representative of the hardware features. It was determined to fabricate the witness samples in the form of representative "racetracks" or harvest boxes in single-wall builds. There is still additional characterization work to be completed and the final mechanical test specimen configuration to be determined. An example of the racetracks or harvest boxes are shown in Figure 4.

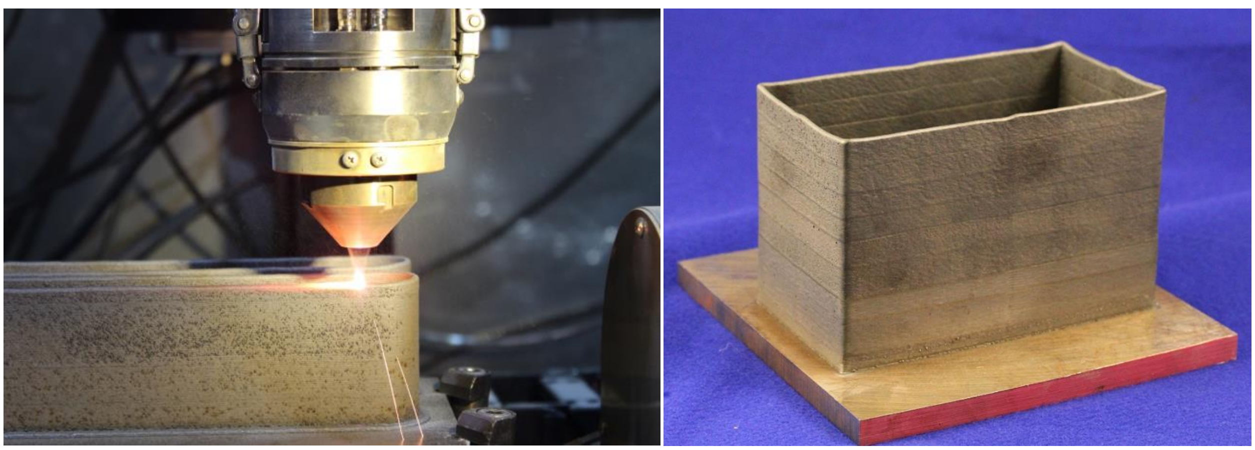

Figure 4. Examples of witness samples for DED: (Left) Racetracks during build and (Right) Example of harvest box.

Following the fabrication of the witness samples metallography was completed in the as-built condition and heat treatment development completed. This included the appropriate stress relief cycle as in addition to the homogenization for Inconel 625 and Solution and Aging for the JBK-75. The basic tensile properties at room temperature are shown in Table 2. A prior publication by Fullen et al. described the Inconel 625 heat treatment and material characterization in further details[40]. There were significant variations observed between the various vendor's materials based on powder supply and build strategies; the different vendor samples also responded differently to the heat treatments. The JBK-75 additive DED material has also shown sensitivities to varying heat treatment conditions.

There is significant development and characterization work that is continuing on the characterization of the blown powder DED materials for nozzles. The feasibility work demonstrated that the materials could meet the requirements for designers of channel wall nozzles. The process is continuing to evolve with new build strategies being developed and NASA is continuing to invest in this technology.

Table 2. Basic properties for Blown Powder DED materials selected.

	JBK-75	**Inconel 625**
Condition	Solution + Age	Solution
Yield, 70˚F (ksi)	108	47
Ultimate, 70˚F (ksi)	145	110
Elongation, 70˚F (%)	29	37
Density (lb/in^3)	0.292	0.305

IV. Hardware Fabrication

Following the process development, NASA completed fabrication of two (2) different subscale nozzles in serial development with the Inconel 625 followed by the JBK-75. These subscale nozzles were designed to be tested in LOX/Kerosene (LOX/RP-1) and Liquid Oxygen/Hydrogen (LOX/GH2) environments.. The purpose of the testing was to demonstrate the performance of the design and material using the DED process. The lessons learned from process development were applied to the design of the subscale test articles.

The subscale nozzles were designed for approximately 2,400 lb_f thrust using various regenerative cooling techniques. A similar channel design was also applied to GH2 and RP-1 cooling with varying performance discussed below. Initially the nozzles were tested with water cooling to characterize the heat load prior to the fully regenerative cooling. The subscale nozzles were fabricated in three (3) pieces which included the DED integral channel liner, the forward manifold, and the aft manifold. The subscale nozzles used a design approach to optimize the build process and considered a weight-optimized approach for future applications. With the increasing diameter a bifurcated channel design was implemented. This maintained the desired channel dimensions for cooling and structural reasons. A summary of the nozzle configuration can be seen in Table 3.

Table 3. Configuration of DED Integral Channel Nozzle Test Units.

	Nozzle Unit #3	**Nozzle Unit #4**
Liner Fabrication Technique	Blown Powder DED AM	Blown Powder DED AM
Liner Material	Inconel 625	JBK-75
Interim Heat Treatments	Stress Relief	Stress Relief
Final Heat Treatment	Solution	Solution and Age
Channel Forming	Integral	Integral
Post-processing Techniques	Final Machined Hotwall	Final Machined Hotwall Repaired Hotwall leaks
Fwd Manifold Material	Stainless 304L	Stainless 347
Aft Manifold Material	Stainless 304L	Stainless 304L

The fabrication approach was to deposit in an inverted position. There were several challenges with this since it was not part of a standard deposition strategy based on distortion concerns. However, this approach was preferred for the design since it allowed for the manifolds to be welded further outboard radially eliminating any joints on the hotwall at the forward end. This did present some challenges for the inlets and outlets to the channels, but a design was finalized that met all requirements.

The subscale nozzle design allowed for the manifold (standoff) preparations to be machined and the manifolds directly welded with electron beam (EB) welding. The forward manifold was assembled from the forward end and aft manifold assembled from the aft end. The internal coolant channels were tested in the as-built condition with no post-processing. Surface roughness in the as-built condition was higher than desired, but provided some heat transfer augmentation to reduce hot wall temperatures. A generic process overview is shown in Figure 5.

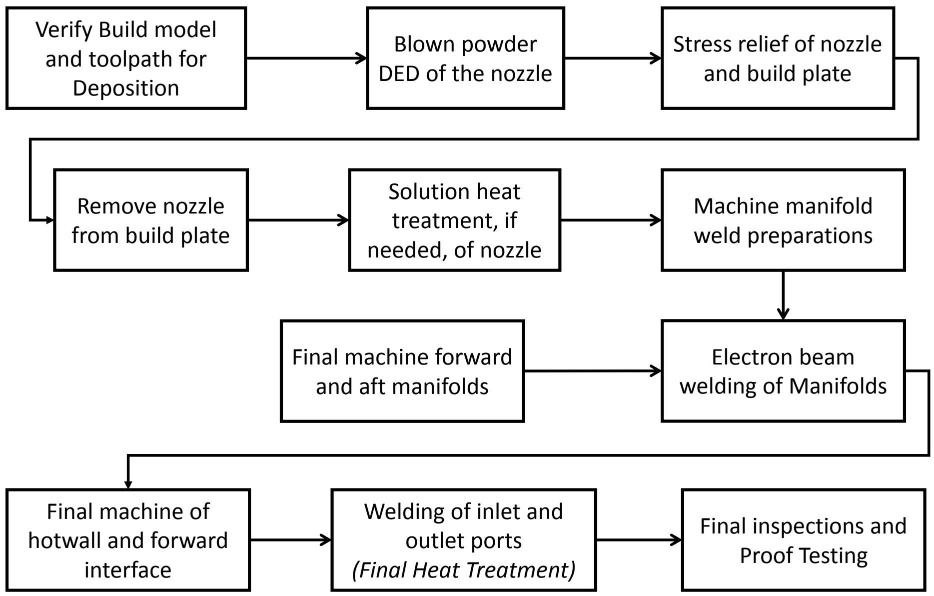

Figure 5. Generic process flow chart for fabrication of subscale DED nozzles.

A. Nozzle Unit #3, Inconel 625 DED

Nozzle #3 was designed using the freeform blown powder DED technique fabricated with RPM Innovations (RPMI). This nozzle was fabricated from Inconel 625. The nozzle was designed for and built using minimum feature size with RPMI fine deposition parameters. The nozzle was designed for all the channels to be open at the forward and aft end, including appropriate support features within the design eliminating the need for sacrificial support features. The channels were bifurcated, doubling the number of channels within the design. The nozzle was built starting at the forward end and deposited toward aft with all build angles at a maximum of 30° from vertical. This build orientation minimized the uncooled region at the forward interface with the MCC and allowed for welding on the hotwall at the aft end. Additional material was also required in the areas for the manifold land preparations to allow added stock to minimize unsupported features.

The nozzle was built on a mild steel plate and stress relieved prior to removal. After removal from the plate, the nozzle completed a homogenization heat treatment step. This nozzle only required minimal machining prior to welding of the manifolds. All welds were EB welds with Stainless 304L manifolds.

Following welding of the SS304 manifolds to the Inco 625 base structure, small cracks were observed on the inboard size of the forward and aft manifold. It is hypothesized the cracks were initiated in a portion of the additive material that was not final machined and had residual stress during weld causing the overload. These cracks were repaired using a manual Tungsten Inert Gas (TIG) process. The final operation completed machining of the hotwall. This operation was completed on a CNC lathe using structured light scan data and methods developed to machine directly from this data[45]. The nozzle was proof tested to 1800 psig and no leaks were observed. An image of the nozzle following all operations can be seen in Figure 6.

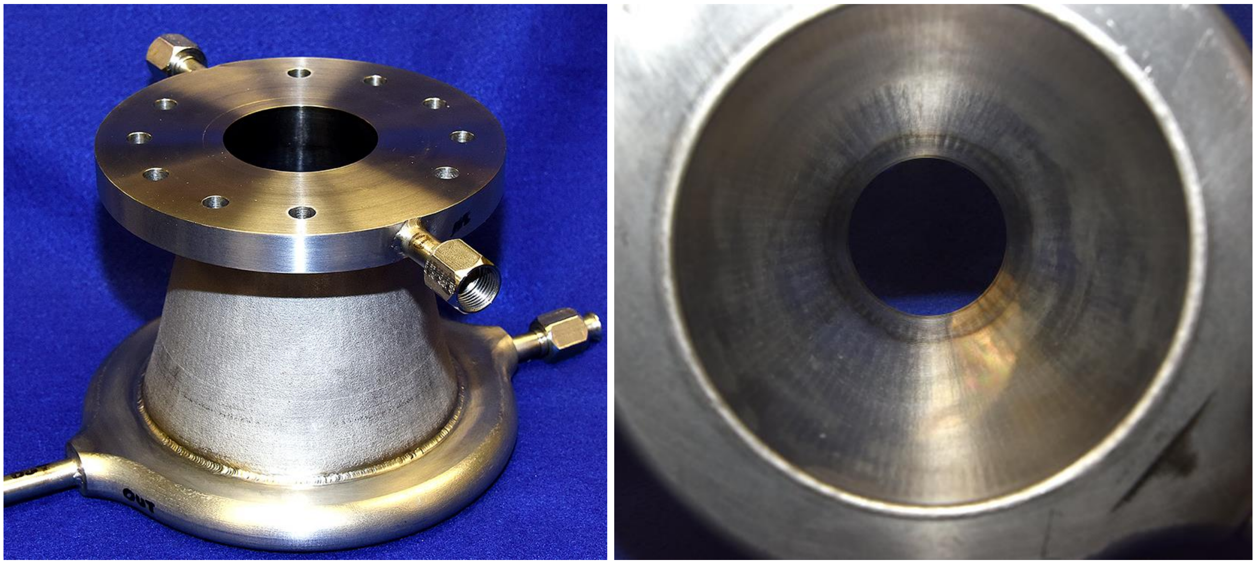

Figure 6. Completed Nozzle #3 Inconel 625: EB Welded Manifolds (left) & Final Machined Hotwall (right)

B. Nozzle #4, JBK-75 DED

Nozzle #4 was fabricated using a the integral channel DED process demonstrated with the previously described nozzle and used JBK-75 as the material. This nozzle was also fabricated at RPM Innovations (RPMI). This nozzle maintained a similar channel design to the Inconel 625 DED nozzle tested. The manifolds were similar, but pressure taps were added for Delta P across the nozzle.

The nozzle design and toolpath programming was updated to reflect the JBK-75 material. It was built on a mild steel build plate and then stress relieved. This was the first part that was DED fabricated using the JBK-75 material (prior fabrication using JBK-75 DED was limited to material samples). There was some shrinkage observed during the build and also additional shrinkage observed following the stress relief, but still fit within tolerances to machine for manifolds. The part was then removed from the build plate after stress relief.

After fabrication and stress relief, some small inward dimples (pinholes) were observed on the hotwall in the axial station where the channels bifurcated towards the aft end. Visually, it appeared that a few holes were into the channels and decision was made to repair these pinholes. Although not all areas of the bifurcation appeared to have pinholes, it was decided to repair all locations. They were repaired using manual Tungsten Inert Gas (TIG). Low heat was used and no distortion observed or any other issues observed with the repair. A picture of the nozzle in the as-built condition and pinhole repairs can be seen in Figure 7.

The manifold weld preps were final machined on the liner to match the manifolds and electron beam (EB) welded. The EB welding achieved full penetration as observed visually with drop-thru into the manifolds. Following EB welding the nozzle completed structured light scanning to determine datums for final machining of the hotwall. The ID profile was then generated from the scan data. The part was scanned again after machining and met the wall thickness required.

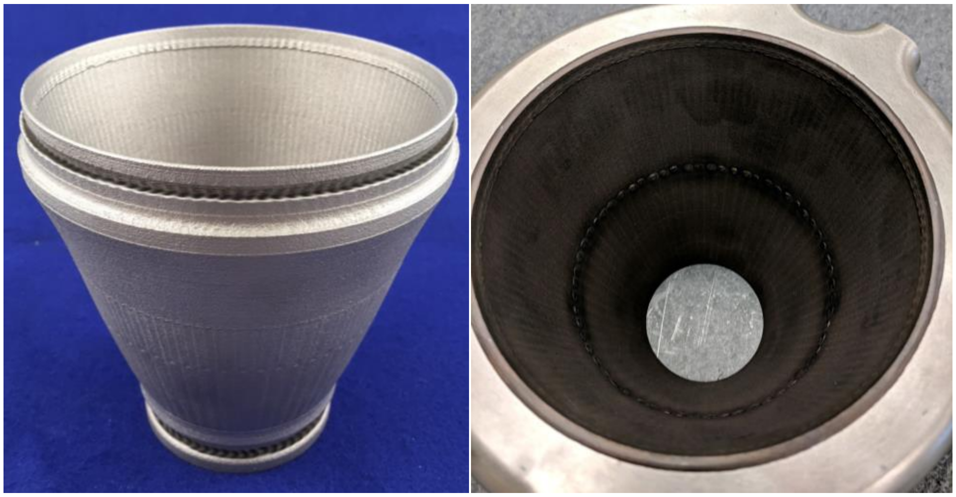

Figure 7. JBK-75 Nozzle #4 (Left) As-built condition and, (Right) repairs of pinholes on hotwall.

Following the ID hotwall machining, the nozzle completed solution and aging to achieve desired properties. The nozzle was then final machined on the forward flange mating interface to meet the surface finish for sealing and axis alignment. The tubes and B-nuts were then welded to the forward and aft manifolds. The nozzle completed a hydro-proof tested at 2,000 psig. There was only one (1) minor leak at 2,000 psig and only made visible when held at pressure for 60 sec. The leak manifested as a small drop of water forming in the area of one of the hotwall repairs. The pressure was held constant though and no further issues observed with this. An image of the final assembled nozzle and finished nozzle in the test stand can be seen in Figure 8.

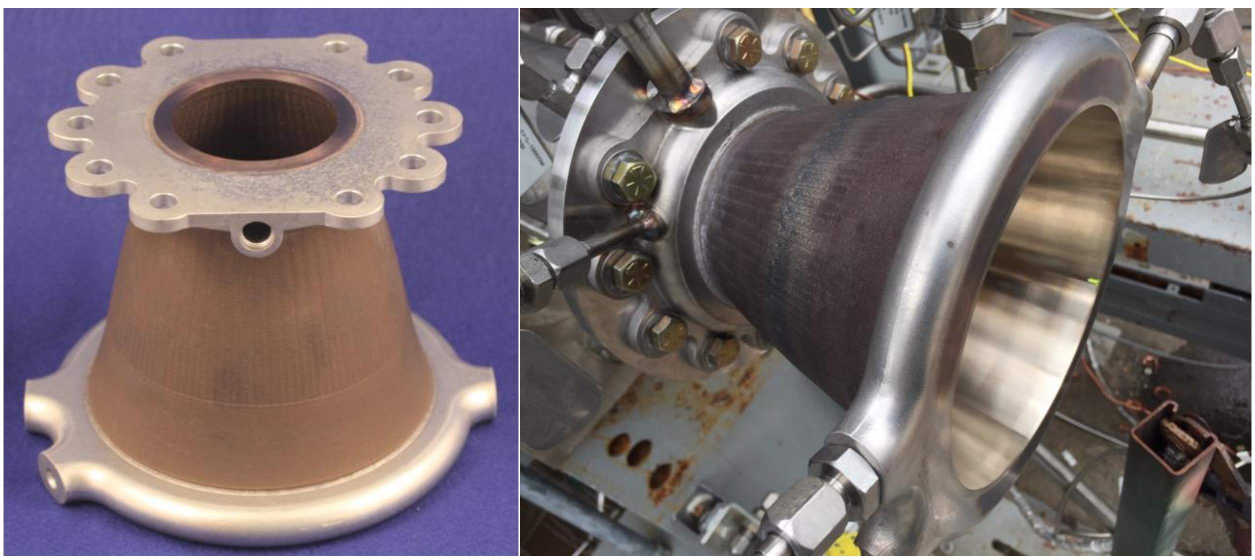

Figure 8. JBK-75 Nozzle #4 (Left) During fabrication following heat treatment and (Right) Installed in test stand.

V. Hot-fire Testing and Results

Since 2015, MSFC has successfully used the subscale nozzle test rig at Test Stand 115 (TS115) to evaluate a variety of advanced manufacturing nozzle, chamber and injector components. NASA MSFC's TS115 is ideal for testing quick turnaround subscale test articles, such as regeneratively-cooled channel wall nozzles and combustion chambers. The test rig has been successfully demonstrated through a variety of test campaigns and offers long mainstage durations (up to 210+ seconds) and high internal combustion temperatures (~6000 °F). It has been successfully used for evaluation of a variety of channel-cooled and radiatively-cooled nozzles and chambers since

2015, as well as for a variety of heritage tests dating back to the 1960's. Various propellant combinations can be used depending upon the desired combustion environment. The test stand offers extensive instrumentation to allow monitoring of test hardware, including high and low speed data channels, standard and high speed imaging, infrared (IR) thermographic imaging, and still frame cameras. MSFC TS115 can complete quick turnaround testing and often completes multiple tests in a single day, while still collecting all of the necessary data.

Several test series were completed to evaluate the channel-cooled nozzles including PH034, PI084-1, PJ024, PI084-2, PI100, and PJ038. Hot-fire testing was completed from December 2017 through June 2019. Cooling with deionized water was completed for each propellant combination to characterize and validate the heat flux curves used for the thermal analysis for each of the nozzles. The first test series, PH034, completed a single hot-fire test on the Inconel 625 (Nozzle #3) to show initial feasibility. This was with LOX/GH2. Following this test series the Inconel 625 DED nozzle completed more extensive testing in LOX/RP-1. There were several programs with a variety of conditions that this was tested under. It started initial testing under PI084-1 with water-cooling and continued testing under PJ024. This program used an additively manufactured impinging injector and operated a chamber pressures (Pc) up to 800 psig and mixture ratios (MR) of 2.8. A follow-on program under PI084-2 used an identical chamber and injector configuration but provided for full regenerative cooling of the nozzle using RP-1 at higher Pc.

Two hot-fire test series, PI100 and PJ038, were completed using the JBK-75, Nozzle #4, to evaluate performance. The testing was conducted on a Liquid Oxygen /Gaseous Hydrogen (LOX/GH2) thrust chamber assembly with an additively manufactured SLM GRCop-42 liner and SLM shear coaxial injector[46,47,48]. The PI100 program was setup to provide initial performance characterization of the liner and various channel wall nozzles in single-cycle tests[49]. Direct spark ignition was using during the PI100 test series and completed single cycle tests with up to 180 seconds of mainstage duration for this test series. Follow-on testing under PJ038 performed cyclic testing to achieve high duty cycles (significant testing at mainstage conditions) to understand performance and durability of the hardware. The PJ038 testing that followed completed a series of cyclic tests with up to 7 full hot-fire and purge cycles per test at 30 seconds mainstage per test cycle using TEA/TEB for ignition. The latter test series allowed for fully reversal strains and cycling for fatigue conditions to challenge the hardware under these conditions.

A total of 142 tests and over 5,242 seconds were accumulated in various configurations using the blown powder DED integrated channel nozzles. A summary of the testing and on the nozzles can be seen in Table 4.

Table 4. DED nozzle test summary

Program	Material	Propellants	Coolant	Peak Pc (psig)	Mixture Ratio (MR)	Cumulative Starts	Cumulative Time (sec)
PH034	Inconel 625	LOX/GH2	Water	719	6.02	1	15
PI084-1	Inconel 625	LOX/RP-1	Water	751	2.8	8	288
PJ024	Inconel 625	LOX/RP-1	Water	801	2.8	10	440
PI084-2	Inconel 625	LOX/RP-1	RP-1	1,253	2.4	**28**	**1,072**
PI100	JBK-75	LOX/GH2	Water/GH2	1,224	6.35	5	900
PJ038	JBK-75	LOX/GH2	GH2	1,140	6.50	**114**	**4,170**

The thrust chamber assembly (TCA) for the PI100 and PJ038 test series that the nozzle was tested on used an additively manufactured shear coaxial injector and SLM additive manufactured GRCop-42 combustion chamber liner[50,51]. The injector was previously tested and characterized under several similar test programs demonstrating good mixing and high performance[52]. The TCA for the PI084 and PJ024 series used an additively manufactured triplet impinging injector also demonstrating high performance. Pictures from hot-fire testing are shown in Figure 9 through Figure 11. Following each test the hardware was inspected and documented. There were some observations in the wall conditions, mostly minor discoloration. The subsequent performance data demonstrated repeatability across all test conditions. There were no leaks or issues observed with the DED nozzles during each of the test series.

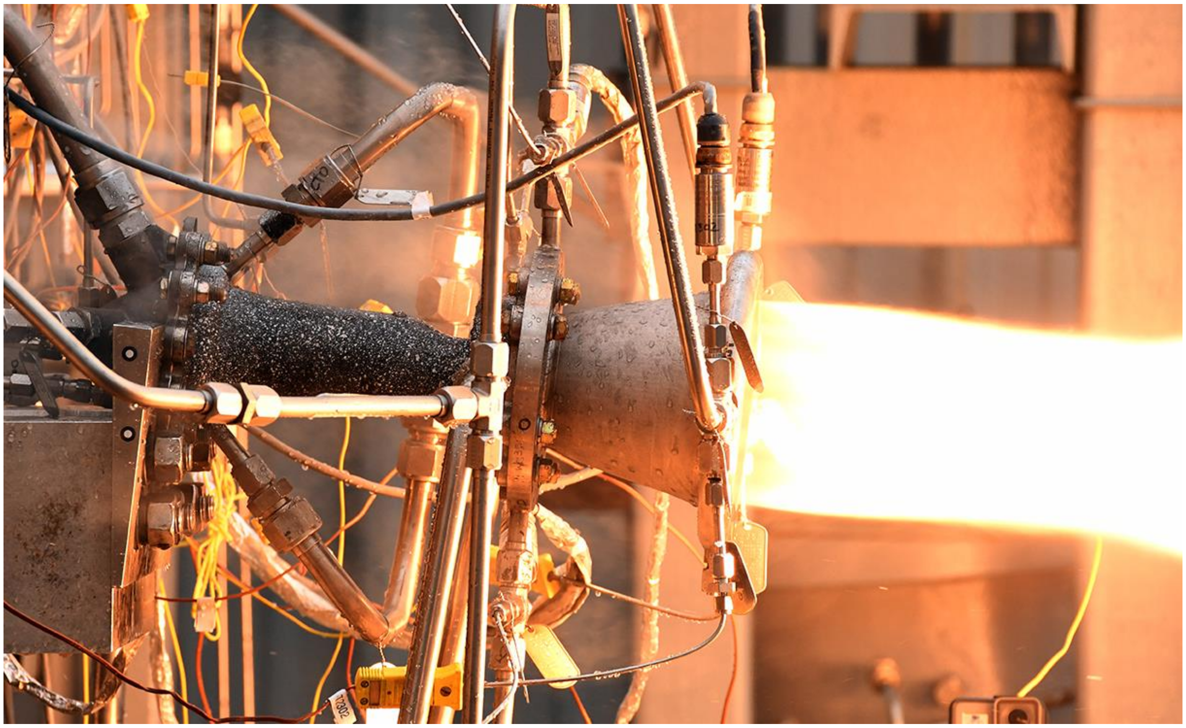

Figure 9. Mainstage hot-fire testing of Inconel 625 Nozzle #3 in PI084-2.

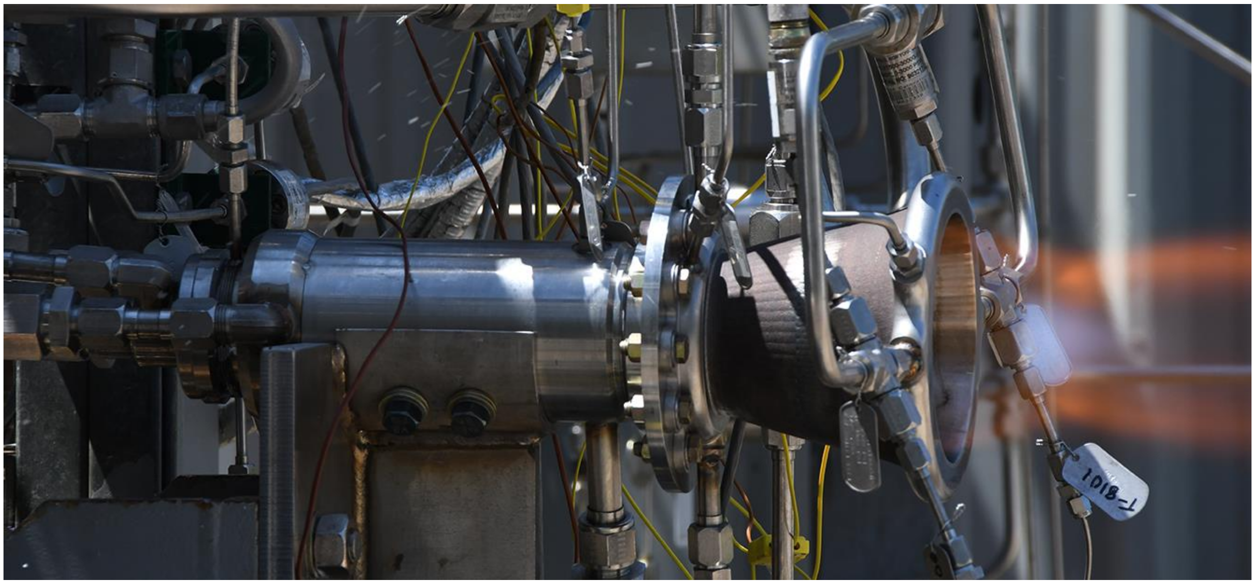

Figure 10. Start transient of JBK-75 Nozzle #4 during PI100 testing.

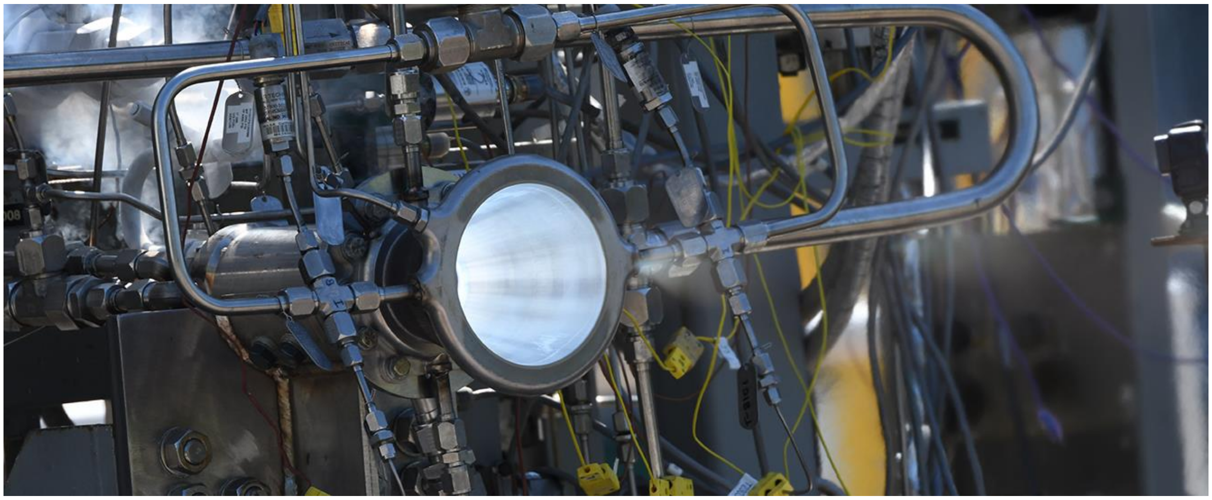

Figure 11. Mainstage operation of JBK-75 Nozzle #4 during PJ038 cycles testing.

In order to estimate thermal environment experienced over the entire hot wall surface of the nozzle, modeling was employed on the as-run conditions. A quasi 3-D thermal analysis solver was utilized to derive wall temperatures. The solver takes the chamber flow path, coolant channel geometry, coolant conditions and flow and hot wall heat flux as inputs. The Bartz correlation for hot-side heat transfer coefficient was used to provide an initial estimate of heat flux and to generate the shape of the heat flux profile. This initial heat flux was input into the solver and then scaled until the integrated heat load derived from the experimental results of coolant temperature and pressure changes for the experimental coolant mass flow matched the integrated heat load input to the model.

The hot wall temperatures for conditions at higher chamber pressures during the PI084-2 and PI100 test series are shown in Figure 12. Wall temperatures for the RP-1 cooled case (shown in blue) reached a peak of ~1,350°F, and for the hydrogen cooled case reached a peak near 1,300°F. The wall temperatures peak near the forward end of the nozzle, where the heat flux is highest. Test conditions were intentionally chosen to provide aggressive wall temperatures in order to include large thermal strains in the coolant passage walls. Testing in this manner demonstrates the capability of nozzles produced in this manner to withstand cyclic loading experienced in regeneratively cooled nozzle applications.

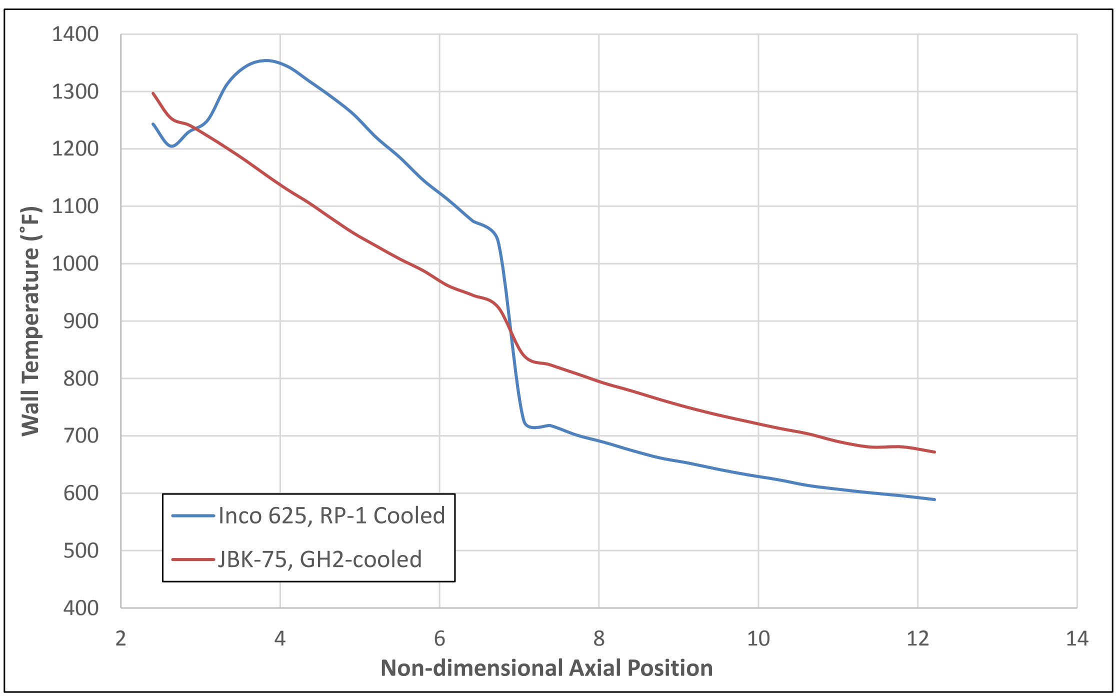

Figure 12. Hotwall temperatures for the integrated channel DED nozzles, Inconel 625 and JBK-75.

For the PJ038 cyclic test series, the total heat load observed on Nozzle #4 was very consistent from test to test. The non-dimensional heat load can be seen in Figure 13. Variations in test conditions are represented in the data. This data was used to anchor the wall temperatures, shown above. The resistance of the Nozzle #4 is also shown in Figure 13. The resistance, R, of the nozzle was calculated based on equation (1).

$$R = \frac{\Delta P \times \rho}{\dot{m}^2} \qquad (1)$$

The resistance, based on ΔP across the nozzle cooling circuit, for the JBK-75 DED nozzle was very consistent throughout the duty cycle testing. It demonstrated no changes in the channels and good performance throughout the 114 cyclic hot-fire tests.

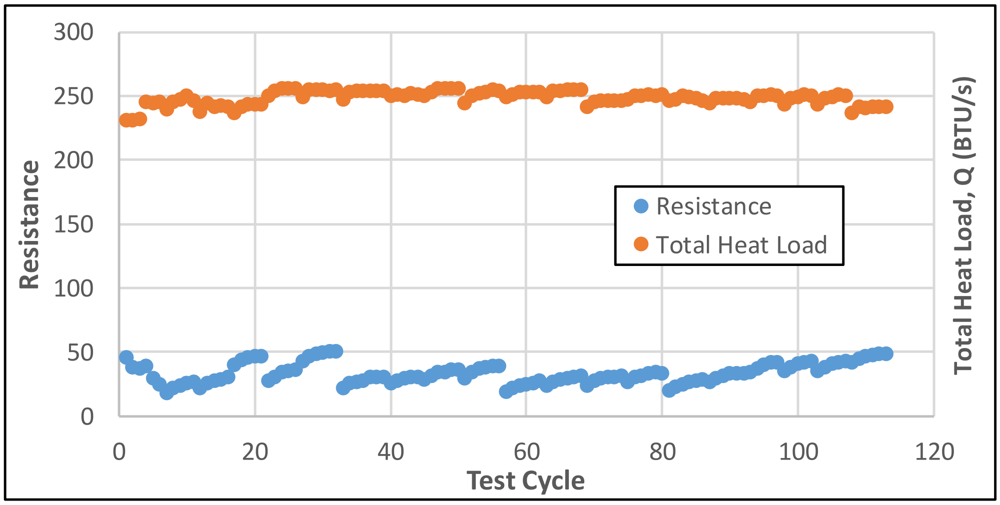

Figure 13. Total heat load and resistance for Nozzle #4 during cycle testing.

During individual long-duration tests under the PI100 test series, the nozzle also demonstrated repeatable data. As previously described, the nozzles were initially cooled with water and then transitioned to regenerative cooling using GH2. The nozzle pressure drops were very consistent during each test providing the propellants to the injector manifold. This can be seen in Figure 14. The low pressure drop across the nozzle used for the subsequent resistance above can also be seen in the data below.

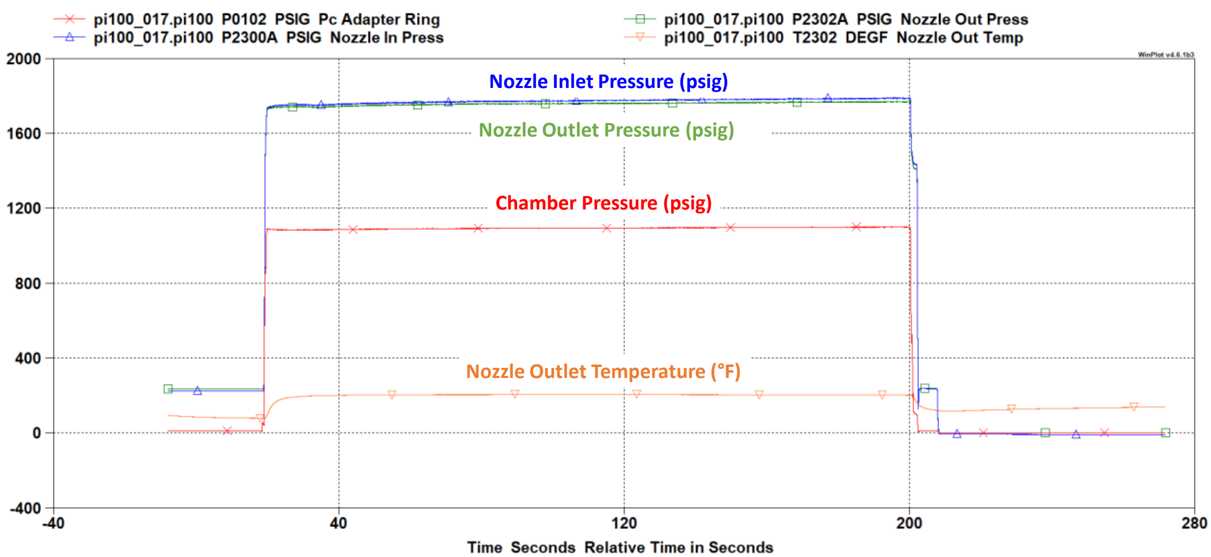

Figure 14. Long duration mainstage test of JBK-75 nozzle with GH2-cooling.

Following the long duration testing under the PI100 test series, nozzle #4 completed cyclic testing. Multiple cycles were completed during a single hot-fire tests to accumulate starts and hardware time while introducing fully reversal strains and loading on the nozzle. The test conditions remained very similar between the cycles and an example of the data can be seen in Figure 15. Nozzle #4 accumulated a total of 114 starts and 4,170 seconds without any issues observed. There was some accumulation of TEA ash on the nozzle hotwall, but no indication of temperature changes based on repeatable outlet temperatures.

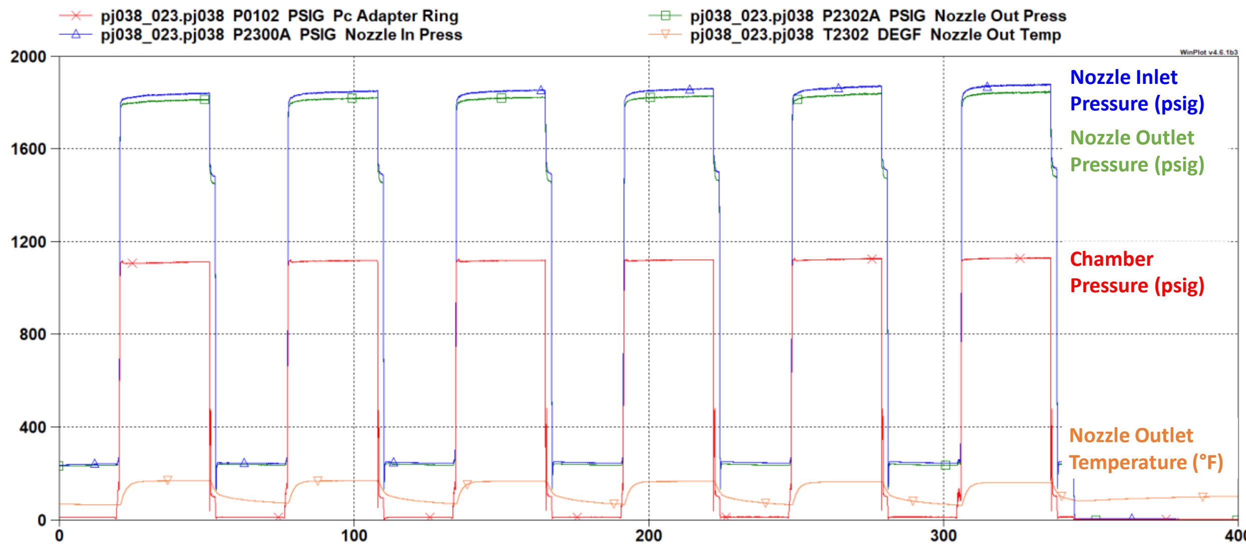

Figure 15. Cycle testing of JBK-75 DED nozzle #4 (data from starts 109 - 114).

Based on the aggressive wall temperatures during operation, there was some bluing observed at the forward end of the nozzle. This generally propagates at small region that is uncooled, providing higher temperatures than the channel and land areas. There was no indication of cracking or any other failures induced during testing or observed in any data. The final condition of the nozzles after testing can be seen in Figure 16. Nozzle #3 still has some residual soot, so some of the wall is masked in the image. Nozzle #4 has some residual TEA ash with some removed following cleaning.

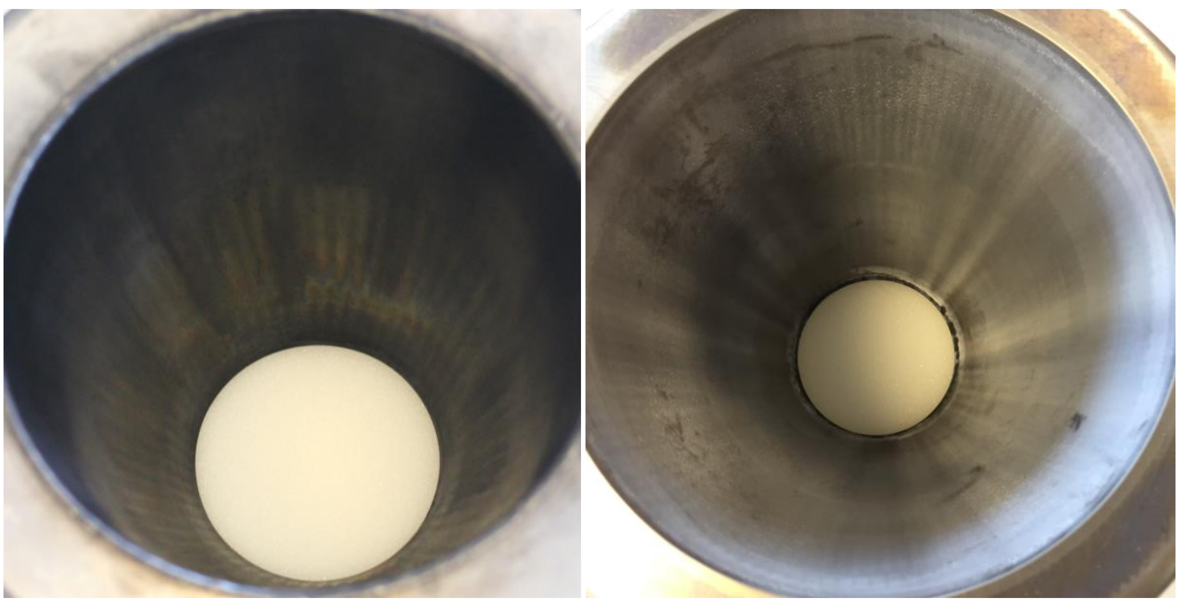
Figure 16. Post-test images of DED nozzles (Left) Inconel 625 Nozzle #3 and (Right) JBK-75 Nozzle #4.

VI. Conclusions

NASA has started exploring blown powder directed energy deposition (DED) as an alternate technology to further enable additive manufacture of large build volume regeneratively cooled nozzles for propulsion applications. MSFC has completed work in the materials selection, process development, fabrication, and test of subscale nozzles to evaluate the technology and mature the process for integral channel wall nozzles. Directed Energy Deposition (DED) is a family of additive techniques that use a deposition head to locally add material using a powder or wire stock. Thus, the process is a free-form process and allows parts to be additively manufactured at larger scales then currently possible in additive processes such as Powder Bed Fusion.

In the current effort, JBK-75 iron-nickel based superalloy was selected for hydrogen applications and Inconel 625 nickel-based superalloy selected for kerosene and methane-based applications. Development and characterization was performed to provide initial properties for the powder DED materials for nozzles. NASA completed a series of mechanical tests and characterization samples with various industry vendors using the JBK-75 and Inconel 625 materials. The feasibility work demonstrated that the materials could meet the requirements for designers of channel wall nozzles.

Following the process development, NASA completed fabrication of two (2) different subscale nozzles in serial development with the Inconel 625 followed by the JBK-75. These subscale nozzles were designed to be tested in Liquid Oxygen/Hydrogen (LOX/GH2) and LOX/Kerosene (LOX/RP-1) environments.. The purpose of the testing was to demonstrate the performance of the design and material using the DED process. The lessons learned from process development were applied to the design of the subscale test articles.

Several test series were completed to characterize the performance of the nozzles in the various environments. Hot-fire testing was completed from December 2017 through June 2019. Cooling with water was completed for each propellant combination to characterize and validate the heat flux curves used for the thermal analysis for each of the nozzles, followed by regenerative cooling with the respective propellants. Wall temperatures were modeled for the tested conditions.

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

The blown powder DED process was shown to be feasible for integral channel wall nozzle structures and demonstrates a rapid fabrication method for fabricating regen-cooled nozzles. In future work, NASA's Game Changing Development (GCD) Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project is evaluating blown powder DED one if its key technology areas. The blown powder DED process will be further developed using the NASA HR-1 material as an alternative to the JBK-75 for channel-cooled nozzles. The goal of this actively-funded project is to increase scale, significantly reduce cost, and improve performance for regeneratively-cooled thrust chamber assemblies, specifically the combustion chamber and nozzle for government and industry programs. The process development work detailed here will be carried into RAMPT in order to develop regen-cooled channel wall nozzle structures at large scale. Additional scale-up and process development is also being pursued under technology development for the Liquid Engines Office to demonstrate channel-cooled nozzles with the JBK-75 material.

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