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Integral Channel Nozzles and Heat Exchangers using Additive Manufacturing Directed Energy Deposition NASA HR-1 Alloy

Paul Gradl[a*], Angelo Cervone[b], Piero Colonna[c]

[a] Component Technology Development, NASA Marshall Space Flight Center, Huntsville, AL, 35812, USA, Paul.R.Gradl@nasa.gov
[a] Space Systems Engineering, Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, 2629 HS, Delft, The Netherlands
[c] Propulsion and Power, Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, 2629 HS, Delft, The Netherlands
[*] Corresponding Author

Abstract

Heat exchangers for use in propulsion applications are very critical components because they must be efficient, compact and light and often operate with working fluids at extreme temperatures or pressures or both. Various components and systems use heat exchangers such as combustion chambers of gas turbines and internal combustion engines, fuel cells (air supply and thermal management), electric batteries (thermal management), evaporators and recuperators of waste-heat-to-power systems, and rocket engines. Even if the results are more generally applicable, the heat exchangers applications to which this study is more closely related are regeneratively cooled rocket nozzles and chambers, and repressurization systems for the launch vehicles. These components are often thin-walled and contain pressurized fluids, like propellants at cryogenic or elevated temperatures. Given that the environments that these propulsion components must endure are challenging, the manufacturing to meet these specifications often require long lead times due to specialty processes and unique tooling associated with the combined thin-wall integral channel and large-scale structures. Additive manufacturing (AM) offers programmatic advantages for reduction in processing time and cost in addition to various technical advantages, including the possibility to achieve enhanced hardware complexity targeted to superior performance, part consolidation, and the capability of processing of novel alloys. While AM is already being utilized for heat exchanger components in propulsion applications, almost all these AM components are made by means of Laser Powder Bed Fusion (L-PBF). L-PBF allows for fine features but is rather limited with respect to the overall size of the components that can be manufactured. Recent developments are maturing the Laser Powder Directed Energy Deposition (LP-DED) process which may be used, for example, to make integral channel thin-wall regeneratively-cooled rocket nozzles with diameters greater than 1 m. This paper highlights some integral channel heat exchanger demonstrator hardware applications of LP-DED, as well as the characterization of this process in combination with the use of the NASA HR-1 alloy. To properly utilize LP-DED for heat exchanger manufacturing, various aspects are being characterized such as geometry limitations, measurement of surface texture and geometric angled surfaces, surface enhancements for internal channels, and material evaluation. NASA HR-1 (Fe-Ni-Cr) is a high strength hydrogen resistant superalloy developed for use in aerospace applications, such as heat exchangers. Some aspects and considerations about the design of heat exchangers are summarized together with data relevant to LP-DED manufacturing in combination with the NASA HR-1 alloy. Microchannels were successful deposited down to 2.54 mm and 1 mm wall thickness, wall angles of 30°, both with high reproducibility. It was also found that the areal surface roughness is highly dependent on the size of the powder feedstock used for deposition. The characterization of these LP-DED features is critical for fluid flow and heat transfer predictions as it can be exploited to enhance heat transfer at the cost of increased pressure drop.

Keywords: Additive Manufacturing, Heat Exchangers, Directed Energy Deposition, Nozzles, Laser Powder Directed Energy Deposition, DED, LP-DED, Channel Wall Nozzles

Acronyms/Abbreviations

Abrasive Flow Machining (AFM), Additive Manufacturing (AM), Average Areal Surface Roughness (Sa), Chemical Mechanical Polishing (CMP), Chemical Milling (CM), Computed Tomography (CT), Design for Additive Manufacturing (DfAM), Design of Experiments (DOE), Directed Energy Deposition (DED), Electrochemical machining (ECM), Electropolishing (EP), Hot Isostatic Pressing (HIP), Laser Powder Bed

Fusion (L-PBF), Laser Powder Directed Energy Deposition (LP-DED), Kerosene (RP-1), Liquid Hydrogen (LH2), Liquid Methane (LCH4), Liquid Oxygen (LOX), magnetic abrasive finishing (MAF), NASA HR-1 (Fe-Ni-Cr hydrogen resistant alloy), Particle Size Distribution (PSD), Ultrasonic Additive Manufacturing (UAM), Vacuum Plasma Spray (VPS)

1 Introduction

Heat exchangers are used in various aerospace, industrial, power, and automotive applications. Heat exchangers are particularly critical in aerospace propulsion applications as they require system and component-level operation with working fluids at cryogenic (-253 °C) or extreme temperatures (> 3300 °C) and high pressures (> 400 bar), or both. For a liquid rocket engine system, a regeneratively-cooled or channel-cooled combustion chamber and nozzle are components critical to the system functionality because walls must be properly cooled to maintain structural safety margins while the temperatures of propellants must be kept as high as possible to increase the performance of the thermodynamic cycle. Other heat exchangers within a propulsion system may allow for repressurization of a tank or subsystems. These types of heat exchangers consist of micro-channels, passages, or fins to increase the surface area and requires thin-walls (< 2 mm) and compact form factors to minimize overall mass. While complex designs can be conceptualized and analyzed, the heat exchanger must be manufacturable, which often limits the design space. In addition to meeting technical performance and manufacturing requirements, programmatic requirements (cost, schedule, reliability, risk tolerance) must also be considered to ensure that a part is optimized for integration and use in the overall system.

In case of propulsion systems, heat exchanger designs have often been conceptualized only to determine that parts cannot be fabricated, that the manufacturing limitations have unintended performance consequences, or that the manufacturing cost is too high. Even if a design concept is deemed manufacturable, there are often a series of problems or non-conformances that arise during the manufacturing process. This results in a component not meeting the full design intent.

Various manufacturing techniques have been evaluated for fabrication of heat exchangers for propulsion systems. In the case of rocket engines, traditional manufacturing techniques such as brazing, joining (welding), and plating have matured and can produce cooling channels capable of containing the high pressure propellants in nozzles and combustion chambers [1–3]. Several more advanced techniques have also been developed including pressure-assisted hot isostatic pressing (HIP) bonding and vacuum plasma spray (VPS) for the realization of combustion chambers, and of laser welded sandwich wall nozzles [4,5]. These novel techniques have provided advantages over the more traditional brazing and plating processes but suffer from limitations with respect to optimal designs. These techniques and manufacturing lifecycle result in several sequential steps and potentially long-lead material (i.e. forging, liner machining and slotting, closeout, etc) where issues can arise [6,7]. Any manufacturing process is affected by limitations which in turn have repercussions on the entire lifecycle, therefore they must be well understood and solutions for these limitations must be incorporated into the design at an early stage. Therefore, when a manufacturing process is being industrialized, it must be fully characterized to determine limits, tolerances, repeatability, and reproducibility to allow designers to achieve optimal solutions [8]. Once a manufacturing process has been baselined, adjustments or improvements can be made to further optimize it, like, for example, the inclusion of secondary steps if gaps were identified.

Additive manufacturing (AM) enabled the realization of novel complex heat exchanger designs which overcome many of the barriers due to traditional manufacturing processes [9]. AM for example has allowed for the production of single-piece components by eliminating joining, inspection, and interim machining operations that were required by traditional techniques. Each of these manufacturing steps add cost and scheduled time [10]. As AM technical and economic benefits have been realized, several types of metal AM processes have concurrently advanced offering different advantages and associated challenges. Given the design specifications for a given component, various criteria are used to select appropriate AM processes depending on complexity of features and resolution, material and feedstock availability, overall size, deposition rates, industrial maturity and post-processing requirements [11]. The AM processes that can be employed to produce heat exchangers include powder bed fusion (PBF), directed energy deposition (DED), and solid-state processes such as cold spray and ultrasonic additive manufacturing (UAM).

An AM process commonly adopted for the realization of heat exchangers is laser powder bed fusion (L-PBF), which offers the ability to fabricate thin-walls (0.2 to 0.4 mm), small passages (0.2 mm diameter), and complex shapes [12]. There are many examples of combustion chambers, nozzles, and other heat exchangers that have been manufactured using L-PBF with integral channels and successfully tested in liquid rocket engines and even flown [13–15]. While this process has been shown to be of great benefit for propulsion heat exchangers, its main limitation is the maximum volume of the component, as the most commonly available machines can only handle a 400 mm and up to 600 mm build diameter [11]. Custom machines capable of dealing with up to 1 m build diameter have been developed, but they are not readily available in industry. The manufacturing of heat transfer surfaces of combustion chambers or of regeneratively-cooled rocket nozzles demand for the capability of treating large volumes as ever increasing sizes are needed to accommodate the ever-increasing thrust requirements. For engines and heat exchanger components produced using L-PBF, the thrust class is generally limited to just below 200 kN; a common size for the components produced by many commercial space companies. To increase the scale, other AM processes such as DED must be explored. Figure 1 shows a comparison of various AM processes in terms of build volumes and minimum feature sizes. The design of heat exchangers for power and propulsion applications requires thin walls (typically below 1.5 mm).

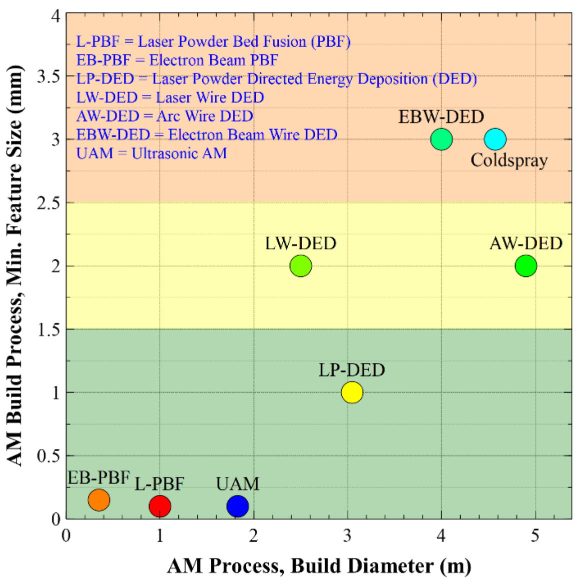

Figure 1. Comparison of AM processes considering feature size and build diameter. Green shows the AM processes that can produce wall thickness below 1.5 mm, while yellow and orange indicate AM techniques that may require additional levels of post-processing.

The laser powder DED (LP-DED) process is being matured and it has been demonstrated that a good level of feature resolution (such as a 1 mm wall thicknesses) and large build diameters fitting the requirements of many rocket engine nozzles can be achieved. LP-DED has been developed starting from the late 1980's mainly as a cladding process for coatings or repair. This included hard facing or use of multi-alloys for wear or erosion resistance. In the last 10 years, the LP-DED process has been further evolved to allow for freeform structures including thin-walls and integral channel features.

The working principle of the LP-DED process is based on creating a melt pool using laser energy to liquefy a small region on the base surface and metal powder is blown into the beam focused melt pool and rapidly cooled. The blown powder head and the laser beam delivery are mounted on a gantry robot to allow for the precise motion control needed to manufacture thin-wall features. Freeform structures are fabricated based on toolpaths generated from CAD models. The size of the powder particles and particle size distributions (PSD) can vary from coarse (45 – 105 µm) to fine (15 – 45 µm). Within the research program of which the research documented in this paper is part, the National Aeronautics and Space Administration (NASA) has demonstrated the possibility of manufacturing large scale nozzles using LP-DED the process with the aim of understanding its limitations and collect data to further improve this manufacturing technique. A large-scale integral channel nozzle is shown in Figure 2, which stands 1.78 m in height and 1.52 m in diameter. This nozzle was manufactured in 90 days by depositing the powder of a hydrogen-resistant alloy, the NASA HR-1. This realization time represents a significant savings (>3x) over traditional manufacturing processes.

Figure 2. Large-scale LP-DED integral channel nozzle manufactured with LP-DED in 90 days (1.52 m dia. and 1.78 m height).

Figure 3. Example of a combustion chamber liner built using LP-DED with internal channels.

While a rocket nozzle features a high level of complexity when it comes to the shape of the internal channels, the axisymmetric conical shape is more simplistic for toolpath planning. The possibility of handling more complex toolpath contours such as those of combustion chambers was also demonstrated (Figure 3). Demonstrating the ability to use LP-DED for the construction of such nozzles and combustion chambers represented significant advancements of the technology, which, however, would not have been possible without prior development work to determine geometry, surface texture, material properties, and to ensure that the overall build process could meet the design specifications.

The objective of the research documented here is to provide insights on geometry limitations affecting the LP-DED process including angles, manufacturing tolerances, wall thicknesses, features, and surface texture (Figure 4). Geometry cannot be solely responsible for the quality of a component, but this is also due to the microstructure and resulting properties (mechanical and thermophysical), which in turns derives from the parameters and feedstock inputs. Post-processing (such as heat treatments and surface enhancements), and validation are also critical to ensure the high density and defect-free requirements to meet design specifications.

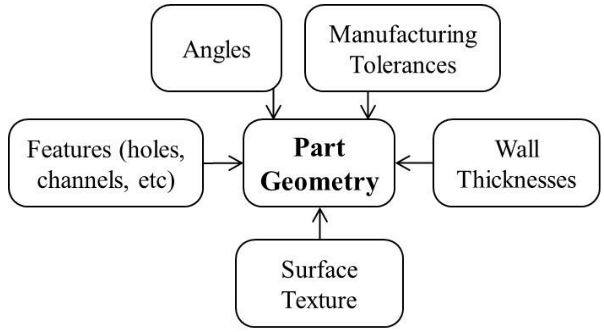

Figure 4. Aspects affecting the LP-DED process that need to be studied to characterize overall geometry limitations inherent in the manufacturing technique.

The application of Design for Additive Manufacturing (DfAM) best practices is critical with respect to successful builds [16]. The LP-DED process was initially developed for applications other than heat exchangers, therefore developmental lessons had to be learned in order to apply this process to freeform integral channel heat exchangers. This study covers the characterization of the LP-DED process applied to heat exchangers in combination with the use of the NASA HR-1 alloy. The NASA HR-1 alloy (Fe-Ni-Cr) was developed as a high-strength hydrogen resistant (ie. "HR") alloy for use in high pressure hydrogen environments [17,18]. This alloy was selected for this study since it is being considered for hydrogen-based engine applications [19]. Various aspects are being characterized such as channel geometry limitations, measurement and understanding of surface texture and manufacturing with geometric angled surfaces, surface enhancements for internal channels, and material evaluation. Characterization of these various aspects is critical for using LP-DED for heat exchangers manufacturing as the heat transfer and associated pressure drop can be tuned to meet the optimal design requirements.

2 Process Development and Characterization

2.1 Channel Geometry

In order to determine what types of microchannel geometries could be produced, the LP-DED process was tested to obtain various channel shapes. These sample channels included tube-like structures (round and oval) more representative of traditional tube-wall rocket nozzles. These types of channels offer an advantage in terms of heat transfer as they help cool the rib or land regions [20]. More traditional square and rectangular channels were also built. Finally, Hybrid D-shaped channels were deposited allowing for increased cooling of the ribs and a smooth coldwall for easier secondary processing or fabrication such as a composite overwrap structural jacket [21]. All channels were built with a targeted 1 mm wall thickness using a single-bead deposition strategy. The possibility of obtaining channels sizes (width) down to 1.4 mm was demonstrated, but accumulation of packed powder occurred more often in these types of channels, making post-processing challenging. These channel samples were deposited with no openings on the side interfacing with the build plate, so the powder was not able to flow through freely. Samples described later in Section 2.1 were deposited at 2.54 mm width with the inclusion of powder outlets (at the build plate interface) and did not experience any packed or trapped powder. A lesson was learned from these observations: openings must be incorporated in the channels for powder to flow through. The various channel geometries deposited with coarse powder (45 – 105 µm) are shown in Figure 5.

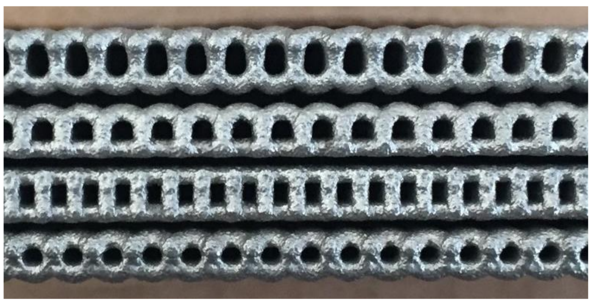

Figure 5. Various types of channels built with LP-DED 45 – 105 µm powder: Oval, D-shaped, Rectangular, Round (tube-like).

The design of heat exchangers made of channels obtained with this technique requires the understanding of various manufacturing characteristics, including the expected flow area. Therefore, a study was conducted on square channels of different sizes to determine the repeatability of the process, the differences from the design nominal, and the resulting surface texture. Five sets of square channels were produced with internal widths of 12.7, 10.2, 7.62, 5.08, and 2.54 mm. These samples were all built in the vertical build orientation (representative of the same build approach for a heat exchanger) and included powder outlets at the bottom of the channels as shown in Figure 6. Two sets of samples for each channel size were deposited, using coarse powder (45 – 105 µm) and fine powder (10 – 45 µm). The samples were all deposited successfully and did not experience any packed or trapped powder. The same machine toolpath was used for each of the coarse and fine powder samples.

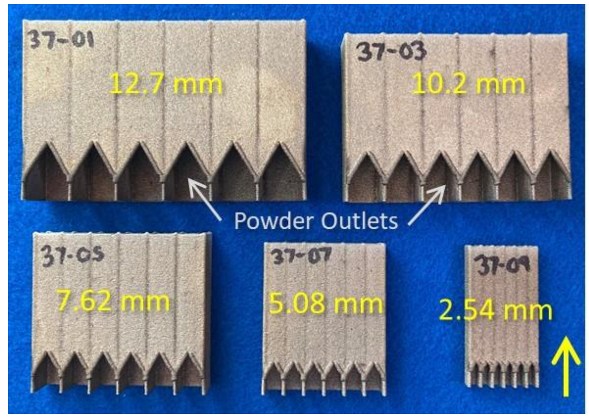

Figure 6. Various sized channel samples with coarse powder and powder exits. Build direction shown with arrow.

Each sample was sectioned using a metallographic saw, mounted, and polished to determine the as-built cross-sectional area. The areas of three channels per sample (Appendix, Figure A) was measured using an optical microscope. The difference of the measured area from the as-designed area is plotted in Figure 7, which also shows the effect of manufacturing with a coarse and fine powder particle size distribution (PSD). It can be observed that the measured area is always smaller than the specified area and that the deviation generally increases as the channel size decreases. One cause of the resulting smaller dimensions of the channels is the shrinkage occurring during the deposition process as the samples cool. The size reduction can be experimentally determined and thus predicted, so that CAD models can be appropriately scaled. A smaller cross-sectional area with a decreasing channel width is expected since the channel inner surface becomes larger due to texture. A higher deviation in area was also expected using coarse powder. The prior study on thin-wall LP-DED [22] observed that the surface texture is estimated by 2x the maximum powder diameter, which can help determine the approximate as-built area of the channels (Figure B in Appendix).

From the same samples shown in the Figure 7, the cross-sectional area and comparison between channels of the same size were analyzed and shown to be highly reproducible (Appendix, Figure A). Approximately 1% difference is observed between channels of the same size. The only outlier from this data is the 2.54 mm fine powder channel with a 2.7% difference between channels. Some of this error is due to a single (end) channel that has extra stock added with the outer radius (observed in Figure 10). While differences from designed to as-built channels are observed, the reproducibility data shows that with established parameters and feedstock, consistent microchannels can be produced.

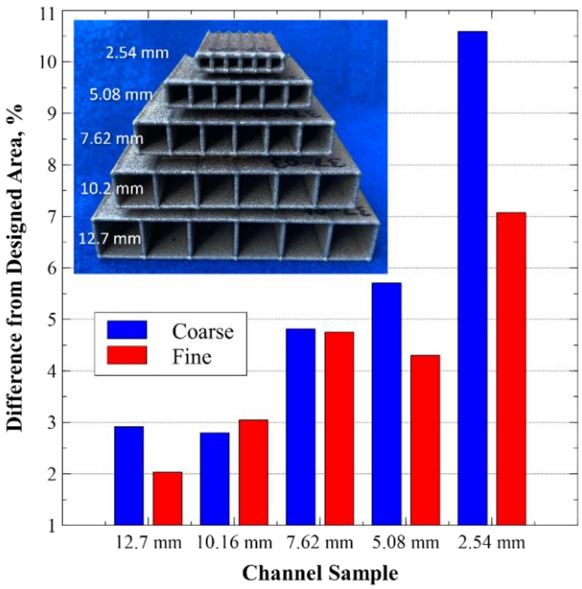

Figure 7. Difference of cross-sectional area (compared to as-designed area) for each channel sample.

2.2 Surface Texture

The surface texture is critical to component design since it can impact heat transfer, friction factors resulting in pressure losses, and fatigue life of a heat exchanger. Surface texture, defined as the profile that encompasses the form, waviness, and roughness, not only has implications for the component, but also the system. Due to variations that can be caused by the changes in pressure, heat loads, or fatigue performance, texture may influence overall engine system performance. While assumptions can be made about the surface texture during conceptual design, there is often uncertainty in the value until hardware could be fabricated. The sensitivity of surface texture has been shown in prior studies and can increase component pressure drops by 70% or more [23]. Surface roughness has been shown to be much higher in AM compared to traditional fabrication methods and can approach 50 µm depending on the AM process [24]. Traditional manufacturing methods, such as milling, allowed for surface roughness typically less than 3.2 µm within channels [25]. There are novel opportunities in AM though to obtain samples early in the development process to characterize surface texture for analysis. This can be on channel witness samples of wedges (pie slices) representative of a full-scale heat exchanger.

The surface roughness inside small cross-sectional area channels is extremely critical to meet the expected performance of a rocket engine combustion chamber or nozzle with systems requirements [26]. It is important to understand and measure surface texture (when possible) in AM components immediately following the build process and throughout the AM lifecycle since it can change during post-processing or operation [27]. Since AM often requires post-processing, there is another unique opportunity to tune the surface texture with surface enhancements to further optimize performance of the heat exchanger. Surface enhancements are briefly discussed in Section 2.5. A holistic view of surface texture throughout the AM lifecycle and systems design is shown in Figure 8. The surface texture of the internal microchannels is important for fluid flow of the propellants in heat exchangers, while the outer surface will make up the hotwall or coldwall of a chamber or nozzle. This is also critical to understand the hot gas flow and resultant heat load. Researchers have shown that AM surfaces in the as-built condition can cause 20-30% increases in heat loads [23,28].

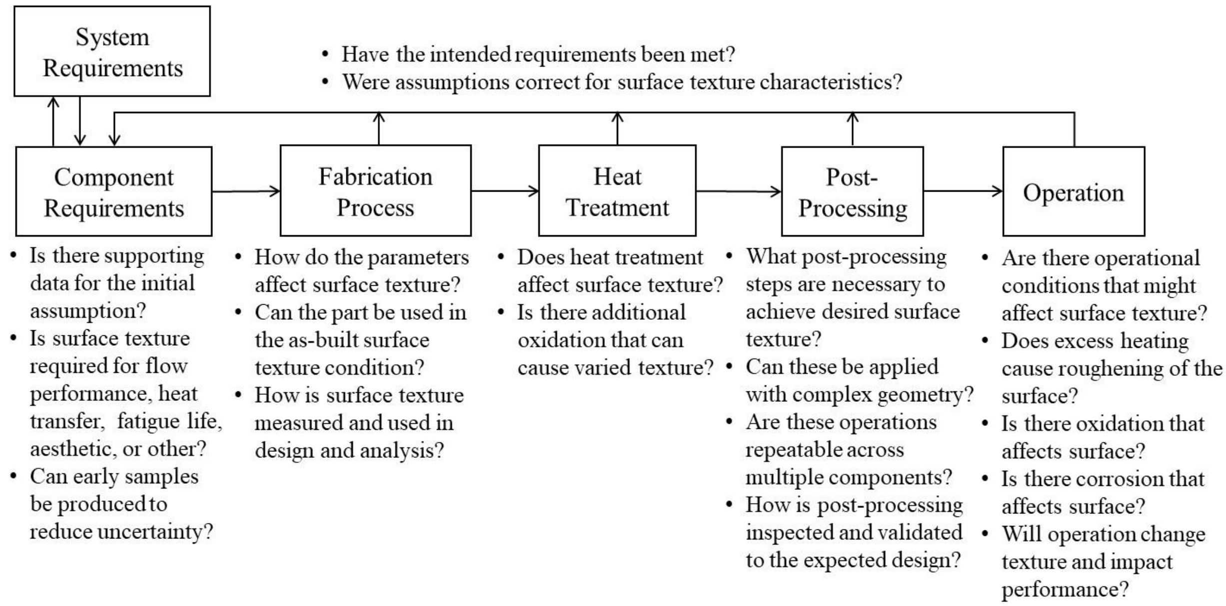

Figure 8. A holistic view of surface texture throughout the AM lifecycle.

Due to the importance of surface texture from the component and system perspective, several studies are being completed to characterize texture. A prior study was completed to evaluate the surface texture of the LP-DED process using 1 mm thin-wall NASA HR-1 alloy oval racetracks (flat walls with connecting half circles, shown in Figure 11) while varying build parameters [22]. A design of experiments (DOE) was used to determine optimal parameters to minimize texture (inclusive of roughness and waviness). It was determined that the texture is derived from excess powder captured in the trailing edge of the deposited melt pool as it solidifies and is dominated by peaks (from the powder). Using fine powder reduced the roughness by 23% compared to coarse powder. There was also a difference in texture shown between the inner (internal) surface (trapping additional powder) compared to the outer (external) surface due to the enclosed space trapping excess powder that recirculated. A reduced layer (build) height, from 0.254 mm to 0.229 mm, also showed a decrease in surface texture but would result in increased build times. While the samples in this DOE study were thin wall, the walls were spaced too far apart to representative microchannel heat exchangers.

To properly apply surface texture assumptions in a heat exchanger analysis, a further study was completed on a series of various sized microchannels (the same as shown in Fig. 6 and 7). These channels were sectioned along the length and scanned using an optical profilometer (Keyence VR-5200). The average areal surface roughness, Sa, was then obtained for each sample on the inner (internal) and outer (external) surfaces. The Sa was selected to study these samples as a commonly used parameter to characterize roughness for AM components due to the complexity of the surface [29]. It is recognized there are many other surface characterization parameters and will be presented in future studies. The Sa data is plotted for the coarse (45 – 105 µm) and fine (15 – 45 µm) powders in Figure 9. The coarse powder is shown to have a higher average roughness than fine powder. This higher roughness is consistent with the prior study but to a higher degree (45% compared to 23%). The surface roughness across the various sizes of channels is generally constant except for the 2.54 mm channel. The 2.54 mm coarse powder channel shows an increase that averages 17% while the fine powder channel averages 10%.

The difference between the inner and outer surface is minor but shows slightly higher average roughness on the outer surface. For the fine powder, the difference is about 6% comparing inner and outer surfaces. This is opposite of what was shown in the prior study using oval racetracks [22]. The channel samples in the current study have an outlet designed at the bottom of each channel (Figure 6). This allows the powder to fully exit and not recirculate internal to the channel. The central gas used for inert purge of the deposition and carrier gas for the powder travels through the internal channel at a high velocity allowing excess powder to flow through the channel instead of stagnating (compared to the prior closed oval racetracks in [22]). During deposition of channels, another observation with the fine powder was the suspension in the atmosphere of the machine (particles on lower end of PSD). These fine particles can bond to the outer surface as it melts and solidifies causing the higher roughness observed in Figure 9.

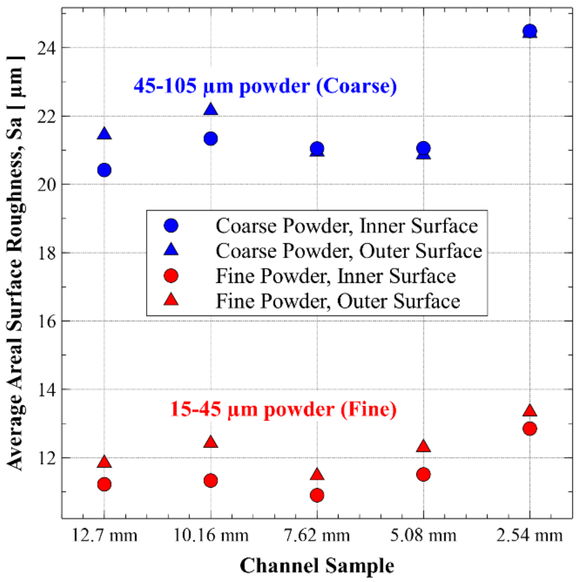

Figure 9. Surface texture of various sized channel samples.

The difference in texture is also apparent from the cross-sectional micrographs shown in Figure 9. The coarse powder is observed to have the higher roughness that could help enhance heat transfer, but potentially results in higher friction factors. The wall thickness is also observed in the cross sections with slight thinning as the center rib approaches the outer walls. There are slightly raised areas on the outer surfaces where the ribs tie into the inner and outer walls during caused by deposition and more apparent on the fine powder samples. The raised region on 2.54 mm channel using fine powder averages 118 µm and coarse powder 35 µm. This region is not a significant concern for chamber or nozzle component since it would be parallel to the direction of flow (assuming axial channels). It may also be removed during post-processing operations.

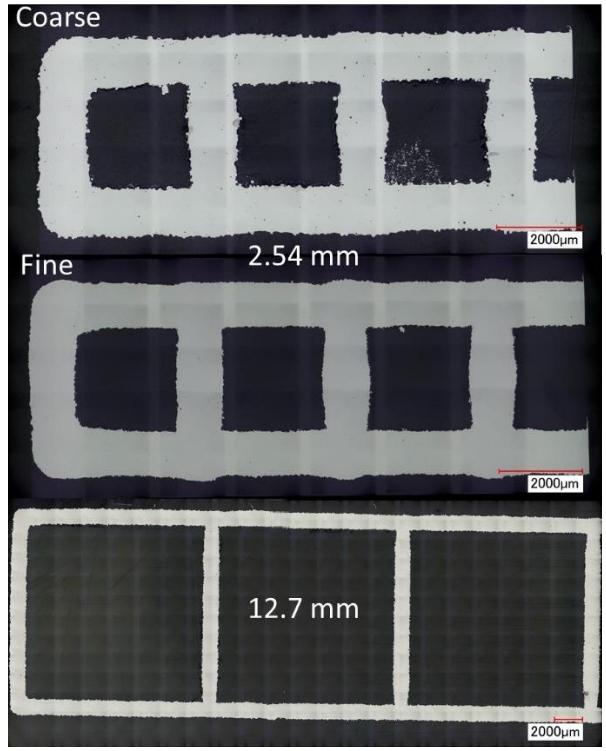

Figure 10. Optical micrographs of select channel samples showing fine and coarse powder (2.54 mm channels) and 12.7 mm channel for comparison (bottom).

2.3 *Wall Angles*

Wall angles continuously varying throughout nozzle and chamber designs. The limitations for an AM process must be understood to apply design constraints to avoid build failures. While the LP-DED process allows for 5-axis motion control, it is generally not the best toolpath options. Instead, a 2+1 axis build approach, or layer by layer, is more commonly used to build heat exchanger development hardware. Based on this limitation, it is necessary to understand the build angle limitations for the process. A series of oval samples were deposited using coarse powder in increments of 5° up to 45° (relative to vertical build direction) or until a sample failed. These samples are shown in Figure 11.

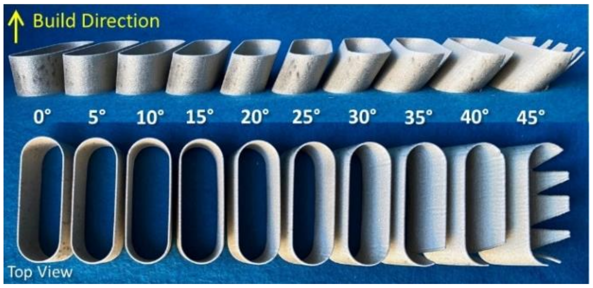

Figure 11. Varying angle LP-DED enclosed samples using coarse powder.

Visually, the limitation of the LP-DED process is observed with samples failing in local regions above 30°. Although these issues are in the compound angle of the radius, a manufacturing process should not be operating at the margin of a failure. From this, a build angle of 30° is recommended for the NASA HR-1 alloy with a wall thickness of 1 mm. An alternate approach to LP-DED builds for chambers and nozzle components is to split the wall angle (from forward to aft end of a nozzle) to minimize angle offsets. The trunnion table can also be varied throughout the build at discrete points, but continuously varying causes challenges with toolpaths at more complexity of the deposition.

2.4 Wall Thickness

Wall thickness is an important characteristic of heat exchanger design since it will impact heat transfer and the peak temperatures the hotwall will experience during operation. The wall thickness must be thin enough for proper cooling, but provide adequate thickness to maintain positive structural margins for strength and fatigue life. The rib thickness between channels is also important since it impacts cooling of the hotwall through conduction. A wall thickness of 1.05 to 1.165 mm could be maintained consistently for both the fine and coarse powder samples, which was identical to the prior study on thin-wall NASA HR-1 [22]. Summary data that measured both the rib thickness and the outer wall (i.e. simulated hotwall) thickness of the various width channel samples is shown in Figure 12. Three measurements were collected from each channel rib and outer wall in the cross-sectioned sample and the data was averaged. The measurements were taken in the areas where the wall is constant and not thinning (as shown in Figure 10).

It is observed that the coarse powder samples are slightly thicker by about 2.6%, driven by the larger PSD of the powder causing this difference. There is also a difference observed between the coarse and fine powder outer wall thickness of about 3.8%. Another observation from this study is the slight difference between the rib wall thickness and outer wall thickness that averaged 2.5% and 3.7% for coarse and fine powder, respectively. This difference in wall thickness is due to slightly different build parameters. The outer wall is deposited at a constant travel speed while the rib wall is deposited at a varying travel speed to ensure the intersection with the outer wall is not overbuilt (acceleration and deceleration leading into the intersection). The thickness was expected to be constant between channels since the build parameters do not change based on the channel size.

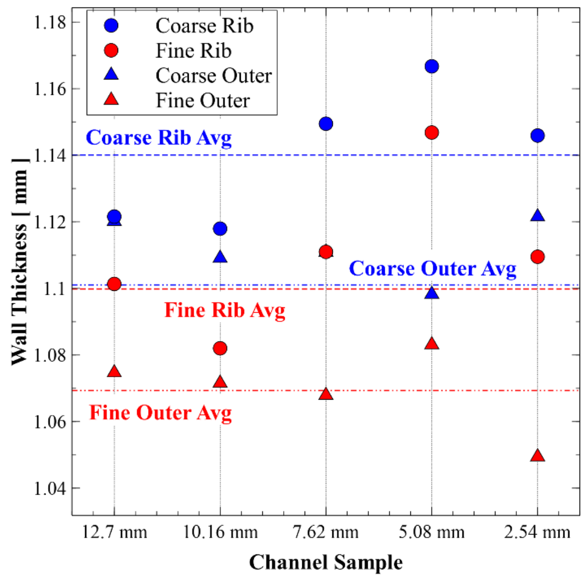

Figure 12. Summary of rib and outer wall thickness for channel samples.

2.5 Surface Enhancements and Inspection

Heat exchangers using AM is highly dependent of the requirements for the end use application. For combustion chambers and channel wall nozzles in liquid rocket engines, the objective is to minimize pressure loss through the component while ensuring the wall temperature is within structural limits for the selected alloy. Increased surface roughening can provide a heat transfer enhancement, but increases the friction factor and subsequent pressure drop; a proper balance of surface texture must be maintained for each design [30]. While each set of requirements is unique there is now an opportunity using AM to tailor the surface finish to meet a set of requirements (as shown in Figure 8). The internal hotwall surface might be left in the as-built condition to allow for heat pickup for an expander cycle rocket engine or may require a surface enhancement, or polishing, to reduce overall heat load. The L-PBF process has been shown that parameters can be adjusted to vary the surface texture with contour parameters [31]. It was shown with the LP-DED process that surface texture can be varied slightly driven by changes in the powder size [22]. However, since the LP-DED process uses a single-bead (no contour passes) and the mechanism for roughness is excess powder being solidified in the melt pool, the parameters cannot be significantly modified to adjust roughness. Because of this, polishing processes are being explored to alter the surface texture to adjust and tune as needed for component and system design requirements.

Surface polishing of LP-DED is not a research area that has been explored for LP-DED except for laser polishing [32,33]. Laser polishing is limited though to line of sight and significant challenges exists to apply for internal passages [34]. Polishing of the internal channels built using the LP-DED process is being investigated in current research to tune the desired surface texture. Processes that have the most potential for internal LP-DED channels include chemical milling (CM), chemical mechanical polishing (CMP), abrasive flow machining (AFM), dissolvable surface sensitization, electropolishing or electrochemical polishing/machining (EP/ECM), magnetic abrasive finishing (MAF) [35–42]. Development, experimental testing, and characterization is being conducted using selected polishing processes for LP-DED microchannels and future results will be made available.

Current processes to characterize the internal surface texture of microchannels involve sectioning the samples to view a direct surface, as shown in this paper. For heat exchanger hardware produced for an end-use application, destructive evaluation is not feasible. Techniques such as nano-computed tomography (nanoCT) and microscale CT (microCT) are being explored to determine surface texture. The development of these processes will be further important in conjunction with polishing processes to verify a surface condition of hardware to validate analytical or numerical predictions as part of the system performance. An example of microCT scanning on a LP-DED channel is shown in Figure 13. This scan was completed using a microfocus Pinnacle 225 kV tube with 7.5x magnification and resolution of a 27 µm voxel size.

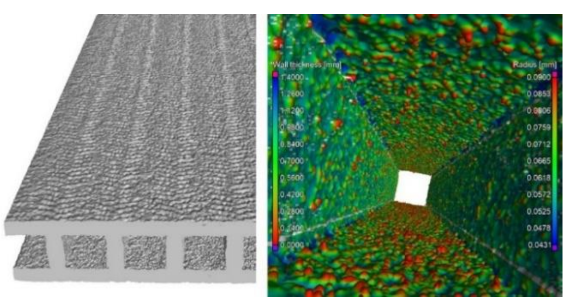

Figure 13. MicroCT scanning of internal LP-DED channels (2.54 mm).

3 Demonstration of Hardware

Various channel wall nozzles were tested using the LP-DED process with metal alloys including NASA HR-1, JBK-75, and Inconel 625 [43,44]. These LP-DED nozzles have been tested using various propellant combinations including Liquid Oxygen/Liquid Hydrogen (LOX/LH2), LOX/Kerosene (LOX/RP-1), and LOX/Methane (LOX/CH4). Several NASA HR-1 LP-DED channel wall nozzles at thrust classes ranging from 8.9 to 156 kN have completed hot-fire testing at NASA Marshall Space Flight Center (MSFC). The purpose of this testing was to demonstrate the alloy and AM processed hardware in a relevant environment and determine heat transfer and pressure drop across various designs. A total of 290 starts and 9,164 seconds of hot-fire testing has been accumulated across six LP-DED NASA HR-1 nozzles. A single nozzle at 8.9 kN thrust accumulated 207 starts and 6,756 seconds with consistent performance between tests. An example of a 31 kN LP-DED NASA HR-1 nozzle is shown in Figure 14A and hot-fire test of a high duty cycle (207 starts) nozzle in Figure 14B. While the NASA HR-1 alloy was demonstrated in the extreme environment, additional design and post-processing (such as polishing advancements) lessons were learned to optimize the process for infusion into flight applications.

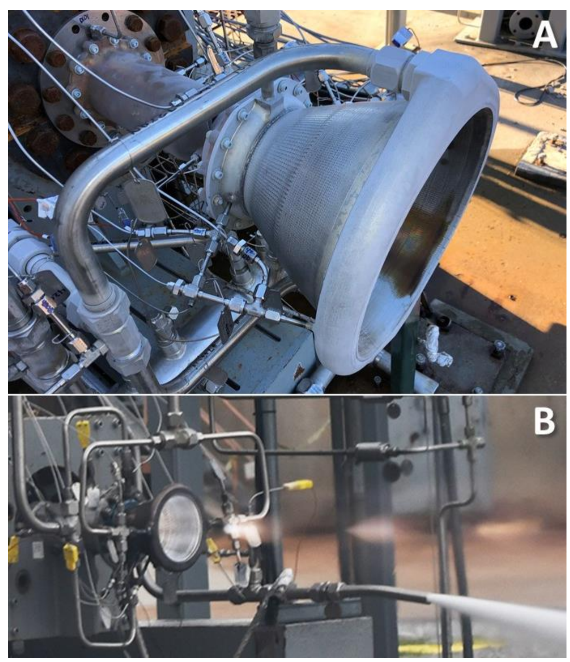

Figure 14. LP-DED NASA HR-1 integral channel nozzles. A) 31 kN nozzle on the test stand, B) Hotfire of a nozzle that accumulated 207 starts and 6,756 seconds.

4 Summary and Conclusions

The laser powder directed energy deposition (LP-DED) process has been demonstrated using integral microchannels for heat exchangers, such as liquid rocket engine nozzles and chambers. The LP-DED process allows for large scale hardware to be manufactured while maintaining small feature resolution (thin-walls) down to 1 mm. The scale of LP-DED hardware with microchannels can easily exceed 1 meter diameter, which is the beyond limitation of high complexity L-PBF. As manufacturing processes are being matured for new applications, it is important to understand the process limitations and geometric constraints. Detailed characterization of these attributes allow engineers to properly apply to new hardware designs. The purpose of this research was to provide a baseline for the LP-DED process since it has not been used for microchannel heat exchangers. This paper focused on characterizing geometric constraints used for microchannel samples including angles, tolerances, channel sizes, wall thicknesses, and surface texture.

Various types of channel geometries were successfully deposited using the NASA HR-1 alloy (Fe-Ni-Cr) including round, oval, square and D-shaped. These channels provide new design opportunities for designers compared to round tubes or square channels for traditionally manufactured tube-wall or channel wall nozzles. Several square channel sizes were successfully deposited with highly reproducible width down to 2.54 mm. Smaller width channels were also successful, but could result in higher risk for excess powder being trapped within. The measured cross-sectional channel areas were smaller than the designed areas and increased in deviation as the channel size decreased. The difference in the area is mostly caused by the excess powder that adheres to the internal surface causing the surface texture in addition to shrinkage from deposition. This difference in channel size can be adjusted by scaling the CAD build models to meet the desired design geometry. Various angles were also demonstrated and 30° (relative to the build direction) was the observed limitation. More severe angles could be built (up to 45°) but may cause build crashes on compound surfaces. Wall thicknesses were also demonstrated to be highly reproducible with only slight differences between powder sizes and the internal channel rib and outer wall.

Surface texture is an important consideration for heat exchangers for heat transfer and fluid flow and should be considered throughout the entire design and manufacturing process lifecycle. The size of the powder (coarse and fine) provided variations in surface texture for various channel sizes, with fine powder having about 45% lower surface texture. The channel size, when properly using powder exits at the build plate interface, had little impact or the inner or outer surface texture. LP-DED has limited ability to adjust surface texture with build parameters. The use of fine powder or application of post-processing polishing techniques may be feasible to tune the surface texture necessary for a design.

The LP-DED process has tremendous potential for manufacturing of large-scale channel wall nozzles or combustion chambers. A 1.52 m dia. and 1.78 m height integral channel nozzles was built in 90 days. This provides a significant opportunity for schedule and cost reductions compared to traditional manufacturing technologies. Hot-fire testing has been conducted on six NASA HR-1 alloy nozzles accumulating 290 starts and 9,164 seconds. While this testing been successfully demonstrated, additional research is required to understand the friction factors and opportunities to improve the surface texture. Being able to adjust surface texture combined with the characterization of build geometry limitations will allow future designs to be implemented for development and flight applications.

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Appendix

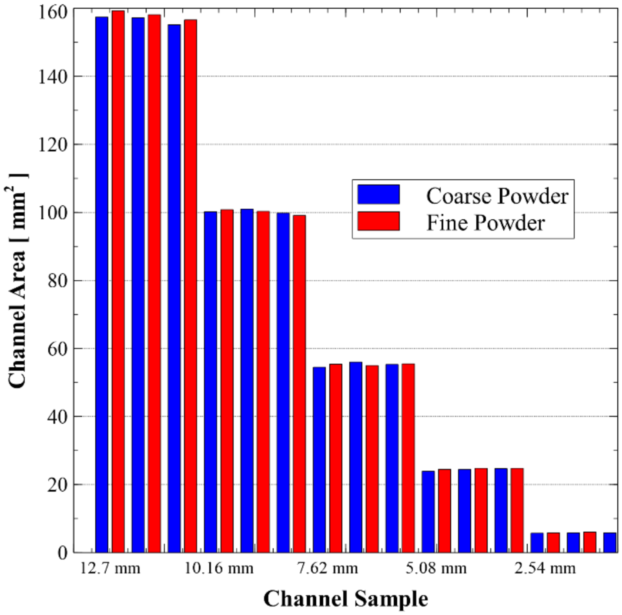

Figure A. Comparison of actual area for each channel size.

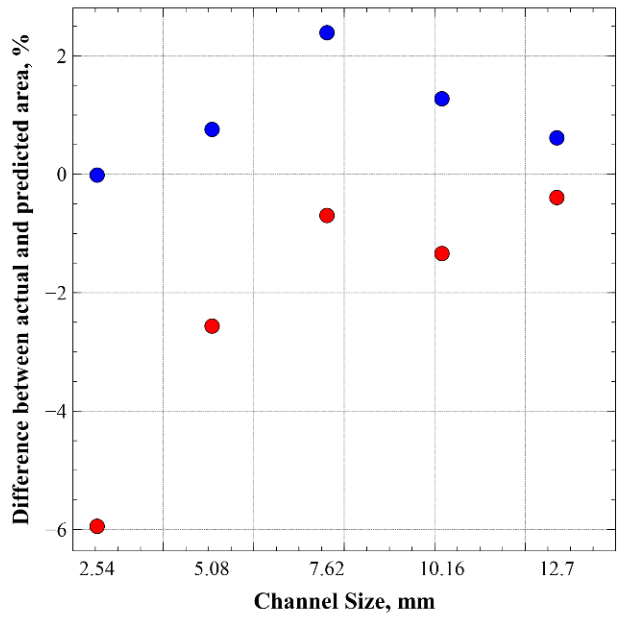

Figure B. Differences in predictions using powder size offset for channel area.