Rapid Large Scale Additive Manufacturing of Full-scale RS-25 Engine Nozzle Liner

B. Dutta[1], M. Lewan[1], V. Singh[1], R. Fortuna[1], F. Ghadamli[1], P. Gradl[2], R. Hickman[2], J. Fikes[2], M. Ogles[3], K. Wheeler[4], V. Hafiychuk[4], H. Hafiychuk[4]

[1]DM3D Technology, [2] NASA Marshall Space Flight Center, [3] National Center for Additive Manufacturing Excellence (NCAME)-Auburn University, [4]NASA Ames Research Center

Problem definition

Recent years has seen the evolution of various metal Additive Manufacturing (AM) technologies at a very rapid rate and subsequent adaption of the technology by wide range of industries; from medical to consumer, from oil & gas to space & aerospace, from automotive to defense etc. While the AM has been dubbed as 4^{th} industrial revolution, it has made little in-road in to the arena of large-scale part manufacturing. Among all the metal AM technologies, Directed Energy Deposition (DED) technologies are more easily scalable than others and therefore well suited for manufacturing large parts. Direct Metal Deposition (DMD®) is one of the DED technologies that uses high power laser as heat source and metal powder as feedstock to 3D print metal parts layer-by-layer directly from the CAD data. This technical brief focuses on additive manufacturing of NASA's RS-25 engine nozzle liner using DMD technology. This liner (10ft in height and 8ft in diameter) is beyond the print capability of existing 3D printing processes. In order to print this part, significant advancements were made to the DMD technology that doubles the process throughput, scales the technology significantly, and coupled with process simulations to make large-scale parts that were not previously considered feasible. This is accomplished by incorporating two simultaneous process heads in the custom machine and expanding the work envelop to allow manufacturing of such large parts in a safe and efficient environment. A successful demonstration of the AM of the RS25 engine nozzle liner marks a new era in 3D printing and elevates the current 3D printing technology to a new level for affordable manufacturing of large metal parts.

Background perspectives

Large-scale booster and upper stage liquid rocket engines (>100,000 lbf thrust) are being developed and used across multiple commercial launch vehicles and defense applications to provide continuing and reduced-cost access to space for current and future missions. As part of this effort, systems-level cost requirements are being flowed down to a component level to reduce associated design, development, manufacturing and test costs while maintaining high performance. Some of these savings can be realized through additive manufacturing. As a result, the space industry has embraced metal AM technologies with Powder Bed Fusion (PBF) based AM emerging as the front runner so far. However, PBF techniques are very limited in scale (max 32"x16"x20"). Electron beam based DED (EB-DED) offers larger area capability (96" diameter x 48"H), but limited in height and in choice of metal alloys (Fig. 1). While high power and large beam size (electron beam in EBAM or wire arc in WAAM) in EBAM/WAAM allow these techniques to achieve high build rate, this results in a reduction complex feature capability and process resolution, while introducing large distortions in the part. Considering the market need and size limitation of existing metal AM technologies, it was determined that there is significant need to advance the current metal DED technology. With this goal in mind, a new generation multi-nozzle DMD system was designed, fabricated and commissioned. This development provides critical capabilities (ability to print up to 120" diameter and 120" height) to the commercial space industry and enhances the throughput while maintaining part resolution. The following section will illustrate the features of the new machine, and demonstrate its capability through a case study involving AM of a full-scale RS-25 engine nozzle liner. The RS-25 engine powers NASA's Space Launch System (SLS) launch vehicle selected for Artemis lunar program. Printing a large part, such as RS25 nozzle liner requires, not only considerations of print capability, but also a thorough understanding of the entire printing process, including effects of residual stress and distortion in order to produce a quality part.

Technical overview

The DMD technology is a DED technology that uses laser as heat source and metal powder as feed stock. Process head is mounted on a CNC/robotic platform to allow for a variety of complex geometries to be created. The part is defined by the CAD geometry and custom software development that allows for the AM toolpath to be created. Some features of DMD systems are:

- Patented closed-loop feedback control for the process stability and quality of the build
- Coaxial nozzle with local shielding of melt pool to provide high quality material
- 5-axis motion capability allows overhang printing and complex geometry

The new generation DMD System is a 9-axes machine with two simultaneous process heads, each equipped with a 5kW fiber delivered laser. This allows for the throughput to be doubled, while maintains a robust design that is capable of upgradation to four simultaneous process heads quadrupling the throughput. A large rotary table and tiltable process heads (±45°) allow for industry unique overhang structures at an unmatched scale. The system employs a Fanuc multi-axis control to produce synchronized motion to all axes (Fig 2. Large capacity high-feed rate powder hoppers were designed and employed to deliver up to 90g/min powder flow from each process head. Pre-heated powder delivery helps to enhance the deposition rate and eliminates any possibility of moisture condensation and resulting in porosity formation in the build. The system was designed, built in-house, and tested during challenging economic and personal times of COVID, but rapidly commissioned to support the RS-25 nozzle liner development build.

The RS-25 nozzle liner was printed with JBK-75 stainless steel, an age hardenable super alloy. JBK-75 superalloy has high thermal conductivity, high temperature strengths and resistance to hydrogen embrittlement, making it a widely popular choice for nozzle liner, hot gas sections, structural jackets, and hot gas manifolds in rocket engines. The first step involved was developing process parameters through a controlled DOE (design of experiments) to optimize the deposition process with the new multi-nozzle DMD System. Figure 3 shows typical columnar dendritic microstructures of a sample built with optimized process revealing low porosity content (>0.2%).

Advancing an enabling metal alloy and building a custom one-of-a-kind machine was no small feat to work in parallel. Following confidence in the JBK-75 alloy development, the next step was focused on the deposition strategy for the nozzle liner (Fig 4). It is well known that distortions are a challenge in AM processes and large parts exhibit larger distortions. A novel solution to resolve this issue was to compute residual tress and distortion simulations to determine the optimal build strategy for the RS-25 nozzle liner. Two types of build strategy were considered; the first strategy with bell end down and second strategy with bell end up. While the first strategy had the benefit of easier part handling, the second strategy offered some advantage during post processing, such as measurements and internal machining. However, the simulation study using Ansys Additive Manufacturing software clearly indicated that the distortion was significantly less when bell end was attached to the build-plate (figure 5). Simulations also revealed potential distortion of the part diameter due to residual stresses and solidification shrinkages during the process. Compensation values to adjust for shrinkage were estimated based on simulation results and DM3D’s past experience.

This simulation result was then used to provide distortion compensation and evaluated using DM3D’s custom toolpath AM software to provide the build strategy. Once the toolpath data was verified, it was uploaded to the machine control system and the printing process started. Figure 6 shows the part during the build process and fig 7 shows the part on completion of the build. In order to control the heat input and distortion, the build rate was maintained at about 6-7 lbs per hour and powder capture rate was approximately 75-78%, which allows for recycling of the powder for future builds. DM3D ran multiple shifts to complete deposition of the full-scale nozzle liner. Following completion of the build, the part was inspected and cleaned of loose powders. The finished part had an estimated weight of about 4,100 lbs on a build plate that weighed about 2,000 lbs. A dimension inspection was completed with 3D structured light scanning using a StereoScan neo R16 – FOV 850 from Hexagon Metrology. The high-resolution scanning system captured 6.5 million triangles (~20 million points) on the entire part surface. This allowed a comparison back to the original CAD file to determine the final geometry of the full-scale nozzle liner (Fig. 8).

Reflections

The goal of this development effort was to design and build a uniquely-scaled machine that is capable of rapidly depositing parts up to 10ft in height with enabling metal alloys for space and other applications. The new generation multi-nozzle DMD technology was developed and the RS-25 engine nozzle liner was successfully printed using this technology to demonstrate the feasibility of 3D printing large metal parts. Manufacturing of nozzle liners using the DMD process is significantly different from traditional manufacturing of such parts where preforms are made using forgings or spin forming. This new AM machine and process enables significant cost and schedule savings over traditional manufacturing on the order of 50%. Overall, this allows for a reduction in processing time, a local on-demand manufacturing supply chain that is minimized and a tool-less manufacturing process that allows for rapid design iterations and deployment. The development team is continuing with part inspections, Non-destructive testing, and destructive material testing to evaluate this alternate method of manufacturing for nozzle liners and similar parts. This successful demonstration opens up a new era of manufacturing large scale metal parts using AM. It also highlights the iterative and integral nature of the manufacturing process, use of advanced tools such as stress-distortion simulation and the need for development of process and material data that is critical to successful manufacturing of such large parts. A successful collaboration of various government, academic, and industry teams included DM3D Technology, NASA MSFC, Auburn University, and NASA AMES. NASA and Aerojet Rocketdyne were the ultimate customer and part design and integrators and early adopters of metal AM. NASA Ames provided expertise in simulation of metal AM processes using unique strategies to provide success of the process. DM3D Technology was the developer of the DMD technology and metal AM expert. This project was established under a public-private partnership with all the partners and contracted through Auburn University NCAME under the NASA Rapid Analysis and Manufacturing Technology (RAMPT) Project. This project showcased the successful implementation of cost-sharing and underscores the need for more collaborative work to enhance and create new disruptive technologies.

It is expected that this demonstration will open up the doors of large-scale metal AM and will directly benefit the fast-growing commercial space industry that are in constant need of large structures. Rapid manufacturing speed, along with ability to incorporate new design changes with minimum effort, will be a perfect tool for current and future design and manufacturing engineers. This could lead to faster innovation and enable future missions to the Lunar surface and Mars. Space programs such as Aerojet Rocketdyne's AR-1, RS-25, RL-10 engines, SpaceX's Merlin, and Raptor engines, Blue Origin's BE4 and BE3/BE3U engine, Virgin Orbit's Newton 3 and Newton 4 engines as well as Relativity Space, Launcher, Firefly, ABL Space System, Astra and many others to incorporate into their production processes. There are multiple military programs that use such engines and large structures that will benefit from this development. Outside of rocket engines, this capability will open up opportunities for other industry sectors, such as aerospace, defense, energy industry etc.

References

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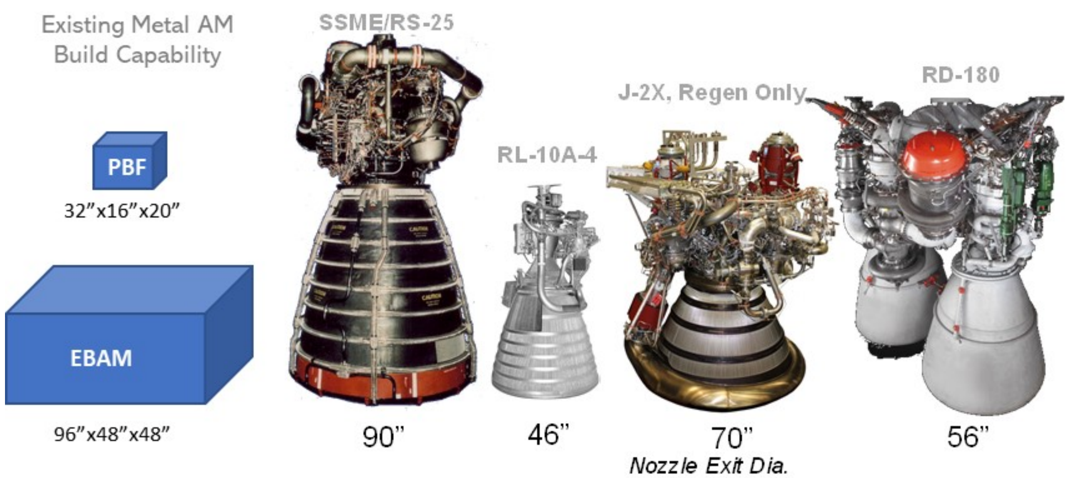

Figure 1. Comparison of current PBF and EBAM machine limitations with rocket engine nozzle needs.

Figure 2. DMD Multi-nozzle system. Left: DMD machine. Right: Dual nozzle technology for rapid 3D deposition.

Figure 3. DMD of JBK75 stainless steel. Left: Cross-section of sample deposit. Right: Microstructure.

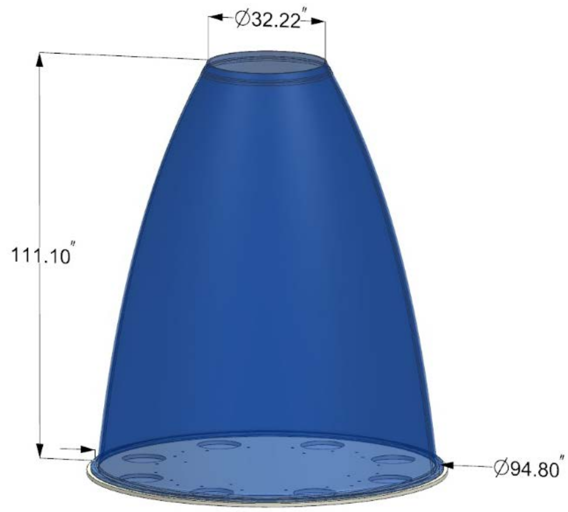

Figure 4. CAD model showing dimensions of the RS-25 engine nozzle liner along with build-plate at the bottom.

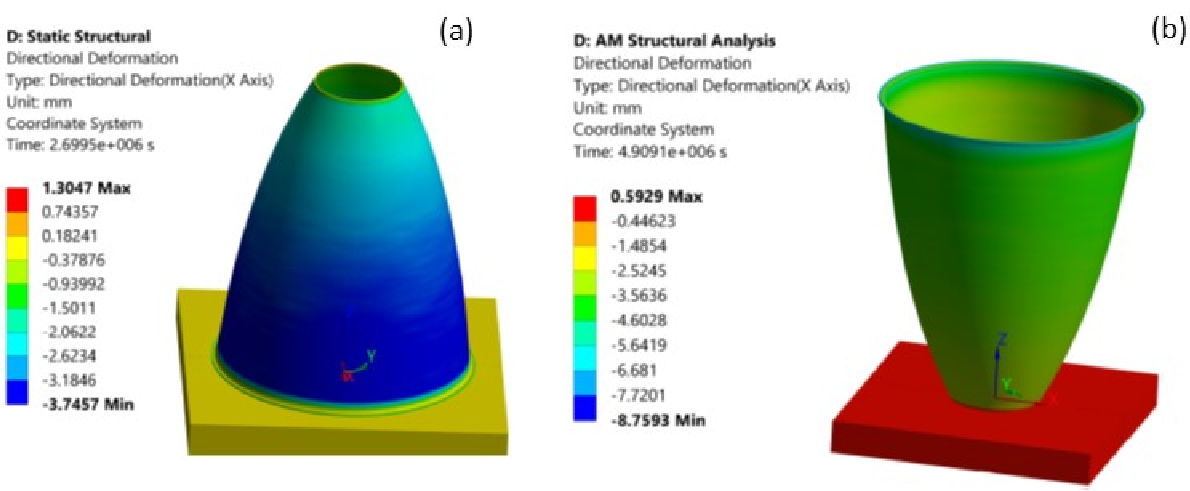

Figure 5. Simulation showing radial distortion of the part in two different build strategies. Left: Bell-end down. Right: Bell-end up.

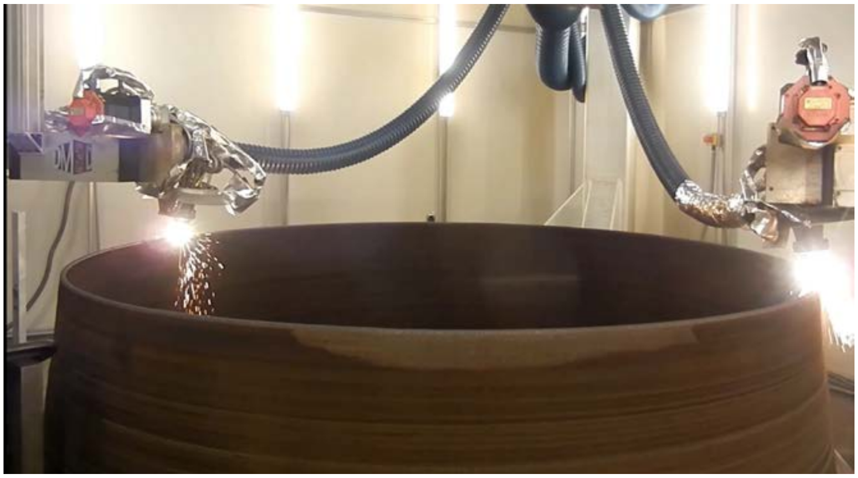

Figure 6. DMD simultaneous dual nozzle printing of the RS-25 liner.

Figure 7. Picture of full-scale RS-25 nozzle liner on completion of the build.

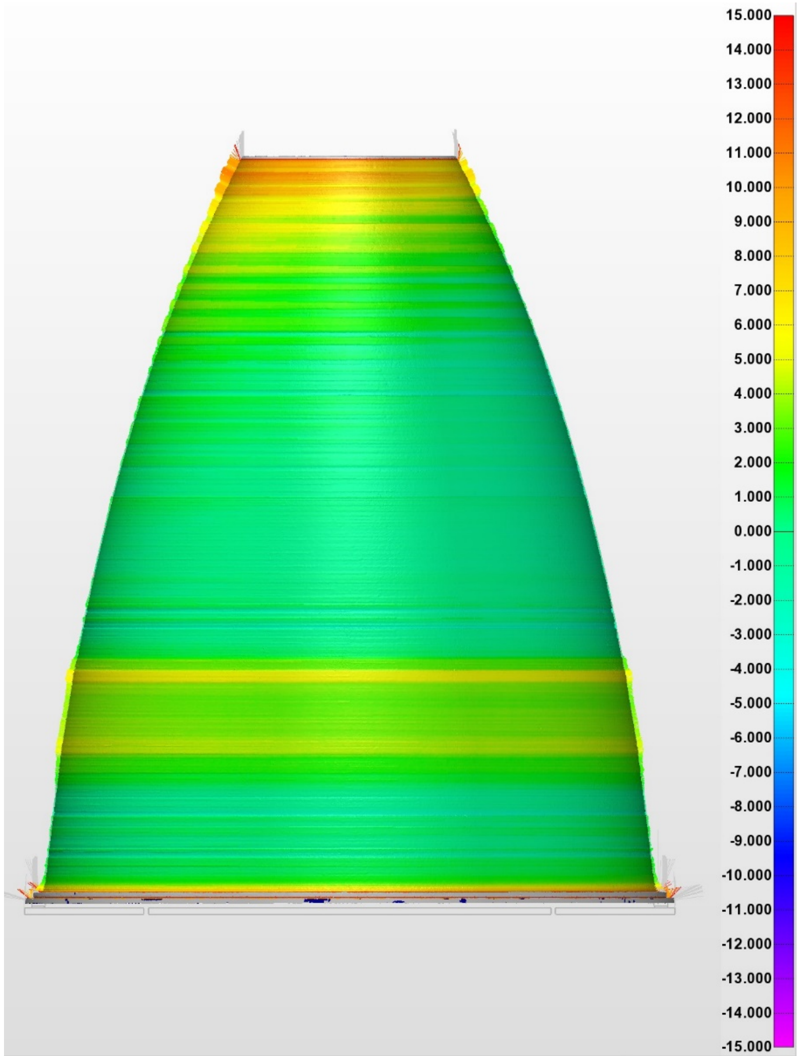

Figure 8. 3D scanned data overlayed on the CAD of the part showing dimensions of the DMD printed part.