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Application of Directed Energy Deposition for Transformational Challenge Reactor Core

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OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The following report focuses on utilizing directed energy deposition (DED) for constructing metal components and structures pertaining to the Transformational Challenge Reactor core. Multiple additive manufacturing processes are under investigation to evaluate the advantages and viability of each process for direct manufacturing of complex structures needed for future nuclear reactors. Technologies under investigation include binder jetting, laser powder bed fusion (LBPF), electron beam powder bed fusion, and DED. Each process has advantages and disadvantages. DED research has focused on processing parameter development, evaluation of toolpath generation algorithms, core designs suitable for DED, manufacturing tolerances for integration of fuel elements, and seamless calibration and integration of laser powder bed manufactured components into a DED build volume to create monolithic structures based on integrating these technologies. The following report highlights the capabilities of DED process to produce relevant structures for the TCR core and provides experimental validation of test components necessary for finalizing the core design.

1. OVERVIEW OF ADDITIVE MANUFACTURING PROCESSES

Additive manufacturing conventionally comprises seven different methods, with an eighth category focusing on hybrid systems that combine multiple manufacturing processes into one system (see Figure 1). (Hernandez 2012) Three of the seven methods, vat polymerization, material jetting and material extrusion, are generally limited to polymers with the prime application being rapid 3D models and prototypes. Powder bed fusion, binder jetting, direct energy deposition and sheet lamination are the standard metal additive manufacturing processes. (Frazier 2014)

Both powder bed fusion and binder jetting build three dimensional structures by depositing and selectively fusing material layer by layer. In terms of locally fusing material each layer, powder bed fusion processes can use lasers (single or multiple), as well as an electron beam (electromagnetically guiding energy). The laser powder bed process has a relatively low powder bed temperature (under 200°C), which has the advantage of very easy powder removal (pours away like sand) and the disadvantage of high residual stress. On the other hand, electron beam powder bed uses the energy source to elevate the powder temperature (over 600°C). In addition, the nature of the electron beam enables simultaneous control of numerous weld pools (in excess of 50). The combination of high powder bed temperature and ability to spread heat out through controlling numerous weld pools provides significantly lower residual stresses but makes powder removal more challenging than laser powder bed. Binder jetting works in a similar nature to laser and electron beam powder bed fusion, except that a binder fuses the material rather than melting. The advantage of the binder jetting process is the ability to manufacturing almost any powder (polymer, metal, ceramic, etc.) at room temperature providing low manufacturing residual stress. The challenges for the binder jetting process are handling the parts while removing from the powder bed, as the parts are held relatively weakly together by a binder, which leads to limitations in manufacturing extremely delicate structures. The parts are likewise porous requiring a post sintering and back infiltration process to create fully dense parts. In all three of these processes, unfused powder in each layer provides mechanical support enabling production of extremely complex geometries.

A typical DED machine consists of a nozzle or deposition head mounted on a manipulation system, which deposits melted material onto a specified surface where it solidifies. The material can come in the form of wire or powder. The energy source can be a laser, electron beam, or wire welding system (metal inert gas, tungsten inert gas). The blown powder systems generally have superior surface finish and ability to blend material but are typically slower and more expensive than wire systems. Powders are usually more expensive than wire feedstock and material utilization is generally under 50%.

The final family of metal additive processes is sheet lamination. Rather than using a powder for the feedstock, sheet lamination uses thin foils of soft metal and fuses layer to layer through solid state welding via an ultrasonic horn. The advantage of this process, like the binder jet, is a low manufacturing temperature enabling integration of sensors within a single structure. The process does require post machining and is limited to relatively soft metals (copper, bronze, aluminum).

Other reports will cover the details on the binder jet and laser powder bed platforms. This effort focuses on reviewing the DED process and its contribution to the main structure of the TCR core.

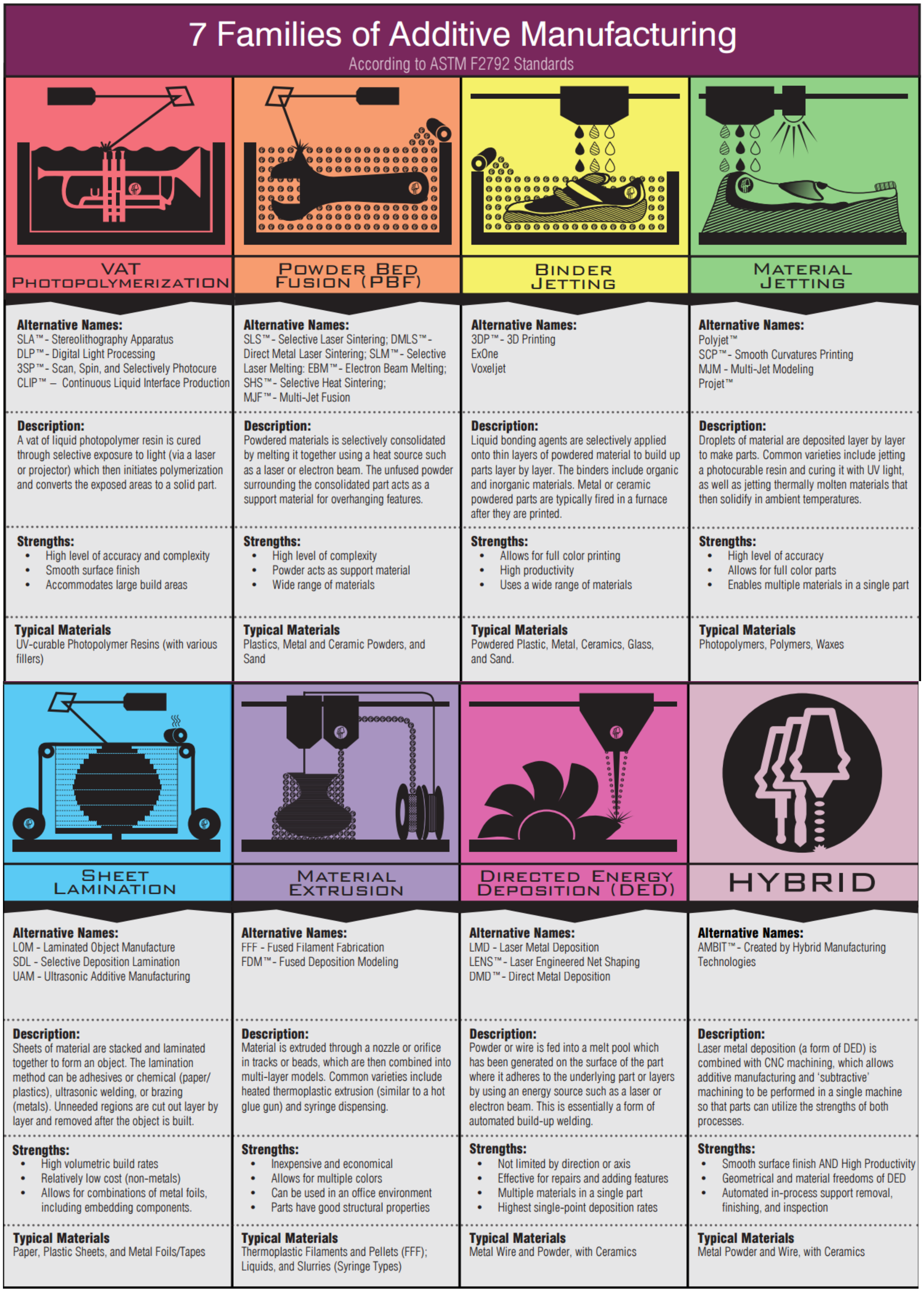

Figure 1. Additive manufacturing processes[1]

[1] Image created and designed by Hybrid Manufacturing Technologies http://www.hybridmanutech.com/resources.html.

2. DIRECTED ENERGY DEPOSITION

Directed energy deposition covers a broad range of materials and processes. A typical DED machine consists of a nozzle or deposition head mounted on a manipulation system (robot, Figure 2, or gantry, Figure 3), which deposits melted material onto a specified surface where it solidifies. The process is similar to material extrusion except that rather than melting and extruding a thermoplastic, an energy source is used to melt and fuse metals to create near net shape structures. The material can come in the form of wire or powder. The energy source can be a laser, electron beam, or wire welding system (metal inert gas, tungsten inert gas). As with additive in general, each process has advantages and disadvantages. The blown powder systems generally have superior surface finish and ability to blend material but are typically slower and more expensive than wire systems. Powders are usually more expensive than wire feedstock and material utilization is generally under 50%.

Figure 2. Robotic wire arc

Figure 3. Gantry laser powder system[2]

2.1 WIRE ARC DED

One of the earliest forms of DED was robotic wire arc additive manufacturing. Low-cost metal inert gas or tungsten inert gas welders are mounted on a robotic positioner or gantry system. The advantages of wire arc DED include high deposition rates (exceeding 5 kg/hr), low cost (using conventional welders and welding wire), and large-scale components. The technology can be scaled to include multiple energy sources and multiple materials on a single part (see Figure 4). The challenge for wire arc DED is surface finish; the beads are generally large (a few millimeters in diameter), thereby limiting surface finish (see Figure 5).

[2] Image from https://3dprint.com/194813/beam-ded-interviews-formnext/.

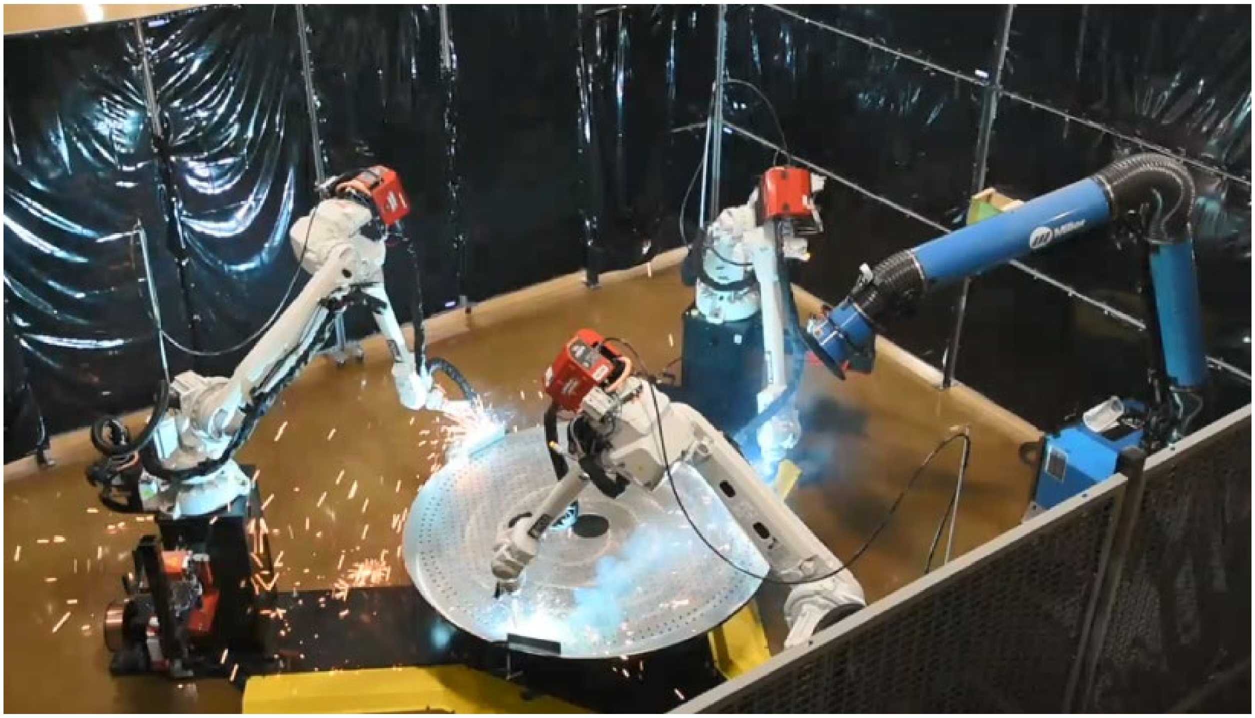

Figure 4. MedUSA multi-arc work cell at ORNL's Manufacturing Demonstration Facility.

Figure 5. Wire arc additive part

2.2 LASER WIRE DED

A second energy source for DED is laser with wire as the feedstock (see Figure 6). With wire arc, there is little control available over the process. Deposition rate is regulated by the wire feed rate with little ability to control the melt pool temperature, which can be critical for managing residual stress, cooling rate, and ultimately the material microstructure. With laser wire fed DED, it is possible to control welding power/temperature, wire feed rate, and robot speed. Current efforts at Oak Ridge National Laboratory focus on weld pool control and modulating wire feed rate and laser power to control layer temperature and temperature gradient as well as part geometry to better influence part resolution, surface finish, and material properties (see Figure 7).

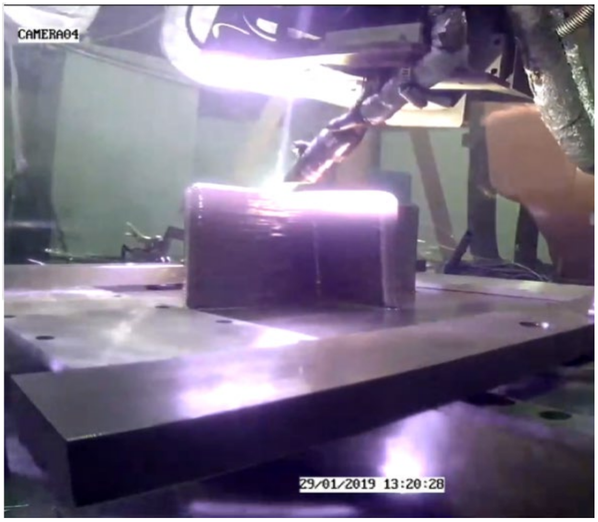

Figure 6. Laser wire arc

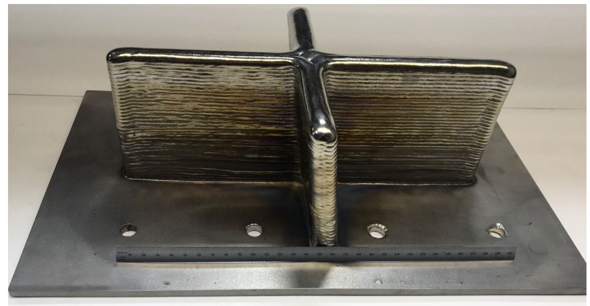

Figure 7. Laser wire final product

2.3 LASER POWDER DED

One of the earliest forms of metal additive manufacturing is the Laser Engineered Net Shape (LENS) process. There are numerous companies that have commercialized laser powder DED. The basic process uses a laser to locally melt a spray of metal powder to create a near net shape part (see Figure 8). The advantages of laser powder DED over the wire fed systems are superior surface finish and the ability to grade or blend material. The disadvantages are material utilization (generally 50–80% of powder does not go into the part) and increased cost of material.

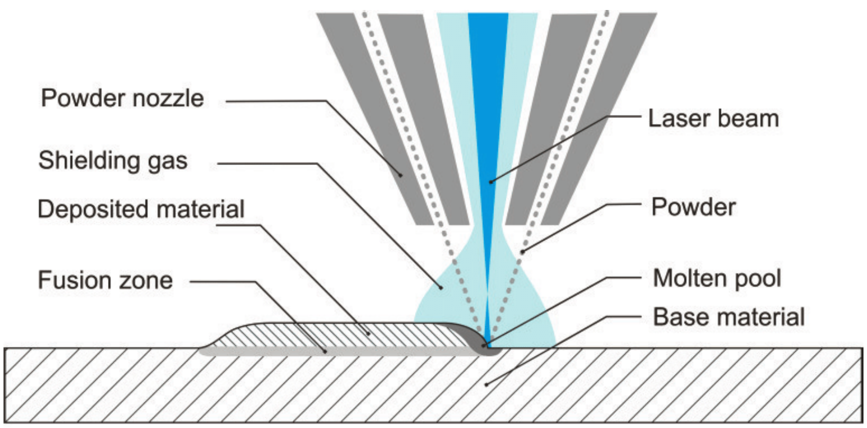

Figure 8. Laser powder DED[3]

One of the systems evaluated is the DED powder system for BeAM (see Figure 9 and Figure 10). The system has a 600 × 400 × 400 mm build volume, 5 continuous degrees of freedom (x, y, z of head, pitch, and yaw of part), and a 500 W laser two-powder feed system to enable graded or multi-material solutions.

[3] Image from https://www.researchgate.net/figure/Laser-metal-deposition_fig1_273536418.

Figure 9. BeAM blown powder DED system

Figure 10. DED deposition head

2.4 HYBRID HOT LASER WIRE ADDITIVE/SUBTRACTIVE PROCESSES

Additive processes compromise surface finish with production rate. As layer sizes decrease, providing improved surface finish, production rates (e.g., kg/hr) typically decrease by the cube of layer size reduction. An emerging trend in additive is the development of hybrid manufacturing processes (i.e., additive and subtractive processes integrated into a single process). An example system is shown in Figure 11 and Figure 12 with an example additive part shown in Figure 13 and Figure 14. The hybrid approach enables a compromise of high deposition rate and low-cost material (welding wire) with high surface finish. The primary challenge today is the integrated toolpath generation (integration of process planning for additive and subtractive processes). The hybrid technology is ideal for system repair and integration of multi-materials in a single part (e.g., cladding and finishing a part in a single process). Multiple companies have commercialized hybrid laser powder systems whereas Mazak has the first commercial laser wire fed DED hybrid system.

Figure 11. Mazak hot laser wire hybrid system

Figure 12. Hybrid hot laser wire

Figure 13. Printed geometry

Figure 14. Machined geometry

3. TCR PROTOTYPE SPRINT

As described in section 1, each additive process has strengths and weaknesses. To accelerate development of the conceptual design and associated manufacturing processes and reduce risk in terms of the manufacturing, the TCR program is conducting a "prototype sprint" activity to rapidly manufacture a scaled version of the reactor to test and evaluate the materials, processes, assembly and integration.

Figure 15 shows a conceptual model of the entire reactor with the core in the center and contained inside a pressure vessel, followed by the reflector and control drums with an outer concrete shield. Note that this conceptual rendering is of a highly preliminary nature and different designs including control elements instead of drums are actively being considered. The goal of this report is to evaluate the merits of direct energy deposition techniques in the manufacture of various reactor components including some of the core structural components. Many of the conventional DED systems are limited in terms of size, material and production rate. Therefore, there are limited options available for the larger sections such as the metallic reflector and cement biological shield. For these two components, we evaluated recent advancements in large scale metal DED and cement additive manufacturing respectively.

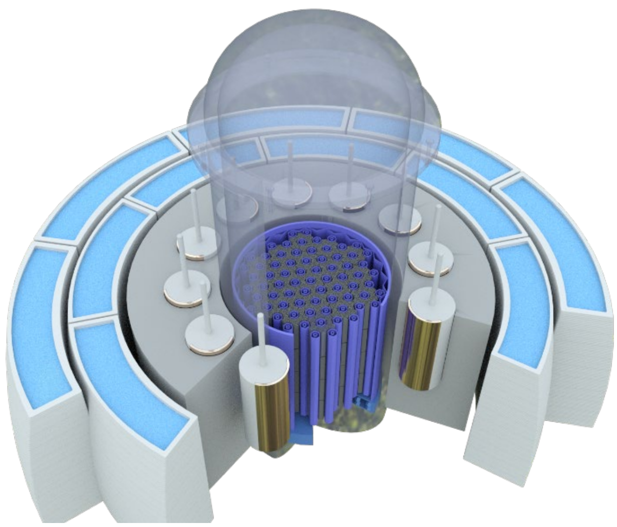

Figure 15. Conceptual model of TCR Reactor

The sprint core, shown in Figure 16 through Figure 19, is a scaled version of a pre-conceptual core design frozen in June 2019. The reactor core will have advanced manufactured components for the top and base manifolds, fuel cans, and main structure.

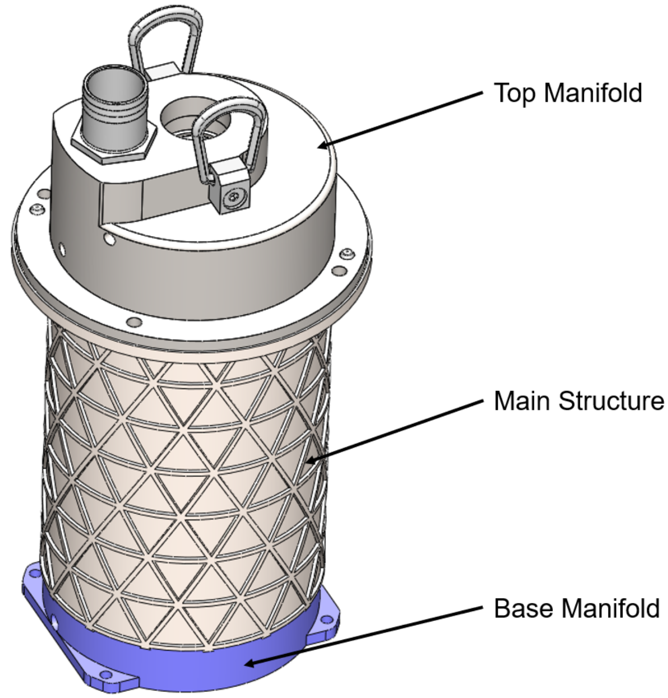

Figure 16. TCR scaled prototype core for summer 2019 sprint

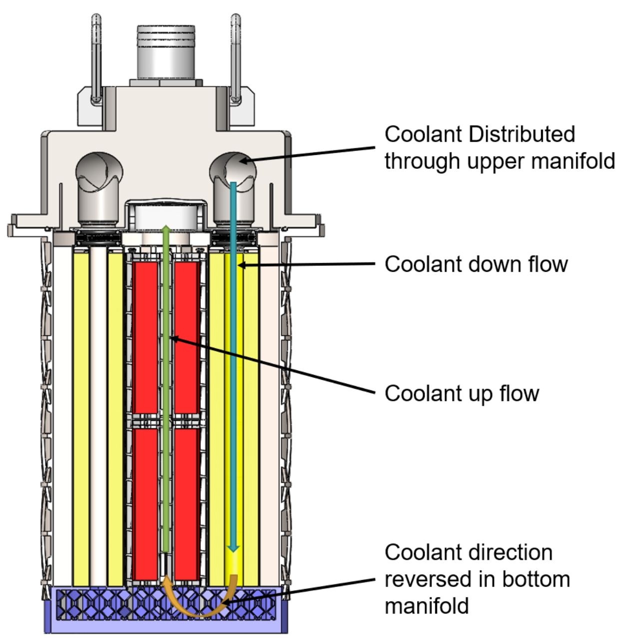

Figure 17. Prototype core cross section for summer 2019 sprint

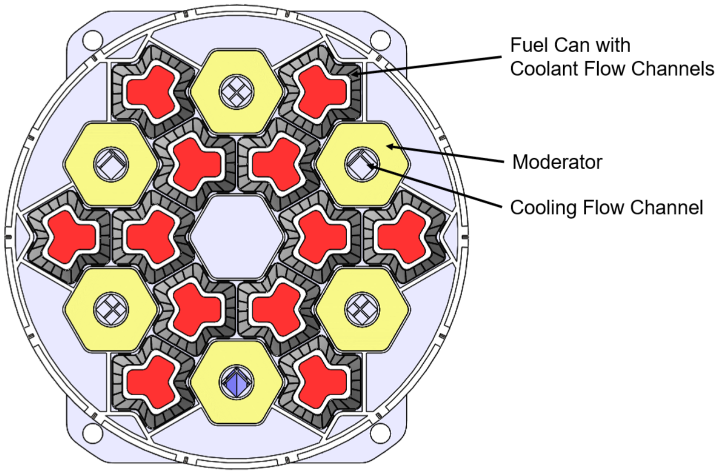

Figure 18. Top view of TCR scaled prototype core for summer 2019 sprint.

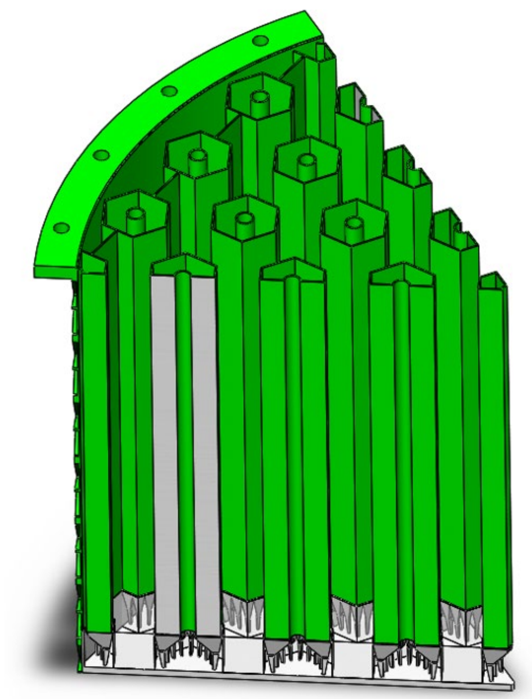

Figure 19. Prototype main structure cross section for summer 2019 sprint

4. DED COMPONENTS RELATED TO TCR SPRINT

A critical analysis was conducted on the manufacturing options of the TCR core components. The conclusion was that different manufacturing processes may be better suited than others for different components of the core. Below are components evaluations using DED.

4.1 DED CORE STRUCTURE

Initial efforts on the BeAM focused on beam control. This effort was followed by focuses on tuning the laser power, powder feed, and gantry motion to calibrate the final bead geometry (bead width and height) that would be used in the toolpath generation (e.g., slicing) software. Figure 20 through Figure 22 show the basic steps of tuning the process. Additive manufacturing process control is a delicate balance between controlling motion of the deposition system and the process control of the material delivery system. The material must have consistent deposition rates (e.g., kg/hr) coupled with consistent motion of the system (e.g., mm/sec). As shown in Figure 20, mismatch between the process control and motion control during transients (starts and stops) can lead to an inability to accurately control part geometry. Likewise, instability in the process or motion control can likewise lead to poor control of the geometry outside of transients (see Figure 21). Proper regulation of laser power, powder flow rate, and system motion control leads to the ability to properly control geometry as shown in Figure 22. The control of these processes leads to geometric control of a bead, which are inputs to the toolpath generation software. The slicing software takes a three-dimensional part geometry, slices it into layers and, within each layer, generates motion and process control commands to fill the geometry based on the measured bead geometries. Figure 23 shows a sample focusing on bead and infill geometry.

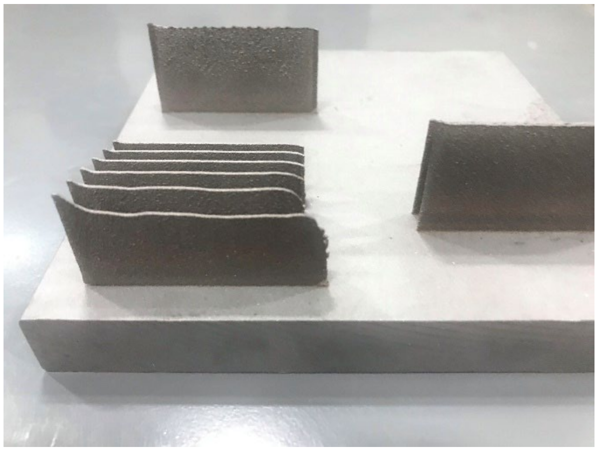

Figure 20. Tuning transients

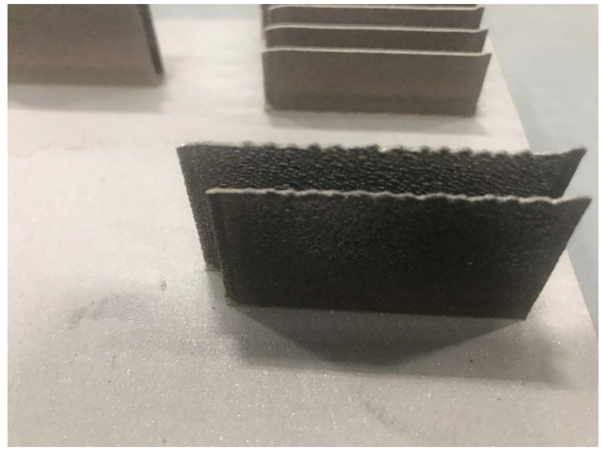

Figure 21. Tuning process control

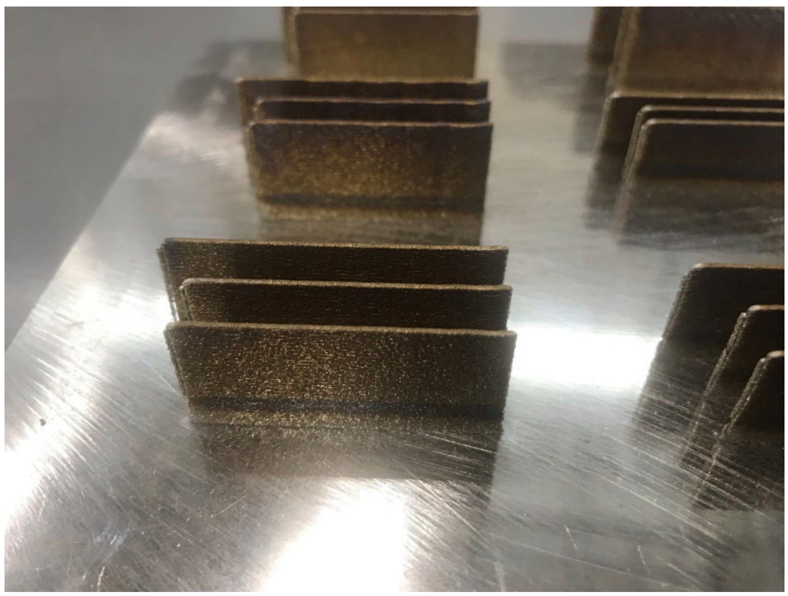

Figure 22. Finely tuned process control

Whereas conventional additive processes typically enable relatively aggressive overhang angles (up to 45 degrees), DED systems are typically far lower (see Figure 24). However, by modifying and controlling the orientation of the part during the manufacturing process, it is possible to significantly increase the overhang angle (see Figure 25).

Figure 23. Tuning bead geometry

Figure 24. Single bead wall

Figure 25. Orientation control

All of the prior steps are necessary for tuning the process control. Once these processes are defined, it is possible to manufacture complex geometries. As shown in Figure 19, the main structure geometry from the DED system will interface with the base manifold made with the LPB system. Figure 26 and Figure 27 show sample components manufactured based on early main structure designs for the TCR.

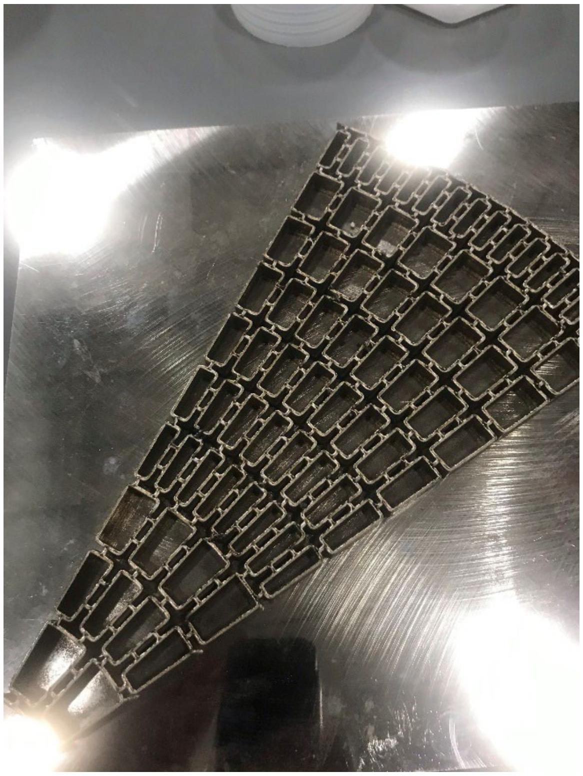

Figure 26. Initial main structure configuration

Figure 27. Optional main structure geometry

4.2 HYBRID LPBF/DED COMPONENTS

As shown in Figure 19, the cladding will interface directly with the base manifold manufactured with a LPBF system. With all additive processes, part manufacturing begins on a base plate. The team's hypothesis is that the base manifold manufacturing on a LPBF system can be used as the base plate for the DED system. As shown in Figure 28 through Figure 31, a segment of the LPBF base manifold is manufactured and installed in the BeAM DED system. Features are designed into the LPBF part with alignment fixtures that are designed to interface directly with the BeAM DED system (see Figure 31). A final example is integrating additively manufactured caps and then using the DED welding to seal the final product (Figure 32 and Figure 33).

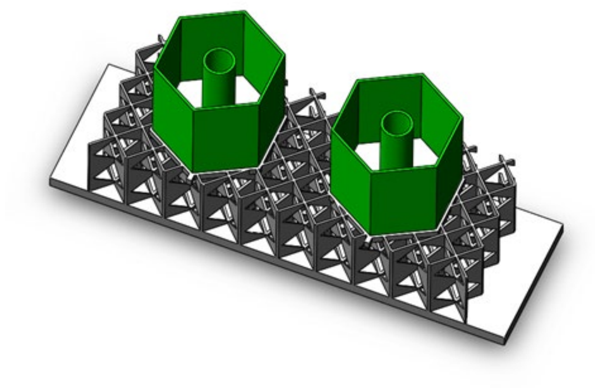

Figure 28. Base and cladding model

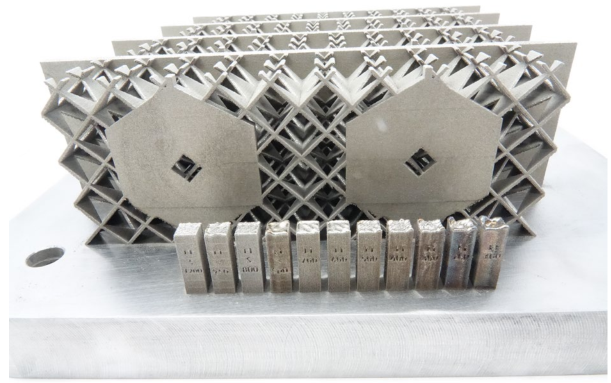

Figure 29. Manufactured base manifold

Figure 30. Cladding geometry in DED

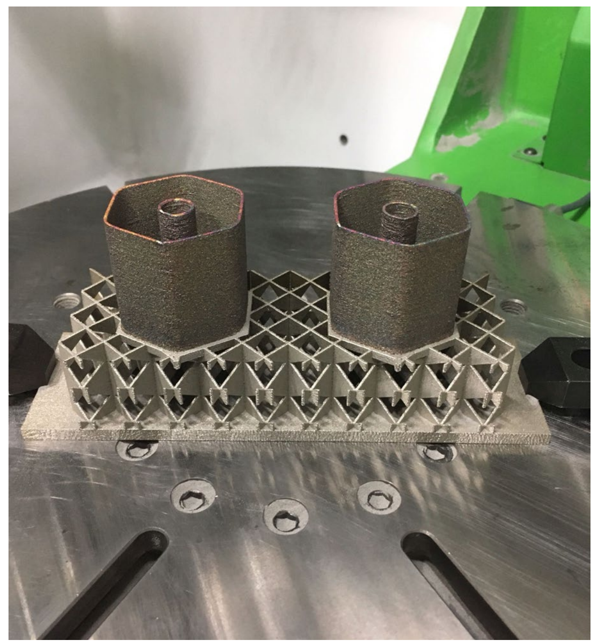

Figure 31. Integrated DED cladding on LPBF base

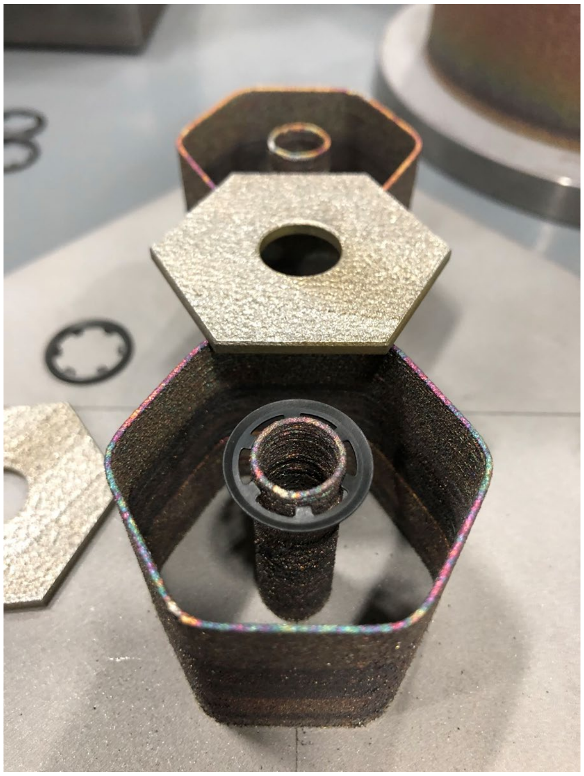

Figure 32. Unwelded cap

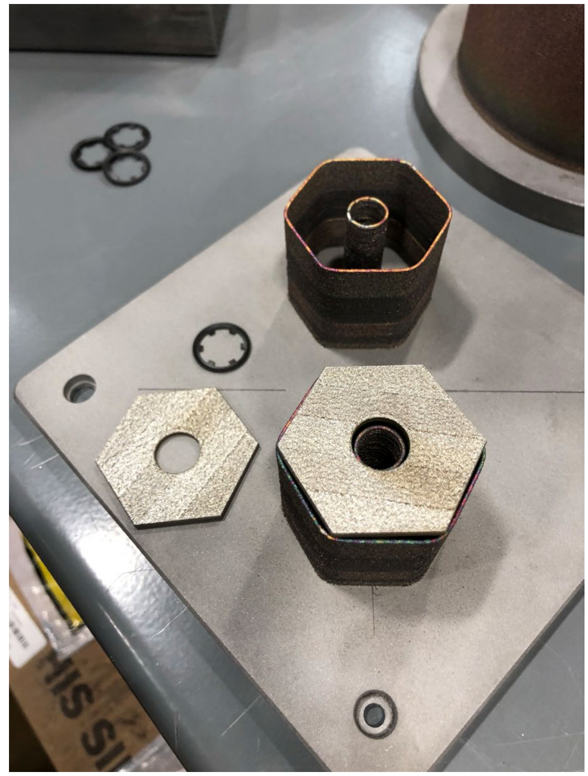

Figure 33. Welded cap

4.3 DED RELATED REFLECTOR AND BIOLOGICAL SHIELD

In addition to manufacture of the core, additive manufacturing can likewise impact the manufacture of the reflector and biological shield (cement). For the TCR, the current design calls for the reflector to be manufactured out of a ferritic steel that is approximately 0.7 m inner diameter, 1.5 m outer diameter and ~0.8 m tall. ORNL is developing a new system, MedUSA (see Figure 4), which is a multi-arm wire arc DED system that has a 2 m diameter by 2 meter tall build volume. The system has a deposition rate of approximately 13 kg/hr but is being upgraded to achieve approximately 52 kg/hr production rate. The shield will require approximately 1.3 cubic meter of steel weighing approximately 11,500 kg requiring approximately 220 hours to manufacture. The high deposition rate results in relatively poor surface finish. To address this limitation, ORNL is evaluating the addition of machining capabilities to MedUSA (see Figure 34 and Figure 35). The system is designed to leverage the rotary table such that the machining capability only needs 2 degrees of freedom, vertical and radial motion.

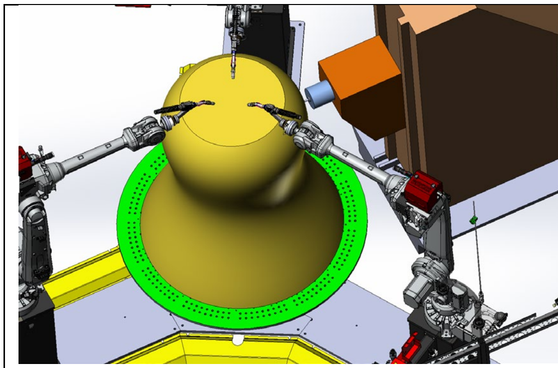

Figure 34: Top view of machining head

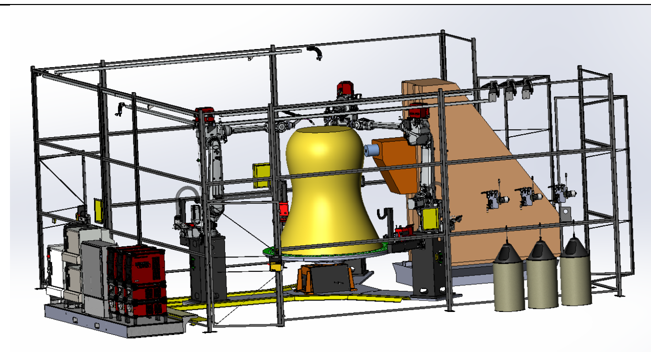

Figure 35: Side View of Hybrid MedUSA

For the cement biological shield, ORNL is developing a new large scale, high deposition rate cement additive manufacturing process called SkyBAAM. The basic concept is shown in Figure 36. The system deposits approximately 900 kg/hr and has a current build volume of approximately 5 m x 5m x 3 m scalable to over 10 m x 10 m x 5 m. The basic concept is to control the movement of a deposition head (see Figure 37 and Figure 38) suspended by an overhead crane and driven by a cable driven system (see Figure 39). The system has an accuracy of approximately 5 mm over the entire build volume (see Figure 40).

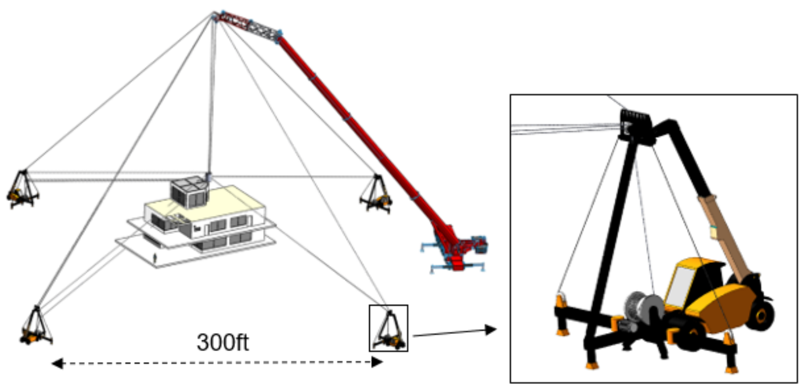

Figure 36: SkyBAAM

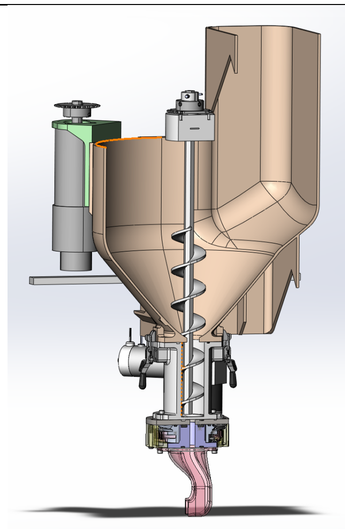

Figure 37. Deposition head with articulated nozzle

Figure 38. Depositing cement

Figure 39. Cable drive mechanism

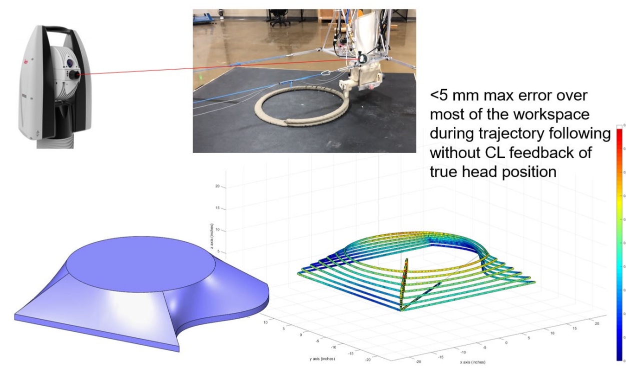

Figure 40. Tracking performance

The biological shield is approximately 1 meter thick and 0.7 m tall weighing approximately 5500 kg and will require approximately 6 hours to manufacture (see Figure 41).

Figure 41. Printed cement structure

5. CONCLUSIONS

The report covers the background and provides an expansive description of various directed energy deposition techniques and their viability for producing components in support of the Transformational Challenge Reactor. There are numerous DED processes, each of which has strengths and weaknesses. Each of these processes and their capabilities and build envelopes were highlighted. A unique manufacturing opportunity, the integration of LPBF with a LENS process is described for manufacturing the TCR cladding as well as emerging technologies such as MedUSA and SkyBAAM for the manufacture of the reflector and biological shield.

6. REFERENCES

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