ELECTRIC POWER RESEARCH INSTITUTE

Quick Insight Brief: Laser Powder Bed Fusion— Additive Manufacturing

RESEARCH QUESTION

Where will the laser powder bed fusion additive manufacturing process (LPBF-AM) be used in the production of "metallic" components for the nuclear industry, and when will the technology be available for the industry? This Quick Insight Brief provides a snapshot on the current state-of-the-art and future of LPBF-AM in the nuclear industry?

KEY TAKEAWAY

LPBF-AM technology holds the promise of more innovative and higher performing equipment designs that engineers can bring to market quicker than ever before. LPBF-AM has been widely adopted in numerous industries outside of nuclear, in particular for medical and dental devices, the automotive industry, and the aerospace industry. The nuclear industry is now seeing LPBF-AM components used in nuclear power plants [1] and even within reactor cores [2, 3]. As the qualification of LPBF-AM process and additional materials become available through codes and standards and regulatory bodies, LPBF-AM components will soon be available for production of a variety of smaller (< 34 kg [75 lbs.]) components, including: replacement (or obsolete parts), reactor internals, safety-related pressure retaining applications such as valve bodies.

KEY POINTS

- LPBF-AM currently offers deposition rates on the order of 0.2 to 1.4 kg per hour (0.5 to 3 lbs. per hour), depending on the material used and accuracy requirements. Maximum build volumes for PBF technologies are currently limited to approximately 800 mm x 400 mm x 500 mm (31.5 inches x 15.8 inches x 19.7 inches) [4].
- Progress is being made toward enabling LPBF-AM use in the nuclear industry for components such as smaller valves, fittings, and reactor internals.
- To date, LPBF-AM processes have not been qualified by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, however the Electric Power Research Institute (EPRI) generated a data package and supported Westinghouse Electric Company's submittal of a Code Case in 2020 for ASME qualification [5].

WHAT IS LPBF-AM?

Additive manufacturing (AM) is a novel fabrication technology that has generated significant interest across various industries. Although polymer-based AM is significantly more mature, LPBF-AM can also be used to build composite, metallic, and ceramic structures. This document specifically focuses on metallic builds, although ceramics are also of future interest to the nuclear industry.

Laser powder bed fusion (LPBF) is a class of technology wherein a powdered material is fused by an laser energy source. The feedstock material for the process is an atomized powder that has been sieved to generate a fine powder that can be easily handled. The LPBF-AM process is shown in Figure 1 and is described below (it should be noted that the build process is preprogrammed into the additive equipment using 3D modeling software and the entire process for the most part occurs automatically). Typically, the process starts when a re-coater blade spreads a thin layer of homogenous powdered material from a hopper across a metallic build plate. This first layer of powder is then exposed to a laser energy, which is rapidly turned on and off, or rastered, at specific locations across a given vertical cross section that melts and fuses the new layer of material to the build plate. The build plate is then incremented downward by a small fixed increment thereby raising the relative location of the feed chamber upward by the corresponding increment. The re-coater blade spreads a layer of powder above the first layer, and this new upper layer is selectively fused by the energy source to the previous layer. These steps are repeated as the part/component is built upward layer-by-layer from the build plate. After the entire build cycle is completed, the used, but unfused, powder is captured for re-processing. The finished parts are subjected to post-processing, which may include stress relief heat treatment before machining the parts off of the build plate, removal of temporary support features, hot isostatic pressing and other heat treatments, and potentially final surface finishing.

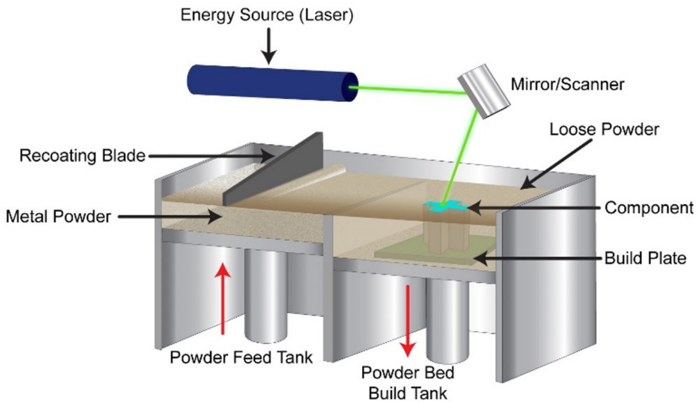

Figure 1. Schematic of the laser powder bed fusion process

There are everal advantages are often associated with the process, namely:

- The ability to build complex geometries that cannot be produced by conventional manufacturing methods (casting, forging, etc.) and subtractive technologies. This allows for parts to be produced with improved flow characteristics or special features that again cannot be made via conventional manufacturing methods.
- A part can be designed for specific performance with specific properties engineered into a specific area of a part.
- Replacement (or obsolete) parts can be generated almost in real time for an application, minimizing the number of parts that need to be warehoused. Laser or structure light geometry scanning may eliminate the need for design drawings and legacy tooling/molds.
- Parts can be fabricated in a fairly rapid fashion (often within a week) depending on the size of the part.
- The ability to increase reliability, reduce part count, and reduce manufacturing costs by integrating part assemblies into a single part.
- In-process monitoring/data capture of each layer build can be recorded for future review.

A few disadvantages and/or technical challenges of the process include:

- Today the process is limited to about the size of a microwave (although a few larger systems are beginning to enter the market) which limits the size of the parts to around 34 kg (75 lbs).
- Deposition rates are relatively slow at approximately 0.2 to 1.4 kg per hour (0.5 to 3 lbs. per hour) depending on material and accuracy requirements.
- Builds may contain porosity, entrapped powder, or lack of fusion defects.
- Residual stresses or distortion can require intermediate heat treatment at certain stages of the build.
- Inspection of thicker section parts and complex geometries can be an issue.
- Understanding bulk properties of each build. This is often addressed by building "witness coupons" in three major directions and then testing those coupons to make sure that minimum properties are met.

Due to some of these disadvantages, parts and components often require post processing by exposing the part to a hot isostatic pressing cycle and subsequent heat treatment.

WHERE WILL LPBF-AM BE USED TO MANUFACTURE NUCLEAR COMPONENTS?

It is anticipated that LPBF-AM will be primarily be used to manufacture a variety of nuclear components, including: small reactor internals (fuel pins, springs, instrumentation brackets, control rod drive internals, etc.), fuel assemblies and fuel handling equipment (core components, grids, spacers, nozzles, etc.), small spray nozzles, valves, tees, and wyes, and actual fuel pellet configuration. In fact, various vendors and utilities have already installed LPBF-AM components in their plants, including core components [2], fuel assembly components [3], and replacement of non-pressure retaining plant parts [1]. The industry is also pursuing qualification of the LPBF-AM process of pressure retaining components via codes and standards organizations such as ASME [5].

ALTERNATIVE NEAR-NET-SHAPE FABRICATION METHODS TO CONSIDERED FOR MANUFACTURE OF NUCLEAR COMPONENTS

Due to limits on chamber size and deposition rates, LPF-AM should not be considered for production of medium (34-227 kg [75-500 lbs.]) and large (>227 kg >500 lbs.) components. Even if larger chambers with multiple laser heads are developed in the near future, other technologies such as directed energy deposition-AM (DED-AM) and powder metallurgy-HIP (PM-HIP) may prove more advantageous for production of such components. Additionally, the technology doesn't lend itself to component attachments or nozzles that are added to existing or new parts. Adding such features to larger parts is difficult because the LPBF-AM process typically builds parts within a microwaved size chamber. Other technologies such as DED-AM or PM-HIP offer greater applicability toward attaching features or larger component builds.

WHAT ABOUT FUNCTIONALLY GRADED MATERIAL AND COMPOSITE COMPONENTS?

Although dissimilar metal and bi-metallics are not new to the nuclear industry, functionally graded material (FGM) components have been recently discussed by industry. Therefore, it is worthwhile to look at specific applications where LPBF-AM could be used to employ composite and graded materials in nuclear applications. Although both have two materials with distinct functions, it is good to first clarify the key difference generally understood between FGM and bi-metallics or composites – bi-metallics/composites have a distinct interface between the two different materials, while FGM change chemistry or structure gradually (both continuously or discontinuously) as a function of position [9] where the overall properties of FMG are unique and different from any of the individual materials that form it. Use of FGM transitions can greatly reduce differential thermal expansion stresses versus abrupt dissimilar metal joints.

Both bi-metallics and FGM may be fabricated from LPBF-AM by starting with a base material (wrought or printed) and building up a different alloy with successive layers. The LPBF-AM process has the capability of fabricating both bi-metallics by changing feedstock material and blending feedstock powders, respectively [6, 7, 8]. However, the process of blending powders and understanding the processing parameters during the build is a new concept with very little research to date.

The nuclear industry has great interest in low alloy steel–austenitic stainless steel composite structures. Certainly, such composite materials can be generated, but the issue then becomes heat treating such structures. The heat treatment is normally dictated by the low alloy steel heat treatment parameters which call for elevated (650°C [1200°F]) temperatures. This unfortunately sits right in the temperature range where austenitic stainless steels sensitize, thus rendering the process not useful for nuclear applications.

Another roadblock that is often not considered for composite and FGM structures is that qualification and acceptance by codes and standards (e.g., ASME BPVC) and/or regulators may prove difficult. Although LPBF-AM technology can fabricate components that include distinct materials with different properties, codes and regulatory bodies only consider distinct materials and not graded materials.

One good application of the LPBF-AM technology in dissimilar metal joints, however, is for build-up of wear-resistant surfaces (hard-facing) on small valves [10] or other high wear components (e.g., reactor internals, flow defectors, jet pumps, etc.).

EMERGING ADVANCED MANUFACTURING TECHNOLOGIES

AM Focus Area

Collaborative efforts between EPRI's Advanced Nuclear Technology program and the Welding and Repair Technology Center are focused on enabling LPBF-AM for the nuclear industry applications. Current work includes in-situ monitoring [5], investigating defect tolerance, nondestructive examination benchmarking, testing of demonstration parts, and development of an ASME data package for 316L stainless steel via LPBF-AM [5]. This work will support Code and regulatory acceptance of LPBF-AM in the near future. Some of the materials of most interest by the nuclear sector for near future LPBF development and qualification include alloys 718, 625, 690, 617 and 316H. EPRI has also recently released technical report "Additive Manufacturing Roadmap for the Nuclear Industry" which provides a more in-depth discussion on the AM state-of-the-art, an assessment of gaps for future nuclear deployment and development of a roadmap for the nuclear industry to address those gaps.

REFERENCES

1. "Printing Nuclear Parts," Nuclear Engineering International, Vol. 62, No. 755, pp. 26–28, 2017.
2. Cleary, W., and Karoutas, Z., "Fuelling Additive Manufacturing," Nuclear Engineering International, Vol. 62, No. 758, pp. 24–25, 2017.
3. "First-of-its-kind 3d printed nuclear fuel component to enter use," World Nuclear News, December 3, 2020.
4. Wohlers Report 2019: 3D Printing and Additive Manufacturing, State of the Industry, Wohlers Associates, Inc., Fort Collins, CO, 2019.
5. *ICME and In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder Bed Additive Manufacturing Processes for Nuclear Structural Applications*. EPRI, Palo Alto, CA: 2020. 3002018273.
6. Wessel W. Wits, Marc de Smit, Kamaal Al-Hamdani, Adam T. Clare, Laser powder bed fusion of a Magnesium-SiC metal matrix composite, Procedia CIRP, Volume 81, 2019, Pages 506-511.
7. Geng, Yaoyi & Harrison, Noel. (2019). Ti-6Al-4V Functionally Graded Material by Laser Powder Bed Fusion (BCS Belfast 2019 Poster).
8. Tan, Chaolin & Zhou, Kesong & Tongchun, Kuang. (2018). Selective laser melting of tungsten-copper functionally graded material. Materials Letters. Volume 237.
9. Debroy, T. et al., "Additive Manufacturing of Metallic Components – Process, Structure and Properties," Progress in Materials Science, Vol. 92, pp. 112–224, 2018.
10. Poole, Rolls-Royce Nuclear Developments in AM: Presentation to the USA Nuclear Regulatory Commission – Nov 2017, NRC ML17338A901.

CONTACT INFORMATION

Marc Albert, Sr. Technical Leader
704.595.2187, malbert@epri.com

David Gandy, Sr. Technical Executive
704.595.2695, davgandy@epri.com

Stephen Tate, Technical Leader
980.495.7417, state@epri.com

Advanced Nuclear Technology

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com