Laser powder-bed-fusion additive manufacturing as a transformative technology for plasma-facing materials and components

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Introduction and applicability of technology for fusion energy sciences

The transformation of the magnetic fusion reactor from ITER (an experimental reactor) to energy-producing DEMO Power Plant presents numerous challenges in reactor design, as well as future advanced materials manufacturing. Due to a number of advantageous properties of pure tungsten including a high melting temperature (~3422 °C), low sputtering yield, high thermal conductivity (174 Wm⁻³K⁻¹), and a low coefficient of thermal expansion (CTE~4.5×10⁻⁶ K⁻¹) [1], in both EU and U.S. divertor design for DEMO (i.e., HEMJ divertor and T-tube divertor, respectively) [2-4], tungsten is the ultimate material-of-choice as armor for plasma-facing components (PFCs). Conventional machining approach to manufacture tungsten components imposes challenges due to the high hardness and brittleness of tungsten materials [3]. Other legacy manufacturing techniques [3, 5, 6] (such as magnetron sputtering [6], milling, and hot pressing) lack design freedom; i.e., require a long period (typically a few years) of development from the divertor design to the manufacturing maturity [7].

Additive manufacturing (AM) is an advanced manufactured technology that has the potential to transform our ways of making engineering components in 21th century. In contrast to conventional manufacturing processes, AM has the unique advantages of fast build time (near net shape components without the need for further machining), little materials waste, and the freedom of manufacturing complex geometry components. The unlimited design freedom offered by AM technology is unprecedented and particularly powerful for prototyping of various design concepts (e.g., divertors). AM is intrinsically an agile and responsive technology that can substantially shorten the time-period required from the design to the production. Provided that the properties of a material are thoroughly quantified, the “born certified” nature of AM technology could find applications in future fusion materials/products. This white paper intends to outline some current materials-related issues using AM technology.

Description of technology and capability

We choose laser powder-bed-fusion (L-PBF) AM as a main technology for fusion materials due to its ability to melt and print refractory metals. Materials made by L-PBF are known to have unique microstructures and mechanical properties that require thorough investigations. For example, our studies in 316L stainless steels suggest that AM metals commonly have high strength, an excessive amount of small-angle grain boundaries, dislocations, voids, local misorientations, and impurities. The high strength and the existence of extra boundaries could make these materials more radiation resistant. In the meantime, these defects could also affect the heat transport properties that require to be investigated for fusion materials applications. L-PBF materials and components also have very high residual stresses, which not only affect the dimension accuracy, but also often lead to cracking during the build. Tungsten, for example, is notoriously difficult to manufacture by AM because the ductile-to-brittle transition during melting and ultrafast cooling processes. The intrinsically high residual stresses also play an
important role in cracking behavior. Therefore, laser processing parameters development including the scan strategy is one critical part of AM technology. The limited build volume available for most commercial AM machine is another concern. A typical Concept machine, for example, has a build volume of 250mm × 250mm × 300mm, which is substantially smaller than most PFCs. With the progress of AM technology, however, the build volume is of less concern as larger build volume is achievable once the technological challenge of the residual stress can be overcome.

Due to the ultrahigh melting temperature of tungsten and its alloys, L-PBF should be the primary choice for producing PFCs. At LLNL, we have a host of selective laser melting AM machines that allow us to meet the needs for a variety of materials fabrications. We have accumulated expertise in powder-bed-fusion AM technology, and developed powder models, effective media models, surrogate models, and experimental procedures to produce materials/parts for national security applications. In addition to commercially available Concept Laser AM machines (build volume 250mm × 250mm × 300mm) and an SLM machine (build volume 300mm × 300mm × 300mm), LLNL also hosts a customized Fraunhofer Open-Architecture Selective Laser Melting (OASLM) AM machine. The unique capability of Fraunhofer AM machine exists its open architecture and source code that allows for dual laser processing and feedforward processing parameter control during the builds. This will allow us broad control in laser processing parameters that is likely needed for refractory metal AM processes. This unique capability has positioned LLNL as one of the leaders in AM technology. The large build volumes of these AM machines will also allow us to build prototype divertor components (such as divertor blocks).

**Expected performance of the technology**

At the highest level, one single print is possible from the design to component level. Three major technological challenges need to be overcome. 1. Residual stress issue in both small and large components; 2. A full understanding of processing-microstructure-property relationship of AM metals for fusion energy; (3) A “smart” AM machine that can recognize the structure-property relationship of the target materials and change the build parameters on-the-fly.

**Design variables**

1. Geometry dependent laser parameters and subsequent microstructure and properties. A “smart” AM machine is need to reach this goal.
2. Location specific composition (for tungsten alloys) and microstructures.
3. Enhanced mechanical properties and radiation resistance.

**Potential risks**

1. 3D printed materials may never meet the mechanical and radiation performance requirements for DEMO and ITER.
2. Scale-up of 3D printing for large volume build.

**Required development**

The following outlines some near-term research areas that are relevant for AM PFCs.

1. **AM full-density tungsten and/or tungsten alloy materials.**
First and for most challenge in AM of PFCs is laser processing parameters development and understand the processing-structure-property relationship of AM-ed tungsten materials. Mechanical behavior and radiation resistance of AM materials are completely unknown, and should have the highest priority in the future research.

Using AM technology to manufacture refractory metals is frontier research due to the challenges associated with the high melting temperatures of many refractory metals. The synthesis of tungsten using selective laser melting has been previously attempted in the literature [8, 9]. The tungsten materials synthesized typically have a density <90%, which does not meet the materials requirements for fusion applications. One of the biggest hurdles is thus to synthesize near fully-dense tungsten materials with the appropriate combination of strength and ductility. Nevertheless, this earlier work demonstrates the feasibility of using SLM technology to fabricate refractory metals. The initial effort of AM should focus on increasing the density of tungsten materials, as well as the control of impurities as the thermomechanical behavior of tungsten is known to be sensitive to impurities.

2. Mechanical behavior of AM tungsten and its alloys

It is known from the literature that AM metals have unique microstructure that is completely different from any conventional materials. These microstructure features include voids, welding pool, grain size distribution, small-angle grain boundaries (GBs), dislocations, compositional inhomogeneity, texture, and impurities. All these factors will affect the mechanical strength and ductility of AM tungsten. It is thus important to thoroughly evaluate the microstructure and mechanical properties of tungsten. Post-AM heat treatment and/or HIP have also been found to substantially alter the microstructure and materials properties of AM components. It is known that the properties of AM metals are strongly influenced by the sample geometry and build orientation, as the microstructure of materials is impacted by the cooling rate involved during the fabrication. Different geometry samples offer different cooling pathways and thus different microstructures. The impurities and pre-existing dislocations in as-fabricated materials are also considered important, since impurities are the main cause of embrittlement in tungsten. For tungsten divertor applications, the thermo-mechanical properties and recrystallization behavior of tungsten materials is critical.

3. Post-AM treatment and recrystallization behavior of AM tungsten metals (or alloys)

First-principles calculations suggest that impurity segregation substantially changes the electronic structures of GBs and subsequently increase or decrease cohesion [14]. For example, N, O, P, S, and Si are found to weaken granular cohesion in tungsten, whereas B and C enhance intergranular interaction across GBs. It is also known that high-angle GBs are one of the main sources of electron scattering in metals, with an electron scattering factor nearly one order of magnitude higher than TBs [15]. When GB decohesion occurs due to impurity segregation, it is expected to substantially decrease electrical conductivity. The heat treatment or HIP processes in as-AM tungsten could lead to impurity segregation and thus materials properties. The recrystallization behavior of AM tungsten is relevant to fusion applications. Due to the existence of sub-grain structures and dislocations, AM tungsten could have very different recrystallization than conventional tungsten materials [4].

4. Theoretical modeling

Bounded by the unavailability of high-flux neutron testing facilities, computer modeling remains to be one of the most valuable tools to investigate and understand neutron damage and
subsequent embrittlement behavior, especially for AM materials. Such modeling would need to take into account the unique microstructure (e.g., voids, impurities, small angle grain boundaries, etc.) of AM materials. In these simulations, grain distribution, gradient structure, pre-existing dislocations, and other detailed microstructure from experiments will help to formulate models, which are important to understand and predict the real-material behavior. In turn, simulation results will offer valuable guidelines for further reiteration of experiments.

Summary

AM is a potentially transformative technology for manufacturing PFCs. However, the technology readiness level (TRL1-2) is not high for fusion energy component applications. From the most basic level, 3D printing tungsten materials is immature. The materials produced have not reached the nearly full density yet. A comprehensive assessment of processing-microstructure-mechanical remains missing but it critical to validate the potentials of AM technology. A fundamental understanding of flow, fracture, and recrystallization behavior of AM materials in a wide range of temperatures is also needed and will help build scientific foundation for developing and maturing AM technology for manufacturing tungsten as PFCs. The radiation resistance of AM materials has not yet been evaluated but is of obvious importance in the future. Nevertheless, the benefits of AM technology for future fusion technology are expected to be unprecedented.

References


