

Advanced Characterization of Additively Manufactured 316L Stainless Steel for Nuclear Applications

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Metal additive manufacturing (AM) is an emergent advanced manufacturing method that can create complex net-shape geometry directly from CAD model. Over the last decade, AM has gained great interests in nuclear industry through several government and industry-sponsored initiatives. Such technology provides the capability to rapidly fabricate parts during plant refueling outages, fast prototyping, and support design-driven manufacturing. AM can also provide through-life supply chain (40-60 years) for the high-value low-volume components.

Concerns still exist in nuclear industries and regulatory bodies in regard to the scattered metallurgical, mechanical and radiation properties of AM produced alloys. Taking radiation damages (voids, dislocation loops, etc.) as the example, some studies reported AM microstructure leads to the elevated void swelling and high-density dislocation loops [1]. In contrast, other work suggest that AM induced microstructural features may suppress dislocation loop formation [2]. Different from conventional cast/wrought materials, the extremely fast solidification by laser AM resulted in non-equilibrium heterogeneous microstructure, including hierarchical boundary structures, ultrafine dislocation structures, nanoscale inclusions, and inhomogeneous element segregation. The disagreement among different studies are probably due to the process-dependent microstructural variations. More careful characterization is needed to establish the microstructure-property relationship.

The objectives of this study are two-folds: first, the research employs advanced characterization methods to reveal the relationships between the AM specific microstructural features and the radiation properties; second, the study explores the potential benefits of minor refractory elements on refining AM microstructure and improving radiation resistance. 316L stainless steel (SS) is identified as the candidate material to study due to its popularity in reactor applications. AM 316L SS, and its variants doped with minor refractory elements (Hf, Y, Ta, etc.) were fabrication by direct energy deposition AM. Proton irradiation was performed on all the samples at multiple dose levels to simulate radiation damage in reactor environment. Fig. 1 shows the AM microstructures of AM 316L SS and the modified variants. Compared to the coarse grain AM 316L SS, the alloy modification leads to unique grain refinement which may be beneficial to damage resistance. The microstructure and microchemistry changes under irradiation (Fig. 2), including dislocation loops, voids, segregations and their relationships with radiation hardening and swelling are investigated using advanced electron microscopy (scanning electron microscopy, electron backscatter diffraction, scanning/transmission electron microscopy, energy dispersive X-ray spectroscopy, electron energy loss spectroscopy) and atom probe tomography techniques.

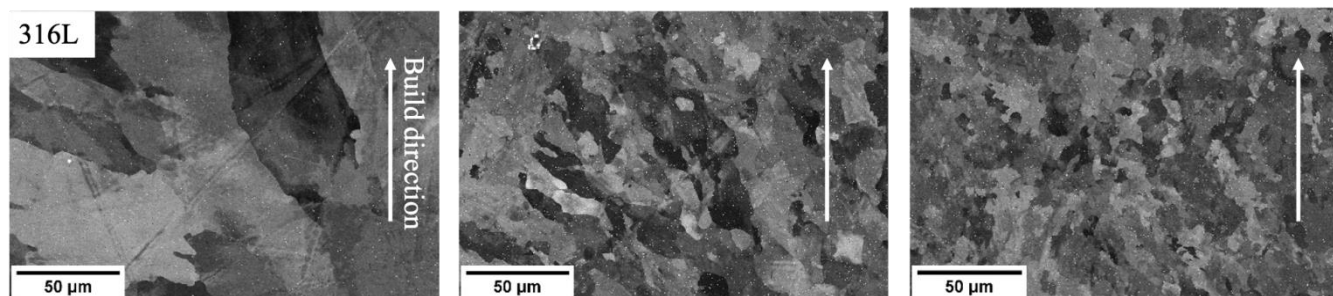


Figure 1. Microstructure evolution of AM 316L SS with different Hf content

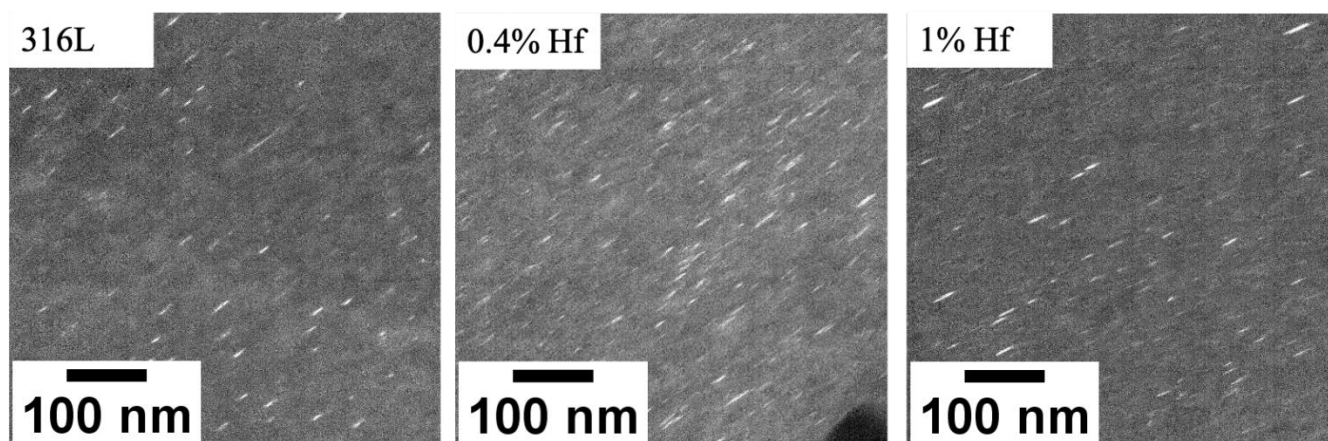


Figure 2. Dislocation loops evolution of AM 316L SS with different Hf content

References

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