Resistance to fracture and fatigue in additively manufactured alloys

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Abstract: Ti-6Al-4V fabricated by the laser powder bed-fusion (LPBF) process consists of metastable α' microstructure and columnar prior β grain (PBGs) mesostructures. These micro-and mesostructures adversely affect fracture toughness (K_{Ic}) in as-built conditions. After an optimized post-processing heat-treatment, the K_{Ic} of LPBF Ti-6Al-4V improves by ~104%; however, the anisotropy in K_{Ic} persists due to preferential crack growth along the columnar PBGs. In another LPBF fabricated β Ti-alloy, Ti41Nb, the crack tortuosity from the mesostructures formed by compositional segregation improves the K_{Ic} by ~80%. These results demonstrate extrinsic toughening in AM alloys. While such toughening from mesostructures enhances AM alloys' reliability, the processing-induced defects present in them, *i.e.*, porosity, significantly reduce their high cycle fatigue (HCF) resistance. Therefore, in the second part of the present study, the HCF life of 316L and 17-4 PH steels produced by the binder jet printing process was investigated. The hot isostatic pressing (HIP) was employed on these steels to improve their HCF life. The HCF life of HIPed 17-4 PH steel is comparable to their conventionally manufactured counterparts; however, in 316L, HIP fails to improve the fatigue life. Based on these findings, the microstructural origin for fracture and fatigue resistance in AM alloys are discussed.

1. Introduction

The quest for stronger and tougher structural materials is challenging because of the mutually exclusive nature of strength and ductility. In additively manufactured (AM) alloys, the combination of metastable micro-mesostructures and inherent micro-scale heterogeneity provides an opportunity to fine-tune the combination of extrinsic and intrinsic toughening for producing strong and fracture-resistant materials. Nevertheless, the processing-induced defect in the AM alloys severely limits their adoption in critical fatigue-intensive structural applications. This work investigates these two aspects for laser powder bed fusion fabricated Ti-alloys and binder jet printed stainless steels. Based on the findings of this study, unique aspects of the micro- and mesostructures of the AM alloys, process-related attributes, and their effect on fatigue and fracture resistance are discussed.

2. Results

2.1 Fracture resistance in LPBF Ti alloys

In Ti-6Al-4V, the rapid solidification during additive manufacturing results in a basket-weave martensitic (α') metastable microstructure. The line-by-line and layer-by-layer printing process imparts a mesostructure in the form of columnar prior β grains (PBGs), whose size depends on the length scales of the process parameters (Fig. 1). However, these micro-and mesostructures in as-built conditions adversely affect the fracture resistance of the alloy. Post-processing heat-treatment was employed on Ti-6Al-4V to optimize its microstructure and fracture resistance. The observed enhancement of ~104% in the fracture toughness (K_{Ic}) upon the heat treatment is due to the formation of lamella α–β microstructure, which is considerably more ductile than metastable α'. Unlike the rolled Ti6Al4V, where the crystallographic texture can induce

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anisotropy, the lack of a strong crystallographic texture in the AM alloy suggests that the columnar PBG structure is responsible for the anisotropy observed. The mesoscopic PBG structure aids crack tortuosity where the PBG boundaries act as weakened interfaces. The results show that anisotropy in K_{Ic} is related to plastic zone size (r_p), which is only ~ 0.2 mm in the as-built condition and increases by order of magnitude to 2–3 mm after the heat treatment. Since r_p in the as-built condition is similar to the spacing between the PBGs (~ 0.14 mm), preferential crack growth along the boundary is possible only when a crack tip is close to a PBG boundary. A columnar to near-equiaxed PBG transition can be induced by altering the scan rotation from 90° to 67°, as illustrated in Fig. 1a and b. The specimens with equiaxed PBGs obtain a near isotropic K_{Ic} in the as-built condition (~ 48–54 MPa√m) as well as after the annealing treatment (~ 96–93 MPa√m).

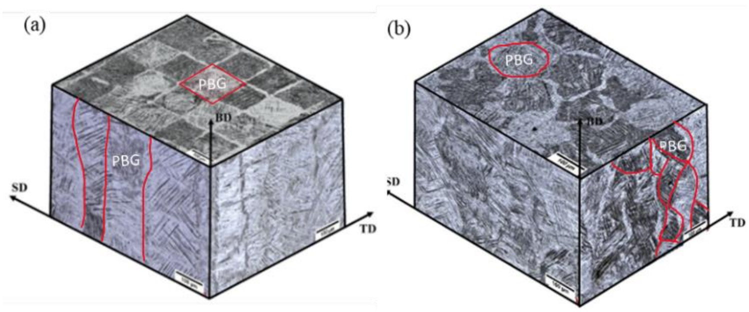

Fig.1 - Representative microstructure of LPBF Ti6Al4V produced using 0.14 mm hatch spacing and scan rotation of (a) 90˚ and (b) 67˚ between subsequent layers. The red lines in the images show the boundaries of prior β grains (PBGs)

In Ti-41Nb, a β-Ti alloy, the heat accumulation during the LPBF process leads to the formation of ω_{iso} precipitates resulting in improved strength but very low ductility. However, the meso-structures formed by compositional segregation during the in-situ alloying in the LPBF process promote crack deflection (from mode I), leading to ~80% improvement in K_{Ic} due to crack mode mixivity.

2.1 Fatigue of binder jet printed steels

In conventionally manufactured parts, smaller and larger grains resist the crack initiation and propagation, respectively. However, in additively manufactured (AM) alloys, fatigue crack can easily initiate from pores. Considering this, we examine the effect of grain size on the fatigue resistance of 316L and 17-4 PH steels fabricated by the binder jet printing process with various porosity levels. Steels of distinct work hardening behaviors were produced by employing different aging treatments on the 17-4 PH steel, and hot isostatic pressing (HIP) was used to reduce the overall porosity. The small and equiaxed grains are beneficial for fatigue resistance, and the HCF life of HIPed 17-4 PH steel is comparable to their conventionally manufactured counterparts. However, in 316L, HIP fails to improve the fatigue life.

3. Conclusions

The extrinsic toughening by mesostructures in AM alloys provides additional freedom in designing strong and tough materials. Although, in some instances, such heterogeneity can promote anisotropy in the mechanical properties. Moreover, processing-induced defects adversely affect their high cycle fatigue resistance, and HIP is not always necessary and sufficient to improve the fatigue life of the AM alloys.

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