Investigate Tensile and Stress Rupture Behavior of Crystallographic Lamellar Microstructure in Ni Superalloy Prepared by Laser Powder Bed Fusion

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Abstract

As a unique solidification microstructure of Ni superalloys produced by laser powder bed fusion (L-PBF), the crystallographic lamellar microstructure (CLM) exhibits a strong texture with <001> and <110> orientation, but in-depth mechanical properties studies remain lacking. In this study, comparative studies are conducted to reveal the unique deformation and strengthening mechanism of the CLM under different tensile and stress rupture conditions. The mechanical properties results showed that the specimen with CLM exhibited an outstanding strength-ductility synergy and exceptional stress rupture plasticity due to the presence of high-proportioned <110> texture and unique <001>/<110> boundary. The regularly distributed <001> grains can serve as strong obstacles for slip bands and cracks propagating in <110> grains. Moreover, the <110> texture together with <001>/<110> boundary can elevate the local flow stresses and result in the activation of profuse deformation mechanisms, such as Planar slip bands, Stacking faults (SFs), and deformation twins. This work provides cross-scale insights into the deformation mechanisms and underscores the potential of CLM for developing high-temperature structural applications in Ni superalloy.

Keywords: laser powder bed fusion; crystallographic lamellar microstructure; Ni superalloys; mechanical property; scanning strategy.

Introduction

Laser powder bed fusion (L-PBF), one of the mainstream additive manufacturing technologies, possesses the unprecedented capacity to fabricate high-precision superalloy parts (resembling multi-cavity hollow structure blades) attributed to its ultrafine spot size and digit control technique [1, 2]. In the L-PBF process, the solidification microstructure is governed by the heat input and melt pool geometry, which can be manipulated by various printing parameters, such as laser power, scanning speed, laser spot size, scanning strategy, etc [3].

In 2021 [4], a unique crystallographic lamellar microstructure (CLM) in Inconel 718 alloys was first designed through variation laser power and scanning speed in the L-PBF process. This CLM has a strong texture with a regular alternant <110>-oriented layer and <100>-oriented layer. In the original, the CLM exhibited exceptional strength-ductility combination at room temperature compared to single-crystal and polycrystalline-like microstructure [4]. However, the CLM reports are scarce, and some particular areas need to be clarified: First, it remains to be seen whether such a CLM with a strong texture is suitable for high-temperature conditions. At present, there are relatively fewer reports of L-PBF fabricated superalloy that apply service temperatures up to 1000℃. Second, the stress rupture behavior of CLM at different loading conditions has not been reported. To investigate the stress rupture feature of ZGH451 with CLM is crucial, especially under prolonged exposure to high temperature and stress.

Therefore, this study aims to comprehensively understand the observed mechanical differences and microstructural evolution from L-PBFed CLM superalloy. The tensile and stress rupture tests with different conditions were conducted to evaluate applicability in different service environments. A suite of complementary characterization techniques is carried out to reveal the strengthening mechanism and deformation behavior. This work provides insights into the deformation mechanisms of CLM superalloy for high-temperature applications.

Experimental procedure

The L-PBF experiments were conducted in a sealed working chamber filled with argon gas to keep the oxygen level below 10 ppm. A Concept Laser M2 machine manufactured all specimens ($25 \times 25 \times 60$ mm^3) with the same powder feedstock, scan strategy, and substrate preheating (100 ℃) to minimize the effects of other factors.

The as-built microstructure and fracture morphologies were investigated by a suite of complementary characterization techniques including optical microscopy (OM), scanning electron microscopy (SEM), electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) et.al,

Uniaxial tensile samples were tested in the universal testing machine with a constant strain rate of 10^{-3} s^{-1} at room temperature and 10^{-2} s^{-1} at 1000℃. The stress rupture test was conducted at a constant condition of 760 ºC/780 MPa and 980 ºC/260 MPa. The mechanical properties tests were conducted three times under each condition.

Result and discussion

The CLM specimens exhibit a higher yield strength (YS) and uniform elongation (UE) compared to non-CLM at both different tensile conditions, indicating synergistically enhanced strength-ductility. Meanwhile, the non-CLM samples exhibits the shorter stress rupture life, whereas the CLM sample demonstrates the longer stress rupture life. Regarding stress rupture plasticity, the non-CLM exhibit relatively lower plasticity compared to CLM alloy. Upon comparing of the life and plasticity, it is evident that the CLM sample demonstrates superior stress rupture life while maintaining a relatively high level of plasticity.

In the sub-grain scale, both CLM and non-CLM alloys exhibited typical cellular structures with dense dislocation accumulation at their boundaries, and relatively few were distributed at cellular interiors. The CLM specimens possess more multiple ultrafine planar slip bands than non-CLM samples. These planar slip bands and dislocation cells strengthen the dislocation pinning and enhance the strain hardening during plasticity deformation. The <110> texture is relatively easy to initiate planar slip band associated with rearrangement of dislocations due to its low yield stress and pronounced back stress[5]. The proportion of the <110> and <001> texture layers is approximately 3.6:1 in CLM specimens. Hence, large amounts of planar slip bands are generated within <110> texture layer and increased global plasticity. Simultaneously, these dispersed slip bands facilitate homogeneous plastic deformation and avoid stress concentration at the local region. In addition, the sufficient dislocation pile-ups and theoretically higher effective stacking faults energy in CLM can be enough to slide partials a long distance [6]. Hence, the PLBs and SFs behavior in the CLM specimen is expected during the high strain stage.

Conclusion

The texture-related strengthening plays a dominant role in CLM alloys. The asynchronous deformation of <001> and <110> oriented layer induced strain gradient and produced HDI strengthening, which enhanced yield stress and strain-hardening ability. In addition, the abundant deformation mechanism can be activated in CLM alloys under room temperature tensile, including Planar slip bands (PLBs), Stacking faults (SFs), and deformation twins (DTs).

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