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EFFECTS OF DEFECT, LOADING MODE AND MICROSTRUCTURE ON LPBF 316L FATIGUE BEHAVIOR

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Abstract
The present study aims to investigate the high cycle fatigue (HCF) performance of steel 316L fabricated by the laser powder bed fusion (LPBF) process. Bending and torsional fatigue test specimens built horizontally (0°), inclined (45°), and vertically (90°) have been prepared and tested in the as-built and polished states. The presence of multiple lack-of-fusion defects at the surface or subsurface is detrimental to the endurance under cyclic loading. A more pronounced defect sensitivity in bending compared to torsion is found. Microstructural features are seen to compete with inherent defects to affect fatigue performance in the condition that the effective defect sizes are close to the critical fatigue crack size.

1. Introduction

Previous investigations concerning the fatigue behavior of LPBF 316L were mostly performed under uniaxial tension or bending loading. To date, torsional fatigue tests for LPBF 316L have been seldomly mentioned in the existing literature. For the wrought 316L, it was observed that the ratio of the torsional fatigue strength to the uniaxial fatigue strength is close to 0,6. The presence of large defects may lead to an increase in that ratio, i.e., the uniaxial fatigue strength will be close to the torsional fatigue strength. This may be the case with LPBF metallic materials. Further study about the relationship between inherent defects and fatigue performances under different loading modes will be essential to promote the industrial application of LPBF 316L. The current study aims to investigate the properties of LPBF 316L with a focus on fatigue behavior.

2. Results

We study the material built with different building directions in the as-built state and use only hand-polishing procedures for comparison purposes. A stress-relieving treatment was carried out consisting of a temperature holding of 620 °C for 90 minutes followed by a natural cooling in the air atmosphere. Bending, tension, and torsion fatigue tests have been performed. Fractography observations are conducted. The relationship between fatigue strengths and observed defects at the crack initiation sites is discussed.

Monotonic tension and fatigue properties of LPBF 316L have been listed in Table 1. The fatigue strengths have been characterized using the staircase method. The effect of stress gradient seems to be masked by the surface effect. By removing a thick layer of the surface to get rid of the surface defect to the greatest extent, the fatigue strength under bending/tension loading is not recovered to the expected level as high as that of the wrought material. The torsional fatigue strength is found slightly higher than those of the machined LPBF or wrought counterparts. The bending fatigue behavior of LPBF 316L is anisotropic: fatigue resistance is the weakest when the stress is perpendicular to the plane separating the successive layers. Most of the tested specimens exhibit evident LoF defects on the fracture surfaces. However, some specimens fatigued due to microstructural features indicating the inherent defects are sometimes small and thus compete with microstructure in triggering fatigue crack. Unlike bending, fatigue behavior is almost isotropic when stressed in torsion. Results suggest the characteristic LPBF inherent defect sizes are in the range that may influence the bending fatigue strength while not the torsion fatigue strength due to different sensitivities to defects.

Inherent defects are measured at the fatigue initiation sites. The selected torsion and bending fatigue loading modes revealed that in LPBF 316L, the size and distribution of the process-induced defects might be just at the threshold of the critical fatigue defect. Under the bending loading, the changes in the projection area due to different building directions have brought direct changes to fatigue performance; under the torsion loading, the size of the inherent defects has not reached the threshold of fatigue sensitivity. Even with the building direction changing, the resulting materials were always close to non-defective materials. In Fig. 1, we can see that when the equivalent loading levels were higher than about 250 MPa which were mostly for the 0° bending specimens and all the torsion specimens, the fatigue failure mechanisms were mixed by the defect-inducing and the microstructure-inducing.

Table 1 Monotonic tension and fatigue properties of LPBF 316L (Unit: MPa)

Building direction	Surface finish	Monotonic Tension		Fatigue strengths (R=-1, run-out 2E6 cycles)		
		YS	UTS	Tension	Bending	Torsion
90°	As-built	**450 - 470**	**610 - 630**	**92.5**	**90**	**127**
	Simple-polished	**-**	**-**	**115**	**116**	**143**
	Total-polished	**450 - 470**	**610 - 630**	**-**	**138**	**173**
45°	Total-polished	**-**	**-**	**-**	**215**	**172**
0°	Total-polished	**460 - 475**	**630 - 635**	**-**	**249**	**151**

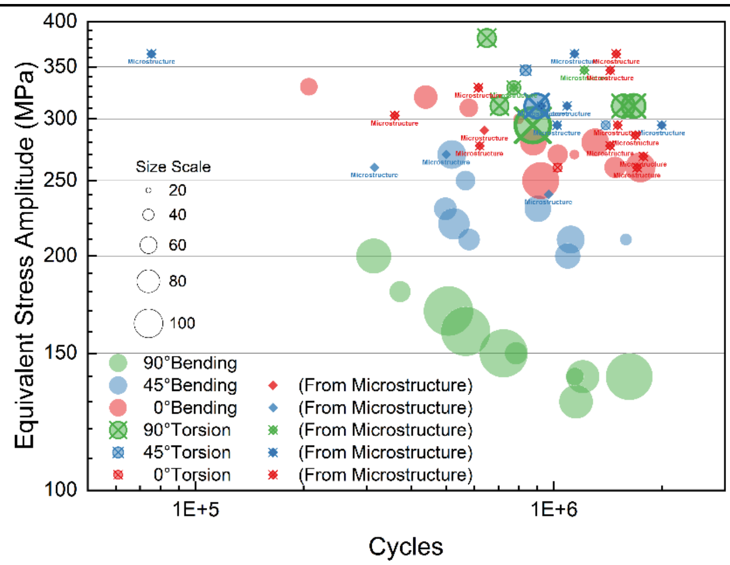

Fig.1 – Plot of fatigue performances of all polished LPBF 316L specimens, R=-1 (defect size scale in μm)

3. Conclusions

1. Surface treatment can improve fatigue performance. But the improvement is seen much more pronounced in bending/tension than in torsion. The multiple clustering defects act synergistically as one large defect to initiate the fatigue crack.

2. The ratios of the torsion fatigue limit to the bending fatigue limit show very different values depending on the building directions. For the horizontal building direction, this ratio is close to 0.6 confirming the defects are no more influential. The fatigue behavior under multiaxial loading for the 0° case is hence expected to be close to other metallic alloys (wrought 316L, 1045 steel, HIP Al-Si alloys …).

3. Under torsion loading mode, all the building directions lead to a better fatigue strength than the wrought 316L. These results show the fundamental role played by the defect and the loading mode and illustrate the difficulty to use all the potential of the specific solidification sub-grain structures known as being responsible for the very good monotonic mechanical properties in AM metallic alloys.