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Influence of surface orientation on fatigue performance of as-built additively manufactured Inconel 718

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Abstract

The fatigue performance of materials, such as Inconel 718, when produced by Laser Powder Bed fusion, needs to be fully understood to manage and exploit the full potential of this Additive Manufacturing technology. Microstructure and as-built surface morphology are strictly related to process parameters and are known to affect the fatigue response. The present contribution examines experimentally the fatigue behavior of laser powder bed fused Inconel 718 testing specimens printed along three different orientations with respect to the built direction. The observed directional fatigue behavior is discussed in terms of surface quality, near-surface microstructure and their interaction with the fatigue crack initiation mechanisms.

1. Introduction

Additive manufacturing (AM) is an advanced technology for fabrication of metal parts characterized by complex geometries and features impossible to be produced with traditional manufacturing methods. The potential of additive manufacturing attracts many industrial sectors and the range of metallic materials processable with this technology is already considerable. Inconel 718 (IN718), one of the most common nickel based super-alloy, is extensively used in the aerospace sector because of its remarkable mechanical properties at high temperatures and successfully processed by AM because of its good weldability (Hosseini and Popovich 2019). Among the different additive manufacturing technology for processing, fabricating or repairing engineering components made of IN718 (Jinoop, Paul, and Bindra 2019), Laser Powder Bed Fusion (L-PBF) is one of the most widely used (Sanchez et al. 2021). The relationship between process parameters and mechanical properties of L-PBF IN718 is subject of extensive investigation (Reeks, Davies, and Marchisio 2020).

The present contribution is especially concerned with the performance of components subjected to dynamic loading conditions in service and therefore fatigue properties are of special concern. The role of as-built surfaces on fatigue strength is here investigated because the surfaces of complex L-PBF parts may be impractical or even impossible to machine. In the literature this topic has been investigated with vertical standard specimens (Morgan and Wells 2016). However, the fatigue performance is expected to depend on the actual surface orientation with respect to build direction. Staircase effect due to surface tilt angle and dross formation on a down-skin surfaces are two examples where surface morphology deviates from what is observed in vertical specimens. The present study adopts a methodology using miniature prismatic specimens tested in cyclic bending that simultaneously introduces freedom in specimen surface orientation during build and reduces material consumption (Nicoletto 2017).

The objective of this contribution is to present the fatigue performance of as-built L-PBF IN718 obtained by testing specimens with surfaces in the upskin and downskin orientations and compare them to the conventional vertical orientation. The directional fatigue behavior is discussed considering the process-dependent surface quality, the near-surface microstructure and their influence on fatigue crack initiation and propagation.

2. Materials and Methods

Miniature specimens (Figure 1a) of IN718 were produced with an EOS M290 system (EOS GmbH Germany) featuring a 400-watt fiber laser to melt metal powder and a building volume of 250 x 250 x 325 mm, using a nominal layer thickness of 40 μm and optimized process parameters by an established service provider (BEAM-IT Group – Italy). After fabrication all specimens were heat-treated with a solution treatment followed by a two-step aging treatment (Popovich et al. 2015). Chemical composition and reference mechanical static properties were coherent with EOS datasheet (EOS, n.d.). Specimens were tested under plane bending under fixed rotation control (Figure 1b), at a frequency of 25Hz and a load ratio of R = 0 so that crack initiation occurred at the center of the flat surface opposite to the round notch. Run-out condition (test interruption without failure) was fixed at 2 10^6 cycles.

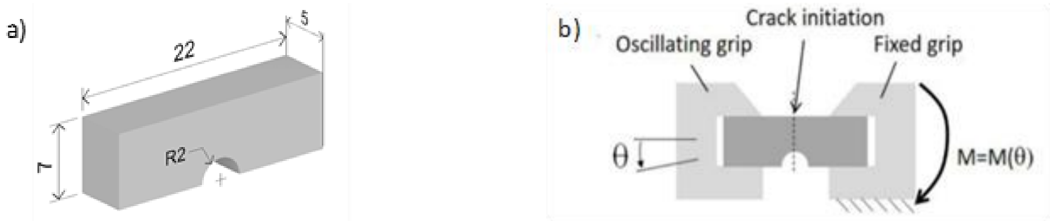

Figure 1: a) Miniature specimen geometry and dimension; b) Fatigue testing configuration and indication of crack initiation point during cyclic plane bending

A total of 36 specimens with three different surface orientations with respect to build direction were produced and tested in the as-built condition. The three orientations are shown in Figure 2a: vertical specimen (C) with flat surface parallel to the built direction and +/-45 degree tilted specimens (i.e. up skin or US 45- and down skin or DS 45+ that is at the limit for support).

3. As-built surface characterization

The morphology of as-built surfaces is the most detrimental factor affecting fatigue performance of L-PBF metals in the as-built condition because the typical irregularities and defects act as micro notches or stress concentrators (Greitemeier et al. 2016). When a component is printed according to an optimized orientation from the producer perspective, the influence of the local surface orientation with respect to build direction must be understood and accounted for in the fatigue assessment. Therefore, Light Optical Microscopy (LOM) was performed on longitudinal cross-sections after polishing and etching in a Zeiss Axio Observer Z1M as shown in Figure 2b. The black arrows identify the build direction and form an angle with the test surface in the two cases of DS 45+ and US 45-. The down skin surface is evidently rougher than the other two orientations.

Figure 2: a) Specimen orientation and denomination; b) Surface morphology and near-surface microstructure obtained on etched specimens by LOM

Quantitatively, standard surface roughness parameters were measured with a contact profilometer (SamaTools SA6220) on each specimen before fatigue testing and are reported in Table 1. The flat surface of down skin specimens (DS 45+) is characterized by highest roughness and by a complex surface profile morphology observed on the cross section of Figure 2b. Typical features of this orientation are deep valleys and many irregularities (i.e. dross) caused by the collapse of melted layers under the effect of gravity. The surface morphologies of the vertical (C) and the up skin (US 45-) specimens shown in Figure 2b are considerably less rough and apparently similar. The slightly higher roughness of up skin (US 45-) specimens reported in Table 1 is attributed to the stair stepping effect that is absent in the vertical specimens.

Table 1: Roughness parameters of as-built surfaces measured with a contact profilometer (SamaTools SA6220)

	Ra [μm]	Rz [μm]	Rq [μm]	Rt [μm]
Down skin (45+)	32.36	91.52	33.78	96.44
Vertical (C)	4.41	12.49	1.90	12.61
Up skin (45-)	4.60	13.01	2.08	13.12

4. Fatigue Behavior

The fatigue data of the present experimental campaign are presented in terms of maximum stress vs. number of cycles to crack initiation in Figure 3. The highest fatigue performance (i.e. estimated fatigue strength at $2x10^6$ cycles of about 460 MPa) is achieved by the specimens with the up skin surface (US 45-). The second-best performance is associated to the vertical specimen(C) orientation and a fatigue strength of approximately 400 MPa. The worst fatigue performance is exhibited by the specimens with the down skin surface (DS 45+), which show a fatigue strength of about 330 MPa. The present data for the vertical orientation (C) can be correlated with published reference data obtained using as-built vertical standard specimens of L-PBF IN718 tested at R = 0 by (Morgan and Wells 2016). Their value of 340 MPa obtained in IN718 printed in a Concept Laser M2 system working for a layer thickness of 30 μm compares favorably to the present fatigue strength of 400 MPa at $2x10^6$ cycles. The comparison demonstrates that the present innovative test methodology drastically reduces material and production costs that typically hamper fatigue testing campaigns and nonetheless obtains reliable fatigue data (Uriati, Nicoletto, and Lutey 2021).

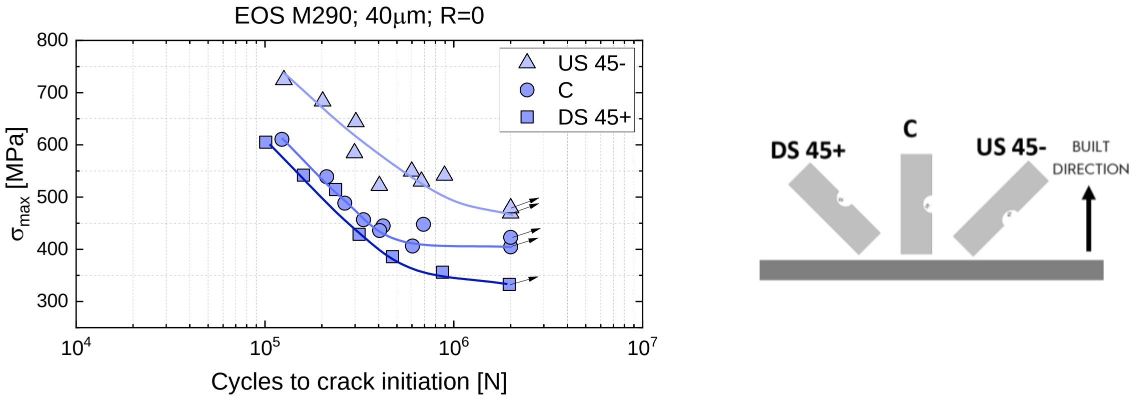

Figure 3: Fatigue behavior of as-built IN718 specimens produced along three different orientations. Symbols with arrows identify test run outs at $2x10^6$ cycles

5. Discussion

As-built surfaces at 45-degrees with respect to build direction exhibit a decrease in performance of almost 40%, going from up-skin to down-skin. The reduction agrees with the significantly higher surface roughness of down skin (DS 45+) specimens compared to up skin (US 45-) specimens. Surprisingly, however, up skin specimens (US 45-) and vertical specimens (C) are characterized by similar surface roughness and similar surface morphology but a significantly different fatigue performance, especially at high number of cycles (i.e. 17 % higher for (US 45-) orientation). So roughness alone cannot explain the fatigue strengths of up skin (US 45-) specimens, of vertical (C) specimens and down skin (DS 45+) specimens. It appears that the tilted specimen orientations are associated to an improved fatigue behavior compared to the reference vertical specimens. The LOM images of etched cracked specimens in the three specimen types are presented in Figure 4 to help interpreting the fatigue response. Contours and hatched regions associated to the fabrication process are clearly identified especially in the (C) and (US 45-) specimens. A characteristic columnar grain structure perpendicular to the layers is known to form in L-PBF IN718, Popovich et al. (2015). Therefore, fatigue crack initiation and early growth is affected by its interaction with the surface features and local microstructure.

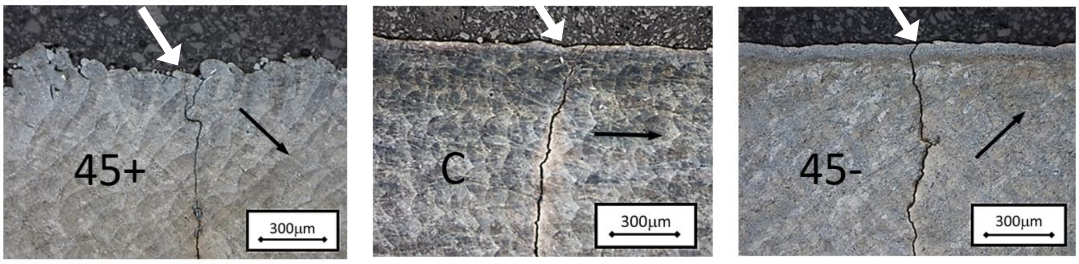

Figure 4: Magnified views of fatigue crack path obtained by polishing and etching specimen after testing using LOM; (Black arrows indicate the columnar grain structure orientation and white arrows indicate the crack initiation point)

The applied cyclic stress parallel to the free surface readily initiate cracks at deep sharp notches of the DS 45+ surfaces. The surface roughness of vertical and US 45- specimens is similar but the initiated fatigue crack in the US intersects at an angle the directional columnar grain structure. The fatigue crack in the vertical specimen (C) apparently grows perpendicular to the surface and relatively straight (Mode I growth). Fatigue cracks in the tilted specimens, both for down skin (DS 45+) and up skin (US 45-), show meandering paths with crack/elongated grain interaction with local Mixed mode I-II growth. This local mixed mode crack growth contribution may explain the higher fatigue strength of up skin specimens than the vertical specimens of as-built L-PBF Inconel 718.

6. Conclusions

The present contribution has demonstrated that the characterization of the fatigue strength of L-PBF IN718 in relation with built direction and surface morphology contributes to the understanding of the anisotropic fatigue behavior of parts introduced by layer-wise fabrication. The best fatigue performance is reached by specimens with as-built up skin surfaces because this orientation combines a reduced surface roughness and the strengthening effect on crack growth introduced by the inclination of the columnar structure with respect to the ideal crack plane. It is concluded that: i) the orientation of the parts in the build chamber and the associated surface roughness are confirmed to be fundamental aspects to be considered in the fatigue design of additively manufactured components; and ii) the usefulness and the efficiency of the proposed miniature specimen testing method is confirmed by this experimental campaign.

References

EOS. n.d. "EOS NickelAlloy IN718 Material Data Sheet". Accessed March 9, 2022. https://www.eos.info/03_system-related-assets/material-related-contents/metal-materials-and-examples/metal-material-datasheet/nickelalloy-inconel/material_datasheet_eos_nickelalloy_in718_m290_premium_en_web.pdf.

Greitemeier, D., C. Dalle Donne, F. Syassen, J. Eufinger, and T. Melz. 2016. "Effect of surface roughness on fatigue performance of additive manufactured Ti–6Al–4V". *Materials Science and Technology* 32, no. 7: 629-34. https://doi.org/10.1179/1743284715Y.0000000053.

Hosseini, E., and V. A. Popovich. 2019. "A review of mechanical properties of additively manufactured Inconel 718". *Additive Manufacturing* 30: Article number 100877. https://doi.org/10.1016/j.addma.2019.100877.

Jinoop, A. N., C. P. Paul, and K. S. Bindra. 2019. "Laser-assisted directed energy deposition of nickel super alloys: A review". *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 233, no. 11: 2376-400. https://doi.org/10.1177/1464420719852658.

Morgan, K., and D. Wells. 2016. "Overview of fatigue and damage tolerance performance of SLM Alloy 718". Presented at the 2016 National Space and Missile Materials Symposium, Westminster, CO, United States, June 2016. https://ntrs.nasa.gov/citations/20160007853.

Nicoletto, G. 2017. "Anisotropic high cycle fatigue behavior of Ti–6Al–4V obtained by powder bed laser fusion". *International Journal of Fatigue* 94: 255-62. https://doi.org/10.1016/j.ijfatigue.2016.04.032.

Popovich, A. A., V. Sh Sufiiarov, I. A. Polozov, and E. V. Borisov. 2015. "Microstructure and mechanical properties of Inconel 718 produced by SLM and subsequent heat treatment". *Key Engineering Materials* 651-653: 665-70. https://doi.org/10.4028/www.scientific.net/KEM.651-653.665.

Reeks, W., H. Davies, and S. Marchisio. 2020. "A review: Interlayer joining of nickel base alloys". *Journal of Advanced Joining Processes* 2: Article number 100030. https://doi.org/10.1016/j.jajp.2020.100030.

Sanchez, S., P. Smith, Z. Xu, G. Gaspard, C. J. Hyde, W. W. Wits, I. A. Ashcroft, H. Chen, and A. T. Clare. 2021. "Powder bed fusion of nickel-based superalloys: A review". *International*

Journal of Machine Tools and Manufacture 165: Article number 103729. https://doi.org/10.1016/j.ijmachtools.2021.103729.

Uriati, F., G. Nicoletto, and A. H. A. Lutey. 2021. "As-built surface quality and fatigue resistance of Inconel 718 obtained by additive manufacturing". *Material Design & Processing Communications* 3, no. 4: Article number e228. https://doi.org/10.1002/mdp2.228.