

As-built surface quality and fatigue resistance of Inconel 718 obtained by additive manufacturing

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Abstract

It has been recognized that parts produced by additive manufacturing with surfaces in the “as-built” state exhibit reduced fatigue properties. On the other hand, post-process surface finishing is expensive and often unfeasible due to the complexity of parts. Therefore, surface quality parameters must be considered when designing as-built parts for structural applications. This work investigates the as-built surface topography of Inconel 718 samples manufactured via laser powder bed fusion (L-PBF) with three different production systems (SLM 280HL, EOS M290, and RENISHAW AM250) and discusses their respective experimental fatigue behavior. The aim of the investigation is to identify a link between the fatigue response of L-PBF IN718 alloy without post fabrication finishing and the surface morphology; a preliminary comparison among the main surface roughness parameters and the fatigue strength is reported and further investigations are planned to find a univocal correlation. Samples with a mean height (S_a) of approximately 20 μm exhibit lower fatigue strength than those with S_a of approximately 5 μm . Skewness (S_{sk}) and kurtosis (S_{ku}) are instead found to be discriminating parameters when comparing surfaces with relatively low surface roughness (S_a 5 μm), with higher values of S_{sk} and S_{ku} associated with inferior fatigue performance.

KEYWORDS

as-built surface quality, fatigue, Inconel 718, laser powder bed fusion (L-PBF), miniature specimen

1 | INTRODUCTION

Additive manufacturing (AM), also known as 3-D printing, is defined according to ASTM F2792-10¹ as “the process of adding materials to create objects” from a 3-D model, usually layer by layer, as opposed to subtractive production with traditional manufacturing processes. The most advanced AM technology currently available for production of metal parts with complex geometry is laser powder bed fusion (L-PBF). The relationship between process parameters, material microstructure, and mechanical properties has been extensively discussed in the literature for this process.² The potential to produce parts with few limitations in terms of geometrical complexity makes L-PBF competitive for product innovation and optimization.

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On the other hand, surface finishing of parts characterized by complex geometry is uneconomical and often impossible. Therefore, parts with surfaces in the as-built state must be used. Unfortunately, it is well known that parts with as-built surfaces exhibit reduced fatigue properties compared to their machined counterparts. For its design relevance in key sectors, the fatigue strength of as-built L-PBF metals has been increasingly investigated recently.^{3,4} Experimental evidence demonstrates that with current high-quality L-PBF systems, surface roughness is of greater influence than internal defects on fatigue properties.⁵ Therefore, surface quality parameters must be considered when designing as-built parts for structural applications.

This work investigates the fatigue strength and as-built surface topography of Inconel 718 samples manufactured via L-PBF with three different industrial production systems: SLM 280HL, EOS M290, and RENISHAW AM250. The aim of the research is identification of a link between the fatigue response of L-PBF IN718 alloy without post fabrication finishing and surface roughness parameters determined using an optical profiler.

2 | MATERIALS AND METHODS

2.1 | Inconel 718 and processing equipment

Inconel 718 is a Ni-based super alloy characterized by high-temperature strength, high fatigue resistance, and remarkable wear and corrosion resistance.⁶ It is routinely used in the production of gas turbine parts in the aerospace, naval, and energy industries.² In this study, three industrial L-PBF systems operated by a primary AM service company (BEAM IT, Fornovo di Taro, Italy) were used to produce fatigue specimens from Inconel 718 alloy powder using optimized process parameters. The production systems employed for sample preparation were (i) an SLM[®] 280HL (SLM Solution Group AG, DE) equipped with two 400-W fiber lasers working with a layer thickness of 50 μm , (ii) a Renishaw AM250 (Renishaw plc., UK) equipped with one 400-W laser working with a layer thickness of 30 μm , and (iii) an EOS M290 (EOS GmbH, DE) equipped with one 400-W fiber laser working with a layer thickness of 40 μm . After fabrication and removal from the build plate, all specimens were heat treated with a solution treatment followed by a two-step aging treatment.^{7,8}

2.2 | Fatigue test methodology

The study adopted a testing methodology based on the use of miniature (22-mm-long) specimens characterized by a prismatic shape and dimensions shown in Figure 1A.⁹ Specimens were tested under plane cyclic bending loading with a load ratio of $R = 0$ so that crack initiation occurred at the center of the flat top surface in an unnotched configuration. This innovative test methodology¹⁰ drastically reduces material and production costs that typically characterize, and therefore limit, fatigue testing campaigns.

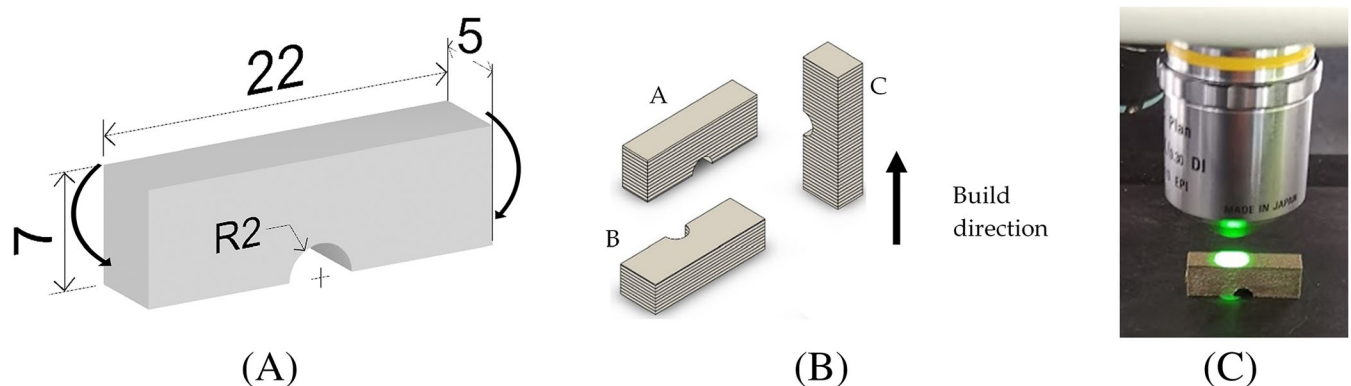


FIGURE 1 (A) Miniature specimen dimensions (22 mm \times 5 mm \times 7 mm and 2-mm-radius notch) and load application configuration. (b) Miniature specimen denomination and orientation. (c) Flat specimen surface under investigation using a Taylor Hobson CCI optical profiler

Figure 1B shows how miniature specimens can be readily produced with different orientations with respect to the build direction to obtain different anisotropic fatigue responses.¹¹ Surfaces with vertical orientation, parallel to the build direction, are typically considered when testing specimens in an as-built state^{12,13} as the resulting surface morphology is characterized by a series of layers, affecting fatigue crack initiation mechanisms and fatigue strength. The present work therefore focused on miniature specimens with orientation *C* only, as the surface morphology of interest was expected on the flat top surface where crack initiation would take place with the fatigue testing methodology employed.

2.3 | Methods and tools for as-built surface characterization

The instrument employed for experimental characterization of surface quality (i.e., topography) was a noncontact green light interferometer. The topography of the flat top surface of each specimen was acquired with a Taylor Hobson CCI optical profiler having a minimum horizontal scanning resolution of 1.3 μm and a vertical resolution of 1 nm; see Figure 1C. The measurement area was $3 \times 3 \text{ mm}^2$, while data collection and analysis were performed with the dedicated software TalyMap. Several relevant roughness parameters were calculated and averaged over three specimen surfaces.

The three-dimensional maps obtained with the optical instrument provided both two-dimensional profile and three-dimensional areal surface roughness parameters. According to Leach,¹⁴ functional information about the surface can be obtained from the areal surface topography while manufacturing process changes significantly affect the surface profile. Figure 2 shows the topography of the vertical as-built surfaces of representative specimens obtained with the three industrial L-PBF systems. Figure 2A,B clearly shows the presence of a layer-by-layer pattern produced by the SLM280HL and EOSM290 systems. On the other hand, this effect is not clearly visible in Figure 2C for the Renishaw AM250 system due to the extensive presence of partially melted particles.

The main areal roughness parameters were extracted from the acquired profiles, including the root-mean-square (RMS) height (S_q), arithmetic mean height (S_a), skewness (S_{sk}), and kurtosis (S_{ku}). S_q is defined as the RMS value of the surface height with respect to the mean plane within the sampling area, while S_a is defined as the arithmetic mean of the absolute value of the height with respect to the mean plane within the sampling area. Both parameters are strongly correlated to each other, with the former having greater statistical significance (it is the standard deviation) and often greater physical importance than the latter. The skewness (S_{sk}) is unitless and can be positive, negative, or 0, describing the shape of the topography height distribution. The kurtosis (S_{ku}) is also unitless but strictly positive, representing a measure of the sharpness of the surface height distribution. S_{sk} and S_{ku} are less mathematically stable than the other parameters since they use high order powers in their equations, leading to faster error accumulation.

The profile surface roughness parameters R_a , R_q , R_{sk} , and R_{ku} were extracted from the three-dimensional topography maps acquired for each sample, with substitution of R in place of S . Even though the equation for S_a is the areal extension of the equation for R_a , their values cannot be directly compared as different filtering methods must be performed in line with different specifications¹⁴ and standards, namely, ISO 25178¹⁵ and ISO 4287,¹⁶ respectively.

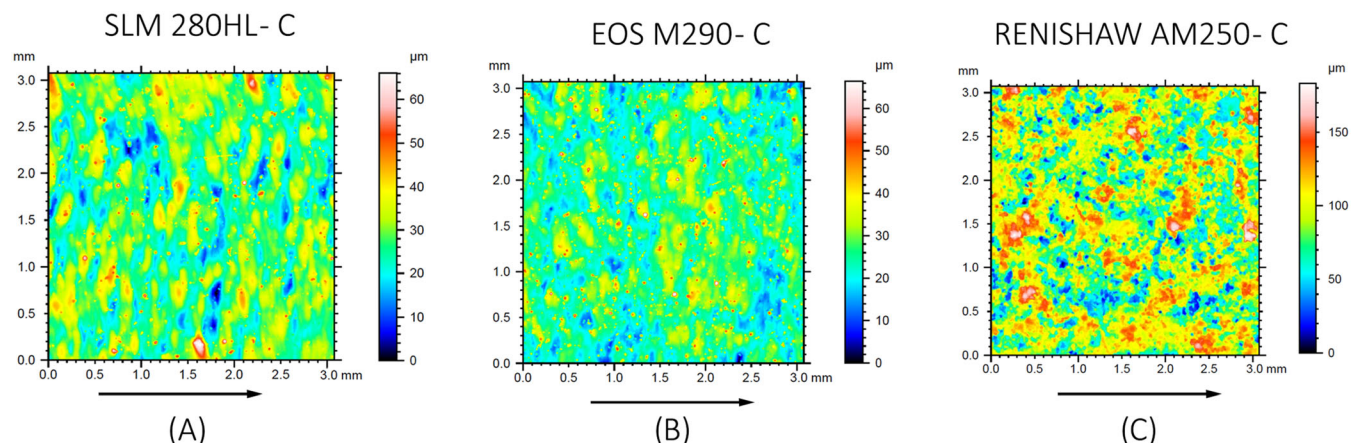


FIGURE 2 Surface topography of as-built IN718 specimens with orientation *C* produced with different production systems. Arrows represent the build direction in each case

3 | RESULTS AND DISCUSSION

Fatigue data for the three sets of vertical miniature specimens (orientation *C* in Figure 1B) are plotted in Figure 3, while the respective values of fatigue strength at 2×10^6 cycles are summarized in Table 1. The *S/N* curves are characterized by similar slopes in the log–log plot but are shifted relative to one another. Samples produced with the SLM280 system exhibit best fatigue performance, followed by those produced with the EOSM290 system then the Renishaw AM250 system.

The fatigue strength (i.e., maximum cyclic stress σ_{\max} with a load ratio of $R = 0$) at 2×10^6 cycles of specimens with orientation *C* varies from $\sigma_{\max} = 455$ MPa for the SLM280HL system to $\sigma_{\max} = 390$ MPa for EOSM290, and $\sigma_{\max} = 260$ MPa for RenishawAM250. The reported values of σ_{\max} include the effective stress factor of correction of 0.91 obtained via elastic FEA and explained in previous work.¹¹

As all specimens underwent the same post-processing heat treatment, characterized by stress relief with heating to 970°C for 1 h followed by cooling in Argon atmosphere and heating to 710°C for 8 h, further aged at 610°C for 8 h and final cooling to room temperature in Argon, the large difference registered in the fatigue strength of the three different sets can be attributed mainly to the surface condition and morphology induced by the fabrication process itself. An investigation of the as-built surfaces obtained with the three different L-PBF systems will be reported in the next section.

To support the significance of the present fatigue testing program using miniature specimen geometry, reference fatigue data from¹² are also plotted in Figure 3, obtained using as-built standard cyclic tensile specimens produced in

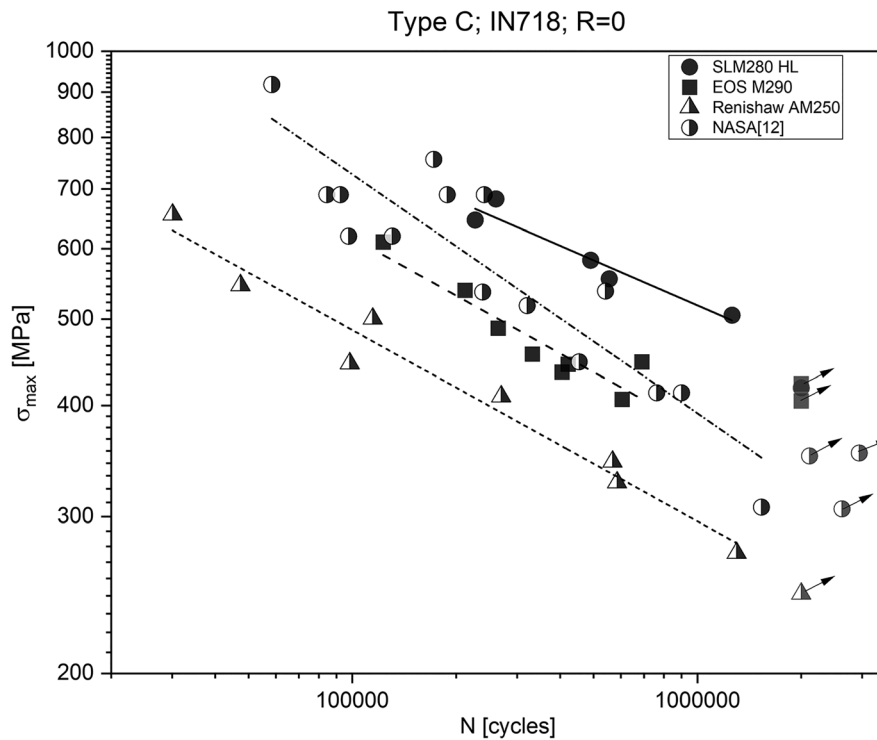


FIGURE 3 Fatigue behavior of as-built IN718 samples produced with different L-PBF systems, arrows represent run out test at 2×10^6 cycles

	σ_a (MPa)	Layer thickness (μm)
SLM280—C	455	50
EOS290—C	387	40
RENISHAW AM250—C	260	30
NASA ¹²	340	30

TABLE 1 Experimental fatigue strength at 2×10^6 cycles and layer thickness characteristics of each set of specimens

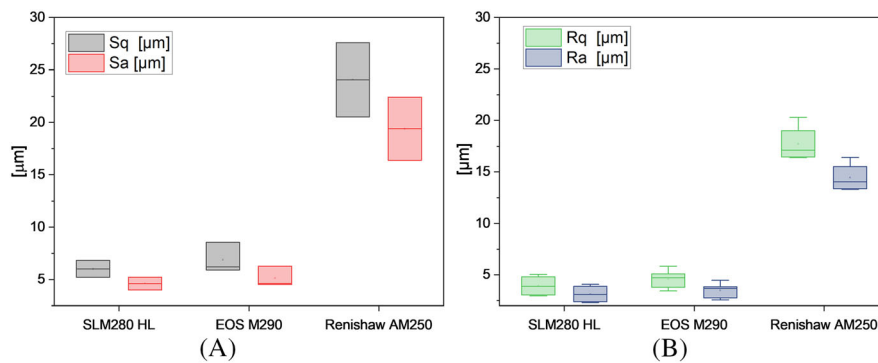


FIGURE 4 Box plots showing the areal (A) and profile (B) root-mean-square height and arithmetic mean height of the investigated surfaces

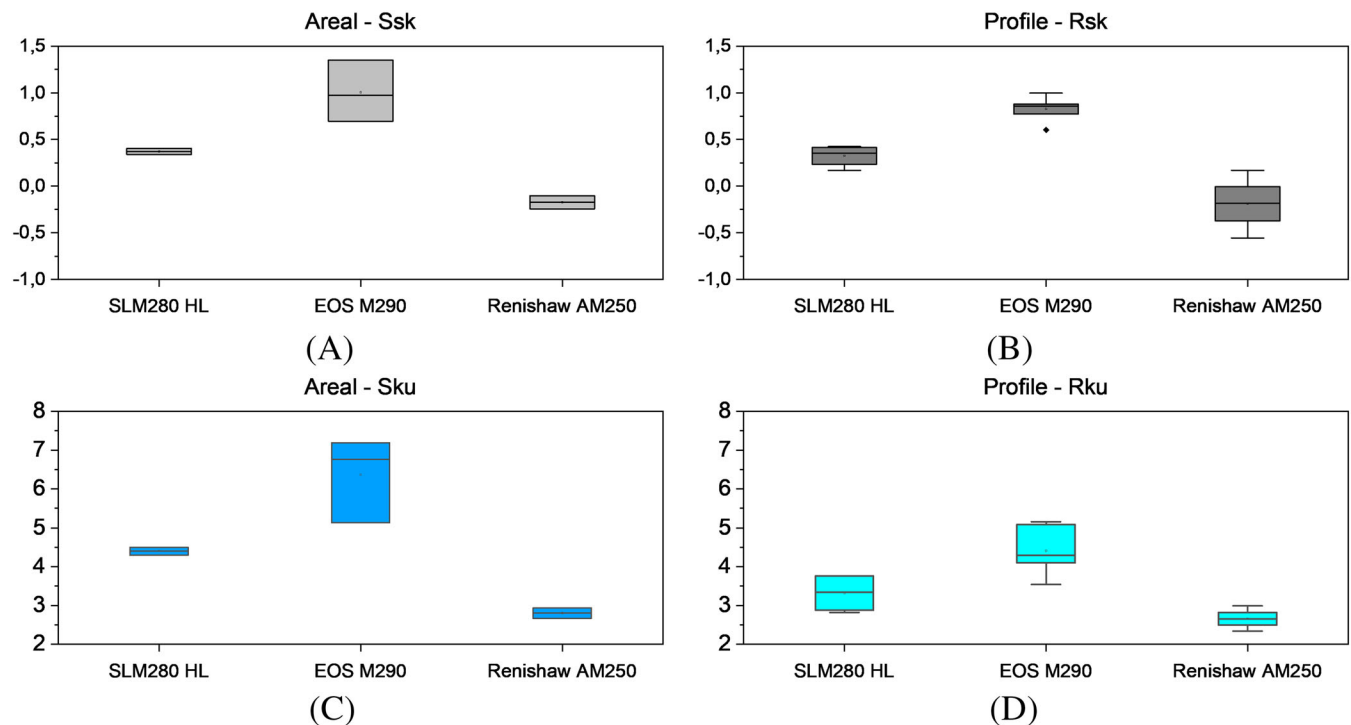


FIGURE 5 Box plots showing the skewness (A and B) and kurtosis (C and D) of the investigated surfaces

the vertical direction with a Concept Laser system working with a layer thickness of 30 μm . Fatigue data from Morgan and Wells¹² fall within the range obtained in the present study, again confirming the reliability of the novel method based on the use of miniature specimen for the evaluation of fatigue properties of metals.¹⁷ However, the slope is somewhat steeper, and the fatigue strength is estimated as 340 MPa, therefore intermediate between data obtained with the EOS M290 and Renishaw AM250 systems.

The following plots compare areal and profile surface roughness parameters extracted from different parallel profiles in both vertical and horizontal directions on specimens obtained with the three production systems.

The morphology of samples produced with the Renishaw system is characterized by higher values of roughness compared to those produced with the EOS and SLM systems in relation to both areal and profile roughness parameters (Figure 4). The high values are also coherent with the lowest fatigue strength evaluated during the experimental campaign. Roughness measurements performed on specimens produced with the EOS and SLM systems (i.e. S_a [R_a] and S_q [R_q]) are instead similar and do not support the hypothesis that the magnitude of the surface roughness is the main factor governing fatigue performance, which is instead significantly different in the case of the SLM280 and EOSM290 systems.

To further investigate the correlation between the fatigue limit and surface morphology, other representative parameters were considered, namely, skewness (Figure 5A,B) and kurtosis (Figure 5C,D), representative of the asymmetry of the surface with respect to the mean plane/line and sharpness of the height distribution, respectively. Comparing these two parameters, samples produced with the SLM and EOS systems reveal a significant difference. Samples produced with the EOS M290 system are characterized by a lower fatigue strength and higher skewness and kurtosis, thus indicating a surface characterized by a higher and sharper height distribution. Samples produced with the SLM280 system are instead characterized by higher fatigue strength and lower skewness and kurtosis, indicating a surface with a regular peak-valley distribution and a reduced profile acuity.

The role of skewness and kurtosis in relation to the fatigue strength is not confirmed by data obtained for samples produced with the Renishaw system, which are characterized by the lowest values. Therefore, the fatigue performance of as-built surfaces obtained by L-PBF processing of Inconel 718 is the result of a complex interaction between different surface morphology parameters. The arithmetical mean height (S_a and R_a) and RMS height (S_q and R_q) clearly apply to the low fatigue strength of RenishawAM250 specimens but not to discriminate between the fatigue response of SLM 280 and EOS M290 specimens. Skewness and kurtosis inversely correlate with fatigue strength in the latter two cases.

4 | CONCLUSIONS

Three different industrial L-PBF systems were used to produce miniature vertical IN718 specimens, which were subsequently tested to evaluate their fatigue strength. The results displayed differences that were examined in relation to the as-built surface morphology in an attempt of identifying a unique link.

The surface topography of the different specimens was determined experimentally using a non-contact optical profiler, with the main surface roughness parameters calculated and compared. Among the many parameters available, the most representative when considering the fatigue performance were found to be (i) the surface roughness and (ii) the surface kurtosis and skewness.

The present study did not reveal a unique surface quality indicator that correlates with the experimental fatigue strength of as-built L-PBF Inconel 718. Nonetheless, the present approach is currently being investigated further by considering other AM materials, test specimens and surface orientations with the aim of establishing an empirical surface parameter that correlates with the fatigue behavior.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. ISO/ASTM52900-15. Standard terminology for additive manufacturing—general principles—terminology, ASTM International, West Conshohocken, PA, 2015, www.astm.org
2. Hosseini E, Popovich VA. A review of mechanical properties of additively manufactured Inconel 718. *Addit Manuf.* 2019;30:100877. <http://dx.doi.org/10.1016/j.addma.2019.100877>
3. Greitemeier D, Dalle Donne C, Syassen F, Eufinger J, Melz T. Effect of surface roughness on fatigue performance of additive manufactured Ti-6Al-4V. *Mater Sci Technol.* 2016;32(7):629-634. <https://doi.org/10.1179/1743284715Y.0000000053>
4. Lee S, Pegues JW, Shamsaei N. Fatigue behavior and modeling for additive manufactured 304L stainless steel: The effect of surface roughness. *Int J Fatigue.* 2020;141:105856. <http://dx.doi.org/10.1016/j.ijfatigue.2020.105856>
5. Solberg K, Berto F. Notch-defect interaction in additively manufactured Inconel 718. *Int J Fatigue.* 2019;122:35-45. <http://dx.doi.org/10.1016/j.ijfatigue.2018.12.021>
6. Reed RC. *The Superalloys: Fundamentals and Applications.* Cambridge: Cambridge University Press; 2006.

7. Caliarì FR, Candioto KCG, Reis DAP, Couto AA, de Moura Neto C, Nunes CÂ. Effect of aging treatment on Inconel 718 superalloy: application in elevated temperatures. *Mater Sci Forum*. 2014;805:199-203. <https://doi.org/10.4028/www.scientific.net/MSF.805.199>
8. Popovich AA, Sufiiarov VS, Polozov IA, Borisov EV. Microstructure and mechanical properties of Inconel 718 produced by SLM and subsequent heat treatment. *Key Eng Mater*. 2015;651-653:665-670. <https://doi.org/10.4028/www.scientific.net/KEM.651-653.665>
9. Nicoletto G. An efficient test method for the quantification of technology-dependent factors affecting the fatigue behavior of metallic additive manufacturing components. In: Shamsaei N, Daniewicz S, Hrabe N, Beretta S, Waller J, Seifi M, eds. *Structural Integrity of Additive Manufactured Parts*. A c. di 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International; 2020: 484-506.
10. Nicoletto G. Efficient determination of influence factors in fatigue of additive manufactured metals. *Procedia Struct Integr*. 2018;8:184-191. <https://doi.org/10.1016/j.prostr.2017.12.020>
11. Nicoletto G. Anisotropic high cycle fatigue behavior of Ti-6Al-4V obtained by powder bed laser fusion. *Int J Fatigue*. 2017;94:255-262. <https://doi.org/10.1016/j.ijfatigue.2016.04.032>
12. Morgan K, Wells D. Overview of fatigue and damage tolerance performance of SLM alloy 718. NASA, 2017.
13. Solberg K, Torgersen J, Berto F. Fatigue behaviour of additively manufactured Inconel 718 produced by selective laser melting. *Procedia Struct Integr*. 2018;13:1762-1767. <https://doi.org/10.1016/j.prostr.2018.12.371>
14. Leach R. *A c. di, Characterisation of Areal Surface Texture*. Berlin, Heidelberg: Springer Berlin Heidelberg; 2013.
15. ISO 25178-1:2016. Geometrical product specifications (GPS)—surface texture: areal—part 1: indication of surface texture.
16. ISO 4287:1997. Geometrical product specifications (GPS)—surface texture: profile method—terms, definitions and surface texture parameters.
17. Konečná R, Nicoletto G, Kunz L, Bača A. Microstructure and directional fatigue behavior of Inconel 718 produced by selective laser melting. *Procedia Struct Integr*. 2016;2:2381-2388. <https://doi.org/10.1016/j.prostr.2016.06.298>

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