Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Fatigue Behavior of Laser Beam Directed Energy Deposited Inconel 718 at Elevated Temperature

Alexander S. Johnson[1], Rakish Shrestha[2,3], P.D. Nezhadfar[2,3], Nima Shamsaei[2,3*]

[1]TriVector Services Incorporation, Huntsville, AL
[2]Department of Mechanical Engineering, Auburn University, Auburn, AL
[3]National Center for Additive Manufacturing Excellence (NCAME), Auburn University, Auburn, AL

[*]Corresponding author: shamsaei@auburn.edu

Abstract

Nickle based super alloys such as Inconel 718 are being extensively used to manufacture turbine blades for jet engines due to their superior mechanical properties at higher working temperatures. Furthermore, poor machinability associated with Inconel 718 also makes it an attractive material for additive manufacturing processes, which possess the capability to fabricate near net shaped parts. Hence, in this study, the fatigue behavior of Inconel 718 fabricated using laser beam directed energy deposition (LB-DED) is investigated under strain-controlled, fully-reversed conditions at an elevated temperature of 650° C. Fractography analysis was conducted to determine the failure mechanism for additive manufactured Inconel 718 due to higher working temperatures. The results obtained from the fatigue and fractography analysis were then compared with the results obtained from fatigue tests conducted at room temperature. At elevated test temperature, LB-DED Inconel 718 specimens exhibited lower fatigue resistance compared to the tests conducted at the room temperature, primarily in the low cycle fatigue regime. Whereas, in the high cycle fatigue regime the effect of test temperature was observed to be minimal. Furthermore, secondary cracks resulting from the formation of brittle behaving precipitates on the grain boundaries was also evident from the fractography analysis indicating significant changes in the microstructural features of LB-DED Inconel 718 as a consequence of elevated test temperature.

Keywords: Inconel 718, Fatigue, Elevated temperature, Laser beam directed energy deposition

Introduction

Inconel 718, a nickel based super alloy, with superior mechanical properties and corrosion resistance in a wide range of temperatures (i.e. from ambient temperature to elevated temperatures) are being extensively used in nuclear reactors and in the fabrication of turbine blades for jet engines [1, 2]. Along with its superior mechanical properties, Inconel 718 also possess high toughness, which makes this alloy difficult to be machined [3, 4]. As a result, fabrication of these materials using additive manufacturing (AM) techniques is recently gaining attention due to the ability of AM process to manufacture near-net shaped parts, which would eliminate/decrease the need for machining.

Despite various advantages of AM processes, parts fabricated using these techniques also come with some drawbacks, which includes, presence of defects resulting from lack of fusion (LoF) between the subsequent layers and gas entrapped pores [5]. Furthermore, due to high cooling rates inherent to AM processes, the microstructural features also vary greatly when compared with those of wrought counterparts [6]. Therefore, to ensure the reliability of additive manufactured (AM) Inconel 718 parts, effect of defects and microstructural features on the fatigue behavior of this alloy at room and elevated temperatures need to be thoroughly understood.

Johnson et al. [7] studied the uniaxial strain-controlled, fully reversed room temperature fatigue behavior of Inconel 718 fabricated using laser beam directed energy deposition (LB-DED) process. Results showed that the employed heat treatment procedure was capable of transferring large elongated grains, resulting from directional heat dissipation during manufacturing process, into finer and more equiaxed grain structure. However, LB-DED Inconel 718 exhibited a lower fatigue resistance as compared to the wrought counterpart, which was attributed to the presence of brittle inclusions of metal-carbide/oxide and gas entrapped pores located near the surface of the specimens.

Konecna et al. [8], studied the effect of layer orientation on the resulting room temperature fatigue behavior of near-net shape (i.e. as-built surface condition) Inconel 718 manufactured using laser beam powder bed fusion (LB-PBF) process. This study showed that the crack always initiated from pore-like defects close/on the surface of the specimens. Furthermore, a good correlation between the surface roughness values and the resulting fatigue lives was reported as specimen with higher surface roughness always exhibited shorter fatigue lives. Some anisotropy in the fatigue behavior of LB-PBF Inconel 718 was also evident as the lowest fatigue resistance was found to be obtained for specimens with loading direction parallel to the build direction.

Yadollahi and Shamsaei [6] reported a minimal effect of surface roughness on the fatigue behavior of LB-PBF Inconel 718 subjected to uniaxial force-controlled loading in laboratory environment (i.e. 26°C). Similarity in fatigue resistance of machined and as-built (non-machined) specimens was associated to the migration of large sub-surface defects that were brought to the surface through the machining process. Such defects acted similar to the surface roughness in the as-built specimens resulting in the similar fatigue lives. Hence, this study highlighted the importance of depth of machining and its effect on the resulting fatigue behavior of AM parts.

Recently, many studies have focused on investigating the influence of defects and microstructure on the room temperature fatigue behavior of AM Inconel 718. However, to the best of authors' knowledge there is no study on the effect of defects and microstructural features on the fatigue strength of AM Inconel 718 at elevated temperatures in the literature. Therefore, in this study, the fatigue behavior of LB-DED Inconel 718 is investigated under uniaxial strain-controlled fatigue test at elevated temperature of 650°C. The experimental procedure for fabricating parts and conducting fatigue tests are explained. Results obtained from the experimental tests are presented. Eventually, based on the results, important conclusions are drawn.

Experimental Procedure

Plasma rotate electrode processed (PREP) Inconel 718 powder with size distribution ranging between 45 to 150 µm were used to fabricate parts in an OPTOMEC LENS^{TM} 750, an LB-DED system. Prior to the fabrication of specimens, preliminary line test was conducted to determine appropriate process parameters capable of producing desired geometry as well as good fusion with the build plate [7]. Based on the results obtained from the line test, laser power of 350 W, scan speed of 15 mm/s, powder flow rate of 0.057 g/s, and hatch spacing of 0.529 mm were proposed as the optimal process parameters [7]. Cylindrical rods with diameter of 8 mm and 80 mm length were fabricated one at a time in vertical direction (i.e. perpendicular to the build plate) in an argon purged environment using the proposed process parameters. Cylindrical rods were fabricated instead of net shaped parts in order to ensure that sufficient material is removed during the machining process and minimize the effect of surface roughness. This is important as previous studies have shown that when insufficient material is removed, machined specimens exhibits similar fatigue resistance to that compared to the as built specimen [6].

Cylindrical rods were further machined into specimens with uniform gage section following ASTM Standard E606 [9] with the final dimensions shown in Fig. 1. It also needs to be mentioned that the gage diameter of the specimen was slightly deviated from the minimum recommended dimension of 6.35 mm by ASTM Standard E606 [9] to minimize the machining process. Machined samples were further subjected to standard heat treatment procedure for Inconel 718 reported in [10]. Specimens were first heated up to 940°C for 2 hours followed by air cooling at the rate of 50°C per hour. Once the specimen reached to 621°C, the temperature was then held constant and the specimen was aged for 8 hours followed by air cooling.

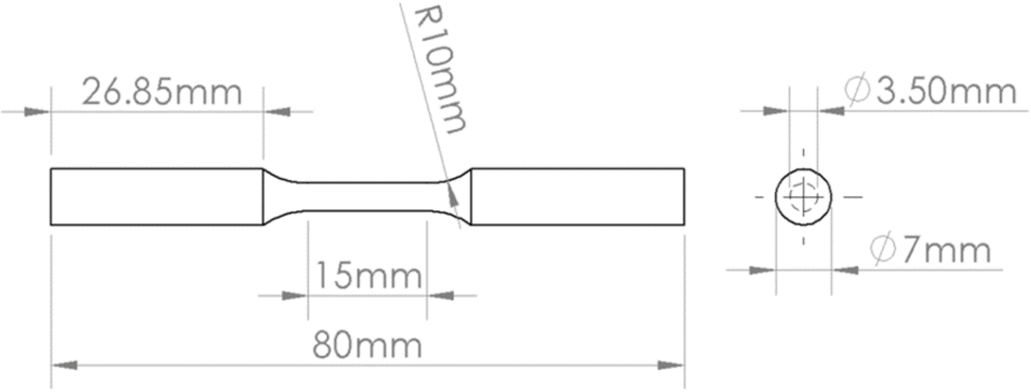

Figure 1: Specimen geometry of LB-DED Inconel 718 alloy used for fatigue testing.

Strain-controlled fatigue tests were conducted in an MTS Landmark servo-hydraulic test frame with load cell of 100 kN. Furthermore, the test frequency applied was calculated based on the strain amplitude to obtain similar average strain rate for all of the fatigue tests. MTS high temperature extensometer was used to monitor the deformation on the gage section of the specimen as well as to control the fatigue tests. All of the mechanical tests at the elevated temperature were conducted in an MTS high temperature chamber at 650°C using a sinusoidal wave form. In order to only heat the gage section of the specimens, grips were cooled using running water during the fatigue test as shown in Fig. 2, which illustrates the complete test setup. Fractography analysis was conducted using scanning electron microscope (SEM) to investigate factors responsible for crack initiation and the failure mechanism at elevated temperatures.

Figure 2. High temperature fatigue test setup showing all of equipment used in the study.

Experimental Results and Discussions

Uniaxial strain-controlled fatigue test results presented in Fig. 3 show some effect of testing temperature (i.e. room temperature vs. high temperature) on the fatigue behavior of LB-DED Inconel 718, which primarily depended on the fatigue life regimes. As it can be clearly seen from Fig. 3, in low cycle fatigue regime, LB-DED Inconel 718 specimens possessed better fatigue resistance at room temperature as compared to the isothermal high temperature fatigue tests conducted at 650°C. On the other hand, in high cycle fatigue regime, the effect of test temperature was observed to be minimum. Such variation in the fatigue behavior in different fatigue regimes of LB-DED Inconel 718 may be attributed to the change in microstructure resulting from the elevated test temperature.

At high cycle fatigue regime, the majority of fatigue life is spent for the initiation of crack, which is not affected by the microstructure in presence of defects such as pores [11]. As a result, in the high cycle fatigue regime effect of test temperature on the fatigue life may have been minimal. Whereas, in the low cycle fatigue regime, majority of the fatigue life is spent in the crack growth state, which can be significantly affected by the microstructural features [11, 12]. Hence, significant effect of test temperature may have been evident on the fatigue life of LB-DED Inconel 718 at higher values of strain amplitudes (i.e. low cycle fatigue). It has been reported that brittle precipitates will be formed at elevated temperatures on the grain boundaries, which exacerbate the fatigue resistance of material at elevated temperatures [13].

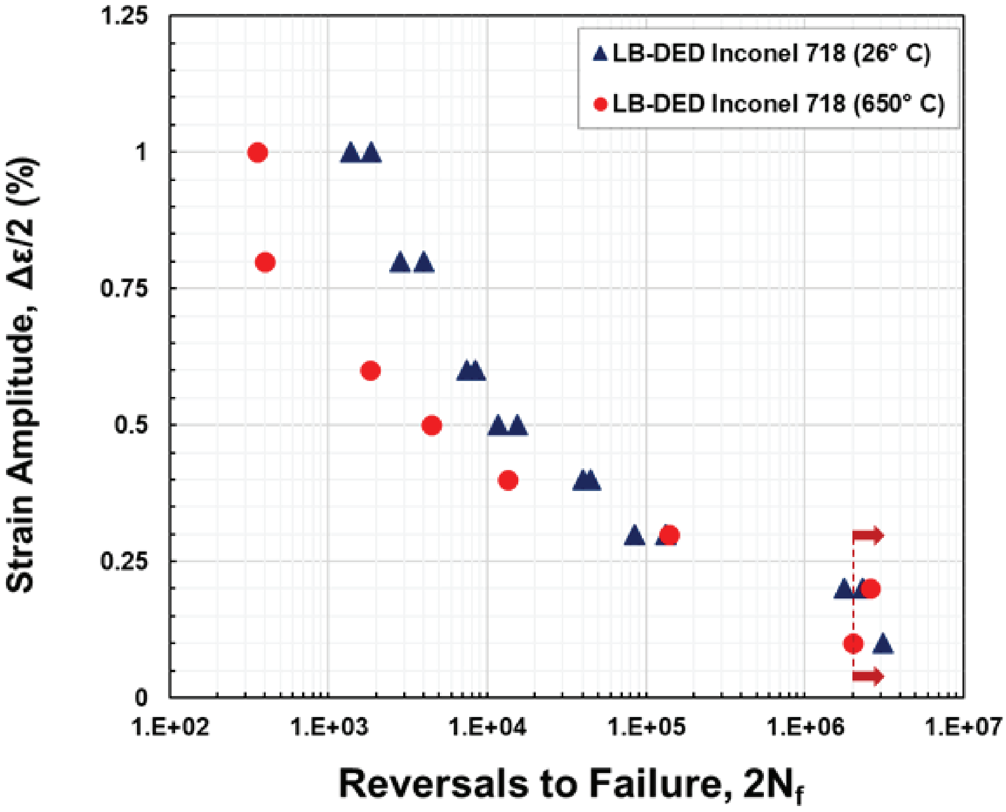

Figure 3: Comparison of fatigue life obtained for LB-DED Inconel 718 from the fatigue tests conducted at room temperature and at 650° C

Figure 4 shows the fracture surface of the specimen subjected to 0.1 mm/mm strain amplitude at the 650° C. To further understand the failure mechanism under isothermal high temperature fatigue loading, the fracture surface shown in Fig. 4 was compared with the one at obtained from room temperature test adopted from [7]. For the test conducted at the room temperature, the fracture surface was seen to be somewhat flat with the crack initiating from a metallic inclusion located at the surface of the specimen as shown in Fig. 4(a) and (b), which is presented in detail in [7]. On the other hand, for the test carried out at elevated temperature, the fracture surface was observed to be more irregular indicating a more torturous crack path, which may have resulted from the change in the microstructure during the test at elevated temperature. In addition, upon closer analysis, secondary cracks were also seen on the fracture surface of the specimen indicated by the red dashed arrow shown in the zoomed-in images in Fig.4. Presence of such secondary cracks may be attributed to the formation of brittle precipitates at high temperature, which consequently affects the resulting isothermal high temperature fatigue lives of LB-DED Inconel 718.

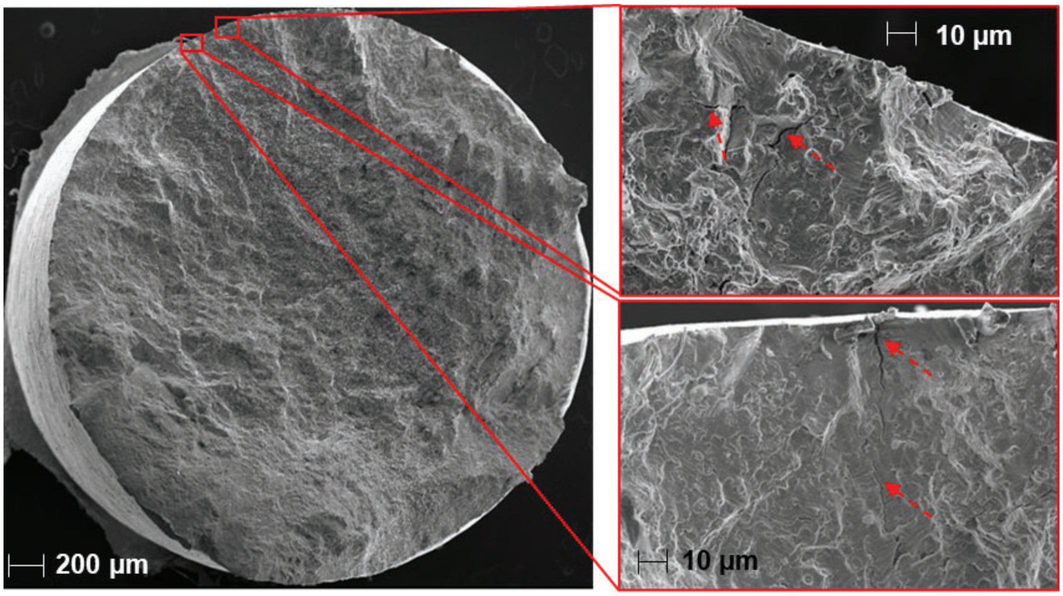

Figure 4: Fracture surface of LB-DED Inconel 718 subjected to 0.1 mm/mm strain amplitude at 650ºC.

Conclusions

In this study, the fatigue behavior of Inconel 718 fabricated using a laser beam directed energy deposition (LB-DED) process was investigated under uniaxial strain-controlled fatigue tests at the elevated temperature of 650°C. Based on the results obtained from the experiments and fractography analysis, following conclusions are drawn:

1. Testing temperature was seen to significantly affect the fatigue resistance of LB-DED Inconel 718 specimens. Under identical value of strain amplitude, higher fatigue life was observed for the tests conducted at the room temperature.

2. Larger variation in the fatigue life data was observed at low cycle fatigue regime, in which the majority of the fatigue life is governed by crack growth stage, when compared to the high cycle fatigue regime, in which the majority of the fatigue life is spent in crack initiation stage. Such a result can be attributed to the change in the microstructure resulting from the high test temperature, which primarily affects the crack growth behavior and not the crack initiation behavior.

3. Fractography analysis of specimen tested at high temperature revealed secondary cracks on the fracture surface, which may indicate the formation of brittle precipitates as a result of higher test temperature that can have a detrimental effect on the fatigue lives of LB-DED Inconel 718 specimens.

Acknowledgements

The experiments were conducted when the authors were at Mississippi State University.

References

[1] F. Liu, X. Lin, C. Huang, M. Song, G. Yang, J. Chen, and W. Huang, The effect of laser scanning path on microstructures and mechanical properties of laser solid formed nickel-base superalloy Inconel 718, Journal of Alloys and Compounds, 509 (2011) 4505-4509.
[2] S.-H. Chang, In situ TEM observation of γ′, γ ″and δ precipitations on Inconel 718 superalloy through HIP treatment, Journal of Alloys and Compounds, 486 (2009) 716-721.
[3] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquere, V. Zerrouki, and J. Vigneau, A review of developments towards dry and high speed machining of Inconel 718 alloy, International Journal of Machine Tools and Manufacture, 44 (2004) 439-456.
[4] B. Izquierdo, S. Plaza, J. Sánchez, I. Pombo, and N. Ortega, Numerical prediction of heat affected layer in the EDM of aeronautical alloys, Applied Surface Science, 259 (2012) 780-790.
[5] S. Daniewicz and N. Shamsaei, An introduction to the fatigue and fracture behavior of additive manufactured parts, International Journal of Fatigue, 94 (2017) 167.
[6] A. Yadollahi and N. Shamsaei, Additive manufacturing of fatigue resistant materials: Challenges and opportunities, International Journal of Fatigue, 98 (2017) 14-31.
[7] A.S. Johnson, S. Shao, N. Shamsaei, S.M. Thompson, and L. Bian, Microstructure, fatigue behavior, and failure mechanisms of direct laser-deposited Inconel 718, JOM, 69 (2017) 597-603.
[8] R. Konečná, G. Nicoletto, L. Kunz, and A. Bača, Microstructure and directional fatigue behavior of Inconel 718 produced by selective laser melting, Procedia Structural Integrity, 2 (2016) 2381-2388.
[9] ASTM E606-04, Standard Practice for Strain-Controlled Fatigue Testing, ASTM International, West Conshohocken, PA, (2004).
[10] C. Brinkman and G. Korth, Strain Fatigue and Tensile Behavior of Inconel® 718 from Room Temperature to 650 C, Journal of Testing and Evaluation, 2 (1974) 249-259.
[11] R.I. Stephens, A. Fatemi, R.R. Stephens, and H.O. Fuchs, Metal fatigue in engineering, John Wiley & Sons2000.
[12] P.D. Nezhadfar, R. Shrestha, N. Phan, and N. Shamsaei, Fatigue behavior of additively manufactured 17-4 PH stainless steel: Synergistic effects of surface roughness and heat treatment, International Journal of Fatigue, 124 (2019) 188-204.
[13] A. Thomas, M. El-Wahabi, J. Cabrera, and J. Prado, High temperature deformation of Inconel 718, Journal of Materials Processing Technology, 177 (2006) 469-472.