A Comparative Study of Selective Laser Melting Processed Inconel 625 Superalloy: Fatigue Performances under Constant Amplitude Loading and Single Tensile Overload

D Q Ren¹², Y Jiang¹²*, Y Zhang¹², and X A Hu¹²

¹ School of Aircraft Engineering, Nanchang Hangkong University, Nanchang, China;
² Jiangxi Key Laboratory of Micro Aeroengine (Nanchang Hangkong University), Nanchang, China;
³ School of Materials Science and Technology, Nanchang Hangkong University, Nanchang, China.

*Corresponding author: Jiang Yun, E-mail: jycake245@126.com

Abstract. The Inconel 625 used in this study was fabricated by the selective laser melting technology. The fatigue properties of this alloy were investigated at room temperature. The compact-tension specimens were used to study the fatigue crack growth behaviors under stress ratio R = 0.1, and overload ratio ROL = 1.4. Three typical behaviors of overload fatigue crack growth (increase, drop and increase) were studied.

1. Introduction

Selective laser melting (SLM) is a promising additive manufacturing (AM) technology [1, 2]. Due to its convenience of fabricating superalloy, SLM technology has received wide attention in metal processing industries. SLM materials have good static performance [2]. But for many components used in the aerospace industries, the fatigue properties always are the main focus points because of the components always suffer the fatigue failure. In order to solve this engineering problem, it is necessary to study the fatigue properties of SLM materials.

As one kind of Nickel-based deformation superalloy, Inconel 625 has good tensile property and fatigue performance. This alloy is reinforced by solid solution with the Molybdenum and Niobium [3]. With all those good characteristics, Inconel 625 is widely used to process the components of air-engine. Therefore, in order to apply SLM Inconel 625 into the manufacturing of air-engine hot section components, the fatigue behaviour of SLM alloy should be studied.

Konečná et al. [3] studied the long fatigue crack growth of Inconel 718 produced by SLM. They proposed that the SLM Inconel 718 shows the less resistant to the fatigue crack growth (FCG) in near threshold region, while in Paris region the SLM Inconel 718 shows the similar FCG behaviour with wrought alloys. Poulin et al. [4] investigated the fatigue crack growth behaviour of Inconel 625 processed by laser powder bed fusion and reported that the scatter influence of SLM alloy is mainly occurred in the near threshold region.

This present study was, therefore, aimed at investigating the FCG behavior of SLM Inconel 625. The fatigue fracture surface was observed by scanning electron microscope (SEM).
2. Materials and Experimental details
As-received the SLM Inconel 625 was made from the pre-alloyed gas-atomized spherical powder, and was subjected to solution annealing heat treatment at 1,100 °C/hour in an argon protected environment to eliminate the residual stress and optimize the anisotropy of the microstructure. Inconel 625 powders were featured the following chemical composition (in wt. %): 65.17 Ni, 8.34 Mo, 3.96 Nb, 0.9 Fe, 0.37 Al, 0.0732 C, 20.68 Cr, and 0.04 Mn. The CT specimens with characteristic size $w = 40$ mm and thinness $t = 5$ mm according to the geometry specified in ASTM E647 have been cut from the SLM Inconel 625 block. The crack propagation direction has been identical with the build direction, see Figure 1. The as-produced CT specimen is shown in Figure 2.

Fatigue tests were performed at Instron 8872 Electro-hydraulic servo fatigue machine under the constant amplitude load (CA) ratio ($R = P_{\text{max}}/P_{\text{min}}$) of $R = 0.1$, and overload ratio ($ROL = POL/P_{\text{max}}$) of $ROL = 1.4$, the $P_{\text{max}}$ was 2770 N and $POL$ was 3878 N, respectively. The crack mouth clip gauge was used to measure the crack length. The overload was applied in Paris region with the stress intensity factor range about $\Delta K = 22$ MPa$\sqrt{\text{m}}$. To observe the net effect due to overload, the exactly same load range was maintained just before and after overload. After the samples fractured, fatigue fracture surface was observed by scanning electron microscope (SEM).

3. Result and Discussion

3.1. Fatigue crack growth behaviour
The experimentally determined points of the crack growth curve describing the behaviour of crack in the investigated SLM Inconel 625 are shown in Fig. 4.

The crack growth rate $da/dN$ was plotted against the stress intensity factor range $\Delta K = K_{\text{max}} - K_{\text{min}}$. It can be seen that the fatigue crack grown in a relative stable increment under the constant
amplitude load with the stress ratio of 0.1. Three typical results while overloading applied can be observed in Figure 3 compared with the line of CA. That is, including: (I) the instantaneous acceleration period, (II) delayed retardation period, (III) retardation period. After these three periods, the FCG would get into the stable growth period again until the specimen fractured. Generally, the crack tip blunting will be caused because of the overload applying. So that the fatigue crack is suddenly free from the influence of crack closure, as a result, a transient initial acceleration of crack growth rate occurs immediately after the overloads [5]. But the overloads also can make the residual compressive stress increasing. Due to this reason the fatigue crack growth rate will decrease to approach the minimum value. Meanwhile, the crack plastic zone caused by overload also is the dominant factor of fatigue crack growth. After the crack goes through the region affected by overload, the crack behavior will be the same as before overload.

![Graph showing Fatigue Crack Growth Rate vs. Stress Intensity Factor Range](image)

**Figure 3.** Comparison of FCG rates data obtained for the investigated SLM alloy.

3.2. Fractography

The local crack growth rate is determined by the stress intensity factor, local microstructure and residual stress. Examples of characteristic fracture surfaces, as observed by SEM, are presented in Figures 4 and 5.

The macroscopic plane of the fracture surface is parallel to the building direction of SLM process. Figure 4 shows the crack surface of Y-Z sample under stress $R = 0.1$. It can be seen that the small numbers of secondary micro-cracks and micro-voids. The enlarged map in Figure 4b shows the clear fatigue striations. The phenomena in Figure 4 are also observed in Figure 5c. This indicates that the overload is indeed loaded in Paris region. Figure 5a and b show the fracture surface near the threshold region. Figure 5a is characteristic by elongated areas covered by fine slip lines. Figure 5a and b shows the transgranular manner of crack propagation. The red arrows in Figure 8 are illustrating the local crack growth directions. In Figure 5a, it locally differs a lot from the building direction. Figures 5a-d show the cleavage-like fracture features. Figures 5e-g both show the secondary crack and appear the random local crack growth directions. It may be caused because of the the overload application that the high level stress will be introduced to affect the fatigue crack growth behavior. At the left of the red line in Figure 5g, in which shows a relative flat surface (maybe this is caused the angle of SEM
electron beam). Figure 5g and h were obtained in the near region, by comparing the two pictures. It can be observed that a new fracture mechanism appears in this area. The local crack growth direction begins to lean to the building direction. In Figure 5i, it can be obtained clearly that the typical fatigue striations occur in this area which indicating that the crack has gotten out of the overload affected region. The dimples are observed in Figure 5j at the transient breaking region, indicating the SLM Inconel has good plastic performance.

Figure 4. The fracture surface of the Y-Z specimen at a stress ratio of 0.1 in the Paris region [6].

Figure 5. SEM images of the whole fracture surface in different locations at ROL = 1.5: (a) and (b) are in pre-crack region; (c) is located in the region between pre-crack and overload application line; (d) and (e) is in the area of overload application line; (f), (g), (h) and (i) is in the region between after overload application and before transient breaking line; (j) is the micrograph of the transient breaking area. The black arrows in outline are indicating the crack growth direction. The white icons in the pictures are showing the relationships among them.

4. Conclusion
1. The fatigue crack growth behaviour of SLM Inconel 625 in Paris region can be influenced by the level of load application. Under the constant amplitude load with the stress ratio of 0.1, the fatigue crack growth rate increases in a relative stable increment. While the overload is introduced, the crack will undergo the three typical processes i.e. increase-drop- increase.

2. When the single overload applied in the fatigue test, the secondary cracks appears clearly due to the relative high level load application.
References

[1] Brandl E, Heckenberger U, Holzinger V, Buchbinder D. Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Mater Design. 2012;34:159-69.

[2] Konečná R, Kunz L, Nicoletto G, Bača A. Long fatigue crack growth in Inconel 718 produced by selective laser melting. International Journal of Fatigue. 2016;92:499-506.

[3] Li S, Wei Q, Shi Y, Zhu Z, Zhang D. Microstructure Characteristics of Inconel 625 Superalloy Manufactured by Selective Laser Melting. Journal of Materials Science & Technology. 2015;31:946-52.

[4] Poulin JR, Brailovski V, Terriault P. Long fatigue crack propagation behavior of Inconel 625 processed by laser powder bed fusion: Influence of build orientation and post-processing conditions. International Journal of Fatigue. 2018;116:634-47.

[5] Li S, Zhang Y, Qi L, Kang Y. Effect of single tensile overload on fatigue crack growth behavior in DP780 dual phase steel. International Journal of Fatigue. 2018;106:49-55.

[6] Hu X, Xue Z, Ren T, Jiang Y, Dong C, Liu F. On the fatigue crack growth behaviour of selective laser melting fabricated Inconel 625: Effects of build orientation and stress ratio. Fatigue & Fracture of Engineering Materials & Structures. 2020;43.