Relationship between internal defect size and fatigue limit in selective laser melted Inconel 718

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Abstract

Inconel 718 is a Ni-based superalloy, which shows excellent mechanical properties such as tensile strength, fatigue strength, and creep strength at high temperatures up to 700 °C. However, as Inconel 718 is a difficult-to-cut material, it causes severe wear of machining tools. Fabricating Inconel 718 by Selective laser melting (SLM), a type of additive manufacturing (AM), is therefore expected as the manufacturing method to deal with this problem. However, it is impossible to completely prevent the occurrence of the internal defects in SLM parts. These internal defects deteriorate the mechanical properties such as the fatigue strength of SLM parts. Though the effect of the internal defect size on the fatigue limit of SLM alloys such as Ti6Al4V and AlSi10Mg has been extensively investigated, its effect on SLM Inconel 718 has not yet been investigated. In this study, Inconel 718 specimens with various internal defect sizes were fabricated by SLM and the effect of the internal defect size on their fatigue strength was investigated. Internal defect size distribution in as built specimen can be approximated by Gumbel distribution. The specimens containing internal defects with a diameter of about 400 μm showed no significant decrease in the fatigue strength. In the case of the plane specimen, the fatigue limit predicted using the statistic of extremes and the $\sqrt{\text{area}}$ parameter model was 40% higher than that obtained experimentally.

Keywords : Additive manufacturing(AM), Selective laser melting(SLM), Inconel 718, Fatigue, Internal defect

1. Introduction

With the rapid growth of modern industries, additive manufacturing (AM) has emerged as an efficient approach for processing alloys. This technique produces light parts using complicated structures and topology optimization. It has also enabled the replacement of multiple machine parts by a single part. In addition, unlike conventional processing methods, AM allows a wide variety of parts to be produced in small quantities. Selective laser melting (SLM) works on the principle of powder bed fusion and shows the highest repeatability among metal AM processing methods. SLM involves the use of one or more lasers to selectively melt the powder layers with thicknesses of several tens of μm each.

Aerospace parts are made up of lightweight alloys which are obtained in low yields and require long processing times. Aerospace parts are mainly fabricated using aluminum, nickel, and titanium alloys (Zhang et al., 2018) (Arunachalam et al., 2004). Inconel 718 is the most widely used Ni-based alloy owing to its excellent high-temperature (above 700 °C) mechanical properties and corrosion resistance (Akca and Gursel, 2015) (Sharman et al., 2001). However, though casting, forging, and powder metallurgy have been used to process Inconel 718 (Akca and Gursel, 2015), it is difficult to cut and requires extensive processing with tools, which must be replaced frequently (Arunachalam et al., 2004) (Sharman et al., 2001).

Although SLM is widely used for fabricating machine parts, it inevitably generates internal defects and induces anisotropy in the fabricated parts (Sridharan et al., 2016) (Kempen et al., 2012) (Deng et al., 2018) (Yang et al., 2017).

Therefore, parts fabricated by SLM show mechanical properties different from those of conventional parts (Trosch et al., 2016) (Amato et al., 2012) (Kobryn and Semiatin, 2001). The formation of the internal defects in SLM parts can be attributed to porosity, lack of fusion, and cracks. Porosity is induced by the trapping of atmospheric gas at high cooling rates (Thijs et al., 2010) (Bayat et al., 2019) (Gajera et al., 2019). Lack of fusion occurs when the input energy is insufficient to create a molten pool large enough to melt the entire powder layer (Vilaro et al., 2011) (Anl et al., 2018). The generation of cracks is attributed to the residual stress caused by steep temperature gradients (Gu et al., 2012) (Kaufmann et al., 2016) (Harrison et al., 2015) (Han et al., 2018). Owing to these internal defects, SLM parts exhibit mechanical properties inferior to those of forged parts (Zhang et al., 2017) (Balachandramurthi et al., 2018) (Konečná et al., 2016) (Nasab et al., 2019) (Voisin et al., 2018). Internal defects cause stress concentration (Talemi, 2020) and deteriorate the mechanical properties, especially the fatigue properties, of SLM parts. Fatigue fracture in SLM parts originates from their internal defects. (Rao et al., 2019) (Günther et al., 2017) (Beevers et al., 2018) Therefore, as the mechanical properties of SLM parts are significantly affected by the internal defects present in them, computed tomography (CT) has been used to detect the presence of the defects in SLM parts (Snell et al., 2020) (Sangid et al., 2020) (Wits et al., 2016) (Kasperovich et al., 2016). However, from the viewpoint of strength design, it is necessary to determine the internal defect size and investigate its effect on the fatigue characteristics of SLM parts before production.

The effects of the internal defect size on the mechanical properties of aluminum and titanium alloys have been investigated (Romano et al., 2018) (Wycisk et al., 2014) (Masuo et al., 2018) (Biswal et al., 2019) (Beretta and Romano, 2016). However, for Inconel 718, the relationship between the internal defect size and fatigue limit is still unclear. In this study, we carried out fatigue tests on Inconel 718 specimens with internal defects of various sizes. The potential of the $\sqrt{area}$ parameter model for estimating the internal defect size-dependent fatigue limit of Inconel 718 was evaluated.

2. Materials and methods

2.1. Specimen preparation

Gas atomized Inconel 718 powder (3D Systems, USA) was used. The chemical composition of Inconel 718 powder is listed in Table 1. Figure 1 shows the scanning electron microscopy (SEM) image of the powder particles. The particle diameter distribution of the powder is shown in Fig. 2, and the average particle diameter of the powder was 35.3 μm .

Inconel 718 specimens with the dimensions of 15 $\times$ 15 $\times$ 105 mm were fabricated using an SLM machine (ProX DMP 320, 3D Systems, USA). The SLM processing conditions are listed in Table 2. In order to investigate the effect of the internal defect size on the fatigue properties of Inconel 718, three specimens with different internal defect sizes were fabricated. The introduced defect diameters used in this study were 0, 100, and 400 μm and the corresponding specimens were labeled as plane, defect S, and defect L specimens, respectively. Table 3 and Fig. 3 show the CAD data dimensions of the defects introduced into each specimen. In Table 3, ϕ is the diameter of the defect, $\sqrt{area}$ is the square root of the cross-sectional area of the defect, and l is the length of the defect.

All the specimens were solution treated at 1065 $^{\circ}\text{C}$ for 1.5 h followed by dual-temperature precipitation ageing at 720 $^{\circ}\text{C}$ for 4 h and at 620 $^{\circ}\text{C}$ for 4 h.

2.2. Hardness and fatigue test

Hardness tests were carried out using a microhardness tester (HMV microhardness tester, Shimadzu, Japan). The tests were carried out using polished samples on a cross-section perpendicular to the build direction. The Vickers hardness of the specimens was measured by applying a load of 0.98 N for 10 s. For each specimen, 50 indents were performed.

The specimens were machined prior to fatigue testing. The geometry of the specimens is shown in Fig. 4. Fatigue testing was carried out according to ASTM E466 standard using a fatigue tester (Model 1318.10, MTS, USA). Fatigue tests were run under force-controlled constant amplitude conditions at room temperature. All the tests were run at a

Table 1 Chemical composition of Inconel 718.

Element	Ni	Cr	Fe	C	Mn	Si	Cu
Wt [%]	50.00-55.00	17.00-21.00	Bal.	≤ 0.08	≤ 0.35	≤ 0.35	≤ 0.30
Element	Mo	Co	Nb+Ta	Al	Ti	B	
Wt [%]	2.80-3.30	≤ 1.00	4.75-5.50	0.2-0.8	0.65-1.15	≤ 0.006	

stress ratio (R) of 0.1 at a frequency of 25 Hz. The maximum number of cycles was 10^7 . The risk volume of the fatigue test specimens, to which maximum stress and minimum stress were loaded, was 339 mm^3 . After the fatigue testing, fracture surfaces were cut from the fatigue specimens and were then examined using a scanning electron microscope (SEM, Miniscope TM3030Plus, Hitachi, Japan).

2.3. Defect analysis

The densities of the heat-treated specimens were measured using the Archimedes principle. The relative densities of the specimens were calculated by dividing their densities by 8.22 g/cm^3 . To measure the size of the introduced defects, the defect S and defect L specimens were cut perpendicular to the building direction. To estimate the maximum internal defect size of the plane specimen, its internal defect size distribution after the heat treatment was measured. The specimens were cut in the plane perpendicular to the building direction. The surfaces of the specimens were ground gradually up to #4000 SiC papers. The ground specimens were then polished with $3 \mu\text{m}$ and $1 \mu\text{m}$ diamond powders. Seventy images were acquired from each polished sample using an optical microscope (Multizoom AZ 100, Nikon, Japan) to capture seventy fields of view for measuring the maximum internal defect size. The area of the field of view was 2.51 mm^2 .

Fig. 1 SEM image of Inconel 718 gas atomized powder.

Fig. 2 Particle diameter distribution of Inconel 718 powder.

Fig. 3 CAD data dimension of the introduced defect.

Table 2 Processing conditions.

Laser power	[W]	220
Scan pitch	[μm]	100
Scan speed	[mm/s]	1180
Layer thickness	[μm]	30
Laser	Yb fiber laser (CW)	
Atmosphere	Ar	

Table 3 CAD data dimension of the introduced defects.

	ϕ [μm]	$\sqrt{\text{area}}$ [μm]	t [μm]
plane	0	0	0
defect S	113	100	2000
defect L	451	400	2000

Fig. 4 Shape and dimensions of fatigue specimen.

2.4. Fatigue limit prediction

The maximum inclusion size in an arbitrary volume can be predicted by using the statistic of extremes method (Wycisk, 2014). This method can be applied not only for inclusions, but also for the defects. Gumbel distribution is used as an approximation of the maximum internal defect size distribution in a part. In Eq 1 and 2, Φ is a cumulative distribution function and y is a standardized variable.

$$\Phi(x) = \exp\{-\exp(-y)\} \quad (1)$$

$$y = \alpha_n(x - u_n) \quad (2)$$

The maximum internal defect size in the risk volume of each specimen could be predicted by extrapolating their Gumbel distribution curves (Gumbel, 2004).

To predict the fatigue limit of alloy parts considering the relationship between the fatigue limit and the size of the largest internal defect, Murakami proposed the $\sqrt{area}$ parameter model (Murakami, 2014). In this model, the specimen is first cut and the internal defect size is measured. The fatigue limit is then determined from its Vickers hardness and the internal defect size according to Eq. 3.

$$\sigma_w = 1.56(HV + 120) \times (\sqrt{area})^{-1/6} \times [(1 - R)/2]^{0.22 + HV \times 10^{-4}} \quad (3)$$

Here, HV denotes the Vickers hardness of the specimen and $\sqrt{area}$ is the square root of the cross-sectional area of the defect (μm).

The $\sqrt{area}$ parameter model was devised for fatigue of steel materials. For Inconel materials, it has been reported that the fatigue limit is affected by the crack propagation limit (Kawagoishi et al., 1997). Figure 5 shows the results of investigating the relationship between hardness and tensile strength (Johannes et al., 2015) (Logsdon et al., 1978) (Popovich, et al., 2017) (Schirra, 1997) (Szustecki et al., 2017) and between tensile strength and fatigue limit (David et al., 2020) (Wan et al., 2018) (Zhong et al., 2019) based on the published strength of Inconel materials. There is a linear relationship between hardness and tensile strength, and that there is a linear relationship between tensile strength and fatigue limit. Based on the above, we considered that the material system has the same fatigue properties as steel, and consulted the application of the $\sqrt{area}$ parameter model for estimating the internal defect size-dependent fatigue limit of Inconel 718.

3. Results and discussion

Figure 6 shows the cross-sectional optical microscopy images of the defect S and defect L specimens. These specimens showed uneven surfaces resulting from the partially melted particles adhering to the inner walls of the

Fig. 5 A linear relationship between hardness and tensile strength (a), and a linear relationship between tensile strength and fatigue limit (b).

introduced defects. The defect S specimen showed the spherical and irregular defects. The defect L specimen showed the spherical defects (excluding the partially melted particles). As the adhered particles did not bear the load, they were considered as the defects.

Figures 7 show the introduced defect size distributions of the defect S and the defect L specimens. No significant change was observed in the introduced defect size of the specimens after the heat treatment. The reproducibility of the defect S specimen was low. Therefore, its $\sqrt{area}$ variation was larger than that of the defect L specimen. The maximum introduced defect size of the defect S specimen was $\sqrt{area} = 93.0 \mu\text{m}$, whereas that of the defect L specimen was $\sqrt{area} = 416 \mu\text{m}$.

The average relative density of 3 specimens, as calculated using the Archimedes principle was 100.2%. Figure 8 shows the cross-sectional optical microscopy image of the plane specimen. Even though the relative density of the specimen was high, the many internal defects with the diameters of several tens of μm were observed. The internal defects present in the specimens were of two types: spherical (induced by the porosity) and irregular (induced by the lack of fusion).

Figure 9 shows the distribution of the maximum internal defect size occurring in a unit area of the plane logarithm of the cumulative distribution function F . The maximum internal defect size observed in 70 field of view was $\sqrt{area} = 32.5 \mu\text{m}$. As the difference between the experimental and Gumbel distribution results was very small over the entire measurement area and the coefficient of determination was 0.979, it can be stated that the maximum internal defect size values of the specimens followed the Gumbel distribution. When extrapolated using this distribution, the maximum internal defect size in the hazardous volume of the fatigue specimen ($\sqrt{area}$) was estimated to be $62.6 \mu\text{m}$. The average Vickers hardness of the heat-treated specimens was 409 Hv0.1. By substituting the predicted $\sqrt{area}$ and the Vickers

Fig. 6 Cross-sectional OM images of (a)(b)(c) defect S specimen with 100 μm internal defect, (d)(e)(f) defect L specimen with 400 μm internal defect.

Fig. 7 Introduced defect size distributions of defect S and defect L.

hardness in Eq 3, the fatigue limit of the plane specimen was estimated to be 335 MPa. Similarly, the fatigue limits of the defect S and defect L specimens were estimated to be 310 and 246 MPa, respectively.

Figure 10 shows the fatigue properties of each specimen. The fatigue limits of the plane, defect S, and defect L specimens were 239, 245, and 248 MPa, respectively. Hence, the specimens showed comparable fatigue limits. At the same stress amplitude, the specimens showed comparable fatigue life values. Although the introduced defects and internal defect size affected the fracture morphology of the specimens, the effect on the fatigue limit was negligible.

Figure 11 shows the SEM images of the fracture surfaces of the specimens. The plane and defect S specimens showed similar fracture morphologies. The fracture surfaces of plane and defect S specimens showed smooth regions. In the smooth regions, cracks propagated from the existing internal defects to the opposite side of the specimen surface. The fracture surfaces of plane and defect S specimens showed smooth regions. In the smooth regions, cracks propagated from the existing internal defects to the opposite side of the specimen surface. Nishitani and Murakami (1974) showed that when internal defects are formed near the surface, the stress intensity factor of the internal cracks increases. Therefore, the internal defects close to the surface act as crack initiation points. The fracture morphology of the defect L specimen was different from those of the plane and defect S specimens. At low stress amplitudes, only the fracture surface of the defect L specimen showed the internal defects. The fracture morphology of the defect L specimen varied with the stress amplitude. At low stress amplitudes, cracks propagate from the introduced defects. On the other hand, at high stress amplitudes, cracks propagate from the subsurface defects. Sakurai et al. (2017) also observed this change in the crack initiation point of SLM alloys with the stress amplitude. The fracture morphology of the defect L specimen varied because the introduction of the large internal defects caused stress concentration.

The measured and predicted fatigue limits of the specimens are listed in Table 4. The predicted fatigue limits of the specimens were lower than their experimental fatigue limits. The predicted fatigue limit (335 MPa) of the plane specimen (using the $\sqrt{area}$ parameter model) was 40.2% higher than its experimental value (239 MPa). The defect L specimen showed a relative error of 0.94%. Thus, the prediction was sufficiently accurate in the case of the defect L specimen. During the fabrication of SLM parts under optimum conditions, the possibility of the formation of the internal defects with diameters as large as 400 μm is very low. Therefore, the use of the $\sqrt{area}$ parameter model for the prediction of the fatigue limit leads to large errors and overestimation.

4. Conclusions

In this study, three Inconel 718 specimens with different internal defect diameters were fabricated by SLM. The effect of the internal defect size on the fatigue properties of the specimens was investigated. The following conclusions were drawn:

Fig. 8 Cross-sectional optical microscopic images of heat treated plane specimen. (White arrows are spherical pores, black arrows are unmelted regions)

Fig. 9 Defect size distribution of plane specimen and approximation by using Gumbel distribution.

1. The plane specimen showed internal defects generated by porosity and lack of fusion. The size distribution of the internal defects in this specimen could be approximated by the Gumbel distribution, which is one of the extreme value distributions. When extrapolated using this distribution, the maximum internal defect size in the risk volume of the fatigue specimen was estimated to be $\sqrt{area} = 62.6 \mu\text{m}$.

2. The fatigue limits of the plane, defect S, defect L specimens were 239, 246, and 248 MPa, respectively. The fatigue limits of the three specimens were comparable. At the same stress amplitude, the specimens showed comparable fatigue life values. The internal defect size showed negligible effect on the fatigue limit and fatigue life of the defect S and defect L specimens.

3. In the case of the plane specimen, the fatigue limit predicted using the $\sqrt{area}$ parameter model was 40% higher than that obtained experimentally. This error can be attributed to the failure mechanism of Inconel 718 fabricated by SLM. In the future, we will investigate this mechanism.

Fig. 10 Fatigue properties of the three specimens.

Table 4 Tested and predicted fatigue strength.

	Fatigue strength [MPa]		Relative Error [%]
	Experimental	Predicted	
plane	239	335	40
defect S	246	310	26
defect L	248	246	0.94

Fig. 11 Fractographs obtained from the crack initiation locations. (a), (b) plane ($\sigma_a = 243$ MPa, $N_f = 1988593$), (c), (d) defect S ($\sigma_a = 252$ MPa, $N_f = 336692$), (e), (f), defect L ($\sigma_a = 306$ MPa, $N_f = 260052$), (g), (h) defect L ($\sigma_a = 266$ MPa, $N_f = 6151719$)

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