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Effect of Loading Frequency on Fatigue Properties of Ni-base Super Alloy Inconel 718

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Abstract: Fatigue tests under rotating bending and ultrasonic loading were carried out using plain specimens with different grain sizes of Ni-base super alloy, Inconel 718, in order to investigate the effects of grain size and loading frequency on fatigue properties. Fatigue strength was increased with decreasing in grain size under both tests. Moreover, the fatigue strength under ultrasonic loading was higher than that under rotating bending. The resistance to crack initiation was larger in smaller grain sized alloy under both tests, and larger under ultrasonic loading than under rotating bending. Effects of loading frequency and grain size on crack initiation were explained from the points of view of the effects of those on flow stress. On the other hand, the effect of grain size on crack growth rate was small in both loading conditions. The crack morphology was rougher in the larger grain sized alloys, meaning that the crack growth in the larger grain sized alloys was suppressed by roughness induced crack closure effect. However, flat facets caused by twin boundary cracking and intergranular cracking were observed in the larger grain sized alloys, which inversely led to crack growth acceleration. Consequently, the effect of grain size on crack growth rate was decreased.

Keywords: Fatigue, Inconel 718, loading frequency, grain size, crack initiation, crack propagation, fracture mechanism.

1 Introduction

In order to reduce the environment load, it is effective to being light weight and using machines for long term. Moreover, it is important to insure the reliability for strength of materials. Therefore, many studies on fatigue properties of high strength metals in long life region have been carried out. However, it is time consuming task

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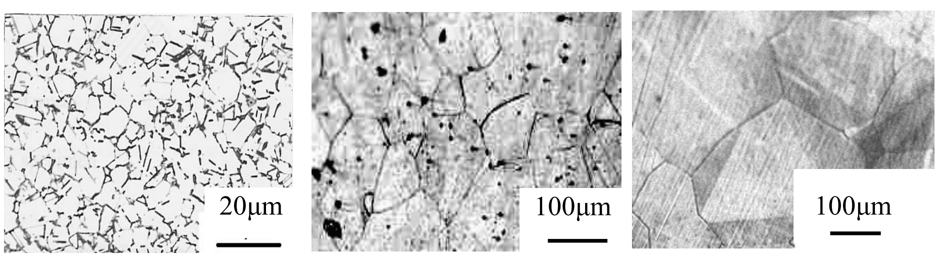
to study the fatigue properties in long life region. Ultrasonic fatigue test is one of attractive methods to reduce the testing time. However the effect of loading frequency on the fatigue properties is not fully clarified. In the present study, fatigue tests under ultrasonic loading and rotating bending of plain specimens with different grain sizes were carried out using a Ni-base super alloy, Inconel 718, in ambient air in order to investigate the effects of grain size and loading frequency on fatigue properties.

2 Material and Experimental Procedure

The material used was a Ni-base super-alloy, Inconel 718, with a chemical composition (in wt. %) of 0.02C, 0.11Si, 0.12Mn, 0.009P, 0.001S, 18.67Cr, 3.09Mo, 0.09Co, 0.01Cu, 0.66Al, 0.90Ti, 18.67Fe, 0.004B, 5.12 Nb and Ta, and balance Ni. In order to change the grain size, the alloy was solution treated for 1 h at three different temperatures of 982 °, 1050 ° and 1100 ° and then water quenched. After the solution treatment, all of the alloys were aged at 720° for 8 h, and then furnace cooled to 621° and aged at 621° for 8 h followed by air-cooling. Figure 1 shows their microstructures. These microstructures have a wide scatter. The mean grain sizes of the alloys were about 18, 88 and 276 μm, respectively. In the following, these alloys will be denoted by their grain sizes. In all alloys, precipitated particles of Ni_3Nb were observed at grain boundary by EDX. Table 1 shows their mechanical properties.



(a) 18 μm (b) 88 μm (c) 276 μm

Figure 1: Microstructures of tested alloys

Figure 2 shows shape and dimensions of specimens. Prior to fatigue testing, all of the specimens were electro-polished by 40 μm in diameter from the surface after machining and emery paper grinding in order to remove the worked layer and to make the observation of surface damage at fatigue process easier. The successive observation at fatigue process and the measurement of crack length were conducted under an optical microscope using plastic replica technique. The crack length ℓ was

Table 1: Mechanical properties

Material	$\sigma_{0.2}$(MPa)	σ_B(MPa)	σ_T(MPa)	ψ(%)
18 μm	1050	1236	1876	40.9
88 μm	990	1167	1812	35.6
276 μm	988	1175	2143	49.1

defined as the length along the circumferential direction on the specimen surface. Fracture surface was examined by a scanning electron microscope (SEM). Fatigue tests were carried out using a rotating bending fatigue testing machine and an ultrasonic one at room temperature in ambient atmosphere. Their loading frequencies were 55Hz and 19.5 kHz, respectively. The stress ratios were -1 in both tests. In ultrasonic loading, the increase in specimen temperature due to internal friction was suppressed by a pulse-pause test with a pulse and pause times of 1s and 5s, respectively. By this method, the maximum temperature rise was less than 3°.

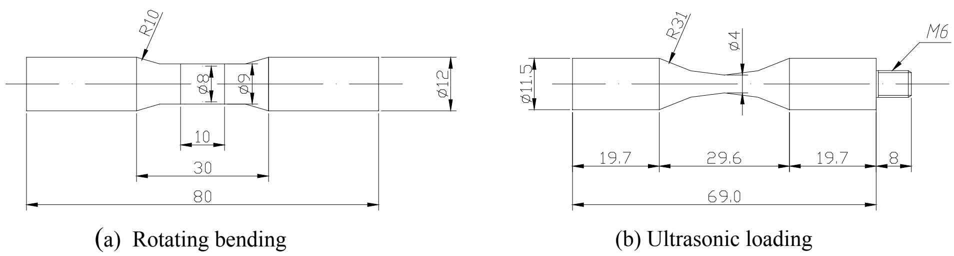
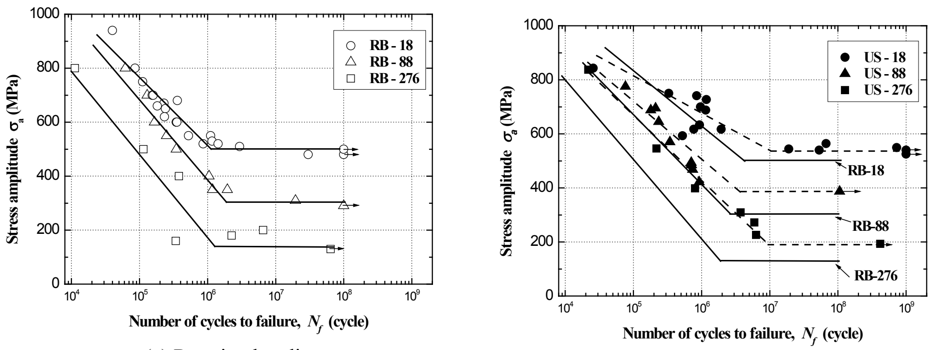


Figure 2: Shape and dimensions of specimens

3 Experimental Results and Discussion

Figure 3 shows $S-N$ curves of (a) rotating bending and (b) ultrasonic loading tests. In the figure 3(b), the results of rotating bending were also indicated by dotted lines only for comparison. Fatigue strength decreased in larger grain sized alloys in both tests, and was a little higher under ultrasonic loading than that under rotating bending loading.

Figure 4 shows grain size dependence on fatigue strength at 10^8. In the figure, the dependence on flow stress was also indicated. The relation between fatigue strength and a reciprocal of root of grain size is approximated by a straight line, meaning that the relation similar to Hall- Petch equation holds in fatigue strength like a flow stress.



(a) Rotating bending (b) Ultrasonic

Figure 3: S-N curves

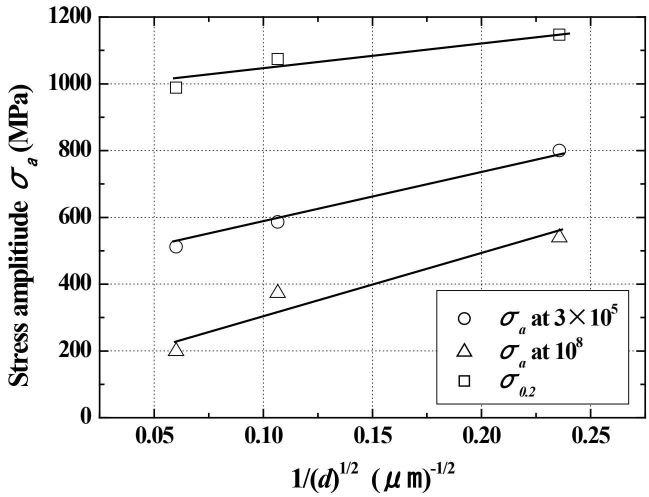


Figure 4: Grain size dependence of fatigue strength

Figure 5 shows crack growth curves at the same stress level (σ_a=700MPa). Crack initiation was delayed in smaller grain sized alloys and under ultrasonic loading than under rotating bending. Moreover the rate of increase in crack initiation life by grain size was larger under ultrasonic loading than under rotating bending. Grain size dependence of crack initiation life may be explained by Hall- Petch relation, and the delay under ultrasonic loading is related to the increase in flow stress under high strain rate. The reason for the effect of loading frequency on grain size dependence may be explained from the results in high strength steel [7] as follow.

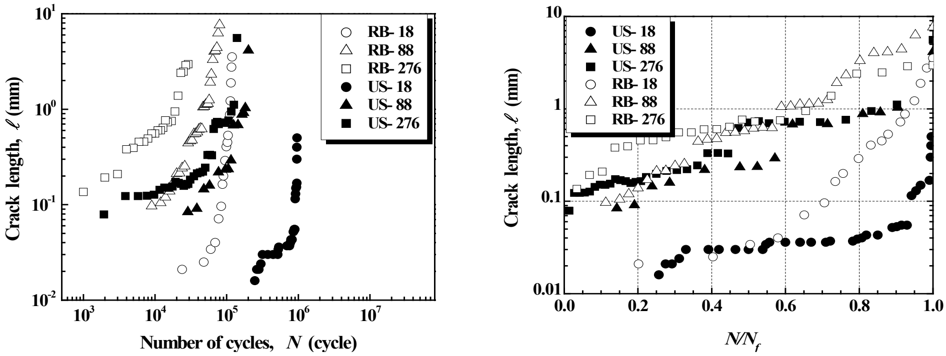


Figure 5: Crack growth curves (σ_a=700MPa)

Flow stress increases and Hall- Petch relation, $\sigma_y = \sigma_0 + kd^{-1/2}$, holds even under high strain rate. The increase in flow stress is mainly due to increase in σ_0 in the relation. Moreover value of k is also increased meaning that the increase in flow stress is larger in small grain sized alloy. If so, it corresponds to the present result showing that the delay in crack initiation was larger in smaller grain sized alloys. However the grain size dependence of value of k in the present alloy should be confirmed.

Figure 6 shows relation between crack growth rate and crack length at the same stress in all of alloys. Grain size dependence of the crack growth rate is very small, though crack growth rate is a little higher under rotating bending than under ultrasonic loading. The lower crack growth rate under ultrasonic loading may be caused by the increase in flow stress similar to the effect on crack initiation.

Figures 7 and 8 show the crack morphology and the fracture surface in each alloy under ultrasonic loading, respectively. As seen from Fig.7, a crack propagates in zigzag fashion and the degree of zigzag is larger in larger grain sized alloys reflecting grain size. The growth of a crack in zigzag fashion induces the decrease in crack growth rate by roughness induced crack closure effect. The decrease in crack growth rate by effect of roughness induced crack closure in Ni-base super alloy was reported in long crack. [8] On the other hand, twin boundary cracking (↑) and grain boundary cracking ( ) are observed on fracture surface as shown in Fig. 8. The volume fraction of these cracks is larger in larger grain sized alloys. The increase in these cracks means the acceleration of crack growth rate. That is, there are two opposite effects of grain size on crack growth rate. This may be main reason for small dependence of grain size on crack growth rate. These features under ultrasonic loading shown in Figs. 7 and 8 were similar under rotating bending.

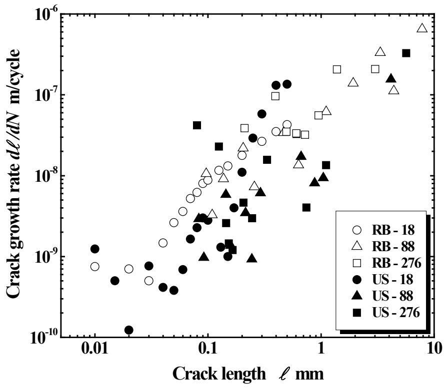
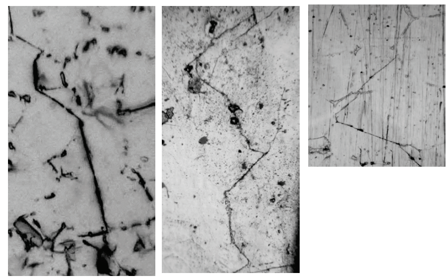


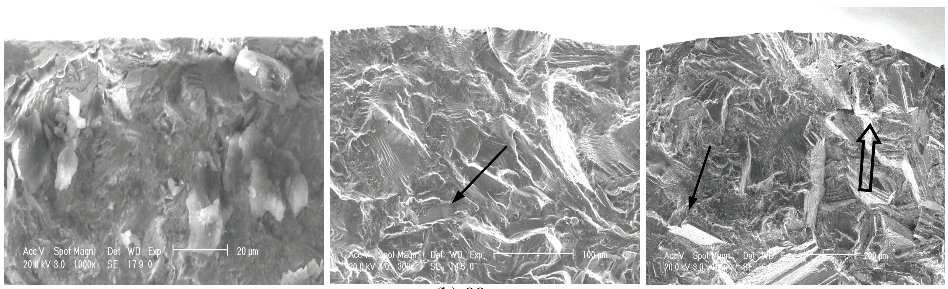
Figure 6: Crack growth rate against for crack length ($\sigma_a \fallingdotseq$ 700MPa)



(a) 18 μm (b) 88 μm (c) 276μm

$\sigma_a \fallingdotseq$ 700M Pa, ⟷ Axial direction

Figure 7: Morphologies of cracks under ultrasonic loading



(a) 18 μm (σ_a=564MPa, N_f=6.2×10^{7}cycles) (b) 88 μm (σ_a=387MPa, N_f=1.0×10^{8}cycles) (c) 276 μm (σ_a=272MPa, N_f=5.9×10^{6}cycles)

Figure 8: Fracture surfaces under ultrasonic loading

4 Conclusions

Fatigue tests under rotating bending and ultrasonic loading were carried out using plain specimens with different grain sizes of Ni-base super alloy, Inconel 718, in order to investigate the effects of grain size and loading frequency on fatigue properties. Fatigue strength was increased with decrease in grain size under both tests. Moreover, fatigue strength under ultrasonic loading was higher than that under rotating bending. The resistance to crack initiation was larger in smaller grain sized alloy under both tests, and larger under ultrasonic loading than under rotating bending. Effects of loading frequency and grain size on crack initiation were explained from the points of view of the effects of those on flow stress. On the other hand, the effect of grain size on crack growth rate was small in both tests. The crack morphology was rougher in the larger grain sized alloys, meaning that the crack growth in the larger grain sized alloys was suppressed by roughness induced crack closure effect. However, flat facets caused by twin boundary cracking and intergranular cracking were observed in the larger grain sized alloys, which inversely led to the acceleration of crack growth. Consequently, the effect of grain size on crack growth rate was decreased. That is, the increase in fatigue strength by refining grain size or high loading frequency was mainly caused by the suppression of crack initiation.

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