Effect of microstructure on high-cycle fatigue properties of Alloy718 plates

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Abstract. Effect of microstructure on high-cycle fatigue properties of Alloy718 were investigated at 77 K by using samples with three different microstructures; fine-grained (FG), coarse-grained (CG) and bimodal-grained (BG) ones. The BG sample consisted of FG and CG microstructural regions and grain sizes of those regions were close to those of the FG and the CG samples, respectively. High-cycle fatigue strength of the FG sample was higher than that of the CG sample. High-cycle fatigue strength of the BG sample was clearly lower than that of the FG sample and almost the same as that of the CG one. Flat area (facet) was found at fatigue crack initiation site in all specimens. Facet size was similar to the grain size and found to be almost same in the CG and the BG samples. Observations of the microstructure beneath the fatigue crack initiation site of the BG sample revealed that the facet corresponds to transgranular cracking in the course grain, meaning that fatigue crack initiated at the coarse grain in the BG sample. It is deduced that the high-cycle fatigue strength of Alloy 718 with the BG microstructure is strongly affected by that of the CG region in that material.

1. Introduction

Ni-base superalloy 718 (Alloy718) is a precipitation-strengthened material mainly deriving from $\gamma'$-Ni$_3$Al (L1$_2$) and $\gamma''$-Ni$_3$Nb (DO$_{22}$) precipitates [1]. This alloy has been widely used in gas turbines and jet engines with temperature range up to 923 K, because of its high temperature strength and corrosion resistance. This alloy is also used for some cryogenic applications in aerospace industry, since this alloy exhibits high strength at cryogenic temperatures and good weldability [2-4].

It was reported that Alloy718 with finer grains achieves better high-cycle fatigue properties [5]. Delta-phase ($\delta$: Ni$_3$Nb) plays an important role to obtain fine grains [6]. If distribution of Nb is not homogenized properly, sufficient amount of $\delta$ doesn’t precipitate in the Nb-lean region at high temperature. It causes the growth of $\gamma$ grains there and the formation of bimodal-grained (BG) microstructure that consists of fine-grained (FG) and coarse-grained (CG) regions [6].

In this study, Alloy718 with BG microstructure had been obtained actually. It’s very interesting to comprehend the effect of certain amount of coarse grains on mechanical properties of Alloy 718 with BG microstructure. Therefore, we also prepared samples that have homogeneously FG and CG microstructures, respectively. Then we investigated high-cycle fatigue properties of three samples and observed fracture surfaces and microstructures of fatigue-fractured specimens, and discussed the effect of microstructure on high-cycle fatigue properties.
### Table 1. Chemical compositions of Alloy 718 plates used in this study (mass%).

|        | C   | Si  | Mn  | P   | S   | Cu  | Ni  | Cr  | Mo  | Co  | Al  | Ti  | Nb  | B   | Ta  | Fe  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Plate 1 (Bimodal-grained) | 0.03 | 0.05 | 0.16 | 0.002 | <0.001 | 0.02 | 52.57 | 18.12 | 2.85 | 0.21 | 0.43 | 1.02 | 5.09 | 0.005 | <0.01 bal. |
| Plate 2 (Normal-grained)  | 0.03 | 0.02 | 0.13 | 0.007 | <0.001 | 0.01 | 53.49 | 18.27 | 2.92 | 0.13 | 0.43 | 1.06 | 5.16 | 0.004 | <0.01 bal. |

#### Figure 1. Dimensions and sampling direction of the specimens for tensile test (a) and high-cycle fatigue test (b). All dimensions are shown in mm.

### 2. Experimental procedure

Two plates of Alloy718 used in this study had been produced in accordance with Aerospace Materials Specification 5596. They had bimodal-grained (BG) and normal-grained microstructures, respectively. The chemical compositions of those plates are shown in Table 1. The BG plate was hot-rolled at a reduction of 80%. After the rolling processes, it was solution-treated at 1228 K for 3.6 ks, followed by air-cooling. Regarding the plate for obtaining the FG and the CG microstructures, it was hot-rolled at a reduction of 90% and then subjected to the solution-treatment at the temperatures of 1228 K and 1318 K for 1.8 ks to control the γ grain size. Finally, three solution-treated samples were double-aged at 993 K for 28.8 ks and 893 K for 28.8 ks, followed by air-cooling. The processing details are summarised briefly in Table 2.

Figure 1 shows the dimensions and sampling direction of tensile (a) and high-cycle fatigue (b) test specimens. The longitudinal direction of those specimens is parallel to transverse direction (TD) of the plate. Tensile tests and fatigue tests were carried out at 77 K. Tensile tests were performed at an initial strain rate of $4.2 \times 10^{-4} \, \text{s}^{-1}$. Fatigue tests were conducted up to $10^7$ cycles using sinusoidal waveform loading and uniaxial tension-compression loading under stress ratio ($R$) of -1. Test frequency was 10

#### Table 2. Processing details for three samples evaluated in this study.

| Plate          | Reduction ratio in hot-rolling process (%) | Sample       | Solution treatment       | Aging               |
|----------------|-------------------------------------------|--------------|--------------------------|---------------------|
| Plate 1 (BG)   | 80                                        | Bimodal-grained (BG) | 1228 K, 3.6 ks → Air-cooling | 993 K for 28.8 ks → Air-cooling |
| Plate 2 (FG)   | 90                                        | Fine-grained (FG) | 1228 K, 1.8 ks → Air-cooling | 893 K for 28.8 ks → Air-cooling |
| Plate 2 (CG)   | 90                                        | Coarse-grained (CG) | 1318 K, 1.8 ks → Air-cooling |                     |
Hz at 77 K. The microstructure was observed with an optical microscope and a scanning electron microscope (SEM). Fracture surfaces were observed with the SEM.

3. Results and discussion

Figure 2 shows microstructures of the FG (a), the CG (b) and the BG (c), (d) samples. The mean grain size of the FG sample was 40 μm. The solution-treatment temperature of 1228 K for the FG sample was lower than δ solvus, which was reported around 1283 K [7]. Therefore, plate-like δ was observed mainly along grain boundaries and pinned the grain boundaries effectively during the solution treatment. The mean grain size of the CG sample was 100 μm. The solution-treatment temperature of 1318 K for this sample was higher than δ solvus, resulting in coarsening the grains easily. On the other hand, the BG sample was obtained after the almost same heat treatment as that of the FG sample. It consisted of FG and CG regions (c). Mean grain size of each region was 30 μm and 100 μm, respectively. Figure 2(d) is a backscatter image of the CG region and a dark-etched area observed in the BG sample (c). Dark-etched areas shown in figure 2(c) correspond to grains indicated by arrows in figure 2(d). Variation of contrast was easily found within those grains. This contrast is derived from residual strain, meaning that they seem to be recovered (unrecrystallized) grains. Nb-enriched MC-type carbides were observed in all samples [8].

Tensile properties of the samples are summarized in table 2. The 0.2% proof stress and tensile strength of the FG sample are higher than those of the CG sample due to grain refinement. Regarding the BG sample, the 0.2% proof stress is close to that of the CG sample. Tensile strength of it lies in between those of the FG and the CG samples.

![Figure 2](image-url)

Figure 2. Optical images of the FG (a), the CG (b) and the BG (c) samples and a backscatter electron image of the BG sample (d).
Table 3. Tensile properties of the BG, FG and CG samples of Alloy 718 plates at 77 K.

| Microstructure            | 0.2% proof stress $\sigma_{0.2}$ / MPa | Tensile strength $\sigma_b$ / MPa | Elongation $\delta$ (%) | Reduction of area $\phi$ (%) | Number of specimens tested |
|---------------------------|----------------------------------------|-----------------------------------|-------------------------|-----------------------------|----------------------------|
| Bimodal-grained (30 μm, 100 μm) | 1,310                                  | 1,758                             | 21                      | 30                          | 2                          |
| Fine-grained (40 μm)      | 1,393                                  | 1,817                             | 26                      | 30                          | 3                          |
| Coarse-grained (100 μm)   | 1,331                                  | 1,661                             | 27                      | 50                          | 2                          |

Figure 3 shows the results of the high-cycle fatigue tests at 77 K. High-cycle fatigue strength of the FG sample was higher than that of the CG sample, as the 0.2% proof stress and tensile strength are. On the other hand, high-cycle fatigue strength of the BG sample was clearly lower than that of the FG sample and almost the same as that of the CG sample. It is known empirically that there is a good correlation between high-cycle fatigue strength and tensile strength [9]. However, the results obtained in this study don’t meet this empirical law.

Figure 4 shows a whole image of fracture surface (a), a magnified image of the fracture surface around fatigue crack initiation site (b), a magnified image of the area surrounded by broken line in (b) (c) and an optical image of microstructure beneath the fracture surface in cross section along A-A in (c) of the BG sample (d). In this specimen, flat area (facet) was found at fatigue crack initiation site, as indicated by an arrow in figure 6 (b). Each facet size was similar to the grain size of each specimen. In the BG sample, the facet size was close to 100 μm the same as that of the CG sample. Figure 6 (d) shows that the facet corresponds to transgranular cracking in a coarse grain.

![Figure 3. S-N diagrams of the FG, the CG and the BG samples obtained at 77 K.](image-url)
Facet was observed in all fatigue-fractured specimens. NbC wasn’t confirmed at fatigue crack initiation site in the specimens used in this study, though it was identified in the Alloy718 fatigue-tested at $R=0.01$ [8]. Regarding the BG samples, fatigue crack initiated only at the coarse grain. It was reported that fatigue crack initiates much easier in CG sample than in FG sample [5]. Thus, the high-cycle fatigue strength of Alloy 718 with the BG microstructure seems to be strongly affected by that of the CG region.

4. Summary
Effect of microstructure on high-cycle fatigue properties of Alloy718 were investigated at 77 K by using three samples with different microstructures; fine-grained (FG), coarse-grained (CG) and bimodal-grained (BG) ones. High-cycle fatigue strength of the FG sample was higher than that of the CG sample. High-cycle fatigue strength of the BG sample was clearly lower than that of the FG sample and almost the same as that of the CG sample. Fatigue crack initiated at a coarse grain in the BG sample. It is deduced that the high-cycle fatigue strength of the BG sample is strongly affected by that of the CG region, resulting in lowering the high-cycle fatigue properties.

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