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#### Abstract

 $\rm X-ray$  diffraction method was used for the purpose of characterizing fatigue damage in mill-annealed and shot peened Alloy 718. Some parameters obtained by  $\rm x-ray$  diffraction were found to be sensitive to identify the fatigue damage in the alloy. In addition to the  $\rm x-ray$  diffraction method, microstructural changes due to fatigue damage were examined by TEM (Transmission Electron Microscope) and Vicker's hardness tester.

#### Introduction

Alloy 718 is one of the component materials which are often used in nuclear and aerospace industries because of its excellent high — temperature and corrosion — resistant properties. However, fatigue damage is one of the primary degradation mechanisms that limit the service life of Alloy 718 components. Consequently, in order to maintain the operation of Alloy 718 components without experiencing fatigue failures, it is essential to establish reliable nondestructive methods for forecasting fatigue failures through the measurement of fatigue damage. In addition to the safety related problem, more industries have become aware of the potential importance of life assessment because it would allow the conservative safety margins to be reduced and is therefore desirable from economical efficiency.

A number of NDE (Non Destructive Evaluation) methods have been investigated over the years for the purpose of assessing the integrity of engineering components.[1, 2] Regarding fatigue failure, however, it seems still rather difficult for most of the currently used NDE methods to evaluate fatigue remaining life, because they are mainly devoted to detection and characterization of macro—size cracking which generally appears at the late stage of fatigue life. It is therefore highly desirable to develop NDE methods which can detect material degradation and can contribute to the prediction of fatigue remaining life prior to crack initiation.

The current study was focused on characterization of fatigue damage in mill — annealed and shot peened Alloy 718 specimens. Because shot peening is one of the popularly used methods for improving fatigue strength of various

Superalloys 718, 625, 706 and Various Derivatives Edited by E.A. Loria The Minerals, Metals & Materials Society, 1994 components, fatigue behavior of Alloy 718 with and without shot peening was studied. X - ray diffraction was adopted here as an NDE method to evaluate crystallographic changes during fatigue process. The x - ray diffraction is known to give a sensitive indicator to the microstructure of material surface or near - surface where fatigue damage is most likely to occur. As a result, many approaches using x - ray diffraction have been conducted so far in order to evaluate fatigue damage of materials.[3 - 12]

In addition to the x-ray diffraction, TEM and Vicker's hardness tester were used to examine fatigue—induced microstructural changes in the alloy.

### Experiments

#### Specimens

The specimens were machined from mill — annealed (982  $^{\circ}$ C for 3.5min.) Alloy 718 sheet and their dimensions and configuration are shown in Figure 1. The chemical composition and mechanical properties are shown in Table I and II, respectively. After the machining, some specimens were shot peened in order that the effect of shot peening on fatigue behavior is examined. The shot peening was carried out using glass beads (250~297  $\mu$  m) with a flow pressure of 5.0 kgf/cm². The surface roughness of shot peened specimen increased up to ~28.0  $\mu$  m from the original roughness of ~4.2  $\mu$  m.

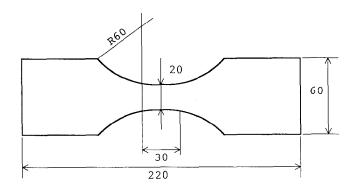


Figure 1 Test specimen. (unit: mm, thickness: 3.18mm)

Table I Chemical composition of the test specimen.(w	Table	emical composition of	the test s	specimen.(	wt%)
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С	Mn	Fe	S	Si	Cu	Ni	Cr
0.03	0.05	18.21	<0.001	0.10	0.01	54.01	18.26
Al	Ti	Со	Мо	Ta	P	В	Cb+Ta
0.51	1.01	0.02	2.87	0.01	0.008	0.002	4.91

Table II Mechanical properties of the test specimen.

Yield strength (kgf/mm²)	Tensile strength (kgf/mm²)
45.2	89.1

## Fatigue testing

The constant — stress — amplitude fatigue testing was performed on the specimens using servo — controlled hydraulic fatigue testing machine. The conditions of fatigue testing are listed in Table  $\mathbb{H}$ .

Table III Conditions of fatigue testing.

Fatigue mode	Frequency (Hz)	Maximum stress (kgf/mm²)
repeated tensile	10	80, 70, 60, 50, 40

## Evaluation by x - ray diffraction

The material parameters detected by x-ray diffraction included peak intensity (peak height), FWHM (Full Width at Half Maximum intensity) and residual stress. These parameters were surveyed whether possible to detect fatigue damage in the alloy. The x-ray diffraction was conducted by two methods: the parallel beam method (Cr target) for measuring residual stress in the longitudinal direction of the specimen and the focusing beam method (Cu target) for the other parameters. The measured diffraction planes included (111), (200), (220), (311), (222) and (400) planes. The diffraction was performed on the same specimen at several selected numbers of fatigue cycles up to the rupture of the specimen.

# TEM and Vicker's microhardness measurement

Fatigue induced microstructural changes in Alloy 718 were evaluated by  $\mathsf{TEM}$  and  $\mathsf{Vicker's}$  hardness measurement.

## Results and Discussions

## Peak intensity

<u>Mill - annealed specimen</u> Figure 2 shows the transitions in peak intensity ratio during fatigue process under several stress levels. The peak intensity ratio means  $I/I_o$ , where I is the peak intensity of fatigued specimen and  $I_o$  is the initial value. As shown in Figure 2, the behavior of the peak intensity depended strongly on the stress levels and lattice planes. The changes took place during the initial stage of fatigue life followed by the saturation of the changes. All the diffracted lattice planes except (220) plane showed decrease in their peak intensities. The increase in peak intensity of (220) plane appears to be due to the slip of the lattice plane, since (220) plane, like other planes, suffered fatigue—induced microstrain as can be seen from the behavior of FWHM (see next section).

The changed ratios of the diffracted peak intensities ( $|I_o-I|/I_o$ ) are plotted for fatigue stress levels in Figure 3(a). From Figure 3(a), it is seen that the changed ratios had linear relations with applied fatigue stresses above approximately  $50 \text{kgf/mm}^3$ , showing a possibility of detecting the applied fatigue stress from the change in peak intensity.

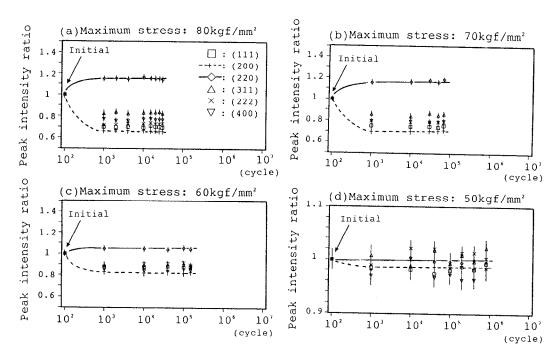


Figure 2 Transition in peak intensity ratio during fatigue life. (mill - annealed specimens)

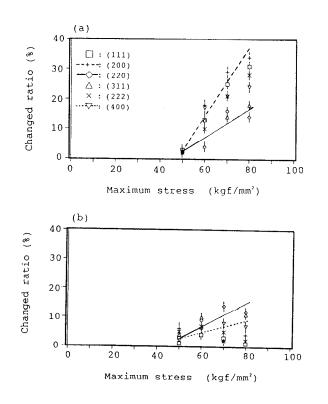


Figure 3 Changed ratio of peak intensity.
((a): mill - annealed, (b): shot peened)

Shot peened specimen Figure 4 shows the transitions in peak intensity ratio during fatigue life under several stress levels. As shown in Figure 4, the behavior of the peak intensity depended strongly on the stress levels and lattice planes. Although the amount of the change was not so large compared with the case of mill — annealed specimens, saturation of the change did not take place during the initial stage of fatigue life, suggesting a possibility of predicting a fatigue remaining life from the peak intensity change.

The maximum changed ratios of the diffracted peak intensities are illustrated versus fatigue stress levels in Figure 3(b). The changed ratios were generally less than those of mill—annealed specimens, and some did not have linear relations with the applied stresses.

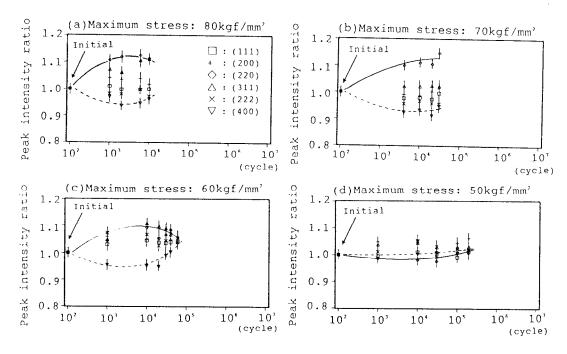


Figure 4 Transition in peak intensity ratio during fatigue life. (shot peened specimens)

## FWHM

<u>Mill - annealed specimen</u> The FWHM is known to be sensitive to the microstrain in materials and it has been often used as a fatigue damage indicator. Figure 5 reveals the transitions in FWHM ratio during fatigue period. Because the dispersion of measured FWHMs of (311), (222) and (400) planes was so large, FWHMs of (111), (200) and (220) planes were evaluated here. The change in FWHM ratio indicated an inverse trend to the change in peak intensity ratio except (220) plane. Like the case with the peak intensity, the behavior of the FWHM depended strongly on the stress levels and lattice planes. However, the FWHM generally changed less than the peak intensity at the same applied stress levels. Furthermore, the dispersion of FWHM data during fatigue life was larger than that of peak intensity data. Therefore the peak intensity serves as a better indicator of fatigue damage than FWHM.

Shot peened specimen Because the dispersion of measured FWHM became much larger after shot peening, evaluation of FWHM was conducted only for (111) plane which showed the maximum diffracted peak intensity. Unlike the case with mill - annealed specimens, no change was observed for the FWHM of (111) plane at several applied stress levels. (Figure 6)

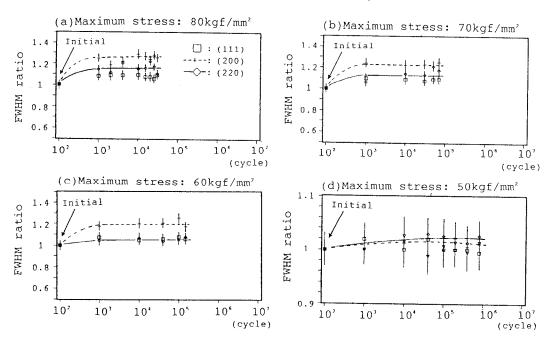


Figure 5 Transition in FWHM ratio during fatigue life. (mill - annealed specimens)

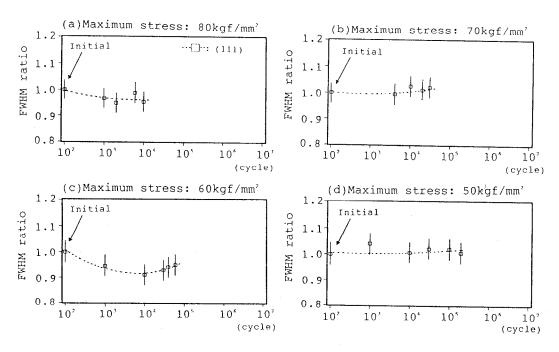


Figure 6 Transition in FWHM ratio during fatigue life. (shot peened specimens)

#### Residual stress

 $\underline{\text{Mill}-\text{annealed specimen}}$  Figure 7 reveals transitions in the residual stress as a function of fatigue cycles. Like the other parameters, the change occurred at an early stage of fatigue life. At a maximum stress of  $40 \, \text{kgf/mm}^2$ , no change was observed for the mill – annealed specimen.

The changed ratios of the residual stress are plotted for fatigue stress levels in Figure 8. As can be seen in Figure 8, the residual stress was more sensitive to fatigue damage at a maximum stress of  $50 \, \mathrm{kgf/mm^2}$  in comparison with the peak intensity and FWHM.

Shot peened specimen Figure 7 also reveals transitions in the residual stress of shot peened specimens during fatigue life. As illustrated in Figure 7, the residual stress indicated more sensitivity to fatigue damage in comparison with the peak intensity and FWHM. A clear change in residual stress was seen for the shot peened specimen at a maximum stress level of  $40 \text{kgf/mm}^2$ , while no change was observed at the same applied stress for the mill — annealed specimen. Consequently, it was found that the change in residual stress was a useful indicator to detect high cycle fatigue damage caused by a maximum stress less than the yield strength of the specimen.

The maximum changed ratios of the residual stress are plotted versus fatigue stress levels in Figure 8. As can be seen in Figure 8, the change in residual stress of the shot peened specimen was more significant than that of the mill — annealed specimen. From a linear extrapolation of the data, the threshold of detecting fatigue damage in the shot peened specimen appears to be approximately 30 kgf/mm² under repeated tensile fatigue.

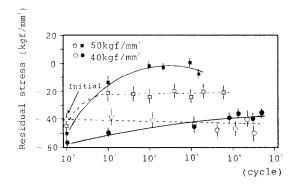


Figure 7 Transition in residual stress during fatigue life.

(open symbols: mill - annealed, solid symbols: shot peened)

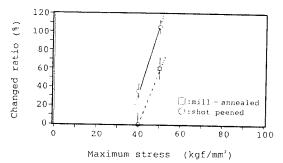


Figure 8 Changed ratio of residual stress.

#### TEM observation

<u>Mill - annealed specimen</u> Fatigue damage was observed by TEM for the mill - annealed specimens at  $\sim 90\%$  fatigue life at maximum stress levels of 40, 50, 60, 70 and  $80 \text{kgf/mm}^2$ . The dislocation densities measured by the observation are summarized in Figure 9, showing a slight increase with increasing the stress level.

Typical TEM photographs of the specimens are shown in Figure 10. The dislocation structure before fatigue revealed a typical planar structure. At higher stress levels, the dislocation structure changed from a planar structure to complex structures.

Shot peened specimen Fatigue damage was observed by TEM for the shot peened specimens at ~90% fatigue life at maximum stress levels of 50, 60, 70 and  $80 \text{kgf/mm}^2$ . The dislocation density measured by the observation is summarized in Figure 9. A slight increase in the dislocation density was found with the stress level.

Typical TEM photographs are shown in Figure 11. The dislocation structure before fatigue revealed a complex structure, which was also observed for the mill — annealed specimens fatigued at higher stress levels. (Figure 10) It is therefore considered that repeated fatigue loads and shot peening had a similar effect on the change in dislocation structure. At higher stress levels, the dislocation structure showed more complex structures.

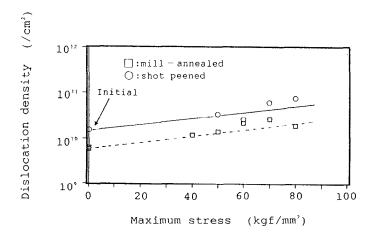


Figure 9 Dislocation density of fatigued specimens at various maximum stress levels.

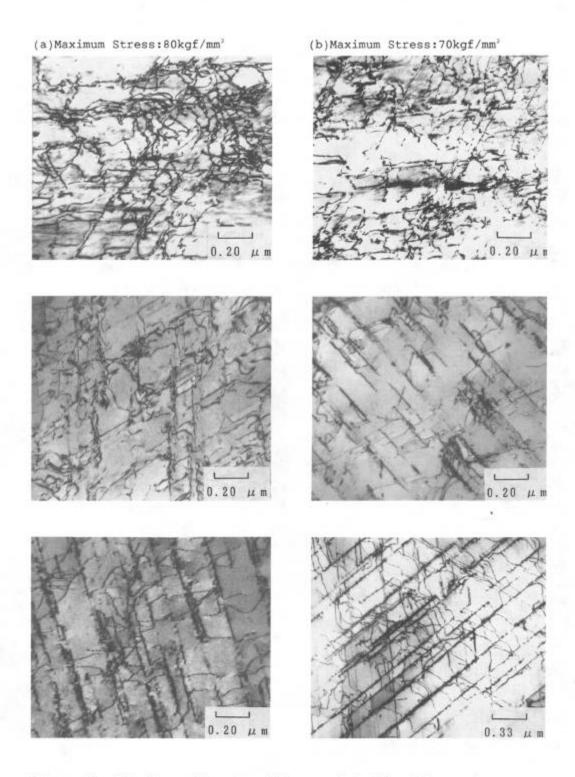


Figure 10 TEM observation for mill — annealed Alloy 718 specimens at ~90% fatigue life under various maximum stress levels.

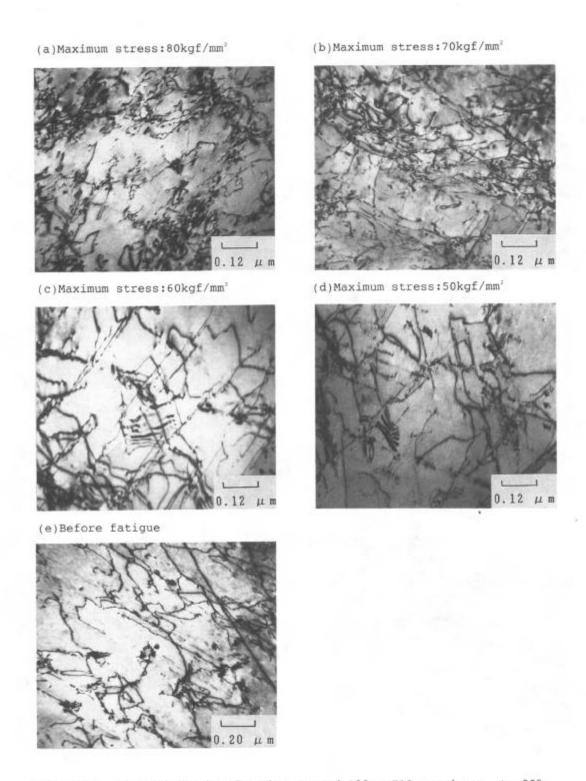


Figure 11 TEM observation for shot peened Alloy 718 specimens at ~90% fatigue life under various maximum stress levels.

#### Vicker's hardness measurement

 $\underline{\text{Mill}-\text{annealed specimen}}$  Vicker's hardness was measured for the same specimens observed by TEM. (Figure 12) For mill—annealed specimens, Vicker's hardness increased as the stress level increased, suggesting the occurence of work hardening due to the applied stress.

Shot peened specimen Vicker's hardness measured for shot — peened specimens decreased as the stress level increased, suggesting the occurence of work softening due to the applied stress. (Figure 12)

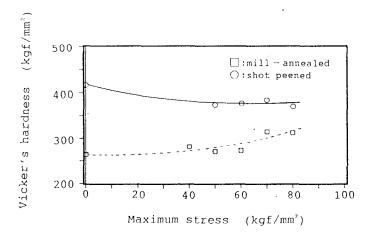


Figure 12 Vicker's hardness of fatigued specimens at various maximum stress levels.

# Conclusion

Fatigue damage was characterized for mill — annealed and shot peened Alloy 718 using x — ray diffraction method.

Although the fatigue behaviors of measured parameters were different for mill — annealed and shot peened specimens, residual stress was found to be most sensitive to fatigue damage of both specimens.

The transitions in the residual stress of shot peened specimens were more significant than that of mill — annealed specimens when fatigued at the same stress levels.

As for the shot peened specimen, the change in residual stress could detect high cycle fatigue damage caused by a maximum stress less than the yield strength of the specimen.

The dislocation density was slightly increased by the applied stress for both mill — annealed and shot peened specimens.

It was found by Vicker's hardness measurement that the mill — annealed specimens indicated work hardening during fatigue life, while the shot peened specimens showed work softening.

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