Effect of Small Artificial Defects and Shot Peening on Fatigue Strength of Ti-6Al-4V Alloys at Elevated Temperatures

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Abstract

Rotary bending fatigue tests of Ti-6Al-4V alloy have been conducted in the temperature range of 20 ℃ to 450 ℃ using both unnotched and notched specimen with several small drilling holes on their surface. High temperature fatigue strengths at 10^7 cycles are observed, and shot peening effects are discussed.

1 Introduction

Mechanical surface treatments such as shot peening are known to enhance the resistance of metal alloys to fatigue. It has been established that an increment in fatigue strength can be attributed to compressive residual stresses and strain hardening in near surface regions developed by shot peening. On the other hand, a decrease in fatigue strength also results because of severe stress concentration due to a deterioration in surface topography (rough surface) produced by this procedure. However, the role of the individual effects of residual stresses, strain hardening and rough surface on fatigue properties and fracture mechanisms, in particular at elevated temperatures, has not yet been studied in any great detail[1].

In the present study, in order to investigate the effects of small defects and shot peening on fatigue strengths of Ti-6Al-4V alloys, rotary bending fatigue tests have been conducted in the temperature range of 20℃ to 450℃. The results obtained were discussed based on Murakami's $\sqrt{area}$ parameter model[2].

2 Materials and experimental procedures

Chemical components, mechanical properties and fatigue specimens
Materials chosen were three kinds of $(\alpha + \beta)$-Titanium alloys previously received at respective times and designated as Material A, Material B and Material C. The specimens were annealed at 690℃ for an hour. The chemical compositions and mechanical properties are listed in Tables 1 and 2, respectively.

Table 1: Chemical composition of Ti-6Al-4V alloys(wt%)

	N	H	Fe	O	Al	V	C	Ti
A	0.01	0.001	0.15	0.16	6.38	4.17	0.01	Bal.
B	0.01	0.002	0.15	0.17	6.45	4.10	0.01	Bal.
C	0.01	0.0009	0.17	0.17	6.37	4.11	0.01	Bal.

Table 2: Mechanical properties of Ti-6Al-4V alloys

	Yield strength σ_{ys} MPa	Tensile strength σ_B MPa	Elongation ϕ%	Reduction of area ψ%
A	1012	1078	17	48
B	1040	1101	16	47
C	943	985	18	40

The fine microstructure of a transverse section normal to the specimen axis is shown in Fig. 1.

Round bar with a diameter of 15 mm was machined to the shape of a fatigue specimen as shown in Fig. 2. The surface of unnotched specimens (smooth specimens) was polished by emery paper of ♯800 to ♯2000 and then finished by buffing. Notched specimens had small drilling holes in their surfaces. The number of holes ranged between 1 to 8. They were 0.1 mm in diameter and 0.1 mm deep.

Experimental procedures
Rotary bending fatigue tests were conducted at 20℃, 250℃, 350℃ and 450℃ in air at a frequency of approximately 50 Hz.

Shot peening was done over a length of 30 mm in a central portion of the specimens. The details of shot peening procedures are listed in Table 3.

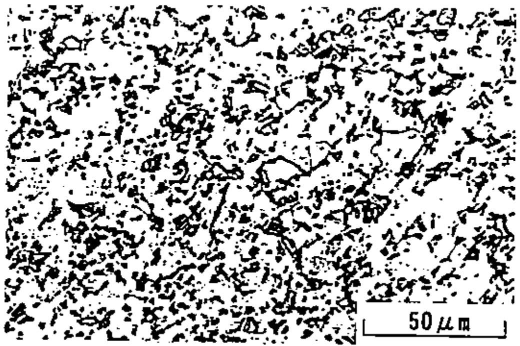


Figure 1: Micrograph of transverse section normal to specimen axis (Ti-6Al-4v alloy, Material-A)

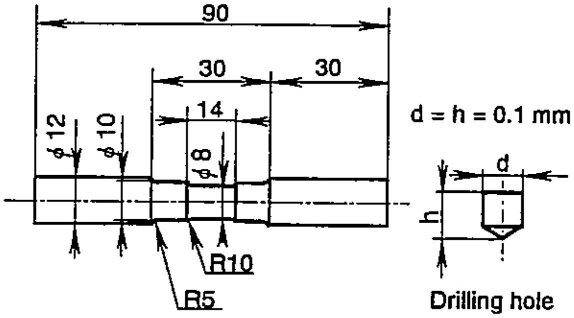


Figure 2: Shape and dimensions of unnotched and notched specimens with drilling holes of 0.1 mm in diameter and 0.1 mm deep

Table 3. Details of shot peening procedures

Shot media		Peening conditions	
		Machine	Air blast machine
Material	Cast steel	Air pressure	0.5MPa
Hardness	HV420	Projection time	72 s (54kg/min)
Size	400μm	Coverage	300%
		Peening intensity	0.237mmA

The surface roughness was measured in the loading direction of the specimens. The mean roughness about central line, Ra, and the maximum roughness, Rmax, were 1.1μm and 7.8μm, respectively, after shot peening. The respective values were 0.1μm and 1.0μm before shot peening.

The residual stress was determined by X-ray measurement with a Ψ-diffractometer and by the so-called $\sin^2\Psi$ method with vanadium k_α- radiation. The measured value of compressive residual stress was in the range of 620MPa to 680MPa in the surface layer.

3 Results

Relationships between fatigue strength and temperature
The fatigue strengths at 10^7 cycles were observed from the S-N diagrams. The strengths of the unnotched-unpeened, the unnotched-shot peened, the drilled-unpeend and the drilled-shot peened specimens are denoted by σ_F, σ_{FP}, σ_{FN} and σ_{FNP}, respectively. The relationships between these fatigue strengths and temperatures are shown in Fig. 3.

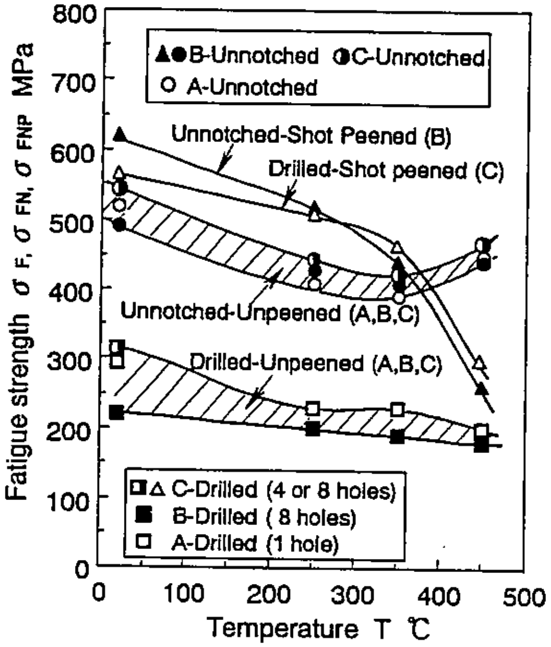


Figure 3: Effects of shot peening on fatigue strength of unnotched specimens and notched specimens with small holes

Effects of shot peening on fatigue strength of unnotched specimens
The fatigue strengths of unnotched specimens (Material-B) were increased by 27%, 21% and 7% at 20℃, 250℃ and 350℃, respectively, by shot peening. At 450℃, however, shot peening caused a 41% reduction in fatigue strength. The temperature dependence of shot peening effects on fatigue strength was similar to that obtained by Gray *et al.*[1]. It was clear that compressive residual stress decreased during stress cycling, and that this decrease became more remarkable with increasing temperature. Therefore, the reduction in fatigue strengths caused by residual stress relieving should also be more striking with increasing temperature. At 450℃, the fatigue strength of peened specimens was only 280MPa, whereas that of unpeened specimens was 440MPa. The reduction might be attributed to the rough

surface produced by shot peening, because the compressive residual stress could vanish completely during stress cycling [1]. The peened specimens, however, following electropolishing of approximately $50\mu m$ in near surface regions, showed an excellent performance of 460MPa, since polishing improved the surface topography.

Reduction of fatigue strengths due to drilling holes

The fatigue strengths, σ_{FN}(symbols □, ■ and ◨), of the drilled-unpeened specimens showed a severe reduction when compared to those, σ_F (symbols ○, ● and ◑), of the unnotched-unpeened specimens. The mean values within scatter bands of the fatigue strength of the unnotched specimens were 520MPa, 440MPa, 420MPa and 457MPa at 20℃, 250℃, 350℃ and 450℃, respectively, and the respective values of drilled specimens were 277MPa, 215MPa, 210MPa and 190MPa. The reduction in fatigue strengths due to such a small drilling hole reached approximately 47%, 51%, 50% and 58% at 20℃, 250℃, 350℃ and 450℃, respectively.

Effects of shot peening on fatigue strength of drilled specimens

The fatigue strengths, σ_{FNP} (symbol △), of the drilled-shot peened specimens were comparable to those, σ_{FP} (symbol ▲), of the unnotched-shot peened specimens at each temperature. Reductions in fatigue strengths due to drilling holes were not observed under shot peened conditions.

4 Discussions

Both the drilling hole and the rough surface might be regarded as surface defects. Murakami's $\sqrt{area}$ parameter model was applied to examine the effect of these surface defects on the fatigue strengths at elevated temperatures.

Murakami's $\sqrt{area}$ parameter model

Murakami *et al.*[2] have proposed the $\sqrt{area}$ parameter model to evaluate the effect of small defects, cracks and inclusions on fatigue strength. This model may be able to predict fatigue limits σ_w in terms of one material and one geometrical parameter, i.e. Vickers hardness HV and $\sqrt{area}$ (defined as the square root of the area of a defect projected onto a plane perpendicular to the maximum tensile stress). They confirmed that this model could be of practical use for predicting the fatigue limits of many metals. For surface defects, the experimental expression of fatigue limits σ_w is given by

$$\sigma_w = 1.43(HV + 120)/(\sqrt{area})^{1/6} \tag{1}$$

where σ_w is in MPa, HV is in kgf/mm^2 and $\sqrt{area}$ is in μm.

This equation is applicable to defects having $\sqrt{area}$ less than approximately 1000μm.

Vickers hardness HV at elevated temperatures

Vickers hardness numbers, HV, were observed to apply to the $\sqrt{area}$ model at elevated temperatures. The results are shown in Fig. 4.

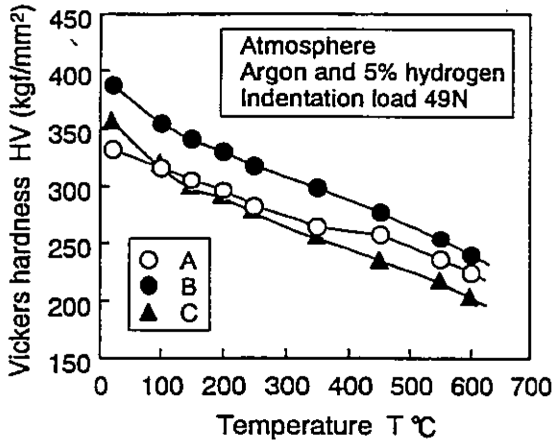


Figure 4: Vickers hardness at elevated temperatures (Material A, B and C), in argon atmosphere including 5% hydrogen. Indentation load of 49 N.

Prediction of fatigue strength of drilled specimens

The averaged values, HV$_M$, of Vickers hardness number HV of Material A, B and C, and the fatigue strengths, σ_{FNM} , predicted from Eq.(2) are listed in Table 4. Eq.(2) was obtained from Eq.(1) by substituting σ_w and HV to σ_{FNM} and HV_M , respectively.

$$\sigma_{FNM} = 1.43(HV_M + 120)/(\sqrt{area})^{1/6} \qquad (2)$$

where $\sqrt{area}$ is 92.5 μm for the 0.1 mm-diameter and 0.1 mm-deep drilling hole.

The observed fatigue strengths, σ_{FN} , were considerably smaller than the predicted fatigue strengths, σ_{FNM}, at all temperatures tested. The fatigue strength ratios R $(= \sigma_{FN}/\sigma_{FNM})$ were in the range of 0.75 to 0.86. Murakami *et al.*[2] showed that the ratios, R, were in the range of 0.9 to 1.1 for many metallic materials. It was noticed that the ratios, R, obtained in this investigation were smaller than a lower limit of 0.9 in scattering of R as shown by Murakami *et al.*, and that such tendency was remarkable at elevated temperatures. As shown in Figs. 3 and 4, the measurements of HV and σ_{FN} varied widely. This wide variation, however, might not be considered to cause such small fatigue strength ratios. For example, at 450 ℃ where the strength ratio was the least, measured values in the hardness of Material A and B were 258 and 277, respectively. The respective values in the fatigue strength were 200MPa and 180MPa. The fatigue strength ratios of Material A and B were 0.79 and 0.67, respectively. At 450℃, since the variations of the measurements were not so wide, some other explanations is necessary. The authors could not provide this information in the present situation.

Table 4: Comparison between observed fatigue strength σ_{FN} and predicted fatigue strength σ_{FNM} due to Murakami's

	Averaged value of Vickers hardness HV_M kgf/mm^2	Predicted fatigue strength σ_{FNM} MPa	Observed fatigue strength σ_{FN} MPa	Strength ratio $R=\sigma_{FN}/\sigma_{FNM}$
20℃	359	322	277	0.86
250℃	293	278	215	0.77
350℃	273	264	210	0.80
450℃	257	254	190	0.75

Defect size, $(\sqrt{area})_{RN}$) , equivalent to rough surface produced by shot peening

At 450℃, the fatigue strengths, σ_F, σ_{FP} and σ_{FPE}, of the unnotched-unpeened, the unnotched-shot peened and the unnotched- shot peened- electropolished specimens of Material-B were 440MPa, 280MPa and 460MPa, respectively. In the shot peened specimens, compressive residual stress in near surfaces could be relieved during the stress cycle at 450℃ [1]. Therefore, the two factors of strain hardening and rough surface should remain. The difference between the fatigue strength, 440MPa, of the unnotched-unpeened and that, 460MPa, of the unnotched-shot peened-electropolished specimens could be regarded as due to strain hardening, because the surface of both specimens had been polished. In Eq.(1), using symbols of the fatigue strengths, σ_F and σ_{FPE} , denoted here instead of the fatigue limits, σ_w , the following equations were obtained.

$$\sigma_F = 1.43(\mathrm{HV} + 120)/(\sqrt{area})^{1/6} \tag{3}$$

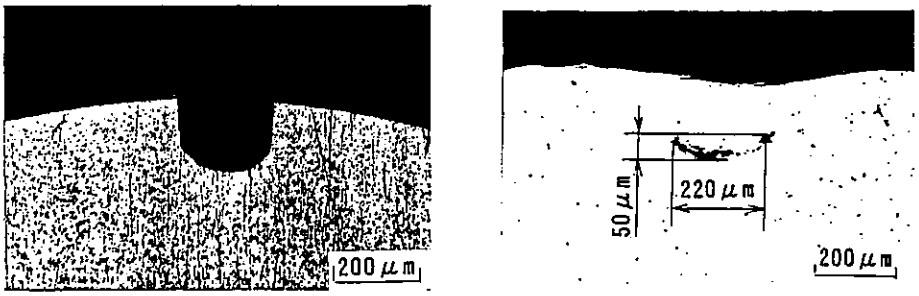
$$\sigma_{FPE} = 1.43(\mathrm{HV}_P + 120)/(\sqrt{area})^{1/6} \tag{4}$$

where HV and HV_P are Vickers hardness of the unpeened and shot peened conditions, respectively. The number of HV was 277. The values of σ_F and σ_{FPE} were 440MPa and 460MPa, respectively. By substituting these values into Eq. (3) and Eq. (4), the number of HV_P under the shot peeed condition was predicted to be 304.

Defect size, $(\sqrt{area})_{RN}$, equivalent to the rough surface produced by shot peening, was obtained by Eq.(5)

$$\sigma_{FP} = 1.43(\mathrm{HV}_P + 120)/[(\sqrt{area})_{RN}]^{1/6} \tag{5}$$

The fatigue strength, σ_{FP}, has been influenced by the two factors of strain hardening and rough surface. The value of σ_{FP} was 280MPa, and the number of HV_P was 304. Therefore, the value of $(\sqrt{area})_{RN}$ could be predicted to be could be predicted to be 103μm. This defect size, $\sqrt{area}$, of the 0.1 mm-drilled specimens was 93μm. The defect size, $(\sqrt{area})_{RN}$, equivalent to the rough surface could be comparable to that, $\sqrt{area}$, of the drilled specimens. The fatigue strength of drilled-shot peened specimens,σ_{FNP}, with a defect of 103μm due to the rough surface was not substantially different from that of unnotched-shot peenot peen due to surface roughness was not substantially differ from that of unnotched-shot peenened specimens which had no drilling holes but the same rough surface.



(a) Unpeened condition

(b) Shot peened condition

Figure: 5 Optical microphotogr of transverse section in a plane including drilling hole.

Configuration change of drilling holes by shot peening

Fig. 5 (a) and (b) are optical microphotographs of the transverse section in a plane including a drilling hole under the unpeeneened and the shot peened conditions, respectively.

The 0.2 mm-diameter and 0.2 mm-deep drilling holes were used. The holes were observed to be crushed by shot peening. The $\sqrt{area}$ of 185μm prior to shot peening was reduced to approximately 89μm when the crushed hole was regarded as an interior defect. The interior defect of 89μm might be converted into the surface defect of 52 μm . The crushed size in the 0.1 mm drilling hole could be considered to have diminished further than in the 0.2 mm drilling hole.

5 Conclusions

In the present study, in order to investigate the effects of shot peening on the fatigue strength of Ti-6Al-4V alloy, rotary bending fatigue tests were conducted at 20℃, 250℃, 350℃ and 450℃. The unnotched and 0.1 mm-drilled specimens were used. The results obtained were summarized as follows:

(1) The fatigue strengths of the unnotched specimens are increased by 27%, 21% and 7% by shot peening.

At 450℃, however, shot peening causes a 41% reduction in fatigue strength. The reduction is attributed to the rough surface produced by shot peening, because compressive residual stress can vanish completely during stress cycling.

(2) The fatigue strengths of the 0.1 mm-drilled specimens show a severe reduction when compared to those of unnotched specimens. The reduction in fatigue strengths due to such a small drilling hole reach approximately 47%, 51%, 50% and 58% at 20℃, 250℃, 350℃ and 450℃, respectively.

(3) The observed fatigue stregnths of the 0.1 mm-drilled pecimens, σ_{FN}, are smaller than the predicted fatigue strengths,σ_{FNM}, by Murakami's $\sqrt{area}$ parameter model. The fatigue strength ratios $R(=\sigma_{FN}/\sigma_{FNM})$ are in the range of 0.75 to 0.86

(4) The fatigue strengths of the 0.1 mm-drilled specimens are increased drastically by shot peening and are comparable to those of unnotched-shot peened specimens at each temperature.

(5) When Murakami's $\sqrt{area}$ parameter model was applied, the defect size $(\sqrt{area})_{RV}$, equivalent to the rough surface produced by shot peening, was about $105\mu m$. The defect size, $\sqrt{area}$, of the 0.1 mm-drilling hole crushed by shot peening is observed to be smaller therved to be smaller than $52\mu m$. The fatigue strengths of notched-shot peened specimens with a defect size of 52 μ m are comparable to those of unnotched-shot peened specimens with a defect size of $105\mu m$ due to the rough surface.

Acknowledgements

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