EFFECT OF SHOT PEENING ON FATIGUE STRENGTH OF TITANIUM ALLOY

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ABSTRACT

It is well known that the fatigue strength of titanium alloys can be improved by shot peening. This study is aimed at optimizing the peening media and peening conditions to improve the high-cycle fatigue strength of the $\alpha-\beta$ type Ti-3Al-2V alloy components with lamellar microstructures and chemically polished surfaces. Stainless steel beads were selected as the most suitable peening media because of the relatively smooth peened surface compared to glass beads and steel beads. Rotating-bending fatigue tests were done for specimens peened with stainless steel beads at various peening intensities. The maximum fatigue strength was achieved at the optimum Almen intensity of approximately 0.2 mmN.

KEYWORDS

Shot peening, Stainless steel beads, Steel beads, Glass beads, Titanium alloy, Fatigue strength, Peening intensity, Residual stress, Surface roughness, Hardness

INTRODUCTION

Titanium alloy connecting rods were put to practical use for a commercial automobile engine (1). These connecting rods are made of the $\alpha+\beta$ type free machining titanium alloy whose basic grade is Ti-3Al-2V. They are die-forged at β-phase temperature, and then chemically polished in an acid bath of HNO_3+HF to remove the so-called α-case which causes low fatigue strength. The aim of the present work is to optimize the shot peening conditions to improve the high-cycle fatigue strength of the $\alpha+\beta$ type Ti-3Al-2V alloy parts with lamellar microstructures and chemically polished surfaces.

It is known that the fatigue strength of titanium alloys strongly depends on the surface conditions such as surface roughness, hardness and residual stress. Surface roughness has a damaging effect on crack initiation. On the other hand, the work-hardened layer and the compressively stressed layer is beneficial in increasing resistance to crack initiation. The chemically polished surface is sufficiently smooth and has no work-hardened or compressively stressed layer. Therefore, addition of work-hardening and residual compressive stress to the surface layer can improve the fatigue strength of the chemically polished parts.

Shot peening is a widely-used technique to improve fatigue strength. Many authors have investigated the effect of shot peening on the fatigue behavior of titanium alloys. The mechanism effecting the change in fatigue strength has been evaluated (2,3). Concerning the change in fatigue strength of titanium alloys, however, inconsistent results have been obtained. Negative effects as well as little effect of shot peening have been reported. These investigations are mostly performed on Ti-6Al-4V alloy specimens with electrolytically polished surfaces. The number of investigations concerning shot peening for other grades of titanium alloy or surface conditions are still limited. Therefore, determination of the most effective and reliable peening conditions for a certain titanium alloy part has some difficulties.

EXPERIMENTAL PROCEDURE

Material and specimens

The chemical composition of the material used in this study was: 3.03 Al, 1.91 V, 0.14 Fe, 0.14 O_2, balance Ti (all units in mass %). The material was forged to 45 mm and 20 mm diameter bars at a β-phase temperature (1373 K). The forged bars were annealed for 3.6 ks at 978 K for the purpose of stress relief. The test program was carried out in two stages: (a) Determination of the most suitable peening media in view of the surface condition [Stage I]; (b) Optimizing the shot peening intensity to improve the high-cycle fatigue strength [Stage II]. In Stage I, blocks with dimensions of 40x40x10 mm were cut out of the annealed 45 mm diameter bars. The fatigue specimens for Stage II with 8.3 mm diameter by 22 mm gage length were machined from the annealed 20 mm diameter bars. Both specimens were chemically polished in an acid bath of HNO_3+HF. By this chemical polishing, a surface layer of about 150 μm was removed to obtain a smooth and lusterless surface.

Shot peening media

Table 1 shows the materials, hardness and sizes of the peening media used in this study. Spherical beads less than 500 μm diameter were made of three kinds of materials: (a) Glass [BG-series]; (b) Carbon steel [BC,SC-series] and (c) Stainless steel [BS-series]. BC-series, steel beads having a hardness of 835 HV, were made by the process of gas atomizing. SC500, steel shot having a hardness of 420 HV and a maximum diameter of 500 μm, was water-atomized and heat-treated. BS-series, stainless steel beads made of austenitic stainless steel (18Cr-8Ni), have a hardness of 260 HV. The numbers in the name of the media indicate the maximum diameter (μm). All media except SC500 and BS500 were used in Stage Ⅰ. SC500 and some of BS-series including BS500 were used in Stage Ⅱ.

Table 1 Materials, hardness and sizes of peening media

Grade	Material	Hardness [HV]	Size range [μm]
BG60	Glass	480	30- 60
BG90			60- 90
BG210			150-210
BG300			210-300
BC100	Carbon steel	835	50-100
BC300			150-300
SC500		420	300-500
BS70	Stainless steel (18Cr-8Ni)	260	- 70
BS100			50-100
BS200			100-200
BS300			150-300
BS500			300-500

Shot peening conditions

In Stage Ⅰ, a 40×40 mm plane was shot-peened in an air blast machine with a 9 mm inside diameter nozzle at an air pressure of 0.39 MPa. In Stage Ⅱ, the fatigue specimens were shot-peened in a centrifugal peening machine with various projection velocities of 40-100 m/s and various sizes of stainless steel beads to achieve a wide range of peening intensity. During shot peening in both stages, the specimens were exposed to ten times the time required to achieve 100% coverage in order to achieve saturation of peening intensity. Peening intensities were measured with Almen ”N” strip.

Investigation of surface characteristics

The shot-peened surface was observed with a scanning electron microscope (SEM). Surface roughness was measured in the loading direction of the fatigue specimen by a profilometer. Vickers hardness was measured on a surface polished with a buff to remove a 5 μm layer. The depth distribution of the hardness was determined on the buff-polished plane which was oriented 15 degrees away from the surface. 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 depth distribution of the residual stress below the surface was determined after removal of the surface layers by electrolytical polishing.

Fatigue test

Rotating-bending fatigue tests (R=-1) were done on the smooth specimens at room temperature. The fatigue strength at 10^7 cycles was evaluated. The fracture surface was observed with the SEM to determine the crack initiation sites.

EXPERIMENTAL RESULTS AND DISCUSSION

Stage I (Effect of peening media on surface conditions)

Table 2 shows the Almen intensity, hardness, residual stress and roughness of the surfaces shot-peened with the glass, steel and stainless steel beads. The Almen intensity strongly depends on the sizes and materials of the beads under constant air pressure and coverage. The Almen intensity increases with the increasing size and hardness of the beads. This change can be attributed to the high kinetic energy and the high yield strength for the heavy and hard bead. Surface hardness, roughness and residual compressive stress tend to increase with peening intensity. The relationships among these parameters are investigated in detail in the following.

Table 2 Peening intensity and properties of peened surface (Stage I)

Grade of media	Almen intensity [mmN]	Hardness [HV]	Residual stress [MPa]	Roughness Ra [μm]	Rmax [μm]
BG60	0.06	289	- 660	1.0	8.2
BG90	0.12	319	- 600	1.5	13.5
BG210	0.26	351	- 820	1.4	9.5
BG300	0.42	374	- 760	1.6	14.0
BC100	0.18	340	- 670	1.6	13.3
BC300	0.45	391	- 700	2.6	19.0
BS70	0.06	309	- 490	1.1	8.8
BS100	0.11	331	- 800	1.0	7.7
BS200	0.14	314	- 550	1.1	9.4
BS300	0.17	342	- 710	1.2	11.1
Unpeened		269	+ 10	1.2	9.4

Figure 1 shows the relationship between the surface roughness R_a--arithmetical mean deviation from the mean line--and the change in the surface hardness. The increase in the surface hardness is roughly proportional to the surface roughness. However, the surface roughness of the stainless steel bead peening is lower than the glass bead and the steel bead shot peening to obtain the same surface hardnesses.

Figure 2 shows the relationship between the surface roughness R_a and the surface residual stresses. In the case of the steel beads, the residual compressive stress does not increase with the bead size, although the surface roughness increases. In the case of the stainless steel beads, the residual stress varies with the bead size, although the surface roughness does not change. The surface peened with stainless steel beads has lower roughness than the other media at an equal level of residual stress.

Figure 3 shows the surface states of the samples which were peened with (a) glass beads and (b) steel beads. Many scratches and implanted beads are observed on the surface peened with glass beads [Fig.3(a)]. Similar implantation is observed in the case of steel beads [Fig.3(b)]. Broken beads having sharp edges cause these scratches and implantation. On the other hand, the surface peened with stainless steel beads is relatively smooth, and neither scratches nor implantation are found there. This advantage of surface integrity is due to higher toughness of stainless steel beads. In the case of glass beads, although brand-new glass beads were used in this study, the surface defects were caused by beads which had been broken in the projecting equipment. Therefore, it seems to be difficult to avoid these defects in the case of glass beads.

Wagner et al.(4), studying the influence of shot peening on the fatigue strength of Ti-6Al-4V, found that an increase in the surface roughness promotes fatigue crack initiation. Due to this disadvantage, the effect of shot peening on the fatigue strength of titanium alloys was often insufficient (5). Similarly, scratches and implantation on the surface can act as fatigue crack nuclei and result in a degradation in fatigue strength. Considering the surface roughness and integrity, stainless steel beads are estimated to be the most suitable shot media for the fatigue strength of chemically polished Ti-3Al-2V alloy parts.

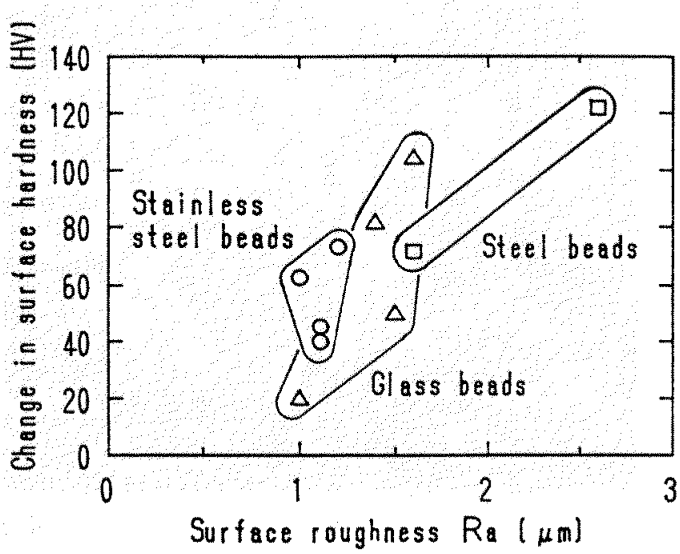


Fig. 1 Change in surface hardness versus surface roughness for various bead materials

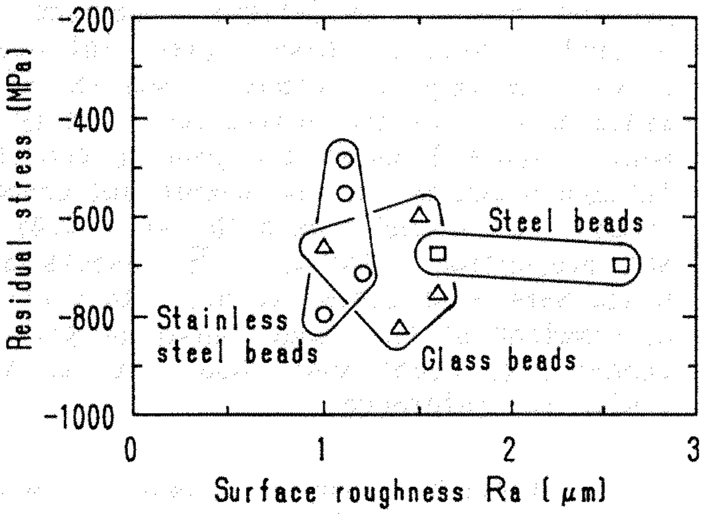


Fig. 2 Residual stress versus surface roughness for various bead materials

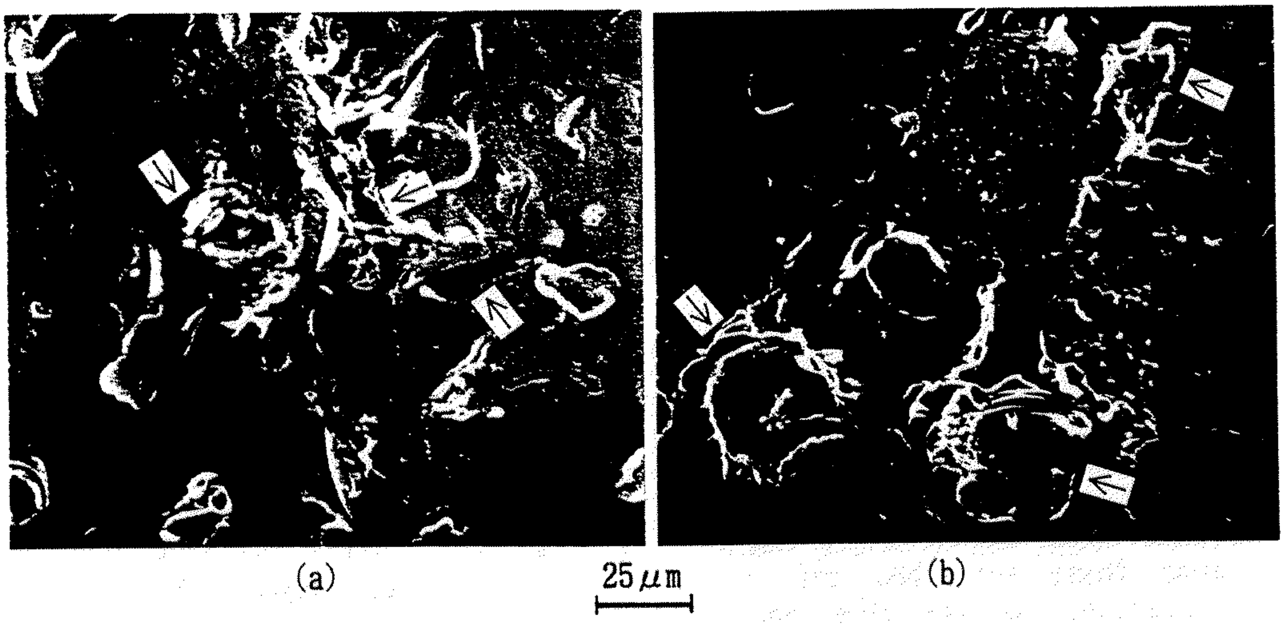


Fig. 3 Examples of shot-peened surfaces: (a) Implantation and scratches by peening with glass beads; (b) Implantation of steel beads (See arrows.)

Stage II (Effect of peening intensity on fatigue behavior)

A wide range of peening intensity was required for evaluating the influence of peening intensity on fatigue properties. The size of the peening media and the projection velocity have a great influence on the peening intensity. In this study, the peening intensity was varied by changing the size of the peening media as well as the projection velocity considering the capacity of our equipment. Table 3 shows the peening conditions, the surface conditions and the fatigue strength for the peened and unpeened fatigue specimens. The Almen intensity was varied from 0.10 mmN to 0.44 mmN with the stainless steel bead size and projection velocity. The specimens peened by the used stainless steel beads were also tested in order to clarify the influence of work-hardening and deformation of the beads caused by previous use. Additionally, the specimens peened with steel shot (SC500) at an Almen intensity of 0.72 mmN were also tested for reference.

Table 3 Peening intensity, properties of peened surface and fatigue strength (Stage II)

Grade of media	Projection velocity [m/s]	Almen intensity [mmN]	Vickers hardness [HV]	Residual stress [MPa]	Roughness		Fatigue strength [MPa]
					Ra [μm]	Rmax [μm]	
BS200	40	0.10	317	- 372	0.6	5.0	382
BS300	40	0.21	321	- 815	1.3	11.0	412
BS500	60	0.32	352	- 487	2.1	18.5	382
BS500	100	0.44	356	- 650	3.4	23.5	373
SC500	100	0.72	352	- 472	5.3	36.2	392
BS300*	40	0.19	351	-1438	1.0	9.2	451
Unpeened			259	- 60	0.6	6.7	363

*:Previously used beads

Figure 4 shows the S-N curves obtained from the rotating-bending fatigue tests. The curves for shot-peened specimens lie higher than that for unpeened (chemically polished) specimens. However, the fatigue strength varies depending on the peening parameters, and some curves indicate only a slight increase in the 10^7 cycle fatigue strength.

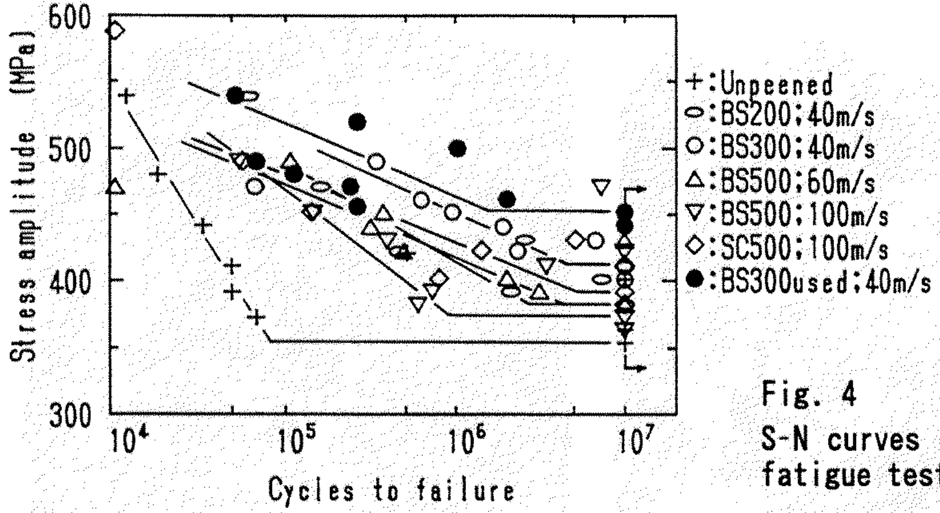


Fig. 4
S-N curves of rotating-bending fatigue tests

Figure 5 shows the 10^7 cycle fatigue strength as a function of the Almen intensity. The fatigue strength increases to a maximum level with the Almen intensity up to 0.19 mmN. This increase corresponds to an increase of 24% compared with the chemically polished (unpeened) state. With the Almen intensity increasing from 0.19 mmN to 0.44 mmN, the fatigue strength decreases to a level almost equal to that for the unpeened state. The fatigue strength for an Almen intensity of 0.72 mmN produced with steel shot is slightly higher than that for the Almen intensity of 0.44 mmN produced with stainless steel beads. It was still lower than the maximum value for stainless steel beads.

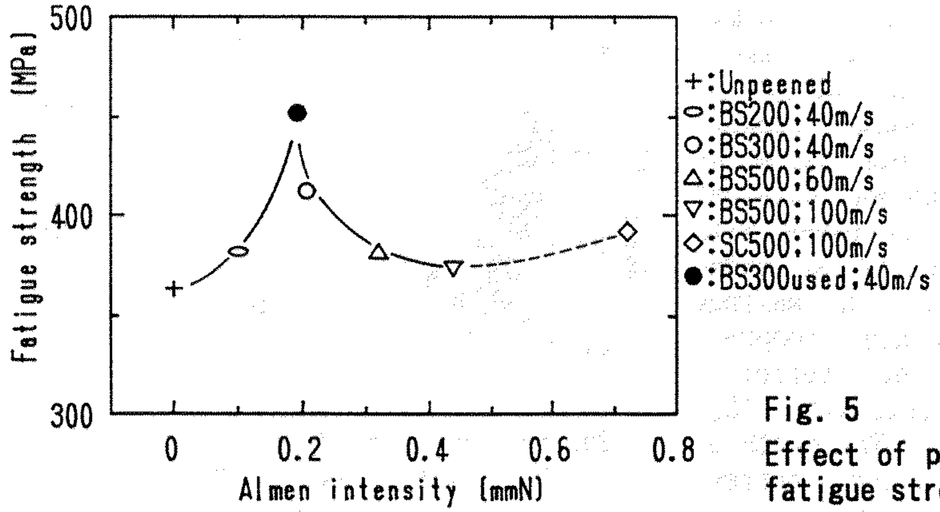
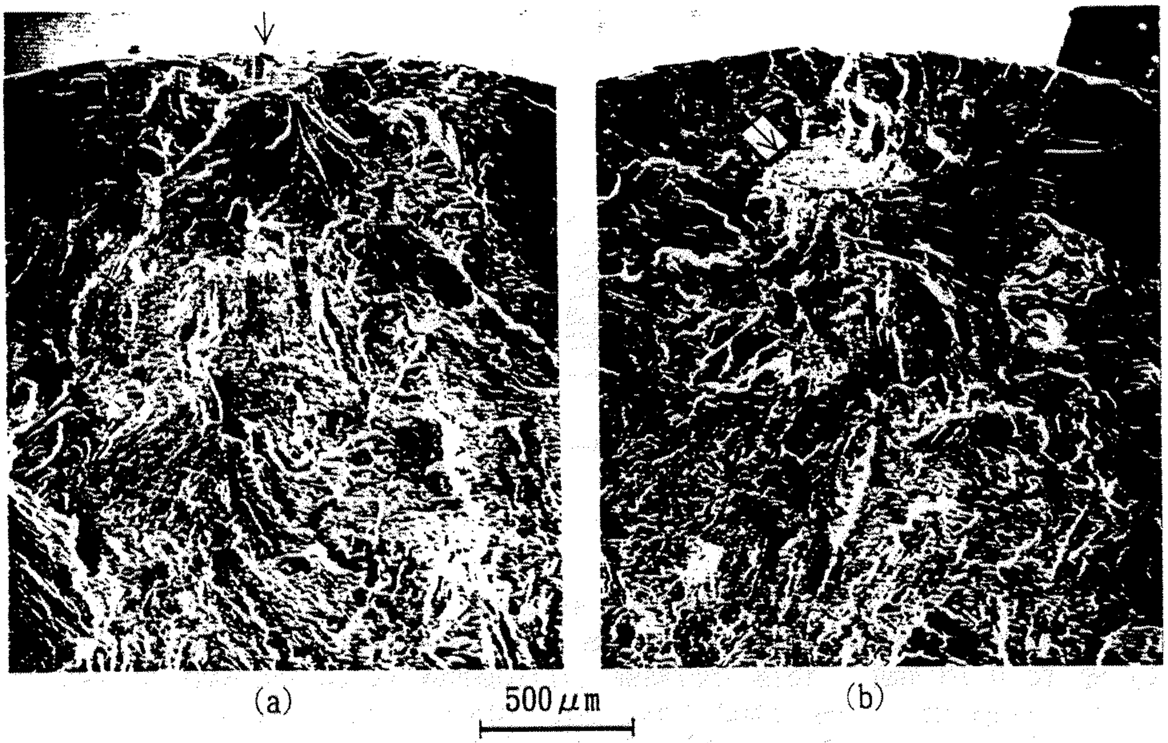


Fig. 5
Effect of peening intensity on fatigue strength

Figure 6 shows the examples of the fracture surfaces obtained from the rotating-bending fatigue tests. For states unpeened and peened at an intensity of 0.10 mmN, fatigue crack initiated on the surface as shown in Fig.6(a). On the other hand, for the states peened at intensities above 0.10 mmN, fatigue cracks initiated at approximately 100-500 μm below the surface as shown in Fig.6(b). The depth of crack initiation had a tendency to increase with the peening intensity.



(a) (b)

Fig. 6 Examples of fractured surfaces in rotating-bending fatigue tests: (a) Surface crack initiation site in unpeened specimen; (b) Subsurface crack initiation site in specimen peened at Almen intensity of 0.44 mmN

Figures 7 and 8 show the depth distribution profiles of Vickers hardness and residual stress of the fatigue specimens, respectively. The maximum value of the hardness, which was obtained at the surface, increases with the peening intensity as shown in Fig.7. However, the maximum value of the residual compressive stress does not correlate with the peening intensity. (See Fig.8 or Table 3.) The depth of the work-hardened and compressively stressed layers increases with the peening intensity and corresponds to the depth of the fatigue crack initiation.

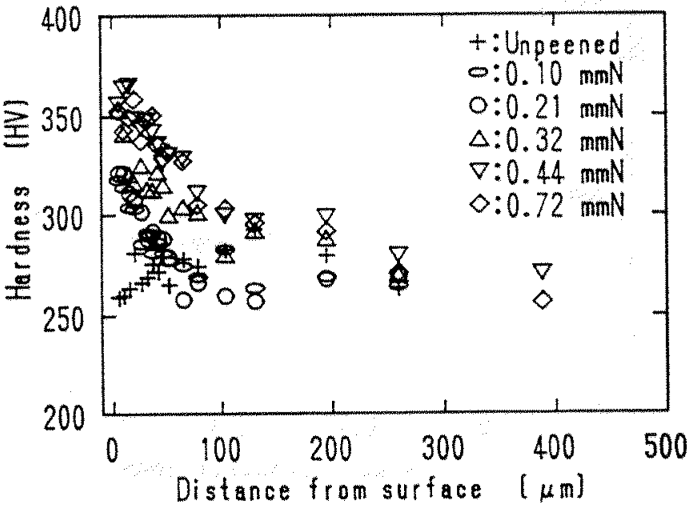


Fig. 7 Vickers hardness as a function of distance from surface for fatigue specimens

The degradation in fatigue strength with increasing peening intensity observed in this study cannot be due to the increase of the surface roughness because the fatigue cracks initiated below the surface. According to the literature (6,7), the decrease of the fatigue strength caused by the higher peening intensity is due to residual tensile stress below the surface, which promotes internal fatigue cracks. However, residual tensile stress was not observed at the crack initiation depth in this study. (See Fig.8.) The increase in the crack initiation depth with the peening intensity cannot explain the degradation of the fatigue strength because the distance from the crack initiation site to the surface is also increased.

As shown in Figures 7 and 8, the surface hardness increases with the peening intensity, while the surface residual stress does not correspond to this. The increase in the peening intensity above 0.2 mmN induces the decrease in the surface residual compressive stress. These changes in the surface conditions at high peening intensity may reduce the resistance to crack propagation at the surface. Figure 9 shows the relationship between fatigue strength and surface residual stress. Surface residual stress appears to have a dominating influence on fatigue strength in comparison with other factors such as surface roughness, surface hardness, depth of work-hardened layer and depth of compressively stressed layer. The highest fatigue strength is achieved at the highest surface residual compressive stress produced by stainless steel bead peening. The high residual compressive stress on the surface is obtained with the relatively thin compressed layer. This implies that the resistance to crack propagation at the surface is more effective on fatigue strength as compared with the resistance to crack initiation or propagation below the surface at an early stage.

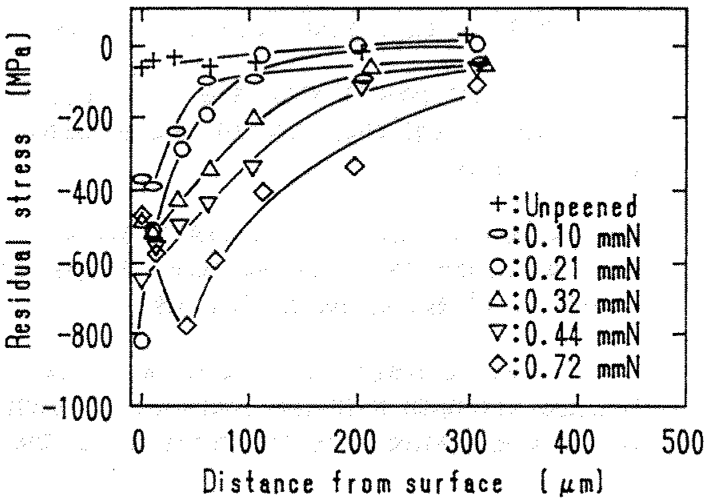


Fig. 8 Residual stress as a function of distance from surface for fatigue specimens

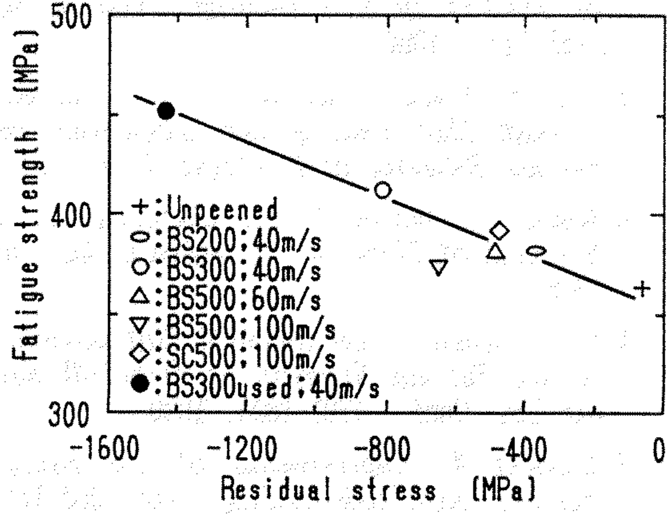


Fig. 9 Effect of surface residual stress on fatigue strength

The fatigue strength for specimens peened with used stainless steel beads (worn out by previous use) was higher than that for brand-new beads. It is obvious that the higher residual compressive stress on surfaces peened with used stainless steel beads causes higher fatigue strength, though the mechanism effecting the change in the residual stress remains to be elucidated. This phenomenon is desirable for improving fatigue strength because stainless steel beads are usually used repeatedly in practical use.

CONCLUSIONS

The material for peening media and peening intensity has been optimized for the purpose of improving the fatigue strength of Ti-3Al-2V alloy. The conclusions obtained from this study are as follows:

- Surfaces shot-peened with stainless steel beads are relatively smooth and have no scratches or implantations of broken beads, while steel beads and glass beads induce these defects.
- The fatigue strength of specimens peened with stainless steel beads varies with the peening intensity. The maximum fatigue strength is obtained at the optimum Almen intensity of approximately 0.2 mmN.
- The fatigue strength correlates with the surface residual stress. The decrease in fatigue strength with the increase in peening intensity at a range above the optimum value is explainable on the decrease in the surface residual compressive stress.

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