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Mechanical Surface Treatments on the High-Strength Alpha-Titanium Alloy KS 120

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1 Abstract

The α titanium alloy KS 120 was specifically developed by Kobe Steel, Japan to possess a fine grained microstructure resulting in high yield stress - high tensile ductility combinations and excellent HCF performance. In the present investigation, shot peening and roller-burnishing were performed to determine to what extent the HCF life of KS 120 can be further improved by mechanical surface treatments. While both shot peening and roller-burnishing increased the fatigue life of KS 120 by roughly one order of magnitude, the 10^7 cycles fatigue strength of the electropolished reference was not improved.

2 Introduction

Titanium alloys which are well known for their aircraft, chemical and biomedical applications are now entering the market as potential candidates in automotive engineering due to its increasing demand for high-strength light-weight alloys in order to reduce vehicle weight and fuel consumption. Recent developments in titanium application in cars are suspension coil springs for the VW Lupo FSI made of TIMETAL LCB and the exhaust system for the Chevrolet Corvette Z06 made of commercially pure titanium. In both cases, the substitution of titanium alloys for steels resulted in substantial weight savings.

Previous work has shown that the fatigue life improvement caused by mechanical surface treatments in α titanium alloys is often more pronounced than that observed in (α+β)- or β alloys [1, 2].

The α titanium alloy KS 120 with the composition Ti-0.5Fe-0.6Si and 0.3 % oxygen is already used for adornments, casings of watches and as facing plates of buildings. Owing to its excellent forgeability, KS 120 may be used in future automotive application as forging material for tire rims and suspension parts.

The present investigation was undertaken to evaluate the effects of thermal and thermomechanical treatments on fatigue performance in KS 120 and to determine to what extent the HCF strength can be further improved by mechanical surface treatments such as shot peening and roller-burnishing.

3 Experimental

The material was delivered by Kobe Steel, Kyoto, Japan as rolled plate with a thickness of 25 mm. From this plate, blanks 50 × 40 × 25 mm were machined. These blanks were solution heat treated above the β transus temperature at 1050 °C for 0.5h followed by air-cooling (AC). The material was unidirectionally rolled (UR) either at 800 or 900 °C in 8 steps from 25 to 9 mm thickness ($\varphi = -1.0$)/AC with $\varphi = \ln h_0/h$ with h_0 = original thickness and h = final thickness. From the rolled material, blanks 9 × 9 × 45 mm were taken in rolling (RD) and in transverse direction (TD) and final heat treated at 700 °C for 2h.

From these blanks, tensile specimens were machined having a gage length and gage diameter of 20 and 4 mm, respectively. Tensile properties for both thermomechanical treatments are compared with the as-received condition in Table 1.

Table 1: Tensile test results of the various conditions of KS 120

Heat treatment	RD			TD		
	$\sigma_{0.2}$ [MPa]	UTS [MPa]	*El* [%]	$\sigma_{0.2}$ [MPa]	UTS [MPa]	*El* [%]
as-received	675	800	16.9	745	830	16.0
TMT1*	715	800	19.0	785	860	17.0
TMT2**	700	805	19.5	755	810	15.8

*0.5h 1050°C, UR 900 °C ($\varphi = -1.0$), 2h 700 °C
**0.5h 1050 °C, UR 800 °C ($\varphi = -1.0$), 2h 700 °C

Crystallographic textures were determined by X-ray diffraction and will be illustrated by (0002) pole figures.

Fatigue tests were performed only in TD. To study cyclic deformation behavior, stress controlled LCF tests were performed on threaded cylindrical (d_0 = 4 mm, l_0 = 20 mm) specimens in fully reversed ($R = -1$) axial loading using a servohydraulic testing machine. Tests were done at 0.1 Hz. Hysteresis loops were recorded by strain gage measurements. From these hysteresis loops, half of the plastic strain range at zero load ($\Delta\varepsilon_{pl}/2$) was taken and plotted versus number of cycles.

For HCF tests, hour-glass shaped specimens having a minimum gage diameter of 3.6 mm were machined. Part of these specimens was shot peened by means of an injector type machine using spherically conditioned cut wire (SCCW 14) having an average shot size of 0.36 mm. Almen intensities were widely varied to determine conditions for best fatigue life improvements.

Other specimens were roller-burnished using a one-roll hydraulic system operating in a conventional lathe. A hard metal ball with a diameter of 6 mm was used. The rolling force was varied in a wide range to determine best fatigue response.

The change in surface layer properties caused by these mechanical surface treatments was evaluated by surface roughness measurements and microhardness profiles. In addition, residual stresses were measured by the hole drilling method as described elsewhere [3].

The HCF-tests were performed in rotating beam loading ($R = -1$) at frequencies of about 60 Hz. An electrolytically polished condition was taken as reference to which the mechanically surface treated specimens were compared.

4 Results and Discussion

The as-received microstructure of KS 120 is shown in Figure 1 indicating highly deformed grains as a result of previous hot work.

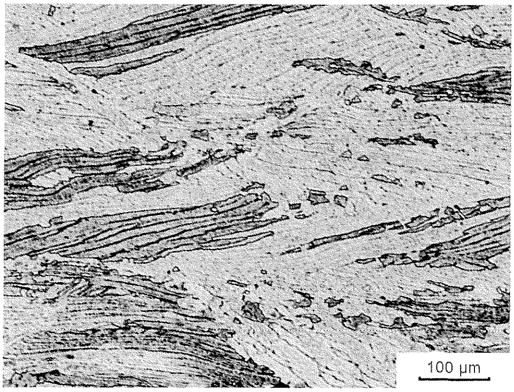
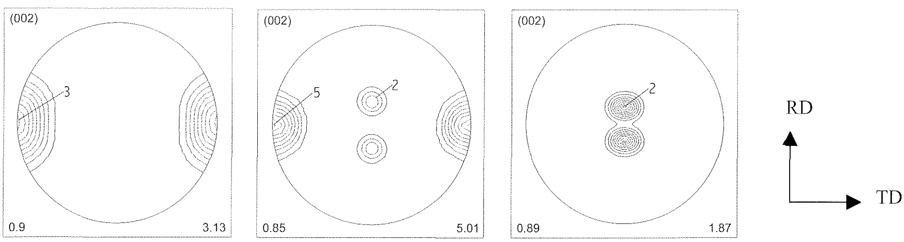


Figure 1: Microstructure of as-received KS120

Compared to this as-received condition, no significant changes in optical microstructure were found after both thermomechanical treatments TMT1 and TMT2. The (0002) pole figures are illustrated in Figure 2 comparing the as-received crystallographic texture (Fig. 2a) with those after unidirectional rolling (UR) at 900 °C (Fig. 2b) and at 800 °C (Fig. 2c).



a) as-received b) TMT1 c) TMT2

Figure 2: (0002) pole figures of KS 120

Figure 2a indicates a sharp T-type of texture in the as-received plate since most grains are oriented with the basal planes being aligned in rolling direction and perpendicular to the rolling plane. This explains why the yield stresses in TD are markedly higher than in RD (Table 1) because plastic deformation is difficult in c-direction of the hexagonal unit cell. After unidirectional rolling at 900 °C, this T-type of texture is slightly altered by additional basal pole components (B/T-type of texture) indicating that additional grains are mostly oriented with the basal planes aligned almost parallel to the rolling plane (Fig. 2b). With a decrease in rolling temperature from 900 to 800 °C, the T-pole disappears (Fig. 2c). By comparing the various pole figures in Figure 2, it can be argued that the as-received plate presumably had been unidirectionally rolled at temperatures significantly above 900 °C. Furthermore, reducing the rolling temperature to 750 or 700 °C may result in a fully symmetrical B-type of texture with mechanical properties being isotropic in the rolling plane [4].

The cyclic deformation behavior of KS 120 is shown as an example for the condition TMT1 in Figure 3. After a few cycles of cyclic hardening, marked cyclic softening was observed at both stress levels for most of the fatigue life.

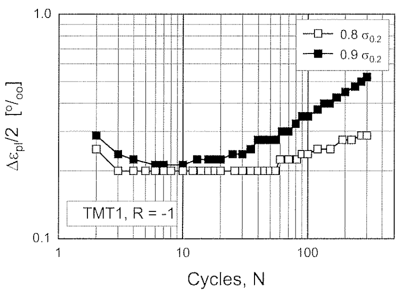


Figure 3: Cyclic deformation behavior ($R = -1$) of KS 120

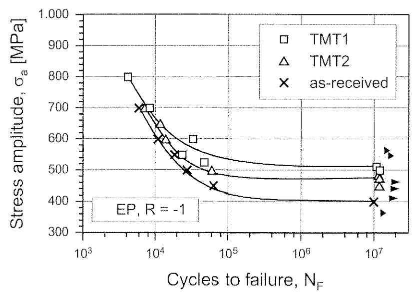
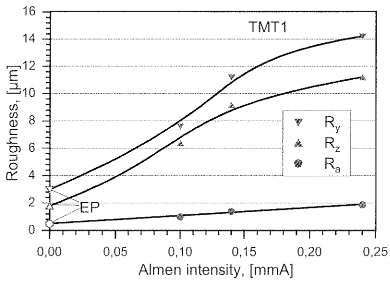


Figure 4: S-N curves of KS 120 (rotating beam loading in air)

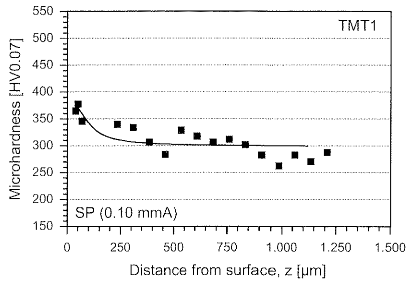
The S-N curves of KS 120 are illustrated in Figure 4 comparing results of TMT1 and TMT2 with the as-received condition. According to the observed differences in yield stress (Table 1), highest 10^7 cycles fatigue strength was observed on TMT1 (500 MPa) followed by TMT2 (480 MPa) and the as-received condition (400 MPa). Despite the cyclic softening behavior of KS 120, the fractions 10^7 cycles fatigue strength to yield stress $\sigma_{a10^7} / \sigma_{0.2}$ are fairly high amounting to 0.54 and 0.64 for the as-received and both TMT1 and TMT2 conditions, respectively. Further testing was performed on TMT1 only.

The changes in surface layer properties as caused by shot peening are shown in Figure 5. Starting with the electropolished reference (EP), surface roughness values clearly increase with an increase in Almen intensity (Fig. 5a). Owing to shot peening-induced plastic deformation, there is an increase in microhardness in near-surface regions from roughly 300 HV (bulk) to 370 HV close to the surface (Fig. 5b). The magnitude of the shot peening-induced residual compressive stresses and their penetration depth clearly increase with Almen intensity as illustrated in Figure 5c.

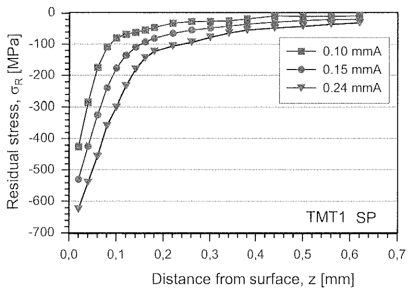
The effect of Almen intensity on fatigue life at a stress amplitude of σ_a = 600 MPa is shown in Figure 6. Highest lifetime improvements of roughly one order of magnitude were observed after peening with intermediate Almen intensities. From Figure 6, an Almen intensity of 0.10 mmA was taken as optimum. The S-N curve of this optimum shot peened condition is compared with the electropolished reference in Figure 7. While at intermediate and high stress amplitudes, the fatigue life is improved by shot peening by roughly one order of magnitude, no increase of the 10^7 cycles fatigue strength was observed (Fig. 7).



a) surface roughness



b) microhardness-depth profile



c) residual stress-depth profiles

Figure 5: Surface properties of KS 120 after shot peening

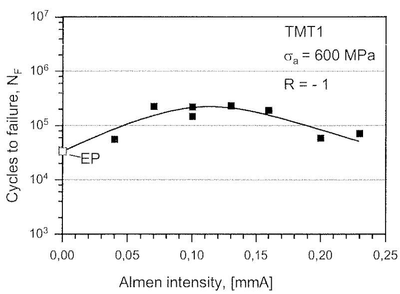


Figure 6: Fatigue life (σ_a = 600 MPa) vs. Almen intensity

Roller-burnishing which did hardly change the roughness of the electropolished reference led to similar increases in near-surface microhardness (Fig. 8) as those measured after shot peening (Fig. 5b). However, the penetration depth of plastic deformation is much greater. Interestingly enough, roller-burnishing was not superior to shot peening with regard to fatigue life (Fig. 9, compare Figure 9 with Figure 6).

Very similar to optimum shot peening, the S-N curve after optimum roller-burnishing (F = 500 N) gave an improvement in fatigue life by a factor of about 10 at high and intermediate stress amplitudes as compared to the electropolished reference (Fig. 10). Again, no increase of the 10^7 cycles fatigue strength was observed. This behavior is quite similar to results on meta-

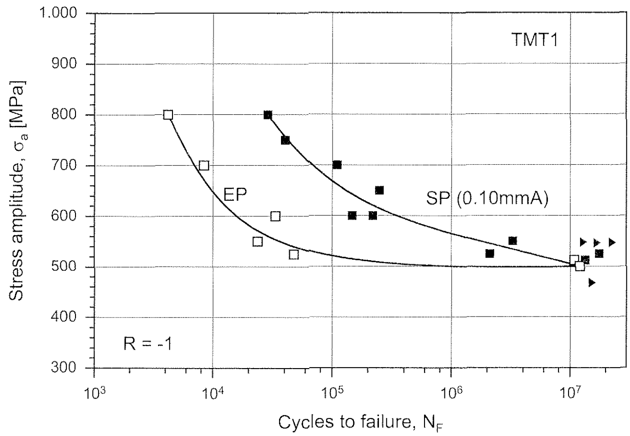


Figure 7: S-N curves of KS 120 after optimum shot peening (rotating beam loading in air)

stable β-titanium alloys such as Beta C and Ti-10V-2Fe-3Al which also exhibit cyclic softening behavior [5, 6].

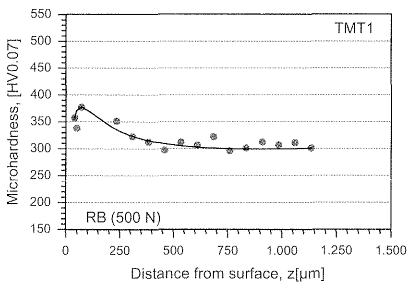


Figure 8: Microhardness-depth profile of KS 120 after roller-burnishing

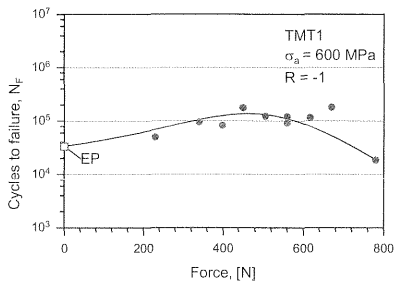


Figure 9: Fatigue life (σ_a = 600 MPa) vs. rolling force

Comparing the fracture surfaces of fatigue specimens (Fig. 11), it is seen that the fatigue crack nucleation site shifted from the surface for the electropolished condition (Fig. 11a) to subsurface regions for shot peened (Fig. 11b) as well as roller-burnished specimens (Fig. 11c). Therefore, surface roughness is not involved in the HCF failure of mechanically surface treated KS 120. In case of subsurface fatigue crack nucleation, both magnitude and cyclic stability of the residual tensile stresses balancing the outer compressive stress field, the mean stress sensitivity of the fatigue strength and the fatigue strength value in vacuum need to be taken into account.

More work is needed to understand why the 10^7 cycles fatigue strength of KS 120 is not improved by mechanical surface treatments.

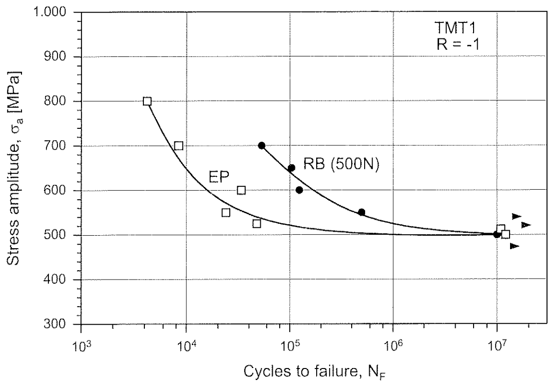
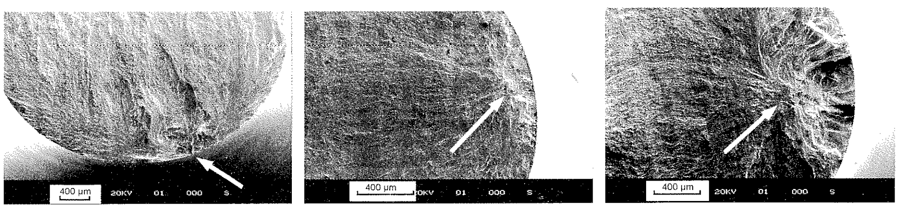


Figure 10: S-N curves of KS 120 after optimum roller-burnishing (rotating beam loading in air)



a) EP b) SP c) RB

Figure 11: Fracture surfaces of fatigue failed KS 120 specimens, TMT1 (arrow indicates crack nucleation site)

5 Acknowledgements

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6 References

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