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Shot Peening and Roller-Burnishing to Improve Fatigue Resistance of the ($\alpha+\beta$) Titanium Alloy Ti-6Al-4V

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1 Introduction

It has long been recognized that mechanical surface treatments such as shot peening or roller-burnishing can significantly increase the fatigue performance of structural components. Regarding the application of light-weight alloys, it is known that titanium and magnesium alloys as opposed to aluminum alloys can respond quite critically to a shot peening treatment. For example, a very marked over-peening effect was observed on the high-strength magnesium alloy AZ80 [1, 2], i.e., the fatigue life as a function of Almen intensity first dramatically increased compared to an electropolished reference followed by a drastic drop as the intensity increased. This sensitivity was attributed to the limited deformability by slip of the hexagonal magnesium crystal structure.

The response of titanium alloys to shot peening is reported to strongly depend on many factors, as alloy class (α, ($\alpha+\beta$) and metastable β) and its cyclic deformation behavior which in turn determines the cyclic stability of the process-induced residual compressive stresses. For example, metastable β alloys exhibited only slight improvements of the fatigue performance while α alloys responded much more beneficially. Further, previous work [3] has shown that the response of the ($\alpha+\beta$) titanium alloy Ti-6Al-7Nb to shot peening and roller-burnishing was clearly related to the mean stress sensitivity of the particular microstructure and crystallographic texture. Conditions with an anomalous mean stress sensitivity [4, 5] showed little improvement in fatigue performance as opposed to conditions with a normal mean stress sensitivity.

The present investigation was performed on the well known ($\alpha+\beta$) titanium alloy Ti-6Al-4V having a typical commercially available mill annealed microstructure. In order to establish optimum conditions with regard to fatigue performance, shot peening and roller-burnishing were performed using a wide variation in Almen intensity and rolling force, respectively. Additional polishing treatments were performed to reduce process-induced roughnesses and microcracks in order to find out if the fatigue behavior can be further improved.

2 Experimental

The ($\alpha+\beta$) titanium alloy Ti-6Al-4V was received as ∅10 mm rod hot rolled below the beta transus temperature. Prior to rolling, the ingot had been β-forged. The crystallographic texture was determined by X-ray diffraction and will be presented as (0002) pole figure. Tensile and fatigue specimens were machined in rolling (RD) direction. Tensile tests were performed on threaded cylindrical specimens with gage lengths and diameters of 20 mm and 4 mm, respectively. The initial strain rate was $8.3 \times 10^{-4}s^{-1}$. Tensile test results are listed in table 1.

Table 1: Tensile properties of Ti-6Al-4V

$\sigma_{0.2}$	UTS	*El*	RA
890 MPa	960 MPa	13 %	46 %

For fatigue testing, hourglass shaped specimens (3.8 mm gage diameter) were prepared. Specimens were turned (**T**) under well defined process conditions. The turning parameters are listed in table 2.

Table 2: Turning parameters of the final passes in the as-machined (**T**) condition

Tool bit	$TiN/Al_2O_3/TiCN$-CVD coated WC
Chisel radius	0.4 mm
Infeed	0.2 mm
Feed rate	0.15 mm/rev.
Spindle speed	2500 min^{-1}
Cooling fluid	oil-water mixture (1:10)

One part of these specimens was electrolytically polished (**EP**) to serve as further reference. Roughly 100 μm were removed from the surface to ensure that any machining effect that could mask the results was absent.

Others were shot peened (**SP**) by means of an injector type machine and a direct pressure blast system for low and high Almen intensities, respectively. Shot peening was performed using cast steel shot S 330 (0.8 mm average shot size). All peening was done to full coverage.

Another part of the turned specimens was roller-burnished (**RB**) using a one-roll hydraulic system with 6 mm hardmetal ball operating in a conventional lathe. Spindle speeds of 36 min^{-1} (**RB1**) and 780 min^{-1} (**RB2**) were used. Rolling forces were varied in a wide range.

In addition, mechanical polishing was performed on some shot peened (**SP+MP**) or roller-burnished specimens (**RB+MP**). This was done to reduce process-induced roughnesses and possible microcracks.

For the various surface treated conditions, roughnesses were determined by profilometry and residual stress-depth profiles by the incremental hole drilling method as described in [6].

To study cyclic deformation behavior, stress controlled LCF tests were performed on threaded cylindrical specimens with gage lengths and diameters of 10 mm and 5 mm, respectively. Tests were done in fully reversed ($R = -1$) loading using a servohydraulic testing machine at a frequency of 0.05 Hz. Hysteresis loops were recorded by strain gage measurements. From the hysteresis loops, half of the plastic strain range at zero load ($\Delta\varepsilon_{pl}/2$) was taken and plotted versus number of cycles.

HCF tests were performed on the various surface treated conditions in rotating beam loading ($R = -1$) at frequencies of about 60 Hz in ambient air.

3 Results and Discussion

The microstructure of the Ti-6Al-4V alloy is illustrated in figure 1. This mill annealed structure consists of fairly equiaxed α grains with an average size of about 10 μm and of roughly 20 % transformed β phase.

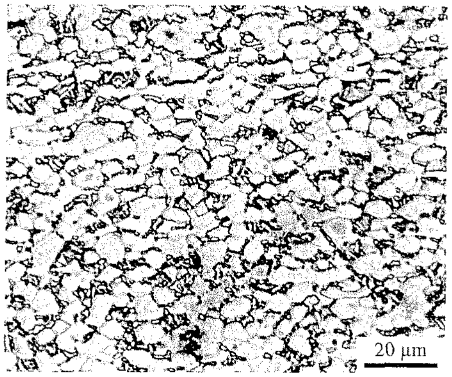


Figure 1: Microstructure of Ti-6Al-4V

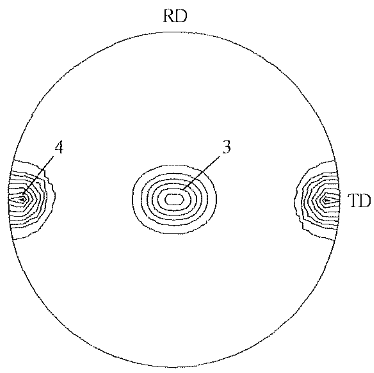


Figure 2: (0002) pole figure of Ti-6Al-4V

The (0002) pole figure of the Ti-6Al-4V alloy is illustrated in figure 2. The mixed basal/ transversal (B/T) type of texture is typical for unidirectional rolling in the (α+β) phase [7].

The cyclic deformation behavior is illustrated in figure 3. Marked cyclic softening was observed at the various stress levels for most of the fatigue life.

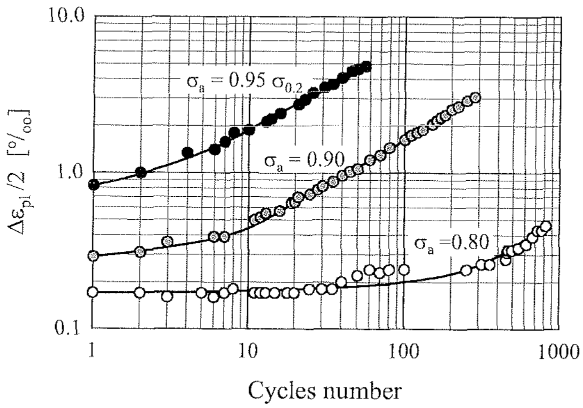


Figure 3: Cyclic deformation characteristics in Ti-6Al-4V (R = –1)

The surface roughness profiles of both the as-turned and electropolished references are shown in figure 4. Removing a surface layer of about 100 μm of the as-turned surface by electropolishing reduced the measured surface roughness from R_a = 1.7 to 0.2 μm and R_y = 9.4 to

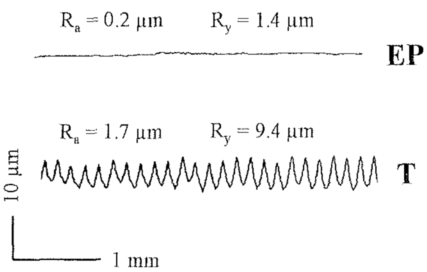


Figure 4: Roughness profiles of reference conditions T and EP

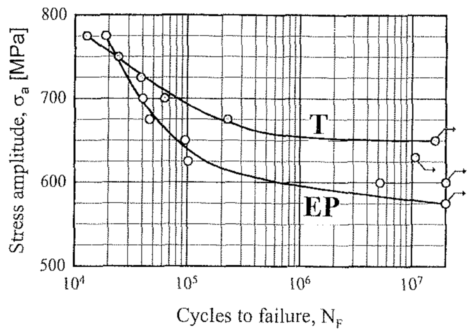


Figure 5: S-N curves in rotating beam loading of reference conditions T and EP

1.4 µm. From earlier investigations [8], it is known that this surface layer removal of 100 µm is sufficient to remove also the turning-induced high dislocation densities and residual stresses.

The S-N curves of these two reference conditions **T** and **EP** are illustrated in figure 5. Interestingly, the 10^7 cycles fatigue strength of condition **T** is roughly 80 MPa higher than that of condition **EP** indicating that the turning-induced high dislocation densities and residual stresses markedly overcompensate the detrimental influence of high surface roughness. Similar results were reported in earlier work on Ti-6Al-4V [9]. It is obvious that any assessment of possible improvements in fatigue performance caused by shot peening or roller-burnishing will highly depend on the reference condition taken for comparison.

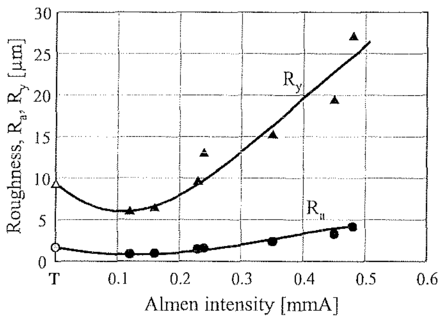


Figure 6: Surface roughness vs. Almen intensity (SP)

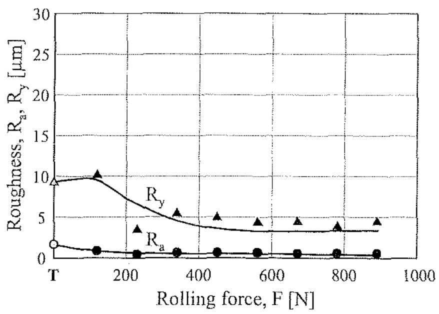


Figure 7: Surface roughness vs. rolling force (RB1)

The influence of shot peening and roller-burnishing on the resulting surface roughness values are plotted in figures 6 and 7. Starting with condition **T** (fig. 6), the surface roughness first decreases by shot peening **SP** if low Almen intensities up to 0.22 mmA were applied followed by an increase in roughness at higher Almen intensities. It should be noted that slight polishing after even heavy peening (**SP+MP**) again resulted in very low roughnesses. Since only about 20 µm were removed from the as-peened surfaces, residual stress and dislocation density profiles were hardly affected. Similarly to the effect of Almen intensity (fig. 6), roughness values after roller-burnishing (**RB**) first decrease with rolling force (fig. 7), but then level off at low values at rolling forces higher than about 300 N.

The effect of Almen intensity on the residual stress-depth profile is shown in figure 8. With an increase in Almen intensity from 0.12 to 0.48 mmA, the magnitude of the residual compressive stresses close to the surface and the penetration depth of the residual compressive stress field significantly increase.

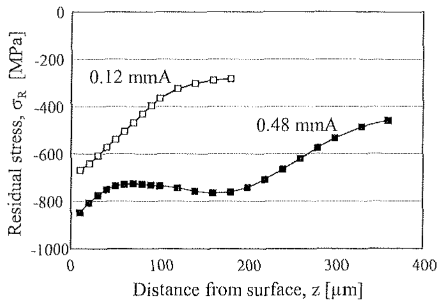


Figure 8: Residual stress-depth profiles after shot peening (SP)

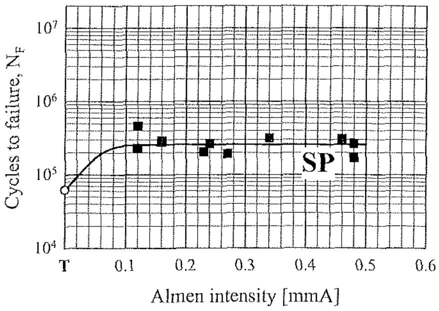


Figure 9: Fatigue life (σ_a = 700 MPa) of SP condition

The effects of Almen intensity and rolling force on the fatigue life at a constant stress amplitude of σ_a = 700 MPa are illustrated in figures 9 and 10, respectively. Starting with the as-turned reference (figure 9), the fatigue life owing to shot peening increases by less than one order of magnitude and then levels off at intensities as low as 0.12 mmA, i.e., no over-peening effect was found. Obviously, the pronounced increases in surface roughness at higher Almen intensities (fig. 6) are counterbalanced by opposing effects of dislocation densities and residual compressive stresses (fig. 8). If slight polishing is done after heavy shot peening (**SP+MP**), the fatigue life dramatically increases as shown in figure 10. This indicates the importance of surface roughness on fatigue performance after shot peening.

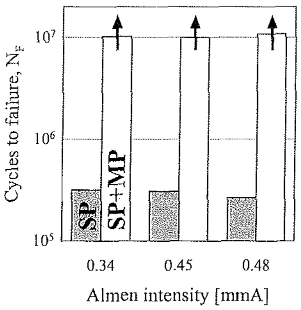


Figure 10: Fatigue life (σ_a = 700 MPa) of SP condition after mechanical polishing SP+MP

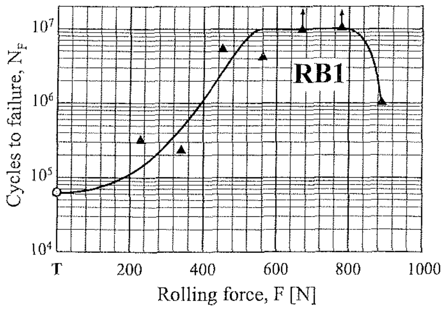
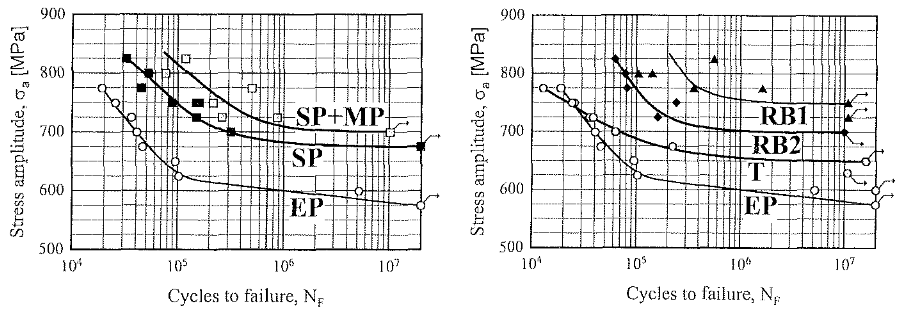


Figure 11: Fatigue life (σ_a = 700 MPa) of RB1 condition

Not surprisingly, the fatigue life (σ_a = 700 MPa) of roller-burnished specimens continuously increases with rolling force (fig. 10) since low roughnesses (fig. 7) are combined with increasing depths of high dislocation densities and residual compressive stresses (fig. 11). Similar polishing, as done on shot peened specimens did not improve fatigue life of roller-burnished specimens.

From Figures 9–11, the optimum process parameters for **SP** and **RB1** with regard to fatigue performance were taken and further testing was performed for establishing S-N curves. These results are summarized in figure 12. Effects of optimum surface treatments on improvement of 10^7 fatigue strengths are summarized in table 3.



a) Effect of **SP** (0.34mmA) and **SP+MP** a) Effect of **RB1** (670 N) and **RB2**

Figure 12: S-N curves in rotating beam loading of the various surface treated conditions in Ti-6Al-4V

Table 3: Improvements of 10^7 fatigue strengths after optimum surface treatments

Reference condition	SP	SP+MP	RB1	RB2
EP	≈ 15%	≈ 20%	≈ 30%	≈ 20%
T	≈ 5%	≈ 5%	≈ 15%	≈ 5%

Comparison of **RB1** and **RB2** conditions indicates that for Ti-6Al-4V, a lower deformation rate in roller burnishing (36 min^{-1} spindle speed) is superior to the higher deformation rate (780 min^{-1} spindle speed). No such effect of spindle speed was observed in parallel work on 42CrMo4 and 54SiCr6 [10]. More work is needed to understand why the response of Ti-6Al-4V to such a variation in deformation rate in roller-burnishing is different from that of steels.

4 References

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