Fatigue Performance of Shot Peened Cp-Ti: Effect of Prior Severe Plastic Deformation

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Abstract

Shot peening was done on commercially pure titanium (cp-Ti) and the changes in surface and surface layer properties such as surface roughness, micro-hardness and residual stresses were evaluated. Results were compared with material that had been severe plastically deformed by rotary swaging before applying shot peening. High cycle fatigue (HCF) performance of both material conditions was investigated in rotating beam loading. While shot peening alone resulted in the often documented marked improvement in fatigue strength, prior plastic deformation followed by shot peening led to pronounced losses in fatigue performance.

Introduction

Mechanical surface treatments such as shot peening, laser shock peening and ball-burnishing are well known to enhance the fatigue performance of light alloys based on aluminum, magnesium and titanium [1]. Generally, the improved performance is explained by the combined beneficial effects of surface strengthening due to the increase of near-surface yield stress that increase the resistance to crack nucleation and of residual compressive stresses that retard micro-crack growth [2]. Earlier work had shown that residual compressive stresses that were induced by shot peening can drastically reduce the growth rate of surface cracks [3], thus leading to increases in overall lifetime. Recently, severe plastic deformation processes such as equal channel angular pressing (ECAP) [4] or rotary swaging (SW) [4] have also shown marked potential of enhancing the fatigue strength. Since the increase in strength due to grain refinement and induced dislocation substructure are the main reason for the improved fatigue performance after ECAP or SW, it was interesting to find out if shot peening could lead to further improvements of the fatigue performance.

Experimental

Commercially pure (cp) titanium grade 1 was received as 32 mm diameter bar stock. Chemical composition of this material is listed in Table 1.

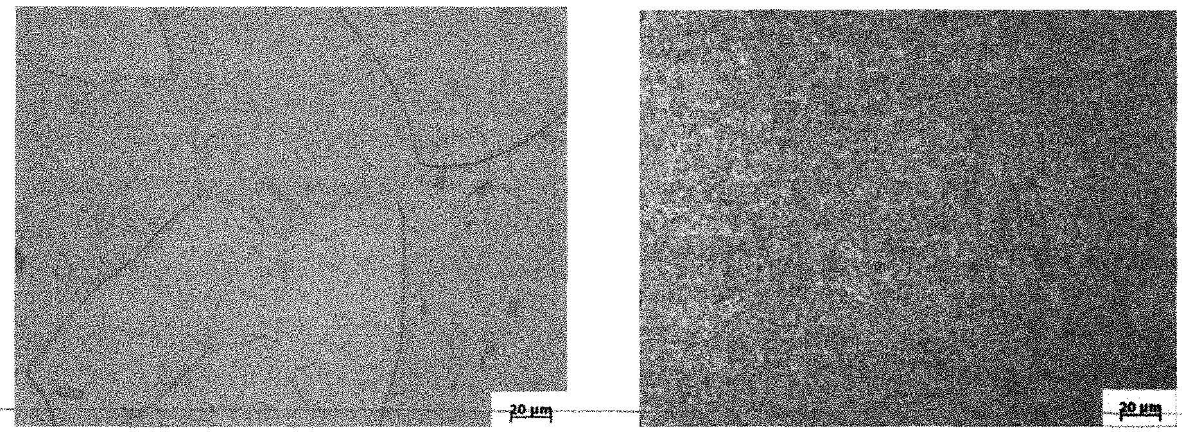
Table 1: Chemical composition of cp-Ti grade 1 (wt. %)

N	C	H	Fe	O	Ti
0.015	0.009	0.0018	0.04	0.0613	balance

Part of this bar stock was taken as reference condition (REF). Another part was rotary swaged at room temperature to various degrees of deformation up to $\varphi = \ln (A/A_o) = 3$ corresponding to a final diameter of 7 mm. This condition was denoted as severe plastically deformed (SPD). Shot peening (SP) was performed on hour-glass shaped specimens of both REF and SPD conditions. Peening was done using SCCW14 shot and an Almen intensity of 0.20 mmA at full coverage. X-ray measurements on (213) planes of the titanium were performed to evaluate the shot peening induced residual stresses (RS). Cu Kα radiation was used and the stresses were calculated by the $\sin^2\psi$ method [5]. A Young' modulus of E = 113 GPa and Poisson's ratio of $\nu = 0.32$ were used. In addition, the full width at half maximum (FWHM) of the interference lines was measured. In order to examine the depth profiles of RS and FWHM, X-ray measurements were taken after successive material removal from the surface by electrolytical polishing. HCF tests on shot peened specimens were performed in rotating beam loading ($R = -1$) at ambient temperature in lab air. Tests were done at frequencies of 50 Hertz on four point bending machines from Sincotec, Clausthal-Zellerfeld. Testing was interrupted in case of specimen failure or after 10^7 cycles. Results were compared to specimens with electrolytically polished surfaces. In addition, HCF tests were performed on shot peened specimens after removal of the high peening-induced roughness by electrolytical polishing (SP+EP).

Results and Discussion

The change in microstructure due to swaging at $\varphi = 3$ can be seen in Figure 1 by comparing condition REF (Fig. 1a) with condition SPD (Fig. 1b). As seen, SPD leads to a drastic decrease in grain size.



a) Ref b) SPD

Fig. 1: Microstructures of cp-Ti grade 1

Tensile properties of these conditions REF and SPD are illustrated in Table 2. Yield stress (YS) and ultimate tensile strength (UTS) are much increased after SPD. As expected, the uniform strain (e_U) of condition SPD is very low indicating exhausted work hardening capability. On the other hand, the tensile ductility (ε_F) is still rather high, this result probably, being caused by the very fine grain size [6].

Table 2: Tensile properties of conditions REF and SPD

Condition	YS (MPa)	UTS (MPa)	e_U (%)	ε_F
REF	240	350	20	1.1
SPD	940	970	0.3	0.5

After shot peening, FWHM values are plotted for conditions REF and SPD in Figure 2.

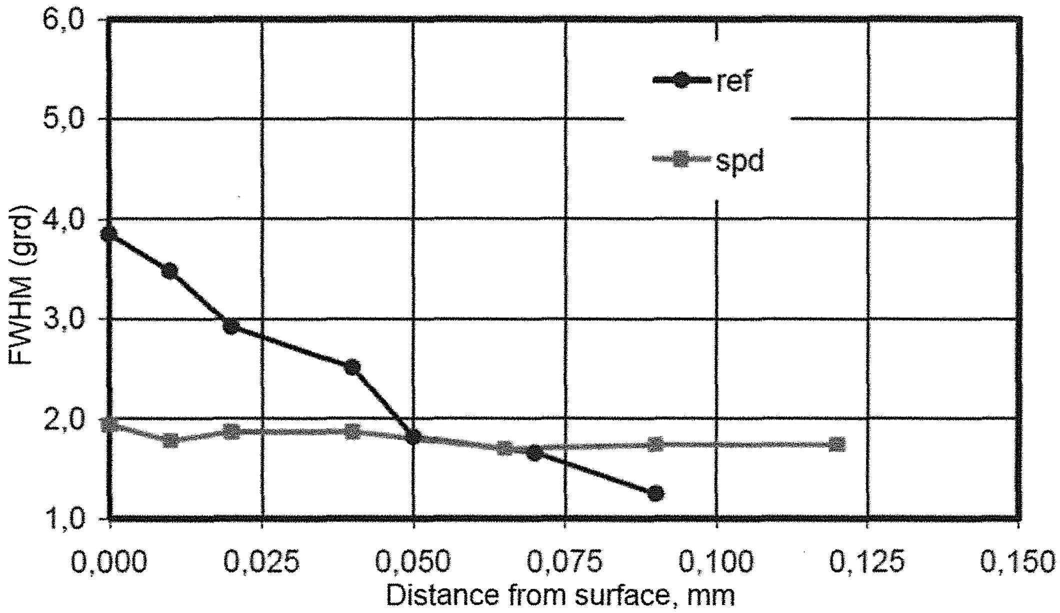


Fig. 2: FWHM values vs. distance to surface after shot peening

The FWHM values of shot peened condition REF show the typical increase in near surface regions due to the increase in dislocaion density with a gradual decrease in greater depths. On the contrary, the FWHM values of condition SPD are hardly affected by the shot peening treatment. Presumably, this result is caused by the low work hardening capability of this condition (Table 2).

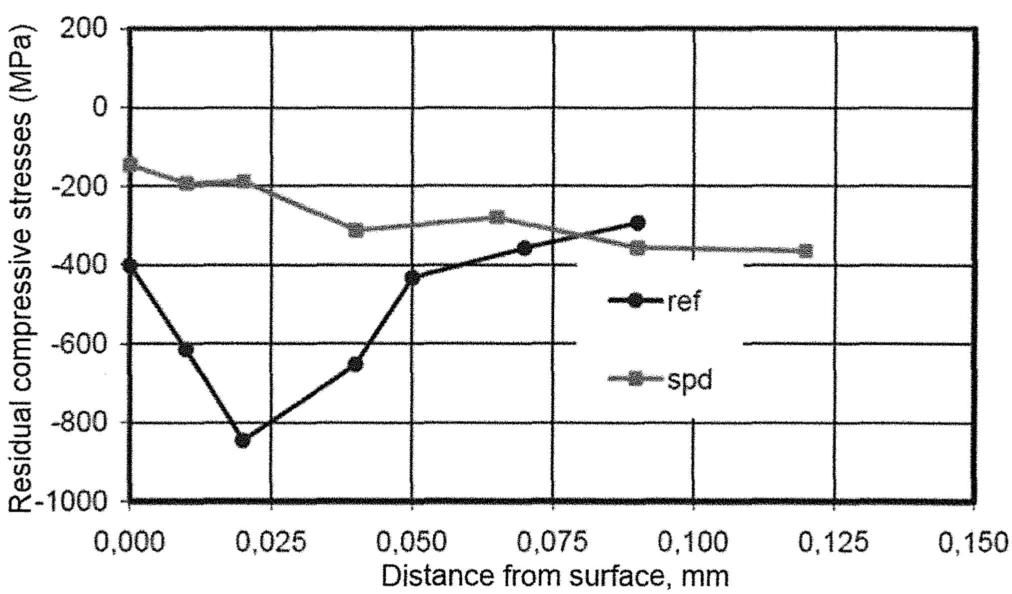


Figure 3: Shot peening induced residual stress (RS) values vs. distance to surface

The condition REF shows a typical residual stress-depth profile after shot peening with high residual compressive stresses and a marked maximum of these stresses below the surface. On the contrary, only low residual compressive stresses were measured in condition SPD. This result is clearly related to the low work hardening capability of this condition.

The HCF performance of electrolytically polished specimens of conditions REF and SPD are illustrated in Figure 4.

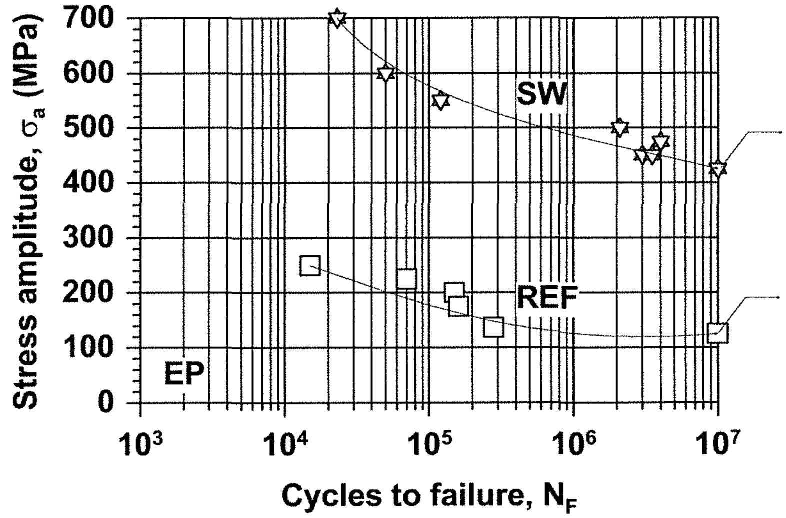


Fig. 4: S-N curves in rotating beam loading (R = -1) of cp-Ti grade 1

The SPD condition has HCF performance much superior to that of condition REF (Fig. 4). The HCF strength amounts to about 420 MPa as opposed to 125 MPa of the condition REF. This is clearly related to the marked increase in YS from 240 to 940 MPa (Table 2). Shot peening of condition REF results in a marked increase of the fatigue strength from 125 MPa to 250 MPa (Fig. 5).

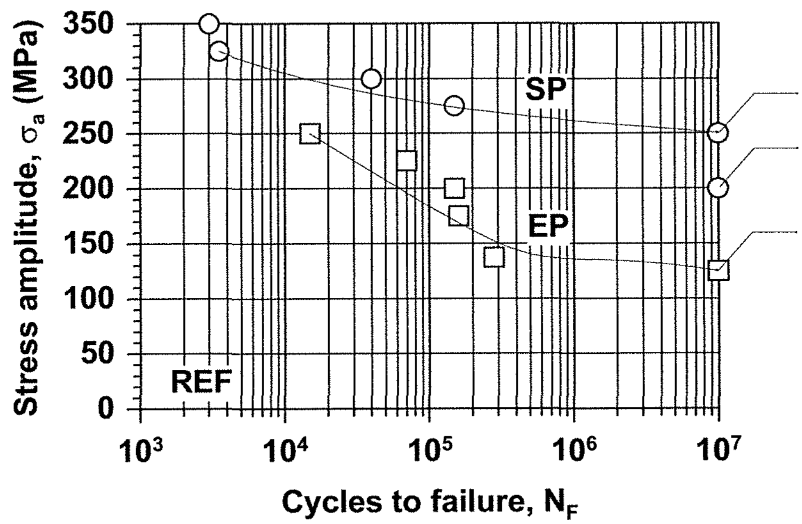


Fig. 5: S-N curves in rotating beam loading (R = -1) of cp-Ti grade 1 in reference condition

On the contrary, shot peening of condition SPD results in a pronounced loss of the fatigue strength from 450 MPa to 300 MPa (Fig. 6).

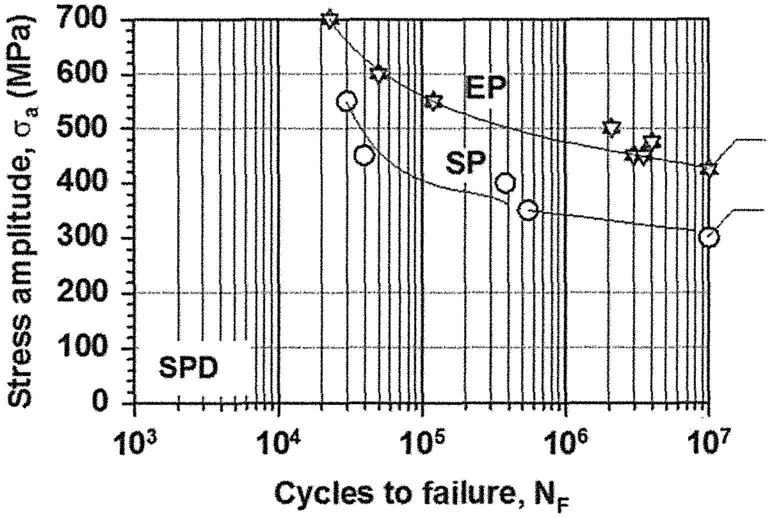


Fig. 6: S-N curves in rotating beam loading (R = -1) of cp-Ti grade 1 in condition SPD

In order to evaluate if the shot peening induced roughness was the reason for this drop in fatigue performance, shot peened specimens were slightly electrolytically polished to remove the roughness. The change in fatigue performance is illustrated in Fig. 7. Due to the removal of the roughness, the fatigue strength increased from 300 to 450 MPa.

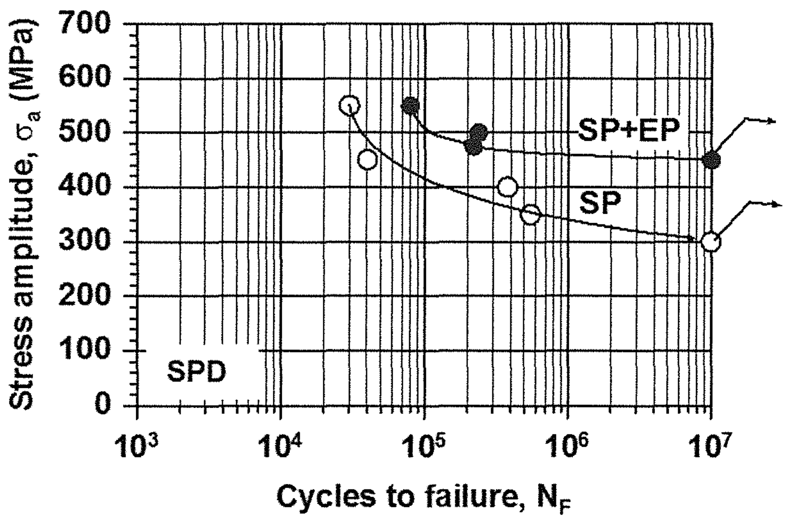


Fig. 7: S-N curves in rotating beam loading (R = -1) of shot peened condition SPD: Effect of surface removal

Conclusions

Rotary swaging (φ = 3) leads to YS, UTS and HCF strength values of condition SPD markedly higher than those of the coarse grained reference condition. This is explained mainly by the swaging induced high dislocation densities and the generation of very fine grain sizes. Shot peening of the reference condition of cp-Ti grade 1 strongly improves the HCF strength whereas the fatigue strength of condition SPD markedly decreases. The latter is explained by the very low work hardening capability and resulting absence of high residual compressive stresses. Thus, the shot peening induced surface roughness is the reason for the drop in fatigue strength. However, if the roughness is removed, the fatigue strength increases again to the value of the non-peened condition.

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