RESIDUAL STRESS-INDUCED SUBSURFACE FATIGUE CRACK NUCLEATION IN SHOT PEENED TITANIUM ALLOYS

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ABSTRACT

High-cycle fatigue performance of shot peened titanium alloys is associated with subsurface fatigue crack nucleation. This phenomenon may be related to the presence of process-induced residual tensile stresses necessarily present below the mechanically treated surface and required to balance the outer compressive stress field. Although an analysis of these deeply located residual tensile stresses is quite difficult, there is evidence to what extent the HCF strength of the various titanium alloy classes can be affected by residual tensile stresses. Most important are tensile mean stress and environmental sensitivities of the materials HCF strengths. Anomalous mean stress sensitivities as observed in (α+β) titanium alloys as well as low environmental sensitivities as found in metastable β-alloys can result in drastic losses in HCF performance relative to residual stress-free electropolished references. On the other hand, both normal mean stress sensitivity as well as high environmental sensitivity as typically observed in α-titanium alloys can lead to marked enhancements in HCF performance. Applied stress gradients as present in bending tend to improve the HCF performance by reducing the critical stress level at the subsurface fatigue crack nucleation sites.

KEY WORDS

Subsurface fatigue cracks, residual tensile stresses, mean stress sensitivity, environmental sensitivity

INTRODUCTION

The beneficial influence of shot peening on the fatigue performance is often explained by two main contributions, namely surface strengthening by the process-induced high dislocation densities and residual compressive stresses. Generally, the total fatigue life (N_F) of a component can be divided into a crack-free initial stage, i.e., the number of cycles to fatigue crack nucleation (N_I) and the number of cycles for propagating fatigue cracks (N_P) until final fracture: $N_F = N_N + N_P$. Table 1 summarizes the individual effects of the surface layer properties on fatigue life.

Table 1: Effects of surface layer properties on the various stages on fatigue life (schematic)

Surface layer property	Fatigue crack nucleation	Fatigue micro-crack Propagation
Surface roughness	Accelerates	No effect
Cold work	Retards	Accelerates
Residual compressive stresses	Minor effect	Retards

Although, residual compressive stresses must necessarily be balanced by residual tensile stresses as schematically illustrated in Figure 1, their existence is hardly taken into account in the literature.

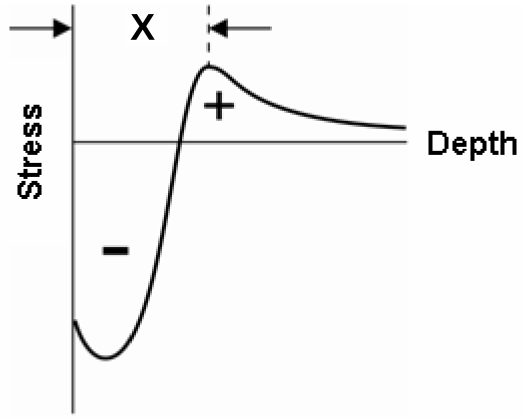


Fig. 1: Residual stress-depth profile (schematic) illustrating location of fatigue crack nucleation (X)

The present investigation is intended to highlight the importance of residual tensile stresses in understanding the HCF performance of shot peened titanium alloys.

EXPERIMENTAL PROCEDURE

The investigation was performed on a number of titanium alloys belonging to the various alloy classes. Tensile properties of these materials are listed in Table 2.

Table 2: Tensile properties of the various titanium alloys

	$\sigma_{0.2}$ (MPa)	UTS (MPa)	EL (%)
Ti-8.6Al	830	890	5
Ti-6Al-4V, FE	1175	1225	13
Ti-6Al-7Nb, D/AC	920	995	14
Ti-6Al-7Nb, D/WQ	1030	1120	15
LCB, 8h 540°C	1180	1210	13
LCB, PS + 0.5h 500°C	1665	1730	3

Shot peening was performed using steel shot S230 (Ø6 mm), S330 (Ø8 mm) and SCCW14 (Ø0.36 mm). In addition, a very hard shot (Ø6 mm, 800 HV0.1) was used for shot peening the alloy LCB. All peening was done to full coverage at various Almen intensities. For comparison, a few LCB specimens were ball-burnished using a conventional lathe and a hydrostatic tool by which a hardmetal ball (Ø3 mm) is pressed onto the rotating specimen surface.

Fatigue tests on hour-glass shaped specimens having a minimum gage diameter of 4 mm were performed in axial loading (R = -1 and R = 0.1) in vacuum and aqueous 3.5 % NaCl solution. Other fatigue tests were done in rotating beam loading (R = -1) in laboratory air. In addition to shot peened (SP) and ball-burnished (BB) conditions, electrolytically polished (EP) specimens were prepared to serve as reference. Roughly 100 μm were removed from the as-machined surfaces to ensure that any maching effect that could mask the results was absent.

Fatigue fracture surfaces were studied by SEM.

RESULTS AND DISCUSSION

The S-N curves in fully reversed loading of the experimental α-titanium alloy Ti-8.6Al are illustrated in Fig. 1 comparing results on condition EP between laboratory air and vacuum. The HCF strength in vacuum is by far higher than in air, this presumably being related to detrimental hydrogen effects on the hcp α-phase. The effect of shot peening on the HCF performance in rotating beam loading is shown in Figure 2. Shot peening increases the HCF strength in this α-titanium alloy Ti-8.6Al by as much as 200 MPa.

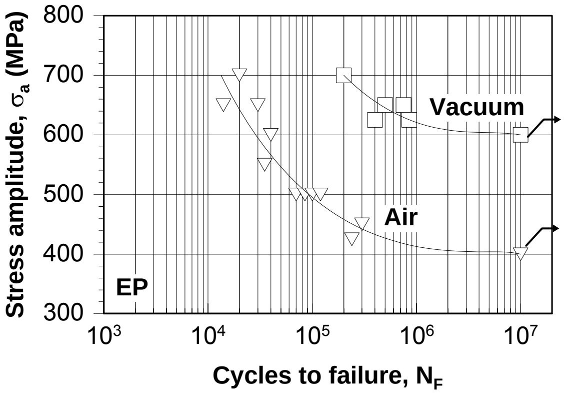


Fig. 1: S-N curves of Ti-8.6Al in axial loading (R = -1)

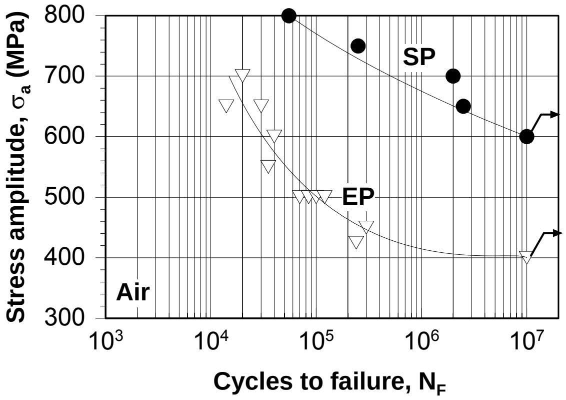


Fig. 2: S-N curves of Ti-8.6Al in rotating beam loading in air

This drastic enhancement of the HCF strength by shot peening is mainly related to the shift in fatigue crack nucleation site from the surface (EP) to subsurface regions (SP), i.e., from the air to a quasi-vacuum environment (Fig. 3).

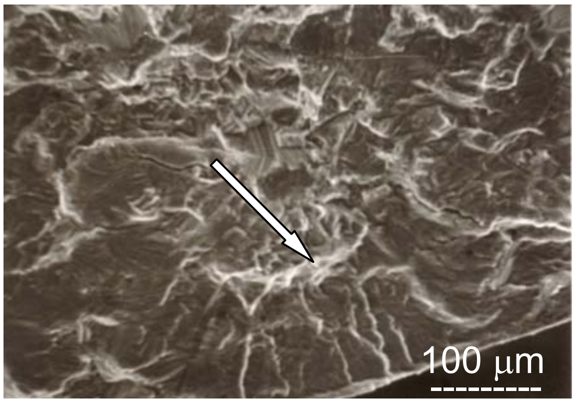
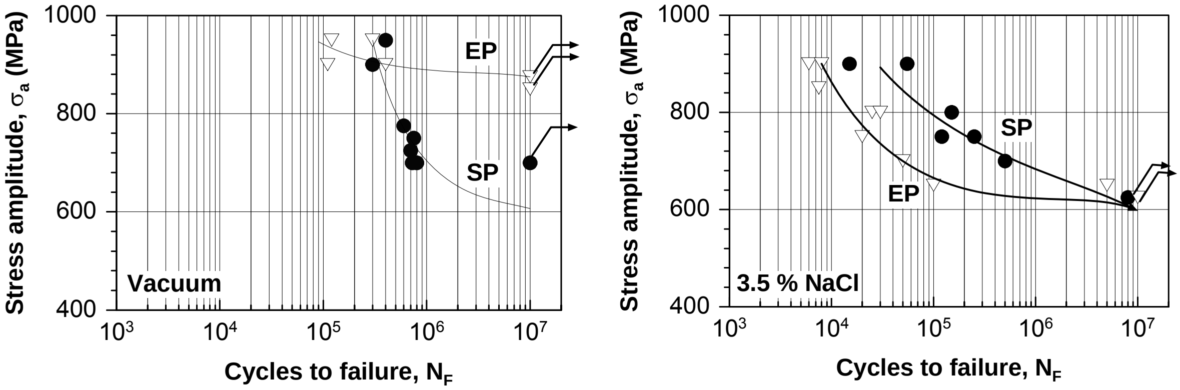


Fig. 3: Subsurface fatigue crack nucleation in shot peened specimen

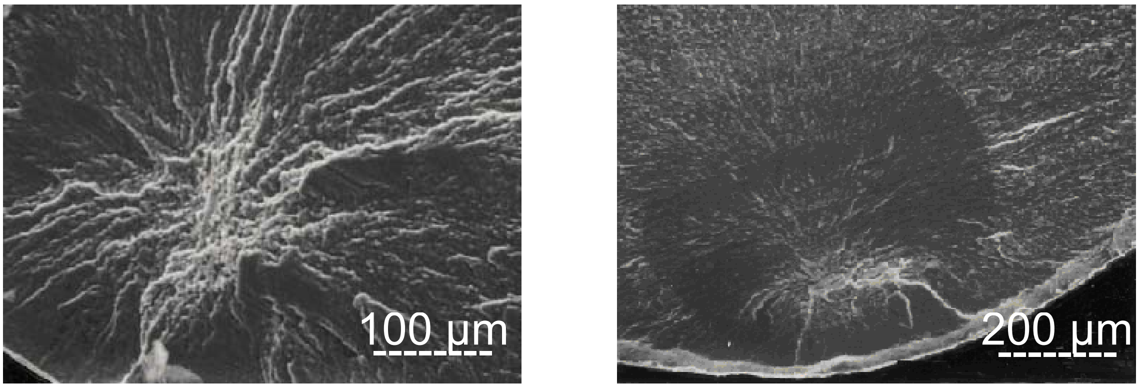
The effects of shot peening and test environment on the fatigue performance of the two-phase (α+β)-alloy Ti-6Al-4V in axial loading (R = -1) are illustrated in Figure 4.
Under vacuum conditions, the high cycle fatigue performance of Ti-6Al-4V following mechanical surface treatment is found to be inferior to that observed following electropolishing (Fig. 4a). Increasing the aggressiveness of the fatigue environment from vacuum to 3.5 % aqueous NaCl does not substantially alter the HCF behavior of shot peened Ti-6Al-4V (Fig. 4b). However, the condition EP is highly affected showing a loss in HCF strength from 875 MPa (Fig. 4a) to 625 MPa (Fig. 4b).
As illustrated in Figure 5, HCF cracks in shot peened specimens nucleated subsurface irrespective of the fatigue test environment, this being varied between vacuum (Fig. 5a) and aqueous 3.5% NaCl (Fig. 5b). In the latter, the area of early crack growth in quasi-vacuum can be clearly differentiated from subsequent crack



a) Vacuum b) 3.5% NaCl

Fig. 4: S-N curves in axial loading (R = -1) of Ti-6Al-4V

propagation in the aggressive environment, this taking place once the crack front has reached the specimen surface. As opposed, fatigue cracks in condition EP always nucleated at the surface, this explaining the very marked effect of the environment on HCF performance of this condition (Fig. 4).



a) Vacuum b) Air

Fig. 5: Subsurface fatigue crack nucleation

Since the depth of fatigue crack nucleation was not statistically distributed over the cross-section of the fracture surfaces but instead directly related to the Almen intensities applied (Fig. 6) the assumption of a residual tensile peak stress below the near-surface compressive stress field as schematically illustrated in Figure 1 is quite reasonably. Rotating beam fatigue test results in laboratory air on shot peened Ti-6Al-7Nb are illustrated in Fig. 7. Depending on the rate of cooling from the duplex anneal, the HCF performance can be drastically improved by shot peening (WQ, Fig. 7a) or hardly affected (AC, Fig. 7b). Very similar results are also reported on Ti-6Al-4V (J. Müller et al. 2007). Fatigue crack nucleation in shot peened HCF specimens of both Duplex/WQ and Duplex/AC of Ti-6Al-7Nb tested in laboratory air in rotating beam loading was again subsurface, i.e., in a quasi-vacuum environment similar as observed in axial loading (compare Fig. 8 with Fig. 5b).
In order to determine if the observed marked differences in HCF performance of shot peened specimens between Duplex/WQ (Fig. 7a) und Duplex/AC (Fig. 7b) are caused by different sensitivities to residual tensile stresses (J. Lindemann et al. 1997), fatigue tests were performed on electropolished specimens at tensile mean stresses (R = 0.1). Comparing now the HCF performance of both conditions between R = 0.1 and R = -1 (Fig. 9) it is evident that Duplex/WQ and Duplex/AC exhibit low and high tensile mean stress sensitivities, respectively.

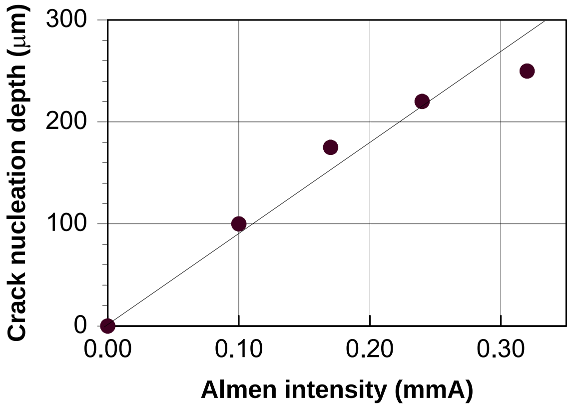
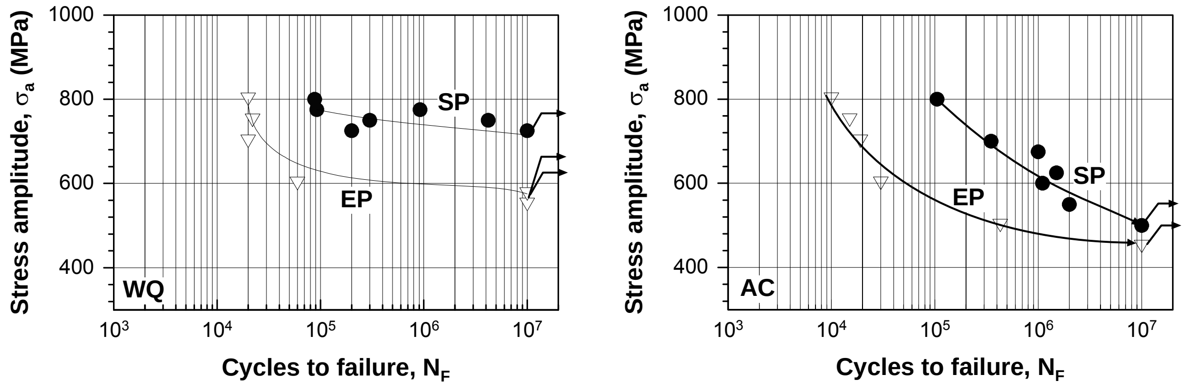


Fig. 6: Depth of fatigue crack nucleation site vs. Almen intensity



a) Duplex/WQ

b) Duplex/AC

Fig. 7: S-N curves of Ti-6Al-7Nb in rotating beam loading (R = -1) in air

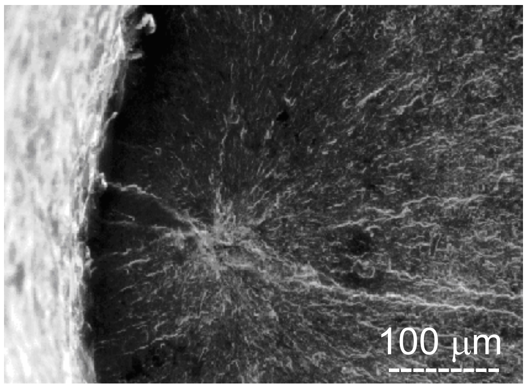


Fig. 8: Subsurface fatigue crack nucleation in rotating beam loading of Ti-6Al-7Nb

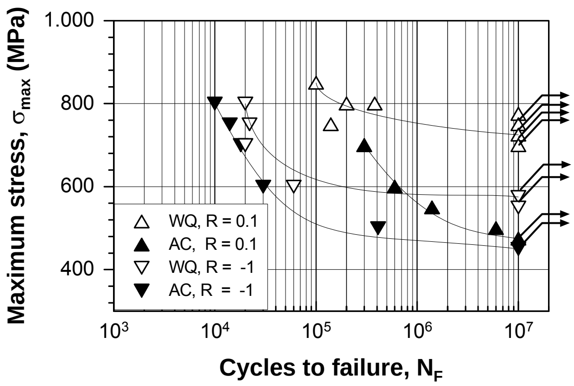


Fig. 9: S-N curves of Ti-6Al-7Nb at R = 0.1 and R = -1 in air

Accordingly, the HCF performance of shot peened specimens tested at R = -1 (Fig. 7) exhibits the same tendency as the fatigue performance of the electropolished reference at R = 0.1 (Fig. 5).

In addition to the mean stress sensitivity, the environmental sensitivity of the fatigue strengths as already discussed above needs to be considered when comparing fatigue performance of electropolished and shot peened specimens tested in air. There are only a limited number of HCF tests performed on metastable β-titanium alloys in vacuum. These have shown no significant life improvements compared to tests in laboratory air, this result indicating the absence of detrimental hydrogen effects on the bcc β-phase (M. Kocan et al. 2005). Thus, the occurrence of subsurface HCF cracks in shot peened specimens tested in laboratory air will not improve the HCF strength over the electropolished reference *per se*. Instead, fatigue tests on the metastable β-titanium alloy TIMETAL LCB illustrate that shot peening or ball-burnishing can even dramatically decrease the HCF strength relative to an electropolished reference (T. Ludian et al. 2006) although subsurface fatigue crack nucleation was always observed (Fig. 10).

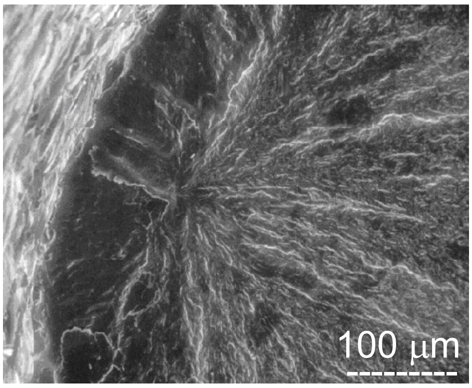


Fig. 10: Subsurface fatigue crack nucleation in rotating beam loading of TIMETAL LCB

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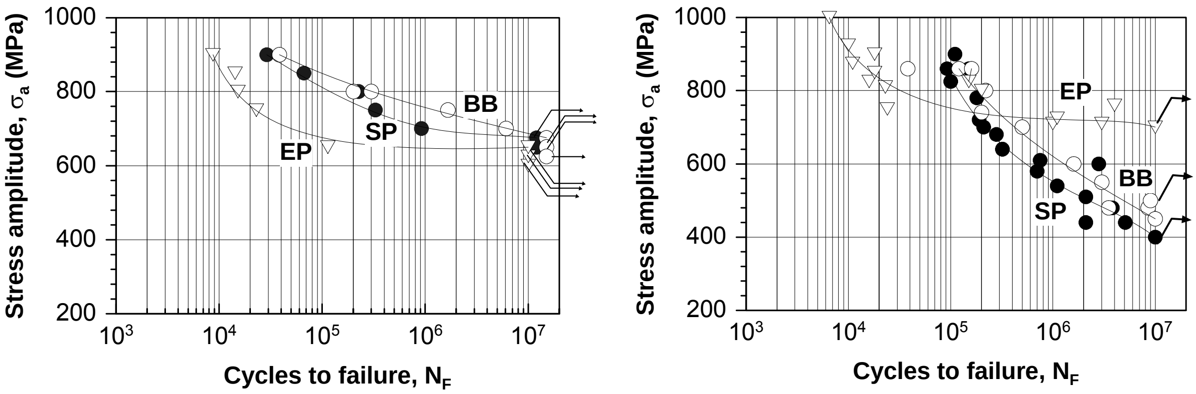
To what extent the HCF strength in TIMETAL LCB after mechanical surface treatments decreases depends on the mean stress sensitivity of the tested material. Since this mean stress sensitivity typically increases as the materials strength is enhanced, higher strength conditions can exhibit higher losses in fatigue strength caused by shot peening (Fig. 11).



a) low strength ($\sigma_{0.2}$ = 1180 MPa)

b) high strength ($\sigma_{0.2}$ = 1665 MPa)

Fig. 11: S-N curves of TIMETAL LCB in rotating beam loading (R = -1) in air

SUMMARY

Subsurface fatigue crack nucleation is a common feature in shot peened HCF specimens of titanium alloys and may result from residual tensile stresses being necessarily present below the residual compressive stress field. For understanding the change in HCF performance in air relative to an electropolished reference, mean stress as well as environmental sensitivities need to be taken into account.

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