

INFLUENCE OF SHOT PEENING ON THE FATIGUE BEHAVIOUR OF Ti-6Al-4V IN RESPECT OF MULTIAXIAL LOADING

B. Oberwinkler, H. Leitner, M. Stoschka

University of Leoben, Franz-Josef-Straße 18, A-8700 Leoben, Austria

ABSTRACT

Although shot peening treatment is commonly used in engineering practise for their beneficial effect on fatigue life, only few quantitative data is available from literature in respect of multiaxial loading. This contribution presents results of a long-term research program that aims for developing quantitative design guidelines for the influences of mechanical surface treatments on the fatigue life of structural components.

Rotating bending, alternating torsion and multiaxial fatigue tests were performed on the titanium alloy Ti-6Al-4V. The heat treated and machined specimens were subjected to a shot peening process according to the MIL-S-13465C and MIL-P-81985 standards. It can be observed that shot peening leads under uniaxial loading to an increase of the fatigue strength both in the finite life and lower loaded high cycle fatigue region. Under multiaxial loading the S/N-curve is not affected by shot peening, neither in the low cycle fatigue regime nor in the high cycle fatigue region. For an assessment of the fatigue failure mechanism, investigations of the surface layer were performed.

KEY WORDS

High Cycle Fatigue, Titanium Alloys, Shot Peening, Multiaxial Loading;

INTRODUCTION

The most common titanium alloy, Ti-6Al-4V, is currently one of the most important materials in aerospace. The reasons are manifold e.g. low density, high strength, corrosion resistance and excellent fatigue behaviour. The fatigue behaviour is affected by a multitude of parameters like microstructure, surface treatment, residual stress state, roughness, type of load and geometry, resulting in an enormous variation of the fatigue limit (300...800 MPa).

Surface treatments like shot peening act in the surface layer by inducing compressive residual stresses and strain hardening. The aim of such treatments is the increase of the fatigue strength of the material, where the local load stress gradient plays a major role. Another influencing variable on the fatigue behaviour of Ti-6Al-4V is the microstructure – either lamellar, equiaxed, or bimodal. Depending on the microstructure the S/N-curve varies in a wide range. However, independently from the microstructure, shot peening with appropriately chosen process parameters leads to an improvement in the fatigue behaviour. Shot peened components are often loaded under multiaxial conditions by a combination of normal and torsional stress, whereas the fatigue tests are carried out under uniaxial loading, especially under rotating bending or tension/compression loading. By no means, it can be taken as granted that the determined benefits of shot peening under uniaxial loading are also valid under multiaxial loading. So, the objective of this paper is to assess and compare the effects of shot peening on the fatigue behaviour of Ti-6Al-4V under rotating bending, torsional and multiaxial loading.

Shot Peening of Ti-6Al-4V

The fatigue behaviour of Ti-6Al-4V is well investigated. However, the published results have only a very narrow range of validity with respect to microstructure and heat treatment, owing to the strong influence of the microstructural parameters on the resulting fatigue behaviour. This becomes particularly obvious if one studies the inconsistencies in the results communicated in the literature regarding the effects of surface treatments on the fatigue behaviour of Ti-6Al-4V.

Gray et al. (H. Gray, 1989) tested unnotched rotating bending specimens peened with an intensity of 0.28 A(mm), exhibiting an increase of the fatigue limit at 10^7 load cycles by 23% over unpeened specimens. Wagner et al. (L. Wagner, 1981) as well as H.E. Franz & A. Obricht (H.E. Franz, 1987) obtained improvements of the fatigue limit at 10^7 load cycles in the range of 15%. H. Wohlfahrt (H. Wohlfahrt, 1981) reported a decrease of the fatigue limit in combination with an increase of the slope of the S/N-curve at 0.25 A(mm) peening intensity. However, with additional glass bead shot peening the fatigue limit was increased by 25% compared to milled specimens. In many of the references found, detailed information about the microstructure and the surface layer is missing or at least incomplete.

In summary it may be stated that the literature shows a considerable fatigue strength optimization potential due to shot peening up to 25% unless the shot peening intensity is too high. Shot peening with inappropriate parameters may easily result in a decrease of the fatigue strength. Results describing the effect of shot peening on torsional and multiaxial fatigue are extremely rare, as well as experiments in the very high cycle fatigue (VHCF) regime. The majority of the documented experiments were performed up to a maximum cycle count of 10^7 . Taking this information as a starting point, a systematic investigation of the effects of shot peening on the fatigue behaviour of Ti-6Al-4V was initiated; the results are reported in what follows.

METHODS

The material used for this study was forged from ingots with a diameter of 350 mm to bars with a diameter of 110 mm. These bars were machined and hot rolled to bars with a diameter of 20 mm. Finally, the bars were annealed, 1 hour at 830°C and air cooled, stretched and machined to bars with a diameter of 18 mm.

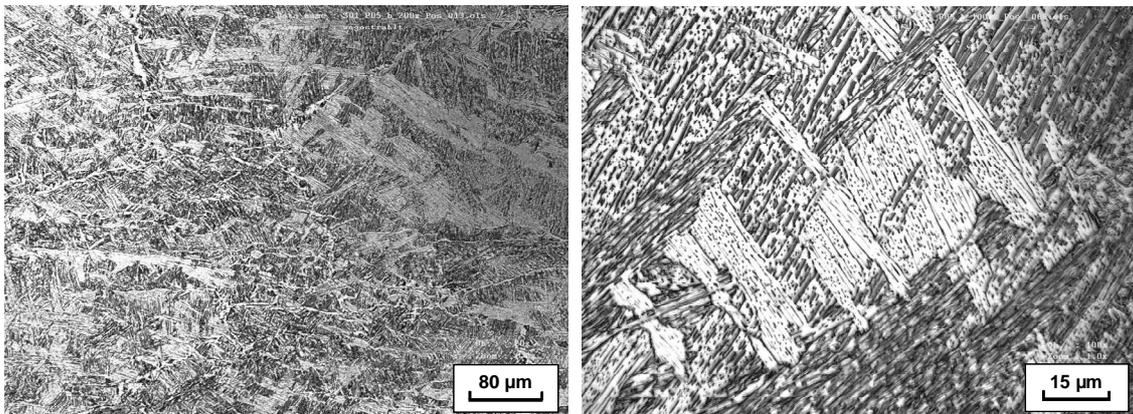


Figure 1: Micrographs of the lamellar microstructure

The microstructure of the bars is very inhomogeneous and fine lamellar (cf. Fig. 1). A second structure in the material, caused by the large primary beta grain boundaries can be found. At these grain boundaries an alpha seam was determined. The primary beta structure shows furthermore a texture due to the forming.

The 0.2 percent yield and ultimate tensile strength in the longitudinal direction were determined to be 885 MPa and 938 MPa respectively.

Specimens were excised of the bars and precision turned. Unnotched hourglass probes were used for all applied loadings. The shot peening process was carried out with an intensity of 0.16 A(mm) and a coverage of 200 %, using a STD-G3-0.35-HV640 shot according to the military specifications MIL-S-13165C and MIL-P-81985.

The fatigue tests were performed at different types of test stands. The rotating bending experiments were carried out on a rotating bending test bench. The tests under torsional loading and multiaxial loading were conducted on a purpose-designed test rig. Testing was performed at room temperature in lab air at 63 Hz (rotating bending) or 30 Hz (torsion and multiaxial loading) with a sinusoidal waveform and a stress ratio $R = -1$. For the multiaxial loading, consisting of rotating bending and torsional loading, a shear stress to normal stress ratio of 0.5 was chosen.

RESULTS

Characterization of the Surface Layer

Crack initiation takes place typically at the surface or close to the surface, respectively. For a deeper understanding of the shot peening mechanism, the surface layer was analyzed extensively. For evaluating the state of a surface layer, four characteristic values exist: residual stresses, roughness, hardness and microstructure.

Fig. 2 (left, middle) shows three-dimensional images of a machined as well as a shot peened surface. The surface roughness increases significantly due to shot peening, cf. Fig. 2, where R_a is the arithmetic mean height and R_z the mean height according to ISO 4287.

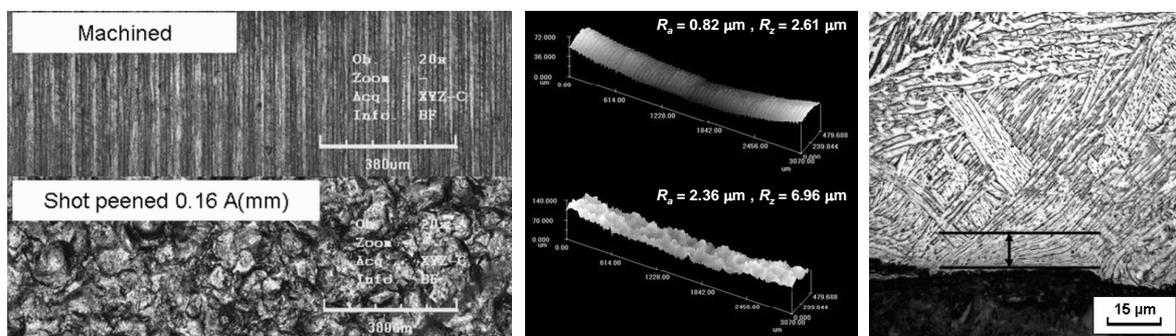


Figure 2: Surface roughness (l, m) and micrograph of a shot peened surface layer (r)

Fig. 2 (right) presents the micrograph of the surface layer of a specimen shot peened with an intensity of 0.16 A(mm). The fine lamellar microstructure is plastically deformed up to a depth of 10 to 15 μm due to shot peening treatment.

The hardness distribution was measured with an instrumented indentation test according to ISO 14577. No increase or decrease of Martens-hardness due to shot peening was detectable near the surface.

One of the most important parameters for the interpretation of the shot peening process is the residual stress state in the surface layer. The residual stress analysis was carried out with the non-destructive $\sin^2\psi$ -method. Fig. 3 depict the residual stress distributions of a specimen peened with 0.16 A(mm) as well as of a machined specimen, both measured before cyclic loading. In case of the shot peened specimen a nearly constant residual stress level of -700 to -750 MPa is observed due to the shot peening treatment.

In addition, residual stress measurements were performed after cyclic loading to investigate the residual stress relief in respect of the level and type of loading. Therefore specimens were tested in the high cycle fatigue (HCF) region under rotating bending loading and in the finite life regime under torsional as well as under rotating bending and multiaxial loading, all at the same level of equivalent stress according to Mises. The investigated specimens showed no stress relief at low load levels in the HCF regime, but a considerable stress relief at higher loads. Furthermore multiaxial loading leads to a more distinct stress relief compared to torsional or rotating bending loading.

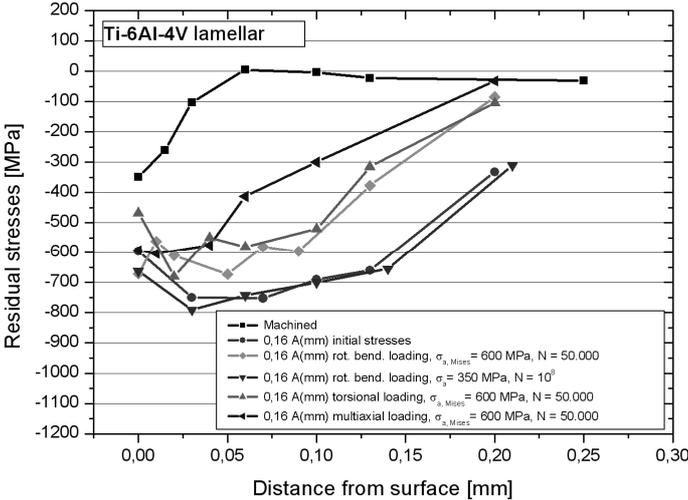


Figure 3: Residual stress distribution in the surface layer

High Cycle Fatigue

Figure 4 (left) shows the results of the rotating bending, torsional and multiaxial fatigue tests of unpeened and shot peened specimens, respectively. The experimental data points are fitted by a two-slope S/N-curve model. In this model the slope of the S/N-curve in the high cycle fatigue regime is five times as high as in the finite life region. All S/N-curves correspond to a survival probability of 50 %.

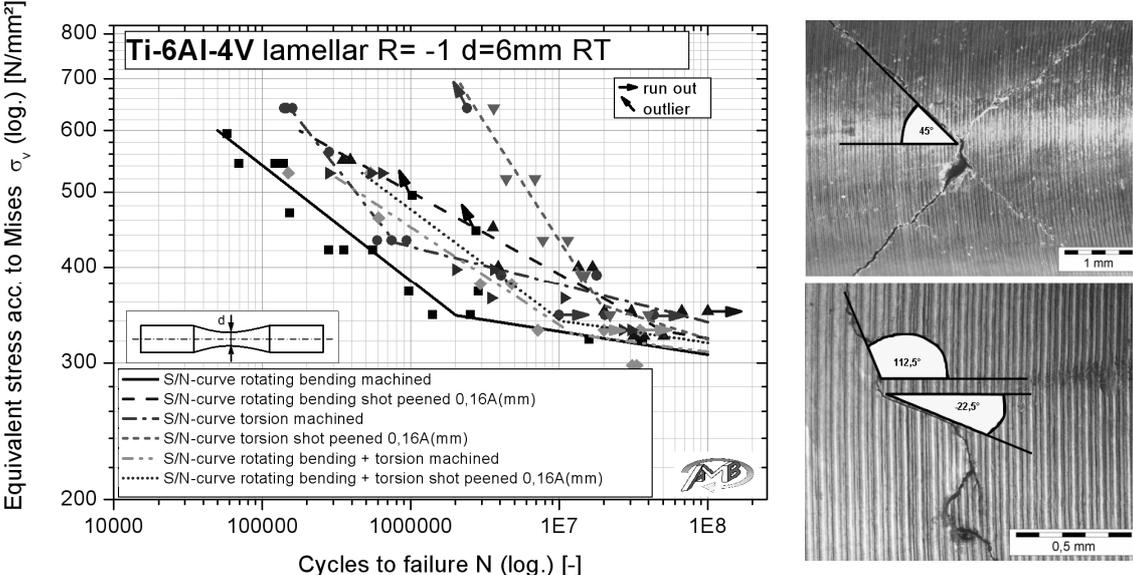


Figure 4: S/N-curves for different types of loading (l) and fracture analyses (r)

Due to the lamellar microstructure of the material, the S/N-curve for the unpeened specimens under rotating bending loading displays a relatively low fatigue strength of 330 MPa at 10^7 load cycles, compared to strengths as high as 600 MPa for equiaxed or bimodal microstructures (L. Wagner, 1981; H.E. Franz, 1987; B. Oberwinkler, 2007). A comparison of fatigue strength under different types of loading at 10^7 load cycles with literature data (T. Delahay, 2004) depicted as Gough/Pollard elliptical fatigue hypothesis is shown in Figure 5 left. The shapes of the ellipses are almost the same which confirms – at least in part - the validity of the experimental results.

It can be observed, that for the unpeened as well as for the shot peened material, specimens under rotating bending loading, torsional loading and multiaxial loading show almost identical fatigue strength for the very high cycle fatigue regime if the equivalent stress amplitude is calculated according to Mises.

The fatigue strength increase under rotating bending loading due to shot peening with 0.16 A(mm) is significant in the finite life region with about 18 % enhancement compared to the unpeened specimens at 10^7 load cycles. Under torsional loading up to a number of load cycles of $2 \cdot 10^7$ a significant enhancement was achieved. Contrary to the increase of fatigue strength under uniaxial loading, for multiaxial loading shot peening results neither in an improvement nor in a degradation of the fatigue strength in the finite life region as well as in the high cycle fatigue (HCF) regime. This circumstance can be depicted as Gough/Pollard elliptical fatigue hypothesis (Figure 5 right).

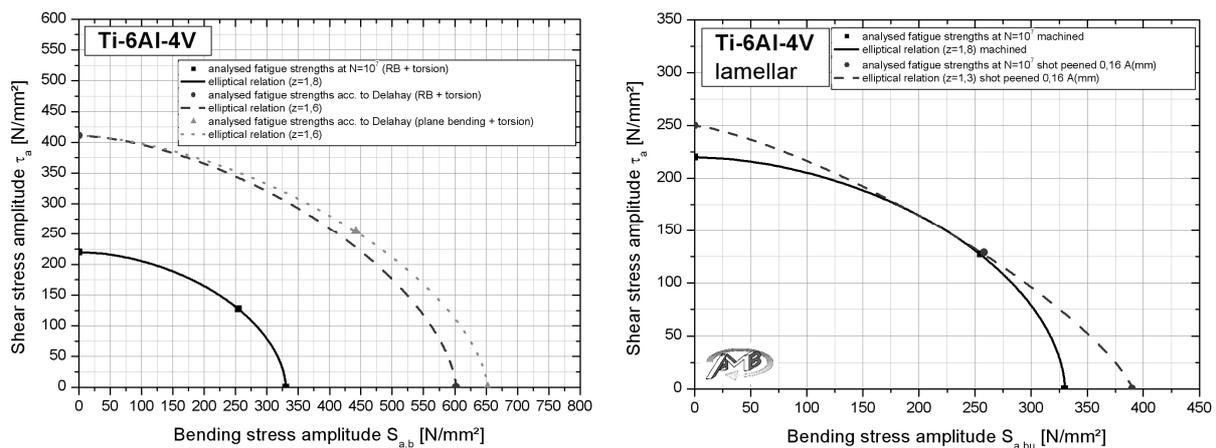


Figure 5: Gough/Pollard elliptical fatigue hypothesis

Fracture Analyses

The fracture areas of the rotating bending test specimens were typical normal stress controlled. For all unpeened specimens the initial crack is found at the surface of the specimen, in case of the peened specimen the crack initiation is observed in the edge layer in a depth of 0.2 ... 0.3 mm. Fracture surfaces of specimens loaded in torsion or multiaxial respectively are shown in Fig. 4 right top and bottom. For both, the crack initiation starts shear stress controlled. During crack propagation the crack growth process changes into a normal stress controlled mode.

DISCUSSION

Contrary to the literature, rotating bending tests up to 10^8 load cycles showed that Ti-6Al-4V has no fatigue limit, so a model for the slope of S/N-curves in the high cycle fatigue region has been implemented.

Shot peening gives, under optimized process conditions, compressive residual stresses ranging from 600 to 800 MPa in a surface layer of 0.1 ... 0.15 mm thickness.

In HCF, no residual stress degradation is observed; this ties in well with the widespread assumption that, at or near the endurance limit, no cyclic plasticity must occur. On the other hand, under loading at higher stress levels, the residual stress degradation is quite pronounced, due to a large amount of cyclic plasticity. Thereby the multiaxial loaded specimen shows the most distinct stress relief.

Shot peening increases the fatigue resistance under rotating bending and torsional loading in the finite life region and lower HCF ranges; however, the VHCF behaviour near the endurance limit is almost left unchanged. In alternating torsion, shot peening likewise results in an increased fatigue resistance in the LCF and lower HCF ranges, whereas the VHCF behaviour is again nearly unaffected. A detailed discussion about these topics is shown in a separate paper (H. Leitner, 2007). The VHCF regime of multiaxial loaded Ti-6Al-4V is uninfluenced by shot peening which corresponds to the results of uniaxial loading. But for the multiaxial loading, the finite life region is also unaffected by shot peening. This may be explained by the complex multiaxial stress state in the surface layer which leads to more plasticity and in addition to a stronger residual stress relief.

CONCLUSION AND IMPLICATIONS

Unpeened and shot peened unnotched specimens under rotating bending loading, torsional loading and multiaxial loading show that under multiaxial loading conditions shot peening has almost no effect on the fatigue strength of Ti-6Al-4V. So, a shot peening treatment for components with low stress gradients under multiaxial loading increases the manufacturing costs but in general not the fatigue strength, and assuming an effect of shot peening on the fatigue limit under multiaxial loading conditions bears the additional danger of a non-conservative design.

Former investigations, cf. (B. Oberwinkler, 2007), showed that notched specimens show a much more pronounced fatigue strength increase in the high cycle fatigue regime due to shot peening than unnotched specimens. So, the notch effect under different types of loading is subject of further investigations.

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