Influence of the Shot Peening Parameters on the Surface Layer Properties and the Fatigue Life of Ti-6Al-4V

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ABSTRACT

The influence of the shot peening parameters (peening pressure and exposure time) on the surface layer properties (dislocation density, residual stresses, material hardness, and surface roughness) was evaluated on various microstructures of Ti-6Al-4V. Compared to the electrolytically polished condition shot peening generally decreased the fatigue life tested at R = -1 under vacuum conditions. However in an aggressive environment shot peening was found to improve the fatigue life. A pronounced overpeening effect i.e. a decrease in fatigue life with increasing peening pressure as well as exposure time was observed for those conditions of the Ti-6Al-4V alloy, which were age-hardened and exhibited cyclic softening during the shot peening process. No overpeening effect with exposure time was observed for the unaged condition.

KEYWORDS

shot peening; dislocation density; residual stresses; surface roughness; cyclic hardening and softening; cyclic stability of the residual stresses; fatigue crack nucleation and propagation; environmental effects.

INTRODUCTION

It is often reported that shot peening can lead to a marked increase in fatigue life of higher strength materials (Schreiber et al, 1977 and Wohlfahrt, 1981). Besides the well known development of a high dislocation density and residual compressive stresses in the surface layer, accompanied by a change in surface roughness, it should be considered that the shot peening procedure is usually a fatigue process to the surface layer of the material. The repeated impact of the shots results in cyclic plastic deformation of the surface layer and the impact can be described qualitatively as the stress amplitude, and the exposure time as the number of cycles in a LCF-test (Wagner, 1981a). Previous research on Ti-6Al-4V (Wagner et al, 1981b) in which the influence of each of the main parameters (dislocation density, residual stresses, and surface topography) on the fatigue behavior was studied separately, showed that the fatigue behavior after shot peening was primarily determined by residual stresses. It was shown that the cyclic stability of the residual stresses was dependent on the LCF-behavior of the material. Microstructures exhibiting cyclic hardening or slight softening showed less decay of the residual stresses during fatigue testing as compared to those which undergo pronounced cyclic softening.

EXPERIMENTAL PROCEDURE

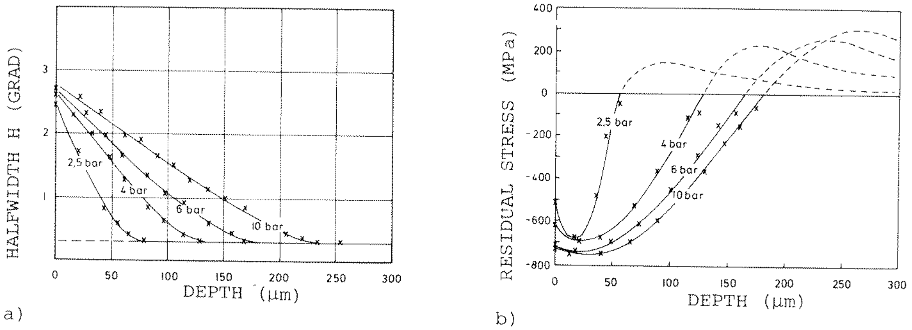
The shot peening treatment was performed using cast steel shot with an average shot size of 0,6 mm and a Vickers hardness of 490. The highest peening pressure used resulted in shot velocities of nearly 40 m/s and an Almen intensity value of 35A(mm/100). After peening, the dislocation density distribution within the surface layer, the residual stress profile, material hardness, and surface roughness were measured as described elsewhere (Wagner et al, 1981b).

Fatigue tests were performed under push-pull loading on hour-glass shaped specimens (diameter: 2 mm) in vacuum and 3.5 % NaCl solution and on rotating beam specimens (diameter: 3,6 mm) in laboratory air. The investigations were performed on lamellar and equiaxed microstructures of the Ti-6Al-4V alloy (Peters et al, 1980a). In contrast to the lamellar microstructure, having no crystallographic texture, the equiaxed structure exhibited a strong textures of the hexagonal α-phase with basal and transverse portions due to the unidirectional rolling process at 800°C (Peters et al 1980b). From this textured material specimens were taken with the loading axis parallel (RD) and perpendicular (TD) to the rolling direction. Besides the unaged condition (800°C/waterquenched), aged specimens were studied. For this purpose specimens were heat treated 24h at 500°C in order to harden the α-phase by Ti,Al and the β-phase by fine distributed α-particles (Welsch et al, 1977).

EXPERIMENTAL RESULTS

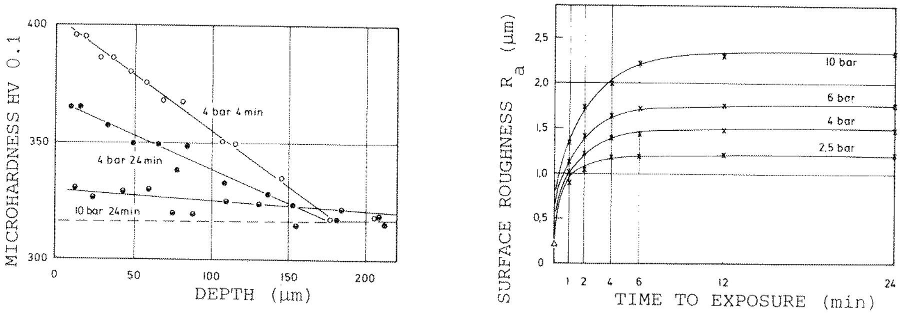
For the coarse lamellar microstructure, age-hardened 24h at 500°C, the dislocation density profile and the distribution of the residual stresses as a function of peening pressure are shown in Fig. 1a, b. It can be seen that the induced dislocation density at the surface was nearly independent of peening pressure whereas the plastic deformation zone strongly increased with peening pressure reaching 230 µm at a pressure of 10 bars (Fig. 1a). The compressive residual peak stress and its depth below the specimen surface increased with peening pressure (Fig. 1b). At a pressure of 10 bars the maximum compressive stress was 750 MPa at a depth of 50 µm. For the fine equiaxed microstructures similar profiles of the residual stress were measured with somewhat higher maximum compressive values (800 - 900 MPa). No significant change of the profile of dislocation density and residual stresses was found after prolonging the exposure time from 4 to 24 minutes. For these age-hardened microstructures, which exhibited cyclic softening, a marked decrease in surface layer hardness was observed with increasing peening pressure and exposure time (Fig. 1c). The surface roughness (Fig. 1d) first strongly increased with exposure time and then reached a saturation value which depended on peening pressure.

The results of push-pull fatigue tests in vacuum (σ_a = 800 MPa) of the fine equiaxed microstructure, age-hardened 24h at 500°C and tested in TD-direction, are shown as a function of peening pressure and two exposure times in Fig. 2. It can be seen that compared to the electrolytically polished starting condition shot peening decreased the fatigue life with increasing peening pressure. An even greater loss in fatigue life was observed after prolonging



a)
Dislocation density distribution after shot peening with different peening pressures (time: 4 min.)

b)
Residual stress distribution after shot peening with different peening pressures (time: 4 min.)



c)
Microhardness profile in the surface layer after shot peening

d)
Surface roughness after shot peening

Fig. 1

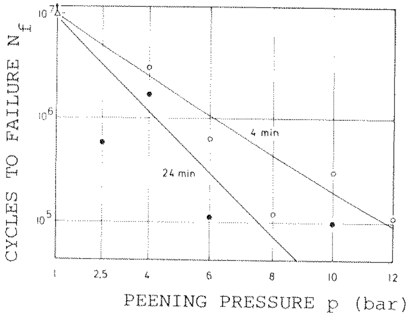


Fig. 2
Fatigue life vs. peening pressure push-pull loading in vacuum
(σ_a = 800 MPa, R = -1)
alloy condition: fine equiaxed (TD)

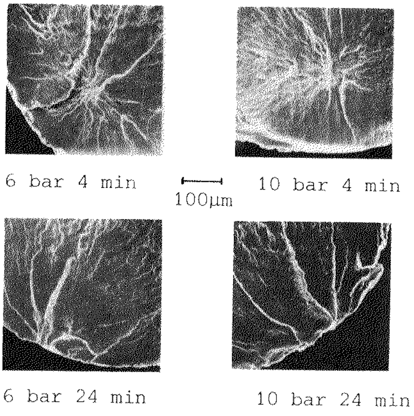


Fig. 3
Fracture surfaces (SEM) of shot peened specimens (see Fig. 2)

the exposure time from 4 to 24 minutes. Specimens shot peened for 4 minutes exhibited internal fatigue crack nucleation (Fig. 3). After prolonging the exposure time from 4 to 24 minutes the fatigue crack nucleation site shifted from the interior to the surface (Fig. 3). It should be noted that for the electrolytically polished condition the fatigue cracks always nucleated at the specimen surface.

The results of push-pull fatigue testing in 3.5 % NaCl solution (σ_a=700 MPa) are shown in Fig. 4. In contrast to the fatigue results in vacuum the fatigue life of shot peened specimens first strongly increased with peening pressure and then declined. Only for the intermediate range of pressure ($4 \leq p \leq 8$ bars) the main fatigue cracks nucleated in the specimen interior, similar as observed in vacuum, but many secondary microcracks (crack depth < 100 μm) were detected at the specimen surface (Fig. 5).

In addition to push-pull loading, rotating-beam fatigue tests in laboratory air were performed. It is well known that for the Ti-6Al-4V alloy laboratory air is already a quite aggressive environment (Peters et al, 1980a). The fatigue results (σ_a = 650 MPa) for the coarse lamellar microstructure, age-hardened 24h at 500°C, are shown in Fig. 6 as a function of peening pressure and exposure time. It can be seen that, similar to the push-pull results obtained on the fine equiaxed age-hardened microstructure tested in 3.5 % NaCl solution (compare Fig. 4), the fatigue life first strongly increased with peening pressures reaching a maximum at 4 bars, and then slightly decreased. The longest life-times were achieved at exposure times between 2 and 6 minutes. In contrast to the fine equiaxed microstructure, shot peened specimens of the coarse lamellar age-hardened microstructure all exhibited interior fatigue crack nucleation (Fig. 7). In addition to the age-hardened conditions the influence of exposure time on the fatigue life was also studied on unaged conditions of the coarse lamellar and fine equiaxed microstructures. The fatigue results for the coarse lamellar microstructure are given in Fig. 8 comparing the results of the unaged with the age-hardened condition. No overpeening effect with exposure time was found for the unaged condition. Similar to the age-hardened condition the fatigue life first increased with exposure time but then was nearly unaffected by prolonging the exposure time. The fatigue cracks for the unaged microstructure nucleated in the specimen interior as was the case for the age-hardened condition. The fatigue results for the fine equiaxed microstructure tested in RD-direction are shown in Fig. 9 (σ_a = 775 MPa). For the age-hardened condition the observed overpeening effect with exposure time was more pronounced than for the age-hardened coarse lamellar microstructure (compare to Fig. 8). Again for the unaged condition the fatigue life of the fine equiaxed microstructure was nearly unaffected by prolonging the exposure time.

DISCUSSION

Previous work showed that residual stresses induced by shot peening could decrease or increase the fatigue life (Wagner et al, 1981b). Whereas residual compressive stresses are known to have a beneficial influence on fatigue life, due to the retardation of microcrack propagation, it was also shown that the residual tensile stresses balancing the compressive stress field induced by shot peening could lead to early crack nucleation in the specimen interior (Wagner et al, 1981b).

The occurence of internal fatigue crack nucleation of shot peened specimens in push-pull testing (Fig. 3), associated with a loss in fatigue life in vacuum (Fig. 2), indicated that the residual tensile stresses induced by shot peening were stable enough to cause early fatigue crack nucleation and propagation.

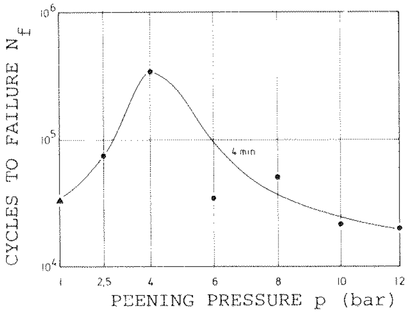
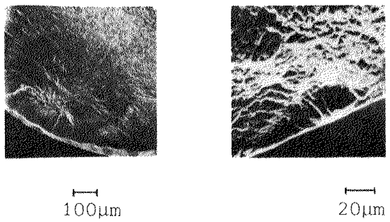


Fig. 4:
Fatigue life v.s. peening pressure push-pull loading in 3.5 % NaCl (σ_a = 700 MPa, R = -1) alloy condition: fine equiaxed (TD)



4 bar 4 min

Fig. 5:
Fracture surfaces (SEM) of shot peened specimens (see Fig. 4)

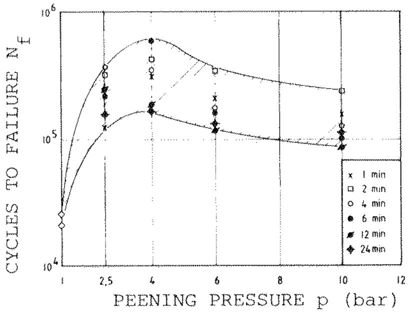
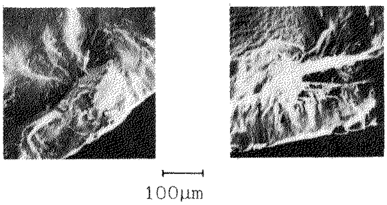


Fig. 6:
Fatigue life vs. peening pressure rotating-beam loading in air (σ_a = 650 MPa, R = -1) alloy condition: coarse lamellar



4 bar 24 min 10 bar 24 min

Fig. 7:
Fracture surfaces (SEM) of shot peened specimens (see Fig. 6)

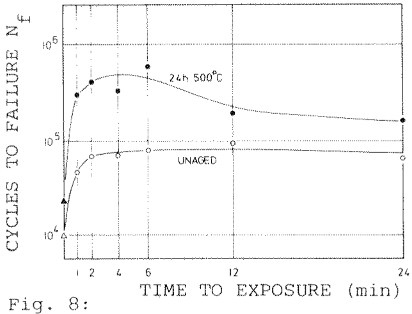


Fig. 8:
Fatigue life vs. exp. time (p: 4 bar) rotating-beam loading in air (σ_a = 650 MPa, R = -1) alloy condition: coarse lamellar

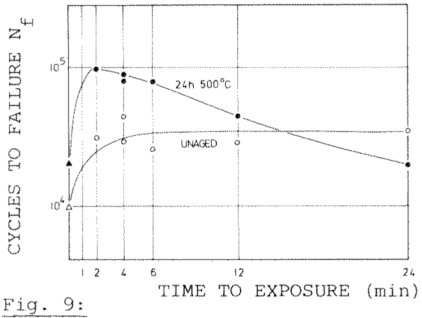


Fig. 9:
Fatigue life vs. exp. time (p: 4 bar) rotating-beam loading in air (σ_a = 775 MPa, R = -1) alloy condition: equiaxed (RD)

Increasing peening pressure resulted in higher residual tensile stresses leading to even earlier fatigue failure. It was found that by testing shot peened specimens in an aggressive environment this internal (vacuum) crack nucleation could still occur (Fig. 5). For the case of internal crack nucleation an improvement or deterioration of fatigue life due to shot peening may occur for tests in aggressive environments. This depends on the difference of the resistance against crack nucleation between vacuum and the aggressive environment and on the intensity and cyclic stability of the residual tensile stresses induced by shot peening. A large difference of the fatigue limit between vacuum and the aggressive environment and a low cyclic stability of the residual tensile stresses may result in the most marked improvement of the fatigue life due to shot peening. On the other hand a low difference of the fatigue limit between vacuum and the aggressive environment and a high cyclic stability of the residual tensile stresses may result in a drastic loss of the fatigue life. For the fine equiaxed microstructure tested in TD-direction the marked difference in the fatigue limit between vacuum and 3.5% NaCl solution (250 MPa) (Wagner et al, 1984) is the main reason for the observed improvement of fatigue life in an aggressive environment due to shot peening (Fig. 4).

For the rotating-beam fatigue tests in laboratory air a similar overpeening effect was found as for the push-pull tests. Again, increasing residual tensile peak stresses with peening pressure are the reason for the decline of fatigue life with peening pressure for the coarse lamellar microstructure (Fig. 6).

The effect of exposure time on the fatigue life can be explained by considering the interaction between the impact of the shots and the surface layer of the material. The fatigue life tested in aggressive environments first generally increased with exposure time (Fig. 8, 9) because of the increasing degree of coverage (peened area/total area) and the building up of the residual stress field.

After reaching saturation (100 % coverage) by prolonging the exposure time the fatigue life may stay unchanged or decrease depending on the reaction of the material to the cyclic plastic deformation within the surface layer caused by the repeated impact of the shots. It was shown that microstructures exhibiting cyclic hardening or slight softening showed less decay of the residual stresses induced by shot peening during fatigue testing as compared to those which undergo pronounced cyclic softening (Wagner, 1981a). From LCF-tests the cyclic deformation behavior of the microstructures used in this study is known (Däubler et al, 1982). For the aged conditions (24h 500°C) softening was measured to be most pronounced for the fine equiaxed microstructure tested in RD-direction followed by the TD-direction. Reduced softening was found for the coarse lamellar microstructure. For the unaged condition of the equiaxed microstructure softening was somewhat more pronounced in RD-direction than in TD-direction but for both softening was much less than observed after aging at 500°C. The coarse lamellar unaged microstructure was found to exhibit cyclic hardening.

For the fine equiaxed microstructure tested in TD-direction the shifting of the fatigue crack nucleation site from the interior to the surface after prolonging the exposure time (Fig. 3) and the concurrent decrease in fatigue life (Fig. 2) can be explained by pronounced softening of the surface layer during shot peening leading to a marked decay of the residual compressive stresses during subsequent fatigue testing. No shifting of the fatigue crack nucleation after prolonging the exposure time was found for the coarse lamellar microstructure (24h 500°C) (Fig. 7). The slight decrease in fatigue life with exposure time can be explained by a somewhat accelerated propagation of the internal fatigue crack through the cyclic softened surface layer. Correspondingly for the unaged condition which are known to exhibit cyclic hardening the fatigue life was nearly unaffected by exposure time (Fig. 8). The pronounced cyclic softening of the fine equiaxed microstructure tested in RD-direction (24h 500°C) is the reason for the marked overpeening effect with exposure time (Fig. 9) whereas for the unaged condition which does not exhibit cyclic softening the fatigue life was nearly unaffected by exposure time similar as found for the unaged coarse lamellar microstructure (compare Fig. 9 with Fig. 8).

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