Influence of a Shot Peening Treatment on the Fatigue Limit of Ti-6Al-4V

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ABSTRACT

The effect of shot peening on the fatigue limit of various microstructures of the Ti-6Al-4V alloy tested at R = -1 in inert and corrosive environments was studied. From a previous work on the influence of the shot peening parameters on the fatigue life on Ti-6Al-4V (Wagner et al, 1984) the shot peening treatment, which resulted in the most marked improvement of fatigue life in an aggressive environment, was chosen. The fatigue tests were performed using push-pull loading in vacuum and 3.5 % NaCl solution and rotating-beam specimens in laboratory air. For the push-pull tests in vacuum generally a drastic loss in the fatigue limit of shot peened specimens compared to the electrolytically polished condition was observed. On the other hand, by testing in 3.5 % NaCl solution no change or a slight improvement in fatigue limit, depending on the microstructure, was found after shot peening. In contrast to push-pull loading the fatigue limit of shot peened rotating-beam specimens tested in laboratory air was always improved compared to the electrolytically polished condition.

KEYWORDS

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

INTRODUCTION

It has long been recognized that shot peening can increase the fatigue lifetime of a material. Investigations on Ni-base superalloys (Burck et al, 1970) and Ti-alloys (Leverant et al, 1979) indicated that much of the beneficial effect of shot peening derived from a very low rate of crack propagation under the high compressive stresses in the surface layer. On the other hand, on a precipitation hardened austenitic steel (Hornbogen et al, 1981) the increase in fatigue life-time after shot peening was mainly explained by a strong retardation of fatigue crack nucleation because of the homogenization of the slip distribution in the surface layer. From extensive studies on various types of carbon steels (Wohlfahrt, 1981) it was concluded that the effect of residual stresses on the fatigue limit of steels was only pronounced for medium and higher strength conditions (HV ≳ 350) whereas for soft conditions (HV ≲ 250) the strengthening of the surface layer (increase in dislocation density) played the dominant role in improving the fatigue limit. Previous research on Ti-6Al-4V (Wagner et al, 1981), in which the influence of each of the main parameters (dislocation density, residual stresses, and surface roughness) was studied separately, showed that the fatigue behavior after shot peening was primarily determined by residual stresses.

EXPERIMENTAL PROCEDURE

The shot peening procedure used for the Ti-6Al-4V alloy was described in detail elsewhere (Wagner et al, 1981). A certain peening treatment (peening pressure: 4 bars, exposure time: 4 min) which resulted in the most marked improvement in fatigue life in an aggressive environment (Wagner et al, 1984) was chosen to study the effect of shot peening on the fatigue limit of various microstructures of the Ti-6Al-4V alloy. The microstructures and textures of the Ti-6Al-4V alloy used in this study were described elsewhere (Wagner et al, 1984). Fatigue tests (R = -1) were performed in push-pull loading on hourglass shaped specimens (diameter: 2 mm) in vacuum and 3,5 % NaCl solution and on rotating-beam specimens (diameter: 3,6 mm) in laboratory air. As the fatigue limit the fatigue strength after 10^7 cycles was measured.

EXPERIMENTAL RESULTS

For the push-pull fatigue tests of the fine equiaxed microstructure tested in TD-direction a drastic loss in fatigue strength after shot peening compared to the electrolytically polished condition was observed in vacuum (Fig. 1). Due to shot peening the fatigue limit was lowered from 875 MPa (electrolytically polished condition) to less than 700 MPa. From the S-N curve it can be seen that shot peening decreased the fatigue life in particular at lower stress amplitudes. At higher stress amplitudes there was an unusual increase of fatigue life of shot peened specimens tested in vacuum. For the tests in vacuum the fatigue cracks of the shot peened specimens were always nucleated in the specimen interior independent of stress amplitude (Fig. 2). At low stress amplitudes ($\sigma_a \lesseqqgtr 800$ MPa) a constant depth of fatigue crack nucleation site below the specimen surface of about 175 µm was observed. At the stress amplitude of $\sigma_a = 950$ MPa the maximum depth of fatigue crack nucleation site of about 310 µm was found.
For the fatigue tests in 3.5 % NaCl solution a marked improvement of fatigue life due to shot peening was found at high stress amplitudes whereas the fatigue limit was not increased. For the tests in 3.5 % NaCl solution at stress amplitudes $\sigma_a \geqq 800$ MPa the fatigue crack nucleation took place at the surface and at $\sigma_a < 800$ MPa in the interior at a depth of about 175 µm as it was found for the vacuum tests.
Quite different results were obtained when the tests for the same microstructure were performed in RD-direction (Fig. 3). For this testing direction a slight increase in fatigue limit in vacuum as well as in 3.5 % NaCl solution was measured after shot peening. The fatigue cracks of the shot peened specimens nucleated at the surface for tests in vacuum (Fig. 4). On the contrary, shot peened specimens tested in 3.5 % NaCl solution exhibited internal fatigue crack nucleation at stress amplitudes $\sigma_a \leqq 800$ MPa (Fig. 4) whereas at $\sigma_a > 800$ MPa surface crack nucleation took place similar as it was found for the tests in TD-direction.

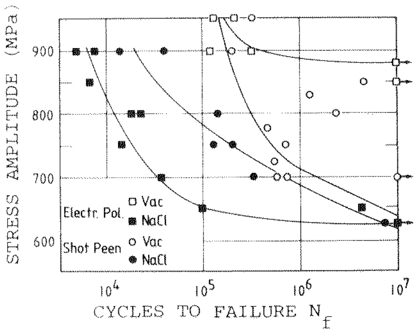

Fig. 1:
S-N curves in push-pull loading alloy condition: fine equiaxed (TD)

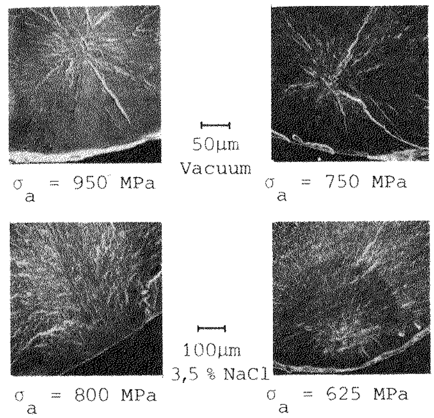

Fig. 2:
Fracture surfaces (SEM) of shot peened specimens (see Fig. 1)

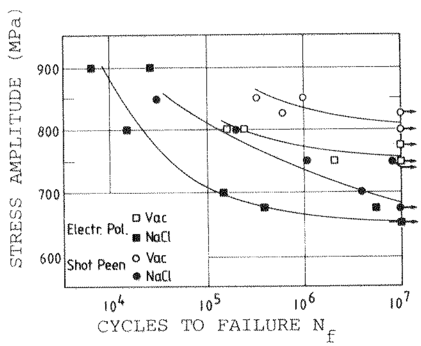

Fig. 3:
S-N curves in push-pull loading alloy condition: fine equiaxed (RD)

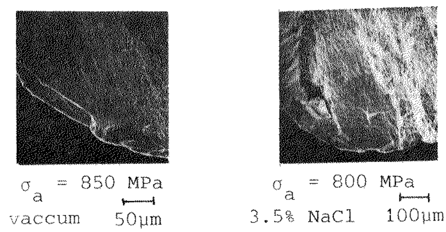

Fig. 4:
Fracture surfaces (SEM) of shot peened specimens (see Fig. 3)

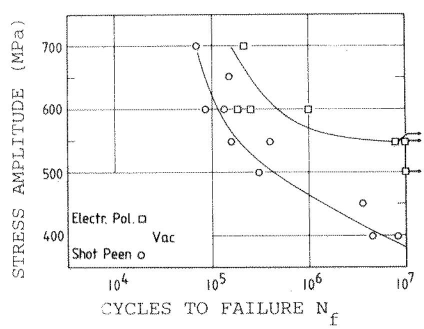

Fig. 5:
S-N curves in push-pull loading alloy condition: coarse lamellar

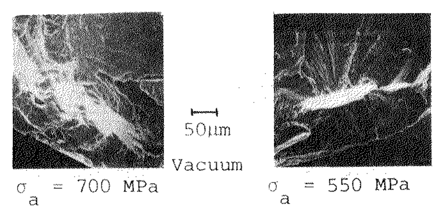

Fig. 6:
Fracture surfaces (SEM) of shot peened specimens (see Fig. 5)

In addition to the equiaxed microstructures the effect of shot peening on the fatigue limit in push-pull loading in vacuum was also studied on a coarse lamellar microstructure (Fig. 5). It can be seen that similar to the equiaxed microstructure tested in TD-direction (compare Fig. 5 with Fig. 1) a pronounced decrease in fatigue limit from 550 MPa to less than 400 MPa was found for the shot peened condition. For the coarse lamellar microstructure no increase of fatigue life of shot peened specimens tested at high stress amplitudes was found. The fatigue cracks of the shot peened condition always nucleated in the specimen interior similar to the equiaxed microstructure tested in TD-direction. For the coarse lamellar microstructure no change in depth of crack nucleation site below the surface was observed at high stress amplitudes (Fig. 6)

In order to study the effect of a stress gradient rotating-beam fatigue tests were performed in laboratory air. It is well known that for the Ti-6Al-4V alloy laboratory air is already a quite aggressive environment almost comparable to 3.5 % NaCl solution (Peters et al, 1980). In Fig. 7 the stress distribution (applied plus residual stresses) is shown schematically for both push-pull and rotating-beam specimens. It can be seen that for rotating-beam specimens the stress amplitude in the critical region of tensile residual stresses in the specimens interior is reduced. The results of rotating beam specimens of the equiaxed microstructure tested in TD- and RD-direction are shown in Fig. 8 comparing the behavior of the shot peened with the electrolytically polished conditions. For the TD-direction a pronounced increase in fatigue limit from 690 MPa to 800 MPa was found after shot peening. A similar marked improvement in fatigue limit from 480 to 550 MPa after shot peening was also observed for the coarse lamellar microstructure. In contrast, for the equiaxed microstructure tested in RD-direction shot peening only slightly improved the fatigue limit from 720 MPa (electrolytically polished condition) to 725 MPa. Microscopic investigation of the fracture surfaces revealed that for the coarse lamellar microstructure the fatigue cracks even at the highest stress amplitudes were nucleated in the specimen interior. For the equiaxed microstructure tested in TD-direction internal fatigue cracking was found at stress amplitudes $\sigma_a \lesssim 850$ MPa (Fig. 9), whereas by testing in RD-direction the fatigue cracks even at the lowest stress amplitude tested (σ_a = 750 MPa) nucleated at the specimen surface (Fig. 9).

DISCUSSION

Previous research on Ti-6Al-4V (Wagner, 1981a) showed that the residual stresses induced by shot peening mainly determined the fatigue properties. The cyclic stability of the residual stresses was found to depend strongly on the LCF-behavior of the material. For the microstructures tested in the present work the coarse lamellar microstructure exhibited only a slight decrease of the residual stresses during fatigue testing. For the equiaxed microstructure by loading in TD-direction a greater decrease of the residual stresses was measured. The most pronounced decrease of the residual stresses was observed by loading in RD-direction due to marked cyclic softening.

The drastic decrease of the fatigue limit in vacuum after shot peening observed for the equiaxed microstructure tested in TD-direction (Fig. 1) and for the coarse lamellar (Fig. 5) can be explained by early crack nucleation in the specimen interior (Fig. 2 and Fig. 6) in the regions of residual tensile peak stresses (Fig. 7). For push-pull loading the influence of the compressive residual stresses in the outer regions was not pronounced because

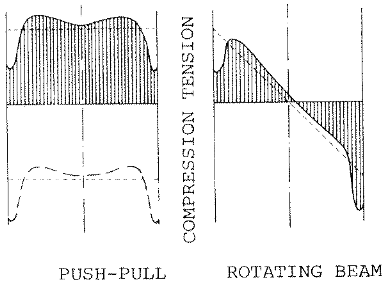

Fig. 7:
Superposition of applied and residual stress (schematically)

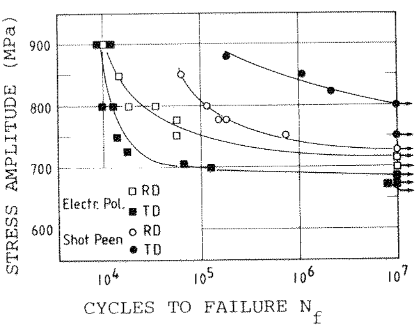

Fig. 8:
S-N curves in rotating-beam loading in air, R = - 1
alloy condition: fine equiaxed

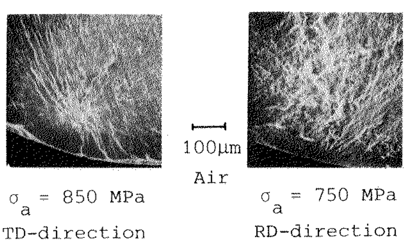

Fig. 9:
Fracture surfaces (SEM) of shot peened specimens (see Fig. 8)

the fatigue crack nucleated in the interior could unhindered propagate into the specimen interior. The low cyclic stability of the residual stresses of the equiaxed microstructure tested in TD-direction lead to an unusual increase of fatigue life of shot peened specimens tested at high stress amplitudes in vacuum (Fig. 1). This behavior was caused by a pronounced decay of the residual tensile peak stresses in the specimen interior due to local plastic deformation during fatigue testing leading to a retardation of internal crack nucleation. A decay of the original residual stresses associated with a change in the stress profile by testing at higher stress amplitudes was also indicated by the shifting of the fatigue crack nucleation site deeper into the specimen interior (Fig. 2). By comparing the fatigue limit between the electrolytically polished condition (875 MPa) and after shot peening (< 625 MPa) (Fig. 1) it can be concluded that the value of the residual tensile peak stresses was at least 250 MPa. Because of this high value the fatigue cracks in the shot peened specimens still nucleated in the interior (vacuum conditions) even if the tests were performed in an aggressive environment (Fig. 2).

It should be pointed out that purely by chance the fatigue limits in 3.5 % NaCl solution were the same for the electrolytically polished condition and for the shot peened condition (Fig. 1). Taking the fatigue limit in vacuum of the electrolytically polished condition as the baseline of the material, the drop in fatigue limit (250 MPa) of the electrolytically polished condition in 3.5 % NaCl solution was determined by the influence of aggressive environment on crack nucleation and propagation (cracks nucleated at the surface of the specimens). In contrast, the drop in fatigue limit (250 MPa) of the shot peened condition in 3.5 % NaCl solution was determined by the residual tensile stresses because the cracks nucleated in the interior of the specimens and therefore also in "vacuum".

For the fine equiaxed microstructure tested in RD-direction (Fig. 3) an increase in fatigue limit in vacuum after shot peening compared to the electrolytically polished condition was found. As can be seen from the micrographs (Fig. 4) the fatigue cracks in the shot peened specimens tested in vacuum nucleated at the surface. Probably due to an early decay of the residual tensile peak stresses during fatigue testing at these high stresses amplitudes of σ_a = 825 - 850 MPa no internal fatigue crack nucleation took place. The increase of fatigue limit after shot peening was found because fatigue cracks at the surface were hindered to propagate by residual compressive stresses in the surface layer.

On the other hand for tests in an aggressive environment, which were done at lower stress amplitudes (Fig. 3), shot peened specimens exhibited internal fatigue crack nucleation (Fig. 4) similar as it was found for tests in TD-direction. Although no shot peened specimens were tested at lower stress amplitudes in vacuum, it is obvious from the internal crack nucleation of the shot peened specimens tested in 3.5 % NaCl solution that the fatigue limit in vacuum should again approach the fatigue limit in 3.5 % NaCl solution as was the case for the TD-direction. The results obtained on the equiaxed microstructure tested in RD-direction showed that a shot peened material with pronounced cyclic softening could exhibit two different "fatigue limits" in vacuum (Fig. 3). The upper "apparent" fatigue limit was found because fatigue cracks at the surface were hindered to propagate by residual compressive stresses in the surface layer. At these high stress amplitudes internal fatigue crack nucleation was absent (Fig. 4) because the residual tensile peak stresses (Fig. 7) could relax partially during cycling due to local plastic deformation. The lower true fatigue limit (Fig. 3) depended on magnitude of these residual tensile peak stresses.

The difference between the push-pull and rotating-beam fatigue results of shot peened specimens were mainly caused by the presence of the stress gradient in the rotating-beam specimens (Fig. 7).

For the equiaxed microstructure tested in TD-direction the observed difference in fatigue limit of shot peened specimens between push-pull and rotating-beam loading (150 MPa) (compare Fig. 8 with Fig. 1) was due to a retardation of internal crack nucleation because of the reduced stress amplitude in the rotating-beam specimens but even more to the marked influence of the stress gradient on propagation of these internal cracks in the rotating-beam test.

For the equiaxed microstructure tested in RD-direction (Fig. 8) the stress gradient and the low cyclic stability of the residual stresses inhibited internal crack nucleation of the shot peened specimens (Fig. 9). Similar as for the fatigue results for push-pull loading in vacuum (compare Fig. 8 with Fig. 3) the slight increase in fatigue limit of shot peened specimens (tested in RD-direction in rotating-beam loading) can be explained by the beneficial influence of the residual compressive stresses in the surface layer on microcrack propagation.

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