Influence of Shot Peening on Notched Fatigue Strength of Ti-6Al-4V

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ABSTRACT

The fatigue strength of smooth and notched specimens was investigated for four different microstructures of the Ti-6Al-4V alloy. Comparing the S-N curves of smooth and notched specimens in the electrolytically polished condition and plotting the maximum stress at the root of the notch ($\sigma_a \cdot K_t$) for the notched specimens the same 10^7 cycles fatigue strength was obtained if resistance against crack nucleation determined the fatigue strength. A higher fatigue strength for the notched specimens was obtained if resistance against microcrack propagation determined the fatigue strength. This latter behavior was also found for all shot peened conditions indicating that the influence of residual compressive stresses on microcrack propagation determined the fatigue strength. This point could be proven by measuring the fatigue strength of shot peened specimens after the internal stresses had been relieved to a large extent by annealing. Furthermore, by separating the remaining two parameters (surface roughness and dislocation density) the tremendous beneficial effect of dislocation density on fatigue strength can be seen.

KEYWORDS

fatigue strength, smooth and notched specimens, electrolytically polished surface, shot peening, residual stresses, surface roughness, dislocation density.

INTRODUCTION

It is well known that the surface finishing procedure has a drastic influence on fatigue strength. Taking the electrolytically polished condition as the basic fatigue strength of a material any surface finishing by mechanical methods (machining, grinding, shot peening) can increase or decrease the fatigue strength depending on various parameters. The change of the material due to the surface finishing procedure can be described by three parameters: surface roughness, internal compressive and tensile stresses, dislocation density (strength). The influence of these three parameters on fatigue strength can be separated (Wagner et al, 1981).

Other important parameters are the environment in which the fatigue strength is evaluated and the type of applied stresses (tension-compression, bending, mean stress). For each testing condition it is necessary to investigate whether the cracks are nucleated at the specimen surface or inside the material (Wagner et al, 1981).
The purpose of the present investigation was to evaluate the fatigue strength of notched specimens. Comparing smooth and notched specimens it is necessary to use the same surface finishing for the root of the notches as for the smooth specimens. The experimental testing conditions used in the investigation resulted in crack nucleation at the specimen surface in all cases.

EXPERIMENTAL PROCEDURE

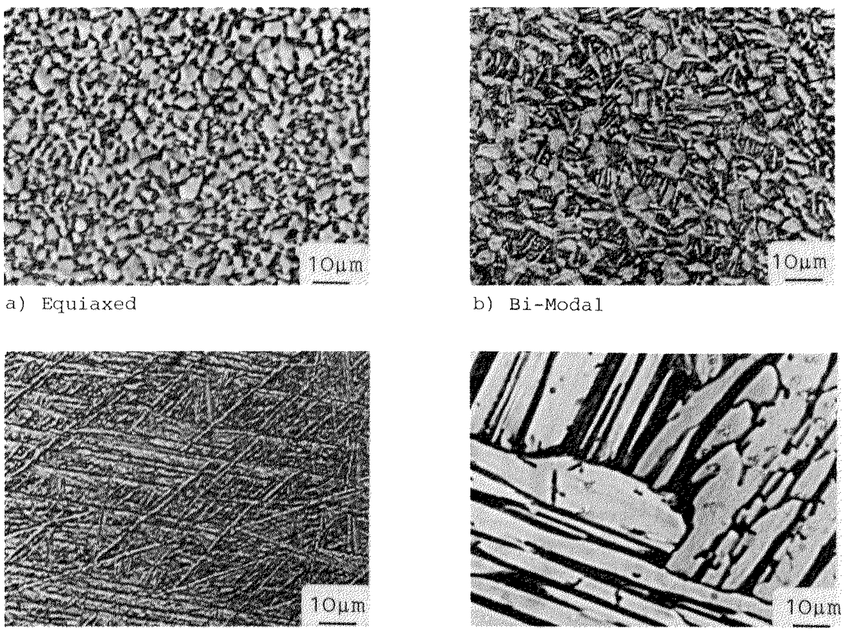
The material used for this investigation was a two phase (α + β) Ti-6Al-4V alloy with the following basic composition (wt-%): 6.3 % Al, 4.2 % V, 0.20 % oxygen, 0.005 % hydrogen.
Different microstructures (Fig. 1) were prepared by thermo-mechanical treatment (equiaxed and bi-modal) or by heat treatment alone (fine and coarse lamellar). In the equiaxed and bi-modal microstructures the equiaxed α-phase had a grain size of 6 µm and a strong crystallographic texture (B/T). For these two microstructures specimens were tested with the stress axis parallel to the rolling direction (RD). More details about these four different material conditions were published elsewhere (Gerdes, 1983). All specimens were finally aged at 500°C for 24 hours and the resulting yield stresses ($\sigma_{0.2}$) were as following: equiaxed 1060 MPa, bi-modal 1080 MPa, fine lamellar 1080 MPa, coarse lamellar 940 MPa.
The fatigue tests were performed on rotating beam specimens in laboratory air with a frequency of about 60 Hz. The smooth, hour-glass shaped specimens had a diameter of 6.4 mm. The round notched specimens had a diameter of 8.0 mm and a circumferential notch was introduced with a depth of 0.8 mm and a semi-circle root shape (radius 0.3 mm). This geometry resulted in a stress concentration factor K_t of about 2.4 and the exact value was calculated for each specimen individually.
Two surface conditions were tested (electrolytically polished and shot peened). Care was taken that for the electrolytically polished condition all machining effects were removed. The shot peening was performed on these electrolytically polished specimens using steel shot with an average shot size of 0.3 mm and a Vickers hardness of 490.
For this investigation a certain peening treatment (peening pressure 4 bars, exposure time 4 min.) was used which resulted in the most pronounced increase in fatigue life in aggressive environments (Wagner et al, 1984). The Almen intensity was about 12 A (mm/100).

EXPERIMENTAL RESULTS

The results of the fatigue tests for the four different microstructures are shown in Figs. 2-5. For the notched specimens the maximum stress in the notch root ($\sigma_a \cdot K_t$) was plotted for these S-N curves. For the equiaxed, bi-modal and fine lamellar microstructures (Figs. 2-4) no difference was found for the 10^7 cycles fatigue strength between smooth and notched specimens in the electrolytically polished surface condition. By contrast, for the coarse lamellar microstructure the notched specimens showed still a higher fatigue strength after 10^7 cycles as compared to smooth specimens (Fig. 5 , compare curves C and A).

A drastic increase in the 10^7 cycles fatigue strength was found for all four microstructures after shot peening. In contrast to the electrolytically polished condition, after shot peening a higher 10^7 cycles fatigue strength was observed for the notched specimens as compared to smooth specimens of the equiaxed, bi-modal and fine lamellar microstructures (Figs. 2-4 , compare curves D and B). The most pronounced difference between notched and smooth specimens in the shot peened condition was observed for the coarse lamellar microstructure (Fig. 5, compare curves D and B).

To evaluate the influence of compressive stresses in the surface layer on this difference between smooth and notched 10^7 cycles fatigue strength values, shot peened specimens were annealed at 500°C for one hour. This heat treatment removed the internal stresses to a large extent keeping the other two parameters (surface roughness and dislocation density) nearly constant (Wagner et al, 1981). The results of the subsequent fatigue tests are shown in Fig. 6 for the equiaxed microstructure. It can be seen that due to the heat treatment the 10^7 cycles fatigue strength values were reduced drastically and nearly the same value was found for smooth and notched specimens (475 MPa). This value was now much lower than the reference value of the material (575 MPa) in the electrolytically polished condition (Fig. 2, curves A and C).



a) Equiaxed

b) Bi-Modal

c) Fine Lamellar

d) Coarse Lamellar

Fig. 1: Light micrographs of microstructures

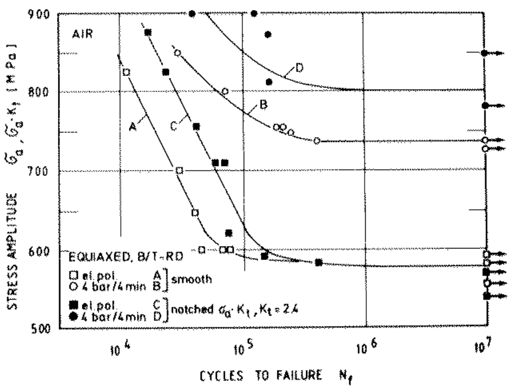


Fig. 2: S-N curves of equiaxed microstructure

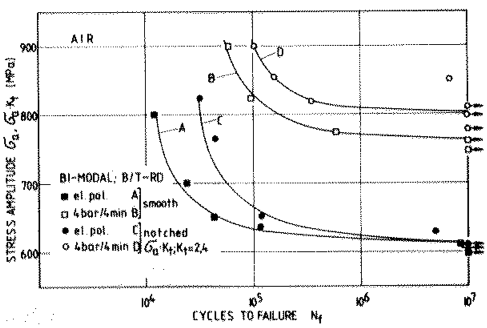


Fig. 3: S-N curves of bi-modal microstructure

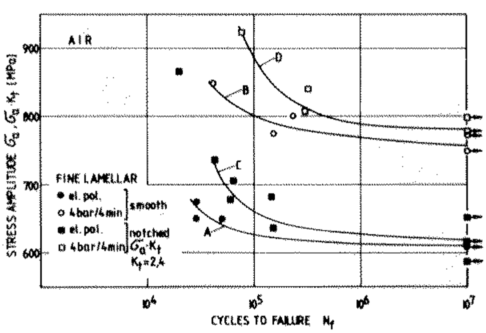


Fig. 4: S-N curves of fine lamellar microstructure

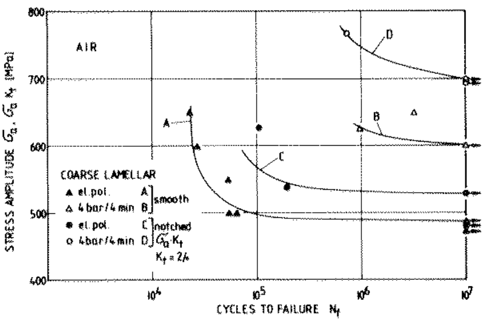


Fig. 5: S-N curves for coarse lamellar microstructure

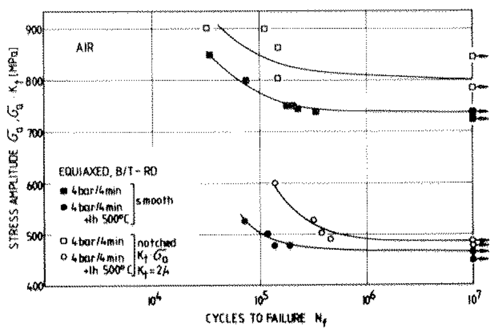


Fig. 6: S-N curves of shot peened specimens after 1 h at 500°C (equiaxed microstructure)

DISCUSSION

Comparing smooth and notched specimens and plotting for the notched specimens the maximum stress at the root of the notch ($\sigma_a \cdot K_t$), the notched specimens should show a longer fatigue life because the cracks propagate away from the stress concentration of the notch. The two S-N curves should approach each other if the fatigue strength is dominated by the resistance against crack nucleation. This behavior was observed for the equiaxed, bimodal and fine lamellar microstructures in the electrolytically polished condition (Figs. 2-4). These three microstructures are known to have a high resistance against crack nucleation (high yield stress) but a low resistance against crack propagation. The contrary is true for the coarse lamellar microstructure which exhibits a lower resistance against crack nucleation (low yield stress) but a higher fatigue crack propagation threshold (Peters et al, 1983). Thus the 10^7 cycles fatigue strength of smooth specimens was relatively low (σ_a = 475 MPa) and the notched fatigue strength was higher indicating that microcracks were nucleated already but did not or only slowly propagate (Fig. 5, curves A and C).

Shot peening increased the fatigue strength of smooth and notched specimens for all four microstructures tested (Figs. 2-5). This is due mainly to the internal compressive stresses induced by shot peening hindering microcrack propagation. Thus, a distinct difference in fatigue strength between smooth and notched specimens was found after shot peening also for the equiaxed, bi-modal and fine lamellar microstructures (Figs. 2-4, compare curves B and D) indicating that the 10^7 cycles fatigue strength was determined by microcrack propagation or non-propagating cracks. This difference between smooth and notched specimens after shot peening was especially pronounced for the microstructure with the highest fatigue crack propagation threshold, namely the coarse lamellar microstructure (Fig. 5). It should be pointed out that the threshold values obtained from conventional CT-specimens should be used only in a qualitative manner for this problem because recently it has been shown that microcracks propagate much faster than long cracks at same ΔK-values and well below these threshold values (Gerdes et al, 1983).
The influence of the internal compressive stresses on microcrack propagation can be shown by annealing shot peened specimens at 500°C for one hour removing nearly all internal stresses. The S-N curves after this annealing treatment exhibited the same 10^7 cycles fatigue strength for smooth and notched specimens indicating that the fatigue strength was now determined again by the resistance against crack nucleation (Fig. 6). The lower value of the 10^7 cycles fatigue strength after annealing (σ_a = 475 MPa) as compared to the reference value of this material in the electrolytically polished condition (σ_a = 575 MPa) showed that from the two remaining parameters (surface roughness and dislocation density) the negative influence of surface roughness dominated. The influence of these two remaining parameters on fatigue strength can be separated by removing about 20 µm from the surface of the annealed specimens by electrolytically polishing thus creating a smooth surface. After this treatment the 10^7 cycles fatigue strength increased to a value of about 800 MPa (Wagner et al, 1981). Thus, the effect of dislocation density alone was even higher than the effect of shot peening (combination of surface roughness, internal stresses, dislocation density) on fatigue strength (σ_a = 725 MPa).

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REFERENCES

Gerdes, C., (1983), Forschr.-Ber. VDI-Z., Reihe 5, Nr. 72

Gerdes, C., A. Gysler and G. Luetjering, (1983), Proc. Symposium on "Concepts of Fatigue Crack Growth Threshold", Philadelphia, AIME

Peters, M. and G. Luetjering, (1983), EPRI CS-2933

Wagner, L. and G. Luetjering, (1981), First Intern. Conf. on Shot Peening, Pergamon Press, 453

Wagner, L. and G. Luetjering, (1984), Second Intern. Conf. on Shot Peening, Chicago