Fatigue behaviour of shot peened TiAl6V4 in the temperature range $20\ ^{o}C \leq T \leq 450\ ^{o}C$

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Introduction

The (α + β)-titanium alloy TiAl6V4 is applied as rotor blade and disc material for compressor cascades of modern flight engines. These aircraft structures are exposed to fatigue loading at temperatures up to T = 450 °C. Therefore knowledge about fatigue behaviour, especially fatigue crack growth in this temperature range is important. The number of investigations concerning the fatigue crack growth characteristics of TiAl6V4 at elevated temperatures are still very limited, with exception of temperatures around of 540 °C (2). These results indicate a pronounced environmental effect, particularly at low ΔK levels where time dependent effects such as oxidation would be expected to predominate. In tests conducted in vacuum there was no intrinsic temperature effect up to 350 °C. Other investigations show a significant increase in crack growth rates with increasing temperature (up to 320 °C), especially at low ΔK and high R values. In other tests, the material appeared at T = 290 °C slightly more resistant to crack growth than at room temperature.

In the present paper, fatigue crack propagation behaviour at room temperature, T = 250 °C and T = 450 °C was investigated. Additionally the influence of shot peening on fatigue crack propagation as a function of temperature was examined because above T = 300 °C there is a significant relaxation of residual stresses by thermal (1) and cyclic loading.

Material and shot peening treatment

Fatigue crack propagation tests were performed with modified compact tension (CT) specimens as shown in Fig. 1. The specimens were machined in T-L orientation from a rolled sheet material of 12 mm thickness which had been annealed for 2 h at 700 °C after hot rolling. The chemical composition of the material was 6.2 Al, 4.0 V, 0.13 Fe, 0.18 O_2, 0.01 C, Ti balance (all units in wt.-%). After vacuum annealing at 650 °C for 1 h (1) the machined specimens were shot peened in an air blast machine (type Baiker). The shot peening conditions were: cast steel shot S 170 (mean diameter 0.43 mm, hardness 44 - 48 HRC), peening pressure 1.6 bar, 3×98 % coverage (0.4 mm A2).

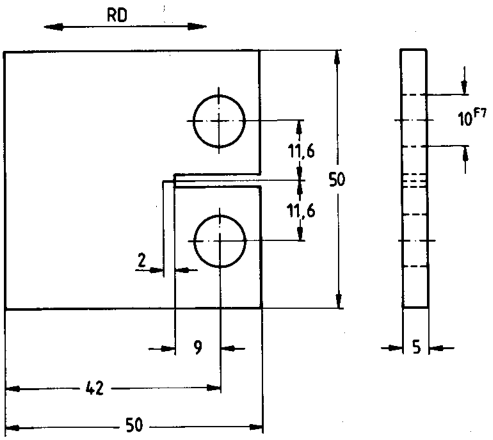

Fig. 1: Shape and size of the modified compact tension specimen (RD: rolling direction)

Experimental details

Fatigue crack propagation tests were carried out on a 63 kN resonance testing machine (type Schenck) at room temperature, T = 250 °C and T = 450°C in laboratory air (3). Loading was sinusoidal at stress ratios $R = 0.2$ and $R = 0.6$, the test frequency was approximately 21 Hz. By the direct current potential drop method the crack length was determined.

With Cu-$K\alpha$-radiation the $\{12\bar{3}3\}$-planes of the hexagonal α-phase were measured. The texture investigations were performed on a goniometer (type Huber), residual stresses of the samples were determined with a ψ-diffractometer and with the so-called $\sin^2\psi$-method (4). After electrochemical removing of material layers, the residual stress distribution was obtained. The data were corrected for the disturbance of the existing residual stress state (5). The half width of the X-ray interference line profiles supply information regarding the work hardening of the near surface layers.

Results and discussion

The texture of the material investigated is schematically illustrated in Fig. 2 by the orientation of the hexagonal unit cell in the fracture surface of the CT-specimen. The $\{12\bar{3}3\}$ - pole figure of the α-phase confirms the above described observations (see Fig. 3a). Taking the milled+annealed 650 °C/1 h condition in the following as reference value of the material, shot peening leads to a decrease of the ratio of impulse values I_{min}/I_{max} (see Fig. 3b). Hence, the texture is not so clearly pronounced, but there is no change in the type of the texture.

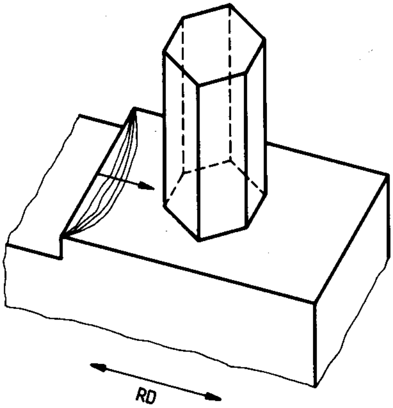

Fig. 2: Orientation of the hexagonal unit cell in the fracture surface (schematically) (RD: rolling direction)

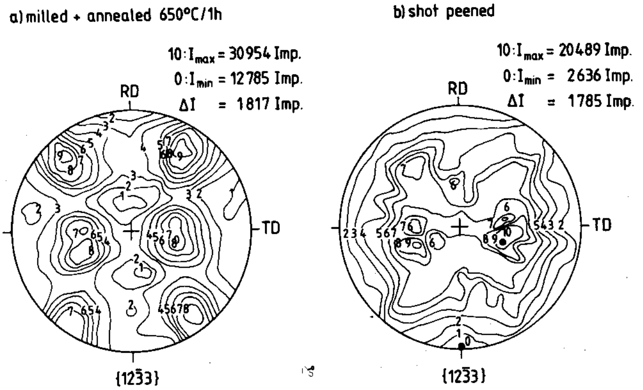

Fig. 3: {12$\bar{3}$3}-pole figures (RD: rolling direction, TD: transverse direction)
a) milled+annealed 650 °C/1h
b) shot peened (S 170, p = 1.6 bar, 3×98 % coverage)

Fig. 4a reveals the characteristic residual stress profile after shot peening with the maximum of residual stress σ^{RS}_{max} = -830 N/mm^2 at a distance of 0.1 mm below the surface. The surface residual stress σ^{RS}_{S} totals -650 N/mm^2. Half width decreases in the 0.1 mm thick near surface layer from 190 min at the surface to a constant level of 130 min (see Fig. 4b). Micro-hardness HV 0.1 as a function of the distance from surface, also presented in Fig. 4b, changes its values from 410 HV 0.1 at the surface to 360 HV 0.1 in a depth of 0.5 mm.

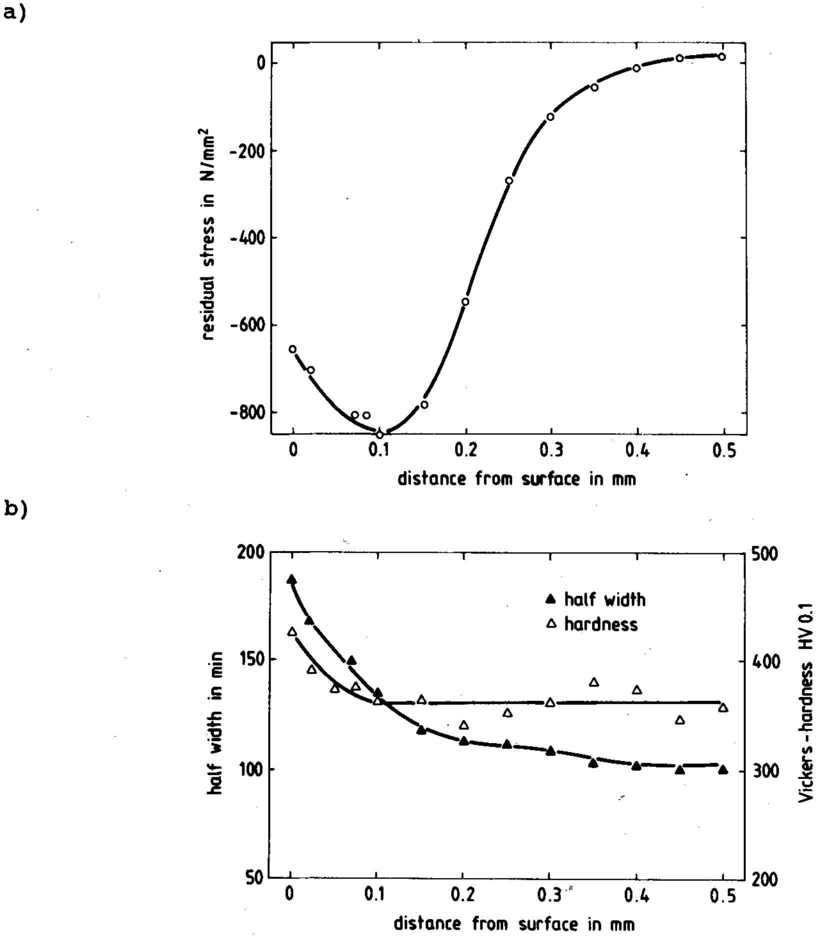

Fig. 4: a) Residual stresses, b) half width and micro-hardness HV 0.1 as a function of distance from surface after shot peening (S 170, p = 1.6 bar, 3×98 % coverage)

The variation of fatigue crack growth (FCG) rate da/dN with the alternating stress intensity ΔK as a function of temperature T and stress ratio R is shown in Figs. 5 to 7.

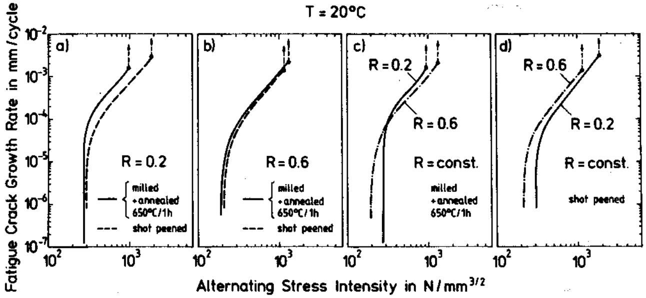

Fig. 5: Fatigue crack growth rate da/dN vs. alternating stress intensity ΔK at T = 20 °C showing the influence of a) shot peening at R = 0.2, b) shot peening at R = 0.6, c) stress ratio R in the milled+annealed 650 °C/1 h condition, d) stress ratio R in the shot peened condition

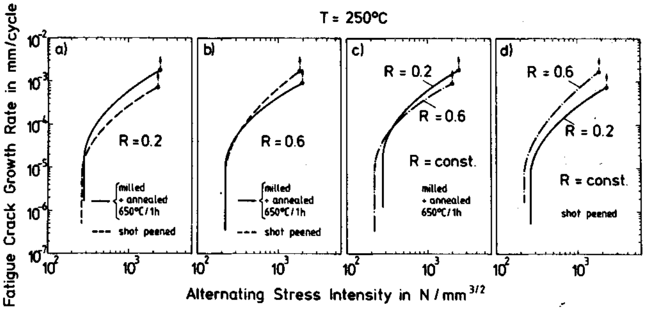

Fig. 6: Fatigue crack growth rate da/dN vs. alternating stress intensity ΔK at T = 250 °C showing the influence of a) shot peening at R = 0.2, b) shot peening at R = 0.6, c) stress ratio R in the milled+annealed 650 °C/1 h condition, d) stress ratio R in the shot peened condition

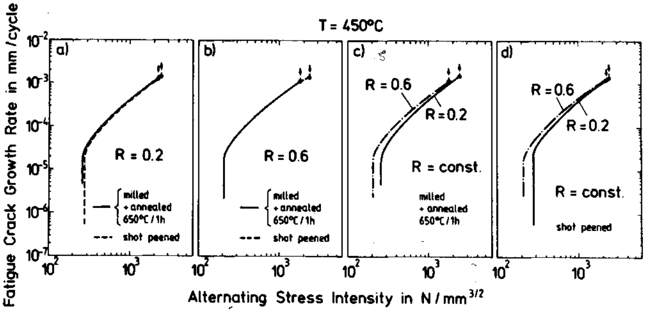

Fig. 7: Fatigue crack growth rate da/dN vs. alternating stress intensity ΔK at T = 450 °C showing the influence of a) shot peening at R = 0.2, b) shot peening at R = 0.6, c) stress ratio R in the milled+annealed 650 °C/1 h condition, d) stress ratio R in the shot peened condition

At room temperature, shot peening evidently increases FCG resistance at both stress ratios R = 0.2 and R = 0.6 (see Figs. 5a, 5b). Up to $da/dN \approx 10^{-5}$ mm/cycle at R = 0.2 the shot peening effect is only slight, but then FCG resistance increases significantly. The shot peening at R = 0.6, however, has only a marginal influence upon decreasing FCG rate in the investigated alternating stress intensity range.

The effect of diminishing FCG rates by shot peening is caused by crack closure. In order to discuss this fact, Fig. 8 schematically illustrates the crack profile in the fracture surface of a shot peened CT-specimen. The shaded portions represent the extent of the zone of compressive residual stresses. The relatively small balancing residual tensile stresses ($\approx$ 100 N/mm^2) acting over a much larger area and the work hardening effect both increasing FCG should obviously be ignored. In this connection, (6) demonstrated by surface crack opening displacement (SCOD) measurements that surface residual stresses exert a significant influence upon the SCOD. A comparison between the SCOD's versus load behaviour of a shot peened sample before and after a stress relief heat treatment emphasized that crack opening begins shortly after the application of load for the stress relieved condition. In contrast, the critical load for the shot peened sample was shifted to a higher value. Hence, even after the majority of the crack has moved out of the residual stress field (see Fig. 8), the surface opening is still reduced substantially by the compressive stress state (near surface layers) which influences the effective alternating stress intensity ΔK_{eff}. It is as well widely accepted that the stress ratio R has a significant influence upon crack closure, too, caused by compressive residual stress fields in the process zone at the crack tip (7). (8) showed that at small ΔK the values of ΔK_{eff} are smaller at R = 0.1 than at R = 0.7. At high ΔK, there is no crack closure. Figs. 5c and 5d demonstrate the crack closure effect as a function of R. Increasing R from 0.2 to 0.6 leads to a shifting of FCG rates to higher values. Summarizing it can be said that ΔK_{eff} is a function of stress ratio R and residual stress state of shot peening. Thereby the influence of crack closure is more evident at R = 0.2 than at R = 0.6.

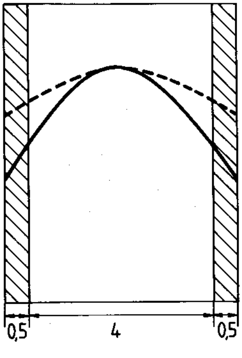

Fig. 8: Schematic crack profiles in the fracture surface of a CT-specimen (— shot peened, - - milled + annealed 650 °C/ 1 h)

The results of fatigue crack propagation tests at T = 250 $^{\circ}C$ are demonstrated in Fig. 6. The trends of the curves are similar to those obtained at T = 20 $^{\circ}C$ with two exeptions. At R = 0.2 (see Fig. 6a) up to da/dN $\approx 1.2 \times 10^{-5}$ mm/cycle shot peening increases slightly FCG rates and for R = 0.6, the curves of the milled+annealed and shot peened condition are reversed.

Total residual stress relaxation caused by thermal and cycle loading at T = 450 $^{\circ}C$ is the reason for the fact that shot peening exerts no influence upon the FCG rates compared to the milled+annealed condition (see Fig. 7).

A summarizing review showing the influence of temperature upon fatigue crack propagation is represented in Fig. 9. It is evident that for R = 0.2 and R = 0.6 (milled+annealed and shot peened condition) the temperature effect is minimal at low ΔK, i. e. there is a marginal increase in FCG with increasing temperature. Upon da/dN$\approx 5 \times 10^{-5}$ FCG curves at T = 250 $^{\circ}C$ and T = 450 $^{\circ}C$ show a corresponding shifting to lower FCG rates compared to the room temperature results. These trends of the curves can be explained by dynamic strain aging processes, i. e. by the interaction of mobile dislocations in the plastic zone at the crack tip with diffusing oxygen atoms. (9) established quite well in α-titanium that at temperatures of 0.3 to 0.45 T_m dynamic strain aging occurs. Thus, in comparison to the results obtained at room temperature, dynamic strain aging leads to a local increase in the cyclic yield strength at the crack tip. Furthermore, the plastic deformations are enlarged, which results in a shifting of the FCG rates to smaller values.

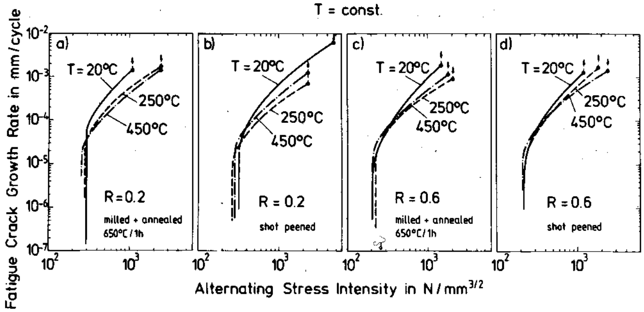

Fig. 9: Fatigue crack growth rate da/dN vs. alternating stress intensity ΔK at T = const. in the

a) milled+annealed 650 $^{\circ}C$/1 h condition at R = 0.2,
b) shot peened condition at R = 0.2,
c) milled+annealed 650 $^{\circ}C$/1 h condition at R = 0.6,
d) shot peened condition at R = 0.6.

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