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ScienceDirect

Scripta Materialia 61 (2009) 343–346

Scripta MATERIALIA

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Stability of shot-peen residual stresses in an α + β titanium alloy

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Received 15 October 2008; revised 23 February 2009; accepted 23 March 2009
Available online 26 March 2009

Shot-peen residual stress relaxation due to thermal exposure and fatigue loading was characterized in Ti–6Al–2Sn–4Zr–6Mo. Approximately 80% of the residual stresses were retained at 399 °C up to 100 h. Under fatigue loading close to yield stress, retention of residual stresses was approximately 85%, 70% and 50% at 260, 316 and 399 °C, respectively. Crack growth calculations demonstrate 1.5–5× benefit in life, even for partial credit for shot-peen residual stresses.
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Keywords: Fatigue; Relaxation; Residual stresses; Shot peen; Titanium alloy

Recent technology development initiatives such as the Engine Rotor Life Extension (ERLE) [1] and Prognosis [2] Programs are aimed at extending the useful lifetime of major, fracture-critical turbine engine components and managing risk through accurate determination of remaining component life. A broad range of related technologies such as life prediction and fracture mechanics, nondestructive evaluation, engine usage and health monitoring, and component repair have been targeted for achievement of these goals. Current life management practice (Engine Structural Integrity Program, ENSIP) [3] by the US Air Force uses a damage-tolerance-based method for managing the life of safety-critical components. This approach is based on systematic inspections of critical life-limiting locations in components. The inspection intervals are determined as 50% of the predicted crack growth life from an assumed initial crack size. The prediction of the crack length vs. cycle behavior at critical locations is based on the expected thermomechanical loading conditions and the crack growth behavior of the material. Prior to insertion in service, most critical locations, such as holes, stress concentration sites, etc., are subjected to surface enhancement procedures, typically shot-peening [4–6]. Shot-peening introduces significant near-surface (within 150–200 μm) compressive residual stresses. The benefits of these compressive residual stresses in improving fatigue life, retardation of crack growth and resistance to foreign object damage have been extensively demonstrated [7,8]. However, current damage-tolerance-based life management practices, i.e. predictions of crack initiation life and crack propagation life, do not explicitly account for the residual stresses induced by surface enhancement procedures [7]. Hence, incorporating residual stresses into crack growth life prediction is a key life extension technology. Many authors have shown that surface treatment, e.g. shot-peen, induced residual stresses relax following thermal exposure [8–15], and static and cyclic mechanical loading [8–12,14,16–19]. An extensive survey of these results for various materials has been reported in Ref. [7]. Therefore, prior to incorporation into life prediction, detailed quantification of the residual stress relaxation is required. This paper provides an assessment of the stability of the shot-peen residual stresses in a titanium alloy under simulated service conditions and the beneficial effect on crack growth life.

The material used in this study was an α + β processed Ti–6Al–2Sn–4Zr–6Mo (wt.%) (Ti-6246). This material was forged and heat treated to produce a fine duplex microstructure of equiaxed primary α phase (hexagonal close packed) in a matrix of platelet α + β (body-centered cubic). Additional details of the material microstructure can be found in Refs. [20,21]. The 0.2% yield strength for this material is 1140, 850, 850 and 800 MPa at 23, 260, 316 and 399 °C, respectively [21].

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1359-6462/$ - see front matter Published by Elsevier Ltd. on behalf of Acta Materialia Inc.
doi:10.1016/j.scriptamat.2009.03.038

The ultimate tensile strength is 1224, 1040, 1048 and 992 MPa at 23, 260, 316 and 399 °C, respectively [21].

The specimens used in this study were part of a fatigue variability study on Ti-6246. These specimens were electrodischarge machined (EDM) with the length aligned in the circumferential orientation from forgings. The final machining was done by low-stress grinding (LSG). The round-bar geometry had a gage diameter of about 4 mm and gage length of about 12.5 mm. Shot-peening was performed on the LSG surface. The peening intensity was 6A (Almen A scale as per the SAE specification), and the coverage was 100%. All the specimens were peened in a single batch.

The fatigue tests were performed under axial, load-controlled isothermal conditions at 20 Hz and stress ratio $(R) = 0.05$. All the fatigue tests were conducted using a constant-amplitude sine wave profile with the maximum stress of 860 MPa, which is slightly higher than the intermediate temperature yield stress of 850 MPa. The test temperatures ranged from 23 to 399 °C and the atmosphere was laboratory air. A four-zone closed-loop controlled quartz-lamp system was used to maintain the required temperatures [21]. The heating rate and the soaking time at temperature before commencing a test were kept constant across all tests to minimize any variation in the thermal relaxation of residual stresses between specimens prior to cycling. The total soak time, including the ramp-up time, was 30 min for all specimens. The heating time from 23 °C to the test temperature was approximately 7–10 min.

All the thermally exposed specimens and interrupted fatigue specimens were cut into two pieces in the middle of the gage length, thus providing two specimens per test condition for residual stress profile measurements. Half of the failed specimens were used for post-fatigue residual stress profile measurements. The residual stress measurements were collected at the surface and at nominal depths of 0.012, 0.025, 0.050, 0.075, 0.125, 0.175, 0.250 and 0.350 mm. X-ray diffraction coupled with serial material removal was used to determine the residual stresses at each depth location. The X-ray diffraction measurements were based on the α phase and the crystallographic elastic constants corresponding to the (21.3) planes. All the residual stress values reported in this study correspond to the loading direction, i.e. longitudinal direction of the specimen.

The baseline residual stress profile (at 23 °C) produced by shot-peening is shown in Figure 1. On the surface, the compressive residual stress was about 860 MPa and the maximum compressive stress was 1000 MPa, about 20–50 μm below the surface. The depth of the compressive layer was about 150 μm.

Figure 1 also shows the data following exposure to elevated temperatures for 100 h. There is no change in the residual stress profile after 100 h exposure at 260 °C. At 316 °C, the surface residual stress and sub-surface peak residual stress decreases to −700 and −900 MPa, respectively. This relaxation in residual stress values corresponds to approximately 19% and 10% decrease in the surface and sub-surface peak values, respectively. At 399 °C, the surface residual stress and sub-surface peak residual stress decreases to −455 and −780 MPa, respectively. This relaxation in residual stress values corresponds to approximately 47% and 22% decrease in the surface and sub-surface peak values, respectively. These results are consistent with the thermal relaxation results reported by Prevey et al. [6] on β forged and heat-treated Ti-6246. Hence, in the absence of mechanical loads, approximately 80% of the sub-surface peak residual stresses are retained, even after 100 h of exposure to 399 °C $\approx 0.35T_H$ (T_H = homologous temperature). In addition, the relative change in surface residual stress is significantly different from that of the sub-surface peak values. Therefore, quantification of the complete residual stress profile relaxation during service is required for accurate component life prediction.

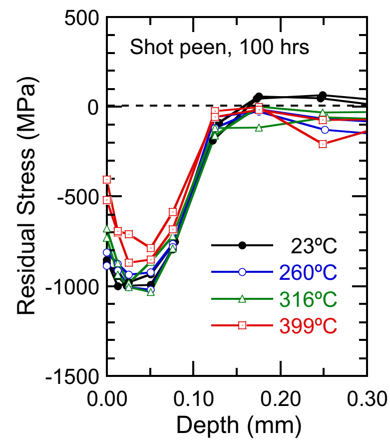

Figure 1. Effect of thermal exposure of up to 100 h on the shot-peen residual stress in Ti–6Al–2Sn–4Zr–6Mo. Number of specimens per temperature = 2.

The results from interrupted and failed fatigue tests are shown in Figure 2. All the results corresponding to 260 °C were obtained from eight specimens that failed in the range 97–351 kcycles [21]. The results corresponding to 316 and 399 °C were obtained from specimens that were tested to 100 cycles and then split, as discussed earlier. Zhuang and Halford [22] showed that the most relaxation under fatigue loading occurred within the initial 10–100 cycles, depending on stress ratio. Hence, the

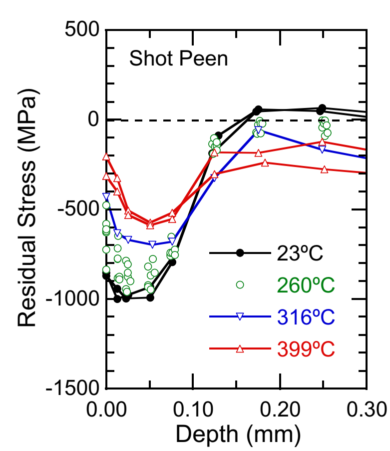

Figure 2. Effect of cyclic loading (860 MPa, $R = 0.05$) on shot-peen residual stress in Ti–6Al–2Sn–4Zr–6Mo at temperatures from 23 to 399 °C.