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Technical note

Dwell-fatigue life dispersion of a near alpha titanium alloy

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ABSTRACT

An experimental study was undertaken to examine the evolution of life, strain, strength and damage in titanium IMI 834 during dwell-fatigue loading conditions. The tests were conducted on smooth cylindrical specimens under load control with trapezoid wave form of 0.033 Hz frequency and zero load ratios. The specimens were cut from identical disk forgings and tested in the same conditions at room temperature, as it is normally done in the industry. Thirty seconds dwell time was imposed at the maximum load test, 824 MPa (90% of the yield strength). The total rigidity decrease during the test was plotted against the number of cycles for all specimens. Jumps were observed in the curves. They may be related to the nucleation and propagation of cracks in the material. Scanning electron microscopy observations show that all failures take place from a sub-surface nucleation site which seems to nucleate at random times during the dwell-fatigue tests.

1. Introduction

An important fraction of service failures of structural materials can be attributed to dwell-fatigue. The failures are caused by irreversible changes in the properties of the material due to the application of cyclic stresses or strain (simple fatigue) with the addition of a dwell time at the maximum stress or strain (dwell-fatigue). These changes result in the degradation of the fatigue life/fatigue strength of the material.

The present work focuses on the dwell-fatigue characterization of titanium alloy IMI 834. It is a near-α titanium alloy used for rotating components in the compressor of jet engines. This alloy's bimodal microstructure consisting of primary and secondary alpha grains has been developed for service temperatures up to 600 °C [1].

This alloy showed a significant fatigue life reduction when a dwell was imposed at maximum load during the fatigue cycle [2–4]. Thus, a great effort has been devoted to studying the dwell-fatigue behavior of near-α titanium alloy [1–9]. In general, previous authors compared different samples having widely different microstructures and reported widely different dwell-fatigue properties. However, it is suspected that the IMI 834 alloy may have varying dwell-fatigue properties within a single part. In this work, specimens obtained from several forged IMI 834 titanium disks are subjected to dwell-fatigue at the same levels of applied maximum tensile stress. Our samples have the same bimodal microstructure consisting in a 20%, 25 μm primary alpha grains in a 30 μm transformed beta grains (Fig. 1). However, as they have been cut from various regions of the forged parts, they may present some variations of microstructure. Such variations are known to affect the dwell-fatigue behavior of the alloys. The present work focuses on this issue by monitory the strength evolution during dwell-fatigue as a function of the number of cycles.

The residual mechanical properties at specified loading cycles and the number of cycles at which the specimens fail are measured. For the material used in this study, the loss in mechanical properties (modulus) is different from one specimen to another. The life and strain in fatigue-dwell vary significantly from one sample to the next.

2. Experimental description

All specimens were tested at constant loading level and a frequency of 0.033 Hz: the stress ratio was $R = 0$ and a trapezoidal wave form with 30 second hold at the maximum load (824 MPa) was used. The test specimens were machined in accordance with E606-04 ASTM standard practice for strain-controlled fatigue testing [10]. The specimen geometry shown in Fig. 2d was chosen with a uniform circular cross section with a gauge diameter of 6.2 mm and 20.5 mm gauge length. During dwell-fatigue testing, an extensometer was connected to the data acquisition system of the hydraulic machine, and fixed on the gauge-length section of the specimen. The strain values of the gauge length, measured by

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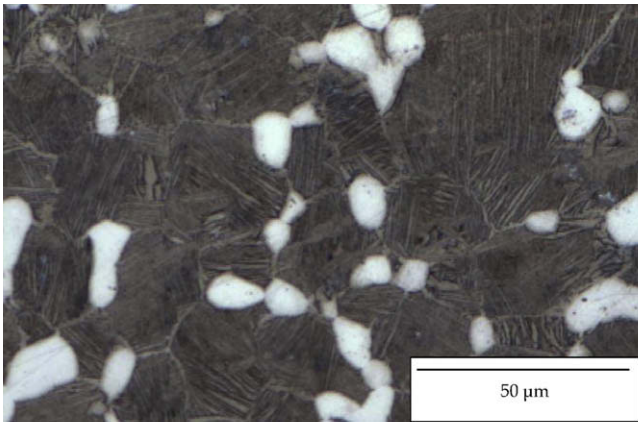

Fig. 1. Optical micrograph showing the bimodal, near-α microstructure of titanium alloy IMI 834.

the extensometer, were recorded electronically for further analyses. The continuous acquisition of the stress ($\sigma_{\min} \leqslant F/S \leqslant \sigma_{\max}$) by the load sensor of and of the strain ($\varepsilon_{\min} \leqslant \varepsilon_x = \Delta L_x/L_0 \leqslant \varepsilon_{\max}$) by the extensometer allows to calculate for each cycles the longitudinal Young modulus. No hysteresis and a linear stress–strain relationship were observed. A linear regression was used to calculate the Young modulus for each cycle.

3. Results and discussion

The results are summarized in Table 1. For all specimens, the fatigue life is less than 10,000 cycles. For this level of load, the results are consistent with those found in the literature [3,5]. We observed a variation in fatigue life between 1658 and 9050 cycles, with an average value of 4630 cycles and a standard deviation of 2426 cycles. There is a factor of 5 in the number of cycles to failure between the highest life (specimen 6) and the lowest life (specimen 5). The table shows a variation in the initial Young's modulus. Young's modules vary between 114.97 GPa and 117.18 GPa, with an average value of 115.73 GPa and a standard deviation of 0.74, which is approximately the absolute measurement accuracy of our experiment (estimated to be about 1%). The strain before the final rupture of the specimens was around 0.011. Only specimen 10 shows a larger strain of 0.015 mm/mm. Fig. 3 shows that a simple Weibull distribution describes very well the number to failure statistics of the obtained results. The 50% probability of rupture is approximately 4400 cycles and the beta coefficient of the Weibull distribution is 2. Therefore, the dwell-fatigue life distribution of samples taken from supposedly homogeneous forged parts displays large variations and can be described using a Weibull distribution.

Figs. 4 and 5 document the evolution of the irreversible strain at the peak load and the loss of the elastic properties (Young's modulus) according to the number of cycles. Three groups of curves can be found in Fig. 4. Specimens 1, 2, 4, 6 and 9 form group A which

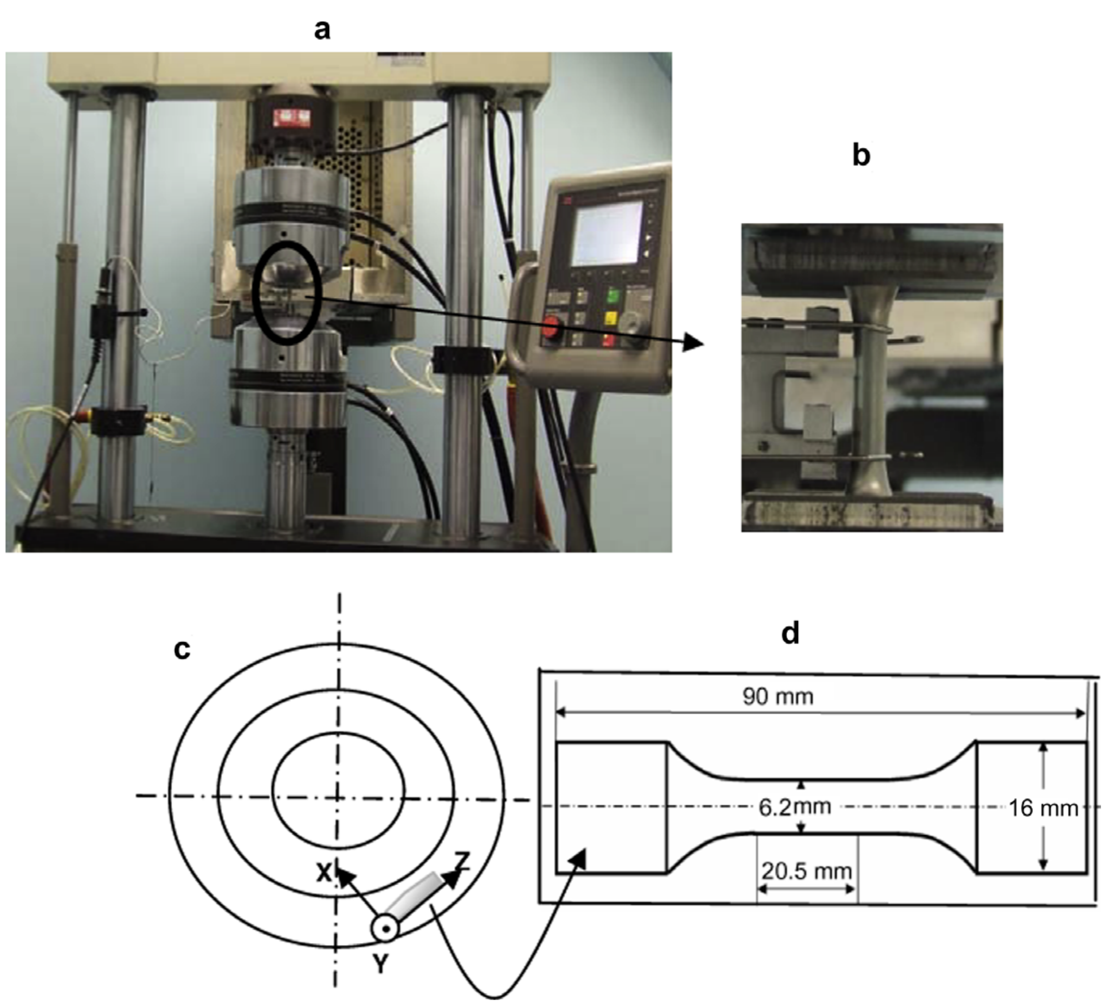

Fig. 2. Test devices (a) fatigue machine, (b) extensometer attached to test sample, (c) forged disk, and (d) test specimen.