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Dwell-fatigue life of a near-alpha titanium alloy and ultrasonic measurement correlation

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Abstract: Early failure during dwell-fatigue of titanium alloys is a research of interest as it directly drives the in-service life of critical parts in turbines. A study was undertaken to examine the evolution of life and strain in six specimens made of near-alpha titanium alloy (IMI 834) during dwell-fatigue loading conditions. The strain accumulation in dwell-fatigue test for one sample was significantly different. This specimen presents a different ultrasonic response from that of the other specimens, that is ultrasonic measurements reveal a different macro-texture for this sample. When this specimen is excluded, it is found that ultrasonic speed correlates well with dwell-fatigue life for the remaining samples. This paper evaluates the usefulness of ultrasound waves to predict the strain and the dwell-fatigue life of a titanium alloy.

1. Introduction

Near-alpha titanium alloys have a good fatigue and creep resistance combined with high strength to weight ratio. However, engine components machined from large forged discs have a fatigue life over an order of magnitude smaller when a dwell period at high stress levels is added to the cold fatigue cycle. Thus, the dwell (cold creep) coupled with fatigue increases the initiation rate of damage in these alloys [1-8]. Experiments showed that some regions of the part are subject to early fatigue damage. It is suspected that these regions are related to specific crystal orientation of highly textured macrostructures (called macrozone) present in the billet prior to forging [9]. A macrozone consists of small grains grouped together within several prior beta grains [10], all grains having very close crystallographic orientations. These macrozones are known to be damage accumulation sites which eventually lead to premature failure of manufactured components [8-9]. Automated Electron Backscattering Diffraction (EBSD) scans can identify and quantify these large scale heterogeneities [8-9], however, the technique is destructive, time consuming and relatively expensive. In this contribution, we show the capacity of the ultrasounds to characterize texture heterogeneities, which are known to play a significant role in fatigue and dwell-fatigue performance in titanium alloy. We also show that sound velocity, a proxy for average texture, correlates with fatigue life.

2. Dwell-fatigue test

The material used in dwell-fatigue tests is an IMI834 titanium alloy. As it is normally done in the industry, specimens were cut from similar locations in identically processed disk forgings and tested in the same conditions at room temperature (Fig. 1). The test specimens were machined in accordance with E606-04 ASTM standard practice for strain-controlled fatigue testing [11]. Specimens were machined smooth in the standard round bar specimens, with a gauge diameter of 6.2 mm and a 20.5 mm gauge length. The specimens were loaded and unloaded in 0.5 s on a hydraulic machine at load ratio R = 0 and load control mode. An extensometer was connected with the data-acquisition system of the hydraulic machine and fixed on the gage-length section of the specimen. The strain values were recorded directly into an acquisition system for further analyses. Thirty-second dwell time was imposed at the maximum load test, 26.5 kN (824 MPa, i.e. 90 % of the yield strength).

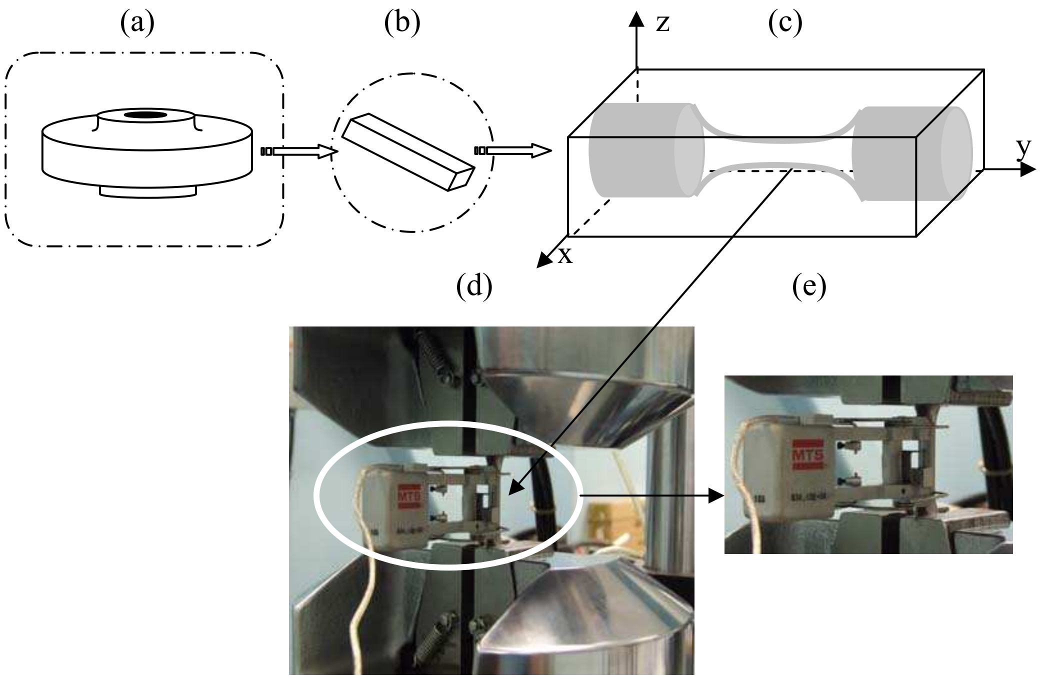

Fig. 1. Test devices (a) Forged disks, (b) Block of titanium, (c) Test specimen, (d) Fatigue machine and (e) extensometer attached to test sample

3. Results and discussion

The fatigue life, measured as the number of cycles to failure and denoted Nf, is summarized in Table 1. We observe a variation in fatigue life between 3169 and 7367 cycles, with an average value of 4824 cycles and a standard deviation of 1572 cycles. There is a factor of 2 in the number of cycles to failure between the highest life (specimens 3) and the lowest life (specimen 4). Figure 2 documents the evolution of the irreversible strain according to the number of cycles. The increase in total strain with respect to number of cycles was much more pronounced for Specimen 6. Clearly, this sample distinguished from the other specimens (fig. 2).

Table 1. Fatigue life for the 6 specimens

Specimen number	1	2	3	4	5	6
Nf (cycles)	5082	4449	7367	3169	5592	3285

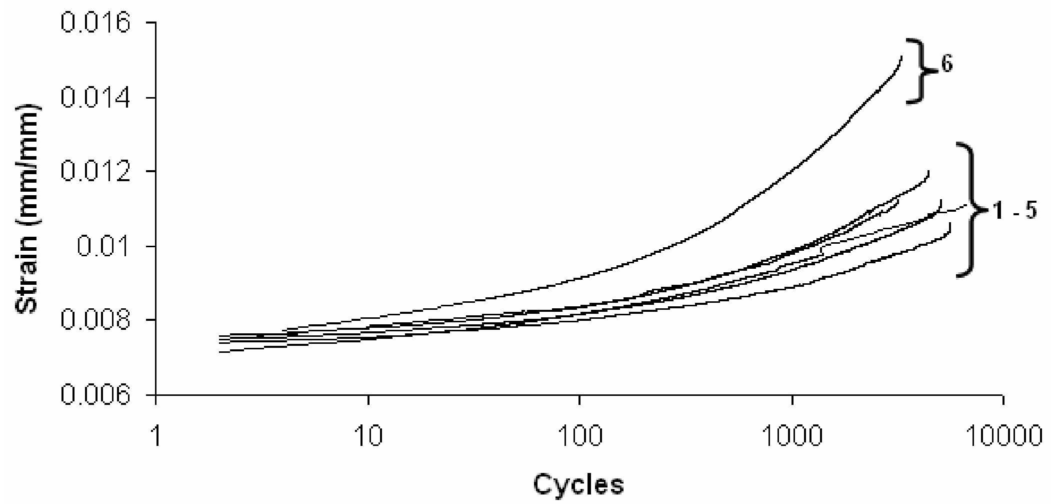

Fig. 2. Strain accumulation under dwell fatigue conditions.

In order to evaluate the quality of a forging, many techniques can be used. Traditionally, to evaluate the grain flow, sections of parts are chemically attacked and visually examined. Other techniques like scanning electron microscopy (SEM) and Electron Backscattering Diffraction (EBSD), or x-ray or neutron diffraction can also be used [8-14]. But these costly techniques are generally destructive and require a good surface preparation. In addition, these techniques are not well adapted for efficient detection in volume (except neutron diffraction).

A non-destructive testing method capable of identifying and/or characterizing macrozone heterogeneities would be very useful for the industries. In this contribution, we show the capability of ultrasound to characterize these heterogeneities in titanium alloys. Before the test specimens were machined from titanium blocks, the blocks were measured with an ultrasonic technique in order to detect highly microtextured regions. Figure 3, illustrates local variations of texture in titanium alloy obtained with ultrasonic measurements. The images for Specimen 1 through 4 cover an area of 60 by 24 mm^2 in the xy plane. The image for Specimen 5 and 6 cover areas of 60 x 20 mm^2 and 40 x 12 mm^2, respectively. The gray scale variations are a representation of local texture variations. All images show vertical structures that reminiscent of the macro-textured regions observed previously in other samples of the same sample set which originally contained 21 samples [15]. Just as for the strain measurements during dwell fatigue tests, the image obtained by ultrasound is qualitatively different for sample

6. Qualitatively samples 1 to 5 have similar macrostructures whereas sample 6 a significantly different.

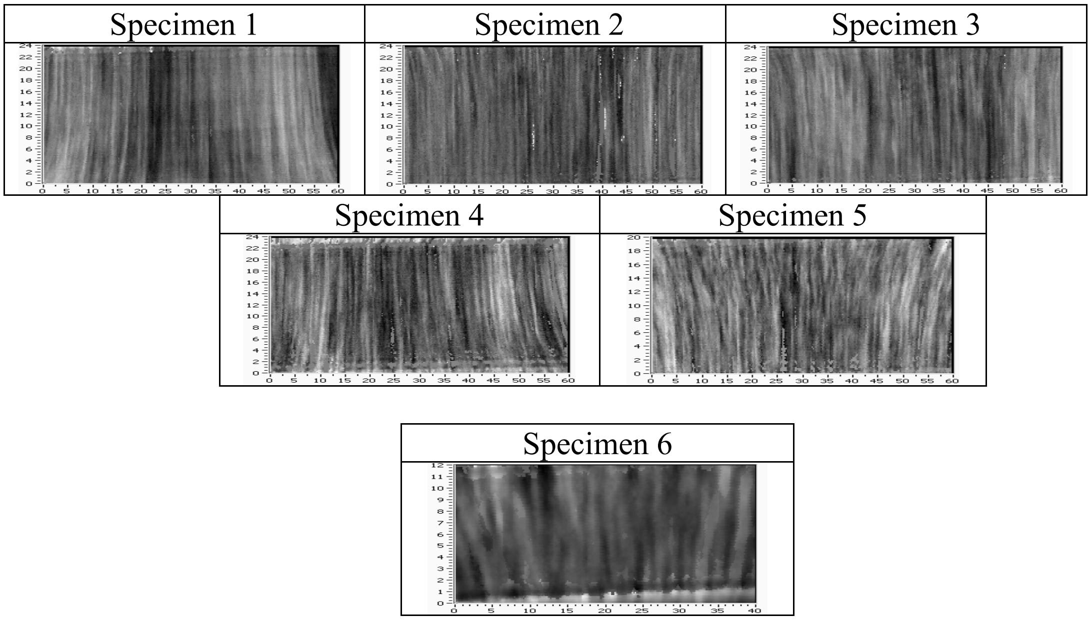

Fig. 3. Ultrasonic representation of local texture variations in the samples

Acoustical waves, when propagating, interact with the micro and macrostructure of materials and acquire a significant amount of information. In particular, the sound velocity is known to be related to the average texture. Measurements of longitudinal-wave velocities were taken in the y-direction (Fig. 1c). The dwell-fatigue life is plotted as a function of these velocities in Figure 4.

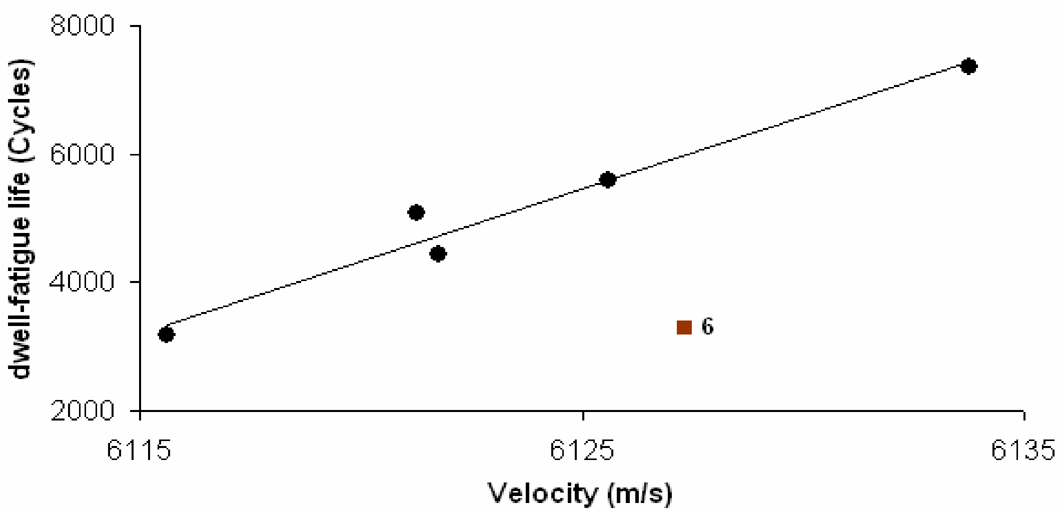

Fig. 4. Ultrasound velocity as a function of dwell-fatigue life; the straight line is a linear least squares fit through the data, excluding specimen 6.

A correlation between ultrasonic velocity and the dwell-fatigue life is found if specimen 6 is excluded. Interestingly, sample 6 presents coarser heterogeneities in the images of Fig. 3. Given that the samples were 100% dense, i.e. they contained no porosity; the observed variations in velocity must be caused by variations in elastic moduli. In turn, elastic moduli variations are often caused by variations in crystallographic texture, but other factors cannot be ruled out. It is then possible to suggest that the dwell fatigue life is proportional to the average ultrasound velocity for samples having similar macrozone structures. For coarser heterogeneities, Samples 6, the dwell-fatigue life is lower than that expected from the correlation.

4. Conclusions

The fatigue behavior of the near-alpha titanium alloy IMI834 is a complex phenomenon which involves the initiation and increase of local damage in the material as it is subjected to cyclic loading conditions. In this contribution, it was shown that ultrasound can characterize macroscopic heterogeneities in titanium alloys. In addition the dwell-fatigue life of the samples having similar ultrasonic heterogeneities was found to increase with ultrasound velocity. The sample having larger heterogeneities had larger strain rate as a function of dwell fatigue cycles.

Although our limited number of specimen is insufficient to draw firm conclusions, the results obtained are encouraging. We hope that this work will eventually allow the prediction of the dwell-fatigue life using non-destructive ultrasonic inspection.

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