REAL-TIME MONITORING OF ACOUSTIC LINEAR AND NONLINEAR BEHAVIOR OF TITANIUM ALLOYS DURING CYCLIC LOADING

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ABSTRACT

Variation in acoustic nonlinearity has been monitored in real time during fatigue, on four dog-bone specimens of Ti-6Al-4V, under low cycle fatigue conditions, from the virgin state all the way to fracture. The results of these experiments show that the acoustic nonlinearity undergoes large changes during the fatigue and follows a similar trend for the material under given fatigue test conditions. Transmission electron microscopic (TEM) examination of the samples with similar composition fatigued to different stages indicates a gradual change in the microstructure and dislocation density, which correlates with the changes in acoustic nonlinearity.

INTRODUCTION

Ultrasonic attenuation and sound velocity measurements in a material undergoing fatigue show very small changes (less than 2%) and are not sensitive enough to characterize fatigue damage. It has been observed in ultrasonic wave propagation experiments, that a measurement of acoustic nonlinearity (β) of the material shows large changes due to fatigue [1, 2, 3]. This methodology seems to be a promising tool to monitor the fatigue damage in materials. In these experiments, a fundamental frequency (f) ultrasonic wave is propagated through the material and the amplitude (A_2) of the second harmonic frequency (2f) signal is measured. The acoustic nonlinearity is determined using equation 1 [4].

$$\beta = \frac{8}{xk^2}\left(\frac{A_2}{A_1^2}\right) \qquad (1)$$

Where k is the ultrasonic wave number and A_1 is the amplitude of the fundamental signal after propagating through the length x of the sample.

This paper presents results of the measurement of sound velocity, ultrasonic attenuation, and acoustic nonlinear property, in dog-bone shaped samples of Ti-6Al-4V, acquired during fatigue. The parameters have been measured continuously from the virgin state of the material, all the way to its fracture. Measurements have been performed on several samples under similar fatigue conditions to observe repeatable and consistent changes in the ultrasonic parameters. Variations in the nonlinear acoustic parameter have been observed to show the same trend in all the samples tested.

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EXPERIMENT

An in-situ technique developed for characterization and early detection of fatigue damage in aerospace materials has been described in detail elsewhere [5]. In short the principle of measurement is based on propagating a fundamental frequency ultrasonic signal through a dog-bone sample and detecting the second harmonic signal at the other end. Several improvements have been incorporated into the instrumentation for real-time measurement of acoustic properties. A newly designed transducer holder and special grips have greatly improved the reliability and reproducibility of the measurements.

A block diagram for the experimental setup is shown in Figure 1. This technique requires a tone burst signal generator and a power amplifier to launch longitudinal sound waves into the specimen at a frequency of 10 MHz. A high power bandpass filter was placed between the power amplifier and the transducer to make sure that unwanted harmonic signals are filtered out. The same transducer was used to detect the fundamental signal reflected from the other end of the specimen. A 20 MHz transducer bonded to the other end of the specimen was used to receive the second harmonic signal. Both transducers were 36^o Y-cut single crystal plates of $LiNbO_3$ and salol (Phenyl salicilate) was used as bonding agent. After the second harmonic signal is detected, it was fed to a linear narrow band amplifier through a 20 MHz bandpass filter. Both fundamental V_1 (mV) and second harmonic V_2 (mV) signals were sent to the D/A converter for digitization. The nonlinear factor is determined from the sampled signals by custom developed software [5].

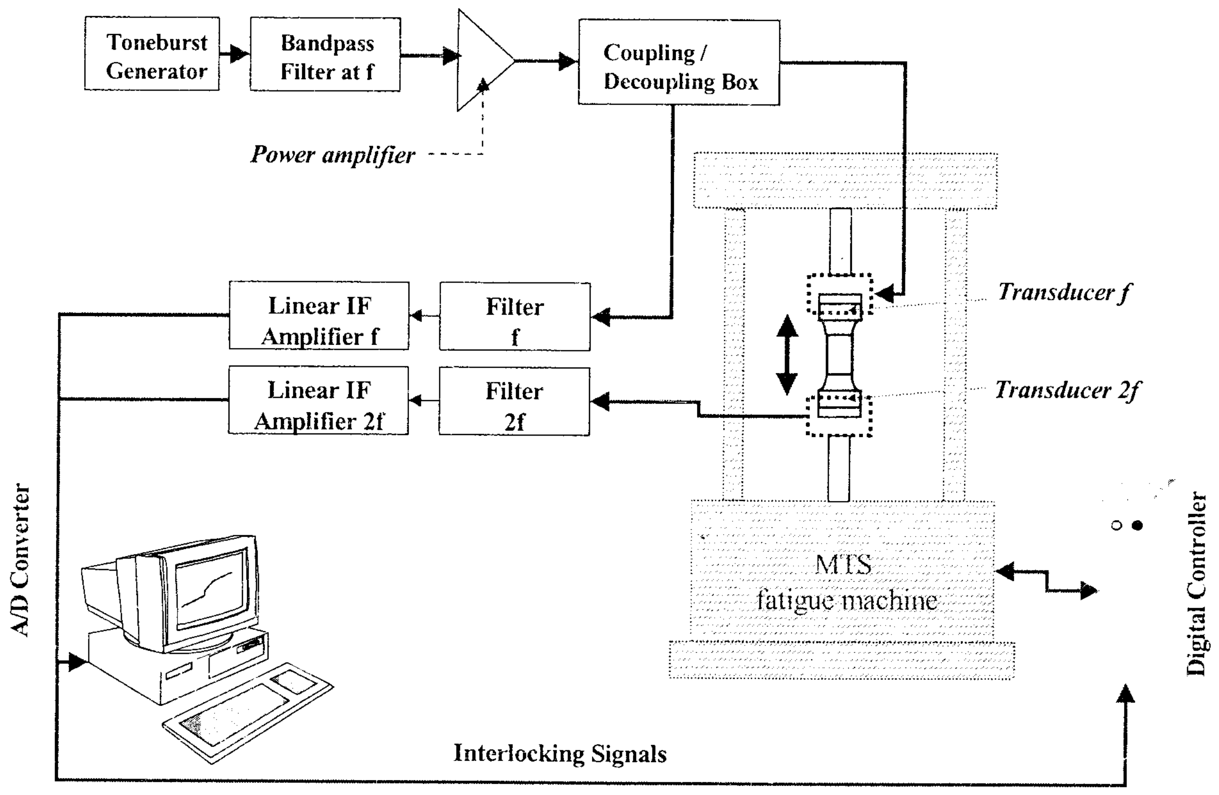

Figure. 1. Block diagram of apparatus for piezoelectric detection of second harmonic.

The sample was subjected to cyclic loading at the frequency of 1 Hz in an MTS fatigue machine. The σ_{max} was set to be at 850 MPa while the R ratio to 0.1. The ultrasonic velocity and nonlinear property were measured at zero load on the sample, at an interval of 100 cycles of fatigue.

RESULTS AND DISCUSSIONS

The acoustic nonlinearity measured in these experiments is an average over the entire length of the sample. The results of five samples of Ti-6Al-4V are shown in figure 2. One of the striking features of the curves is the similarity in the general trend of the variation of nonlinearity parameter for all the samples. Other salient features of the curves are:

(a) The parameter remained almost constant (30% increase) during the first 10-20 % of the fatigue life (region A of the curve). In addition, the nonlinearity parameter was observed to show slight fluctuations.
(b) After the first region the parameter increased linearly for about 40 to 50% of fatigue life (region B). At the end of this period the total increase of the material nonlinearity from the virgin state corresponds to about 100%.
(c) From 50 to 60% of the fatigue life until the final fracture, the parameter exhibits a plateau (region C).

An increase in the nonlinearity parameter due to fatigue is attributed to the continuous change in the microstructure of the material caused by increase in the dislocation density, formation of dislocation dipoles, multi-poles, and substructures developed in the material during the course of fatigue [2]. An investigation of a fractured specimen, fatigued under similar conditions, has shown the changes in the microstructure of the material from the fractured surface to the region of grip section [6]. In the region close to the fractured region a large dislocation density and substructure has been observed. Away from the fractured region the dislocation density and substructure reduces and finally only residual dislocation is observed in the grip section of the sample.

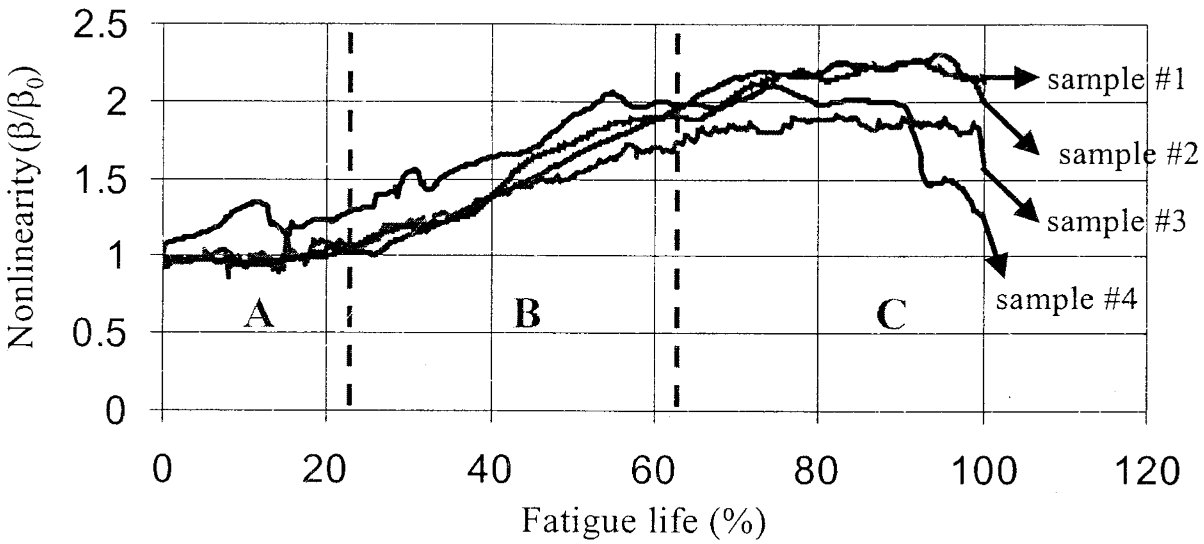

Figure 2. Normalized nonlinear parameter as a function of fatigue level monitored in real- time during the fatigue test for four samples of Ti-6Al-4V.

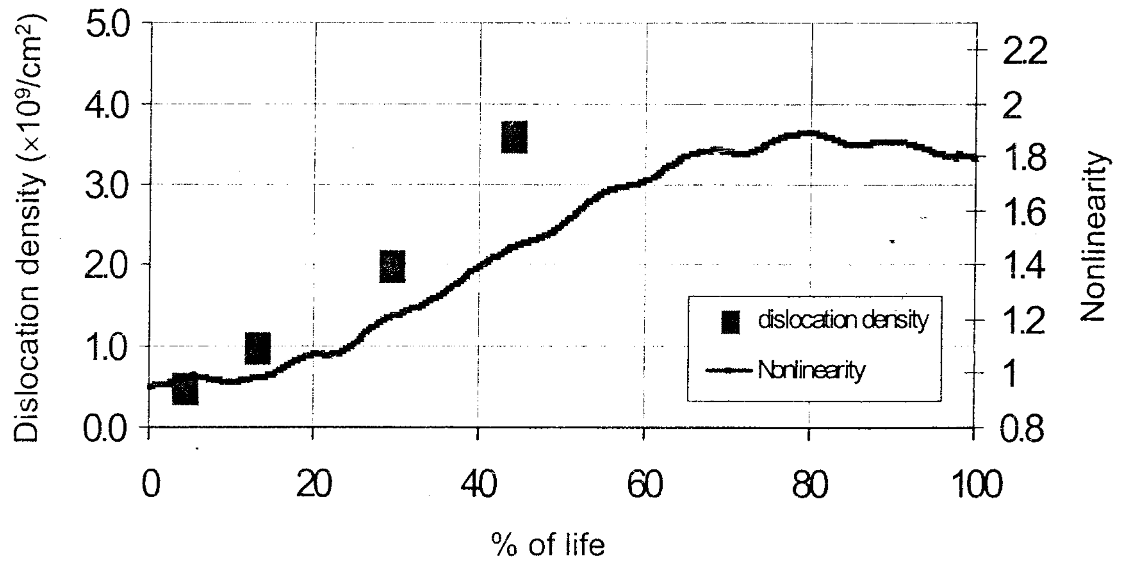

Figure 3. Dislocation density and material nonlinearity as a function of fatigue level.

In order to relate the changes in the nonlinearity to the material structural state, transmission electron microscopy measurements were performed to determine the characteristics and density of dislocations on samples fatigued to different levels to up to 40% of fatigue life [6]. These measurements were performed on slices cut from the central region of the dog-bone sample where the stress concentration is the highest.

Figure 3 shows a plot of the dislocation density and acoustic nonlinearity as a function of fatigue life. It has to be pointed out that the dislocation density and acoustic measurements were performed on different specimens taken from the same material and fatigued under similar conditions. In addition, the TEM measurements were performed over a small volume of the specimen, while acoustic nonlinearity is measured over an entire length of the sample. In spite of the enormous difference in the sensing volume, the measurement shows a good correlation between dislocation density and material nonlinearity. A large increase in the dislocation density has been observed in samples fatigued beyond 50% of the life so that it has been difficult to use traditional methods of extracting dislocation density from TEM. Measurement of dislocation density in the advanced stage of fatigue of the material is essential for an understanding of the mechanisms, responsible for the saturation of the acoustic nonlinearity. Information about the types and volume fractions of different types of dislocations is important to calculate the nonlinear acoustic parameter based on the model of Cantrell and Yost [1, 2].

Figure 4 shows the variation in sound velocity as a function of number of cycles. The changes in the velocity are within 1% during the entire test. This is in accordance with the earlier observations. As expected, the fatigue process does not largely affect the elastic modulus, which is related with the sound velocity. This illustrates that the sound velocity measurements are not suitable for fatigue damage characterization.

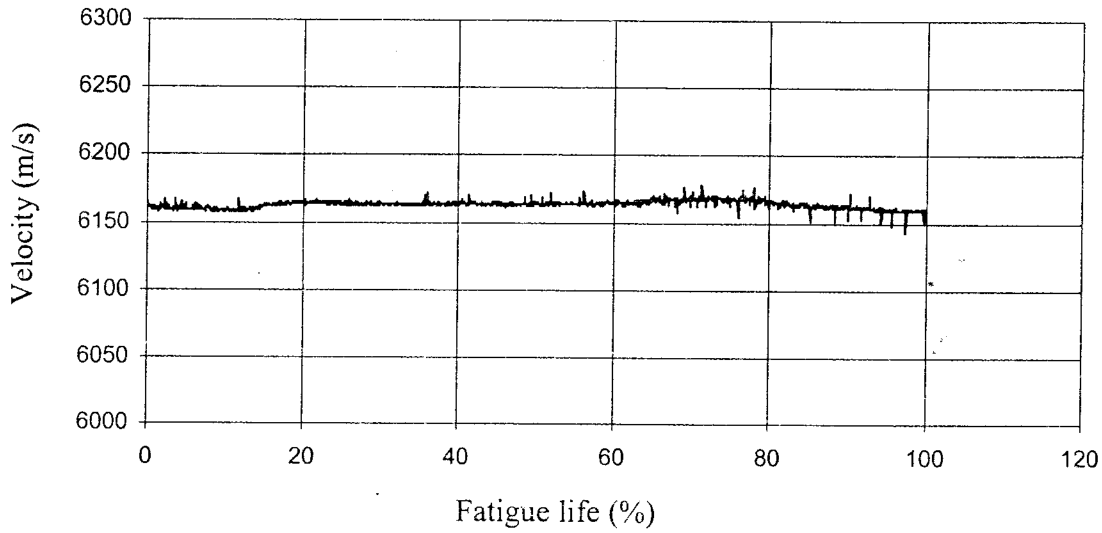

Figure 4. Sound velocity as a function of fatigue level.

CONCLUSIONS

A continuous change in the nonlinear acoustic parameter has been observed during real time monitoring of the fatigue process in five samples of Ti-6Al-4V. The general trend of the curves for all the examined samples is similar, indicating a possible "signature" in the nonlinear acoustic parameter vs. number of loading cycles curve. An initial region of fluctuation, a region of steady increase and saturation after 50 to 60% of life has been observed in the acoustic nonlinearity curves. Transmission electron microscopic measurement of dislocation density in samples fatigued to different level show a gradual increase, which is similar to the acoustic nonlinearity parameter.

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