Journal of
MATERIALS RESEARCH

Ultrasonic linear and nonlinear behavior of fatigued Ti–6Al–4V

Jerome Frouin, Shamachary Sathish, Theodore E. Matikas, and Jeong K. Na
Center for Materials Diagnostics, University of Dayton, 300 College Park, Dayton, Ohio 45469-0121

(Received 10 July 1998; accepted 5 November 1998)

The change in ultrasonic nonlinear property of a titanium alloy subjected to cyclic loading has been studied, with an objective to develop a new characterization methodology for quantifying the level of damage in the material undergoing fatigue. In order to determine the degree of nonlinearity, the ultrasonic second harmonic generation technique has been used. The second harmonic signal was monitored during the fatigue process, and a substantial increase in the second harmonic amplitude (180% increase in nonlinear factor) was observed. This indicates that the second harmonic signal is very sensitive to the microstructural changes in the material caused by fatigue.

I. INTRODUCTION

A reliable inspection technique for quantifying fatigue damage in titanium alloys and for relating the level of damage to the remaining life of the material is essential for preventing catastrophic failures of jet aircraft engines. Many researchers have tried to develop techniques based on linear acoustics for fatigue characterization. Studies on the sound velocity as a function of number of fatigue cycles do not show appreciable changes. On the other hand, ultrasonic attenuation shows large changes, but identifying and attributing the changes due to fatigue are very difficult since several other factors can affect the attenuation in a similar way.

Recent studies on the nonlinear property of fatigued aluminum alloy 2024-T4 and stainless steel 410Cb have shown dramatic changes in their nonlinearity parameter β by the time the material undergoes 30 to 40% of the total fatigue life.[1,2] These measurements clearly show the changes in the nonlinear parameter due to fatigue. However, the measurements have not been performed on a single fatigue specimen. Several dog-bone specimens were prepared, fatigued to different numbers of cycles, and the middle section of each was cut. This process is reliable as long as the test coupons are assumed to have the same microstructural characteristics before fatigue. Because of the statistical variablity from specimen to specimen, this methodology may not provide meaningful information about the fatigue process. Moreover, this type of measurement is not suitable for developing a methodology for continuous monitoring of fatigue. As a first step in the direction of developing a methodology for continuous monitoring of fatigue, this paper reports results and discussion of sound velocity, attenuation, and second harmonic measurements performed on the same dog-bone specimen at several stages of fatigue.

Acoustic nonlinearity parameters of fatigued metals

Acoustic nonlinearity in materials is often determined by measuring the amplitude of the second harmonic signal A_2 generated when a pure sinusoidal longitudinal wave of amplitude A_1 (fundamental) propagates through the material. The dimensionless acoustic nonlinearity parameter of a material β is defined as[3]

$$\beta = \frac{8}{ak^2}\left(\frac{A_2}{A_1^2}\right), \tag{1}$$

where a is the wave propagation distance (sample length) and k is the propagation constant. A_1 and A_2 are absolute amplitudes having units of length.

Recent measurements of acoustic nonlinearity parameter in fatigued aluminum 2024-T4 (face-centered cubic) and stainless steel (body-centered cubic) have been explained by Cantrell and Yost[4] using interaction of acoustic waves with the dislocations in fatigued materials. It is well known that in the process of fatigue of fcc- and bcc-structured metallic materials, the microstructure undergoes dramatic changes, producing substructures such as veins and persistent slip bands (PSB's). It is also known that the basic building blocks of these fatigue substructures are dislocation dipoles. Cantrell and Yost[4] developed a quasi-isotropic model of the interaction of an acoustic wave with dislocation dipoles and dipole array approximations to multipole substructures generated during the fatigue process. The model predicts a substantial acoustic second harmonic generation that is independent of applied stresses or dislocation loop length, but is strongly dependent on the dislocation arrangements in the substructures. Based on theoretical calculations,[4] the acoustic nonlinearity parameter β of fatigued fcc metals, and perhaps bcc metals, can be given as

$$\beta = \beta_{\mathrm{lattice}} + f_{\mathrm{dipole}}\beta_{\mathrm{dipole}} + f_{\mathrm{T-N}}\beta_{\mathrm{T-N}} + f_{\mathrm{pT-N}}\beta_{\mathrm{pT-N}}\,, \tag{2}$$

where the term β_{lattice} is the contribution from the anharmonicity of the crystal lattice, and f_{dipole}, $f_{\mathrm{T-N}}$, and $f_{\mathrm{pT-N}}$ are the volume fractions of material consisting of isolated dislocation dipoles of density Λ, a

Taylor–Nabarro dislocation lattice structure of density Λ_{T-N}, and a polarized Taylor–Nabarro dislocation lattice structure of density Λ_{pT-N}. The factor β_{dipole} is the isolated dislocation dipole contribution to the nonlinearity parameter, β_{T-N} is the contribution from the Taylor–Nabarro dislocation lattice structure, and β_{pT-N} is the contribution from the polarized Taylor–Nabarro dislocation lattice structure. Detailed discussions of these factors are given in Ref. 4. It is important to point out that the dislocation contributions to β are considerably larger than the contribution due to the anharmonicity of the crystal lattice, especially in the advanced stage of the fatigue process.

II. EXPERIMENTAL TECHNIQUE

A. Sample preparation

A 90 mm dog-bone specimen, with a diameter of 12.5 mm for the grip sections and a diameter of 6.25 mm for the middle section, was prepared to be flat and parallel along its length within half wavelength of the green light and less than 2 μm variation across the diameter, respectively. The specimens were fatigued from zero to 40% of the fatigue life in a stress-controlled loading from 85 to 850 MPa (90% of yield strength) at a frequency of 1 Hz on a servo-hydraulic load frame. The specimen was removed from the load frame to measure the acoustic parameters at equal intervals of fatigue life. A separate specimen was fatigued until failure under the same conditions to determine the fatigue life of the material and it was broken at 35,000 cycles.

B. Experimental setup for the acoustic measurement

Details of various systems and methods for the acoustic harmonic generation technique are described elsewhere.[5–7] For this work, a relatively simple and straightforward, two-transducer method (known as f-2f method) was used. A block diagram for the experimental setup is shown in Fig. 1. This technique requires a tone burst signal generator and a power amplifier to inject sound waves with longitudinal mode in the specimen at a frequency of 10 MHz. A 10 MHz 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 as it was reflected from the other end of the specimen. In order to receive the second harmonic signal from the other end of the specimen, a 20 MHz transducer was bonded. Both transducers were 36° 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 amplitude V_1 (mV) and second harmonic V_2 (mV) amplitudes were measured with a digital oscilloscope. Since the fundamental signal is detected by the transmitting transducer after making a round trip twice the length of the specimen, while the second harmonic signal travels only one way before it is detected by the other transducer, the amplitude of the fundamental signal needs to be adjusted by considering the attenuation factor. The longitudinal velocity was measured using the time of flight method on a digital oscilloscope with a sampling capability of 1 Gs/s. Two consecutive echoes on the signal train were selected and expanded on the scope using the expansion option. The same point on each echo was chosen to measure the time difference. With this technique, the accuracy of time measurement is parts in 10^{+4}. The standard deviation is approximately 2 m/s.

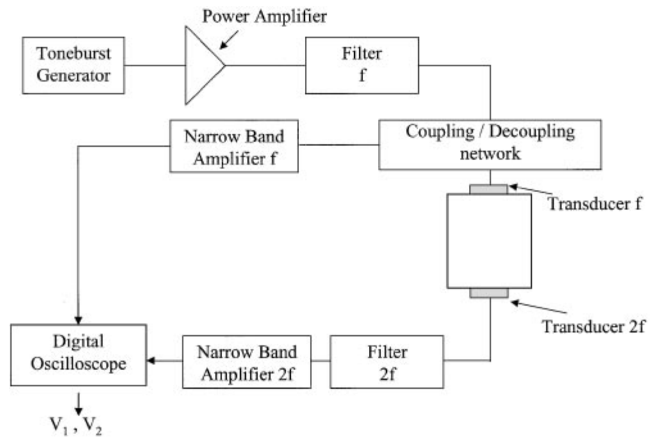

FIG. 1. Block diagram of apparatus for piezoelectric detection of second harmonic.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The acoustic attenuation, velocity, and the amplitudes of the fundamental and second harmonic signals were measured for the fatigued Ti–6Al–4V sample from 0 to 40% of the fatigue lifetime. Measurements were made at every 10% increase of fatigue. For the attenuation measurements, the amplitudes of successive echo trains were measured and an exponential curve fit was calculated by a computer to assess the attenuation. The result of the attenuation measurement at frequency of 10 MHz is shown in Fig. 2. The standard deviation for attenuation measurement is 0.05 dB/cm. The results of the longitudinal velocity of sound measurements are presented in Fig. 3.

To determine the absolute nonlinearity parameter, it is necessary to convert the amplitudes V_1 and V_2 measured in millivolts into absolute amplitudes A_1 and A_2 having unit of length. This can be performed by following the calibration procedure developed by Dace *et al.*,[8] which would introduce a calibration constant into

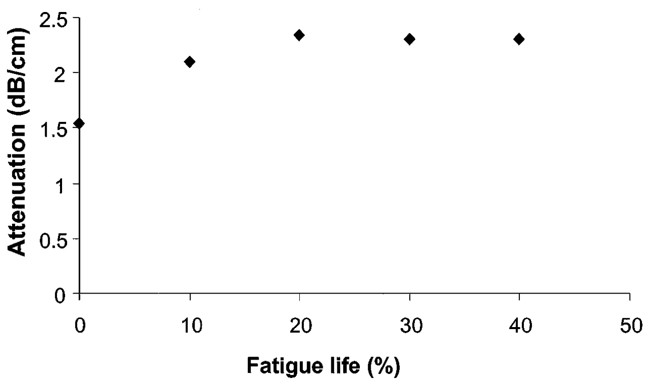

FIG. 2. Attenuation as a function of fatigue level for Ti–6Al–4V with duplex microstructure at 10 MHz frequency.

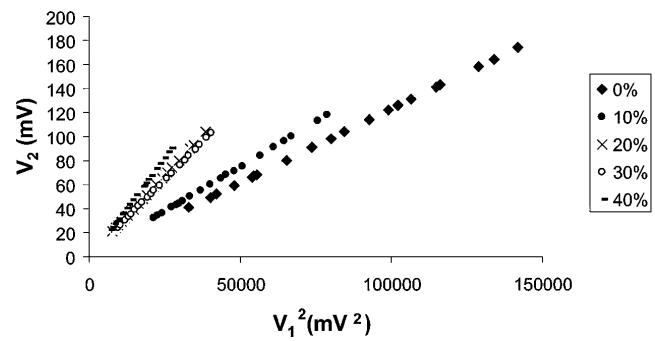

FIG. 4. Amplitude of the second harmonic signal versus the fundamental signal for various stages of fatigue in Ti–6Al–4V with duplex microstructure.

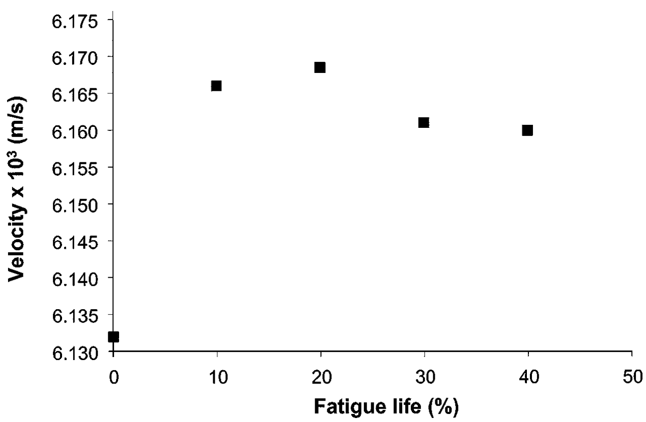

FIG. 3. Longitudinal velocity of sound as a function of fatigue level for a Ti–6Al–4V specimen with duplex microstructure.

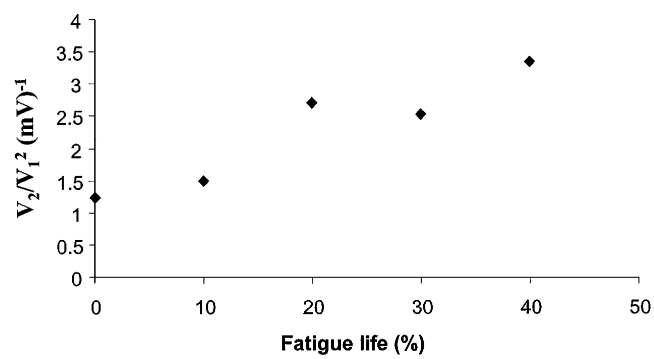

FIG. 5. The amplitude ratio V_2/V_1^2 of acoustic signals as a function of fatigue level for Ti–6Al–4V with duplex microstructure.

Eq. (1). At the present time a calibration procedure is under development. Moreover, for a qualitative explanation of the changes in nonlinear acoustic behavior of the material due to fatigue, it is assumed that it is enough to determine the voltage ratios rather than the absolute amplitude ratios. The calculation of the amplitude ratio, V_2/V_1^2, of the fundamental and second harmonic signals is made at the same fatigue level as the attenuation and sound velocity were measured. The results of the ratio are shown in Figs. 4 and 5. In Fig. 4, the slope of the amplitude ratio at the different fatigue levels is also shown. While in Fig. 5, the value of the amplitude ratio is plotted as a function of fatigue life from 0 to 40%.

From the result shown in Fig. 2, it is evident that there is a significant change in the attenuation during the early stage of the fatigue life. It increases up to 50% until the fatigue life reaches 20% of the entire lifetime and then it stays fairly constant up to 40% of lifetime. The initial 50% increase in attenuation is a significant change; however, it is less sensitive to the fatigue process beyond 20% of the fatigue lifetime.

The longitudinal sound velocity has a measurable change in the beginning of the fatigue process as shown in Fig. 3. As the fatigue process continues, there is an indication of reduction in the sound velocity beyond the 20% of the fatigue lifetime. During the process of fatigue there may be small increase in the specimen length. For an accurate determination of the velocity of sound, it is necessary to incorporate the changes in the specimen length. Since length changes were not monitored during fatigue, no attempt has been made to correct the sound velocity changes.

The slope determined by V_2 versus V_1^2 plotted in Fig. 4 shows a significant change in the material during the process of fatigue. As the material is fatigued, the amplitude of the second harmonic signal increases to give a steeper slope. Figure 4 shows an approximately 180% increase in the amplitude ratio during the 40% increase of fatigue life. There is an indication of continuous increase in its value as the fatigue level increases beyond 40% of the lifetime. This result is in contrast with the results of attenuation and elastic constant. For the latter case the majority of the change occurred before the fatigue lifetime reaches 20%; however, the amplitude of the second harmonic signal keeps growing up to 40% of the life and probably it continues the trend all the way to the fracture point.

The measurements of the attenuation and longitudinal sound velocity show results that generally would be expected in progressively fatigued specimens. The higher attenuation at the higher fatigue cycles may indicate an increase in the scattering of sound waves due to the increased dislocation dipole density from fatigue. As the increase in dislocation density saturates, the level of scattering of sound wave within the material becomes stable. It should be pointed out, however, that the general tendency of dislocation movement is known to migrate to the surface of the material. This could mean that the attenuation measurement in the bulk is less meaningful throughout the entire lifetime of the material.

An increase of 180% in the amplitude ratio V_2/V_1^2 is a substantial change. The second harmonic signal generated during the fatigue process is not only sensitive to the early stage of the process, but it continues to increase. This means that the harmonic signal is very sensitive to the microstructural changes in the material. The change may continue due to additional dislocation dipoles generated by the fatigue process, as predicted by Eq. (2). An attempt to utilize the Cantrell and Yost[4] model to explain the observed changes is not simple because Ti–6Al–4V is a two-phase material (hexagonal close-packed structure and bcc structure). But the overall behavior can be qualitatively understood based on the interaction of acoustic waves with the dislocations structures as suggested in the model.

IV. CONCLUSIONS

Measurements of sound velocity and attenuation performed on a Ti–6Al–4V dog-bone sample show similar behaviors observed in other fatigued materials such as Al 2024-T4 and 410Cb stainless steel. These two acoustic quantities do not seem to be reliable parameters for characterizing the level of fatigue damage. However, a dramatic change in the second harmonic signal (180% increase in nonlinear factor) seems to be a promising physical quantity for characterizing the level of fatigue damage in materials such as Ti–6Al–4V.

ACKNOWLEDGMENTS

The authors acknowledge Mr. Tim Campbell, Mr. Ed. Klosterman, and Mrs. Julia Maurer for their assistance in the experimental measurements. This research was sponsored by the Defense Advanced Projects Agency (DARPA) Multidisciplinary University Research Initiative (MURI), under Air Force Office of Scientific Research Grant No. F49620-96-1-0442.

REFERENCES

1. J.H. Cantrell and W.T. Yost, J. Appl. Phys. **81**, 2957 (1997).
2. J.K. Na, J.H. Cantrell, and W.T. Yost, *Review of Progress in QNDE, Review of Progress in QNDE,* edited by D.O. Thompson and D.E. Chimenti (Plenum, New York, 1992), Vol. 15, p. 1347.
3. J.H. Cantrell, Phys. Rev. B **21**, 4191 (1980).
4. J.H. Cantrell and W.T. Yost, Phil. Mag. A, **69**, 315 (1994).
5. M.A. Breazeale and J. Philip, in *Physical Acoustics* (Academic, New York, 1990), Vol. XVII, p. 1.
6. J.H. Cantrell and K. Salama, Int. Mater. Rev. **36**, 125 (1991).
7. W.T. Yost and J.H. Cantrell, Rev. Sci. Instrum. **63**, 4182 (1992).
8. G.E. Dace, R.B. Thompson, and O. Buck, in *Review of Progress in QNDE,* edited by D.O. Thompson and D.E. Chimenti (Plenum, New York, 1992), Vol. 11, p. 2069.