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Nonlinear ultrasonic characterization of early degradation of fatigued Al6061-T6 with harmonic generation technique

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ABSTRACT

In this paper, a third harmonic was used to investigate microstructural changes in Al6061-T6 due to different fatigue cycles and a relationship between fatigue cycle and third order nonlinearity has been observed. Piezoelectric measurement harmonic generation technique was applied for the specimens with 0%, 55%, 75% and 85% fatigue cycles, respectively. The results shows that the third order harmonics gradually increased up to 55% and rapidly decreased after wards, it was attributed to the behavior of dislocation, dislocation-precipitation interaction and voids with increasing fatigue cycle. Further, it was verified with scanning electron microscope (SEM). We also observed that third order nonlinearity is more sensitive to small change in area of fraction of voids than second order nonlinearity after 55% fatigue life and could be a good candidate to investigate Al6061-T6 specimen with voids.

1. Introduction

Al6061-T6 is one of the widely used structural materials because of its low cost, high corrosion resistance and light weight. Its main application areas includes air craft wing construction, building water crafts, automotive, heat exchangers and so on. During service, it is exposed to fatigue, creep, intermetallic corrosion, and other kinds of material degradation conditions. Most of the structural materials are vulnerable to fatigue irrespective of its working environment, therefore the study of microstructural change of Al6061-T6 associated with fatigue cycle has been an ongoing phenomena. Up to the date, different kinds of methods were employed to characterize microstructural change of materials due to an acting external conditions [1]. In particular, nonlinear ultrasonic techniques have been considered as a potential Nondestructive Testing (NDT) method for the evaluation of microstructural changes that are hard to assess using conventional ultrasonic technique. Nonlinear ultrasonic techniques principally depends on the interaction of an incident wave with the nonlinearity present in a material. When a monochromatic wave passes through a nonlinear medium, the interaction between the wave and nonlinearity generates a higher order harmonics which will be used to identify the degree of material nonlinearity. Second harmonic generation has been used extensively as a damage indictor since it is more sensitive to nonlinearity present in the material [2–4]. Various reports identified the possible way of analyzing second harmonics to track the microstructural changes of fatigued Al6061-T6 [5–7].

Depending on the interaction of ultrasonic wave and nonlinearities present in the material, various approaches have been used to map the higher harmonics with fatigue damage. A model of ultrasonic wave–dislocation dipole interactions that quantifies the wave distortion by means of a material nonlinearity parameter beta was developed [9,10]. New relationship between the relative ratio of simplified second-order parameter and the relative ratio of simplified third-order parameter was derived from the relationship between the absolute second- and third-order parameters. The derived relationship was successfully verified on the experimental results obtained from Al6061-T6 processed for different heat treatment times [11]. Higher order harmonics generation predominantly attributed to the formation of dislocations as the fatigue load progresses [5,12,13]. Cantrell et al. model quantifies the nonlinearity in terms of lattice anharmonicity, dislocation plasticity and crack growth. In the contrary, Kim et al. links the nonlinearity to the change in third-order elastic constants of material [3]. Though precipitates and matrix transformations can contribute to the changes in nonlinearity parameters, the assessment of exact contribution of individual effects is yet difficult due to lack of available elastic constant data pertaining to these effects. The effect of

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precipitate-matrix misfit strains on the matrix dislocation network was likely the dominate mechanism responsible for the change in nonlinearity parameter during precipitation aging of AA2024 [15]. The existence of the precipitates and associated coherence strain in ASTM A710 steel was revealed using X-ray diffraction and small-angle neutron-scattering experiments and second order nonlinearity is calculated [16].

Different trends have been suggested between fatigue life cycle and nonlinearity parameter. Cantrell et al. showed that the experimental measurement of nonlinearity of Al2024-T4 increases as the fatigue cycles increase [5]. Rao et al. investigated AA7175-T7351 specimens using surface acoustic waves and observed two peaks and attributed the first peak to persistent slip bands and the second one to fatigue cracks for all the samples tested independent of the amplitude of fatigue loading. The first peak appeared between 40% and 50% of fatigue life and the second peak between 80% and 90% of fatigue life [7]. Kang et al. observed that as number of fatigue cycles increased the second order non-linearity dropped after 55% of life cycle. The result showed that voids were the main reason for abnormal relation [18].

Besides the use of second order non linearity, third order nonlinearity have been used as a damaged indicator in structural health monitoring. Third harmonic lends itself to the study of the interactions between dislocations and point defects more directly than does the second harmonic [19]. Since the contribution of lattice anharmonicity to the third harmonics was assumed negligible compared to the second harmonics, the microstructural change associated with fatigue can be studied independently without including lattice effect [20]. Using nonlinear guided waves, the third harmonics shear horizontal wave, the relation between fatigued AA2024-T3 plate and third order nonlinearity was studied [21]. Amura et al. also showed that the cubic non-linear parameter evolves during crack propagation by combining the Paris law to the Nazarov-Sutin crack equation and the measurement of cubic non linearity parameter on AA2024-T351 specimens demonstrated high sensitivity to crack propagation [22]. Valluri et al. investigated creep damaged pure copper specimen using higher harmonics and found out that third harmonic is more sensitive to voids compare to second harmonic [8].

Most of the studies focused on the analysis of second harmonic as the microstructural change investigation method. There are no reports up to the knowledge of the author which used third harmonic to investigate fatigued Al6061-T6 with void. In this paper, third order non linearity is used to investigate the microstructural change of fatigued Al6061-T6 specimen. Third order non linearity as a function of fatigue cycles is plotted and the results showed a drop after 55% percent of fatigue life. We also found out that third order nonlinearity is more sensitive to fractional change of area of voids compared to second order nonlinearity. Contribution of vacancy migration to material nonlinearity with respect to the formation of voids was discussed.

2. Theory of third order non linearity

As the sinusoidal wave pass through the material, interaction between wave and the material nonlinearity generates higher harmonics. One dimensional propagation of longitudinal wave through an isotropic medium is given by:

$$\rho \frac{\partial^2 U}{\partial t^2} = \frac{\partial^2 U}{\partial x^2}\left[M_2 + M_3 \frac{\partial U}{\partial x} + M4\left(\frac{\partial U}{\partial x}\right)^2 + \cdots\right] \quad (1)$$

where M_2 is a linear combination of second order coefficients; M_3 is a linear combination of second and third order coefficients and M_4 is a linear combination of second, third and fourth order coefficients. These coefficients are related to the Brugger elastic constants C_{ij}.

$$M_2 = C_{11}$$
$$M_3 = 3C_{11} + C_{111} \quad (2)$$
$$M_4 = \frac{3}{2}C_{11} + 3C_{111} + \frac{1}{2}C_{1111}$$

The wave equation of motion can be rewritten in the following form including the second and third order nonlinear parameters, β and γ.

$$\rho \frac{\partial U}{\partial t} = C_{11}\frac{\partial^2 U}{\partial x^2} + \beta C_{11}\frac{\partial U}{\partial x}\cdot\frac{\partial^2 U}{\partial x^2} + \gamma C_{11}\frac{\partial^2 U}{\partial x^2}\cdot\left[\frac{\partial U}{\partial x}\right]^2 \quad (3)$$

Then, using perturbation solution, third non linearity expression can be expressed as [11].

$$\beta = \frac{8}{k^2 x}\cdot\frac{A_2}{A_1^2} \quad (4)$$

$$\gamma = \frac{32}{k^4 x^2}\cdot\frac{A_3}{A_1^3} \quad (5)$$

where A_1, A_2 and A_3 are the amplitude of fundamental, second and third harmonic, respectively and the relative second order and third order non linearity is defined by Eqs. (6) and (7) respectively.

$$\beta' = \frac{A_2}{A_1^2} \quad (6)$$

$$\gamma' = \frac{A_3}{A_1^3} \quad (7)$$

In this paper, relative measurement was used to estimate nonlinear parameters of experimental specimens.

3. Material and methods

In this experiment, dog–bone shape Al6061-T6 specimens were used according to the ASTM standard, as shown in Fig. 1. The elemental composition of the specimens is shown in Table 1. The yield strength of the specimens were approximately 276 Mpa. Fatigue testing was carried out using an Instron 8081 testing machine from zero to tension fatigue with a frequency of 10 Hz. During the fatigue test, alternating stress (σ_a) and mean stress (σ_m) was fixed to be 124 Mpa. Specimens were prepared as 0%, 55%, 75%, and 85% of fatigue life. Wave generator (Lecroy Teledyne wave station 2022) was used to generate 7-cycle burst tone with a central frequency of 5 MHz by stepping the voltage from 200 mV up to 500 mV. The signal was leveled up by a bipolar power amplifier (AR model 150A100B) and passed through a high power low pass filter that removes higher harmonics generated from the power amplifier, finally fed to a narrow band 5 MHz Lithium-Niobate transducer acting as a transmitter. Benzophenon was used as couplant because it has less non linearity. After the signal passed through Al6061-T6 specimen, a 10 MHz wide band Lithium-Niobate transducer received the response signal. A voltage probe connected with 50 Ω parallel load was used to detect the output voltage and to suppress a noise, pre-amplifier (RITech broadband receiver BR-640) was used to condition the low amplitude signal and finally fed to the oscilloscope (DS-5652A) which systematically collect and store the obtained data, as shown in Fig. 2.

We used the same procedure for each sample by stepping the input voltage 4 times. The data collected from the oscilloscope was further analyzed as shown in Fig. 3. Magnitude peak of the IFFT signal was used to calculate second and third order non linearity. Microstructural images were analyzed using Field emission scanning electron microscope (FESEM IV, JSM-7600F) with