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Nonlinear ultrasound and its applications in quality inspection and damage assessment in metallic materials†

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1. Introduction

Recent experimental studies and new physical models [1] demonstrate the high potential of nonlinear ultrasonics to quantitatively characterize fatigue and creep damage in metals. On the fundamental side, a physics-based model is needed to establish the relationship between the measured higher order harmonic and the parameters that characterizes fatigue damage. Recent advances in metal fatigue research have enables predicting, with reasonable accuracy, the cumulative plastic deformation in a structure component during cyclic loading. Thus, a physics-based relationship between the higher order harmonic and the cumulative plastic strain would allow us to estimate the remaining fatigue life of a component based on the nondestructive nonlinear ultrasonic measurements.

This paper presents our recent experimental and theoretical developments in the nonlinear ultrasonic material characterization technique. The developed experimental techniques are applied to track fatigue and other plasticity-induced damage in nickel-base and aluminum alloys to demonstrate the capability of the techniques. The microplasticity-based model that relates the acoustic nonlinearity and the cumulative plastic strain is introduced and results are compared with experimental data.

2. Experimental results

We have developed robust experimental techniques to track the evolution of fatigue damage in several different alloys including the nickel-base superalloy (IN-100) and aluminum alloys (AA6061-T6, AA2024-T3, Al1100-H14), with the acoustic nonlinearity parameter and demonstrated its effectiveness and robustness by making repeatable measurements of the material nonlinearity parameter (□) in multiple specimens subjected to static, high- and low-cycle fatigue load. Varying geometries of the structure components to be inspected requires the experiment method to adapt to the geometrical constraints. This led to developments of three different techniques that use longitudinal [2], Rayleigh [3], and Lamb [4,5] waves. Each of these has its own advantages and unique applications. In particular, the nonlinear Lamb waves are certainly the best candidate for efficiently performing a long range inspection of plate and shell structures. Due to the dispersive and multi-modal characteristics of the Lamb waves, the measurement of the second harmonic wave is more difficult than in the non-dispersive waves. A theoretical analysis on the conditions to generate a spatially growing higher harmonic has been performed [6]. In addition, an advanced signal processing technique has been applied to extract the fundamental and second-harmonic amplitudes of a measured Lamb wave signal.

The developed techniques have been applied to characterize damage in materials subject to static load, low and high cycle fatigue for various metallic materials.

For example, **Fig. 1** shows results of measured material nonlinearity for the nickel-base superalloy (IN-100) during a low cycle fatigue using both longitudinal and Rayleigh waves. The maximum stress level is 105% of the yield stress, and the fatigue tests are interrupted to perform the nonlinear ultrasonic measurements at different numbers of fatigue cycles. Figure 1 shows a rapid increase in□/□o (up to 30%) during the first 40% of fatigue life, which demonstrates that these nonlinear ultrasonic measurements can be used to quantitatively characterize the damage state of this material in the early stages of fatigue life. Similar trend of large increases in the initial stage is observed in the Lamb wave measurement results. This implies that the dispersive nature of Lamb waves does not alter their interaction with fatigue damage and that there is a fundamental relationship between fatigue damage and acoustic nonlinearity, independent of wave type. **Figure 2** shows the acoustic nonlinearity (versus the plastic strain) measured with Lamb waves for Al-1100-H41 specimens subjected to low cycle fatigue. Note that Fig. 2 can be important baseline data for lifetime prediction of a component subjected to cyclic fatigue loading.

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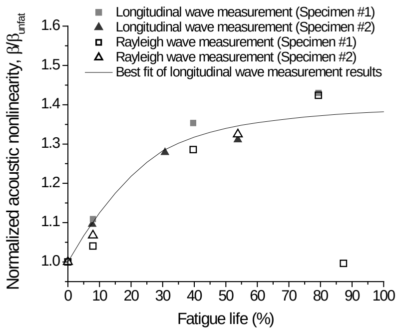

Fig. 1 Normalized acoustic nonlinearity parameter □□□□ as a function of percentage fatigue life for the low-cycle fatigue results, measured using longitudinal and Rayleigh waves.

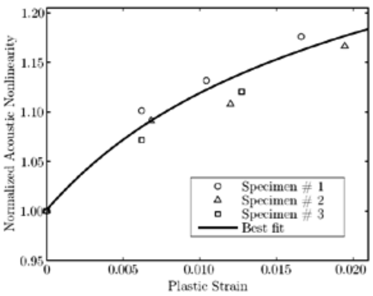

Fig. 2 Normalized acoustic nonlinearity measured using Lamb waves versus measured plastic strain,.

3. Microplasticity-based model

Cantrell [1] proposed a nonlinear elasticity model in which the evolution of sub-structural organization of dislocations is taken into account to predict total acoustic nonlinearity of a polycrystalline nickel under cyclic load. As an engineering alternative to Cantrell model, we proposed a microplasticity-based model [7]. Instead of relating the acoustic nonlinearity parameter directly to the dislocation substructure, this model exploits the continuum manifestation of these dislocations, namely, plastic deformation. The advantage of this approach is that plastic strain is a measurable parameter yet quantitatively characterizes the effect of the dislocations and thus the fatigue damage. The theoretical nonlinearity vs. plastic strain relationship can be used with experimental results (nonlinearity vs. fatigue life) such as that in Fig 2 for predicting the remaining useful life of a critical structure component. Under this mission, the nonlinear wave equation in an elastic medium with localized microplastic deformation is derived

$$\frac{\partial}{\partial X_J}\left[\frac{1}{J}\left(C_{IJKL}+J\sigma^i_{JL}\delta_{IK}+\left(C_{JLMN}\delta_{IK}+\frac{1}{2}D_{IJKLMN}\frac{\partial u_M}{\partial X_N}\right)\frac{\partial u_K}{\partial X_L}\right)\right]=\frac{\rho}{J}\frac{\partial^2 u_I}{\partial t^2}$$

The effects of the microplastcity enter in the coefficient tensors CIJKL and DIJKLMN and the acoustic nonlinearity parameter can be calculated solving this equation. Prediction of the cumulative plastic strain in each grain of a polycrystalline metal requires a finite element simulation of the microplasticity evolution from various types of substructural damage. **Figure 3** shows the nonlinearity parameter predicted with this microplasticity-based model for the nickel-base superalloy (IN-100) under the same loading condition as in Fig.1. The comparison between Figs. 1 and 3 shows a very reasonable agreement and this result proves practical usefulness and capability of the present combined experimental and theoretical framework.

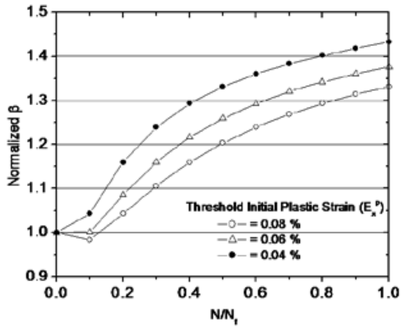

Fig. 3. Normalized acoustic nonlinearity vs. fatigue life of IN100 during low-cycle fatigue, predicted by the microplasticity based model.

4. Knowledgments

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