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INVESTIGATION AND COMPARISON OF CLASSICAL AND NONCLASSICAL NONLINEARITY IN METALS

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ABSTRACT

This research investigates the contribution of different microstructural damage, such as dislocation, precipitates along grain boundaries, and precipitates in grain structure, to the nonlinear elastic behavior. This research focuses on not only investigating but also comparing classical and nonclassical (hysteresis) nonlinearity through the techniques of second harmonic generation and nonlinear resonance ultrasound spectroscopy. This research focuses on nonlinearity that occurs in metals due to these microstructural damages.

Keywords: nonlinear ultrasound, nondestructive evaluation, second harmonic generation, nonlinear resonant ultrasound spectroscopy

NOMENCLATURE

α	alpha, nonclassical nonlinearity parameter
β	beta, second order nonlinearity parameter
ε	strain
f	frequency
f_0	equilibrium resonance frequency
E	elastic modulus
L	length of bar
n	resonance mode
ρ	material density
NRUS	nonlinear resonant ultrasound spectroscopy
RUS	resonant ultrasound spectroscopy
SHG	second harmonic generation

1. INTRODUCTION

With the aging of infrastructure, there is an increased need to determine the remaining life of these aging structures. While remaining life can be determined easily using destructive stress tests, this is not always a viable option. Sometimes it is very difficult or almost impossible to model the exact wear that has occurred in a structure. Therefore, it is important to develop nondestructive evaluation (NDE) techniques so that "original" structures can be tested in order to obtain a more accurate approximation of their remaining life. It is also important to develop portable and easily replicable test methods so that structural components can be tested in situ.

It is very important to detect the initial onset of microstructural damage of structures before macro-cracking occurs. This detection of the amount of microstructural damage can help provide quantitative inputs for algorithms capable of predicting the remaining life of a structure before catastrophic failure occurs. An example of one of these aging structures is the reactor pressure vessel (RPV) in light water nuclear power reactors. With the current fleet of nuclear reactors in the United States entering the first period of license renewal (operation to 60 years) and planning has begun for a second renewal (operation to 80 years), RPV steel will see more neutron exposure and duty cycles than was originally anticipated. Therefore, it is very important to be able to inspect the condition of these RPVs. If microstructural damage is not caught before macro-cracking occurs, the results could be catastrophic. This early detection of microstructural damage would allow for the nuclear reactors to be in service past their predicted lifespan.

Currently, the NDE methods capable of detecting initial microstructural damage in these structures are very limited and have not proven easy to perform field tests. While the prominent NDE method of using linear ultrasound has shown excellent results in many applications, the current research on linear ultrasound has shown that it is unable to detect this initial onset of microstructural damage at very small length scales. However, there have been numerous accounts of promising results with both nonlinear ultrasound techniques of SHG [1–6]and NRUS for this application [7–9]. In one study, SHG gave promising results in the detection of radiation damage in RPV steels [3,4] Another study shows how SHG can be used to determine damage in thermally treated materials [5]. A different study demonstrated the sensitivity of NRUS to precipitate growth [8].

2. MATERIALS AND METHODS

This research investigates material damage such as: dislocations, precipitates in grain boundaries, and precipitates in the grain structure and their effects on the sensitivity of NRUS and SHG.

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2.1 Theory and Experimental Methods

2.1.1 NRUS

NRUS looks at the nonlinear vibrational response through changes in the resonance frequency as a function of input amplitude. This change in resonance frequency is predominantly due to the nonclassical nonlinear hysteretic elastic behavior of the material. The hysteretic behavior of the material is thought to be due to soft regions in hard materials, i.e. microcracks, dislocations, etc. [9]. From these measurements, the hysteretic nonlinearity parameter, α, can be determined by relating the frequency shift, Δf, strain amplitude, Δε, and equilibrium resonance, f_0:

$$\frac{\Delta f}{f_0} = \frac{f-f_0}{f_0} = \alpha\Delta\varepsilon \quad (1)$$

The experimental schematic used for the noncontact NRUS measurements can be seen in Figure 1 [8]. This noncontact setup allows for free boundary conditions without a fixed connection between the specimen and transmitter or receiver. In the setup, a rod or bar sample is hung by two wires in between transmitting transducer and receiving vibrometer. The transmitting transducer paired with an acoustic horn focuses the acoustic energy of a constant amplitude continuous sinusoidal frequency sweep onto the specimen. The acoustic horn is designed using Webster's horn equation. The specimen's motion (out-of-plane velocity) is then detected with a laser vibrometer. After this frequency sweep has been saved, the input amplitude is increased, and the specimen response is measured again. To automate the entire measurement sequence, Labview is used to control the function generator as well as record the signal from the oscilloscope.

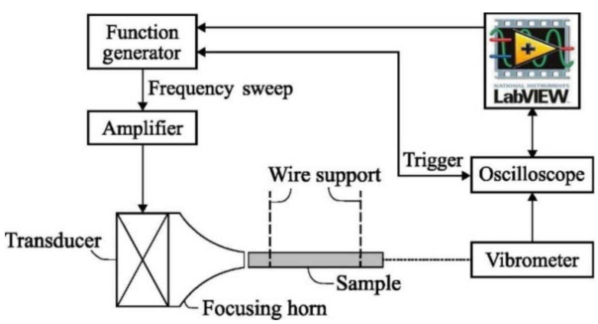

FIGURE 1: SCHEMATIC FOR NRUS MEASUREMENTS [8]

2.1.2 SHG

In SHG, a monochromatic signal with frequency f is introduced into a material where it interacts with microstructural features and generates a second harmonic wave (as well as higher harmonics) with frequency, 2*f. This distortion of the wave to generate higher harmonics is due to the nonlinear stress-strain relationship in the material caused by microcracks, dislocations, precipitates, etc [10]. The amplitude of the second harmonic wave can be related to the amplitude of the introduced wave through the nonlinearity parameter as in Eq. 2, and a full derivation of the nonlinearity parameter can be seen in [10].

$$\beta \propto \frac{A_2}{A_1^2 x} \quad (2)$$

Two different wave types can be used for SHG, through thickness propagation of longitudinal waves or surface propagation of Rayleigh waves. Figure 2 depicts the schematics used for SHG with (a) giving the schematic for longitudinal waves [7] and (b) giving the schematic for Rayleigh waves [2].

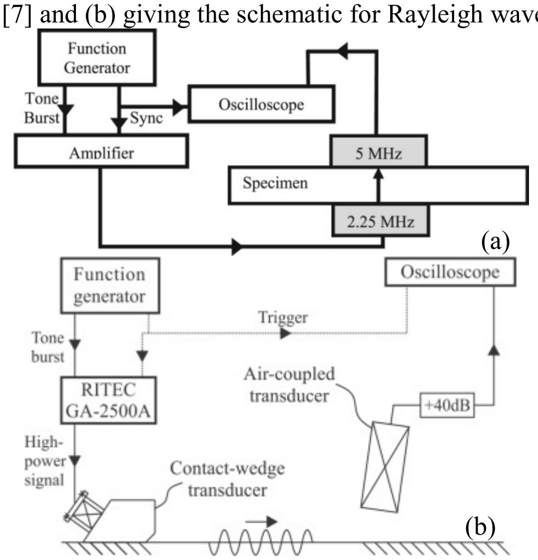

FIGURE 2: SCHEMATICS FOR SHG (A) LONGITUDINAL WAVES[7] (B) RAYLEIGH WAVES[2]

2.1.3 Elastic Modulus from RUS

The elastic modulus for the materials was determined through a linear ultrasound technique, RUS. This technique relates the elastic modulus to the equilibrium resonance frequency, length of the bar, and density of the material as seen in Eq. 3.

$$E = \left(\frac{2Lf_n}{n}\right)^2 \rho \quad (3)$$

2.2 Material

One of the materials studied in this research is 304 stainless steel. When this austenitic stainless steel is exposed to high temperatures for extended periods of time, sensitization can occur. Sensitization is known as the formation of chromium carbide precipitates. The formation of these precipitates results in a chromium depletion zone around the grain boundaries, making the steel more susceptible to intergranular stress corrosion cracking (IGSCC). The research on this material extends a previous study where the researchers examined the sensitivity of SHG to sensitization [11]. This abstract examines an annealed and a sensitized 304 sample. One sample was annealed at 1080°C for 30 min removing any cold working effects in the form of excessive dislocations and residual stresses. The second sample was annealed and subsequently heat treated at 675°C for 4 hr resulting in full sensitization.

Other materials studied in this research include untreated and annealed 316L which examines dislocations, and heat treated Fe-Cu which examines the growth of precipitates in the grain structure.

3. RESULTS AND DISCUSSION

This abstract will give a sample of the results found in this study with the main focus on the annealed and sensitized 304 stainless steel.

Figure 3 compares the normalized values for α, β, and E for the annealed and sensitized 304 stainless steel. The values for β are taken from previous research which can be seen in [11].

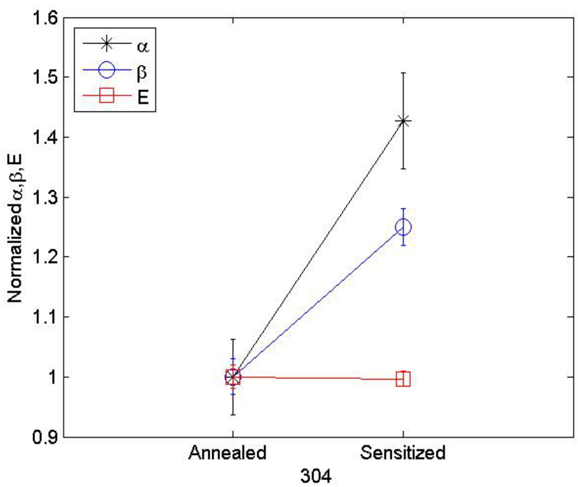

FIGURE 3: COMPARISON OF α, β[11], AND E FOR ANNEALED AND SENSITIZED 304

As to be expected in the case of microstructural damage, there is minimal change, 1%, in the linear ultrasound results, E, from the annealed to the sensitized states. In contrast, both NLU and NRUS techniques show a significant increase in their nonlinearity parameters from the annealed to sensitized state. β sees a 25% increase, and α sees a 43%. These increases in the nonlinearity parameters are due to the formation and growth of the chromium carbide precipitates along the grain boundaries. These results also show that the sensitivity of α is significantly higher than that of β. This indicates that the interaction between the precipitate and the grain boundary results in largerer changes in nonclassical nonlinearity than the classical nonlinearity.

Similar results are seen for the 316L and Fe-Cu samples. The 316L samples demonstrate a decrease in both of the nonlinearity parameters because of the removal of some dislocations from the untreated sample to the annealed sample and α is more sensitive than β in this case as well. The Fe-Cu samples demonstrate a more complicated trend in the nonlinearity parameters with an initial decrease due to the nucleation of the Cu precipitates, an increase due to the growth of the Cu precipitates, and a decrease due to the change in coherency of the matrix [12] with α again being more sensitive than β. However, this decrease in the nonlinearity parameter is not seen in α. This is due to the hysteresis additively feeling the effects of precipitates and dislocations which dominates the coherency effects from the matrix.

4. CONCLUSION

This research demonstrates the sensitivity of α and β to microstructural damage. The results for each material demonstrate that α is much more sensitive to β for each of the damage types studied. This research also paves the way to understanding the contributions different types of damage have on each nonlinearity parameter. This understanding will allow for a better comparison between α and β.

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