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AN EXPERIMENTAL METHOD FOR MAPPING ACOUSTIC NONLINEARITY FROM ACCUMULATED PLASTIC STRAIN FIELD

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ABSTRACT

Nondestructive evaluation (NDE) techniques have been widely used in industry but its application is limited to end-of-life events when the size of defects is already critical. Compared to conventional NDE techniques, nonlinear ultrasound (NLU) is a promising tool for diagnosing early-stage damage, since it is sensitive to nano- and microstructural features such as dislocations and precipitates. Presented in this work is an approach to evaluate the acoustic nonlinearity parameter (β) due to accumulated plastic strain. A dogbone sample of Al2024 was subjected to fatigue cycles and the spatial distribution of accumulated strain fields were measured using digital image correlation (DIC). DIC can capture localized strain at microscale and thus high resolution strain distributions can be obtained. A map of accumulated acoustic nonlinearity was then calculated based on a power law relationship. Using this spatial map of β, we calculated the dependence of A_2/A_1^2 *on propagation distance, as typical in Rayleigh surface wave measurements. Results showed that measure β depends on the propagation path, since there is a spatial distribution of plastic strain. This approach will be useful understanding second harmonic generation at microscale.*

Keywords: plastic strain, nonlinear ultrasound, harmonic generation, Rayleigh wave

NOMENCLATURE

β	acoustic nonlinearity parameter
$\gamma_{pl,n}$	plastic strain amplitude at nth cycle
γ_{pl}^{n}	plastic shear strain on nth slip system
ε_{ij}^{pl}	plastic strain
Λ	dislocation density
Γ	cumulative plastic shear strain
A_1	Amplitude of fundamental wave
A_2	Amplitude of second harmonic

1. INTRODUCTION

Nonlinear ultrasound (NLU) is an NDE technique that is sensitive to damage precursors such as dislocations, precipitates, and microcracks. These defects evolve at the early stages of damage accumulation processes such as fatigue, radiation embrittlement, and stress corrosion cracking [1]. The acoustic nonlinearity parameter measured through NLU is based on harmonic generation due to the interaction between a propagating wave and defects.

However, advancement of NLU as a means of measuring and predicting nonlinear elastic properties is still limited. Physics-based models that relate NLU propagation to dislocation parameters can exhibit large errors compared to measurements, since models relate parameters on size scales of nanometers to NLU wave propagation measured over size scales of millimeters to centimeters [2]. Also, transmission electron microscopy (TEM) required to collect dislocation parameters can only characterize the area of nanometer scale while grains are normally on size scales of microns.

This work seeks to address this length scale discrepancy. The objective is to experimentally measure spatial distributions of localized accumulated strain fields in aluminum during fatigue, and predict the influence of these strain fields on measurements of the acoustic nonlinearity parameter. To measure accumulated strain, we use digital image correlation (DIC), which has proven to be useful in characterization of strain fields at length scales ranging from nanometers to micrometers [3,4]. We estimate beta by assuming a power law relationship between beta and our measured accumulated strain [2]. We demonstrate the influence of such a spatial variation in strain, and thus *β*, on measured nonlinearity with Rayleigh surface waves.

2. EXPERIMENTAL METHODS

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2.1 MEASURING LOCAL STRAIN USING DIC

DIC is a technique that is capable of acquiring high-resolution strain fields on the surface. The conventional strain measurements using the extensometer only provide the global measure of the strain and are not capable of measuring the local strains at multiple scales, which can be achieved by DIC. DIC has been extensively used to characterize strain fields at different scales [3,4]. In DIC, the grayscale microscope images of the same region are taken before and after the deformation. These images are then compared with each other to calculate the relative displacements of the particles. To identify the same particles at two different states, a random and high-contrast speckle pattern are sprayed on the area of interest. Different patterning methods have been developed for a variety of material and at different resolutions [5]. While here we only use DIC, DIC can be combined with electron backscatter diffraction (EBSD) to further characterize the grain structure over the same surface. In an overlaid map of DIC and EBSD, strain localization in different grains can be observed [6].

2.2 DAMAGE ACCUMULATION DURING FATIGUE

During fatigue, damage accumulates on the slip planes by shearing motion of crystal lattice. One of the parameters to quantify this damage process is the cumulative plastic strain. The cumulative plastic shear strain, Γ, is frequently used as it can be directly obtained from the given loading condition. It is expressed as the sum of applied plastic shear strain, $\gamma_{pl,n}$, at each cycle over the number of cycles applied, N.

$$\Gamma = 4\sum_{n=1}^{N}\gamma_{pl,n} \tag{1}$$

This cumulative plastic strain can represent dislocation substructure evolution, for example Kuhlmann-Wilsdorf and Laird [7] found that $\Gamma \propto \Lambda^2$, where Λ is the dislocation density. Based on this finding, Apple et al. showed that β was related to the cumulative plastic strain by power law [2]. Even though this provides insight into the acoustic nonlinearity at macroscopic scale one needs to understand that the cumulative plastic strain does not reflect reversible plastic strain. However, identifying the cyclic slip irreversibility is not straightforward as it is a complex function of loading condition, material composition, and microstructure. Furthermore, Γ cannot describe complex behavior resulting from grain boundary effects in polycrystalline material. A more accurate measure of damage accumulation is plastic shear strain on each slip system, γ_{pl}^{n}. The total plastic strain, ε_{ij}^{pl}, is the sum of all the contributions of shear strain acting on each slip system, γ_{pl}^{n}, which can be written as

$$\varepsilon_{ij}^{pl} = \frac{1}{2}\sum_{n=1}^{s}\left(m_i^n b_j^n + m_j^n b_i^n\right)\gamma_{pl}^{n}. \tag{2}$$

The slip plane normal and slip direction are defined as m_i^n and b_j^n respectively and s is the number of slip systems. The physics-based models for β, for example those used in [2], are derived from the shear strain acting on a slip system, which is γ_{pl}^{n} in the above equation. Thus, if one can measure the shear strains we can quantitatively relate them to β. While there is no experimental technique that can directly measure γ_{pl}^{n}, it is possible to estimate these shear strains by utilizing combined DIC and EBSD measurements [6].

3. RESULTS AND DISCUSSION

A dogbone Al2024 sample of 62.5mm by 12mm gauge section was prepared. The amplitude of cyclic stress is σ=380MPa with R=0. This loading condition was chosen to ensure that localized plastic strain is clearly observed by DIC. An accumulated shear strain map (ε_{xy}) measured after 1000 cycles is presented in Fig. 1. The area characterized by DIC is 22mm by 5mm. The measured shear strain ranges from -0.2% to 0.2% and it is localized in a region or along a line, whose length scale is comparable to the grain diameter presented in the EBSD map. Due to the strong heterogeneity, the local contribution of plastic shear strain to β is expected to significantly vary.

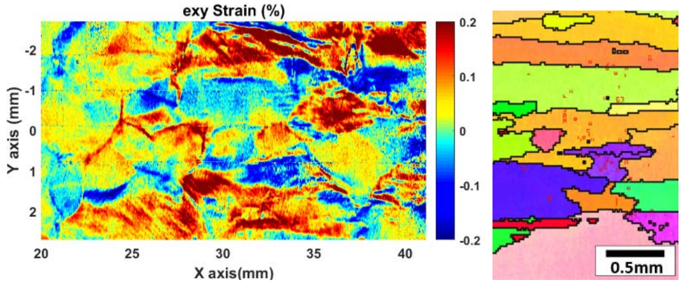

FIGURE 1: HIGH RESOLUTION ε_{xy} MAP OBTAINED FROM DIC (LEFT). REPRESENTATIVE GRAIN GEOMETRY OF THE SAMPLE OBTAINED FROM EBSD (RIGHT).

To evaluate β at each DIC data point, we assumed that the contribution of our measured shear strain to β follows the power law relationship found experimentally and analytically using dislocation-based parameters [2], specifically, $\beta \propto \Gamma^{0.5}$ (Fig. 2). Note that this is a first approximation from the DIC results, since we are measuring only $\varepsilon_{xy}^{pl}$and not γ_{pl}^{n}.

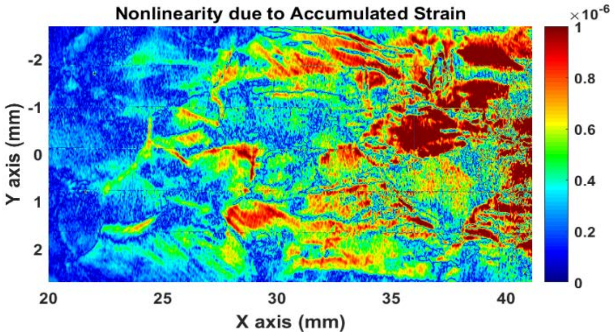

FIGURE 2: LOCAL ACOUSTIC NONLINEARITY MAP DUE TO SHEAR STRAIN, ε_{xy}^{pl}.

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The β map presented in Fig. 2 is not significantly different from the shear strain map as one is simply scaled from another. But this implies that the actual β measured using Rayleigh surface waves will vary along different propagation paths. To understand this variation, we evaluated a relative β along three different propagation paths, at y=+1, 0, and -1, assuming the relationship $A_2/A_1^2 = \beta x$, which is equivalent to $A_2/A_1^2\,(x) = \int_{x0}^{x} \beta(X)dX$ for variable β. The β averaged over *y* position is also presented as a reference. The results are shown in Fig. 3. The dashed lines show β values at each propagation distance and solid lines are linear fits of these β values over the total propagation distance (*x* position). The deviation between the averaged β and β measured along a specific *y* position is as large as 20%. This is not negligible, and the heterogeneity in local strain can be larger for different loading conditions, grain sizes, and misorientation angle between grains. However, these results show that for this particular example, the cumulative relationship between A_2/A_1^2 and propagation distance is approximately valid. Deviations shown in Fig. 3, in terms of linear fit of β over propagation distance compared to β at each propagation distance, would likely be within the range typical of experimental errors.

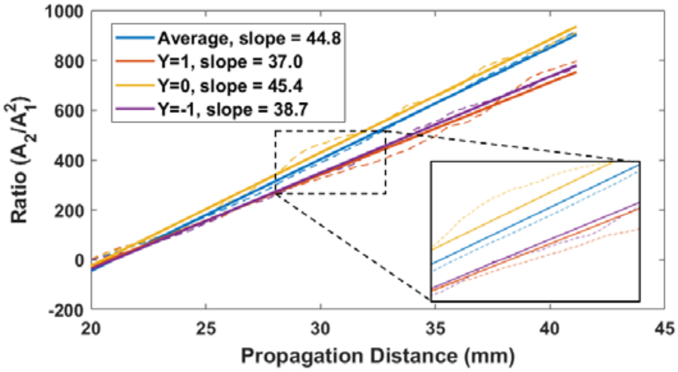

FIGURE 3: ESIMATED β ALONG DIFFERENT PROPAGATION PATHS.

4. CONCLUSION

In this work, a new approach to interpreting the acoustic nonlinearity parameter is introduced. Instead of the cumulative plastic strain, we measure plastic shear strains acting on the slip systems, which can be done by DIC. The advantage of this parameter is that it is able to capture strain localization, which represents dislocation behavior, while the area measured with DIC is comparable to the length scale of the acoustic wave used in NLU. In these preliminary results, it was shown that the variation of β along different propagation paths can be as large as 20% due to heterogeneous deformation of the sample.

While the shear strain measured and used in this work does not directly incorporate contributions from dislocations to β, dislocation behavior can be properly assessed with a proper measure of strain. DIC is capable of capturing localization of strain at the microscale, and further measurements could incorporate grain orientation information from EBSD over the same area characterized by DIC to obtain γ_{pl}^{n}. Compared to the approaches taken in previously developed dislocation-based models, the advantage of the approach introduced in this work is the accurate characterization of accumulated damage at the scale comparable to the wavelength used in NLU testing.

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