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Method and analysis for determining yielding of titanium alloy with nonlinear Rayleigh surface waves

Shifeng Guo, Lei Zhang, Meysam Sharifzadeh Mirshekarloo, Shuting Chen, Yi Fan Chen, Zheng Zheng Wong, Zhiyuan Shen, Huajun Liu, Kui Yao*

*Institute of Materials Research and Engineering, A*STAR (Agency for Science, Technology and Research), 2 Fusionopolis Way, Innovis, #08–03, Singapore 138634, Singapore*

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ABSTRACT

Methods for determining yielding of titanium (Ti) alloy material with second harmonic Rayleigh ultrasonic wave are investigated. Both piezoelectric angle beam transducers and high frequency laser scanning vibrometer (LSV) are used to detect ultrasonic signals in the Ti alloy specimens with different plastic strain levels. Technical features and outcomes with use of piezoelectric transducers and LSV are compared. The method using piezoelectric transducers, with much higher signal-to-noise ratio than LSV, has been further improved by deploying two transducers with central frequencies corresponding to the fundamental and second order harmonic signals respectively to improve the testing reliability and accuracy. Both the techniques using piezoelectric transducer and LSV demonstrate consistently that the acoustic nonlinearity increases with plastic strain, and the second harmonic Rayleigh ultrasonic wave can be utilized for effective determination of yielding in Ti alloy. Our experiments further show that the acoustic nonlinearity increases gradually with plastic strain at small plastic strain level, and there is a more significant increase of acoustic nonlinearity when the plastic strain reaches a higher level. Microscopic investigations using scanning electron microscopy (SEM) and high resolution transmission electron microscopy (HRTEM) are conducted for clarifying the relationship between the observed acoustic nonlinearity and micro-structural changes.

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1. Introduction

An overloading that exceeds the yield strength of metallic materials will modify irreversibly the materials' mechanical behavior, which can lead to early failure of structures with potential catastrophic consequences. It is therefore very important to detect the yielding in order to determine the reliability of structures in service. Although yielding is accompanied by dimensional changes, dimensional measurement is not a fail-safe method for detecting yielding, considering the production tolerance, complex shape of structures and localization of plastic deformation.

Non-destructive testing (NDT) techniques allow examination of structures with negligible or minimal disturbance. Since the nonlinear acoustic signal (or the second harmonic generation (SHG) signal) can indicate microstructural changes in materials [1,2], nonlinear ultrasound-based NDT enables the detection of the microstructural changes before the appearance of macroscopic damage [3]. This technique relies on the detection of the higher order harmonics generated or enhanced by the imperfection of atomic lattices and microstructures. Compared to the conventional linear ultrasonic approach that can detect cracks or features only in the order of wavelength of the ultrasonic wave, nonlinear ultrasound-based NDT methods can detect microstructural features that are orders of magnitude smaller than the wavelength [4]. This method presents significant potential for applications in industries with strong demand for high structural reliability.

To date, the nonlinear ultrasonic technique has been attempted to assess micro-damage of metallic materials under various deformation states, including fatigue [5–7], thermal degradation [8], stress corrosion cracking [9], and plastic deformation [10–12]. Herrmann et al. [6] and Kim et al. [3] studied the acoustic nonlinearity of nickel-based superalloy using Rayleigh waves and noted that acoustic nonlinearity increased with plastic deformation. Zhang et al. [11] and Jhang et al. [13] observed similar behavior in steel alloys using longitudinal and Rayleigh surface waves respectively and found that the nonlinear ultrasonic parameter increased with plastic strain. Zhang et al. [14] and Rao et al. [12] conducted their experiments on aluminum (Al) alloy and showed that the acoustic nonlinearity increased with plastic deformation. In addition, the acoustic nonlinearity of Titanium (Ti)

* Corresponding author.
E-mail address: k-yao@imre.a-star.edu.sg (K. Yao).

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alloy subjected to fatigue was studied and increased acoustic nonlinearity using longitudinal ultrasonic waves was observed in samples experienced increased fatigue level [15].

In this work, we investigated the acoustic nonlinearity with overloading-induced plastic deformation in Ti alloys by using nonlinear Rayleigh ultrasonic waves. The fundamental and second harmonic ultrasonic signals were measured via both piezoelectric angle beam transducers and ultra-high frequency laser scanning vibrometer (LSV) respectively to determine the acoustic nonlinearity at different plastic strain levels. The microscopic analysis of the alloy specimens was conducted with scanning electron microscopy (SEM) and high resolution transmission electron microscopy (HRTEM), and the relation between acoustic nonlinearity and micro-structural changes was discussed.

2. Method and experimental details

2.1. Specimen preparation

The Ti alloy specimens were machined in a dog-bone shape according to the standard of ASTME-8M, with the gauge length, width and thickness of 50.8 mm, 13 mm, and 32 mm, respectively. The specimens were loaded with tensile stress to produce varying strain level at room temperature using a tensile testing machine (Instron 8801, USA) and unloaded to zero stress thereafter. The mechanical loads were delivered by using displacement control at a rate of 1 mm/s. The residual plastic strains for the Ti alloy at different strain levels are shown in Table 1. The ultrasonic characterization was conducted off-line after unloading of the specimens.

2.2. Micro-structural characterization

To investigate the micro-structural evolution of Ti alloys due to plastic strain, two samples were cut from the central region of each of the respective specimens with plastic strain of 0%, 1.97% and 5.10% in the loading direction. One sample was used for the SEM analysis and the other for dislocation analysis using HRTEM. The thin HRTEM samples were fabricated by a two-stage process involving mechanical polishing and ion milling of alloy samples to generate an electron-transparent area. HRTEM micrographs of Ti alloy samples with different plastic deformation level were recorded along [0002] zone axis and subsequently the respective electron diffraction patterns (SAED) of the Ti alloy along [0002] zone axis were analyzed. To be consistent, HRTEM analysis of all samples was conducted along the same zone axis. For visualization of the dislocations, lattice images were digitally constructed by processing a consecutive series of forward Fourier transforms (FFT) of the experimental HRTEM micrograph and inverse Fourier transforms (IFFT) of a selected set of diffraction spots belonging to the same crystallographic plane in the FFT image.

2.3. Measurement of acoustic nonlinearity

In order to characterize ultrasonic acoustic nonlinearity, a nonlinear parameter for Rayleigh wave is required. The expression for the acoustic nonlinearity parameter β in terms of measured acoustic amplitude can be expressed as [6,16]:

Table 1
Percentage of plastic strains induced in the Ti alloy specimens.

Ti specimen ID	1	2	3	4	5	6
Plastic strain (%)	0	0.25	0.90	1.97	3.34	5.10

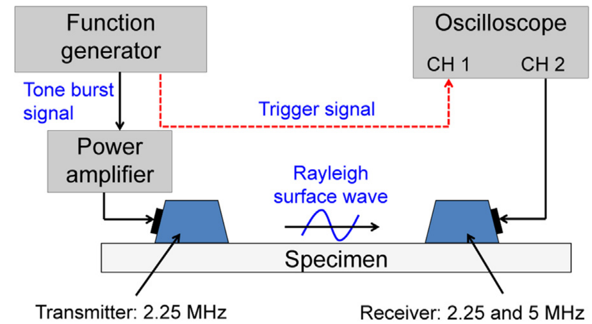

Fig. 1. Experimental setup for ultrasonic measurement using piezoelectric angle beam transducers.

$$\beta=\frac{8A_2}{\omega^2A_1^2X}\frac{C_L\sqrt{C_L^2-C_R^2}}{2(C_S/C_R)^2-1} \qquad (1)$$

where A_1 and A_2 are the measured acoustic magnitudes of fundamental and second harmonic signals respectively, X is the propagation distance of the Rayleigh wave, ω is the angular frequency, C_L, C_R, and C_s are longitudinal, Rayleigh and shear wave velocity in the material respectively.

In carrying out our experimental work, the fundamental frequency and propagation distance are held constant. The fundamental and second harmonic amplitudes are measured at each plastic strain level. The relative acoustic nonlinearity A_2/A_1^2 is used to quantify the acoustic nonlinearity of the alloys under different plastic strain levels.

2.4. Nonlinear ultrasound measurement system

The schematic of the experimental setup using piezoelectric transducers is shown in Fig. 1. A piezoelectric longitudinal transducer (Olympus, A542S) with a center frequency of 2.25 MHz is assembled onto an acrylic wedge after which is clamped to the Ti alloy specimen to convert the longitudinal wave emitted by the transducer into a Rayleigh surface wave in the specimen. In our survey of published research on using piezoelectric transducers for nonlinear ultrasound NDT, we note that only one single receiver is used in the research efforts to obtain both the fundamental and second harmonic signals simultaneously. Due to bandwidth limitation of piezoelectric transducers, the frequency responses of fundamental and second harmonic signals would differ significantly, and this may result in inaccurate data as reported in the literature. To improve testing reliability and accuracy in this work, two transducers are used as receivers with central frequencies corresponding to fundamental and second harmonic signals respectively. A 2.25 MHz tone burst signal with 25 cycles from a function generator (Agilent 33210A, USA) is fed into a high speed linear power amplifier (Ciprian US-TXP-3, France) to drive the transmitter. The 2.25 MHz receiver is used to detect the fundamental signal while the 5 MHz receiver is used to obtain the second harmonic signal. The internal signal from function generator serves as a reference trigger.

In addition, experiments using a LSV-based method are conducted and the results are compared with those from the piezoelectric transducers-based method. In the LSV-based method, the same 2.25 MHz angle beam piezoelectric transducer is used to generate Rayleigh surface wave in the specimen, while an ultra-high-frequency LSV (UHF-120 Polytec) is used to measure the ultrasonic signal, as shown in Fig. 2. A tone burst signal of 100 cycles at 2.25 MHz from the function generator is input into the power amplifier to drive the piezoelectric transducer.

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