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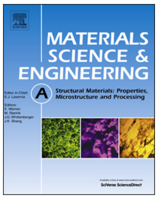

Effect of plastic deformation on nonlinear ultrasonic response of austenitic stainless steel

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ABSTRACT

The effect of tensile plastic deformation on the nonlinear ultrasonic response of austenitic stainless steel was examined, using nonlinear longitudinal wave. The plastic deformation induced the formation of twins and martensite needles in grains. The density of martensite needles increased with increasing plastic strain. The nonlinear ultrasonic parameter increased with increasing the plastic strain experienced by plastically deformed austenitic stainless steel. A simple power–law relation was proposed between the nonlinear ultrasonic parameter and the plastic strain, taking account of the contribution of local microstructures and microplastic deformation. Using this relationship, the stress exponent index was found to be 1.55. Considering the contributions of local microstructures, the deformation-induced phase change and the deformation associated with the formation of new phase, it is suggested that the acoustic nonlinearity of heterogeneous materials depends on local microstructures, phases, misfit, and high-order elastic constants of individual phases.

1. Introduction

Most engineering structures and components experience plastic deformation during the processing and/or service. For crystalline metals, the motion and multiplication of dislocations play an important role in controlling the mechanical properties, such as strength, ductility, and so on [1]. Plastic deformation has been used to change the mechanical strength of metals in order to satisfy the requirements in chemical, transportation, nuclear and aerospace industries, while excessive plastic deformation likely will lower the ductility of metals and lead to early failure of structures and components [2]. It is of practical importance to examine the extent of plastic deformation for the safety control of engineering structures and components.

Various techniques have been developed to characterize the variation of microstructures, including X-ray diffraction [3], electron backscatter diffraction [4], magnetic Barkhausen emission [5], and ultrasonic technique [6,7]. Among these, the ultrasonic technique has been considered as one of the powerful methods of characterizing structural degradation, such as structural damage and plastic anisotropy, during mechanical deformation [8,9] since the propagation of ultrasonic waves is a function of the deformation state of materials. Linear ultrasonic technique, which is based on the measurement of sound velocity and attenuation, is not sensitive to the microstructural change with characteristic dimensions less than ultrasonic wavelength [10]. This has stimulated the research interest of using nonlinear ultrasonic to examine the microstructure changes associated with the multiplication and motion of dislocations and the micro-damage of engineering materials under various deformation states, including fatigue [11,12], creep [13–15], thermal aging [16,17], and plastic deformation [18–20].

Hikata et al. [6] studied the acoustic nonlinearity of single crystal aluminum and polycrystal aluminum, which experienced plastic deformation. They found that the amplitude of the second harmonic wave was more sensitive to the bias stress (larger than elastic limit) for plastically deformed single crystals than that for plastically deformed polycrystals, which was nearly independent of the bias stress (less than elastic limit). Jhang and Kim [21] observed similar behavior that nonlinear ultrasonic parameter increased with tensile stress in a structural steel, especially when the tensile stress was larger than yield stress. Using nonlinear Rayleigh wave and longitudinal wave, respectively, Herrman et al. [22] and Kim et al. [23] examined the structural damage of a Ni-based super alloy introduced by plastic deformation and noted that acoustic nonlinearity increased with increasing plastic deformation. Bermes et al. [24] and Pruell et al. [25] demonstrated that nonlinear Lamb wave could also be used to assess the structural damage in aluminum thick plates when exciting conditions were met. Shui et al. [26] measured the acoustic

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nonlinearity of AZ31 magnesium–aluminum alloy, using both offline and online nonlinear ultrasonic wave techniques, and observed significant increase of acoustic nonlinearity when applied stress was larger than yield stress. Zhang et al. [27] used nonlinear longitudinal wave and surface wave to study the effect of plastic deformation on nonlinear acoustic response of AA7009 alloy and proposed a power law relation between acoustic nonlinearity and plastic strain. Rao et al. [18] attempted to correlate acoustic nonlinearity with microstructural changes for uniaxial tension of AA 7175-T7351 alloy and suggested that nonlinear ultrasonic parameter could be related to the increase of dislocation density and the formation of dislocation cell structures. Viswanath et al. [28] studied the acoustic nonlinearity and strength of AISI 304 stainless steel with various extents of cold working and attributed the increase of acoustic nonlinearity to the increase of dislocation density and the formation of martensite phase. They discussed the relationship between the mechanical properties of the cold-rolled AISI 304 stainless steel and nonlinear acoustic parameter without addressing the effect of deformation state on nonlinear acoustic response.

As discussed above, the nonlinear acoustic response of materials depends on microstructural characteristics, which is a function of deformation state and history. The deformation state also plays an important role in determining the mechanical strength of materials. Currently, there are little studies addressing the effect of the deformation state on the nonlinear acoustic response of materials and the correlation between acoustic nonlinearity and plastic strain in austenite stainless steel. It is the purpose of this work to investigate the nonlinear acoustic response of plastically deformed austenitic stainless steel. The dependence of nonlinear acoustic parameter on plastic strain is examined. The effect of microstructural change on the nonlinear acoustic response of plastically deformed austenitic stainless steel is also discussed.

2. Experimental details

2.1. Materials and sample preparation

The material used in this work was an austenitic stainless steel with a nominal chemical composition of C, 0.05; Si, 0.47; Mn, 1.12; P, 0.034; S, 0.001; Cr, 18.30; Ni, 8.08; Cu, 0.1116; N, 0.04 and balance Fe in wt%, corresponding to commercial 304 stainless steel. The austenitic stainless steel was hot-rolled to plates of 16 mm in thickness, which were heat-treated at 1323 K for 0.5 h and then water-quenched.

Tensile samples in a dog-bone shape were made from the steel plates with loading axis parallel to rolling direction. Fig. 1 shows the schematic of the tensile samples with a gauge length of 60 mm and a cross section of 12 × 10 mm^2.

Tensile tests were carried out at room temperature on a Zwick Materials testing machine (Zwick Z600E). The strain-controlled mode was used to produce plastic strains of 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%. The nominal strain rate was 0.001 s^{-1}. An extensometer with a gauge length of 50 mm was used to measure the length change during tests. The acoustic nonlinearity of the plastically deformed austenitic stainless steel was examined, using nonlinear longitudinal wave.

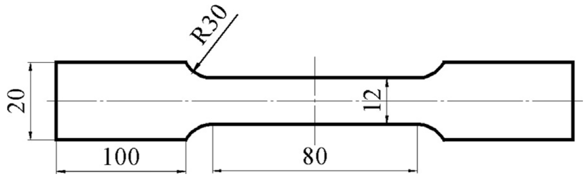

Fig. 1. Schematic of the geometric configuration of tensile samples.

Using electric sparking cutting, small tensile samples in a dog-bone shape with 3 mm thickness was made from the plastically deformed samples in the thickness direction. Tensile tests of the small tensile samples were performed at room temperature to determine the dependence of yield stress on the plastic strain, using a 500 kN servohydraulic tensile machine (Instron 8803). The strain-controlled mode was also used herein.

2.2. Microstructural characterization

Five specimens with the plastic strains of 0%, 10%, 20%, 30% and 40%, were prepared for the characterization of microstructures. Two samples were cut from the central region of the plastically deformed samples in the loading direction. One sample was used for optical microscopy (OM) observation, and the other was for TEM observation. The OM samples were mechanically ground with emery papers progressively to 2000 grit and then electrochemically polished, using a solution of 5% $HClO_4$, 80% CH_3CH_2OH and 15% distilled water at room temperature. The OM samples were then etched, using 10% oxalic acid dihydrate at an electric voltage of 20 V for a few seconds.

The TEM samples were mechanically polished to 0.1 mm thickness and then electrochemically polished at 248 K, using a twinjet electro-polishing system. The chemical solution was the mixture of $HClO_4$ and CH_3CH_2OH at a ratio of 3:97, and an electric voltage of 7.5 V was used in electrochemical polishing. The microstructures were observed, using a JEM-2100 transmission electron microscope at an electric voltage of 200 kV.

2.3. Nonlinear ultrasonic characterization

The RITEC SNAP RAM-5000 system (RITEC Inc., Warwick, RI, USA) with high power gated amplifier was used for the generation of high power tone burst signals. A narrow-band longitudinal piezoelectric transducer with a central frequency of 5 MHz (Olympus NDT Panametrics, A543S) was used as transmitter, and a broad-band longitudinal piezoelectric transducer with a central frequency of 10 MHz (Olympus NDT Panametrics, V544) was used as receiver. Both transducers had the same active window size of 8.75 mm in diameter. A tone burst sine wave signal of 8 cycles at 5 MHz was introduced into specimen through the transmitter. The distorted signal was detected by the receiver, which was recorded by an oscilloscope with a sampling rate of 1.25 GS/s and was stored in a computer. The fast Fourier transform was used to convert the signals in the time space to those in the frequency space. The amplitudes of the fundamental and second harmonics were determined from the frequency spectra, as shown in Fig. 2.

The nonlinear acoustic response of the plastically deformed samples was characterized in five different positions uniformly distributed in the gauge section of each individual sample. Light lubrication oil was used as the coupling between the transducers and the sample, and a fixture was used to align the transmitter with the receiver in the thickness direction on the same centerline under the action of a constant pressure. Calibration was performed to verify the receiving signals of longitudinal waves [27], which assured that the acoustic nonlinearity measured was due to the microstructural change of the plastically deformed material not due to the spuriousness of linear signals or the nonlinearity from instrumentation.

3. Results and discussion

Fig. 3 shows optical micrographs of the plastically deformed austenitic stainless steel. Irregular grains are observed in the as-received steel, which mainly consisted of single phase austenite matrix and annealing twins. There were no significant changes in