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Tensile-Strain-induced Nonlinear Ultrasonic Changes in a Low Carbon steel

低炭素鋼の引張ひずみによる非線形超音波特性の変化

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1. Introduction

As detection method of plastic deformation in metals, there are a corrosion method and a Moiré method, which were limited to specific materials and detection for large deformation on the surface, and required to preprocessing. Therefore, the new detection method is expected[1)].

In this study, we applied nonlinear ultrasonics for detection of plastic deformation, which is capable of probing the change of dislocation structure[2)]. Its sensitivity to microstructural evolutions during plastic deformation is often higher than that of linear properties. We elucidated the relationship between microstructural change and the evolutions of two nonlinear acoustic characterizations; resonant frequency shift [3)] and three-wave mixing[4)], with electromagnetic acoustic resonance (EMAR) [5)] throughout tensile test in a low carbon steel, JIS-S25C at room temperature.

2. Experimental

The material of the specimens was commercially available JIS-S25C, which was heated at 1133K for 0.5h, and then furnace-cooled. To clarify the relationship between nonlinear acoustic characterizations and the strains, interrupted tensile tests were conducted using a plate type specimen of 30 mm wide, 40 mm long and 3mm thick at gauge section. The tensile tests were interrupted at five different strains. **Figure 1** shows interrupted points at stress-strain curve in tensile tests; before upper yield point, at upper yield point, at lower yield point, halfway point between lower yield point and tensile strength, and at tensile strength. Direction of tensile load was paralleled to rolling direction. After unloading of tensile load, acoustic nonlinearities were measured. After measurement of acoustic properties, we observed microstructural change by EBSD (electron backscattering diffraction) and dislocation densities by X-ray[6)].

We measured evolutions of the acoustic nonlinearities with the nonlinear resonant ultrasound

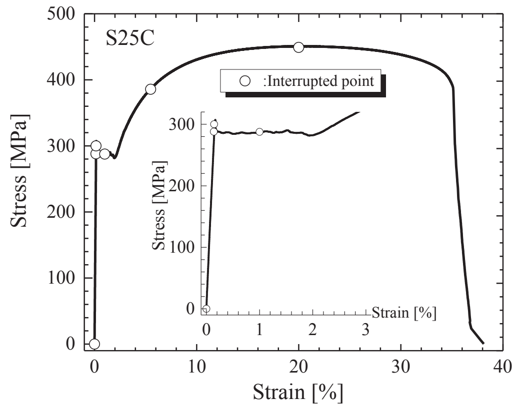

Fig. 1 Interrupted strain-stress condition in tensile test (S25C).

spectroscopy (NRUS) [3)], and three-wave-mixing technique[5)] throughout the tensile test with an electromagnetic acoustic transducer (EMAT) [5)]. We used bulk-shear-wave EMAT, which transmits and receives shear wave propagating in thickness direction of a plate specimen.

NRUS analyses the dependence of the resonance frequency on the strain amplitude while exciting the sample at relative low amplitude[3)]. By observing the relative frequency shift, it is possible to have a measure of internal changes of the microstructural properties of the material. That is, NRUS, the resonant frequency of an object is studied as a function of the excitation level. As the excitation level increases, the elastic nonlinearity is manifest by a shift in the resonance frequency.

Three-wave-mixing technique is based on the fact that material nonlinearities cause interaction between two intersecting ultrasonic waves [4)]. Under certain conditions, this can leads to the generation of a third wave with a frequency and wave-vector equal to the sum or difference of the incident wave frequencies and wave-vectors, relatively. This is much less sensitive to system nonlinearities due to spatial selectively, modal selectively, and frequency selectivity. We applied this three-wave-mixing

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technique to EMAR, which was a combination of the resonant acoustic technique with EMAT[7]. Two EMATs were faced and set in the thickness direction of the sample. Different resonance frequencies; f_n, f_m (*n, m*: resonant modes, $n>m$) were generated by two EMAT, respectively. The difference or sum frequency, $f_n \pm f_m$ was measured by one EMAT. Because material nonlinearity showed independence of the excitation level, the amplitude of the interaction resonant wave A_3, at $f_n \pm f_m$ was normalized to the product of the two input resonant amplitudes A_1 and A_2 . In this study, we measured the amplitude, A_3 at the resonant frequency, f_m-f_n. In selection of resonance mode, *n, m*, the numbers were prime numbers or not with common divisor or common multiple. We measured resonant frequencies for resonant modes with using the systems for a nonlinear acoustic phenomenon (SNAP) manufactured by RITEC.

3. Results

We measured the evolutions of two nonlinear acoustic nonlinearities with NRUS, and three-wave-mixing technique, ultrasonic attenuation and velocity with EMAR in tensile tests. In this measurement in three-wave-mixing, we chose resonant frequencies, f_5, f_7 as input resonant frequencies. We measured the amplitude A_3 of the incident frequency, f_7-f_5. Shown in **Fig.2** are relationships (a) the nonlinearity with three wave mixing, $A_3/(A_1A_2)$, (b) the nonlinearity with NRUS at f_5, f_7, $\Delta f/f_0$, (c) attenuation coefficient, αs at f_5, f_7, and (d) relative velocity, $\Delta V/V_0$ at f_5, f_7 ($\Delta V = V - V_0$, V: velocity, V_0: initial velocity) at interrupted different strain conditions. The polarization direction of shear wave was paralleled to the loading direction. As increase in strain, $A_3/(A_1A_2)$ increases and shows peak at halfway between lower yield point and tensile strength (Fig.2 (a)). The maximum value at peak is ten times larger than that before tensile test. α and $\Delta f/f_0$ show same trends as $A_3/(A_1A_2)$ (Fig.2 (b) and (c)). Amounts of their increases are smaller than that of $A_3/(A_1A_2)$. $\Delta V/V_0$s sharply decreased to lower yield point, and slightly decreased until tensile strength (Fig.2 (c)). The total decrease in velocity is about 0.5 %.

4. Conclusions

We investigated the relationship between microstructural change and the evolutions of two nonlinear acoustic characterizations; resonant frequency shift and three-wave mixing, with EMAR throughout tensile test in a low carbon steel, JIS-S25C. Two nonlinear acoustic parameters and ultrasonic attenuation increased from the start to halfway between lower yield point and tensile strength and rapidly decreased. We interpreted these phenomena in terms of dislocation movement and restructuring during tensile test, with support from the EBSD and X-ray observation.

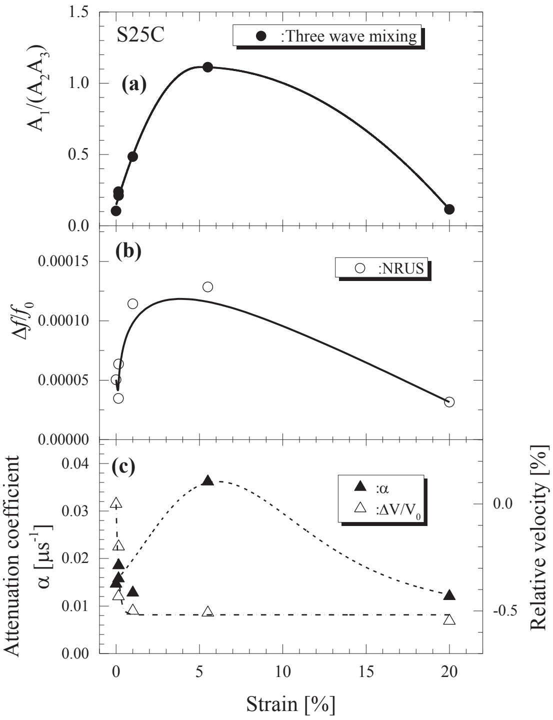

Fig.2 Evolutions of (a) the nonlinearity with three wave mixing, (b) the nonlinearity with NRUS, (c) attenuation coefficient and relative velocity during tensile test for S25C Steel.

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