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Plastic strain-induced nonlinear ultrasonic properties in annular notches in aluminum alloys

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1.Introductuion

The effect of stress concentration is an important issue in the design of structures subjected to static and fluctuating loads. Because welds, notches and other cross-sectional changes in machine elements and structures can easily become the origin of plastic deformation and failure under load. The distribution of stress and strain becomes very complex at these notches. Generally, notched specimens are often used to study the effect of notches on structures. It is well known that notches cause multiaxial stresses and strains in the root zone.

In this study, we applied nonlinear ultrasonics for detection of plastic deformation at the notch root under multiaxial stress, which is capable of probing the change of dislocation structure[1)]. Its sensitivity to microstructural evolutions during plastic deformation is often higher than that of linear properties. We elucidated the relationship between plastic strain at root zone analyzed by the Finite Element Method (FEM) and the evolutions of two nonlinear acoustic characterizations; resonant frequency shift [2)] and harmonic componets[3)], with electromagnetic acoustic resonance (EMAR) [4)] throughout tensile test in JIS-A2017, a High-strength Al-Cu-Mg alloy, at room temperature.

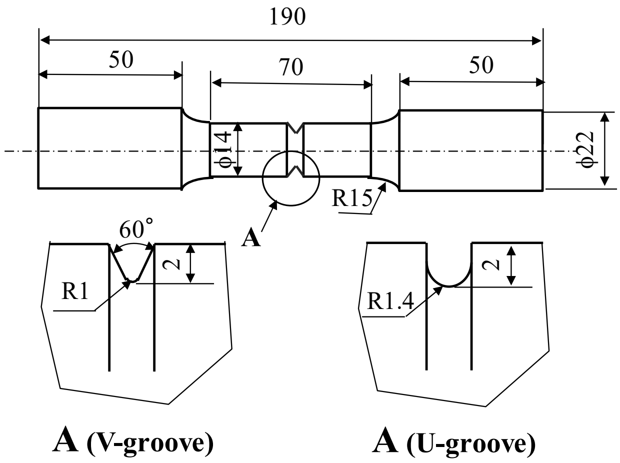

Fig.1 Shape of 2 types of notched samples

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2. Experimental

The material of the specimens was commercially available JIS-A2017-O, Al-Cu-Mg alloy. To clarify the relationship between nonlinear acoustic characterizations and the strains at notch root, interrupted tensile tests were conducted using a cylindrical type specimen of ϕ14 mm, 70 mm at gauge section which a circumferential V grooved notch with root radius of 1 mm and U grooved notch with root radius of 1.4 mm (**Fig.1**). Elastic stress concentration factors (Kt) are 2.5 and 2.3, respectively. The tensile tests were interrupted at two different nominal stresses: 50%, 80% of tensile strength. Direction of tensile load was paralleled to rolling direction. After unloading of tensile load, acoustic nonlinearities were measured. Furthermore, elasto-plastic analysis around the notch root was performed using the finite element method, Femtet manufactured by Murata Software.

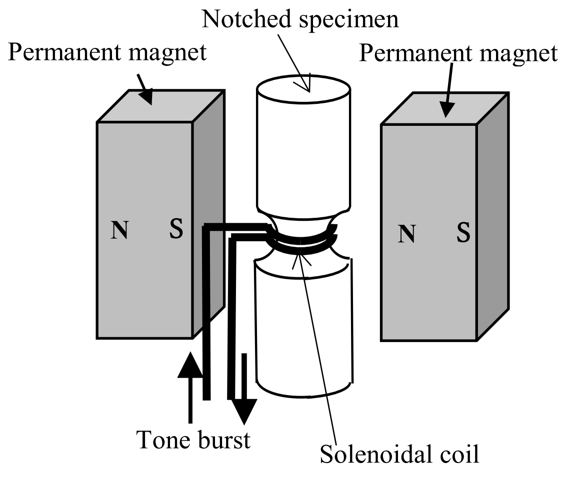

Fig.2 The Lorentz-force mechanism causes an axial-shear-wave EMAT

We measured evolutions of the acoustic nonlinearities with the nonlinear resonant ultrasound spectroscopy (NRUS) [2)], and harmonic components [3)] throughout the tensile test with an electromagnetic acoustic transducer (EMAT)[4)]. We used axial-shear-wave EMAT, which travels in the circumferential direction along the cylindrical surface of a circular rod or pipe specimen. For a paramagnetic material, the axial shear wave can be generated by the Lorentz-force mechanism using a pair of permanent magnets (two poles) and a solenoid coil surrounding circumferential U or V grooved notch. (**Fig 2**). Axial-shear-waves are circumferentially propagating surface SH waves that are deflected in the axial direction. The solenoid coil was made of enamel-coated wire with ϕ 0.2 mm and wound three times around the bottom of the notch.

NRUS analyses the dependence of the resonance frequency on the strain amplitude while exciting the sample from relatively low to high amplitudes[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.

Measurement method for harmonic components with axial-shear-wave EMAT was described in ref 4). From this method, we measured the first resonance peak as the fundamental amplitude, A_1 and peak height as second-harmonic amplitude, A_2, to calculated the nonlinearity A_2/A_1. These measurements were made possible by the system for nonlinear acoustic phenomena (SNAP) manufactured by RITEC Inc.

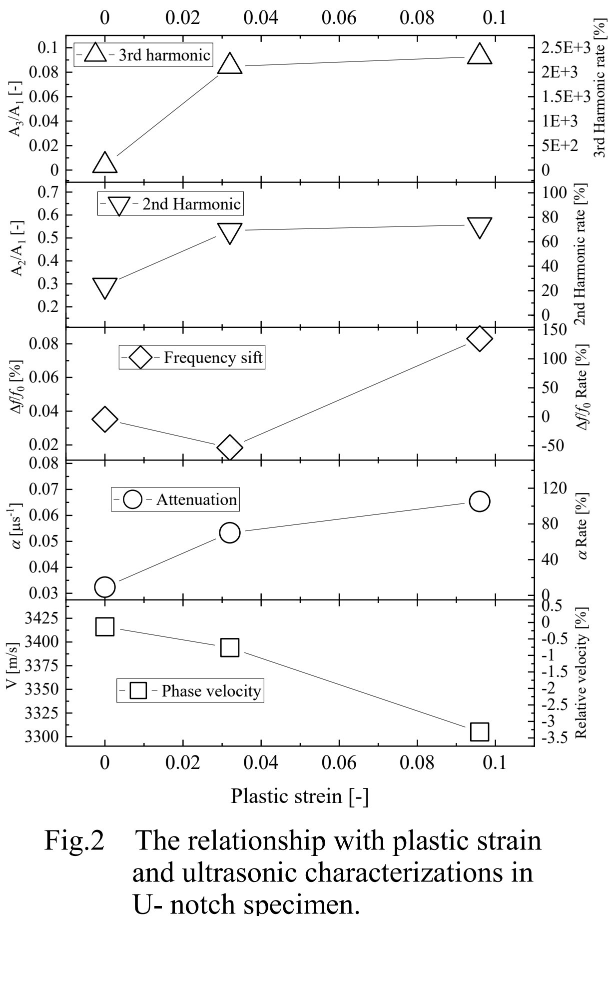

Fig.2 The relationship with plastic strain and ultrasonic characterizations in U- notch specimen.

3. Results and discussion

Figure 3 shows the change in the two nonlinearity, NRUS ($\Delta f/f_0$), harmonic components A_2/A_1, A_3/A_1, ultrasonic attenuation coefficient α, and relative velocity $\Delta V/V_0$ with EMAR in the tensile test of the U-groove notched specimen. A_2/A_1, A_3/A_1, and $\Delta f/f_0$ increased sharply at a strain of 3.2×10^{-2} (50% of the tensile strength) and continued to increase until the plastic strain of 9.8×10^{-2} (80% of tensile strength). α showed a similar trend nonlinearity. $\Delta V/V_0$ tended to decrease with increasing strain, but the rate of change was less than 4%, which was small compared to the rate of change in the amount of nonlinear ultrasound parameters. This trend was also observed in the V-groove notched specimen. Since the FEM analysis showed 6that a large strain occurred near the surface of the notch root, these changes are thought to be due to an increase in dislocation density due to local plastic deformation caused by stress concentration at the notch root[5,6].

4. Conclusion

The changes in two nonlinear acoustic properties (resonant frequency shift and harmonics) due to EMAR were investigated throughout the tensile tests of the notched aluminum alloy A2017-O. The two nonlinear acoustic parameters increased with increasing plastic strain. These phenomena were interpreted in terms of dislocation motion due to localized plastic deformation caused by stress concentration. The nonlinear ultrasonic technique based on the EMAR method has the potential to be used to measure the amount of strain in stress concentration areas.

References

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