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Nonlinear ultrasonic characterization of creep damage in an Austenitic Stainless Steel

オーステナイト系ステンレス鋼のクリープ損傷中の非線形超音波特性

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1. Introduction

Many structural components of the thermal power plants have exceeded the design life of 100,000 hours and continued operating despite undergoing progressive damage like creep. Furthermore, after March, 11th, 1991, aged plants restarted and are operating under severe conditions to satisfy the electricity demand. Under this situation, it is necessary to predict the remaining life for structural materials to using non-destructive technique to keep the safety and reliability of the thermal plants, [1]. It is required to evaluate to the intrinsic damage of these structural components accurately and quickly. Then, we applied electromagnetic acoustic resonance (EMAR)[2], which is combined with electromagnetic acoustic transducer (EMAT) [2] and ultrasonic resonance method, to nonlinear ultrasonics because it exhibits high sensitivity to microstructure change of damaged materials[3]. So, we applied nonlinear resonant ultrasound spectroscopy (NRUS)[4] with EMAR to evaluation of creep damage, which is a method of measuring shift of the resonance frequency of the sample as changes in excitation force. Elastic nonlinearity is causing the moving of resonance frequency by increase of the excitation force. Our objective in this study is to establish the relationship between creep-induced microstructural changes and nonlinearity with NRUS in an austenitic stainless steel, JIS-SUS304.

2. Samples and experimental condition

Materials are formed from hot-rolled commercial plate of JIS-SUS304 austenitic stainless steel. The materials were heat treatment: the solution treatment 1423K for 2 h and quenched. Specimens for creep testing have 35mm in gage length, 18mm in gage width, 5mm thickness. The creep tests were performed at 973 K, and applied stress 120MPa in air. We interrupted creep loading and furnace-cooled the sample. After measuring ultrasonic properties (attenuation coefficient and velocity) and nonlinearity, we restarted the creep test. We repeated this procedure every 30 h until rupture.

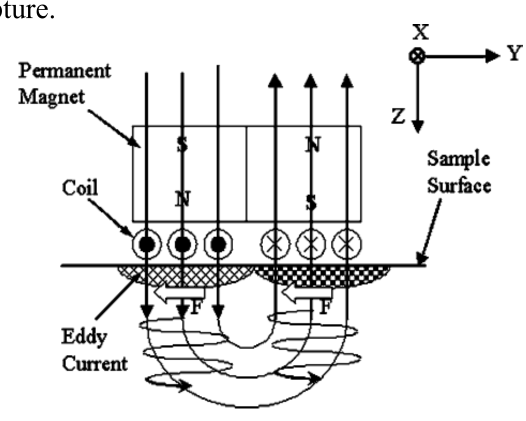

Fig.1 Structure of the shear wave EMAT.

3. EMAR for NRUS

We used a shear-wave EMAT of 10 × 10 mm^2 effective area, which consisted of an elongated-spiral coil and a pair of permanent magnets in opposite directions, normal to the surface, as shown in **Fig. 1**. Operating of EMAT is referred to Ref 2. The shear wave traveled back and forth in the thickness direction.

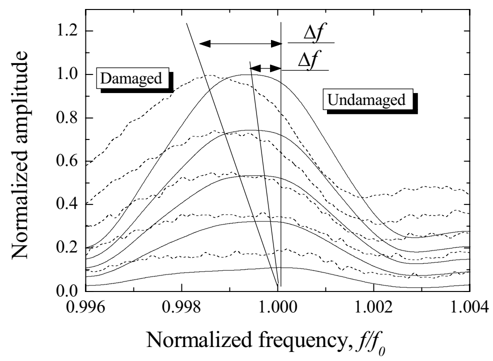

Fig.2 Masured resonant frequency shift with NRUS in intact and damaged samples.

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NRUS analyses the dependence of the resonance frequency on the strain amplitude while exciting the sample at relative low amplitude[4]. By observing the relative frequency shift, it is possible to have a measure of internal degradation 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. **Figure 2** shows a results of this method; according to experimental results with EMAR, the sample under sweep load centered on one of its resonant frequencies shows different behavior of structural response depending on the status of sample: intact or damaged. We defined this frequency shift Δf to as the nonlinear acoustic parameter.

4. Result and Discussion

Figure 3 shows the relationship between the nonlinearity NRUS, relative velocity $\Delta V/V_0$ (velocity change/initial velocity, V_0), ultrasonic attenuation, α, in the 5th resonant mode (around 1.5MHz), the creep strain, the strain rate, and life fraction, t/t_r (the creep time/the creep life). Rupture time was 298 h. The strain rate decreases to t/t_r = 0.3 from start of creep, then remains constant to t/t_r = 0.7, and increases from t/t_r = 0.7 to rupture (Fig. 3(a)). We defined NRUS as $\Delta f/f_0$ (f_0: resonance frequency at lowest drive) [4]. After peaking at t/t_r = 0.5, NRUS drops until t/t_r = 0.6. Then it rapidly increases to the rupture (Fig.3 (b)). α shows the same tendency as the NRUS. $\Delta V/V_0$ increases monotonously to around 7% (Fig.3(c)). The changes of strain and its rate are corresponding to transient creep, steady creep and accelerating creep. We consider that the evolution of non-linearity results from changes in the dislocation structure during creep. The attenuation peak resulted from dislocation mobility during creep [5]. According to string model of Guranato and Lücke[6] the dislocation will be absorbed by the ultrasonic vibration at the same time due to add the varying stress by ultrasonic, and the attenuation, α, dislocation density Λ, effective dislocation length L, to expressed as the following equation

$$\alpha \propto \Lambda L^4 f^2 \tag{1}$$

Furthermore, Δf can be determined using the following equation[4]:

$$\Delta f \propto C_1 \Delta\varepsilon \tag{2}$$

Here, C_1 value is proportional to the hysteresis parameter in the solid, Δε the increment to local strain amplitude for over the cycle of the previous. The change of resonant frequency shift are corresponding to that of the attenuation during creep. Therefore, change in the NRUS is caused by change of dislocation structure during creep.

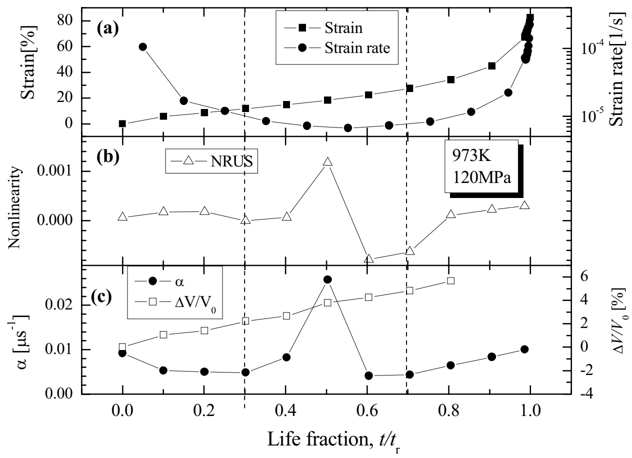

Fig.3 Evolutions of nonlinear acoustic parameter in NRUS and attenuation, velocity, creep strain and rate during creep progression in SUS304 (973 K, 120 MPa).

5. Conclusion

Creep damage in an austenitic Stainless Steel (JIS-304) at 973 K in air was evaluated through the nonlinearity NRUS measured with EMAR method. NRUS showed a peak at around 50% and a minimum value at 60% of the creep life, the attenuation showed the same tendency as the NRUS. The evolution of NRUS and attenuation are arisen by the changes in dislocation structure.

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