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Nonlinear Ultrasonic Characterizations of Welded Joint in High Chromium Ferritic Steel during Creep Damage
フェライト系高 Cr 鋼溶接継手材のクリープ損傷中の非線形超音波特性

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1. Introduction

The ultra-supercritical pressure steam boiler has been operating under high-temperature and high-pressure to improve thermal efficiency, and the high chromium ferritic steels were applied to constituent material. In high chromium ferritic steels, type IV damage at fine grain region in the heat-affected zone (FGHAZ) of the welded joints has become a problem[1)]. The type IV damage occurred at internal area rather than surface one. It is difficult to detect the damage by conventional replica method. Therefore, studies with ultrasonic method for detecting internal damage have been conducting. Then, we applied nonlinear ultrasonic methods with electromagnetic acoustic resonance (EMAR)[2)] for evaluating the creep damage in 9%-Cr steel welded joint. EMAR is combined with the ultrasonic resonance method and electromagnetic acoustic transducer (EMAT)[2)]. The nonlinear behavior of the ultrasonics wave exhibits sensitive response to microstructural change in damaged materials. So, we measured resonant frequency shift with nonlinear resonant ultrasound spectroscopy (NRUS)[3)] and higher harmonic components.

2. Samples and experimental condition

Welding material similar to the chemical composition of base metals to hot-rolled the 9%-Cr steel plate of thickness to 50 mm was used. **Figure 1** showed sampling position from 9%Cr welded joint. In round-bar specimen for creep test, gauge length was 30mm, diameter was 6mm. In the base metal, heat treatment was as follows; normalized at 1343K for 1 h, and tempered at 1053K. In the post welded heat treatment, samples were air cooled after holded at 1013 K for 1 h. The creep tests were performed at 923 K in air, and applied stress was 100 MPa. The creep tests were performed until target time using multiple specimens, and then measuring nonlinearity (NRUS and second and third harmonics amplitude) and ultrasonic property (attenuation coefficient).

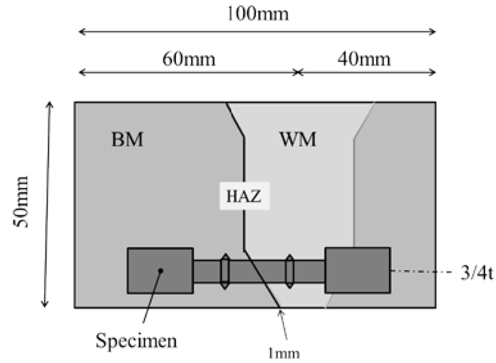

Fig.1 Sampling position of the 9Cr welded joint

3. EMAR for nonlinear acoustic parameter

We used an axial-shear wave EMAT. Operating of EMAT is referred to Ref. 2. The axial shear wave propagates in the circumferential direction by polarizing in the axial direction.

NRUS analyzed the dependence on the strain amplitude of resonance frequency at comparative low amplitude. The elastic nonlinearity caused the resonance frequency shift with increasing the excitation force. By observing the relative frequency shift, it is possible to measure of internal degradation of the microstructural properties of the material. We measured the resonance frequency shift with the EMAR. We defined $\Delta f/f_0$ (resonance frequency shift: Δf, amplitude independent resonance frequency: f_0)[3)] as the nonlinear acoustic parameter. Measurement method of harmonics at the axial shear wave has shown below. To drive the EMAT at the resonance frequency f and the measured amplitude defined the reference amplitude A_1. Then, the EMAT drive at frequency of $f/2$ while retaining of the input power. This condition does not satisfy the resonance condition, but frequency component of twice $f/2$ resonate by nonlinear effect. We defined the second harmonics amplitude A_2 and the third harmonics amplitude A_3

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in the same way. In this study, we defined each A_2/A_1 and A_3/A_1 as the nonlinear acoustic parameter of the second and third harmonics.

4. Results and Discussion

Figure 2 shows the relationships between the nonlinearity, $\Delta f/f_0$, with NRUS, nonlinearity, A_2/A_1, A_3/A_1 by second and third harmonics, attenuation coefficient, α, (attenuation per unit time) in the 3rd resonance mode (around 2.4MHz), and life fraction, t/t_r (the creep time /the rupture time). Rupture time, t_r, was 1882 h. After peaking at $t/t_r = 0.25$, NRUS shows tendency of increase again from $t/t_r = 0.5$ (Fig.2 (a)). α shows the peak at $t/t_r = 0.25$ and the minimum value at $t/t_r = 0.3$, and the tendency of increase from $t/t_r = 0.5$ (Fig.2 (b)). Second harmonics showed a tendency to decrease after peak at $t/t_r = 0.25$ (Fig.2 (c)). Third harmonics shows the same as tendency of the NRUS (Fig.2 (d)). We consider the influence of the evolution of dislocation structure about the change of ultrasonic nonlinearity during creep. We know the peak phenomenon of attenuation coefficient can be caused by the dislocation motion from the study so far[4], their relationships were able to explain by string model of Granato and Lücke[5]. This string model is modeled as the string vibration in viscoelastic material of the dislocation vibration. The relation among the attenuation coefficient, α, dislocation density Λ and effective dislocation length *L* to expressed as the following equation

$$\alpha = Af^2 \Lambda L^4 \qquad (1)$$

Here, *A* is a positive constant to depend modulus of rigidity and Burgers vector. The ultrasonic attenuation is caused by stress of ultrasonic and hysteresis of strain and irreversible dynamic process due to dislocation. The area of hysteresis loop is observed as the ultrasonic attenuation that indicates the absorptance of ultrasonic energy of one cycle. The frequency shift Δf is proportional to the strain amplitude $\Delta\varepsilon$.

$$\frac{f - f_0}{f_0} = \frac{\Delta f}{f_0} = \frac{C_1 \Delta\varepsilon}{2} \qquad (2)$$

Here, C_1 value is nonlinear hysteresis parameter. From these relationships, frequency shift of NRUS can be considered the change due to the nonlinear by the dislocation. Change in the nonlinearity of second and third harmonics has been known to sensitivity reacts by asymmetry of interatomic potential, the nonlinearity of dislocation motion[6] and increase of the void density. However, we have not been able to confirm these influences at the moment because has not been done observation by TEM.

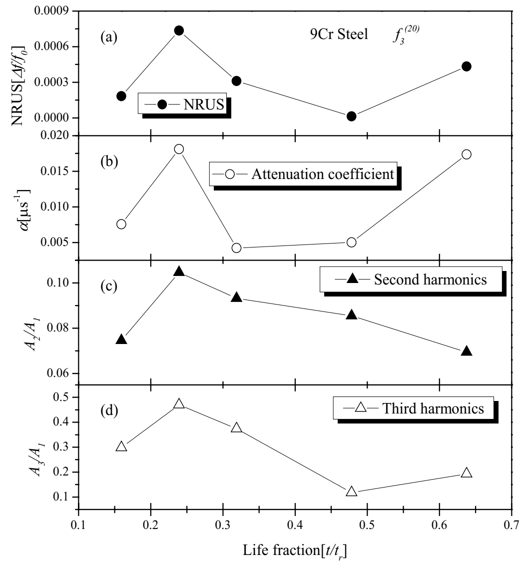

Fig.2 Relationships between nonlinear acoustics parameters and attenuation coefficient during creep in 9Cr steel welded joint (973K, 100MPa, t_r=1882h.)

5. Conclusion

We evaluated creep damage in FGHAZ of 9Cr welded joint by using the nonlinear ultrasonic methods with EMAR. The ultrasonic nonlinearity showed a peak at 25% of the creep life, and similar tendency was also observed in attenuation coefficient. The evolution of ultrasonic nonlinearity and attenuation are considered to have arisen by the change of dislocation structure.

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