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Creep-induced Nonlinear Acoustics in High Cr Ferritic Heat Resisting Steel Welded Joint

高クロム・フェライト系耐熱鋼溶接継手材のクリープ損傷による非線形超音波特性の変化

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1. Introduction

A high Cr ferritic heat resisting steel, ASME Gr. 91 (9Cr-1Mo-MnVNb) has been used for boiler components in ultra-supercritical (USC) thermal power plants at approximately 873 K. The creep life of the welded joints in this steel decreased as a result of Type IV creep damage that forms in the heat-affected zone (HAZ) under long-term use at high temperatures[1)]. We applied nonlinear ultrasonics for evaluation of Type IV damage in welded joint for ASME Gr.91 steels. The nonlinear ultrasonics holds the potential of becoming the primary means of characterizing creep in metals [2)], because it is capable of probing the change of dislocation structure during creep. Its sensitivity to microstructural evolutions during creep 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 higher harmonic components[4)] with electromagnetic acoustic resonance (EMAR) [5)] throughout the creep life in the welded joints of ASME Gr. 91 by conducting creep rupture and interrupted creep tests at 873 K.

2. Experimental

The material used was 25-mm-thick modified ASME Gr.91 [1)]. Using this plate as base metal, a welded joint with a double U groove was made employing gas tungsten arc (GTA) welding. After welding, the welded joint was subjected to post-weld heat treatment (PWHT) for 60 minutes at 1,018 K. Creep specimens with 30mm in gauge length, 6 mm in diameter were cut from the welded joints. In this gauge section, HAZ and weld metal (WM) were included (**Fig.1**). The creep tests were performed at 873 K in air, and applied stress 90MPa. The rupture life (t_r) was 8,000h. Creep tests were interrupted at several creep life ratio (t: creep time), t/t_r=0.2 (t=1,500h),0.4(t=3,000h),0.6(t=5,000h),0.9(t=7,000 h).

We measured evolutions of the acoustic nonlinearities with the nonlinear resonant ultrasound spectroscopy (NRUS) [3)], and higher harmonic components[4)] throughout the creep life in the welded joint with an electromagnetic acoustic transducer (EMAT) [5)]. As shown in **Fig. 2**, we used an axial-shear wave EMAT. Operating of EMAT is referred to Ref 5. The axial shear wave is deflected in the axial direction, and propagates in the circumferential direction.

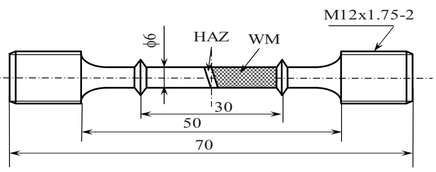

Fig.1 Shape of welded joint specimen.

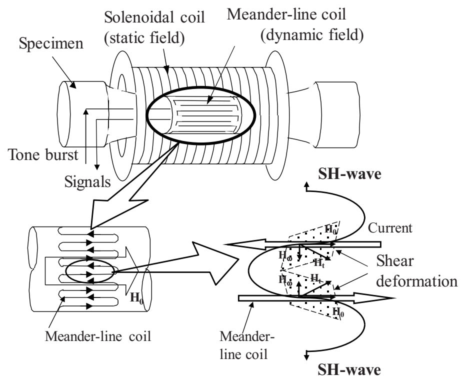

Fig. 2 Axial-shear-wave EMAT consisting of a solenoid coil and a meander-line coil surrounding the cylindrical surface. The magnetostrictive mechanism causes the axial surface SH wave.

NRUS analyzed the dependence of the resonance frequency due to the strain amplitude while excitation the specimen at comparative low amplitude. The elastic nonlinearity brings about 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 applied the measurement of NRUS to the EMAR. We defined $\Delta f/f_0$ (resonance frequency shift: Δf, amplitude independent resonance frequency: f_0) [3)] to as the nonlinear acoustic parameter.

Measurement method of harmonics at the

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axial-shear wave has shown below [4,5]. After driving the EMAT at the fundamental resonance frequency f_1, we measured the maximum amplitude of the resonance peak, A_1. We then excited the axial shear wave by driving the EMAT at half of the resonance frequency ($f_1/2$), keeping the input power unchanged. In this case, the driving frequency does not satisfy the resonance condition and the fundamental component does not produce a detectable signal. However, the 2nd harmonic component having double frequency (f_1) satisfied the resonance condition and the resonance spectrum of the received signal contained a peak at the original resonance frequency. We defined this peak height as the 2nd harmonic amplitude, A_2, to calculate the 2nd harmonic nonlinearity A_2/A_1. We defined the 3rd harmonic nonlinearity, A_3/A_1, in the same way. We used the systems for a nonlinear acoustic phenomenon (SNAP) manufactured by RITEC.

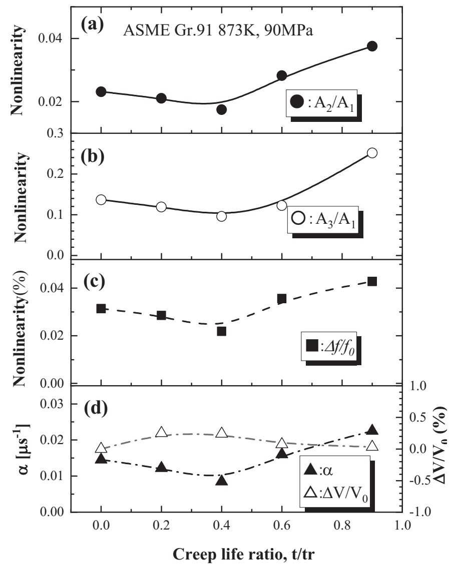

Fig. 3 Evolutions of (a) (b) the nonlinearities in 2nd and 3rd harmonics, (c) the nonlinearity with NRUS, and (d) attenuation coefficient and relative velocity in ASME Gr.91 steel welded joint during creep (873 K, 90MPa).

3. Results and discussions

Figure 3 shows the relationship between the nonlinearity of the 2nd and 3rd harmonics, A_2/A_1, A_3/A_1, nonlinearity of NRUS, $\Delta f/f_0$, attenuation coefficient, α (attenuation per unit time), relative velocity, $\Delta V/V_0$ ($\Delta V=V-V_0$, V: velocity, V_0: initial velocity) in the first resonance mode (around 2.1MHz), and creep life fraction t/t_r. After slightly decreasing from the start to t/t_r=0.4, second harmonics, A_2/A_1, shows tendency of increase to the rupture (Fig.3 (a)). Third harmonics, A_3/A_1, $\Delta f/f_0$ and α show the same as tendency of the second harmonics (Figs.3 (b) (c) and (d)). In metals, possible factors contributing to non-linear acoustics during creep are as follows [6]: (i) nonlinear elasticity due to lattice anharmonicity (ii) inelasticity due to dislocation movement and (iii) crack opening and closure when an acoustic wave impinges on the crack faces. Therefore, (i)-(iii) explains the observed nonlinearity during creep. These first two factors are inseparable in actual nonlinear measurement. From accordance with the trends of A_3/A_1, A_3/A_1, $\Delta f/f_0$ and α during creep in Fig.3, we considered that the evolution of non-linearity results from changes in the dislocation structure at t/t_r<0.4 and formation and development of creep voids at t/t_r >0.4. In previous studies[1], Type IV failure in the welded joint for ASME Gr.91 steel occurred at fine-grained HAZ. The recovery and recrystallization by creep and formation of creep voids arose earliest in fine-grained HAZ. The creep void formations were initiated in the early stage of creep rupture life (0.2 of life) and the development and coalescence of creep voids and formation of crack occurred at the latest stage. Nonlinear acoustic characterizations with EMAR were able to detect initiation and formation of creep voids and cracks throughout the creep life in the welded joints of ASME Gr.91 steel.

4. Conclusion

The high sensitivity and contactless aspects of EMAR enabled the precise measurement of two nonlinear acoustics; resonant frequency shift and higher harmonic components throughout the creep life in the welded joints of ASME Gr.91 steel. Two nonlinear acoustic parameters and ultrasonic attenuation decreased from the start to 40% of creep life. Then, they rapidly increased to rupture. We interpreted these phenomena in terms of dislocation mobility and restructuring and formation of creep voids and micro-cracks.

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