

Creep-induced Nonlinear Ultrasonic changes in ASME Gr. 122 Heat Resistant Steel Welded Joint

ASME Gr. 122 鋼溶接継手のクリープによる非線形超音波特性の変化

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1. Introduction

ASME Grade 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 temperatures¹⁾. We applied nonlinear ultrasonics for evaluation Type IV damage and microstructural degradation in welded joint for high Cr ferritic heat resisting steels. The nonlinear ultrasonics holds the potential of becoming the primary means of characterizing creep in metals^{2,3)}, 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 shift⁴⁾ and three-wave mixing⁵⁾, with electromagnetic acoustic resonance (EMAR)⁶⁾ throughout the creep life in the welded joints of ASME Grade 91 by conducting creep rupture and interrupted creep tests at 873 K.

2. Experimental

The material investigated in this study is ASME Gr.91 steel; (9Cr-1Mo-MnVNb steel) plate with 30 mm thick¹⁾. The plate was welded by gas tungsten arc (GTA) welding using a double U groove. After welding, post-weld heat treatment (PWHT) was conducted for 60 min at 1018 K for the plate. To clarify the relationship between nonlinear acoustic characterizations and the formation and evolution process of creep damage in the welded joint, interrupted creep tests were conducted using a thick plate type specimen (L-welded joint) of 24.5 x 24.5 mm² in cross-section and 120 mm gauge length for the steel weld³⁾. The creep test was interrupted at several time steps of rupture life (t_r) at 873 K and 90 MPa for the steel welds ($t_r=8853.4h$), where a typical

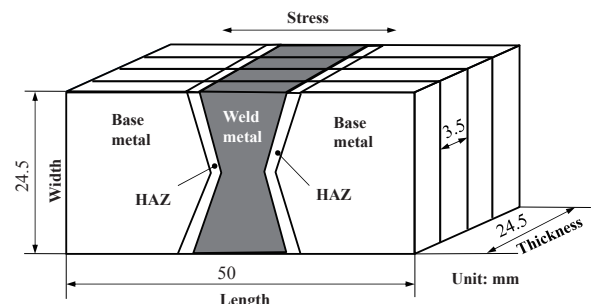


Fig. 1 Plate specimen with 3.5 mm thick for measurement for nonlinear acoustic characterizations.

Type IV failure was observed. Tests were interrupted at approximately 0.1, 0.2, 0.5, 0.7, 0.8, 0.9 of rupture life. As shown in **Fig. 1**, plate specimen with 3.5 mm thick for measurement for nonlinear acoustic characterizations was cut from the interrupted L-welded joints.

We measured evolutions of the acoustic nonlinearities with the nonlinear resonant ultrasound spectroscopy (NRUS)⁴⁾, and three-wave-mixing technique⁵⁾ throughout the creep life in the welded joint with an electromagnetic acoustic transducer (EMAT)⁶⁾. 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 amplitude⁴⁾. 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.

Three-wave-mixing technique is based on the fact that material nonlinearities cause interaction between two intersecting ultrasonic waves⁵⁾. Under certain conditions, this can lead to the generation of a third wave with a frequency and wave-vector

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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 selectivity, modal selectivity, and frequency selectivity. We applied this three-wave-mixing technique to EMAR, which was a combination of the resonant acoustic technique with EMAT. Two EMATs were faced and set in the thickness direction of the sample. Different resonance frequencies; f_n, f_m (n, m : resonant modes, $m > n$) 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 in HAZ with EMAR as creep progress. In this measurement in three-wave-mixing, we chose resonant frequencies, f_5, f_8 as input resonant frequencies. We measured the amplitude A_3 of the incident frequency, $f_8 f_5$. Shown in Fig.2 are relationships (a) the nonlinearity with three wave mixing, $A_3/(A_1 A_2)$, (b) the nonlinearity with NRUS at f_5, f_8 , $\Delta f/f_0$, (c) attenuation coefficient, α_s at f_5, f_8 , and (d) relative velocity, $\Delta V/V_0$ at f_5, f_8 ($\Delta V = V - V_0$, V : velocity, V_0 : initial velocity) at HAZ in Gr. 91 steel welded joint and creep life ratio, t/t_r (t : creep time). $A_3 / (A_1 A_2)$, a decrease from the beginning to the $t/t_r = 0.2$. After that, it increased from $t/t_r = 0.3$ to failure (see Fig. 2 (a)). The amplitude of A_3 was around several hundredths of A_1, A_2 . $\Delta f/f_0$ s decreases from the beginning to $t/t_r = 0.5$, then, showed slightly increase from $t/t_r = 0.5$ to failure. After that, they increased to failure (Fig.2 (b)). The changes of α_s showed same trends of $\Delta f/f_0$ s. (Fig.2(c)) $\Delta V/V_0$ s decreased to $t/t_r = 0.2$, and slightly decreased until rupture (Fig.2 (d)). The total increase in velocity is about 2.0 %.

4. Conclusion

We investigated the relationship between microstructural change and the evolutions of two nonlinear acoustic characterizations; resonant

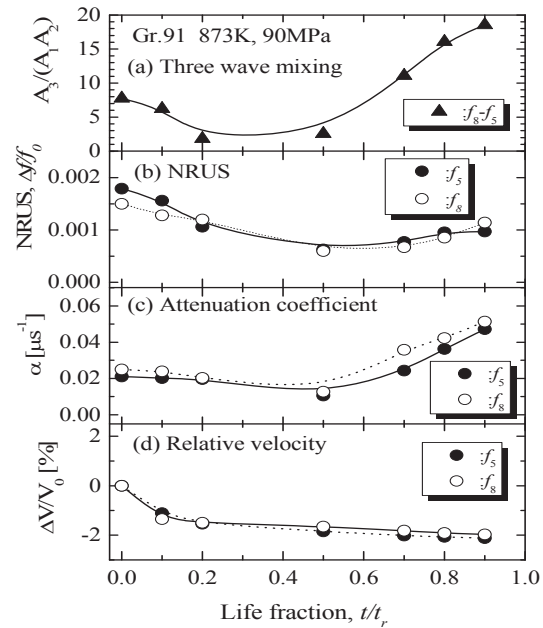


Fig. 2 Evolutions of (a) the nonlinearity with three wave mixing, (b) the nonlinearity with NRUS, (c) attenuation coefficient and (d) relative velocity at HAZ in ASME Gr. 91 steel welded joint during creep (873 K, 90 MPa).

frequency shift and three-wave mixing, with EMAR throughout the creep life in the welded joints of ASME Grade 91. Two nonlinear acoustic parameters and ultrasonic attenuation decreased from the start to 20% of creep life. After slightly increased, they rapidly increased from failure of creep life to rupture. We interpreted these phenomena in terms of dislocation recovery, recrystallization, and restructuring related to the initiation and growth of creep void, with support from the SEM and TEM observation.

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