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Influence of precipitates and dislocations on the acoustic nonlinearity

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Abstract

The influence of precipitates and dislocations on the acoustic nonlinearity was investigated in isothermally aged ferritic CrMo steel and low cycle fatigued copper. The variation in the normalized acoustic nonlinearity parameter (β/β0) was interpreted as resulting from microstructural changes supported by the electron microscopy. The β/β0 of CrMo steel increased abruptly in the initial stage of degradation, and then changed little due to the coarsening of carbide and precipitation of stable M_6C carbide during isothermal aging. Due to the evolution of dislocation cell substructure, the β/β0 of copper increased with the fatigue cycles. These experimental results are illustrated that the acoustic nonlinearity is severely affected by the lattice strain caused by precipitates and dislocations.

Keywords: Acoustic nonlinearity, Precipitates, Dislocations, Isothermal degradation, Fatigue

1. Introduction

During the lifetime of a plant component, the structural materials are exposed to various types of loading and temperature. The most common failures caused to structural materials on prolonged exposure to high temperature and pressure are known to be aging, fatigue and creep. These undesirable damage mechanisms may influence on the material state or behavior during service. For high temperature structural steels such as turbine rotors (i.e., CrMo steel), these steels are liable to subject to aging degradation due to temper embrittlement, carbide induced brittleness and softening of matrix after long time exposure to high temperature. Structural materials subjected to cyclic loading are well known to be closely related to fatigue crack initiation and propagation to failure. The mechanical properties of materials change at the beginning of the fatigue process before crack initiation. Such changes in mechanical properties may be closely related to dislocation density and configuration.

The failure of many plant components would directly impact the safety of the plant facilities. Thus reliable structural health monitoring (SHM) having a high probability of detection is critical. Typical variations in the material properties cannot be detected in situ using conventional destructive methods. Therefore, the development of nondestructive evaluation (NDE) techniques is of utmost importance for detecting defects and evaluating material properties.

The ultrasonic nonlinearity technique has been found to be strongly sensitive to microstructures [1-5]. The nonlinear elasticity of a solid relates to forces acting between atoms in crystals, which are the interatomic potentials characterized by the well depth and equilibrium interatomic separation. Interatomic potentials in real crystals are not harmonic, and the anharmonicity can be treated by higher order elasticity. The potentials are determined by measurements of the sublimation energy of the crystal and of its lattice spacing. When a sinusoidal ultrasonic wave of a given frequency and of sufficient amplitude is introduced into an anharmonic solid, the fundamental wave may be distorted as it propagates, so that the second and higher harmonics of the fundamental frequency will be generated.

In this study, we would like to study structural material and also, understand the relationship between the microstructural changes due to degradation and the features of the acoustic nonlinearity. Therefore, in the present study we attempted to assess the aging and fatigue damage using the acoustic nonlinear effect.

2. Experimental details

2.1. Isothermal aging and low cycle fatigue

A ferritic 2.25Cr-1Mo steel plate specimen (Fe: bal., C: 0.138, Cr: 2.27, Mo: 0.97, Si: 0.142, Ni: 0.17, Mn: 0.46, Al: 0.007, P: 0.014 and S: 0.004, all in % by weight), was tempered at 720℃ after normalizing at 900℃. An accelerated heat treatment was performed at 630℃, and the materials observed at various predetermined degradation time intervals in order to observe differing levels of damage. The polycrystalline Cu specimens were machined to have a gage length of 12 mm, and were annealed in an argon atmosphere for one hour, at 450℃. The final grain size, as determined using an average linear intercept method, was approximately 41 ㎛. The fatigue test specimens were carefully prepared by electropolishing in order to eliminate the surface layer damaged during the mechanical processing. The fatigue experiments were performed under constant strain at room temperature using a servohydraulic fatigue testing machine. A transmission electron microscope (TEM) analysis was conducted in order to observe the morphology and composition of carbides in CrMo steels within thin film specimens that were prepared by electropolishing. All cyclically deformed Cu specimens were cut so the stress axis would be perpendicular to the plane of observation. All thin foils were prepared by electropolishing.

2.2 Ultrasonic nonlinearity

The higher harmonic generation technique [6] was used to measure the acoustic nonlinearity parameter. The ultrasonic nonlinearity measurement system was primarily composed of a high power pulse generator (RAM10000, RITEC Inc.), a high power attenuator (RA-31), a high power 50 Ω termination and a high power 6 dB attenuator. A longitudinal piezoelectric transducer, with a nominal frequency of 5 MHz, was used to generate the fundamental wave. A broad band 10 MHz transducer was used to measure second higher harmonic wave. This detected wave was digitally processed using a power spectrum Fast Fourier Transformation, to obtain the displacement amplitudes, A1 and A2, at the fundamental frequency and second harmonic frequency, respectively.

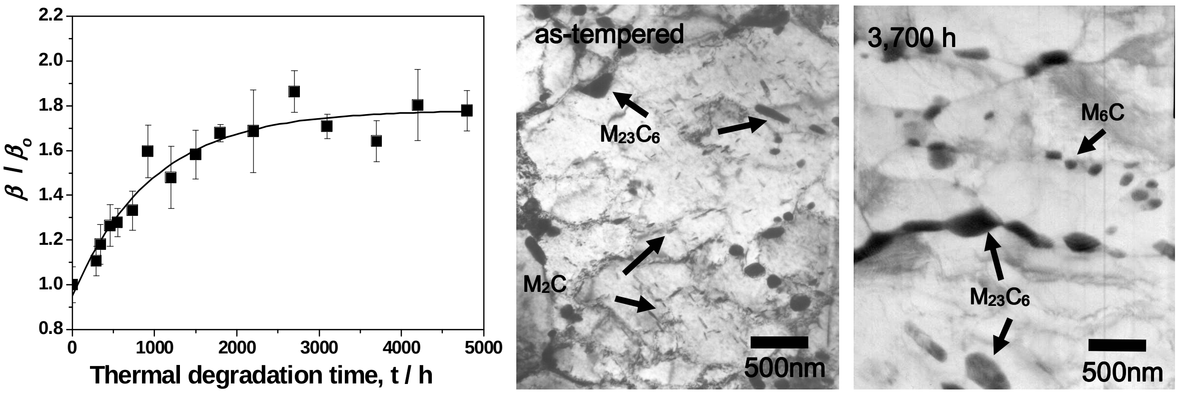
In this study, we measured the normalized ultrasonic nonlinearity parameter (β/β0) in order to evaluate the extent of thermal degradation, where β is the nonlinearity parameter of degraded specimens and β0 is the nonlinearity parameter of an as-tempered specimen.

3. Results

The normalized ultrasonic nonlinearity parameter (β/β0) monotonically increased during isothermal aging as is shown in Fig. 1. The absolute value of β was estimated at the level of ±8% experimental uncertainty. The β/β0 of 2.25CrMo steel progressively increased in the initial stage of degradation, and then changed little after 1,000 h aging time.

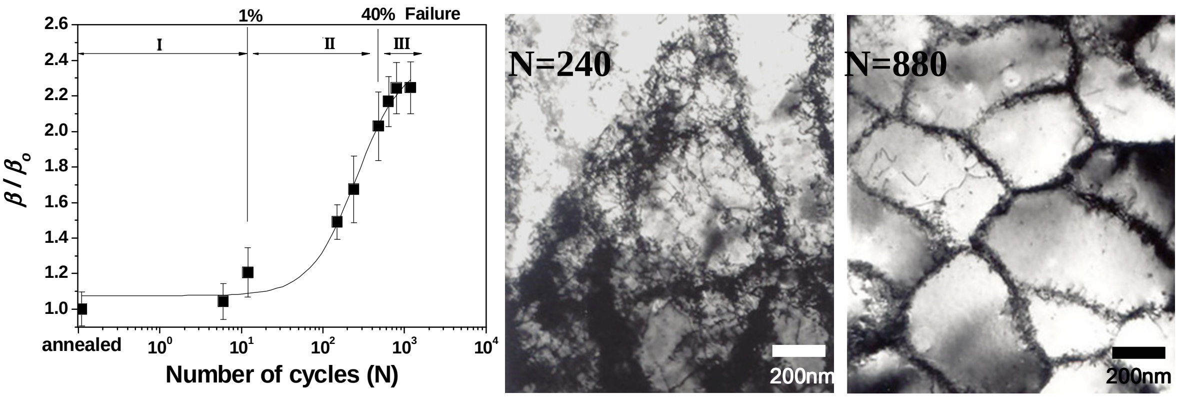
The typical TEM micrographs of the as-tempered and 3,700 h degraded specimens are shown in Fig. 1. Fig. 1(b) reveals numerous acicular carbides with 0.3 μm long which is identified as M_2C carbides. The grain boundary precipitates were identified as the rectangular parallelepiped $M_{23}C_6$ carbides. Fig. 1(c) is the bright field image within grain revealing only the globular M_6C carbide without any fine acicular M_2C carbides. Carbides become coarser and decrease in number with increasing aging time.

Fig. 2 shows the acoustic nonlinearity of Cu as a function of fatigue cycles and typical TEM micrographs. The absolute value of β was estimated at the level of ±7% experimental uncertainty. The nonlinearity parameter increased due to the fatigue driven plastic deformation and exhibited three distinct regions as noted in Fig. 2 (i.e., □, □, □). In the first region (N <1%Nf), there is no change in acoustic nonlinearity. In the second region (1%Nf < N <40%Nf), the acoustic nonlinearity exhibited a steep increase. In the final region (40%Nf <N), the acoustic nonlinearity showed a slight increase. In this study, the development of a dislocation cell substructure in Cu was clearly observed. The results obtained correspond well to those previously reported by Feltner and Laird [7]. The density of dislocations on the cell structure cannot be reliably determined when using thin foils because the dislocation density in the cell walls is too high, notwithstanding the slight decrease in cell size with increasing fatigue life fraction.



(a) (b) (c)

Fig. 1 Variation of acoustic nonlinearity as a function of aging time and typical TEM bright field images of CrMo steel aged at 630°C.



(a) (b) (c)

Fig. 2 Variation of acoustic nonlinearity as a function of number of cycles and typical TEM bright field images of fatigued Cu.

4. Discussion

The higher harmonic components were typically generated by the distortion of the ultrasonic wave during propagation in the anharmonic solid, a phenomenon that is related with the lattice anharmonicity of crystals (such anharmonicity comes, for example, from phonon-phonon interaction, thermal vibrations, etc.). The anharmonicity has been defined phenomenologically as a departure of the medium from Hook's law which means the stress-strain relation is nonlinear. In a solid that contains dislocations that are capable of glide displacements via small shear stresses, these dislocation displacements also effect the nonlinear stress-strain relation. Secondary phases also can influence on the nonlinear stress-strain relation due to the coherency strain with the matrix.

Furthermore, it will be assumed that the nonlinear stress-strain relation for the pure longitudinal wave can be represented by the first two terms of a power series. The higher order terms of this equation are the cause of the generation of higher harmonics of a pure longitudinal wave as it propagates through the materials**.**

$$\sigma = A\varepsilon + \frac{1}{2}B\varepsilon^2 \qquad (1)$$

where σ is the stress, is the displacement gradient $\partial u/\partial x$, and A and B are the coefficients of the second and third-order terms in displacement gradient.

Considering the lattice strain ε_l and the shear strain γ_d caused by the edge dislocation, the total longitudinal strain ε becomes

$$\varepsilon = \varepsilon_l + \Omega\gamma_d \qquad (2)$$

where Ω is the conversion factor from shear strain to longitudinal strain.

In the present study, we have seen that the dominant microstructural changes of aging damage in 2.25CrMo steel are generation of various precipitates and a coarsening which plays a crucial role in the decrease in strength of the bulk steel. The dislocation contribution to the aging damage of 2.25CrMo steel is here considered to be negligible. Therefore, precipitates may be the most effective phenomena governing the distortion of ultrasonic waves during aging of 2.25CrMo steel.

Equation (2) indicates that the nonlinear stress-strain relation is strongly influenced by the dislocation displacement. In this study, the dominant microstructural development during fatigue of Cu is the dislocation evolution such as dislocation density, loop length, and substructures. In general, the loop length of each dislocation may be changed depending on the state of dislocation pinning; that is, sometimes it may be increased or decreased. However, the dislocation density of common metallic materials may be increased during the plastic deformation by about three to five orders of magnitude higher than the annealing state. Therefore, the dislocation density might be a dominant factor influencing the ultrasonic nonlinearity of Cu during the fatigue.

5. Conclusion

We have seen that a coarsening of the carbide occurred with increasing aging time. The volume fraction of stable M_6C carbide increased during isothermal aging. Thus, the mismatch between carbides and matrix was increased by the formation of stable carbides. Such a mismatch gives a resulting increase in the local strain. In this work we found that the change in local strain was enough to cause a noticeable distortion of ultrasonic waves, thereby increasing the acoustic nonlinearity. The acoustic nonlinearity monotonically increased due to the fatigue-driven plastic deformation. We have clearly seen that the dislocation density increased during fatigue of Cu using the electron microscope. We found that the change in dislocation density was enough to cause noticeable changes in the acoustic nonlinearity. Consequently, acoustic nonlinearity has been found to be sensitive to the precipitates and dislocation behavior during isothermal aging and fatigue.

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