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Evaluation of the intergranular corrosion in austenitic stainless steel using collinear wave mixing method

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ABSTRACT

Failures due to intergranular corrosion in components of austenitic stainless steel have always been a tough problem in engineering practice. In this paper, the collinear wave mixing was investigated to evaluate the intergranular corrosion in austenitic stainless steel. An acoustic nonlinearity parameter related to the bispectrum, the propagation distance and the amplitudes of fundamental waves in measured signal is proposed. Nonlinear acoustic measurements were conducted on four tubes with different degree of intergranular corrosion. The experimental results demonstrated that the proposed acoustic nonlinearity parameter is sensitive to intergranular corrosion in samples, and is well correlated with the degree of damage.

1. Introduction

Due to the excellent properties, such as excellent resistance to general corrosion, adequate mechanical properties, good formability and weldability, austenitic stainless steels are most commonly used in a wide variety of industries including nuclear and thermal power, chemical, petrochemical, oil, fertilizer and refineries [1,2]. However, these steels easily suffer from attack by localized corrosion, such as pitting corrosion, crevice corrosion, intergranular corrosion (IGC) and intergranular stress corrosion cracking (IGSCC). Specifically IGC is one of the major localized corrosion problems for austenitic-stainless-steel components used in environments of high temperature and high pressure, and sensitization is the most important phenomenon making austenitic-stainless-steel prone to IGC. Sensitization is a highly undesirable phenomenon in stainless steels exposed to aggressive environments, affecting mechanical and chemical properties of materials. The degradation by sensitization is caused by localized chromium carbide precipitation at the grain boundaries inducing local chromium depletion with a consequent increase of the susceptibility to intergranular corrosion and embrittlement. It has been reported the failures due to the IGC in structures of austenitic stainless steel have always been a tough problem in engineering practice [3,4].

The chemical and metallographic techniques [5,6] are available methods to assess the susceptibility of austenitic stainless steels to IGC. However these methods are destructive, sophisticated and time-consuming. Thus, the non-destructive evaluation of IGC in austenitic stainless steels is a field of great interest.

Extensive research have been conducted on assessment of intergranular corrosion using conventional non-destructive testing (NDT) methods, such as eddy current method and X-ray tomography and ultrasonic technique [7,8]. The eddy current method was successfully used to assess the sensitization and intergranular corrosion (IGC) in 316 stainless steel [7]. However, the measurement needs to be performed on the IGC-attacked surface because of the low depth penetration of eddy current. Knight [8] applied the X-ray computed tomography for assessment of intergranular corrosion in aircraft aluminium alloys, however the measurement needs the access to both sides of the specimen.

Since IGC attack does not result in a macroscopic defect in structures, the defect-echo based ultrasonic method for macroscopic defect detection does not work. As a result, several studies have employed ultrasonic inspection by measurements of ultrasonic parameters, such as attenuation, wave velocity and spectral content, to detect and characterize the IGC attack [9–11]. Stella et al. [9] investigated to characterize the sensitization degree in the AISI 304 stainless steel using spectral analysis and measurements of attenuation and velocity. It was demonstrate that the degree of sensitization can be estimated by combined measurements of attenuation and amplitude of the main peaks on the power spectra, however the velocity measurements of ultrasonic longitudinal waves do not show any sensitivity to sensitization.

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Jothilakshmi [10] measured the depth of IGC attack in Type 304 stainless steel grade plate using velocity ratio. For its independence of thickness, velocity ratio was found to be a useful parameter for characterizing IGC attack. Li [11] measured the degree of sensitization (DOS) in aluminum alloys using electromagnetic acoustic transducer (EMAT) ultrasound, and established a correlation between DOS and ultrasonic shear velocity and attenuation.

However the measurements of ultrasonic parameters rely on changes in the bulk properties of the material, therefore they are insensitive to the onset of localized corrosion. A promising technique to overcome this limitation is nonlinear ultrasonics. It is important to note that the generation of harmonics is perhaps the most widely reported acoustical manifestation of nonlinear behavior. Researchers have extensively conducted on early damage or degradation evaluation using the nonlinear harmonics [12–14], however only a few concerns on the detection of IGC attack. Abraham [15] explored the nonlinear ultrasonic method for assessment of sensitization in AISI 304 stainless steel. It was found that the relative harmonic nonlinearity parameter increases with increase of soaking time which in turn due to increase in degree of sensitization. The major difficulty with the harmonic generation method as a nondestructive testing technique lies in isolating the causes of nonlinearity. Since there are inevitable nonlinear distortions in the transmitting/receiving system, amplifiers, transducers and coupling media are all contributors to the measured harmonics [16,17]. Therefore, it is practically difficult for the harmonic generation technique to determine if the measured nonlinearity is due to the material damage or the equipment.

An alternative method to overcome these limitations is the wave mixing technique, which is based on the fact that material nonlinearities cause the interaction between two intersecting ultrasonic waves [18]. Under certain circumstances, this can lead to the generation of a third wave whose frequency and wavevector equal the sums of the frequencies and wavevectors of the incident waves, respectively. The generated resonant wave is related to the nonlinearity of materials/structures. Therefore, by measuring the generated resonant wave, the nonlinearity might be obtained. As pointed out in the literature [16,19], the wave mixing method is less sensitive to nonlinearities in the measurement system, and allows for great flexibility in selecting the wave modes, frequencies, and propagating directions.

According to the incident directions of two ultrasonic waves, wave mixing can be classified into two major categories: collinear wave mixing and non-collinear wave mixing. According to the possible modes of incident waves, there are several incident wave combinations that can generate a third wave. However, it is crucial to note that, depending on the type of wave mixing method used, the measured material nonlinearity may not be exactly the same as the acoustic nonlinearity parameter commonly used in the nonlinear acoustic literature [20,21]. Croxford et al. [16,18] investigated the application of a non-collinear mixing technique for the assessment of plasticity and fatigue damage. In the experiments, two oblique incident shear waves were interacted in the damaged zone to generate a normal-incident longitudinal wave. A nonlinear parameter related to the amplitudes of the input signals and the amplitude of generated wave was proposed to assess the degree of damage. The experimental results demonstrated that the non-collinear technique is sensitive to both plasticity and fatigue damage. Demčenko et al. [22,23] conducted linear ultrasonic measurement and non-collinear wave mixing measurement for nondestructive testing of the physical ageing of polyvinyl chloride. In nonlinear experiments, a shear wave and a longitudinal wave were oblique incident, and an interaction longitudinal wave was observed. The relative changes in the peak-to-peak amplitude of the generated longitudinal wave were defined as nonlinear parameters to assess the state of the sample. It was demonstrated experimentally that linear ultrasonic parameters, such as velocity dispersion and attenuation, were insensitive to the physical ageing state of polyvinyl chloride. However, the nonlinear parameter has significant sensitivity to the physical ageing of polyvinyl chloride, which has been verified experimentally in the laboratory and field. Escobar-Ruiz [24] applied the non-collinear wave mixing technique for non-destructive evaluation of titanium diffusion bonds. It was shown that the proposed wave-mixing arrangements offered clear and significant advantages compared with both conventional ultrasonic inspections and, importantly, alternative non-linear techniques. Jacob et al. [17,21] measured the nonlinearity parameter of various solids using the phase modulation of a high-frequency longitudinal wave induced by its nonlinear interaction with a lower-frequency acoustic pulse. Since the determination of the nonlinearity parameter is based on the measurement of the phase modulation, the measurement is absolute and the uncertainty is small. The proposed nonlinear parameter is suggested to have potential in the assessment of the degree of damage. Liu et al. [25] introduced a new acoustic nonlinearity parameter associated with the interaction between a longitudinal wave and a shear wave in solids. The nonlinear experiments were conducted in collinear mode, and an interaction shear wave was observed. The experimental results indicate that the collinear mixing technique has higher sensitivity in measuring the acoustic nonlinearity parameter, and is a promising method for the nondestructive assessment of damage in metallic materials. Hillis et al. [26,27] and Courtney et al. [28,29] developed a special collinear wave mixing technique for global crack detection in metal structures. In their experiments, two sinusoidal signals were applied to the same transmitter. To isolate the sideband at the sum or difference frequency, the received signal was processed using bispectral analysis. The bispectrum was shown to be particularly useful in extracting the nonlinearity related to quadratic phase coupling. The amplitudes of the bispectrum at the sum or difference frequency are used as nonlinear parameters to characterize the depth of cracks.

In this paper, collinear wave mixing method is applied to assess the intergranular corrosion in austenitic stainless steel. A nonlinear parameter is introduced for collinear wave mixing measurement using bispectral analysis, and the proposed parameter is experimentally measured and used to assess the intergranular corrosion in austenitic-stainless-steel tubes.

2. Fundamental theories of nonlinear analysis

2.1. Nonlinear response of wave mixing

The one-dimensional governing equation of a longitudinal wave propagating in an isotropic solid can be written as

$$\rho\frac{\partial^2 u}{\partial t^2}=\frac{\partial\sigma}{\partial x}, \tag{1}$$

where t is the time, x is the propagation distance, u is the displacement, σ and is the stress, and ρ is the mass density. In general, the stress–strain relation in degraded material can be described by the nonlinear Hooke law:

$$\sigma=E\varepsilon\left(1+\beta\varepsilon+\cdots\right), \tag{2}$$

where E is Young's modulus and β is the second-order nonlinear elastic coefficient. As described in most of the literature, the acoustic nonlinearity related to the second-order term is considered.

Substitution of Eq. (2) and the strain–displacement relation, $\varepsilon(x,t)=\partial u(x,t)/\partial t$, into Eq. (1) yields the nonlinear wave equation