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In situ nonlinear ultrasonic for very high cycle fatigue damage characterization of a cast aluminum alloy

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ABSTRACT

In this paper, the feedback signal of ultrasonic fatigue system was used to in situ deduce the accumulated fatigue damage via ultrasonic nonlinearity parameter. It was observed that compared with the resonant frequency, the ultrasonic nonlinearity parameter shows a greater sensitivity to fatigue damage like crack initiation and crack propagation. Conventional fatigue testing was carried out and the variation of specimen rigidity and plastic strain of the material were obtained which correlated well with the ultrasonic nonlinearity parameter. Also, the ultrasonic fatigue crack initiation was verified by interrupted test.

1. Introduction

The aluminum alloys are used increasingly in automotive industry because of their low density, high strength/weight ratio and corrosion resistance. Components in vehicle like engine cylinder heads and blocks are subjected to more than 10^8 alternative stress cycles during their service life, so a better understanding of fatigue properties becoming more and more important, especially in the very high cycle fatigue regime. Ultrasonic fatigue testing has attracted more and more people's attention due to its high test frequency (20 kHz) which can dramatically reduce the time for fatigue data generation.

Fig. 1 is the schematic picture that shows the load train of ultrasonic fatigue system and the strain, displacement distribution of each component. It consists of an ultrasonic transducer, an ultrasonic horn, a lambda rod as well as the test specimen. The ultrasonic transducer transforms the electrical sine waves into mechanical vibration sine waves and injected into the one end of ultrasonic horn. The amplitude of vibration sine waves magnified when travel along the ultrasonic horn because of the decreased diameter of this component, then the vibration sine waves enter into the ultrasonic lambda rod and finally enter into the test specimen. Because the specimen is specifically designed so its fundamental resonant frequency is equal to the resonant frequency of load train, finally the incoming waves and reflected waves are superimposed to form a resonant vibration. A vibration gauge installed on the ultrasonic horn and working on induction principal and measuring the displacement which is used as feedback signal of load train to control the test. The displacement amplitude is proportional to the strain amplitude in the center of test specimen and the feedback signal is capable to provide the fatigue degradation of test specimen.

In the past two decades, ultrasonic fatigue technique has been used extensively [1–4]. In order to detect the fatigue damage like crack initiation and crack propagation during ultrasonic fatigue testing, a lot of NDE (non-destructive examination) methods have been developed, such as thermography evaluation [5], FEM based microstructure analysis [6] and Rayleigh surface waves [7].

Different from other NDE methods, the advantage of analysis the feedback displacement signal is that it does not require any additional equipment like thermocamera or wedge transducers to in situ monitor the material degradation. The ultrasonic nonlinearity parameter is based on the generation of second and higher harmonic frequencies due to the distortion of sinusoidal waves as they propagate through a nonlinear solid. During the fatigue testing, with the presence of cracks, the relationship between stress and strain is linearly when the crack is entirely open or fully closed. The nonlinearity of stress and strain is mainly produced by the crack closure effect and the relationship between stress and strain can be expressed using nonlinear version of Hooke's law as shown in Eq. (1) for the simple one-dimension case [8].

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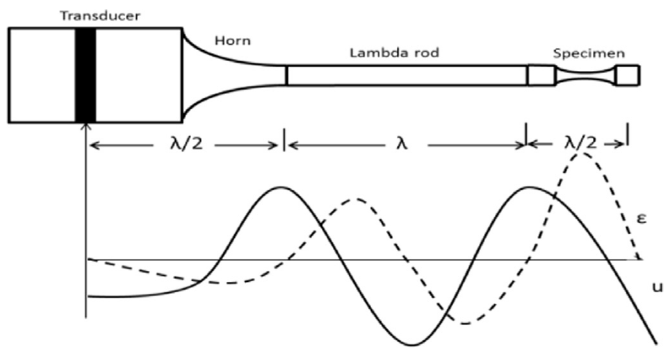

Fig. 1. Schematic of load train in ultrasonic test system. ε and μ are the strain and displacement amplitude.

$$\sigma = E\varepsilon(1 + \beta\varepsilon) \tag{1}$$

where, E is modulus of elasticity and β is nonlinear parameter. If it is assumed that the attenuation can be neglected, the motion equation for longitudinal wave can be expressed as follows:

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

where, ρ is the density of the material, x is the propagation distance and u is the displacement. Using Eqs. (1) and (2), and the relationship between strain and displacement, $\varepsilon(x, t) = \partial u(x, t)/\partial x$, we can obtain the nonlinear wave equation for displacement $u(x, t)$ as follows:

$$\rho\frac{\partial^2 u}{\partial t^2} = E\frac{\partial^2 u}{\partial x^2} + 2E\beta\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial x^2} \tag{3}$$

To obtain a solution, the perturbation theory [9] is applied. The displacement u is assumed as

$$u = u_0 + u' \tag{4}$$

where u_0 represents the initially excited wave and u' represents the first-order perturbation solution. Considering u_0 as a sinusoidal single frequency wave form,

$$u_0 = a_1\cos(kx - \omega t) \tag{5}$$

We can obtain the perturbation solution as follows:

$$u = u_0 + u' = a_1\cos(kx - \omega t) - a_2\sin 2(kx - \omega t) \tag{6}$$

where the amplitude of second harmonic, a_2, is given by

$$a_2 = \frac{\beta}{8}a_1^2k^2x \tag{7}$$

The second term of Eq. (6) represents the second harmonic frequency component and its amplitude depends on the nonlinearity parameter β. The nonlinearity parameter can be evaluated from the amplitude of first and second harmonic frequencies as follows:

$$\beta = \frac{8a_2}{a_1^2k^2x} \tag{8}$$

In this study, the nonlinearity parameter and resonant frequency were measured to in situ monitor the fatigue damage degradation of the material during ultrasonic fatigue testing. The sensitivity of resonant frequency and ultrasonic nonlinearity parameter to monitor the fatigue damage of crack initiation and propagation were compared. Also, conventional fatigue test was carried out, the variation of plastic strain and rigidity of specimen were evaluated using the obtained stress strain loops.

2. Experimental details

The cast aluminum alloy in this study was from the deck surface of vehicle engine's cylinder head as illustrated in Fig. 2(a). Fig. 2(b) shows the typical microstructure of the material. The tensile properties and chemical compositions are summarized in Table 1 and Table 2, respectively. The modulus of elasticity was evaluated from specimen tested under the servo-hydraulic test system by cycling at 1 Hz and $\pm$30 MPa for 10 cycles. SDAS (secondary dendrite arm spacing) was measured using Image Pro software at about 500 mm^2 finely polished area. More than 100 measurements were made in order to get the quantitative value. In order to make sure the surface finish with low residual stress, specimens were machined using low stress turning at Westmoreland Mechanical Testing and Research, Inc.

Ultrasonic fatigue test equipment used in this study was developed by the Institute of Physics and Materials Science, BOKU, Vienna. A sinusoidal wave is injected from ultrasonic transducer into one end of the ultrasonic lambda rod with the velocity determined by the material properties (density, modulus of elasticity and the shape of the component). The waves enter into the specimen and are reflected from the other end of the specimen. If the excited signal frequency is equal to the resonant frequency of the specimen, the injected and reflected waves will superimpose to form a resonant vibration. The details of the ultrasonic fatigue test system are reported elsewhere [10].

3. Results and discussion

The feedback signal obtained from the displacement transducer in the ultrasonic fatigue system provides the cycle-dependent resonant behavior of the system and, in turn, the damage state of the material. The feedback signal was recorded using desktop through USB ports and a LABVIEW program was developed for signal acquisition and analysis. During the ultrasonic fatigue testing, ultrasonic loading was applied in well controlled pluses (100 ms on/ 2000 ms off) to keep the temperature below 25 °C. During the 100 ms, the 10 ms length (2500 data points at a digitization of 250 kHz) of feedback signal was used for analysis at the start delay of 35 ms.

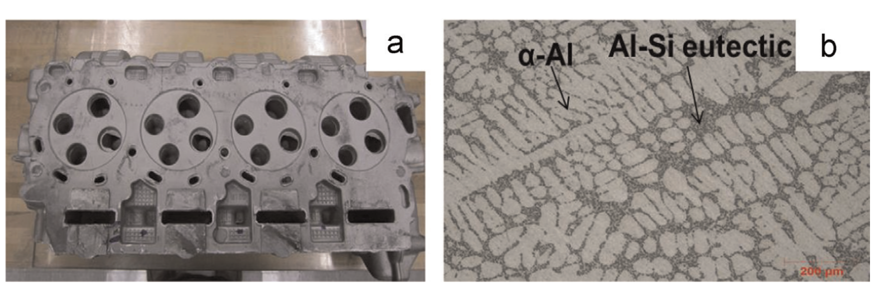

Fig. 2. (a) Cylinder head, (b) Microstructure of AS7GU-T64 cast aluminum alloy.