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In situ characterization of fatigue damage evolution in a cast Al alloy via nonlinear ultrasonic measurements

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Abstract

A new methodology is described for in situ characterization of fatigue damage accumulation using nonlinear ultrasonic measurements via analysis of the feedback signal of a closed-loop ultrasonic fatigue system. In the very high-cycle fatigue regime, ultrasonic nonlinearity increases with initiation and growth of a dominant, life-limiting fatigue crack. Based on the increase in the ultrasonic nonlinearity with fatigue cycling, crack initiation, small fatigue crack growth and fast crack growth regimes have been distinguished during cycling in specimens with different pore sizes tested at various stress amplitudes. The fraction of fatigue life spent in initiation of a life-limiting fatigue crack decreases with increasing stress amplitude. For a constant stress amplitude, the initiation life also decreases with increasing pore size. The present study also demonstrates the applicability of the methodology for fatigue crack growth studies from natural defects located internally or at the surface in smooth specimens.

Keywords: Nonlinear ultrasonics; Fatigue crack initiation; Fatigue crack growth; Casting pores; Cast Al alloy

1. Introduction

The ever-increasing demands on new alloy systems used in the automotive and energy sectors require a thorough understanding of the fatigue behavior of these materials. The ability to detect damage and predict its evolution during cycling can permit assessment of future performance based on a damage prognosis approach [1]. Thus, there is significant interest in identifying new methods to rapidly quantify the damage state in components as a critical step in predicting remaining useful life. One such method with significant promise involves the use of nonlinear ultrasonics to provide a “signature” of an operating component that indicates the accumulation of damage [2]. In the present paper we describe a technique for identifying damage accumulation resulting from the initiation and propagation of fatigue cracks from pores in a cast Al–Si–Cu–Mg alloy (AS7GU) using in situ nonlinear ultrasonic measurement during ultrasonic fatigue. First, we briefly discuss the origin of nonlinear ultrasonics and its use for characterizing fatigue damage and then we briefly review the fatigue behavior of porosity-containing cast Al alloys in the very high-cycle fatigue regime that has previously been investigated using ultrasonic fatigue techniques [3–7].

The applicability of nonlinear ultrasonics to detect and characterize fatigue damage in metals has been demonstrated in several recent studies [8–14]. Nonlinear ultrasonic studies explore the generation of second and higher harmonics of the fundamental frequency due to distortion of sinusoidal ultrasonic waves as they propagate through a nonlinear or anharmonic solid. In a typical experimental setup for nonlinear ultrasonic measurement, a longitudinal ultrasonic wave with a tone burst of amplitude, a_0, at frequency, ω_0, is launched on one side of the specimen under examination. If a_0 is sufficiently large, the wave detected on the other side of the specimen will contain many harmonic components, i.e. the detected wave possesses a component

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of amplitude a_1 at the fundamental frequency ω_0 along with a component of amplitude a_2 at the second harmonic frequency $2\omega_0$, and so on. The ultrasonic nonlinearity parameter is determined experimentally by measuring the absolute amplitudes of the fundamental (a_1) and the second-harmonic (a_2) displacement signals, and is defined as [8–12]:

$$\beta = \frac{8v^2 a_2}{\omega_0^2 z a_1^2}, \tag{1}$$

where v and z are the ultrasonic phase velocity and the propagation distance, respectively.

Very small imperfections such as microcracks can produce very significant excess nonlinearity, which can be orders of magnitude higher than the intrinsic nonlinearity of the intact material [13]. The excess nonlinearity is produced mainly by the strong local nonlinearity of a microcrack whose opening is smaller than the particle displacement caused by the propagation of an ultrasonic wave. In the compression phase, the effective local elastic modulus approaches that of the continuous material as the crack becomes tightly closed. In the tension phase, the local modulus drops to a lower value, corresponding to the discontinuous solid with fully opened cracks. This parametric modulation of the quasilinear material is caused by the stress dependence of the interfacial stiffness, which is usually referred to as "crack closure". The resulting excess nonlinearity is zero for both entirely open and entirely closed cracks. However, at low mean stresses or under fully reversed loading, typical fatigue cracks are partially closed during a portion of each loading cycle, which generates strong excess nonlinearity via crack closure.

The relative β parameter ($\beta_{relative} = \beta/\beta_0$, where β_0 indicates the undamaged material condition) is used as an analysis parameter in nonlinear ultrasonic studies, as it only requires measurement of amplitudes at fundamental and second harmonic frequencies in the damaged and undamaged conditions. An increase in $\beta_{relative}$ with fatigue damage in the low cycle fatigue regime has been reported in several studies [8–13]. The generation of second harmonics in fatigue-damaged Al alloys due to generation and propagation of microcracks has also been reported [14,15]. Recently, Pozuelo et al. [16] observed the presence of nonlinear resonance in specimens fatigued in an ultrasonic fatigue system. They analyzed the frequency spectrum of the vibration velocity signal of virgin and cracked samples using a laser vibrometer, and observed the occurrence of higher harmonics in cracked samples. In spite of the high potential of the nonlinear ultrasonic measurement for characterization of initiation and growth of fatigue cracks, use of the technique has been limited so far due to its application in an offline manner, i.e. the fatigue test is interrupted and the $\beta_{relative}$ is measured in the unloaded condition with independent instrumentation.

Because of their importance in the automotive industry, cast Al alloys have been extensively used in the production of fatigue-critical automotive components, including engine blocks, cylinder heads, pistons, wheels, suspension cross-members and control arms. The increased use of cast Al–Si alloys in these demanding structural applications has required a better understanding of their response to fatigue loading, especially at lifetimes in the very high cycle regime ($N_f > 10^7$). Al castings contain shrinkage and gas pores which vary in size and distribution depending upon the rate at which the metal is solidified, with slower solidification generally resulting in higher fraction of larger pores than with faster solidification rates. Numerous investigations have shown that life-limiting fatigue cracks nucleate from pores [3–6,17–20] and that the fraction of life associated with crack initiation is small and increases with increasing lifetime (lower cyclic stresses) [5,6,17,18].

In general terms, the total fatigue life of a pore-containing cast Al alloy can be decomposed into three consecutive stages: initiation of a life-limiting crack, small crack (SC) growth and long crack (LC) growth:

$$N_{Total} = N_I + N_{SC} + N_{LC}. \tag{2}$$

Here, N_{Total} is the total fatigue life; N_I is associated with very early damage development and is the number of cycles to nucleate crack-like damage at a pore and to propagate the crack through the region influenced by the region of stress intensification associated with the pore; N_{SC} and N_{LC} are the number of cycles required to propagate a SC and a LC, respectively. A growing crack is considered as a SC if its length is of the order of about 20 times the secondary dendritic arm spacing (SDAS) in a cast Al alloy [21]. The N_I in a cast specimen is governed by the stress amplitude and the maximum size of the pore in the specimen. The N_I is estimated to be 50–70% of the total life in the high-cycle fatigue (HCF) regime ($N_{Total} = 10^5$–10^7) for 50 μm pores and about 30–40% of the total life for 200–400 μm pores [18]. A SC to LC transition in crack growth behavior was observed experimentally to occur when [18,22]:

$$a > 30\text{SDAS}\left(\frac{S_y}{\Delta\sigma_{eff}}\right)^2, \tag{3}$$

where the effective stress amplitude range, $\Delta\sigma_{eff}$, is given by $\Delta\sigma_{eff} = \sigma_{max} - \sigma_{op}$, and σ_{max} and σ_{op} are the maximum applied stress and crack tip opening stress, respectively. This criterion corresponds to a cyclic plastic zone enclave at the crack tip of the order of the SDAS. For stress amplitudes of the order of the cyclic yield strength, S_y, this crack length is on the order of 1 mm for ~30 μm SDAS, and increases for lower stress amplitudes and larger SDAS. This indicates that most of the fatigue crack growth life for smooth laboratory specimens is essentially comprised of N_{SC}. The propagation of small cracks in various cast Al–Si alloys and steels is reported to follow the following relation [3,23]:

$$\frac{da}{dN} = A\left(\frac{\sigma_a}{\sigma_b}\right)^n a, \tag{4}$$