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Dynamic stress analysis of the specimen gauge portion with a circular profile for the ultrasonic fatigue test

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ABSTRACT

An hourglass-shaped specimen has been utilized for the ultrasonic fatigue test (UFT) at a resonance frequency around 20 kHz. Although the gauge portion of the actual test specimens was made with a circular arc shape, the stress along the gauge portion has been measured by the conventional stress equation assuming a gauge portion with the form of a hyperbolic cosine. In this study, stress distribution results by finite element analysis (FEA) in forced resonant vibration mode showed that the shape of a circular arc caused considerably higher stresses at the center of the gauge portion than did the hyperbolic cosine. The error of the stress equation occurring due to the difference in the gauge portion profile was compensated for by using the forced vibration factor (C_1) and the gauge shape factor (C_2). Thus, stress concentration effects in specimens with various gauge lengths were quantified to determine the actual fatigue strength.

1. Introduction

Increasing interest in very high-cycle fatigue (VHCF) behaviors has arisen because high-speed transportation machines such as aircraft, automobiles, and trains require a durability period much larger than 10^8 cycles. Fatigue failure behavior in the VHCF range has been found to be different from that in the high cycle range [1–4]. For a fatigue test in the VHCF range, Mason [5] proposed a fatigue test at ultrasonic frequency in the 1950s. Since the ultrasonic fatigue test (UFT) using resonance could not easily measure the very small strains in the gauge portion, Green and Guiu [6] suggested a theoretical stress equation by adopting an hourglass specimen. In this equation, the displacement generated at the free end of the specimen was used to calculate the applied stress at the center of the gauge portion. To solve the partial differential equations involved, the gauge portion profile was assumed to be a hyperbolic cosine (cosh) function instead of its actual geometry of a circular arc. This assumption was based on the results that geometric differences were measured to be less than 1% between the two-gauge portion profiles. Batias and Paris [2] however showed that there was some more difference in the geometry depending on the gauge portion ratio. Green [7] suggested another theoretical stress equation for a dumbbell-shaped specimen. To apply the UFT to specimens with other profiles, Bajons and Kromp [8] calculated the amount of the stress concentration of UFT specimens according to several gauge portion profiles. In most UFT studies [6,9–12] the applied strain (therefore stress) at the middle section of the gauge portion was measured using the displacement amplitude at the free end of the specimen, where the difference in the gauge portion profile between the cosh function and the actual circular arc was neglected despite its considerable influence upon the applied stress. Lage et al. [13] compared the applied strain measured through a direct strain gauge attachment with the strain calculated from the displacement amplitude measured by a nano laser at the free end of the specimen, and showed that the error in strain between the two types of measurement was approximately 2%.

Through finite element methods (FEM), several researchers [9,10,14–16] have studied stress distributions in various structural designs for the UFT device, and they were able to visualize deformation behaviors that were difficult to measure directly. Calvalieri et al. [14] studied an austenitic steel specimen under UFT at a high temperature. The stress at the gauge portion calculated by FEM was found to be higher than the theoretical stress. Kazymyrovych et al. [15] performed a stress calculation of the UFT specimen while taking into consideration a damping effect, but the stress by FEM was lower than the theoretical stress without correction for the geometric difference between the finite element model and the theoretical equation. Accordingly, when UFT is performed in resonance mode, a slight variation in the gauge portion profile may have a significant influence on the resonant frequency and the

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applied stress at the gauge portion. Furthermore, in the theoretical and finite element analysis of VHCF, the effects of forced vibration need to be taken into account because forced vibration has a considerable influence on the level of applied stress and thus the fatigue life.

In this study, the stress accuracy of UFT at 20 kHz is examined through a stress analysis of the gauge portion using FEM. Stress distribution of the gauge portion in forced resonant vibration mode is calculated and compared to experimental test results. The actual gauge portion is processed in the form of a circular arc. The stress analysis by FEM focuses on how much the local stress concentrates in the gauge portion during the UFT. A stress compensation for the real gauge portion is conducted that closely approximates the exact applied stress. The compensated stresses are reflected into the stress-cycles data to deforming the actual fatigue strength.

2. Stress equation of the ultrasonic fatigue test

The piezo-electric exciter of a UFT apparatus generates a mechanical vibration force delivered to a specimen. Through an acoustic horn structure, an acoustic wave transforms to a resonant wave train as it passes through the specimen. The maximum displacement arises at the free end of the specimen. A zero displacement indicating the node point arises at the center of the gauge portion, where the maximum strain takes place. The normal stress is calculated at the center of the gauge portion by the following Eq. (1), assuming the gauge portion to be the hyperbolic cosine shape [6,17] instead of the circular arc shape (Fig. 1).

$$\sigma = \delta \cdot E_d \cdot \beta \cdot \cos\frac{\omega l}{v_{cl}} \cdot \cosh(bg) \cdot \mathrm{csch}(\beta g) \qquad (1)$$

$$b = \frac{1}{g}\cosh^{-1}\frac{R}{H} \qquad \beta = \sqrt{b^2 - \left(\frac{\omega}{v_{cl}}\right)^2}$$

where E_d is the dynamic elastic modulus, δ the displacement amplitude at the end of the specimen, ω the angular speed ($2\pi f$), v_{cl} the longitudinal velocity of sound, g the length of the gauge portion, l the length of the cylindrical shoulder, b and β the parameters depending on the gauge geometry and material properties, and ν the Poisson's ratio.

The longitudinal wave velocity assumes a longitudinal wave propagation along the axial direction of the bulk specimen [18]. This assumption is reasonable in that the UFT employed only a longitudinally resonant mode in the axial direction. The ultrasonic longitudinal velocity (v_{cl}) was measured using the ultrasound-pulse pitch-catch method (ASTM C597 [19], ASTM E494 [20]). Thus dynamic Young's modulus (E_d) for plate specimen with large widths greater than the transducer diameter could be calculated by Eq. (2),

$$v_{cl} = \sqrt{\frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad (2)$$

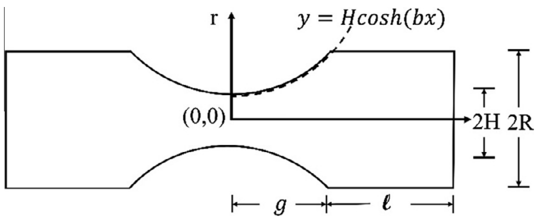

Fig. 1. Specimen with hyperbolically shaped gauge portion flanked by two cylindrical shoulders [6]. The geometrical parameters were used in theoretical equation (1).

For long round bar with diameter equal to the transducer diameter, v_{cl} could be calculated according to Eq. (3). This approach assumes the one-dimensional longitudinal wave propagation.

$$v_{cl} = \sqrt{\frac{E_d}{\rho}} \qquad (3)$$

3. Experiment

3.1. Specimen

For this UFT experiment, an hourglass specimen made of aluminum alloy Al6061 (Fig. 2) was prepared by machining and grinding. Density was measured accurately 2.69 g/cm^3 by Archimedes' principle. Dynamic Young's modulus at 20 kHz was calculated through Eq. (3) by using the measured values of v_{cl} and the density. The profile of the gauge portion was made in a circular form. The diameter of the smallest cross section in the gauge portion was 4.0 mm. The diameter of the shoulder part was 12.0 mm. The specimen was designed to generate a node point at the center of the gauge portion when the specimen was subjected to a longitudinal resonance at 20 kHz [21].

3.2. Ultrasonic fatigue test

The specimen was attached to the ultrasonic fatigue tester (UFT-20X, MediSourcePlus, Fig. 3). The UFT-20X was operated with a dynamic loading mode of a tension-compression sinusoidal cycle (stress ratio, $R = -1$). During the test, the gauge portion was cooled with compressed air at room temperature. Following the temperature control method [22,23], pulse (0.4 s) and pause (0.1 s) duration was selected to avoid excessive heating of the specimen. The maximum stabilized temperature of the gauge center was below 30 °C. The displacement and frequency at the end of the specimen were measured using a non-contact, fiber-optic sensor (D63, PHILTEC).

The frequency of the piezo-electric exciter that generated the node point at the center of the gauge portion was measured at 19.6 kHz, which was very close to the longitudinal resonant frequency of the specimen itself (20 kHz), and was adopted for this UFT. The maximum displacement of 21.4 μm at the specimen end was attained by the exciting frequency under a constant power. Through Eq. (1), the value of the amplitude ($\delta_{\max}$) was transformed to a tensile stress of 130.3 MPa, which might act at the center of the gauge portion (Table 1).

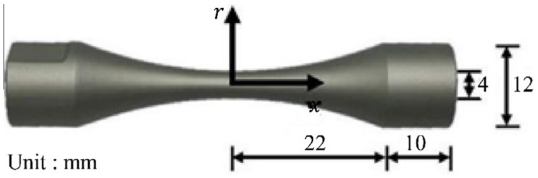

Fig. 2. Actual specimen geometry made with the circular shaped gauge portion for the present ultrasonic fatigue test at 20 kHz.

Fig. 3. Photograph of the structural body of the ultrasonic fatigue tester (UFT-20X, MediSource-Plus corp).