Review of Quantitative Nondestructive Evaluation, Green Bay, USA, July 28-Aug. 1 (2003)

FATIGUE CRACK CLOSURE ANALYSIS USING NONLINEAR ULTRASOUND

Masashi Akino, Tsuyoshi Mihara, and Kazushi Yamanaka

Department of Materials Processing, Tohoku University, Sendai, 980-8579 Japan

ABSTRACT Nonlinear ultrasound is a promising tool for evaluating closed cracks which is difficult with the linear ultrasound. Recently, subharmonics was observed and explained either by a parametric or a forced vibration. However, because the crack was not completely closed, the behavior of crack was complicated and quantitative comparison between theory and experiment has not been achieved.

We prepared a closed fatigue crack in an aluminum alloy by controlling the crack opening with in-situ monitoring of the crack tip echoes. When a tone burst of 6.4 MHz longitudinal waves was obliquely incident on the closed crack, a strong subharmonics at 3.2 MHz was observed. The intensity first increased as the crack closure was reduced by applying a tensile stress, took a maximum larger than the fundamental wave and then decreased moderately as the crack was further opened. The subharmonic intensity was theoretically explained by a low-pass filtered displacement of output crack plane due to the inertia when it is driven by vibrating asperities on the input crack plane at fundamental frequency.

INTRODUCTION

Nonlinearity produced by a large amplitude wave has been employed in ultrasonic measurements to evaluate lattice defects of solids and to enhance the spatial resolution in medical imaging. Recently, the contact acoustic nonlinearity (CAN) has been proposed as a promising tool for evaluating cracks which is difficult to evaluate with the low amplitude linear ultrasound [1,2]. Not only the superharmonics ($2f, 3f$) of the input tone burst of frequency f [1,2], the subharmonics of a frequency $f/2$ have been reported in the medical ultrasound [3] and in the nondestructive evaluation of cracks [2,4]. However, because the crack was not introduced in a controlled way in previous studies [2,4], the behavior of the subharmonics was complicated and a quantitative comparison between theory and experiment was not possible. Therefore, in this study we introduce a controlled fatigue crack after determining the minimum and maximum stress intensity factor by monitoring the crack tip echoes, and prepared a closed fatigue crack in an aluminum alloy. We tried nonlinear ultrasonic measurement on the crack, applying a static load in the range between zero and the maximum load during the fatigue crack preparation. The results are analyzed by the model of the nonlinear contact vibration [5] originally developed in the ultrasonic mode of atomic force microscopy (AFM) [6-8], because there is essential similarity between CAN and ultrasonic mode of AFM [4].

EXPERIMENTAL PROCEDURES

We introduced a fatigue crack in a Al7030 bending test specimen with the maximum stress intensity factor K_{max} =14 kgf/mm$^{3/2}$ and the minimum stress intensity factor K_{min} =2 kgf/mm$^{3/2}$. The crack tip echo from by the oblique incidence longitudinal wave was monitored during the fatigue test, in order to confirm that there is a certain amount of arrival time variation of the echo when the stress intensity factor was varied between K_{max} and K_{min}. The ultrasonic measurement was performed using both the normal incidence and oblique incidence, as shown in Fig. 1(a) and (b). For the oblique incidence measurement, Fig. 1 (b), we employed a 45 degree polystyrene wedge.

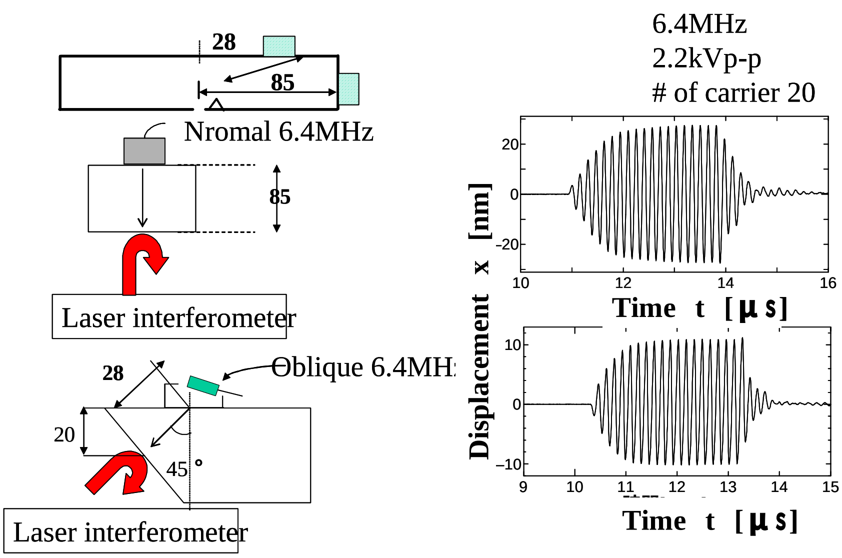

FIGURE 1. Experimental setup for evaluating the amplitude

A sinusoidal wave packet with 20 carriers at the frequency of 6.4 MHz was amplified with a gated amplifier to 2 kV. The displacement amplitude of generated longitudinal wave was estimated using a laser interferometer with the configuration shown in Fig. 1. The amplitude of the observed waveform in Fig. 1 turned out to be larger than 40 nm peak to peak (p-p) in the normal incidence and 20 nm p-p in the oblique incidence, both at the position of the crack. For the detection, we used a 10 MHz longitudinal wave transducer.

EXPERIMENTAL RESULTS

The crack was opened and closed by applying and removing a static bending load. The relation between super- and sub-harmonic generation and the crack closure/opening was investigated.

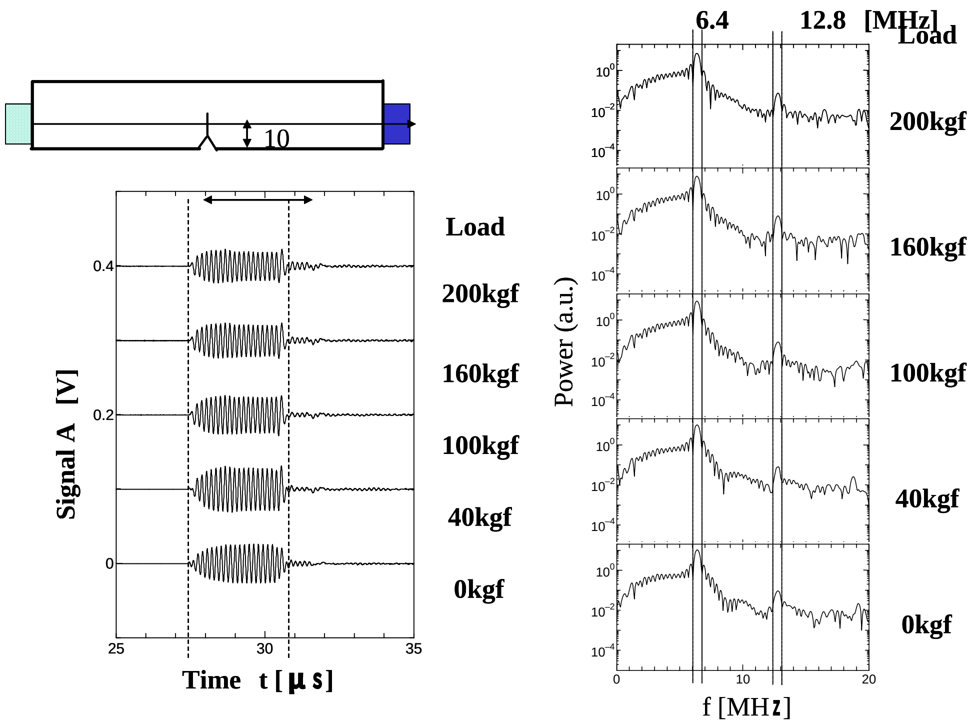

FIGURE 2. The waveforms (left) and power spectra (right) obtained by the fast Fourier transform (FFT) in the normal incidence

In Fig. 2, the waveforms (left) and power spectra (right) obtained by the fast Fourier transform (FFT) are plotted with different loads in the normal incidence test. In the spectra, the second harmonic peak was observed as reported in literature [1]. The amplitude ratio of the 12.8 MHz peak $A_{12.8}$ to that of the 6.4 MHz peak $A_{6.4}$ was plotted against the applied load in Fig. 3. It is seen that the amplitude ratio increased as the load increased, and the magnitude of the ratio was in the order of 0.01, as reported in [1].

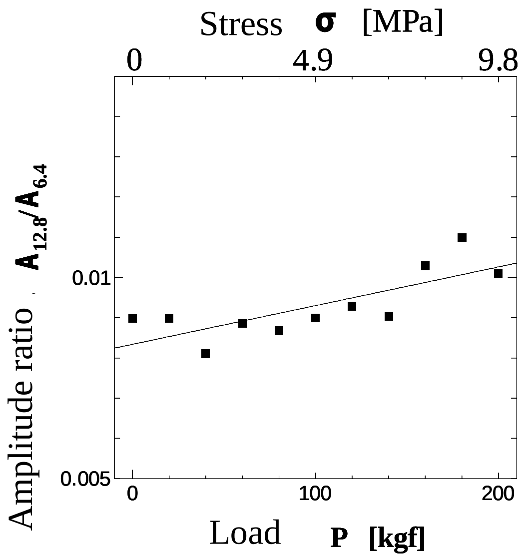

FIGURE 3. Super harmonic amplitude as a function of applied load

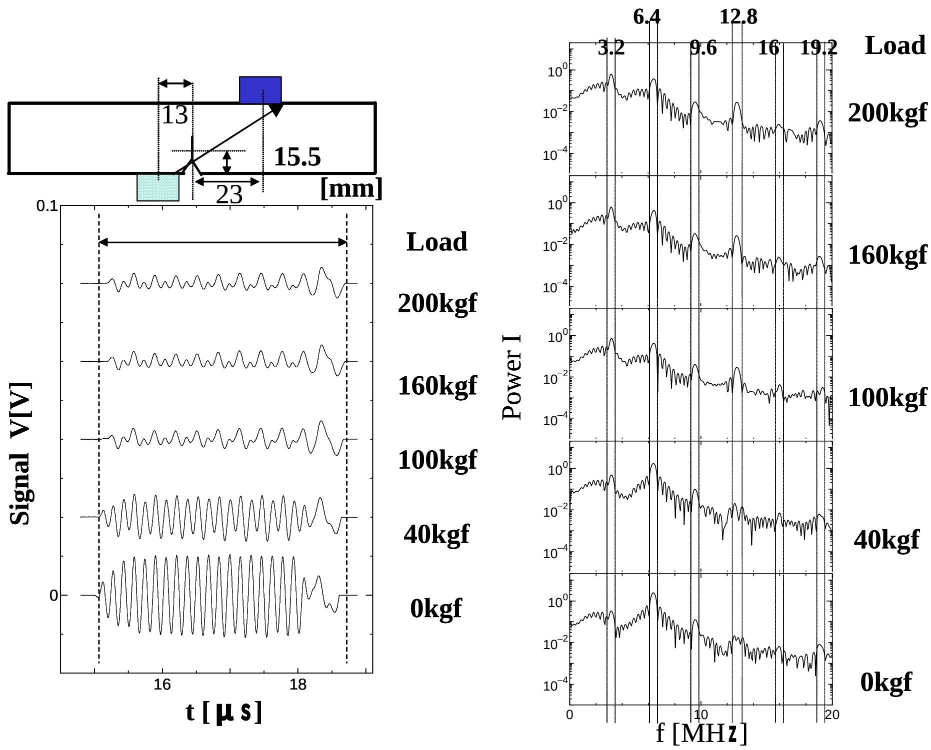

FIGURE 4. Waveforms and corresponding power spectra under load

In Fig. 4, the waveforms (left) and power spectra (right) are plotted with different loads in the oblique incidence test. In the spectra, the second harmonic peak was observed as in Fig.3. The amplitude ratio $A_{12.8}/A_{6.4}$ was plotted against the applied load in Fig. 5. It is seen that the amplitude ratio increased as the load increased, with a threshold at 60 kgf. The existence of a clear threshold is the difference from the case of normal incidence (Fig. 3).

As the crack opening proceeds during loading, the amplitude of received echo decreased, and the amplitude of every other wave was decreased, indicting the generation of subharmonics. The intensity of subharmonics at 3.2 MHz first increased as the crack closure was reduced by applying a tensile load for crack opening, took a maximum larger than the fundamental wave and then decreased moderately as the crack was further opened, Fig.6.

DISCUSSIONS

We analyze the subharmonic generation by assuming that the crack plane on the input side of the ultrasound is vibrated at high frequency and it displaces the crack plane facing it (we denote here as the output crack plane). We assume that the output crack plane has a certain resonance frequency due to its effective mass m and restoring spring constant k. Then, at frequencies much higher than the resonance frequency $\sqrt{k/m}$, the output crack plane should not be able to follow the vibration of the input crack plane. However, since the relation between the contact force and the distance is strongly nonlinear [1,2], a net repulsive

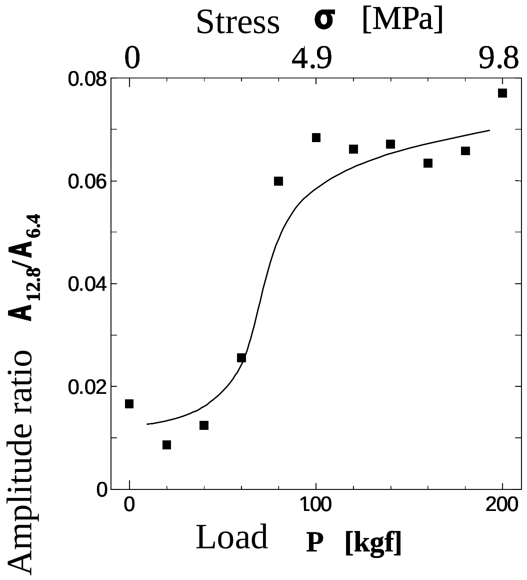

FIGURE 5. Superharmonic amplitude as a function of applied load

force is produced after integrating the contact force over one period of vibration, and the net repulsive force displaces the output crack plane. This situation is analogous to the tip-sample interaction in the ultrasonic force microscopy (UFM), where the tip is lifted up by the net repulsive force operated by the sample vibrating at frequencies much higher than the resonance frequency of the cantilever as shown in Fig. 7 (a) [6].

To analyze the model, we introduce the initial static displacement of the input crack plane z_S before applying the vibration. It is to be noted that the compressive load producing the crack closure, one of the most important parameter representing a danger of crack size underestimation, can be expressed as kz_C, where z_C is the initial displacement of the output crack plane. It is related to z_S through the force balance equation, $s(z_S - z_C) = kz_C$, where s is the contact stiffness between two crack plane.

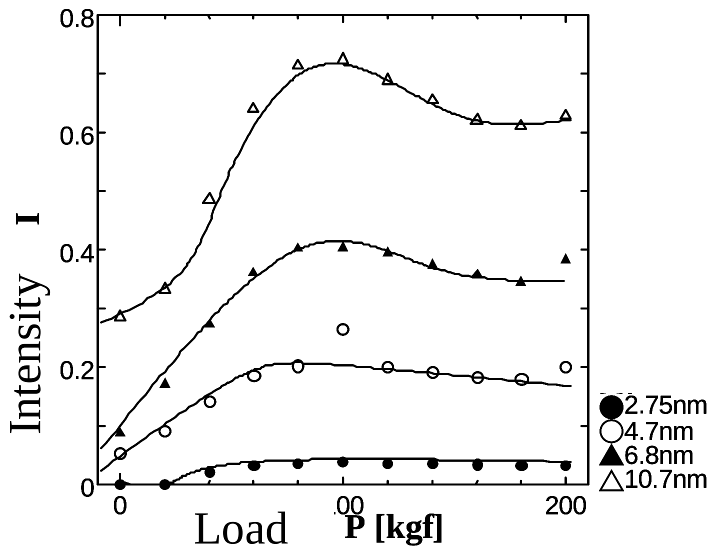

FIGURE 6. Subharmonic intensity as a function of the applied load

In the present analysis we assume that the stiffness s and k are identical and they are constant during the two cracks are in contact, and also assume that the temporal dependence of the vibration is a piece wise linear function of time (lower part of Fig. 7) [6], rather than the sinusoidal function [7]. As a result, we obtained a simple analytic expression for the displacement of the output crack plane as a function of the vibration amplitude of the input crack plane, with a parameter representing the crack closure.

The detail in derivation is quite similar to that for UFM [8], and described elsewhere [5]. The intensity of subharmonics is proportional to $z_a^{\ 2}$. The crack opening is expressed by $-z_S$ and it is biased by 1 nm (temporally assumed for the best agreement between experiment and theory) so that the crack opening by the external tensile load is $1-z_S$. In Fig. 7, we plotted the calculated subharmonic intensity as a function of the crack opening, for each vibration amplitude a of 10.7 nm, 6.8 nm, 4.7 nm and 2.75 nm, which were the measured values in the experiment by using an optical interferometer.

As seen by comparison of Fig. 6 and Fig. 7, the calculation succeeded in reproducing the main feature of observed subharmonic intensity as a function of the crack opening for various vibration amplitudes a. Especially, the presence of a threshold for load with a=2.75 nm in Fig. 6 was reproduced in Fig. 7 for the crack opening. This result shows that a certain value of large vibration amplitude is required for the subharmonic generation, and it is important in designing apparatus for testing closed cracks.

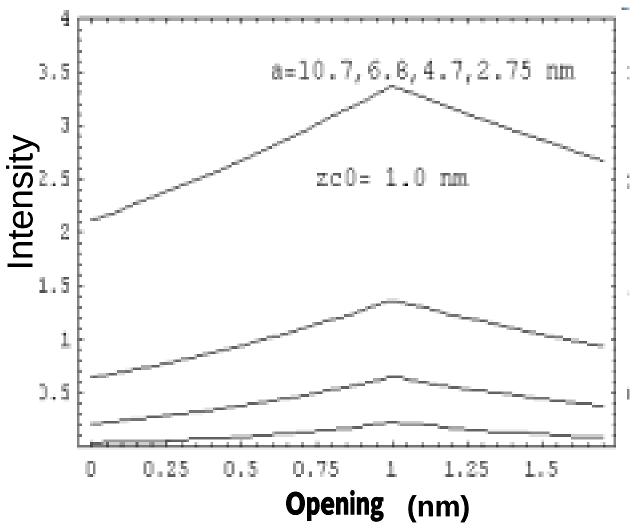

FIGURE 7. Calculated subharmonic intensity as a function of crack opening

Although the relation between the tensile load and crack opening requires a careful calibration, we postpone it to future study. Though the subharmonic intensity showed an abruptly change of slope at $z_S = 1$, we can obtain smooth peak if we assumed more realistic stiffness $s = k$ as a function of the load [7]. Sinusoidal time function rather than the piece wise linear function will provide better agreement with the experiment. And most importantly, subharmonics has a typical waveform which we neglected in this paper. These are subjects of our further study [8].

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