Ultrasonic Imaging of Tight Crack Surfaces by Backscattered Transverse Wave with a Focused Transducer

Koichiro KAWASHIMA, Materials Diagnosis Lab., Nagoya, Japan
Morimasa MURASE and Toshihiro ITO, Nagoya Institute of Technology, Nagoya, Japan

Abstract. A novel ultrasonic imaging technique of tight crack surfaces themselves is proposed. Focusing the transverse wave beams at every point on the rugged cracked surface, and receiving the backscattered wave signal from that point, we can image the tight crack surfaces by the conventional C-scan.

The ultrasonic imaging technique is applied to tight fatigue cracks of carbon and stainless steels with point-focused transducers. The cracked surfaces of partial and through-thickness crack are imaged, from which the crack depth is estimated. The degree of crack closure could be evaluated by combining the higher harmonic images, which is obtained by a high-powered burst wave pulser.

1 . Introduction

Conventional ultrasonic flaw sizing in large structures utilizes the echo waveforms reflected at cracks and defects, namely the echo amplitude and arrival time. To detect the cracks and evaluate their sizes, inverse problems must be solved with limited echo data. This sometimes results in erroneous conclusions.

To solve this problem, TOFD [1], time-of-flight diffraction, method and phased arrays [2] have been developed for imaging of crack tips. For open cracks, they surely delineate the top and bottom edges of the cracks. However, they can’t visualize the cracked surfaces themselves. This may lead to misinterpretation of sizing of small cracks.

More important problem is the detection and sizing of tight cracks. Echo signal from those cracks are significantly lower than the open cracks, because ultrasonic energy is partially transmitted across the crack surfaces. Some techniques to solve this problem have proposed; Harmonic generation at tight cracks [3] and crack opening by local cooling or heating [4]. The former has long history but not easy to apply *in situ* for structural component. The latter takes some ten minutes to open the tight cracks.

In this paper, we present a new imaging technique for tight crack surfaces themselves. Different from the conventional ultrasonic testing, we capture the waveforms backscattered at rugged crack surfaces with a focused transducer in a water bath.

2. Imaging of Crack Surfaces with Backscattered Transverse Wave

2.1 Key Concept

Fatigue-cracked surfaces of metals have rugged striations formed by local plastic deformation at the crack tip. Also, intergranular stress corrosion cracking, IGSCC, have irregular grain boundary gaps of random orientations. These very narrow gaps between cracked surfaces or grain boundaries remain open to a certain extent even when these rugged surfaces are in contact under moderate pressure.

When the incident ultrasonic beams are focused on the peaks of rugged surfaces, some of the backscattered wave would be detected. When we focus the mode-converted transverse wave at every point on the cracked surfaces and capture the backscattered wave signal by scanning a focused transducer, as shown in Fig. 1, we will be able to image the cracked surface itself. The merit of the use of the mode-converted transverse wave is shown in Fig.2. The main ultrasonic beam is reflected away at the water/solid interface, therefore, we can capture the backscattered signal from a defect with high amplification without long reverberation.

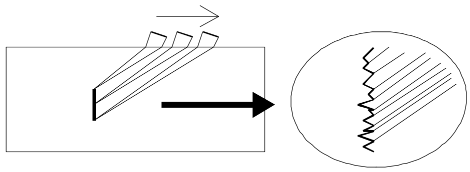


Fig.1. Backscattered transverse wave from a rugged cracked surface.

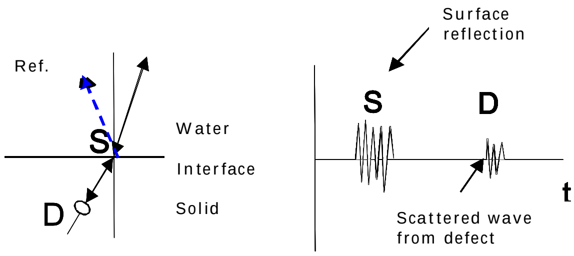


Fig.2. Backscattering model of mode-converted transverse wave.

2.2 Harmonic Generation at Tight Cracks

In addition to harmonic generation in nonlinear elastic continuum, *Contact Acoustic Nonlinearity*, CAN, has been applied to detection of extremely narrow gaps comparable to the incident wave amplitude [5-7].

Nonlinear stress-strain response around the crack having such a narrow gap is modeled by Fig. 3, as a rough approximation for clapping mode, where we assume that the idealized parallel crack surfaces transmit only compressive stress after the crack closure under compressive phase but no stress in rarefied, tensile, phase. The apparent compressive strain corresponding to the crack closure takes different value depending on the gap width; therefore, an overall response is expressed by a nonlinear stress-strain curve shown in (e). Due to this strong nonlinearity around tight cracks, higher harmonics are generated. Even under transverse wave, the crack surface clapping is caused as shown in Fig. 4.

2.3 Ultrasonic Imaging System

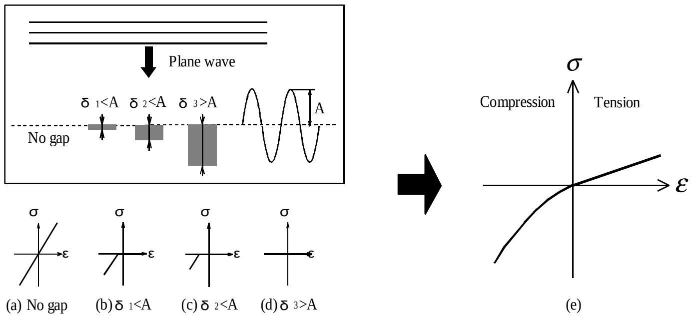


Fig.3. Nonlinear stress-strain response at narrow gaps.

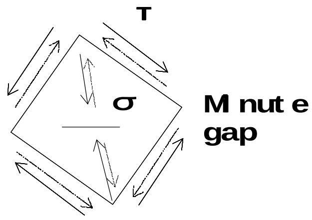


Fig. 4 Clapping of crack surface under transverse wave.

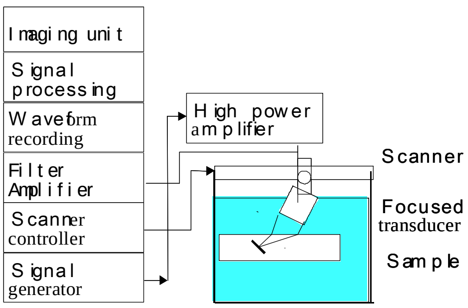


Fig. 5 Ultrasonic imaging system.

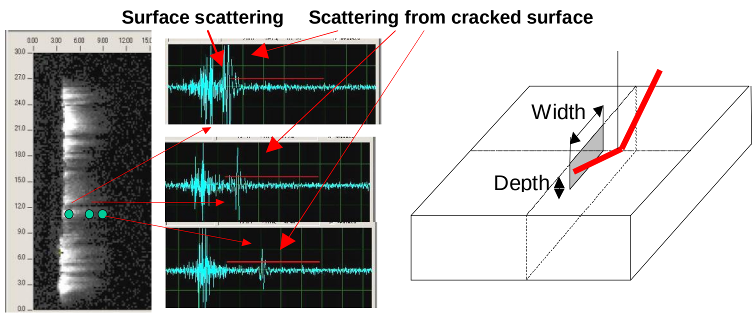


Fig.6 Fatigue crack surface image. Transducer :10MHz, F=100mm.

An ultrasonic imaging system shown in Fig. 5 is used to image crack surfaces themselves by the mode-converted transverse wave. Basic components in this imaging system are same as those of the conventional C-scan acoustic microscope. However, we use a high-powered pulser to excite large amplitude burst waves. In addition, a bandpass or highpass filter is combined to extract higher harmonics.

3. Ultrasonic Images of Cracked Surfaces

3.1 Fatigue Cracked Surface of SUS 304

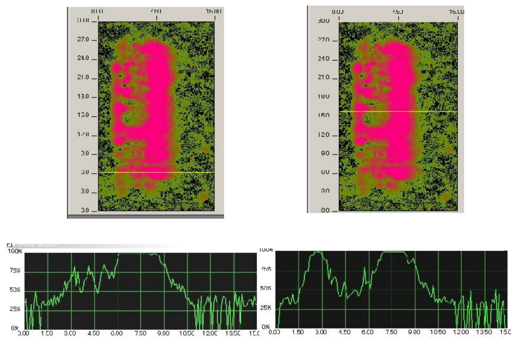
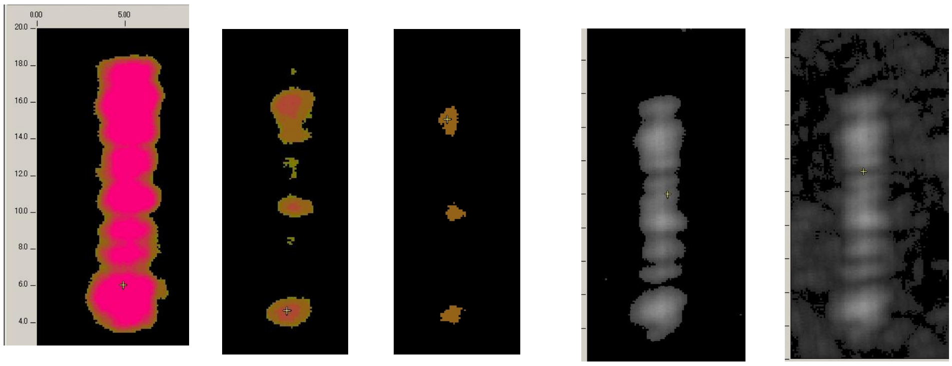


Fig.7 Fatigue crack surface image. Transducer:30MHz, F=25mm.



Strain $3x10^{-4}$ $8x10^{-4}$ $1.2x10^{-3}$ $1.2x10^{-3}$ 25% $1.2x10^{-3}$ 12%

Fig.8 Change in images with compressive strain and imaging gate height.

A fatigue crack was introduced in a SUS 304 plate, thereafter the part of a starter notch was removed. The crack surface image shown in Fig. 6 is constructed with a focused transducer having a central frequency of 10MHz, focal length of 100mm and element diameter of 9mm. The refraction angle is set for 45 degree, therefore, the image width is equal to the crack depth. In the waveforms shown in Fig. 6, the time delay of the backscattered signals at points on the cracked surface with respect to the surface scattering increases with the depth from the surface. Figure 7 shows the same crack surface images taken by another focused transducer having a frequency of 5MHz and focal length 51mm. The crack depth and length are similar in both figures, however, the detail of the images is dependent on the focal length and aperture of the transducer.

3.2 Images of Cracked Surface under Compressive Stress

Some cracks in pipes and vessels remain open under high pressure, however, they may be closed by elastic constraint stress when the applied pressure is reduced to zero. The detection and sizing of such tight cracks is said to be difficult by using the conventional pulse-echo method, because the ultrasonic wave is transmitted across the tight crack surfaces to some extent.

To clear up the effect of compressive stress on the cracked surface images, we applied compressive stress to the cracked surface by three points bending and recorded the backscattered images of the crack surface. The results are shown in Fig. 8. With an increase in compressive strain, the backscattered wave amplitude from the crack surface decreases in most area of the cracked surfaces, when the gate height is 50% of the full scale. However, even at the strain corresponding to the yield point, we can visualize the cracked surface, when the gate height is 25% of the full scale. In this imaging, we used point-focused transducers and high gain up to 80dB. At a gain of 20dB, the incident ultrasonic wave

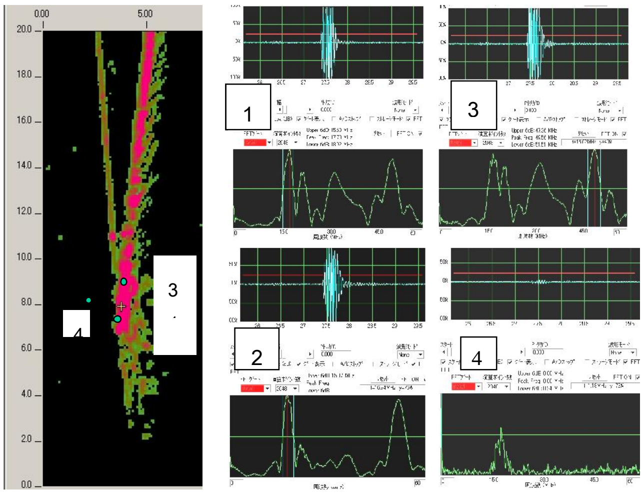


Fig. 9 Higher harmonic images of fatigue-cracked surface. Incident wave: 17MHz, 2nd harmonic: 34MHz, 3rd harmonic: 51MHz. Frequency range: 0- 60MHz.

passes through the tight crack surface, however, the wave is reflected to a certain extent at the surface at a gain of 80dB.

3.3 Higher Harmonic Images of a Tight Crack Surface

Some higher harmonics will be generated when burst waves of finite amplitude are transmitted for tight crack surfaces by the strong nonlinear stress-strain response shown in Fig. 3. This is demonstrated for a through-thickness fatigue crack of aluminum alloy. Figure 9 shows the mixed images of fundamental and higher harmonics. At points 1,2 and 3 just under the V-notch, the scattered waves at the cracked surface have frequency components of the fundamental, 2nd and 3rd harmonics, by which the fundamental amplitude was reduced by 40dB by a high-pass filter of 14 MHz. We notice the fundamental, 2nd and 3rd harmonics at point 1 and 3, but only the fundamental and 3rd harmonic at point 2. By the way, no harmonic is detected at point 4 on the crack-less surface.

4. Concluding Remarks

Ultrasonic imaging of cracked surface itself was demonstrated for several fatigue cracks by using the backscattered mode-converted transverse wave with a point focused transducer. The use of mode-converted transverse wave permits us high amplification up to 80dB without long reverberation. We can evaluate precisely the crack depth and length with cracked surface imaging. This technique would be particularly useful for detection and sizing of scattered SCC.

The higher harmonic imaging with a large amplitude burst wave pulser and highpass filter will be effective for detection of tight cracks, namely the crack tips of fatigue cracks and SCC.

References

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