Enhanced Higher Harmonic Imaging of Heterogeneities and Local Plastic Deformation in Steel Plates

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Abstract. Conventional ultrasonic imaging based on the difference in acoustic impedance fails to detect and visualize small heterogeneities and local plastic deformation in metals. Nonlinear ultrasonic imaging technique visualizes higher harmonic amplitudes which are generated at the heterogeneities by finite amplitude sinusoidal burst waves, therefore, it can be applied for detecting small non-metallic inclusions, local plastic deformation and micro cracks. By transmitting 35 MHz sine burst waves and receiving harmonics of 105 MHz in the maximum, non-metallic inclusions in stainless steel of some ten μm in size and crack tip plastic zone of 2 mm in diameter are visualized.

1. Introduction

Nonlinear acoustic or ultrasonic methods which make use of the waveform distortion from the incident sinusoidal wave are useful for detecting kissing bonds with small difference in acoustic impedance and minute defects within bond layers between dissimilar materials with the large impedance difference. Among them, a higher harmonic method quantitatively evaluates the waveform distortion by higher harmonic amplitudes.

The first author and et al. have developed an immersion higher harmonic imaging system and visualized closed cracks [1], micro voids in diffusion bonded interface [2], non-metallic inclusions [3], and local plastic deformation [4]. In these images, the maximum frequency of incident burst wave was 20 MHz and the third harmonic (60 MHz) amplitude was mapped. The incidence of higher frequency burst wave can enhance the higher harmonic amplitudes due to stronger cyclic stress excited within samples and result in higher spatial and temporal resolution by the short wavelength.

In the present work, we demonstrate higher harmonic images of non-metallic inclusions in stainless steel and local plastic deformation around a hole and crack tip by transmitting 35 MHz sine burst wave and receiving 80-100 MHz harmonic amplitudes.

2. Immersion higher harmonic imaging system

We use the experimental setup shown in Figure 1. The key components are a 100 MHz sine burst wave pulser (RITEC RAM-5000), an amplifier (RITEC RPR-4000), multi-selectable high-pass filters, a scanner and imaging software (InsightScan and InsightAnalysis). Samples were placed horizontally within the water bath, and the water path length is kept constant during scanning, therefore, higher harmonic amplitude exited in water is unchanged during scanning.
We can use either the backscattered mode or the local resonance mode shown in Figure 2 for imaging defects or heterogeneities. By the backscattered mode, we have high spatial and temporal resolutions. On the other hand, we have high sensitivity for harmonic generation by the local resonance mode.

3. Higher harmonic images of non-metallic inclusions in stainless steel
Micro fatigue cracks often initiate at subsurface non-metallic inclusions in thin metal parts subjected to cyclic loading. Therefore, a reliable non-destructive technique is wanted for detecting such subsurface inclusions. The harmonic and conventional UT images of non-metallic inclusions in a SUS 304 plate are shown in Figure 3. The harmonic image was obtained with a focus transducer of 30 MHz in frequency and 25 mm in focal length by transmitting 35 MHz and 4 cycle sine waves and receiving mainly 105 MHz harmonic component with a high-pass filter of 80 MHz. For the conventional UT image, we used a spike wave pulser (Panametrics 5900PR). The received wave amplitude at every point is transformed in colour according to the colour scale shown in the middle.

In the harmonic B- and D-scan images, we clearly identify each inclusion shown in the square, while the identification of the inclusions shown in the circle is difficult in the conventional UT B- and D-scan images due to strong grain scattering noise. By examining SEM images and EPMA map, which are not shown, of the cross section, we found the typical inclusions were alumina and manganese sulphide elongated in the rolling direction.
The sizes of inclusions imaged by higher harmonics are over 50 μm.

Another higher harmonic image of non-metallic inclusion in oxide dispersion strengthened (ODS) fuel cladding tubes for fast breeder reactors is shown in Figure 4. The material is a 9 Cr ferrite stainless steel strengthened by yttria (Y₂O₃) and is made at Japan Atomic Energy Agency. The harmonic image was taken by using the experimental setup shown in Figure 4. The tube of 6.5mm in diameter and 0.5mm in thickness was rotated circumferentially. After every rotation, the transducer was lifted axially by 0.1 mm. By this circumferential and axial scanning, circumferentially developed image of heterogeneities was constructed and it is shown in the left side of Fig. 5. Incident frequency is 20 MHz and 40 MHz high-pass filter is used to extract the 3rd harmonic amplitude.

Among several bright spots in the harmonic image, the spot shown in red circle was selected for detailed examination. After cutting the tube along the white horizontal line, polishing and observing by an optical microscope, we found an object shown in white circle and examined it by SEM. As shown in the central area, the object is found to be a TiO₂ inclusion of 12 × 3 μm in size.

At other 7 points where the higher harmonic amplitude is much higher than the matrix, heterogeneities such as oxide, aggregate of micro voids and Cr-rich segregation are confirmed by SEM and EPMA. Those sizes are smaller than 30 μm, therefore they are allowed for service. By the way, this cladding tube is fabricated by the powder metallurgy technique in extraordinary clean atmosphere, therefore, non-metallic inclusions are far less than those in common steel.

4. Higher harmonic imaging of local plastic deformation

Local plastic deformation around a circular hole in SUS 304 plate which was subjected to 30% plastic strain at the maximum is imaged by the local resonance mode. Incident sine burst wave is 22.35 MHz in resonance frequency and 70 cycles. With a high pass filter of 80 MHz, the 4th harmonic amplitude is mapped. As shown in Figure 6, at the just below the hole around the minimum cross section, the local plastic zone is clearly shown in the C-scan image shown in the top. This image is constructed by the wave amplitude in the white frame at the bottom. Temporal variation of the harmonic amplitude along the red horizontal line is shown in the middle, from which we notice that the delayed wave amplitude is large in the severely deformed plastic zone.

The harmonic image of plastic zone in front of fatigue crack tip and Luders band in a SPC plate of 1mm in thickness is shown in Figure 7. The incident sine burst wave is 21.26 MHz in resonance frequency and 80 cycles. With a high pass filter of 80 MHz, the 4th harmonic amplitude is extracted and it is shown in the middle. We can identify the crack tip plastic zone of approximate 3 mm in diameter and Luders bands. We notice that the delayed wave amplitude around 38.3 μs is large and the peak spectrum is about 85 MHz (4th harmonic) in the left figure.
5. Concluding remarks

With the immersion higher harmonic imaging system, we have non-destructively imaged non-metallic inclusion of $12 \times 3 \mu m$ in size within ODS fuel cladding tube by transmitting 20 MHz sine burst wave and receiving 60 MHz component. In addition, crack tip plastic zone of approximate 3mm in diameter is imaged by transmitting sine burst wave of 21.26MHz in resonant frequency and receiving the 4th harmonic amplitude. These have never been visualized by the conventional ultrasonic imaging.

The harmonic imaging of small non-metallic inclusions and small crack tip plastic zone could lead to evaluate nondestructively material degradation and damage evolution such as fatigue crack growth in the early stage of fatigue life. As pointed by Mayendorf et al. [6], nonlinear acoustic or ultrasonic technique is best fitted for non-destructive evaluation of the initial and middle stage of the crack growth.

Thus, the immersion higher harmonic imaging technique would be indispensable for non-destructive material characterization and evaluation in the future.

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