Laser-Generation Based Imaging of Ultrasonic Wave Propagation on Welded Steel Plates and Its Application to Defect Detection

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This study investigated nondestructive testing of welded steel plates by imaging ultrasonic wave propagation based on laser generation. The specimens were scanned by a pulsed laser, and the signals were received by a fixed piezoelectric transducer. A moving diagram of wave propagation from the fixed point was obtained directly from the collected signals. Wave scattering due to a weld defect (e.g., toe crack or root crack) was successfully imaged on weld specimens, and was easily recognized by visual observation in the measured moving diagrams. These experiments demonstrated the ability of the imaging technique to inspect a large area in a short time and to reliably detect a defect. Furthermore, the position-time-amplitude maps (B-scope images) were reconstructed from the moving diagram along some lines perpendicular to the defect, and the location and the size of a root crack were evaluated based on the B-scope images. [doi:10.2320/matertrans.M2010204]

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1. Introduction

Nondestructive testing is an important engineering field in ensuring structural safety. Of the many techniques developed for damage detection and identification, ultrasonic testing has been widely used to assess reliability of structural components, and various approaches aimed at quantitative evaluation of the damage have been proposed.¹⁻⁵

Ultrasonic testing has frequently been applied to the inspection of welding. Defects were detected by analyzing the manually-measured one-dimensional waveform in the most popular ultrasonic testing. However, interpretation of the one-dimensional waveform, or detection of the signal from the defect, is sometimes difficult, since the scattered signal is measured as a mixed signal of the reflected wave, diffracted wave, and mode-converted wave with smaller amplitude. Accordingly, signal processing has been studied for accurate detection of defects.⁶,⁷ The phased-array method⁸ and the time-of-flight diffraction (TOFD) method⁹ have recently attracted attention, since the resulting two-dimensional (2D) images facilitate understanding of the defect condition and enhance inspection reliability. Komura et al.¹⁰ applied these methods to the inspection of welding in a nuclear power plant. Although phased arrays and TOFD are powerful tools for precise analysis of a specific region, they are not suited for inspection of a large area of a three-dimensional shape with curved surfaces and irregularities, since some additional mechanical devices are needed to scan the surface.

Imaging technique for ultrasonic wave propagation will be a powerful tool of nondestructive testing, since the moving diagram facilitates understanding on the mechanism of wave propagation and detection of wave scattering. However, conventional imaging methods (e.g., photoelasticity)¹¹⁻¹³ apply only to transparent materials and have limited utility. Therefore, these methods have been used only to understand experimentally the mechanism of ultrasonic wave propagation. Recently, Staszewski et al.¹⁴ imaged wave propagation near a fatigue crack in an aluminum plate by using a three-dimensional scanning laser vibrometer that enabled non-contact signal reception. The authors developed a technique for imaging wave propagation by using a scanning pulsed laser for generation, and employed this technique to detect bonding damage in a CFRP skin/hat-stringer structure¹⁵ and artificial corrosion damage in a steel elbow-pipe.¹⁶ Although these studies¹⁴⁻¹⁶ indicated usefulness of the wave propagation images for damage detection, to our knowledge, no study has been reported on engineering applications of the imaging techniques and on the possibility for characterizing damage.

The purpose of this study is then to verify the ability of the laser-generation based imaging technique to detect defects in a steel plate with butt welding. For this purpose, we experimentally visualized wave propagation on weld specimens by the imaging technique, and investigated defect detection from the measured moving diagrams. Furthermore, the characterization of the weld defect is presented by reconstructing B-scope images, and the applicability of the imaging technique to sizing defects is discussed.

2. Procedure for Imaging Wave Propagation

In conventional imaging of ultrasonic wave propagation,¹⁴,¹⁷,¹⁸ ultrasonic waves are generated at a fixed point by a piezoelectric transducer, and non-contact signal reception is performed at grid points by a scanning laser vibrometer. However, the signal-to-noise ratio of a laser vibrometer (or other non-contact reception method) is generally poor compared to that of a piezoelectric transducer.¹⁹,²⁰ Therefore, waveform averaging was carried out in the previous studies,¹⁴,¹⁷ and high-speed inspection is difficult. Here, the key point of the present technique is to exchange the generation and the non-contact reception: ultrasonic waves
are generated at grid points by a scanning pulsed laser, and the signal is received by a fixed piezoelectric transducer. Based on the reciprocity principle in wave propagation,\(^1\) the waveforms obtained by the system with the scanning generation and the fixed reception are the same as the data set of the conventional approach. The amplitude of each waveform at time \(t\) is then plotted on a contour map, which corresponds to a snapshot of the wave propagation. Finally, the snapshots are continually displayed in a time series and appear to be a moving diagram of wave propagation from the fixed reception point.

The system configuration with a scanning pulsed laser and a fixed receiver has the following two advantages over conventional approaches. (1) Scanning a three-dimensional shape with curved surfaces and irregularities is easy, since generation with a pulsed laser needs no control of laser incident angle and focus. (2) Waveform averaging is not necessary since a high signal-to-noise ratio is achieved by a piezoelectric transducer. These two advantages enable high-speed inspection of a structural component with an arbitrary three-dimensional shape.

Figure 1 depicts a laser ultrasonic imaging system. The test piece was illuminated by a fixed pulsed laser through a galvanometer mirror to generate ultrasonic waves. The rotation angle of the mirror was controlled by the computer to scan the tested region. Here, the laser incident angle and focusing control were not needed; ultrasonic generation by thermal expansion alone was sufficient for imaging the wave propagation. A transducer was fixed on the specimen and received the ultrasonic signal that was generated at each grid point. The signals were stored in the computer through an amplifier and a digital oscilloscope (A/D converter). A snapshot of wave propagation at a given time was obtained by plotting the amplitude on a contour map.

3. Experiment

3.1 Setup

Figure 2 depicts the steel plate specimens with butt welding (Sonaspection International). The dimensions of the specimen were 145 mm long, 75 mm wide, and 10 mm thick. The material used was stainless steel. The weld zone was located at the center of the longitudinal \((x)\) direction. Each specimen has a weld defect: a toe crack (Fig. 2(b)), a center-line crack (Fig. 2(c)), lack of fusion (Fig. 2(d)), a root crack (Fig. 2(e)), or incomplete root penetration (Fig. 2(f)). These weld defects were real flaws purposely-induced during the welding process. The defects were 25 mm wide and were located at the center of the transverse \((y)\) direction.

The area including the weld zone was scanned, and its size was 90 mm in the \(x\)-direction and the entire specimen width. The spacing of the grid points was 1 mm in the \(x\)- and \(y\)-directions. The laser used was an YLF laser with the wavelength of 1053 nm. The energy of the laser was less than 1 mJ, and pulse duration was 30 ns. The spot size of the laser was 2.5 mm. The scan rate of the pulsed laser was 200 Hz, and the reverberation was sufficiently attenuated at this generation time lag. Then, the time of scanning was approximately 35 seconds under the measurement condition.

A piezoelectric transducer with a resonance frequency of 1 MHz was used to receive the ultrasonic waves. The receiver was fixed at the end of the \(x\)-direction and the center of the \(y\)-direction. The waveforms measured by the transducer had a wide frequency range due to the laser generation.
Scattered wave (longitudinal) with relatively large amplitude were delayed with increasing distance with a crack on the test surface (toe crack), scattered signals in conventional ultrasonic testing. In the specimen transducer (Fig. 3(a)), which corresponds to one-dimensional propagation in the +x-direction was visualized in all the specimens. Two types of incident waves could be observed in the snapshots; one had higher velocity (5800 m/s) with smaller amplitude, and the other had lower velocity (3000 m/s) with greater amplitude, where the velocity was obtained by a B-scope image described later. As depicted in the dispersion curves calculated by Disperse software (Fig. 5), the velocities of all the Lamb modes changed within the measured frequency range. Moreover, the dispersion characteristic of guided waves did not appear in the measured waveforms (Fig. 3) even if the waveforms contained many frequency components. Therefore, the observed waves were not the Lamb modes; the former was determined as the longitudinal wave and the latter was the shear wave from the wave velocity.

Then, the wave propagation in the toe-crack specimen (Fig. 4(a)) is explained as a typical result. Clear wave scattering was observed at the center of the weld zone when the incident shear wave passed the weld zone (t = 20 μs). The longitudinal wave and the shear wave reflected at the weld zone appeared after the wave scattering and propagated in the −x direction (t ≥ 20 μs). The scattered waves with large amplitudes were generated only at the center of the weld zone, not in all the specimen width. Therefore, the ultrasonic waves were disturbed by the weld defect, not by the welding.

The present study focused on finding the wave scattering, which is the first step in defect detection. Clear wave scattering was observed after 25 μs when the incident shear wave arrived at the weld zone in the specimen with the toe crack (Fig. 4(a)). The reflected waves had two types as observed in the incident waves, and velocities of these reflections were 3000 m/s and 5800 m/s, which corresponded to the shear wave and the longitudinal wave. The shear wave had larger amplitude than the longitudinal one in the reflected waves and mainly appeared. Wave scattering similar to that in Fig. 4(a) was imaged after 25 μs in the specimens with a center-line crack (Fig. 4(b)) and the lack of fusion (Fig. 4(c)). In the other defect types at the back surface (Figs. 4(d) and 4(e)), a reflected wave with a velocity of 5800 m/s (longitudinal wave) was mainly observed after the incident shear wave passed the weld zone, although the two types of reflections appeared as in the toe crack specimen. The scattered wave with the largest amplitude was visible in the toe crack (Fig. 4(a)). Wave propagation in the −x direction was also easily recognized for the center-line crack (Fig. 4(b)) and the lack of fusion (Fig. 4(c)) in the specimen. With the root crack (Fig. 4(d)) and the incomplete penetration (Fig. 4(e)) on the back surface, the scattered wave with smaller amplitude could be detected easily in the moving diagrams (continually displayed snapshots), although specifying it in the still...
snapshots was slightly difficult compared to Fig. 4(a). These results confirmed that wave scattering was easily recognized in the images of wave propagation and that various types of weld defects were successfully detected.

The defect could be found simply from the visual recognition of the wave scattering, even if the specimen contained weld zone and the defect existed in (near) the weld. The visual recognition of the wave scattering in the moving diagram was generally effective and secure. Accordingly, the advantage of the imaging technique was demonstrated that all the engineers could test a large area in a short time and detect defects. The dispersion characteristic was not important for damage detection; recognition of the scattered waves alone was sufficient, although the dispersion curve was depicted in Fig. 5.

4. Discussion

Characterizing the weld defect is another important task of nondestructive testing. The amplitude map is the simplest
way to indicate defect position. Figure 6 presents a contour map of the maximum amplitude of the moving diagram in the root crack specimen depicted in Fig. 4(d). The lines with smaller amplitude along the y-direction appeared at the center in the longitudinal direction. This smaller amplitude resulted from the irregularities on the surface, and these lines corresponded to the weld zone. Moreover, larger amplitude in the welding was found; this peak indicated interference between the incident wave and the scattered wave. This result demonstrated that the source of the scattered wave (i.e., the location of the defect) was approximately indicated by the maximum amplitude map.

In order to quantitatively evaluate the defect, a B-scope image was created along the center line (Fig. 7(a)) of the root crack specimen, as depicted in Fig. 7(b). The horizontal and vertical axes corresponded to the position x and the time t in this image, and the amplitude was represented by the contrast. The wave velocity was then obtained by the slope of the contrast. An incident longitudinal wave with smaller amplitude and a shear wave with greater amplitude are depicted in Fig. 7(b). The slope of the incident shear wave was disturbed in the center of the scanned area corresponding to the weld zone with irregularities, and some reflected waves with the opposite slope were observed in the weld zone. In order to identify the reflection point, the incident waves were removed by using a filtering method. The incident waves and reflected waves were divided clearly in the frequency-wavenumber domain by the three-dimensional Fourier transform of the moving diagram (collected signals at all the grid points). Then, only the reflected wave could be extracted by the three-dimensional inverse Fourier transform of the data without the incident component, which was filtered in the frequency-wavenumber domain. The propagation of the reflected waves is depicted in Fig. 8, and the B-scope image without the incident waves was then obtained (Fig. 7(c)). The generation of the reflected wave with greater amplitude was found inside the weld zone as well as the smaller reflection at the ends of the welding. We could determine that the reflection source (i.e., defect) existed at 39 mm from the left end of the tested area, which...
corresponded well to Fig. 2(e). Thus, the scattering point along the line perpendicular to the crack was clearly determined. However, distinction between the reflection and the diffraction, or specifying the tip of the defect, was difficult only by the B-scope analysis. Figure 9 depicts the B-scope image along the line 15 mm apart from the center line. Although the root crack did not intersect this line, the slope of the scattered wave appeared due to the diffraction and its generation point was near the point (39 mm, 23.6 $\mu$s) found in Fig. 7(c). This may result in overestimation of the defect size.

These experiments and discussions illustrated that easy defect detection was possible by finding the wave scattering in the moving diagram, the wave with the opposite slope from that of the incident waves in the B-scope image, and the large amplitude in the maximum amplitude map. The B-scope image also provided the information on the defect location. However, some overestimation errors would be included when the size of the defect was estimated from the B-scope analysis. Therefore, the imaging technique could be applied to determine the defect that needed a detailed evaluation from a large test area, taking advantage of the fast and easy inspection characteristic. Characterization of defects would be carried out by the other techniques such as phased-array method when the damaged region was found by the moving diagram.

5. Conclusions

This study demonstrated nondestructive detection of weld defects by the imaging technique of ultrasonic wave propagation based on laser generation to clarify its advantage in the engineering applications. Ultrasonic waves were visualized on welded steel plates with various types of defects on the tested (illuminated) surface, on the back surface, or in the specimen. The generation and propagation of the scattered wave were successfully imaged at the defect position in all types of weld defects, and scattering in the wave propagation was easy to find in the moving diagram by visual observation. These results demonstrated the ability of the present imaging technique for accurately detecting defects. Furthermore, characterization of the weld defect was discussed based on B-scope images. Location of the scattered point was well identified by finding the opposite slope from that of the incident waves. However, the B-scope analysis along the line away from the defect suggested that the defect would be overestimated because of the diffraction near the edge of the defect. These results indicated that the imaging technique should be used as the fast inspection to determine the defect that needed detailed evaluation from a large test area.

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REFERENCES