Special Feature: Nondestructive Testing and Evaluation Technology

Research Report

Defect Imaging Technique Using Ultrasonic Waves Produced by Laser Irradiation

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ABSTRACT This paper describes a novel non-immersion defect imaging technique using a scanning laser source in which ultrasonic waves are generated at the object surface by a thermoelastic effect induced by pulsed laser irradiation. The ultrasonic waves are received by ultrasonic transducers. Although defects can be identified from the disorder of the generated ultrasonic wave propagation using the conventional scanning laser source technique, we developed an imaging technique more effective for the recognition of the two-dimensional form of defects.

In this study, a clear image revealing the notch-like defect on the back surface of an aluminum plate was obtained by synthesizing multiple images using multiple ultrasonic transducers. Moreover, it was shown that non-contact defect imaging can be performed by using high sensitivity air-coupled ultrasonic transducers as receiving sensors.

KEYWORDS Defect Imaging, Scanning Laser Source Technique, Ultrasonic Waves, Non-immersion, Air-coupled Ultrasonic Transducer, Nondestructive Evaluation

1. Introduction

Nondestructive evaluation of materials is becoming increasingly important and is a fundamental technology allowing industrial products and production facilities to be used reliably and safely. Especially, imaging of defects such as cracks in materials is important to give objectivity to the quality evaluation of products and the analysis of deterioration over time. For this reason, in recent years, a scan type ultrasonic imaging system has been widely used.[1,2] In this imaging system, an object and an ultrasonic transducer are submerged in a water tank, and then the transducer is scanned over the object. Echoes from the object are acquired at many points over the object to provide a distribution of the amplitude or phase of the echo as an image of the inner characteristics of the object. However, since the use of water is necessary, the applications are mainly limited to sampling inspection of products or inspections of products in the development stage. Therefore, a non-immersion defect imaging technique is highly required.

The laser ultrasonic method [3-5] is attracting attention as a new non-contact ultrasonic testing technology, but for practical use, a crucial issue remains unsolved. The detection of ultrasonic waves with a laser interferometer is strongly affected by surface conditions like roughness, plane angle, and color because reflected or scattered laser beams must be detected. Therefore, we focused on the scanning laser source technique[6-8] as a practical solution to the problem, in which ultrasonic waves are generated by pulsed laser irradiation of the object surface under inspection. The waves are then received by ultrasonic transducers. This paper describes a novel non-immersion imaging technique that obtains a clear image, characterizing defects in materials by utilizing a scanning laser source technique and synthesizing multiple images obtained using multiple ultrasonic transducers.

2. Scanning Laser Source Technique

In the scanning laser source technique (SLS), a pulsed laser which is used as an ultrasonic wave generation source, is scanned by a galvanometer mirror. In the minute area irradiated by the pulsed laser, when the laser power density is large enough, local plasma formation occurs and ultrasonic waves are generated by the reaction force. However, since damage to the object surface may occur, it is necessary to reduce laser power density according to the kind of object under inspection and the inspection specifications. Thermoelastic stresses that act as ultrasonic wave sources are induced by sudden heating and cooling, but since the generated ultrasonic wave is very weak, it is necessary to receive it with ultrasonic transducers fixed on the object.

With the SLS, various kinds of images can be obtained by processing the ultrasonic waves acquired by each pulsed laser irradiation. For example, Takatsubo et al.(7) invented the new defect detection technique in which animations of ultrasonic wave propagation are created from the signals measured at each scanning point and defects are found by the distortion of that propagation. However, this method is not suitable for the confirmation of shape morphology of defects. On the other hand, it has already been reported that the amplitude distributions of ultrasonic waves roughly correspond to the remaining thickness distribution for a plate with rounded defects like corrosions.(9) In the research based on such ultrasonic wave propagation and amplitude distribution, the ultrasonic wave received is the Lamb wave which exhibits long propagation due to low attenuation, vibrating perpendicular to the direction of the specimen. In addition, the Lamb wave in the low frequency range, called the A0 mode, is hardly reflected, although amplitude changes due to changes in thickness are sufficient for defect detection with the SLS. This research also extracted the amplitude of the Lamb wave in the A0 mode, and developed a novel imaging technique which is effective for revealing the two-dimensional form of defects.

3. Imaging Experiments with Contact Receiving Transducers

3. 1 Experimental Setup

Figure 1 shows the experimental setup used in this study. A laser (32 mJ/pulse maximum pulse energy, 7.2 ns pulse width, 532 nm wavelength, 20 Hz maximum repetition rate) was used for ultrasonic wave generation. The power emitted from this equipment is high enough to cause ablation. Therefore, the output laser pulses are reduced by an attenuator to such an extent that ablation does not occur, and ultrasonic waves are generated by the thermoelastic effect. The pulsed laser emitted from the equipment and attenuated is then scanned in the *x* and *y* directions of the specimen shown in the figure by driving a two axis galvanometer mirror type scanner.

The ultrasonic waves generated by pulsed laser irradiation propagate along the specimen and are then detected by ultrasonic transducers of 1.0 MHz center frequency fixed on outside of the tested region. The received signals were stored in the computer after 40 dB amplification by a preamplifier, and the A0 mode of the low frequency region was extracted using a digital low-pass filter with a 400 kHz cut-off frequency.

3. 2 Specimen and Defect Imaging Procedure

A notch-like crack can be the starting point of failure due to stress concentration and is a more likely cause than gradual thinning. Therefore, as the first step of this study, in order to confirm the possibility of defect imaging, an artificial notch-like crack in a plate material was prepared. In flat plate experiments, the specimen was a 3.0 mm thick aluminum plate engraved with 1 mm deep straight and T-shaped notches on the back surface as shown in **Fig. 2**. Moreover, in order to confirm the adaptability to the curved plate, a half pipe of aluminum 132 mm in diameter and 3 mm in thickness was also similarly engraved with notches as shown in **Fig. 3**. In addition, imaging was carried out for every rectangular region enclosed by the dashed lines shown in each figure, and the filled (#1-#4) and open (#5-#8) circles indicate the four ultrasonic receiving points for imaging the straight and T-shaped notches, respectively.

The pulsed laser was scanned over the imaging areas

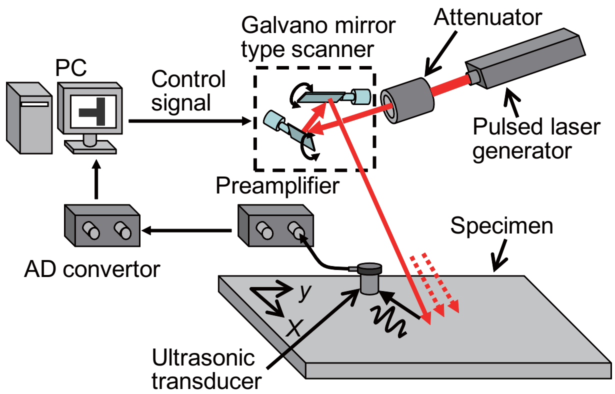

Fig. 1 Schematic diagram of the experimental setup for the defect imaging technique using a scanning laser source.

with a 1 mm pitch, and four corresponding ultrasonic transducers in the imaging area received the ultrasonic waves generated with each pulse. The received waveforms contained a wave propagating directly from the pulsed laser irradiated point and reflected waves from the edge of the plate and defects. Therefore, the waveforms were gated between 15 μs to 50 μs to avoid the affect of reflections as much as possible, and the maximum of the absolute values of the gated signals was defined as the imaging amplitude. An amplitude distribution image was obtained by plotting the measured amplitude values according to the point irradiated by the pulsed laser.

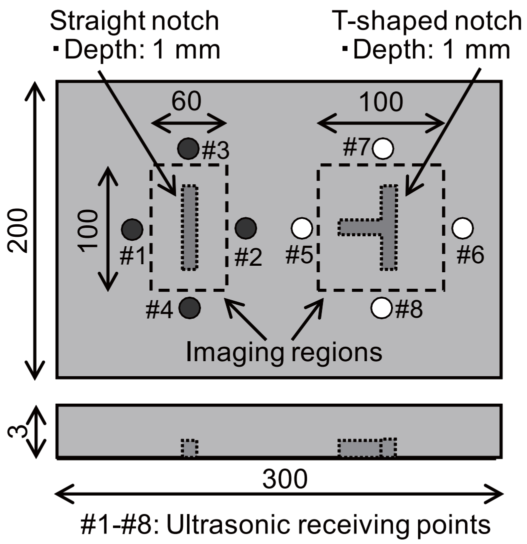

Fig. 2 Illustration of a flat plate specimen with notches, imaging regions and ultrasonic receiving points.

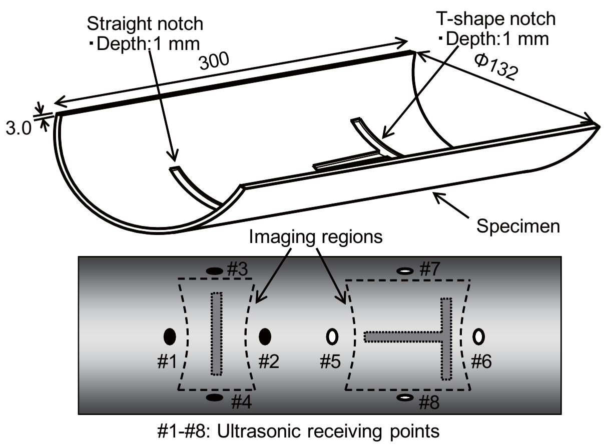

Fig. 3 Illustration of a curved plate specimen with notches, imaging regions and ultrasonic receiving points.

3. 3 Imaging Results for the Flat Plate Specimen

Figure 4 shows amplitude distribution images around the straight notch for four receiving points. The amplitude distributions in Fig. 4 were strongly affected by ultrasonic attenuation and reflection and wave propagation along the notch. For example, the concentric circles caused by the amplitude change over distance due to attenuation are seen in the left region of Fig. 4(a) and in the upper region of Fig. 4(c). Pale straight striped patterns are also seen in the left and right regions of Fig. 4(a) and (b), respectively, which are caused by the interference of waves from the irradiated points and waves reflected from the notch. Moreover, in Fig. 4(c) and (d), curved wavy strips are seen at both the left and right areas of the notch because waves coming directly from the irradiated points to the transducers interfered with the waves guided along the notch. Hence, it is difficult to identify defects using the amplitude distribution image obtained with a single ultrasonic transducer because

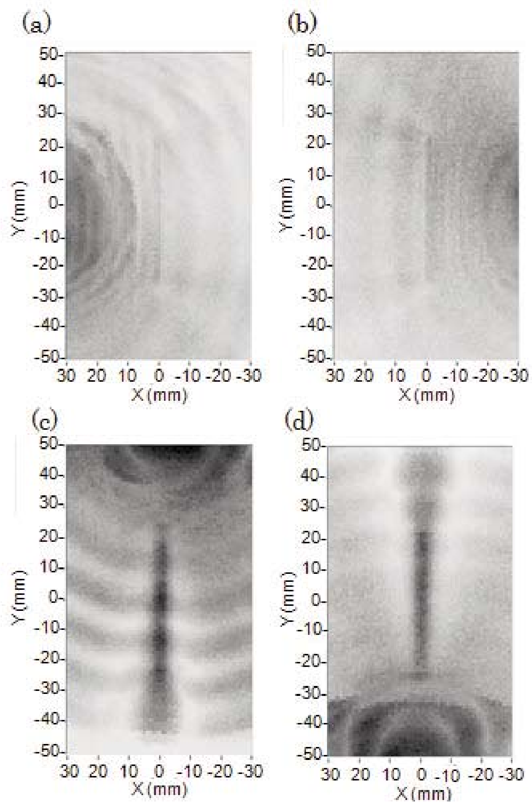

Fig. 4 Amplitude distributions of a straight notch area for four different transducer locations (Transducer locations are shown in Fig. 2), (a) receiving point: #1, (b) receiving point: #2, (c) receiving point: #3 and (d) receiving point: #4.

the images are strongly affected by reflection, refraction and attenuation. Therefore, in the four images shown in Fig. 4, we focused on the fact that the unwanted artifacts are located at different regions and that the defect image is located at the same region. Then, we synthesized these four images to reduce unwanted artifacts and to enhance the defect image. Taking the sum and product of the four images yields **Figs. 5**(a) and (b), respectively. Each image is normalized by the maximum value of amplitude. Although these images do not represent the remaining thickness distributions, the dark areas agree well with the shape of the notch.

The results for a T-shaped notch are shown in **Fig. 6**. Similarly to Fig. 5, Figs. 6(a) and (b) are images synthesized by the taking sum and product of the four images, respectively. Although light striped patterns caused by reflection, refraction and attenuation remain around the defect in both images, we can recognize the T-shaped notch clearly. Thus, this multi-image synthesis technique is effective for emphasizing defects.

3. 4 Imaging Results for the Curved Plate Specimen

Figures 7 and **8** show the synthesized images for the straight and T-shaped notches in the curved plate specimen, respectively. (a) and (b) in each figure represent the sum and product of the four images respectively like the case of the flat plate specimen, and approximately agree with the shape of the notches.

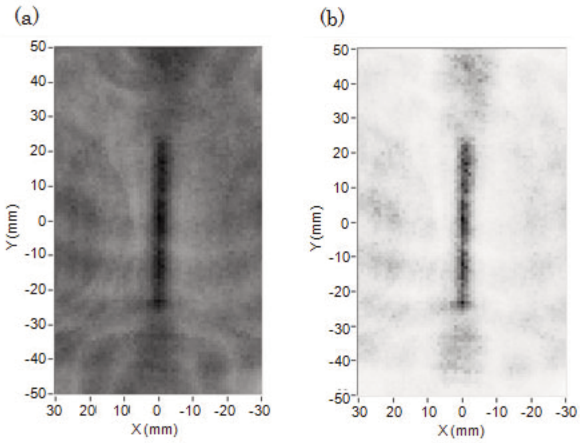

Fig. 5 Synthesized images from the four amplitude distributions shown in Fig. 4, (a) sum of the four images and (b) product of the four images.

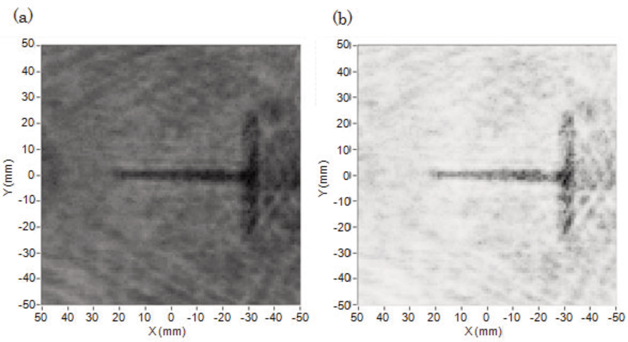

Fig. 6 Synthesized images of the T-shaped notch, (a) sum of the four images obtained at receiving points #5-#8 and (b) product of the four images obtained at receiving points #5-#8.

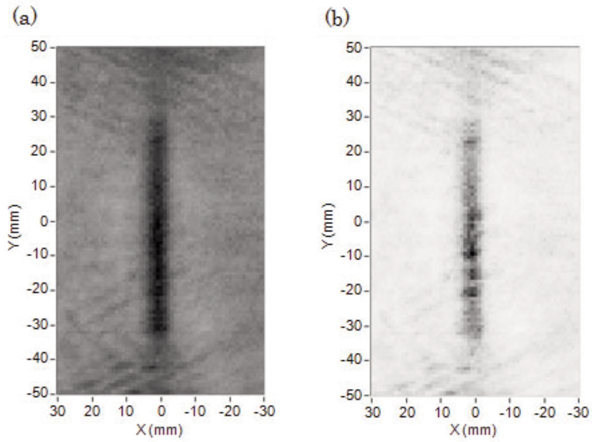

Fig. 7 Synthesized images for the area around a straight notch in the curved plate, (a) sum of the four images obtained at receiving points #1-#4 and (b) product of the four images obtained at receiving points #1-#4.

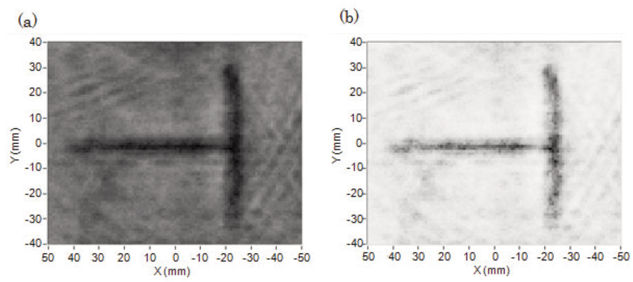

Fig. 8 Synthesized images for the T-shaped notch in the curved plate, (a) sum of the four images obtained at receiving points #5-#8 and (b) product of the four images obtained at receiving points #5-#8.

The edges of the T-shaped notch image were slightly curved since the images obtained here were projection images from the galvano mirror position to the plane. If this compensation is taken into consideration, it can be said that this imaging technique is also applicable to curved plates.

3. 5 Remaining Challenges in Practical Use

In the above experiments, the measurement time was about 300 seconds for 61 × 101 points, about 500 seconds for 101 × 101 points, and about 400 seconds for 81 × 101 points. The repetition cycle of the laser emission was 20 Hz (50 ms time interval), and since the measurement time is approximately equal to the product of the time interval of the pulsed laser emission and the number of scanning points, other processes were mostly performed in real time. However, a large reduction of the measurement time is required for practical use. Moreover, imaging of a larger region may be required depending on the object under inspection. Furthermore, because the SLS requires that an ultrasonic transducer is fixed to the object to ensure the signal level, application is restricted to objects insusceptible to adhesion of foreign substances such as a coupling medium. The following chapter describes technical developments[10,11] made with the aim of solving these issues.

4. Non-contact Fast Imaging Technique

We have already reported that using low frequency ultrasonic waves which exhibits long propagation due to low attenuation is useful when imaging a large region of a plate.[12] A well known sensor which is sensitive in such a low frequency range is the air-coupled ultrasonic transducer which transmits and receives an ultrasonic wave without contact with the object.[13] We focused on the fact that defect imaging might be realizable without contact by using a high sensitivity transducer as a receiving sensor in some kinds of air-coupled ultrasonic transducer. In addition, the high-speed scan of ultrasonic wave excitation is attained by using laser equipment with a shorter pulse emission time interval. Therefore, the laser equipment was transposed to a semiconductor excitation YLF laser with a maximum repetition frequency of 10 kHz. Unfortunately, in the previous experiment system described in chapter 3, since the peak values are detected using software after recording entire waveforms to a computer, detection processing of the peak values cannot be performed before a next ultrasonic wave excitation when the interval time is too short. Then, synchronizing with pulsed laser irradiation, analog peak-hold detectors which extract the peak amplitude between predetermined gates were produced. In this section, a non-contact imaging technique using the air-coupled ultrasonic transducer and a fast measurement system was investigated.

4. 1 Air-coupled Ultrasonic Transducers

Air-coupled ultrasonic transducers are classified into two main types, the resonance cone type transducer and the piezoelectric vibration type transducer. The former is designed for ultrasonic measurement of distance in a low frequency range such as 40 kHz with a narrow-band characteristic to increase the signal-to-noise ratio. The latter, recently developed for the nondestructive evaluation of materials,[14] has a frequency range of 0.1-1.0 MHz. In Ref. (12), we investigated the frequency dependence of the defect image quality, and concluded that we can use a low frequency range (below 100 kHz) for the defect imaging technique. In addition to those results, we found that low frequency ultrasonic waves can propagate over long distances with small attenuation. Moreover, in the low frequency range, leaky Lamb waves can be detected by the air-coupled ultrasonic transducers arranged perpendicularly to the object surface, which means that we can omni-directionally detect signals and create defect images with uniform sensitivity. For these reasons, we selected the resonance cone type 40 kHz air-coupled transducer to receive leaky Lamb waves in this study.

4. 2 Experimental Setup of Defect Imaging and Specimen

Figure 9 shows the non-contact and fast defect imaging system used in this study. The attenuator built into the laser equipment adjusted the laser irradiation power to the level which generates ultrasonic waves through the thermoelastic effect. The concept of the pulsed laser emission and scanning is the same as that of the method described in Chapter 3. In this experiment, a 1.0 mm thick aluminum plate engraved with 0.3 mm deep and 0.5 mm wide straight, zigzag and T-shaped notches on the back surface as shown in Fig. 9 was used as the specimen.

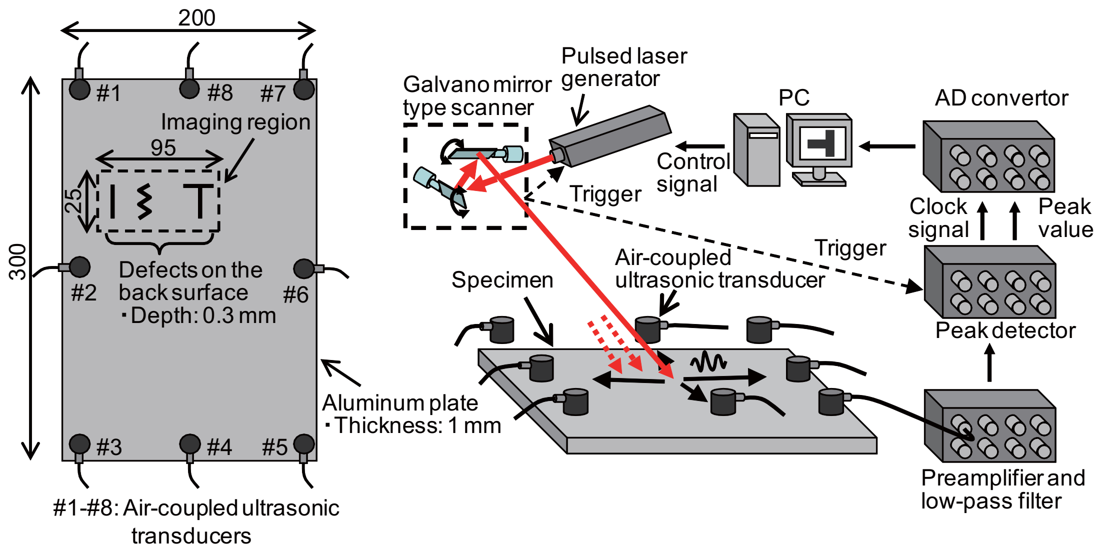

Fig. 9 Schematic diagram of the experimental setup for the non-contact defect imaging technique.

Ultrasonic waves generated by pulsed laser irradiation propagate along the specimen as Lamb waves and leak to the air. The leaky waves were detected by eight 40 kHz air-coupled ultrasonic transducers located at the four corners of the specimen and the four midpoints between them, as shown in Fig. 9. In this experiment, all ultrasonic transducers were perpendicularly located 10 mm away from the specimen surface. The received signals at each ultrasonic transducer were amplified by up to 80 dB and filtered with the 40 kHz band-pass filter. Subsequently the maximum value of the gated signal between 50 μs and 200 μs was obtained by a peak hold detector. The amplitude distribution for every ultrasonic sensor was obtained from the peak hold value of each received signal stored in the computer, and those sums were taken to make amplitude distributions for the quality evaluation of fast defect imaging.

4. 3 Experimental Results

The amplitude distribution images around the zigzag notch measured using the contact method and the non-contact method with a scanning pitch of 0.2 mm and a repetition frequency of 20 Hz are shown in **Figs. 10**(a) and (b), respectively. Although both images clearly showed the zigzag shape, the image shown in Fig. 10 obtained with the non-contact method is slightly indistinct due to the decrease in the signal-to-noise ratio associated with the air-coupled ultrasonic transducers. Since it turned out that the two-dimensional defect shape can be recognized even with the non-contact method, the influence of a high-speed scan on an image was evaluated. In this case, the 25 × 95 mm^2 region in Fig. 9 was scanned and imaging was carried out at a 0.5 mm pitch. The amplitude distribution images at the time of changing the scanning rate according to the repetition frequency of the pulsed laser oscillation are shown in **Fig. 11**. Figure 11(a) is the result with the repetition frequency of 20 Hz, and took 8 minutes to obtain. If the repetition frequency was increased to 400 Hz, as shown in Fig. 11(c), a very similar image to that obtained with 20 Hz was acquired in 25 seconds, and it clearly showed the three artificial

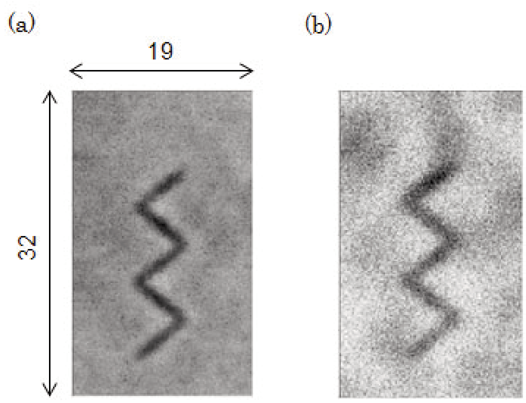

Fig. 10 Comparison of defect images by the difference in the ultrasonic receiving method (Zigzag defect images acquired with repetition frequency of 20 Hz), (a) contact method and (b) non-contact method.

notches on the back surface of the specimen. However, when the repetition frequency was increased to 1 kHz, anomalous spots appeared and recognition of the artificial notches became difficult as shown in Fig. 11(d). With a high repetition frequency, reverberations generated by the previous laser pulse are superposed on the present waveforms, and such large reverberations in a specimen cause such anomalous spots. The influence of such reverberations changes depending on the size and shape of the object and the material which it is made from. Therefore, it is necessary to optimize a signal gate which acquires amplitude and the position of the receiving sensors according to the object under inspection.

As mentioned above, although the subject of reverberations generated by the previous laser pulse was remained behind, it was shown by this research that a repetition frequency of about 400 Hz is suitable for defect imaging with a non-contact method. Moreover, the 40 kHz air-coupled ultrasonic transducer used for the experiment is far less expensive than other types of air-coupled transducers, and leads to a reduction in system cost.

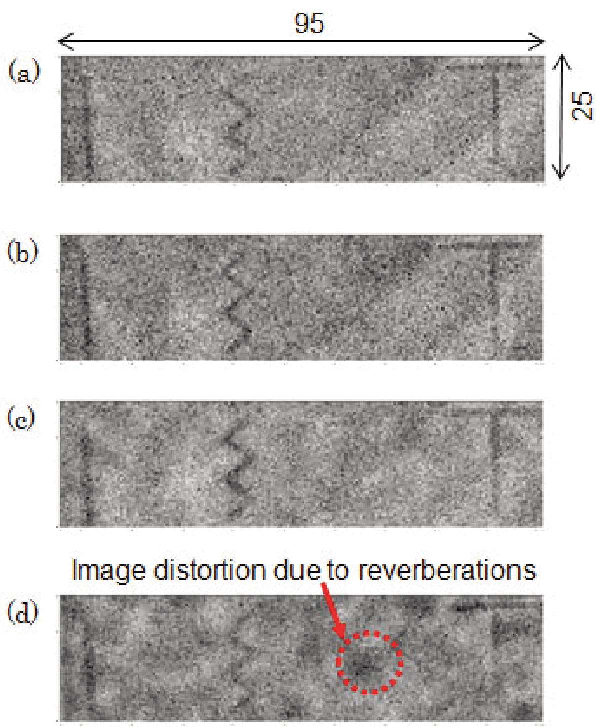

Fig. 11 Defect images for various repetition frequency of the pulsed laser irradiation, (a) 20 Hz (imaging time: 8 min), (b) 100 Hz (imaging time: 100 sec), (c) 400 Hz (imaging time: 25 sec) and (d) 1 kHz (imaging time: 10 sec).

5. Summary

This paper describes a non-immersion imaging technique using a scanning laser source for identifying notch-like defects on the back surface of a plate. Unwanted artifacts were visualized in the images obtained using a single ultrasonic transducer location due to large reflection and refraction at the notch and ultrasonic attenuation. However, an image from which the defects could clearly be identified was obtained by using multiple receiving ultrasonic transducers and synthesizing multiple images. Moreover, it was shown that non-contact defect imaging is possible by using high sensitivity air-coupled ultrasonic transducers as receiving sensors.

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