

An Examination of a Method to Reduce the Effect of Standing-Wave Heat Generation in Ultrasound-Excited Thermography Inspection [†]

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Abstract: A non-destructive inspection technique using infrared thermography and ultrasound excitation (ultrasound-excited thermography method) was focused on in this study. Although this method is effective in the detection of closed defects, the standing waves are generated in the inspection object, and this causes periodic heat distribution in the non-defective area. Such standing wave heat distribution can lead to the misdetection of defects and result in a reduction in inspection capability. In this study, in order to suppress the influence of standing wave heat distribution, we examined a method to average thermal images obtained under different ultrasonic excitation conditions. The experimental results showed that averaging the thermal images obtained when exciting ultrasound at several different points was effective in suppressing the unwanted standing wave heat distributions.

Keywords: non-destructive testing; thermography; ultrasound; crack; standing wave



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1. Introduction

Active thermography is a promising non-destructive inspection method, and pulse thermography, one of the active thermography techniques, is frequently used because of its easy and convenient features. In pulse thermography, the surface of the inspection object is instantaneously heated using flash lamps, and the surface temperature after heating is monitored using an infrared camera. However, pulse thermography is not suitable for the detection of closed defects such as cracks or kissing bonds because heat flow from the heated surface is easily transmitted through the closed defects, resulting in quite a small temperature change in the defective region.

In this study, active thermography inspection using ultrasound excitation (ultrasound-excited thermography) was focused on the detection of closed defects. In this method, ultrasound is excited in the inspection object, and the frictional heat generated in the defective region by the ultrasound vibration is detected using an infrared camera (Figure 1a). Because of this defect detection principle, this method is effective in detecting closed defects [1–3]. Figure 1b shows an example of ultrasound-excited thermography inspection of a poly (methyl methacrylate) (PMMA) specimen with a crack defect. The crack was detected as a high-temperature region. In Figure 1b, however, heat generations are observed periodically also in non-defective areas. This periodic temperature distribution should be caused by standing waves generated in the object during vibration. Such unwanted heat generations (standing-wave heat distribution) can be obstacles to defect detection. Therefore,

in order to improve the defect detection capability in ultrasound-excited thermography, a method to suppress the standing-wave heat distribution is desired. One reported method is exciting frequency-modulated ultrasounds [4,5]; this method has been reported to be effective in eliminating the heat distribution caused by standing waves. However, in the practical inspections, modulating the frequency of high-power ultrasound is not easy. Thus, in this study, we investigated easier and simpler methods to suppress the standing wave heat distribution. For this purpose, we tried a method in which multiple thermal images were obtained under different ultrasound excitation conditions, and the thermal images were averaged. Although the temperature distribution due to the standing wave heating varies depending on the excitation condition, the location of the heat caused by defects is constant; thus, averaging should be effective for suppressing the effect of standing wave heating. In the following sections, the results of the experiments examining the proposed method are presented.

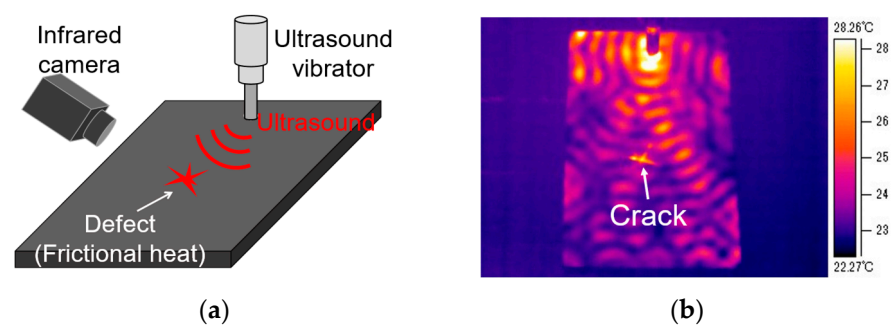


Figure 1. (a) Schematic of ultrasound-excited thermography and (b) an example of inspection result for a PMMA specimen.

2. Experimental Examination on the Effect of Averaging Multiple Thermal Images

2.1. Experimental Setup

Figure 2a shows the experiment setup. A 28-kHz ultrasonic welder (HW-D250H-28, Nippon Avionics Co., Ltd., Yokohama, Japan) was used for the excitation of ultrasound vibration. An ultrasound horn with a tip diameter of 6 mm was pressed onto a PMMA specimen at a load of 50 N. The specimen was $100 \times 150 \times 3$ mm and had an artificial crack defect introduced by an impact of a plastic ball (Figure 2b). The experiments were performed by exciting ultrasounds at three different points along the short side of the specimen. The distances to the excitation point from the left edge L were 20, 50, and 80 mm. The thermal images of the specimen surface during the ultrasound excitation were monitored using an infrared camera (A315, Teledyne FLIR LLC, Wilsonville, OR, USA) with a sampling frequency of 60 Hz. Subsequently, the thermal images obtained when exciting the three different points were averaged; defect detection capabilities in the thermal images before and after the averaging were compared.

2.2. Experimental Results

Figure 3a–c show thermal images obtained when ultrasound was excited at each point, and Figure 3d is a thermal image averaged from Figure 3a–c. In Figure 3a–c, the crack was detected as a higher temperature region. However, the temperature difference in the crack was varied depending on the excitation point; this means exciting only one point can lead to the misdetection of the defect. In addition, the periodic standing-wave heat distribution was also observed, and it also varied depending on the excitation point. Compared to Figure 3a–c, the distribution of standing wave heating was suppressed, and the crack was relatively easy to recognize in the averaged image (Figure 3d). This is due to the different patterns of the standing wave heat distributions and the effect of the averaging process.

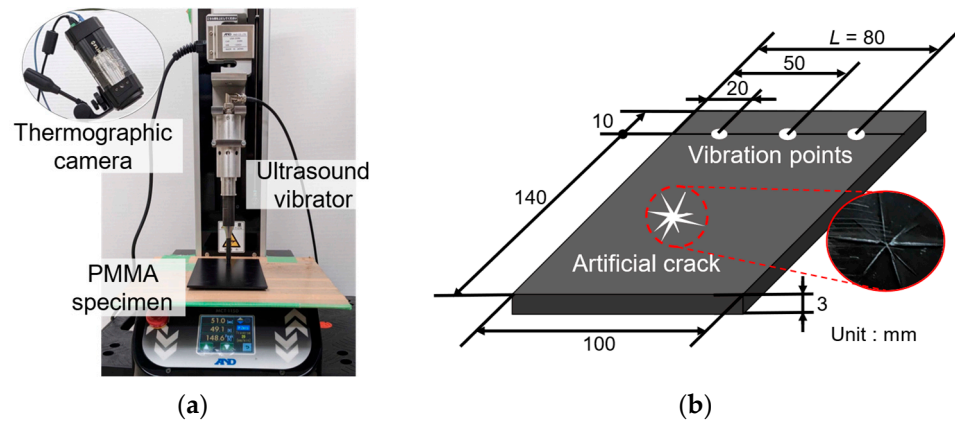


Figure 2. (a) Experiment setup and (b) schematic of PMMA specimen and three excitation points.

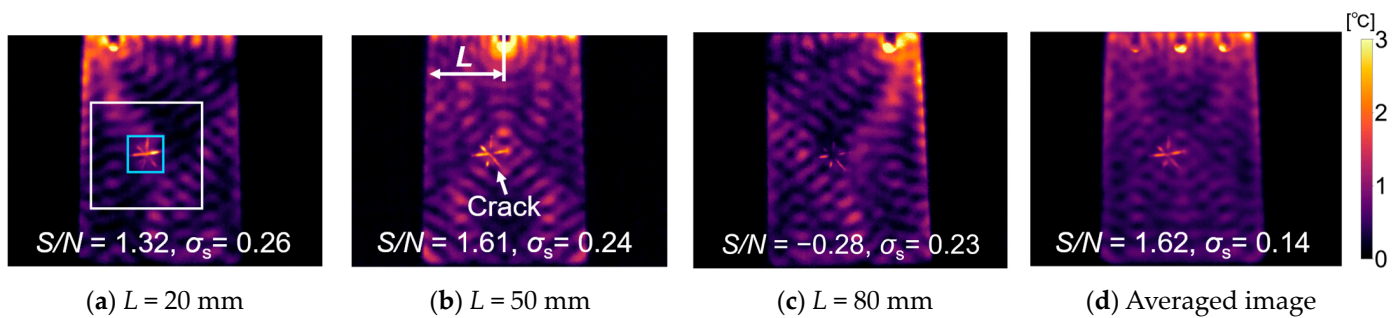


Figure 3. Thermal images obtained at 1.5 s after the start of ultrasound excitation when (a) $L = 20$ mm, (b) $L = 50$ mm, and (c) $L = 80$ mm. (d) Averaged thermal image. Areas enclosed by blue and white lines in (a) indicate defective and non-defective areas used for calculation of S/N , respectively.

In order to compare the defect detection capability of the thermal images before and after the averaging, the signal-to-noise ratio (S/N) was determined as

$$S/N = \frac{T_d - T_s}{\sigma_s} \quad (1)$$

where T_d and T_s are the average temperatures of the defective and non-defective areas, respectively (see Figure 3a), and σ_s is the standard deviation of temperatures in the non-defective area. The pixel number in the defective area was 1287, including the temperature anomaly caused by the defect, and that in the non-defective area was 14,913 surrounding the defective area. The S/N of the averaged thermal image was 1.62 and was higher than that of the other three images. This is due to the suppression of standing-wave heat distribution in non-defective areas; the mean value of σ_s in Figure 3a–c was 0.24 °C, while σ_s of the average thermal image (Figure 3d) was 0.14 °C. These results indicate that averaging thermal images obtained by varying the excitation point is effective in suppressing standing wave heat distribution and enhancing defect recognition in the images.

3. Averaging Thermal Images Obtained at Different Vibration Frequencies

The distribution of standing wave heating also depends on the frequency of ultrasound. Therefore, the effectiveness of averaging thermal images obtained with different ultrasonic frequencies was verified via experiments.

Ultrasonic welders for 20 kHz (W3040-20; Nippon Future Co., Ltd., Tokyo, Japan), 28 and 40 kHz (HW-D250H-28 and HW-D250H-40, Nippon Avionics Co., Ltd.) were used for ultrasound excitation. The excitation point was fixed at 50 mm from the left edge of the specimen (i.e., $L = 50$ mm). Other experimental setups were the same as presented in Section 2.1.

Figure 4a–c show thermal images obtained when exciting ultrasound with three different frequencies, and Figure 4d is the thermal image averaged from Figure 4a–c (since the output power of the ultrasonic welders was different depending on the frequency, the temperature values in Figure 4a–c were corrected based on the values of T_d). The S/N and σ_s of the averaged thermal image were 0.77 and 0.21, respectively; the σ_s of the averaged image was lower than that of the images before averaging. However, although suppression of the standing-wave heat distribution (i.e., reduction of σ_s) was observed, its effect was smaller than the result in the previous section. This should be because of only changing the excitation frequency without changing the excitation position; since the same point was excited, standing waves were generated in similar locations (although the interval between the generated heat spots was varied). These results indicate that only changing the ultrasonic frequency is less effective in the suppression of standing-wave heat distributions.

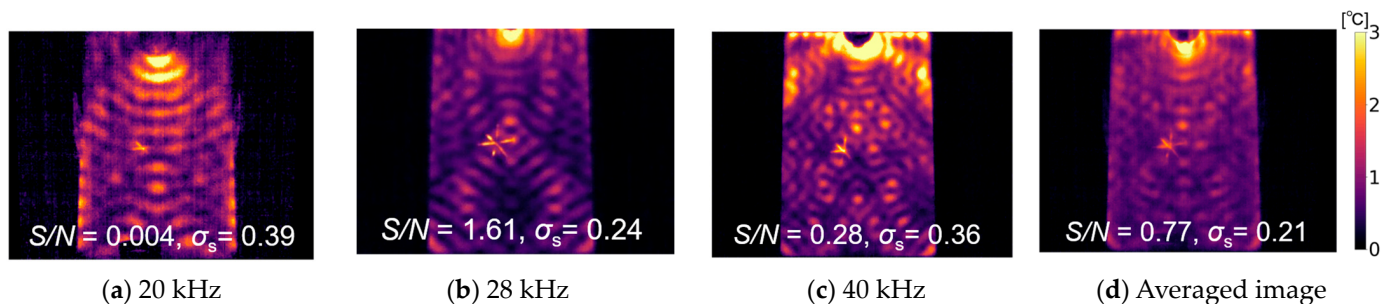


Figure 4. Thermal images obtained at 1.5 s after the start of excitation when exciting ultrasound with a frequency of (a) 20 kHz, (b) 28 kHz, and (c) 40 kHz. (d) Averaged thermal image.

4. Conclusions

This study examined the effectiveness of averaging multiple thermal images obtained under different ultrasound excitation conditions to improve the defect detection capability of ultrasound-excited thermography. The results of the experiments for a PMMA specimen with a crack defect showed that averaging thermal images obtained by varying the ultrasound excitation point was effective in suppressing the standing-wave heat distributions. Although averaging the thermal images obtained at different ultrasound frequencies was also effective in the reduction of σ_s , its effect was smaller than that obtained when the excitation point was changed.

It should be noted that the defect detection capability of the ultrasound-excited thermography method significantly depends on the excitation position; for example, although the crack was clearly detected in Figure 3b, it was difficult to recognize in Figure 3c. Therefore, designing an inspection procedure including ultrasonic excitation at several different points, not only one point, and averaging the images are important not only to suppress the standing-wave heat distribution but also to prevent the overlooking of defects.

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