Nondestructive evaluation of tilted subsurface defects by photoacoustic microscopic imaging

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Abstract. In this study, the nondestructive testing (NDT) of tilted subsurface defects with a concave cross section was performed using a photoacoustic microscope (PAM). The tilted subsurface defects were formed in a metal plane specimen by mechanical processing. The obtained signal distribution was affected by the tilt angle of the subsurface defects, and the relationship between the gradient ratio and the tilt angle value exhibited a good correlation.

1. Introduction
Thus far, various nondestructive testing (NDT) techniques [1] for detecting defects have been studied. In particular, surface defects are those that considerably affect the material strength of structural materials and electronic components, whereas internal defects are those that are immediately below the surface. The authors have shown the efficacy of photoacoustic microscopy (PAM) [2] [3] to detect surface defects based on the increase in the photoacoustic (PA) signal amplitude at surface defects as compared to that at a specimen surface without defect, and by the evaluation of the inclination angle of the surface defect by introducing the “degree of asymmetry” [4].

It is generally difficult to evaluate the complicated shape of a subsurface defect using conventional NDT techniques. In this study, we focused on evaluating the tilt angle of a complicated subsurface defect by using photoacoustic microscopy.

2. Experimental apparatus and specimen
The basic arrangement of the PAM constructed for this experiment is the same as that described in a previous publication [5]. The specimens used in the experiments were pure aluminum plates with dimensions of $40 \times 40 \times 10$ mm that were set in a PA cell. The tilted concave subsurface defect considered was a slit-type simulated defect whose length, depth, and thickness were fixed to be approximately 6.0, 0.3, and 0.5 mm, respectively, by mechanical processing (inclined end-mill cutting) from the rear surface at an angle of $90^\circ - \theta$ with respect to the surface. The tilt angles of the concave plane of the subsurface defect measured from the surface (horizontal) plane $\theta$ were set to be 60, 70, 80, and 90°. The distances from the front surface of the specimen to the two top regions of the tilted concave subsurface defect were both precisely adjusted to be 0.2 mm by measurement with a laser confocal microscope. The distances from the front surface of the specimen to the top of the middle deep region of the defect were precisely adjusted to be 0.35 mm in the same manner. The fabricated concave defect part was attached to a 9.5-mm-thick aluminum body with glue. The defect configuration is shown in Fig. 1. The dimensions shown in the figure are all nominal values.
3. Experimental results and discussions

The experiments were carried out at different modulation frequencies. The PA amplitude and phase images were obtained for the specimen with the tilted concave subsurface defect. The obtained PA signal amplitude and phase images were processed and shown using eight-grade color graphics with a resolution of 100×100 and 150×150 pixels, and the dimensions of the scanned area were 6 mm×6 mm and 3 mm×3 mm.

Fig. 2 shows the PA amplitude image obtained at a modulation frequency of 270 Hz for the specimen with a concave subsurface defect with a tilt angle of 30° (θ = 60°). Two bright areas aligned vertically at the center of the PA amplitude image were observed in Fig. 2(a); these correspond to the tilted concave subsurface defect. The distance from the specimen surface to the tilted subsurface defect is approximately 0.2 mm, whereas the thermal diffusion length at the modulation frequency of 270 Hz is approximately 314 μm. Since the thermal diffusion length is sufficiently long for the thermal wave to penetrate and reach the top of the tilted concave subsurface defect, the thermal wave generated by the laser beam at the surface propagates into the specimen and is reflected at the boundary surface between the defect and the specimen. Therefore, the tilted concave subsurface defect is clearly observed.

(a) Amplitude image  (b) Signal distribution line A-A’  (c) Signal distribution line B-B’

Figure 2. Photoacoustic amplitude image and signal distribution for a specimen with a tilting concave subsurface defect (tilt angle: θ = 60°; modulation frequency: 270 Hz).
Figs. 2(b) and 2(c) show the signal distributions along the A-A’ line and B-B’ line of the PA amplitude image shown in Fig. 2(a), respectively. In Fig. 2(b), it is found that the signal distribution is lacking in bilateral symmetry. Using Fig. 2(c), the total length of the tilted concave subsurface defect (6 mm) and its defect shape were obtained.

In addition, one of the two top regions of the tilted concave subsurface defect was scanned with a size of 3 mm × 3 mm in order to measure the inclination of the tilted concave subsurface defect with high precision. Figs. 3(a) and 3(b) show the phase image and the phase signal distribution along the A-A’ line at a modulation frequency of 54 Hz for a specimen with a concave subsurface defect for a 30° tilt angle. The phase image and phase signal distribution along the B-B’ line at a modulation frequency of 54 Hz for a surface defect for a 0° tilt angle are shown in Figs. 4(a) and 4(b), respectively.

In Fig. 3(b), it is found that the build-up of the right-hand side of the phase signal distribution is more gradual than that of the left-hand side. On the other hand, in Fig. 4(b), the phase signal distribution exhibits a symmetrical form and has a rapid build-up.

We defined the “gradient ratio” as the gradient of the PA signal peak value from its background value divided by the right-hand side distance between the signal peak and the right-hand side of the defect.
background with respect to the gradient obtained at the vertical defect. The relationship between the gradient ratio (PA signal gradient at $\theta$ divided by that at 90 degree) and tilting angle value is shown in Fig. 5. The correlation coefficient for the calibration curve shown in Fig. 5 was calculated to be approximately 0.99. The result showed that linearity exists between the gradient ratio and tilting angle value.

4. Conclusion
In this study, it was found that the tilting of a complicated subsurface defect affects the asymmetry of the obtained PA signal distribution of both the amplitude and the phase images. Therefore, it is possible to estimate the tilt angle of a subsurface defect from the asymmetry in the right- and left-hand side gradients of the obtained signal distribution. In addition, the dependence of the gradient ratio on the angle $\theta$ measured from the surface plane exhibits good correlation and linearity.

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