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Evaluation of the Thickness and Bond Quality of Three-Layered Media using Zero-Group-Velocity Lamb Waves

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Abstract. Bonding conditions such as jointing agent thickness and bond strength (quality) at the interface between two components is a critical concern in an assembled product because the jointing area is often the weakest component in products. Using a laser ultrasonic technique, zero-group-velocity (ZGV) Lamb waves were utilized to characterize the thickness of an adhesive layer for an epoxy-bonded sample and the bond quality for brazed samples. Using two modes of the ZGV Lamb waves, the thickness of the adhesive layer ranging from 0.2 to 0.8 mm can be estimated with high accuracy. In bond quality measurements, poor bond quality lowered the frequency of ZGV Lamb waves. The decrease in the frequency depended on the amount of shear stress along the interface caused by ZGV Lamb waves.

1. Introduction

There are many adhesive components in machines for connecting two different components. It is important to estimate the bonding conditions such as the thickness of the layer and bond strength (quality) for assuring the integrity of the machines. Ultrasonic inspection is a promising method for characterizing bonding conditions. Lamb waves, which propagate in a plate structure, were used for detecting defects at an interface and succeeded in detecting a relatively large defect compared to wavelength of Lamb waves [1]. Reflection waves at interfaces between an adhesive and adherents owing to acoustic impedance mismatch have also been utilized [2]. Frequency dependency of the reflection coefficient revealed the thickness and elastic properties of the adhesive layer. Recently, some researchers have reported that zero-group-velocity (ZGV) Lamb waves have the potential to characterize properties of a layered media [3-5]. ZGV Lamb waves can reveal the elastic properties of anisotropic materials and thickness of a very thin surface layer with high accuracy and high spatial resolution. In this study, ZGV Lamb waves were used to characterize the thickness of an adhesive epoxy layer sandwiched between different materials and the bond quality for brazed material using a laser ultrasonic technique.

2. Zero-group-velocity Lamb waves and experimental setup

Lamb waves are elastic waves that propagate in a plate and have two major modes, symmetric (S) and anitsymmetric (A) modes, in addition to higher modes. Those modes show characteristic dispersions. Figure 1 shows the dispersion relationship of the sample consisting of an epoxy agent (Young's modulus ***E*** = 3.88 GPa, Poisson's ratio ν = 0.38, Density ρ = 1.09 × 10^3 kg/m^3), an aluminum plate (***E*** = 69.0 GPa, ν = 0.335, ρ = 2.8 × 10^3 kg/cm^3, thickness: 3 mm) and an acrylic plate (***E*** = 2.00 GPa, ν = 0.38, ρ = 1.09 × 10^3 kg/m^3, thickness: 1 mm) calculated using Disperse software [6]. The phase velocity of each wave can be calculated by dividing the wavenumber k by the angular frequency ω, while the group velocity corresponds to the gradient of the curve indicating $dk/d\omega$. At the points indicated by the three arrows, the gradient of the curve is zero, which indicates that the group velocity is zero while the phase velocity shows a finite value. These waves are called ZGV Lamb waves. At those points, the wave remains at the area where the wave was generated and creates a resonance vibration. The resonance frequencies of ZGV Lamb waves reflect the local elastic properties, density, and thickness of each plate.

We prepared two different types of samples for estimating the thickness of the bond layer and bond quality. For estimating the thickness, a sample consisting of a 3-mm-thick aluminum alloy plate and a 1-mm-thick acrylic plate glued with an epoxy agent was assembled. The acrylic plate was used for visually checking the bonding condition. The thickness of the epoxy adhesive layer is intentionally changed to estimate the effect of the thickness on the resonance frequency of ZGV Lamb waves. The thickness of the adhesive layer was also measured by subtracting the thickness of the acrylic and aluminum plates from the thickness of the sample with a micrometer. On the other hand, for estimating the bond quality, a sample consisting of an AISI 304 stainless steel plate and a carbon steel plate brazed with Ni amorphous film was fabricated. One sample was treated at the proper brazing temperature (950 °C), and another was treated below the proper temperature (800 °C). To measure adhesive strength with tensile testing, the samples were lap-jointed and the brazed area was 400 mm^2.

Figure 2 shows the experimental setup for measuring the ZGV Lamb waves. A Q-switched pulse YAG laser with a half-duration time of 10 ns, laser spot diameter of 3 mm, and wavelength of 1064 nm was used for generating the ZGV Lamb waves. The energy of the laser pulse was controlled within the thermoelastic region for each sample. The generated ZGV Lamb waves were detected with a laser interferometer with spot size of less than 0.3 mm at the epicenter of the laser irradiation point. The signal from the interferometer was captured with an oscilloscope under 32 time averaging. The samples were set on a two-dimensional translation stage and scanned.

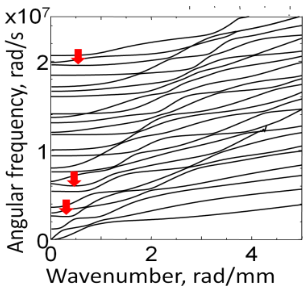

Fig. 1 Dispersion relationship of Lamb waves in three layered media (acrylic/epoxy/steel)

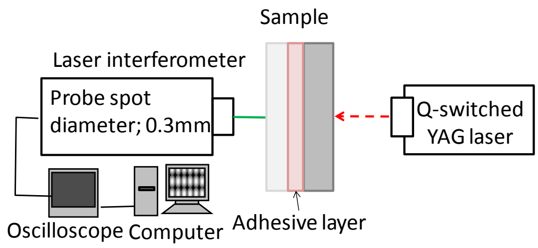

Fig. 2 Experimental setup for generating and detecting ZGV Lamb waves.

3. Results

3.1 Measurement of adhesive thickness

Figure 3 shows the detected waveform and its frequency spectrum for the three-layered sample with an adhesive thickness of 0.25 mm. A thin gold film by DC sputtering was deposited on the acrylic surface to collect a reflection probe beam at the surface. A large pulse corresponding to longitudinal and/or A mode Lamb waves appeared at 30 to 90 μs. The following small oscillating waves corresponded to ZGV Lamb waves. The spectrum shown in Fig. 3 (b) was obtained through a fast Fourier transform of Fig. 3 (a) after a zero padding process. The frequency resolution was improved to 3.84 kHz. Two distinct peaks in the spectrum were observed at approximately 1 MHz and 3.1 MHz and were almost identical to the two higher frequencies of ZGV Lamb waves shown in Fig.1. Figure 4 shows the dependence of two frequencies of measured ZGV Lamb waves on the thickness of the adhesive layer. The frequency of each mode decreased monotonically with an increase in thickness.

The frequency in the high-frequency mode showed a plateau at a thickness less than 0.18 mm and approached the frequency of the S_4 mode ZGV Lamb wave for the substrate aluminum alloy plate (3.1076 MHz). While the peak frequency of the low-frequency mode decreased linearly and at the thickness of less than 0.2 mm, it is difficult to identify the peak owing to its low amplitude. The lines shown in each graph were obtained with the least-squares approximation method. A linear function was selected for the low-frequency mode and a cubic function was selected for the high-frequency mode. The average deviations from the approximation curves were 8 kHz and 9 kHz for the low- and high-frequency modes, respectively, and the estimation errors for thickness were 12 μm and 8 μm for the low- and high-frequency modes, respectively.

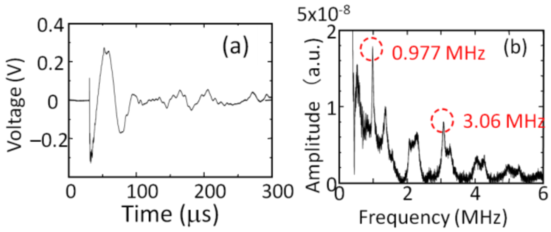

Fig. 3 Waveform (a) and its spectrum (b) for the bonded sample with an epoxy adhesive.

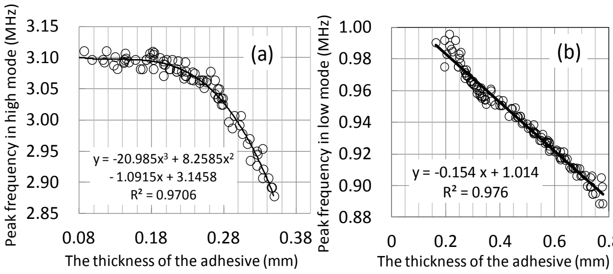

Fig. 4 Relationship between frequency of ZGV Lamb waves and thickness of epoxy adhesive layer.(a) High-frequency mode, (b) Low-frequency mode

3.2 Estimation of bond quality of brazed sample

Figure 5 shows optical microscopy images of cross sections of well- and weak-bonded samples. The thickness of the brazed layer, 80 μm, was almost the same between the well- and weak-bonded samples. In the well-bonded sample, no defect was observed at the interface with the brazed layer, while, black lines at the interface and in the layer can be found in the weak-bonded sample. Those lines correspond to small cracks and imply that the bond quality is poor.

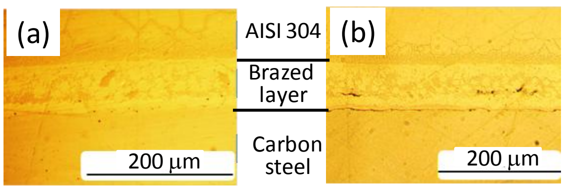

Fig. 5 Cross section of well- (a) and weak- (b) bonded samples.

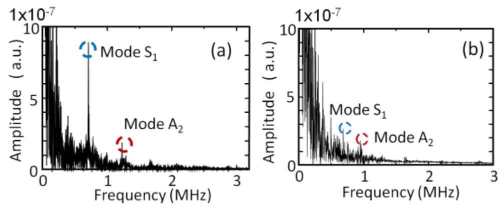

Fig. 6 Amplitude spectra for well- (a) and weak- (b) bonded samples.

Figure 6 shows the amplitude spectra of detected waves obtained with the same experimental setup shown in Fig. 3 for well- and weak-bonded samples. For the well-bonded sample, two distinct peaks at approximately 0.7 MHz and 1.25 MHz appeared. For the weak-bonded sample, two smaller peaks at the same frequency of the two peaks in the well-bonded sample can be found in Fig. 6 (b). To identify the mode for each peak, the dispersion relation for a model that has continuity in displacement and stress through interfaces in the brazed layer was calculated. For the calculation, the Young's modulus, Poisson's ratio, and density of the brazed layer were assumed to be 214 GPa, 0.336, and 5.8 $\times$ 10^3 kg/m^3, respectively [7]. The frequencies of the S_1 and A_2 mode ZGV Lamb waves were calculated as 0.708 MHz and 1.17 MHz, respectively, and were almost equal to the measured peak frequencies. Figure 7 shows the relationship between the peak frequency and amplitude of S_1 and A_2 mode ZGV Lamb waves for well- and weak-bonded samples. Open and closed symbols show the results for the well- and weak-bonded samples, respectively. Circles and squares indicate S_1 and A_2 modes, respectively. The peak frequencies for each mode decreased in the case of the weak-bonded sample, as expected. For the case where the defects are on the interface, the discontinuity in the displacement across the interface is expected, and stiffness at the interface could be reduced [8]. The decrease in the peak frequency of the ZGV Lamb waves could be caused by the reduction in the stiffness. The decrease in the frequency in the A_2 mode was larger than that in the S_1 mode. This implies that the A_2 mode is sensitive to the bond quality. Fig. 8 shows the relative shear stress profiles parallel to an interface between the brazing layer and each substrate through the thickness of the sample for the S_1 and A_2 modes. The stress was normalized with the maximum value in the A_2 mode. The A_2 mode exhibited a high shear stress than the S_1 mode; this implies that the A_2 mode is more sensitive to the bond quality than the S_1 mode in this case. On the other hand, because the peak amplitude of the ZGV Lamb waves in the A_2 mode is almost the same for the well- and weak-bonded sample, and the peak amplitude in the S_1 mode for the well-bonded sample had large dispersion owing to its surface condition, it is difficult to estimate the bond quality of the sample with the amplitude. A tensile test for shear strength for the two brazed samples was conducted using lap-jointed samples. The maximum load for the well-bonded sample (9.13 kN) was much larger than that in the weak-bonded sample (3.91 kN). This result supports the conjecture that a decrease in the peak frequency of ZGV Lamb waves indicates poor bond quality.

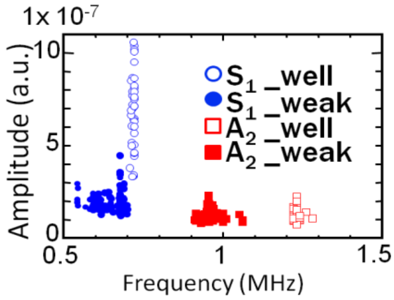

Fig. 7 Relationship between amplitude and frequency of ZGV Lamb waves for the well- and weak-bonded sample.

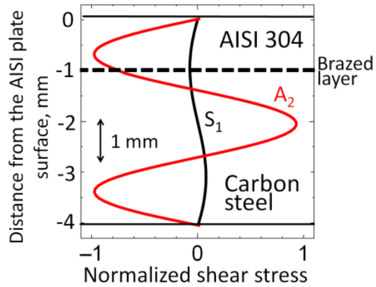

Fig. 8 Shear stress profiles through the thickness of the sample for S_1 and A_2 mode ZGV Lamb waves.

4. Conclusions

The thickness of the adhesive layer for an epoxy-bonded sample and bond quality for a brazed sample was estimated by examining the peak frequency of zero-group-velocity (ZGV) Lamb waves.

In thickness measurements of an adhesive layer in the epoxy-bonded sample, two distinct peaks at around 0.95 MHz and 3 MHz that corresponded to the ZGV Lamb waves were observed. Those peak frequencies monotonically decreased with an increase in the thickness of the adhesive. Average deviations from the approximation curves obtained from the measured peak frequencies were as low as 12 μm and 8 μm for low- and high-frequency modes, respectively.

In the estimation of bond quality in the brazed sample, two peaks appeared at 0.7 MHz and 1.25 MHz, and corresponded, respectively, to S_1 and A_2 mode ZGV Lamb waves. The peak frequencies shifted to a lower frequency for the weak-bonded sample. The decrease in peak frequency of the A_2 mode was larger than that in the S_1 mode for the weak-bonded sample. This difference in the decrease for the weak-bonded sample can be explained with shear stress at the interface on the brazed layer.

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