Vibration characteristics of the welding tip and welding sample in ultrasonic welding using planar vibration

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Abstract: Conventional ultrasonic welding uses one-dimensional linear vibration, which is performed in only one direction and yields low weld strength. A problem with this method is that it may be difficult to perform depending on the direction of installation. In previous studies, we showed that stable welding independent of installation direction can be achieved by using two-dimensional planar vibration. However, the reason for this was unknown. In addition, the vibration of the welding sample in welding using planar vibration has not been reported. In this paper, we investigated the effect of the installation direction on the vibration characteristics of the welding tip and the welding sample. We explained why welding using linear vibration depends on the installation direction of the welding sample, and why welding using planar vibration can achieve stable welding independent of the installation direction.

Keywords: Ultrasonic welding, Planar vibration, Complex vibration source, Dissimilar metals, Relative vibration

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1. INTRODUCTION

Ultrasonic welding does not use heat, so it is suitable for welding dissimilar metals with different melting points, which is difficult with ordinary melt welding, and the mechanical and electrical characteristics of the welded parts are excellent [1,2]. Therefore, ultrasonic welding is used to weld components such as battery electrodes, wire harnesses, and metal terminals [3]. In addition, ultrasonic welding causes less damage and deformation than laser welding or electron beam welding, which are other methods used for welding dissimilar metals.

In conventional ultrasonic welding, linear vibration in one direction is applied to the welding sample [4]. However, using vibrations to apply two-dimensional stress improves the effectiveness of the method [5–9]. We have proposed ultrasonic welding using a planar vibration composed of longitudinal vibration and torsional vibration to apply two-dimensional stress [10–14].

In previous studies, we focused on the weld strength and showed that welding using planar vibration was superior to conventional welding using linear vibration. Welding using planar vibration reached a high strength of about 650 N after only 0.6 s. Furthermore, the weld strength obtained with conventional linear vibration depended on the welding sample installation direction, whereas that obtained with planar vibration did not [14].

The vibration of the welding sample has been investigated by Tsujino et al., Sasaki and colleagues, and us. Tsujino et al. [15] investigated the effect of the dimensions of the upper welding sample on the vibration propagating to the upper welding sample. Welding using conventional linear vibrations was difficult when the upper welding sample had a longitudinal vibration of an odd multiple of the 1/4 wavelength. However, the vibration of the welding sample was not measured, and the vibration of the weld spot was not examined. Sasaki and colleagues [16,17] examined the relative motion of the welding tip and the welding sample, and the behavior of the welding tip and the welding sample, but their relationships to the welding were not examined in detail.

In our previous studies, we measured the vibration around the weld spot of an aluminum plate using longitudinal and torsional linear vibrations when the welding sample was placed so that the longitudinal direction of the welding sample was perpendicular to the longitudinal direction of the ultrasonic vibration source horn. The vibrations of the welding tip and the area around
the weld spot of a vibrated aluminum plate were nearly the same. However, it was difficult to analogize the vibration of the weld spot because measurement was performed only at one place near the weld spot [18].

All these studies used conventional linear vibration, and there are no studies of the vibration of the welding sample using planar vibration. For conventional linear vibration, the success of the welding depends on the direction in which the welding sample is installed, whereas for planar vibration, stable welding can be performed regardless of the sample direction, although the reason for this difference remains unknown.

In this paper, to investigate this difference, we performed ultrasonic welding of an aluminum plate and a copper plate with planar vibration, and we investigated the vibration characteristics of the welding tip and the welding sample for different welding sample installation directions.

To determine the vibration of the weld spot of the aluminum plate for different welding sample installation directions, we measured the vibration at the position of the three vertices of an equilateral triangle with the weld spot of the aluminum plate as the center of gravity. The relative vibration displacement amplitudes between the welding tip and the aluminum plate and between the aluminum plate and the copper plate were obtained from the welding tip vibration and the weld spot vibration on the aluminum plate. Based on these results, we determined the vibration characteristics of the welding tip and the welding sample using planar vibration for different welding sample installation directions. We revealed why welding is difficult in some welding sample installation directions with linear vibration and why stable welding can be performed independent of the welding sample installation direction with planar vibration.

2. ULTRASONIC COMPLEX VIBRATION SOURCE AND VIBRATION LOCI AT THE WELDING TIP

Figure 1 shows a schematic of the ultrasonic complex vibration source used in this work, which we developed previously [13]. The ultrasonic complex vibration source consists of a columnar dumbbell-shaped stepped horn fabricated from A2017 alloy (diameter ratio of 1.5 between the thick-end face and the narrow-end face) connected at one end to a bolt-clamped 27 kHz Langevin longitudinal vibration transducer (D4427PC, NGK Spark Plug Co.) and at the other end to a bolt-clamped 19 kHz Langevin torsional vibration transducer (DAN4419, NGK Spark Plug Co.). The coordinate system is rectangular. The columnar dumbbell-shaped stepped horn has a welding tip made of SUS303 at the center position fixed with M4 screws. Figure 2 shows (a) the external appearance of the welding tip, (b) the bottom view of the welding tip end, and (c) a cross-sectional view of the welding tip end. The welding tip end is circular with a diameter of 4.2 mm, and to facilitate the transmission of vibrations to the welding sample, the distal end portion is knurled to create the pattern shown in Fig. 2(c) [14].

By using longitudinal and torsional vibration transducers with different resonance frequencies, the wavelengths of the two vibrations are matched. Therefore, this vibration source can add the displacement amplitudes at the maximum positions of the longitudinal and torsional vibration and apply them to the welding sample. Furthermore, because the node positions of both vibrations match, the device can be fixed firmly with two flanges. The stepped horn of the vibration source is 328 mm long, which is the length of two wavelengths of the longitudinal and torsional vibrations. In addition, the drive resonance frequencies of the vibration source with a load (static pressure 500 N) are 29.3 kHz for the longitudinal transducer and 19.1 kHz for the torsional transducer. The longitudinal vibration direction is defined as the \( x \) direction, and the torsional vibration direction is defined as the \( y \) direction.

Figure 3 shows the vibration loci at the tip of the welding tip for a constant static pressure of 500 N and vibration displacement amplitude for each vibration of 10 \( \mu \)m. The vibration at the tip of the welding tip was
measured using two laser Doppler vibrometers (LDVs). The longitudinal vibration displacement amplitude \( \langle x \rangle \) direction) is shown on the horizontal axis and the torsional vibration displacement amplitude \( \langle y \rangle \) direction) is shown on the vertical axis. When either the longitudinal vibration transducer or the torsional vibration transducer was used alone, straight linear vibration loci were produced. The torsional vibration is composed of vibration components in the \( \langle y \rangle \) direction and the \( \langle z \rangle \) direction. However, in the present vibration source, the vibration component in the \( \langle z \rangle \) direction was only 0.1% that of the vibration component in the \( \langle y \rangle \) direction. Thus, the vibration component in the \( \langle z \rangle \) direction had a negligible effect on the welding. The torsional vibration was a linear vibration locus when it consisted of only the vibration component in the \( \langle y \rangle \) direction. In contrast, when both of the vibration transducers were used in combination, an almost square planar vibration locus was obtained from the combination of the linear loci. The vibration with the linear locus in the longitudinal vibration direction (i.e., when only the longitudinal vibration transducer is driven) is referred to as longitudinal vibration. The vibration with the linear locus in the torsional vibration direction (i.e., when only the torsional vibration transducer is driven) is referred to as torsional vibration. The vibration with the almost square locus (i.e., when both vibration transducers are driven) is referred to as planar vibration.

3. EFFECT OF WELDING SAMPLE INSTALLATION DIRECTION ON WELDING CHARACTERISTICS

As in our previous study, we investigated ultrasonic welding of an aluminum plate (A1050, length 40 mm, width 20 mm, thickness 0.5 mm) and a copper plate (C1100, length 40 mm, width 20 mm, thickness 2.0 mm), and we placed the welding sample in different installation directions [14]. Figure 4 shows a photograph of the welding equipment. The ultrasonic complex vibration source was secured by holding two flanges with flange fixing tools to a base plate. The welding method was as follows [14]. Two sides of the copper plate were fixed in the precision vise, the aluminum plate was placed on top of it, and the precision vise was raised to press the welding sample against the welding tip of the vibration source from the bottom. The sinusoidal signal was applied to the vibration source, causing vibration of the welding tip and initiating the welding process. Springs were used as shown in Fig. 4 to suppress pressure fluctuations during welding. The vibration of the copper plate during welding was about 0.3% of the vibration of the welding tip, and thus was considered to have a negligible effect on the welding. Figure 5 shows the positional relationship between the horn of the ultrasonic complex vibration source and the welding sample. A welding sample installed in the length directions of the vibration source horn and the welding sample perpendicular was the reference installation direction of 0°. The sample was then rotated clockwise by 30°, 60°, and 90°. The welding conditions were set such that in all 10 welding operations an installation direction of 0° was achieved and the welded strength was substantially improved compared with our previous study [14]. Weld conditions were a constant static pressure of 500 N,
constant vibration displacement amplitude of 10 μm, and a constant weld time of 0.6 s for longitudinal or complex vibration and 2.0 s for torsional vibration. The driving resonance frequency of the torsional vibration was 19.1 kHz, the torsional vibration speed was slower than the longitudinal vibration speed. Therefore, the time required for welding by torsional vibration is longer than that for longitudinal vibration and planar vibration. The welding was repeated 10 times for each set of conditions. Figure 6 shows the relationship between the welding sample installation direction and the number of welded samples for each type of vibration. The horizontal axis shows the welding sample installation direction and the vertical axis shows the number of welded samples in the 10 experiments. After welding, three welding states were observed. In the first, the aluminum plate and the welding tip separated when the welding was finished, and the aluminum plate and the copper plate were welded. In the second, the aluminum plate and the copper plate were separated after welding. In the third, the aluminum plate and the welding tip were firmly adhered to each other after welding, and the aluminum plate and the copper plate separated when the aluminum plate and the welding tip were separated.

The number of welded samples obtained depended on the welding sample installation direction for the longitudinal linear vibrations (Fig. 6). For welding using the longitudinal vibration, the effect of the welding sample installation direction was strong, and no welding occurred at a welding sample installation direction of 90°. On the other hand, for welding using the planar or torsional vibrations, 10 welded samples were obtained regardless of the installation direction.

For longitudinal vibration, even when the weld time and the vibration displacement amplitude were increased, the welding tip and the aluminum plate adhered more strongly, and it was impossible to weld the aluminum plate and the copper plate.

Figure 7 shows the average weld strengths for the cases shown in Fig. 6 in which welding was successful. Weld strength was determined by tensile shear tests. Tensile shear tests were performed using a tensile/compression tester (SDT-503NB, Imada Seisakusho) in accordance with JIS Z 3136, and the tensile speed was 1 mm/min. Spacers were used to make the thickness of the welded sample uniform. The weld strength is usually determined by the weld strength per weld area [Pa]. However, the weld area may be difficult to determine because it is difficult to distinguish the welded portion and the non-welded portion depending on the weld strength. Therefore, in this paper, a simple weld strength [N], which does not require the identification of an ambiguous welded area, was used as the weld strength. The tensile strength of the aluminum plate alone was also measured in this test as about 1,200 N. In Fig. 7, the horizontal axis shows the welding sample installation direction and the vertical axis shows the weld strength. The error bars indicate the deviation (±1σ), which was calculated using only the successfully welded samples for each point. The weld strength was highest for planar vibration, regardless of the installation direction, compared with longitudinal or torsional vibration alone. Although successful welding was not achieved using...
longitudinal vibration with an installation direction of 90°, the combination of longitudinal vibration with torsional vibration to produce planar vibration led to a high weld strength and allowed stable welding to be performed.

4. VIBRATION CHARACTERISTICS OF THE WELDING TIP AND WELDING SAMPLE

The vibration characteristics of the welding tip and the welding sample were investigated to clarify why welding using longitudinal vibration is difficult in certain installation directions and why welding using torsional and planar vibration is independent of the installation direction. The vibration of the aluminum plate near the weld spot was measured at three points using an LDV, and the average value was used as the vibration. The relative vibration displacement amplitudes between the welding tip and the aluminum plate and between the aluminum plate and the copper plate were obtained.

4.1. Vibration Waveform of the Aluminum Plate Weld Spot

Figure 8 is a schematic of the aluminum plate showing the measurement points. To determine the state of vibration of the aluminum plate weld spot, the vibration waveforms for a, b, and c (a: 30° from the angle reference line, 7 mm from the weld spot center; b: 150° from the angle reference line, 7 mm from the weld spot center; c: 270° from the angle reference line, 7 mm from the weld spot center) at three equilateral triangles vertices on the aluminum plate centering on the weld spot were measured. The length of one side of the triangle formed by the measurement points was about 12 mm, which was equal to or less than 1/10 of the wavelength of the longitudinal wave propagating through the aluminum plate. Thus, the effect of the size of the triangle on the measurement of the longitudinal wave propagating through the aluminum plate was negligible. To measure the vibration waveform at each position of the aluminum plate, a mirror 2 mm long, 2 mm wide, and 1 mm high for laser reflection was attached to the measurement position on the aluminum plate. By setting the weld spot of the aluminum plate as the center of gravity of an equilateral triangle, the state of vibration of the weld spot was obtained from the average value of the vibration waveform at the three apexes. The mirror was attached to one position at a time, and three measurements were performed for each position. Figure 9 shows the aluminum plate with a mirror attached for measuring the vibration at position a in Fig. 8 for a welding sample installation direction of 0°, and the arrangement of LDVs for measuring the x direction of the mirror. The mirror was only installed in one of the positions for each set of measurements. Three LDVs were used to measure the vibration waveforms of the welding tip and the aluminum plate during welding. The vibration waveforms were measured under a static pressure of 500 N and vibration displacement amplitude of 10 μm p-p. For welding sample installation directions of 30°, 60°, and 90°, the mirror was rotated so that the laser was perpendicularly incident on the mirror surface, and the mirror was placed at each position on the aluminum plate. In addition, to reduce noise during measurements, only signals of 19 and 29 kHz, which were the driving frequencies of the vibration source, were acquired using a bandpass filter. The vibration waveform of the welding tip and the aluminum plate reached a steady state 0.3 s after welding began. Therefore, the vibration waveform was measured for 200 μs from 0.3 s after welding began. Measurements at positions b and c were performed in the same way. The vibration of each position after 0.3 s became constant and vibrated until the application of vibration of the welding tip was stopped. Figure 10 shows an example of a sample after welding. The knurling marks remain on the weld spot of the aluminum plate.
Figures 11(a)–11(c) show the vibration waveforms of the welding tip and the aluminum plate at positions a–c, respectively, on the aluminum plate for a welding sample installation direction of $0^\circ$ using longitudinal vibration. The elapsed time (time elapsed after 0.3 s) is shown on the horizontal axis and the vibration displacement amplitude is shown on the vertical axis. The black line shows the vibration waveform of the welding tip at 29 kHz in the $x$ direction ($T_x$), the orange line shows the vibration waveform of the aluminum plate at 29 kHz in the $x$ direction ($A_x$), and the purple line shows the vibration waveform of the aluminum plate at 29 kHz in the $y$ direction ($A_y$).

To determine the vibration waveform of the weld spot of the aluminum plate, the average waveform of the three vibration waveforms at positions a–c at each elapsed time was obtained. Figure 12 shows the vibration waveform of the weld spot of the aluminum plate with the same notation as in Fig. 11. The welding tip and the aluminum plate vibrated sinusoidally at 29 kHz, which is the driving resonance frequency on the longitudinal vibration transducer side. The vibration waveforms of the weld spots of the aluminum plates for the different installation directions and vibration methods were obtained in the same manner.

### 4.2. Relative Vibration Displacement Amplitudes between the Welding Tip and Aluminum Plate and between the Aluminum Plate and Copper Plate

Figure 13 shows a schematic of the relative vibrations between the welding tip and the aluminum plate and between the aluminum plate and the copper plate. To describe each vibration and each relative vibration, the welding tip and aluminum plate, which are inherently in contact with each other, and the aluminum plate and the copper plate are shown separated from each other. The vibration displacement amplitude in the $x$ direction of the welding tip is $T_x$, that in the $y$ direction of the welding tip is $T_y$, that in the $x$ direction of the aluminum plate is $A_x$ (that for 29 kHz is $A_{x1}$ and that for 19 kHz is $A_{x2}$), and that in the $y$ direction of the aluminum is $A_y$ (that for 29 kHz is $A_{y1}$ and that for 19 kHz is $A_{y2}$). In addition, the copper plate was fixed with a vice and did not vibrate.
Assuming that the relative vibration displacement amplitude between the welding tip and the aluminum plate is $\xi_a$, its x direction is $\xi_{ax}$, and its y direction is $\xi_{ay}$. $\xi_{ax}$ and $\xi_{ay}$ are obtained by Eqs. (1) and (2).

\[
\begin{align*}
\xi_{ax} &= A_{x1} + A_{x2} - T_x \\
\xi_{ay} &= A_{y1} + A_{y2} - T_y
\end{align*}
\]

Assuming that the relative vibration displacement amplitude between the aluminum plate and the copper plate is $\xi_b$, its x direction is $\xi_{bx}$ and its y direction is $\xi_{by}$. $\xi_{bx}$ and $\xi_{by}$ are obtained by Eqs. (3) and (4).

\[
\begin{align*}
\xi_{bx} &= A_{x1} + A_{x2} \\
\xi_{by} &= A_{y1} + A_{y2}
\end{align*}
\]

We used welding sample installation directions of 0°, 30°, 60°, and 90°, and longitudinal, torsional, and planar vibration. The relative vibration displacement amplitude was obtained and is shown in the Lissajous figure.

Figure 14 shows the results for the longitudinal vibration. The horizontal axis shows the relative vibration displacement amplitude in the x direction, $\xi_{ax}$, and $\xi_{bx}$, and the vertical axis shows the relative vibration displacement amplitude in the y direction, $\xi_{ay}$ and $\xi_{by}$. The results for the welding sample installation directions of 0°, 30°, 60°, and 90° are shown from left to right. The upper part of the figure shows the relative vibration displacement amplitude, $\xi_a$, between the welding tip and the aluminum plate, and the lower part shows the relative vibration displacement amplitude, $\xi_b$, between the aluminum plate and the copper plate.

For the longitudinal vibration, $\xi_a$ was the main locus in the x direction as the welding sample installation direction approached 90°. In contrast, $\xi_b$ was the main locus in the x direction in all installation directions, and the amplitudes in the x direction were 10 to 15 $\mu$m. Thus, for welding using longitudinal vibration, the relative vibration of the aluminum plate and the copper plate occurred mainly in the longitudinal vibration direction. As the welding sample sample installation direction approached 90°, the change in the size of $\xi_b$ was small. However, the size of $\xi_a$ gradually increased as the installation direction approached 90°. The size of $\xi_a$ was 4 $\mu$m in the x direction for an installation direction of 0°, whereas the size of $\xi_a$ was 22 $\mu$m in the x direction for an installation direction of 90°. $\xi_b$ was larger than $\xi_a$ for a welding sample installation direction of 90°. The resonance of the aluminum plate affected this result. The propagating velocity of the longitudinal wave through the aluminum plate was approximately 5,400 m/s. When a 29 kHz longitudinal vibration was applied to an aluminum plate, the wavelength of the longitudinal wave was approximately 184 mm. Thus, the 1/4 wavelength was 46 mm. The aluminum plate was 40 mm in the longitudinal direction and 20 mm wide. When the sample installation direction was 90° in the longitudinal vibration, the longitudinal vibration was applied to the longitudinal direction of the aluminum plate. Therefore, the vibration state of the aluminum plate was close to the 1/4 wavelength resonance state of the longitudinal wave. To confirm this, we measured the vibration of an aluminum plate at a distance of approximately 25 mm from the welding tip in the longitudinal direction using a mirror and an LDV for a longitudinal vibration with an installation direction of 90°. Consequently, the vibration of the remote aluminum plate was 30–40 $\mu$m, which was 3–4 times the vibration of the welding tip. We assumed that the welding tip of the aluminum plate appeared as a node of the longitudinal wave, whereas the far part of the plate appeared as a loop. In other words, the vibration state of the aluminum plate was close to the 1/4 wavelength resonance state of the longitudinal wave. This resonance may have caused a phase difference in vibration between the welding tip and the aluminum plate, resulting in relative vibration between the welding tip and the aluminum plate. As the welding sample installation direction approached 90°, the vibration state of the aluminum plate approached the 1/4 wavelength resonance state of the longitudinal wave. Because of the 1/4 wavelength resonance state of the longitudinal wave for the longitudinal vibration, $\xi_a$ gradually increased as the...
welding sample installation direction approached 90°, and the welding tip and the aluminum plate adhered more strongly. Consequently, it was more difficult to separate the welding tip from the aluminum plate, and for longitudinal vibration, it became difficult to weld as the welding sample installation direction approached 90° (Fig. 6). Tsujino et al. showed that when the vibration state of the upper sample resonated at an odd multiple of the 1/4 wavelength of the longitudinal wave, a weld between the upper sample and the lower sample could not be achieved [15]. These results are consistent with the present results. In addition, if the copper plate is placed on the welding tip side and the relative vibration occurring at each part is the same as this study, the copper plate and the welding tip may weld.

Figure 15 shows the results for torsional vibration and the notation is the same as in Fig. 14. For torsional vibration, $\xi_a$ was a locus of 2 to 4 $\mu m_{pp}$ in both the x and y directions and all installation directions. $\xi_p$ was the main trajectory in the y direction in all installation directions, and the size in the y direction was 8 to 11 $\mu m_{pp}$. Thus, for torsional vibration, the relative vibration between the aluminum plate and the copper plate occurred mainly in the torsional vibration direction. There was almost no change in the magnitude of $\xi_a$ and $\xi_p$ in any installation direction, and $\xi_p$ was larger than $\xi_a$ in all cases. When a torsional vibration was applied, the wavelength of the longitudinal wave propagating through the aluminum plate was about 283 mm. At the 1/4 wavelength, it was approximately 71 mm. In other words, for welding using torsional vibration, the vibration state of the aluminum plate did not produce the 1/4 wavelength resonance state of the longitudinal wave in the present sample size. Consequently, there was almost no relative vibration between the aluminum plate and the welding tip, whereas there was relative vibration between the aluminum plate and the copper plate, and stable welding was achieved.

Figure 16 shows the results for planar vibration and the notation is the same as in Fig. 14. For planar vibration, both $\xi_a$ and $\xi_p$ were planar loci. As the welding sample installation direction approached 90°, $\xi_a$ was generated by the resonance of the longitudinal wave of the aluminum plate, as in the case of using the longitudinal vibration. The relative vibration of the aluminum plate and the copper plate occurred in various directions using the planar vibration. The magnitude of $\xi_p$ was 12 to 16 $\mu m_{pp}$ in both the x and y directions, and $\xi_p$ was larger for the planar vibration than for the longitudinal and torsional linear vibrations in all installation directions. For a welding sample installation direction of 90°, for which welding was not achieved with the longitudinal vibration, combining the longitudinal and torsional vibrations to produce the planar vibration increased $\xi_p$ by about 10 $\mu m_{pp}$ compared with the longitudinal vibration alone. Thus, when the planar vibration was used, $\xi_p$ was larger than $\xi_a$ in all welding sample installation directions. This large $\xi_p$ contributed to the cleaning and adhesion of the welding sample surface. Therefore, when the vibration displacement of the same maximum value was used, $\xi_p$ of the planar vibration became larger than the linear vibration, so the planar vibration allows stable welding (Figs. 6 and 7) with high welding strength. This result suggests that welding with the planar vibration was not affected by the resonance state of the upper welding sample. The planar vibration uses two frequencies. When the upper welding sample resonates at one frequency, a large relative vibration between the upper and bottom samples occurs at the other frequency of vibration, and welding can be achieved, as shown in this study. That is, welding occurs for the planar vibration without the vibration being affected by the resonance state of the upper sample, except where the vibrations of the two frequencies become resonant.

5. CONCLUSIONS

We focused on the state of vibration of the welding sample to explain the superiority of planar vibration for ultrasonic welding. We examined the vibration character-
istics of the welding tip and the welding sample for linear vibrations and planar vibrations. Our results can be summarized as follows.

1. For the longitudinal vibration (driving frequency 29.3 kHz), the magnitude of $\xi_\alpha$ depended on the installation direction of the welding sample. As the welding sample installation direction approached 90°, $\xi_\alpha$ became large. This was because of the effect of the 1/4 wavelength resonance of the longitudinal wave propagated to the aluminum plate by the longitudinal vibration of the welding tip. Consequently, the welding tip and the aluminum plate adhered firmly, making it difficult to weld the copper and aluminum plates.

2. For the torsional vibration (driving frequency 19.1 kHz), $\xi_\alpha$ and $\xi_\beta$ hardly changed, and $\xi_\beta$ was larger than $\xi_\alpha$, even when the welding sample installation direction was changed. Furthermore, $\xi_\alpha$ was much smaller than $\xi_\beta$, and the welding tip and the aluminum plate vibrated substantially in synchronization. Therefore, the aluminum plate did not become resonant, and stable welding could be performed.

3. For the planar vibration, both $\xi_\alpha$ and $\xi_\beta$ were planar loci and $\xi_\beta$ was larger than those for both types of linear vibration in all welding sample installation directions. $\xi_\alpha$ had a planar locus because the longitudinal wave of the aluminum plate resonated at the 1/4 wavelength due to a longitudinal vibration of 29.3 kHz. However, even where the aluminum plate resonated, when the welding tip had a planar vibration, $\xi_\beta$ became larger than $\xi_\alpha$.

These results indicated that the relationship between the magnitudes of $\xi_\alpha$ and $\xi_\beta$ depended on the driving frequency and the welding sample installation direction when linear vibration was used. We speculate that the success of the welding is affected by the relationship between the magnitudes of $\xi_\alpha$ and $\xi_\beta$. Because $\xi_\beta$ is larger for the planar vibration than for the linear vibration in all installation directions, welding using the planar vibration is stable and independent of the installation direction.

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