

PAPER

Tensile shear strength and cross tensile strength in welding using an ultrasonic complex vibration source

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Abstract: The authors have proposed a method of ultrasonic welding using planar vibration composed of longitudinal and torsional vibrations, and obtained higher tensile shear strength in a shorter time than by ultrasonic welding using conventional linear vibration. However, the cross tensile strength was not examined. And, the comparison of tensile shear strength and cross tensile strength in which the size, etc. of the weld samples was unified, and the tensile shear strength in changing the tensile direction and cross tensile strength in changing the peel direction for the vibration direction of the welding tip which applies ultrasonic vibration to weld samples have not been clarified. We performed ultrasonic welding using planar and linear vibrations with a change in weld time when the vibration direction of the tip of the welding tip applied to weld samples was changed. As a result, high tensile shear strength and cross tensile strength were obtained in a short time by ultrasonic welding using planar vibration. It was also clarified that there was almost no effect of the vibration direction of the welding tip on the tensile and peel directions.

Keywords: Ultrasonic welding, Planar vibration, Complex vibration source, Dissimilar metals, Tensile shear strength, Cross tensile strength

1. INTRODUCTION

Recently, the demand for electric automobiles and fuel cell automobiles has been growing as the automobile industry has been working on becoming more environmentally friendly [1,2]. Large-capacity lithium-ion batteries are indispensable for improving the cruising ranges of such automobiles [3]. Since lithium-ion batteries employ different metals for their electrodes, such as aluminum for the positive electrode and copper for the negative electrode, a technology for welding different metals is required [4]. Outside of the batteries, advances are also being made in composite materials used in automobiles, which further increases the demand for welding technologies for different metals [5].

Since ultrasonic welding does not employ heat, the welding of different metals with different melting points, which is difficult by regular fusion welding, can be easily accomplished [6,7]. Therefore, there are many cases of studying and using the electrode jointing of lithium-ion batteries by ultrasonic welding [8,9].

Ultrasonic welding prevents a decrease in weld strength that would be due to the melting and ambient heat effects arising in other methods of welding dissimilar metals such as laser welding and electron beam welding. In conventional general ultrasonic welding, the vibrations applied to the parts to be welded are linear vibrations in only one direction. However, it has been shown that ultrasonic welding can be applied using vibrations that apply two-dimensional stress [7–14].

The authors have proposed an ultrasonic welding technique of using planar vibration composed of longitudinal and torsional vibrations to apply two-dimensional stress [15]. The authors focused on the tensile shear strength, which indicates the breaking strength when a shear load is applied parallel to the weld in a welded material, using an aluminum plate for the upper weld part and a copper plate for the lower weld part, and demonstrated that welding using planar vibration results in higher strength in a shorter time than welding using conventional linear vibration [16]. However, the load that occurs in many industrial products is not only shear load but also peel load that is applied in a direction perpendicular to the weld surface. Therefore, it is important to examine not only tensile shear strength but also cross tensile strength corresponding to peel load in order to raise the industrial

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value of welds made using planar vibration. However, there have been no studies of cross tensile strength, which indicates the fracture strength of the weld material when a peel load is applied perpendicularly to the weld.

Although Watanabe *et al.* previously conducted a study on cross tensile strength, welding using linear vibration was examined, but not welding using planar vibration [17]. Furthermore, in previous studies, weld samples with differing characteristics such as the type of material, dimensions, installation position, and welding position were examined, but there have been no studies on examining tensile shear strength and cross tensile strength under uniform welding conditions [18–20].

Since the vibration applied to the weld zone in welding using linear vibration is only in a single direction, the welding characteristic may vary depending on the vibration direction and the direction of the load applied to the weld zone, even for square or circular weld samples [21–25]. However, the tensile shear strength and cross tensile strength have not been clarified as the tensile and peel directions are changed with respect to the vibration direction of the welding tip that applies ultrasonic vibration during welding.

In this study, we examine the tensile shear strength and cross tensile strength of welding with planar vibration and welding with linear vibration for comparison, using copper and aluminum plates, which are the electrode materials for lithium-ion batteries. The weld time and vibration direction of the welding tip are varied as parameters.

2. ULTRASONIC COMPLEX VIBRATION SOURCE

Figure 1 shows a schematic diagram of the ultrasonic complex vibration source that the authors previously examined, and which was used in this study. The vibration source has a structure in which bolted Langevin-type longitudinal vibrators producing 27 kHz (D 4427 PC, manufactured by NGK Spark Plug Co., Ltd.) and bolted Langevin-type torsional vibrators producing 19 kHz (DAN

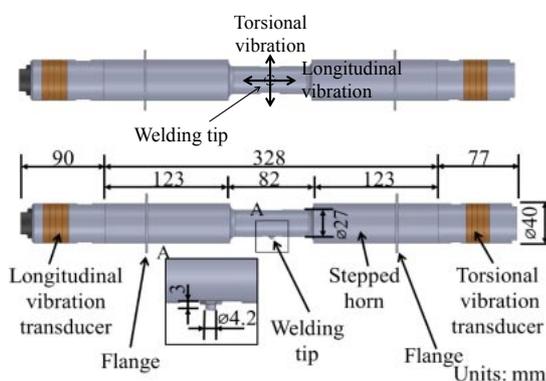


Fig. 1 Ultrasonic complex vibration source.

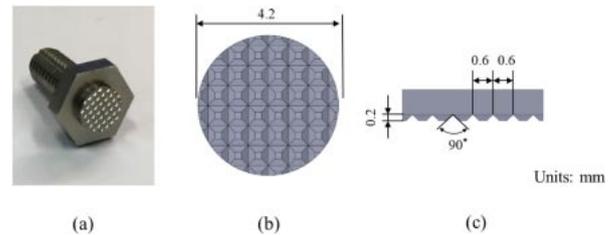


Fig. 2 Welding tip.

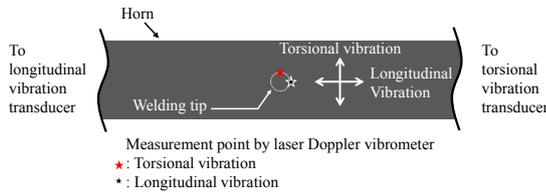
4419, manufactured by NGK Spark Plug Co., Ltd.) are connected to the ends of a cylindrical dumbbell-type step horn made of duralumin. The directions of longitudinal and torsional vibrations are as shown in Fig. 1.

Figure 2 shows (a) the welding tip used to apply vibrations to the weld sample, (b) the bottom view of the welding tip, and (c) a sectional view of the tip. The welding tip is circular and has a diameter of 4.2 mm, and the commonly used knurling process, as shown in the figure, is applied to the tip to facilitate the transmission of vibrations to the weld sample.

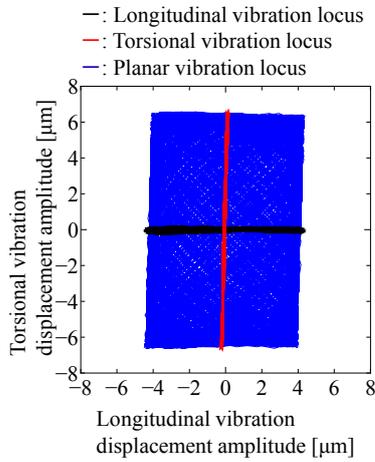
The vibration locus was measured to determine the aspect of the vibration in the welding tip. The vibration displacement amplitudes in the longitudinal and torsional vibration directions of the welding tip were measured using two laser Doppler vibrometers without static pressure. The driving frequency was determined to be 29.3 kHz for the longitudinal vibrator and 18.3 kHz for the torsional vibrator, and the maximum vibration speed of the welding tip in both vibrations was fixed at about 0.8 m/s.

Figure 3 shows (a) the measurement point of longitudinal and torsional vibrations determined using laser Doppler vibrometers, and (b) the vibration locus measured for 10 ms. As shown in Fig. 3(a), the vibration was measured at a position parallel to each vibration direction of the welding tip. In Fig. 3(b), the horizontal axis is the vibration displacement amplitude in the longitudinal vibration direction and the vertical axis is the vibration displacement amplitude in the torsional vibration direction. The figure shows that the vibration loci when only the longitudinal and the torsional vibrators are driven are linear loci. However, when both vibrators are simultaneously driven, the vibration locus becomes a nearly rectangular planar locus that is a combination of individually driven linear loci. The torsional vibration also has a component in the direction perpendicular to the weld samples. However, the component in the direction perpendicular is about 0.1% of torsional vibration in this vibration source. Because of this, the component in the direction perpendicular has almost no effect on welding.

In this paper, the vibration of the linear locus in the longitudinal vibration direction is called longitudinal vibration, the vibration of the linear locus in the torsional



(a) Measurement point of each vibration.



(b) Measurement result for 10 ms.

Fig. 3 Vibration loci. (a) Measurement point of each vibration. (b) Measurement result for 10 ms.

vibration direction is called torsional vibration, and the vibration with an almost rectangular locus is called planar vibration.

3. TENSILE SHEAR STRENGTH AND CROSS TENSILE STRENGTH OBTAINED WHEN USING PLANAR VIBRATION

The vibration direction of the welding tip applied to the weld sample and the weld time were varied for welding performed using planar and linear vibrations for comparison.

3.1. Welding Method and Strength Evaluation of Weld Zone

The weld samples were an aluminum plate (A1050, 27 mm square side, 0.5 mm thickness) and a copper plate (C1100, 40 mm length, 15 mm width, 2 mm thickness). The square aluminum plate was used so that the vibration characteristics of the aluminum plate do not change even if the vibration direction is changed when vibration is applied to the center of the plate.

Figure 4 shows a photograph of the welding device. In the welding method, the copper plate was affixed to a vice, the aluminum plate was placed on top, the vice was raised, and static pressure was applied from the welding tip of the ultrasonic complex vibration source. Vibration was then applied to the welding tip by applying a sine wave signal to the vibration source, and welding was performed.

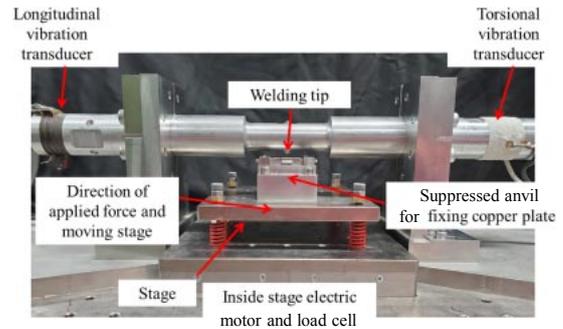


Fig. 4 Welding equipment.

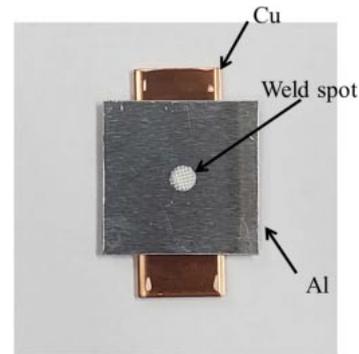


Fig. 5 Welded sample.

Figure 5 shows an example of a welded sample. The welding conditions in this case were a static pressure of 500 N, a weld time of 0.6 s, and the planar vibration of the amplitude as shown in Fig. 3. Figure 5 shows that the aluminum and copper plates overlapped at the center, and a knurled circular weld point was in contact with at the center of the aluminum plate.

The strength of the welded samples was evaluated using tensile shear strength and cross tensile strength. A tensile compression tester (Imada Seisakusho, SDT-503 NB) was used. Tensile shear strength was measured using JIS Z 3136 and cross tensile strength was measured using JIS Z 3137. The tensile speed was 1 mm/min.

3.2. Tensile Shear Strength of Weld Samples with Different Tensile Directions and Weld Times

To examine the relationship between the vibration and tensile directions applied to weld samples in ultrasonic welding and the tensile shear strength of the welded sample using planar vibration, welding experiments were performed by changing the tensile direction and weld time of the weld sample. The welding conditions were varied while maintaining a static pressure of 500 N and a weld time of 0.2 to 1 s, and welding experiments were performed five times each using the three types of vibrations shown in Fig. 3.

Figure 6 shows a schematic diagram of the relationship between the vibration and tensile directions of the welding

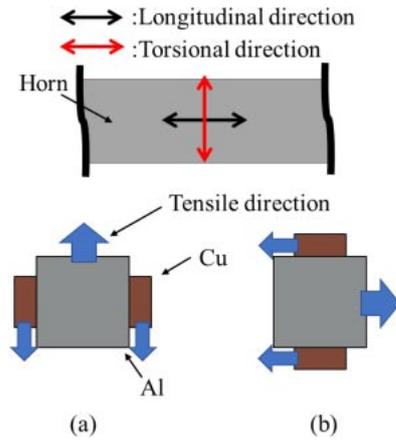


Fig. 6 Relationship between vibration and tensile directions of welding tip.

tip in order to show the relationship between the vibration direction applied to the welded samples and the tensile direction in the tensile shear test. The position of the welded sample is shown with the black line indicating the longitudinal vibration direction, the red line indicating the direction of the torsional vibration for the horn of the ultrasonic complex vibration source, and the blue arrows indicating the tensile direction in the tensile shear test. Figure 6(a) shows the case where the longitudinal direction of the copper plate is parallel to that of the horn of the ultrasonic complex vibration source, and Fig. 6(b) shows the case where the longitudinal direction of the copper plate is perpendicular to that of the horn of the ultrasonic complex vibration source. The tensile direction of the tensile shear test was the width direction of the copper plate. In this paper, the configuration shown in Fig. 6(a) is called installation position (a), and the configuration shown in Fig. 6(b) is called installation position (b).

Figure 7 shows the experimental results for the relationship between the weld time and the average tensile shear strength at installation position (a). In the figure, the horizontal axis is the weld time and the vertical axis is the tensile shear strength, and the parameters are as shown in the table above the graph. Error bars indicate the deviation ($\pm 1\sigma$). The figure shows that the tensile shear strength at installation position (a) was the highest with planar vibration, followed by torsional and longitudinal vibrations within the examined range of weld times. The welded strength of about 700N was obtained at 0.6s with planar vibration, and the deviation was small and stable.

Figure 8 shows an example of the fracture surface of the weld zone from the tensile shear test at installation position (a). The welding conditions were chosen from the results in Fig. 7 for the weld time of 0.6s, and the welded sample has a tensile strength close to the average value. The upper side shows a photograph of the fractured surface

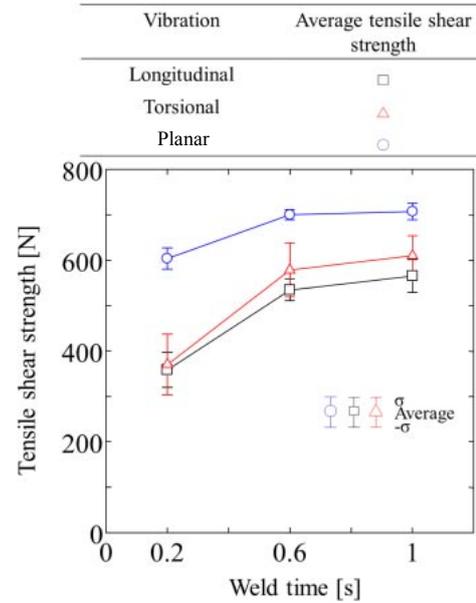


Fig. 7 Relationship between weld time and average tensile shear strength (installation position (a)).

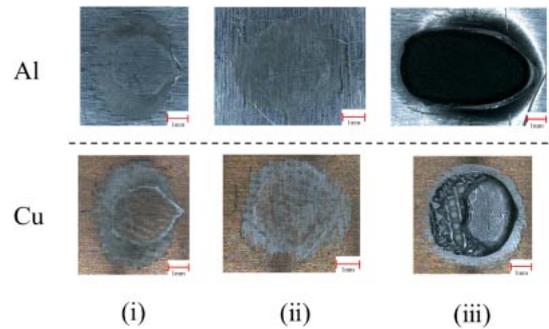


Fig. 8 State of fracture surface of welded samples. (i) Case of using longitudinal vibration. (ii) Case of using torsional vibration. (iii) Case of using planar vibration.

of the aluminum plate and the lower side shows a photograph of the fractured surface of the copper plate. Figures 8(i), 8(ii) and 8(iii) show the cases of using longitudinal, torsional, and planar vibrations. In all cases, the longitudinal and torsional vibration directions for the fracture surface of the welded sample were the same as those shown in Fig. 6.

On the basis of Fig. 8, it is considered that aluminum adhered to the copper plate with any type of vibration, and the amount of adhered aluminum affected the tensile shear strength. The amount of adhered aluminum is considered to be proportional to the welding area. In the area where a connection between the copper and the aluminum plates is achieved, the aluminum, which has the lower strength, adheres to the copper plate after the tensile shear test. On the other hand, the part where welding is not achieved has no adhered aluminum after the tensile shear test. Therefore,

the amount of adhered aluminum is considered to be proportional to the welding area. Since the size of the welding area is considered to be proportional to the weld strength, the amount of adhered aluminum is also considered to be proportional to the weld strength. When using planar vibration, the strength of the weld zone exceeded that of aluminum, with aluminum at the weld trace adhering to the copper plate, and much aluminum adhering to the periphery. In the case of longitudinal vibration, aluminum adhered densely in an ellipse with the longitudinal vibration direction as the major axis, but the aluminum content in the central part was thin. In the case of torsional vibration, aluminum adhered densely in an ellipse with the torsional vibration direction as the major axis, and more aluminum adhered overall compared with the case of longitudinal vibration. From these results, it is thought that higher tensile shear strength could be obtained by torsional vibration than by longitudinal vibration.

Figure 9 shows the experimental results at installation position (b). The notation in the figure is the same as in Fig. 7. The figure shows that the cross tensile strength at installation position (b) was the highest with planar vibration, followed by torsional vibration and longitudinal vibration within the examined range of weld times. The welded strength of about 700N was obtained at 0.6s with planar vibration, and the deviation was small and stable. The fracture surface of the weld zone was the same to Fig. 8.

The tensile shear strength of the planar vibration at installation position (a) was almost the same as that at installation position (b). However, the strength of the

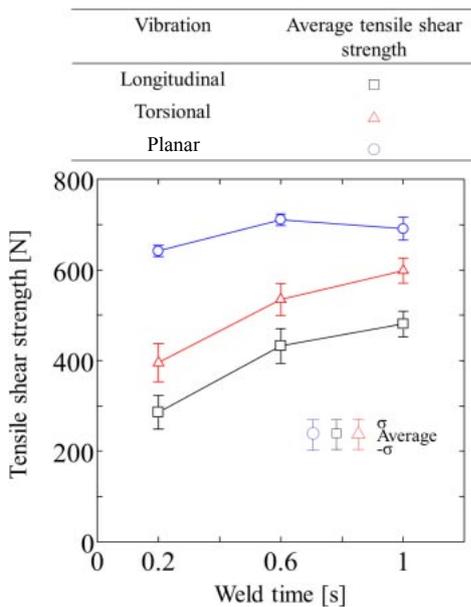


Fig. 9 Relationship between weld time and average tensile shear strength (installation position (b)).

longitudinal vibration was a little higher in installation position (a) than in installation position (b), which proves that the same tensile shear strength was obtained in the torsional vibration regardless of the installation position. In longitudinal and torsional vibration, there was no large difference in the tensile shear strength between the vibration direction and the tensile direction of the welding tip. However, the tensile shear strength of the linear vibration varied depending on the installation position compared with that of the planar vibration.

3.3. Cross Tensile Strength of Weld Samples with Different Peel Direction and Weld Time

In order to examine the relationship between the vibration direction and the peel direction applied to weld samples in ultrasonic welding and the cross tensile strength of the welded sample using planar vibration, welding experiments were performed by changing the peel direction and the weld time of the weld samples. The welding conditions are the same as in Sect. 3.2.

Figure 10 shows a schematic diagram of the relationship between the vibration direction and the peel direction of the welding tip in order to show the relationship between the vibration direction applied to the welded samples and the peel direction in the cross tensile test. The position of the welded samples is shown, with the black line direction indicating the longitudinal vibration direction, the red line direction indicating the torsional vibration for the horn of the ultrasonic complex vibration source, and the blue symbol indicating the tensile direction in the cross tensile test.

Figure 10(c) shows the case where the longitudinal direction of the copper plate was parallel to the longitudinal direction of the horn of the ultrasonic complex vibration source, and Fig. 10(d) shows the case where the longitudinal direction of the copper plate was perpendicular to

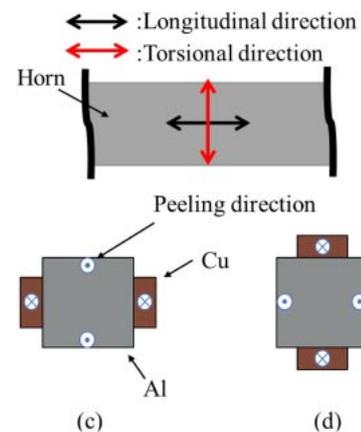


Fig. 10 Relationship between vibration direction and peeling direction of welding tip.

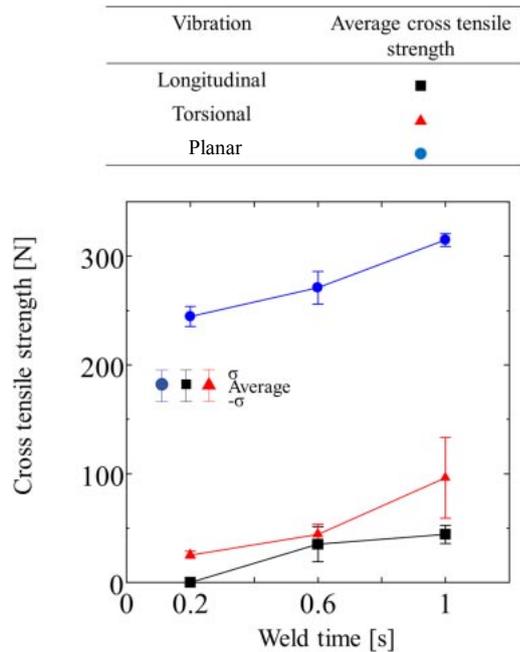


Fig. 11 Relationship between weld time and average tensile cross tensile strength (installation position (c)).

the longitudinal direction of the horn of the ultrasonic complex vibration source. The tensile direction of the cross tensile test was the thickness direction of the copper plate. In this paper, the configuration shown in Fig. 10(c) is called installation position (c), and the configuration shown in Fig. 10(d) is called installation position (d).

Figure 11 shows the experimental results for the relationship between the weld time and the average cross tensile strength at installation position (c). In the figure, the horizontal axis is the weld time and the vertical axis is the cross tensile strength, and the parameters are as shown in the table above the graph. Error bars indicate the deviation ($\pm 1\sigma$). The figure shows that the cross tensile strength at installation position (c) was highest in the planar vibration within the examined range of weld times. Since the longitudinal vibration peeled off before the tensile shear strength was measured at 0.2s, it was set to 0 N, and it saturated after 0.6s. The torsional vibration increased in proportion to the weld time. The planar vibration was obtained with about 300 N in 1 s, and the deviation was also small and stabilized.

Figure 12 shows an example of the fracture surface of the weld zone after the tensile shear test at installation position (c). The welding conditions were chosen from the results of Fig. 11 for the weld time of 0.6 s, and the welded sample was close to the average value of the tensile shear strength. The upper side shows a photograph of the fractured surface of the aluminum plate, and the lower side shows a photograph of the fractured surface of the copper plate. Figure 12(i) shows the case of using

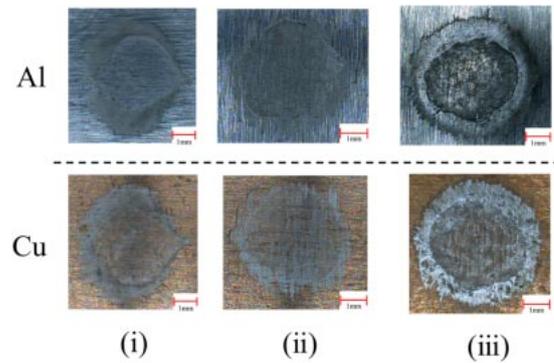


Fig. 12 State of fracture surface of welded samples. (i) Case of using longitudinal vibration. (ii) Case of using torsional vibration. (iii) Case of using planar vibration.

longitudinal vibration, Fig. 12(ii) shows the case of using torsional vibration, and Fig. 12(iii) shows the case of using planar vibration. In both cases, the longitudinal and torsional vibration directions for the fracture surface of the welded sample were the same to those shown in Fig. 10.

From the figure, it is thought that aluminum adhered to the copper plate by any vibration and the amount of adhered aluminum affected the cross tensile strength. In the case of planar vibration, more aluminum adhered to the joint surface compared with longitudinal vibration and torsional vibration. From these results, it is thought that the cross tensile strength of the planar vibration was higher than that of linear vibration. The longitudinal and torsional vibrations were the same to those in Fig. 8.

Figure 13 shows the experimental results at installation position (d). The notation in the figure is the same as in Fig. 10. The figure shows that the cross tensile strength at installation position (d) was highest in the planar vibration within the examined range of weld times. Since the longitudinal vibration peeled off before the tensile shear strength was measured at 0.2 s, it was set to 0 N, and it saturated after 0.6 s. The planar vibration was obtained with about 300 N in 1 s, and the deviation was also small and stabilized.

Comparing the results at installation position (c) with installation position (d), the cross tensile strength of the planar vibration was almost the same regardless of the installation position. However, the cross tensile strengths with longitudinal vibration and torsional vibration at installation position (d) was slightly higher than that at installation position (c). Longitudinal and torsional vibrations showed no significant differences in cross tensile strength depending on the vibration direction and the peeling direction of the welding tip.

The tensile shear strength with planar vibration and linear vibration was higher than the cross tensile strength. It

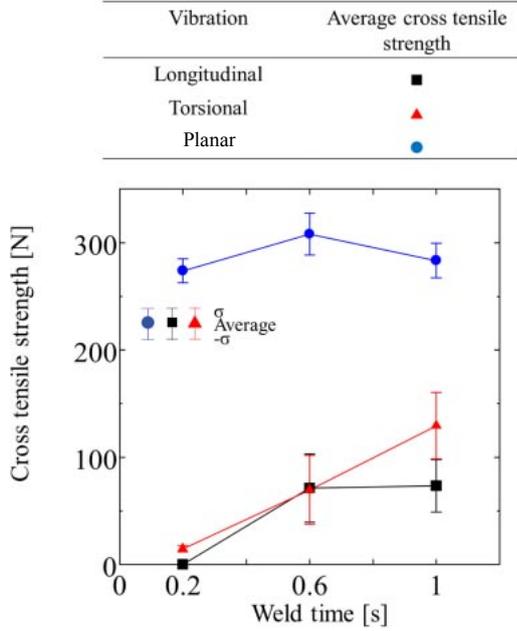


Fig. 13 Relationship between weld time and average tensile cross tensile strength (installation position (d)).

can also be seen that the difference in the strength between the planar vibration and the linear vibration in the tensile shear test was small at about 13–55%, while the difference in the strength between the planar vibration and the linear vibration in the cross tensile test was large at about 54–95%. In Figs. 8 and 12, the appearance of the aluminum adhered to the copper plate differed between linear vibration and planar vibration. For the planar vibration, in particular, the aluminum adhered strongly to the copper plate. In the tensile shear test, the load was applied to the whole weld zone, and in the cross tensile test, the load was applied toward the inside from outside of the weld zone. Therefore, it is thought that the tensile shear strength and cross tensile strength of the linear vibration were different from the case of planar vibration in which the inside was strongly adhered even when peeled from the outside, because the adhesive force decreased remarkably as it was peeled from the outside.

4. DISCUSSION

First, we explain the results the each type of strength of the welded sample based on the work of each vibration locus, using the kinetic energy W and the locus length L of the tip during welding. The locus length L , which is the line integral of the tip displacement at each locus over time, is calculated from the vibration displacement amplitude and frequency of each vibration. The locus length L_P of a tip when using planar vibration is about 1.5 times larger than the locus length L_L when using linear vibration for the same welding time. Therefore, the acceleration a_P of the tip when using planar vibration is about 1.5 times the

acceleration a_L when using linear vibration. The linear locus indicates both longitudinal and torsional vibrations. The longitudinal and torsional vibrations have the same locus length L_L owing to the relationship between the vibration displacement amplitude and the frequency. From this, the kinetic energy W_L corresponding to the work of the tip when using linear vibration is given as follows. The mass m is a constant because the static pressure and the horn mass are constant.

$$W_L = m \times a_L \times L_L. \quad (1)$$

On the other hand, the kinetic energy W_P in the case of planar vibration is given by

$$W_P = m \times a_P \times L_P = m \times 1.5a_L \times 1.5L_L \cong 2.3W_L. \quad (2)$$

From this, W_P with planar vibration is estimated to be about 2.3 times as large as W_L with linear vibration. From these results, it is considered that the increase in each type of strength in the case of planar vibration is due to the effect of the kinetic energy on the smoothness of the sample surface and the exposure of the newly formed surface.

On the other hand, in order to compare W_P and W_L with the same work in the same displacement amplitude, it is necessary to change the weld time in the case of linear vibration and to increase the locus length L_L about 2.3 times. In other words, W_L is equivalent to W_P if the weld time is about 2.3 times longer than that in the case of planar vibration. From Figs. 7, 9, 11, and 13, W_L for a weld time of 0.6 s is larger than W_P for a weld time of 0.2 s. On the basis of this result, the tensor shear strength and cross tensile strength when using planar vibration for a weld time of 0.2 s are higher than those when using linear vibration for a weld time of 0.6 s, indicating that the two-dimensional stress of planar vibration is effectively applied.

It is considered that the vibration mode of the aluminum plate affects the adherence of aluminum to the copper plate. When longitudinal vibration is used, the finite element analysis shows that the vibration mode of the aluminum plate causes displacement in the pressurizing direction around the weld spot. The displacement in the pressurizing direction was about twice as large as the displacement amplitude of the vibration applied from the tip. Because of this effect, the amount of adhered aluminum to the copper plate in the case of longitudinal vibration was small at the center, and it is considered that it covered an area of elliptical shape. On the other hand, when torsional vibration was used, the vibration mode of the aluminum plate was almost uniform in the vicinity of the weld spot. Finally, we had clarified that the welding by planar vibration is not easily affected by the vibration mode of the aluminum plate during welding in a previous study [26]. From this, it is considered that the amount of adhered

aluminum became uniform because the vibration of the tip and the relative vibration between the weld sample were almost equal. Since the amount of attached aluminum is uniform, we concluded that the weld samples are in uniform contact with each other. Such uniform contact occurs when the surface irregularities of the weld samples are smoothed by ultrasonic vibration. In other words, the two-dimensional stress caused by planar vibration is considered to contribute significantly to the smoothing of the weld interface.

Finally, the installation position dependence of weld strength is described. First, we found that there is an installation position dependence of tensile shear strength when longitudinal vibration is used. The tensile shear strength with longitudinal vibration is lower with Fig. 6(b) than with Fig. 6(a). In Figs. 6(a) and 6(b), the vibration mode of aluminum is the same. However, since the copper plate is rectangular, the vibration mode of the weld spot may differ depending on the installation position. In addition, although the copper plate is fixed to the anvil, it is considered that the vibration of the plate has not been completely reduced to zero. Therefore, when the installation position was changed as shown in Figs. 6(a) and 6(b), it is assumed that the vibration mode of the copper plate affected the tensile shear strength. Since it was difficult to reproduce the state fixed to the anvil by finite element analysis, the vibration mode of the weld spot was examined by finite element analysis in the model that neglected the fixation. As a result, it was found that the vibration mode near the weld spot changed on changing the installation position. In the case of Fig. 6(b), the displacement was larger than that at the tip. On the other hand, when torsional vibration was used, the vibration mode near the weld spot was almost unaffected by the installation position. This is probably due to the difference in the frequencies of longitudinal vibration and torsional vibration. In this way, the installation position dependence of tensile shear strength is thought to have occurred only in the longitudinal vibration where the vibration mode of the copper plate changed. Second, the installation position dependence of the cross tensile strength is not likely to occur. Originally, cross tensile strength and tensile shear strength should have the same tendency. However, the cross tensile strength of longitudinal vibration and torsional vibration was 1/3 of that of planar vibration and had a large deviation. Therefore, the low cross tensile strengths in the case of longitudinal and torsional vibrations indicate that welding is insufficient, and the installation position dependence of weld strength is not apparent.

5. CONCLUSION

In this paper, in order to clarify the characteristics of tensile shear strength and cross tensile strength of welding

using planar vibration and linear vibration by an ultrasonic wave complex vibration source, the authors examined the weld time, vibration direction, and tensile direction of the welding tip, and the peeling direction. The following results were found.

- (1) Tensile shear strength and cross tensile strength in the case of planar vibration were higher in a shorter time than in the case of linear vibration, and the deviation was small and stable.
- (2) The difference in the strength between planar vibration and linear vibration in the tensile shear strength was small, but the difference in strength between planar vibration and linear vibration in the cross tensile strength was large. These results suggest that the cross tensile strength in the case of using planar vibration is excellent.
- (3) There was no significant difference in the relationship between the vibration direction of the tip of the welding tip and the tensile and peeling directions within the scope of this study. However, differences in strength were caused by the installation position because the fixed copper plate was rectangular, and the welding characteristics when the copper plate and the aluminum plate are considered as one body differ depending on the installation position. Therefore, the installation position seems to affect the welding characteristics.

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