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Ultrasonic welding of dissimilar metals by vibration with planar locus

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Abstract: A linear vibration locus is conventionally used in ultrasonic metal welding. We have previously proposed the use of a nondirectional planar vibration locus as a means of improving the overall and orientation-dependent weld strength compared with the case of using a linear vibration locus. In this study, experiments in which a copper plate and an aluminum plate were used as welding targets were conducted and the weld strength under various conditions was measured to assess the welding characteristics. We found that for a short welding time, the strength of a weld produced using a planar vibration locus was 1.7-fold that produced using a linear vibration locus. We attribute this result to the aluminum plate vibrating more easily, and thus creating stronger vibrations at the interface between the copper and aluminum plates, when we used the nondirectional planar locus.

Keywords: Ultrasonic welding, Welding of metals, Diagonal slits, Complex vibration, Planar vibration locus

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1. INTRODUCTION

In response to energy problems and environmental issues, the demand for next-generation (hybrid and electric) vehicles has increased rapidly in recent years [1]. Next-generation vehicles require high-capacity rechargeable batteries, the manufacture of which involves welding sheets of dissimilar metals. Currently, dissimilar metals are welded by conventional heat-based techniques, such as spot welding [2,3].

However, heat-based methods are difficult to apply to dissimilar metals since their melting points are typically different. Thus, ultrasonic metal welding has emerged as a strong candidate for effective welding of dissimilar metals. Ultrasonic metal welding is a solid-state welding method in which the welding targets need not be heated, making it particularly attractive for application to dissimilar metals.

A linear vibration locus in conventionally used in ultrasonic metal welding [4,5]. This entails problems such as low overall weld strength, and the dependence of weld strength on the welding target orientation; this dependence is thought to result from the directionality of the vibration locus [6]. To resolve these problems, welding using nondirectional vibration loci has been investigated. Tsujino and coworkers investigated welding using a vibration unit with diagonal slits and a circular vibration locus. This locus was obtained by driving the unit at a single drive frequency to create a phase difference between longitudinal vibrations and torsional vibrations [7,8]. However, if the drive frequency is changed such that the longitudinal and torsional vibrations are in phase, this method can produce a linear vibration locus. Watanabe *et al.* demonstrated that a planar vibration locus could be obtained by combining longitudinal vibrations and bending vibrations through the use of two drive frequencies [9]. However, there have been no investigations into the use of a planar vibration locus to weld thin metal plates, and the properties of such welds have not been elucidated.

Against this background, we proposed the use of a planar vibration locus because it has no specific directionality [10–12], and studied ultrasonic welding using various welding tips [13]. Conceivably, vibration energy is applied to the welding target more effectively by a planar locus than by a linear locus. A planar locus should improve the overall weld strength and reduce the dependence of weld strength on welding target orientation. We therefore developed a method of generating vibrations with a planar locus for metal welding. In this method, a one-dimensional ultrasonic longitudinal-torsional vibration source with diagonal slits on the vibration converter is driven at two frequencies simultaneously. As a fundamental investiga-

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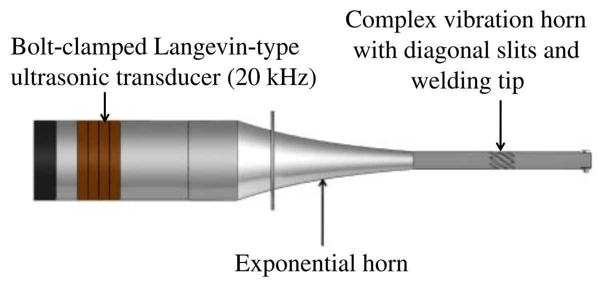


Fig. 1 Ultrasonic vibration source.

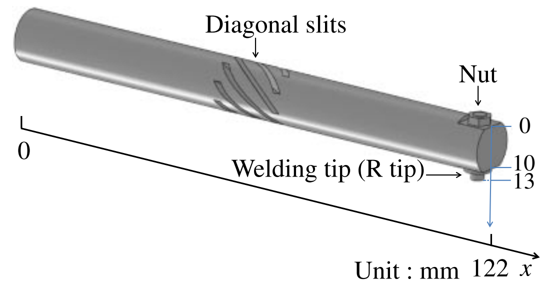


Fig. 2 Complex vibration horn with diagonal slits and welding tip.

tion into welding using a planar vibration locus, in this study, we aim to elucidate the characteristics of longitudinal-torsional vibrations in such welding and compare the weld strength of joints between copper and aluminum plates prepared using planar and linear vibration loci. In addition, we investigate the fundamental characteristics of planar welding of thin metal plates using a planar locus. These characteristics have not yet been investigated in detail.

2. EXPERIMENTAL APPARATUS AND METHODS

2.1. Ultrasonic Vibration Source

Figure 1 shows the ultrasonic vibration source used in this experiment. It consists of a bolt-clamped Langevin-type transducer (D45520, NGK), an exponential horn for displacement amplification (length: 155 mm; large-end diameter: 55 mm; small-end diameter: 12 mm; amplification factor: about 4.6; material: duralumin), and a complex vibration horn with diagonal slits and a welding tip.

Figure 2 shows a schematic diagram of the complex vibration horn with diagonal slits [14,15]. Here, the horizontal axis indicates the measurement position in the x direction. The complex vibration horn is 122 mm long. The center position of the length of the diagonal slits is $x = 61$ mm, which is the position of a node in the longitudinal vibration. The slits act as a longitudinal-torsional vibration converter, and have the following characteristics: length, 19 mm; groove width, 0.5 mm; depth, 3.5 mm; inclination angle, 35°; and number of slits, 8. The small end of the horn bears a welding tip with a diameter of 3 mm, a length of 3 mm, and a curved tip end ($R = 8.0$ mm). The horn and the welding tip are made of stainless steel (SUS303).

2.2. Ultrasonic Welding Apparatus

Figure 3 shows the ultrasonic vibration source for the welding tip and the clamp for applying pressure at the welding tip. An electric motor is used to apply constant force to a vise from underneath to maintain contact between the welding tip and the welding target.

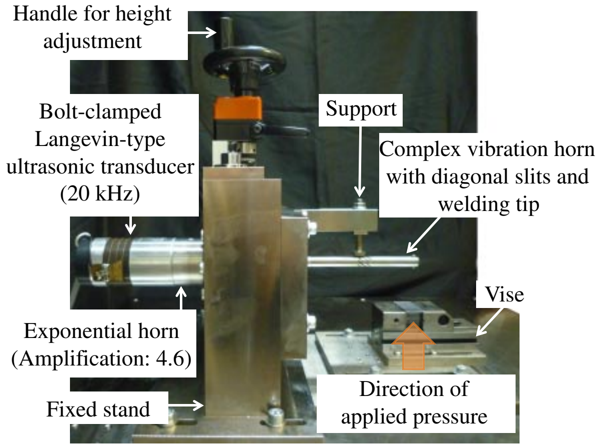


Fig. 3 External appearance of the ultrasonic welding apparatus.

The experimental procedure for welding is as follows. An aluminum plate (material: A1050; length: 40 mm; width: 20 mm; thickness: 0.5 mm) is placed on top of a copper plate (material: C1100; length: 40 mm; width: 20 mm; thickness: 2.0 mm) fixed in the vise. Static pressure is then applied to the aluminum plate by the welding tip, and the ultrasonic vibrations are applied.

3. LONGITUDINAL-TORSIONAL VIBRATION CHARACTERISTICS OF THE ULTRASONIC VIBRATION SOURCE

The longitudinal-torsional vibration characteristics of the ultrasonic vibration source were determined by an experiment on ultrasonic welding of dissimilar metals. In this experiment, the frequency and vibration amplitude characteristics, as well as the vibration loci of the welding tip and the tip side, were examined.

The frequency and vibration amplitude at the welding tip were measured while varying the drive frequency. An experiment was conducted with two laser Doppler vibrometers (LDVs; LV-1710, Ono Sokki) with varying drive frequency in the range of 17–20 kHz, and the terminal voltage of the transducer fixed at 10 V (effective value).

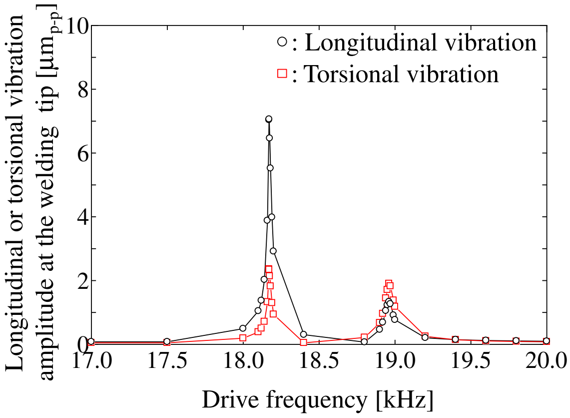
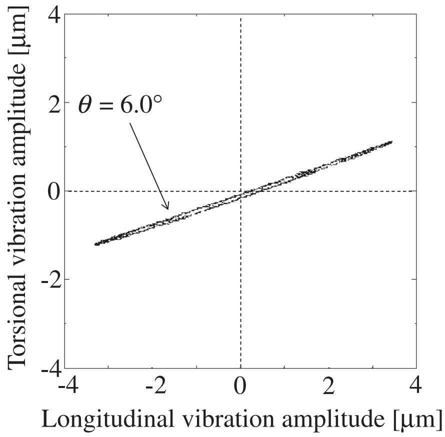


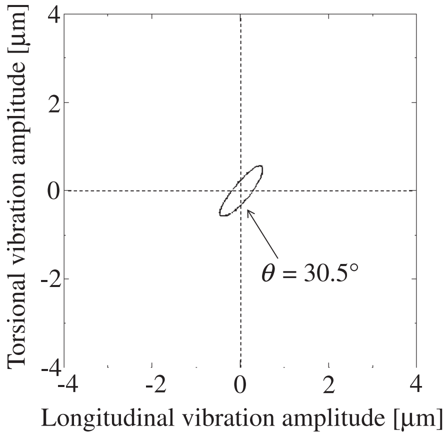
Fig. 4 Relationship between drive frequency and longitudinal or torsional vibration at the welding tip. The terminal voltage of the transducer is 10 V (effective value).

Figure 4 shows the results of the experiment. The vertical and horizontal axes represent the zero-to-peak value of the vibration displacement amplitude (longitudinal or torsional) and the drive frequency, respectively. The longitudinal-torsional vibration amplitude at the welding tip had two local maxima corresponding to drive frequencies of 18.1 and 18.9 kHz. The amplitude of the longitudinal vibration was larger than that of torsional vibration at the drive frequency of 18.1 kHz and slightly smaller than that of torsional vibration at 18.9 kHz. The vibration loci of the welding tip were plotted for both drive frequencies. The longitudinal and torsional vibrations were measured at the same time using the two LDVs with the terminal voltage of the transducer fixed at 10 V (effective value).

Figure 5 shows the longitudinal-torsional vibration loci at drive frequencies of (a) 18.1 and (b) 18.9 kHz at the welding tip. The vertical and horizontal axes represent the displacement amplitudes of torsional and longitudinal vibrations, respectively. In Fig. 5(a), the vibration locus at the drive frequency of 18.1 kHz describes a straight slanted line. Torsional vibration was generated from the longitudinal vibration by a vibration converter consisting of diagonal slits, and the amplitude of the resulting torsional vibration was approximately 32% that of the longitudinal vibration. The longitudinal and torsional vibrations were almost in phase, with a phase difference of approximately 6.0°. In contrast, in Fig. 5(b), the locus at the drive frequency of 18.9 kHz is elliptical. The amplitude of the torsional vibration was approximately 143% that of the longitudinal vibration and the phase difference between the longitudinal and torsional vibrations was approximately 30.5°. At the drive frequency of 18.9 kHz, the ratio of the amplitudes of longitudinal to torsional vibrations was different from the ratio at 18.1 kHz, and the angles formed by the longitudinal and torsional vibrations were also different. This phenomenon likely results from the different dominant vibrations generated in each case.



(a)



(b)

Fig. 5 Longitudinal and torsional vibration loci at the welding tip for drive frequencies of (a) 18.1 kHz and (b) 18.9 kHz. The terminal voltage of the transducer is fixed at 10 V (effective value).

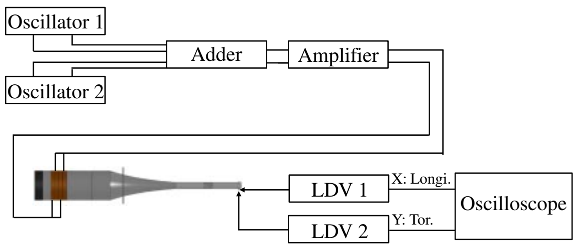


Fig. 6 Circuit for determining the vibration locus.

Next, from the above results, we measured the vibration locus at the welding tip in the case of applying both drive frequencies (18.1 and 18.9 kHz) to the ultrasonic vibration source at the same time. Figure 6 and Table 1 show the measurement circuit and the measurement conditions, respectively [9]. The figure shows that the signals from the two oscillators were added and the resulting signal was applied to the ultrasonic vibration

Table 1 Measurement conditions.

	Oscillator 1	Oscillator 2	Oscillator 1 + Oscillator 2
Frequency [kHz]	18.1	18.9	18.1 + 18.9
Input voltage [V_{rms}]	10	10	10 + 10

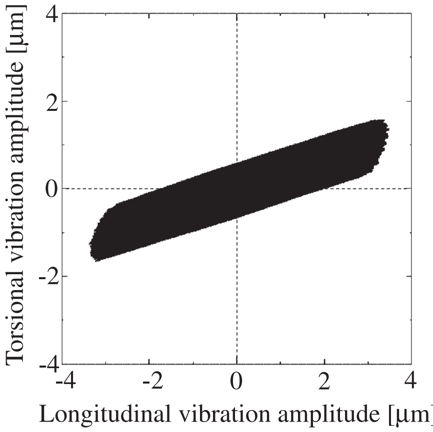


Fig. 7 Vibration locus at the welding tip driven by two drive frequencies. The driving signal is obtained by adding the 18.1 and 18.9 kHz frequencies. The terminal voltage of the transducer is 10 + 10 V (effective value).

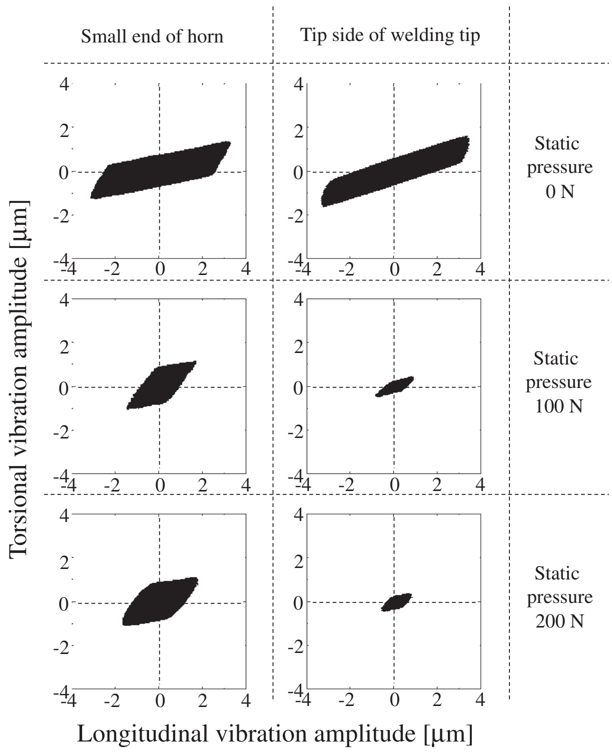


Fig. 8 Vibration loci at the welding tip for various static pressure levels. The driving signal is obtained by adding the 18.1 and 18.9 kHz frequencies. The terminal voltage of the transducer is 10 + 10 V (effective value).

source upon amplification. The table shows the frequency and input voltage of the signal from each oscillator. Furthermore, the experimental results (Fig. 7) clearly show that the vibration locus was planar. The vertical and horizontal axes in Fig. 7 show the same parameters as in Fig. 5. The planar locus was obtained as the sum of the loci of the two drive frequencies. We therefore focused on a planar vibration locus obtained using drive frequencies of 18.1 and 18.9 kHz and a linear vibration locus obtained using a drive frequency of 18.1 kHz. In the latter case, the vibration locus was the same as that in conventional ultrasonic metal welding.

4. VIBRATION LOCUS WITH APPLIED STATIC PRESSURE

Next, the vibration locus was measured while varying the static pressure applied at the welding tip in the case where two drive frequencies were applied to the ultrasonic vibration source. The vibration locus was measured by the method described in Section 3 at two locations, one on the small end of the horn and one at the welding tip, and the results were compared. Static pressures of 0, 100, and 200 N were applied, as shown in Fig. 3.

Figure 8 shows the vibration loci at each location for each static pressure. The vertical and horizontal axes represent the displacement amplitudes of torsional and longitudinal vibrations, respectively. In the case of a static pressure of 0 N, vibration with a planar locus was generated at the horn near the end and at the welding tip. The vibration loci obtained at the other two pressure levels were slightly different, likely because of bending vibrations at the welding tip. Vibration with a planar locus was also obtained on the horn near the end as well as at the welding tip in the case of static pressures of 100 and 200 N. However, the locus at the welding tip was smaller than that on the horn. This is likely the result of suppressed bending vibrations at the welding tip owing to the static pressure, because the point of the welding tip was considered to be under the fixed end condition with increasing static pressure. Nevertheless, vibration with a planar locus at the welding tip was obtained at all static pressure levels, showing that applying two individual drive frequencies to the ultrasonic vibration source was effective for generating vibration with a planar locus when applying static pressure of up to 200 N.

5. WELDING EXPERIMENT: ALUMINUM AND COPPER PLATES

A welding experiment using aluminum and copper plates was carried out by varying the welding time, static pressure, and vibration amplitude. Vibrations with a linear

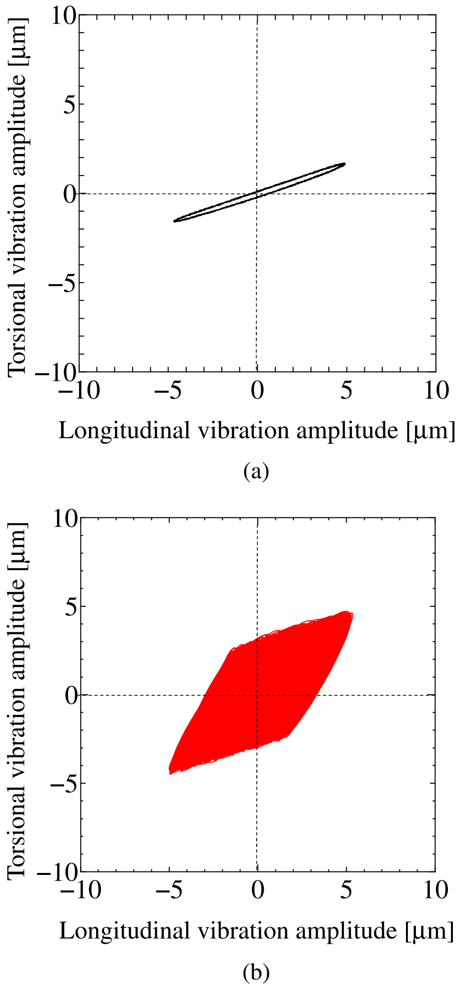


Fig. 9 Linear and (b) planar vibration loci during welding. Static pressure is 100 N.

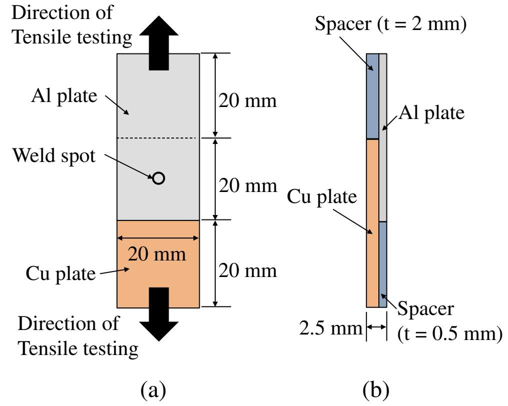


Fig. 10 Front view and (b) side view of tensile shear test specimen (not to scale).

Fig. 11 Photograph of specimen. Vibration locus is the planar locus, and static pressure is 100 N.

locus (longitudinal vibration amplitude: 10 μm_{p-p}) and a planar locus (longitudinal vibration amplitude: 10 μm_{p-p}; torsional vibration amplitude: 8.5 μm_{p-p}) were used in the experiment. Figures 9(a) and 9(b) show the two loci measured at a static pressure of 100 N. The input electric powers of the linear locus and the planar locus were 16 and 20 W in this measurement, respectively. In addition, the weld strength (tensile shear strength) was measured by shear testing according to Japanese Industrial Standard Z 3136:1999 "Specimen dimensions and procedure for shear testing resistance spot and embossed projection welded joints." Figures 10(a) and 10(b) show the front view of the tensile shear test specimen and the side view of the tensile shear test specimen with the spacer, respectively. The overlap of the specimen was 20 mm and it was welded at the center of the overlap area. In the tensile shear test, the specimen was attached to the spacer and the top and bottom of the specimen were clamped on to the spacer 20 mm from the overlap area in the tension testing machine (IMADA SEISAKUSHO, SDT-503NB). The tensile shear test was conducted at a constant tension speed of 1 mm/min. Figure 11 shows the aluminum and copper plates welded together using vibration with a planar locus and a static pressure of 100 N. A clear welding mark resulting from pressing the welding tip onto the plate can be seen.

5.1. Dependence of Weld Strength on Welding Time

Figure 12 shows the experimental results obtained by varying welding time (static pressure: 100 N). Here, the vertical and horizontal axes represent weld strength and welding time, respectively. The input electric powers during welding of the linear locus and the planar locus were about 15 and 20 W, respectively. Curves in Fig. 12 show the trend based on average values. To clarify the differences between the welds made using the two vibration loci, welding times of 0 to 60 s were investigated. The weld strength for both linear and planar loci increased as welding time was increased to 20 s, after which the rate of increase dropped and the weld strength remained almost the same in the range of 20 to 60 s. Weld strength likely leveled off after 20 s because the contact area and the welding area became approximately equal after 20 s had elapsed. For the same welding time, a planar vibration locus produced a stronger weld than a linear vibration locus did. Comparing the vibration loci, we see that they have the same maximum amplitude. However, weld strength was higher when a planar vibration locus was used than when a linear vibration locus was used. This demonstrates

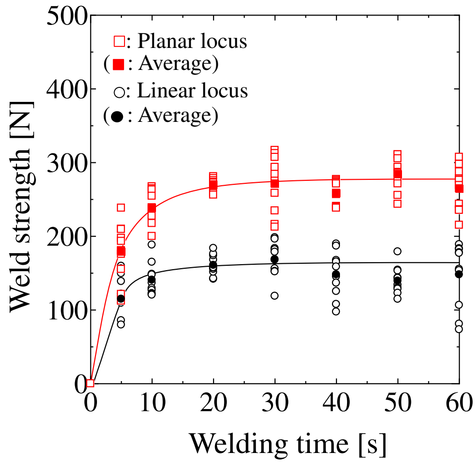


Fig. 12 Relationship between weld strength and welding time. The welding time is 0–60 s, and static pressure is 100 N.

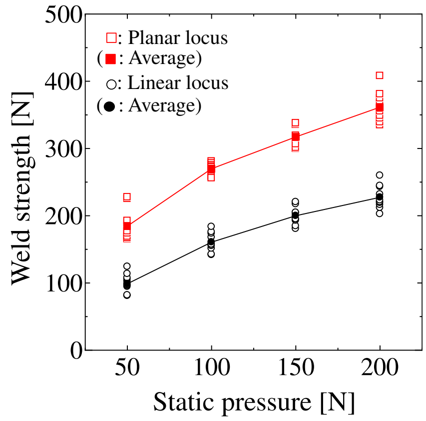


Fig. 13 Relationship between weld strength and static pressure. The static pressure range is 0–200 N, and the welding time is 20 s.

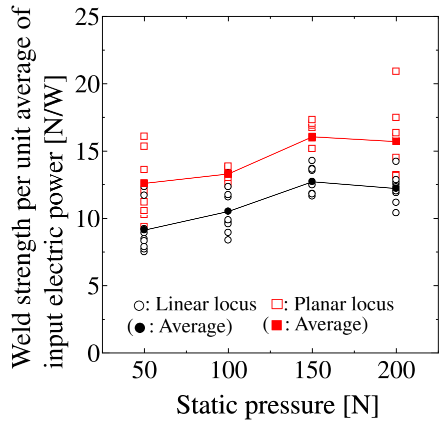


Fig. 14 Relationship between weld strength per unit average of input electric power during welding and static pressure. The static pressure range is 50–200 N, and the welding time is 20 s.

that planar vibration loci are useful as nondirectional vibration loci. The increase in weld strength when using the planar vibration locus is attributable to the increased weld area in comparison with the case of a linear locus. The vibration energy at the interface between the copper plate and the aluminum plate of the planar locus expanded the plastic deformation of the aluminum plate and increased the contact area between the aluminum surface and copper surface compared with the case of the linear locus. We considered that the weld area was increased by increasing the contact area, and that the weld strength is increased by increasing the weld area. Further work to clarify the reason why the use of the planar locus increased the weld area is required. On the basic of this result, the welding time was fixed at 20 s in the subsequent work.

5.2. Dependence of Weld Strength on Pressure

Figure 13 shows the experimental results obtained by varying static pressure in the range of 50 to 200 N. The vertical and horizontal axes represent the weld strength and static pressure, respectively. The ranges of the input electric power during welding using the linear locus and the planar locus were 10 to 21 W and 10 to 28 W, respectively. Clearly, for both the linear locus and the planar locus, the weld strength increased as the pressure was increased. This is attributed to the larger contact area between the aluminum and copper plates at higher static pressure levels. At the same pressure, the weld strength produced by a planar vibration locus was approximately 1.7-fold that produced by a linear vibration locus in both sets of experiments. One plausible explanation is that, in the case of two-dimensional vibration with a planar locus, the vibration energy was distributed more efficiently and the welding area was larger than in the case of a linear locus.

Figure 14 shows the experimental results for the relationship between weld strength per unit average of input electric power during welding and the static pressure, as obtained from the measurements shown in Fig. 13 at various static pressure levels. The vertical and horizontal axes represent the weld strength per unit average of input electric power during welding and the static pressure, respectively. For the linear locus or the planar locus, the weld strength per unit average of input electric power was around 11 and 15 N/W, respectively. The average value of the weld strength per unit average of input electric power of the planar locus was higher than that of the linear locus for each static pressure. From this result, we concluded that using the planar locus is more energy efficient than using the linear locus. This is because the plastic deformation of the welding target with a three-dimensional surface shape was promoted by the nondirectional planar vibration locus rather than the linear locus with directionality. However, the reason for this is not clear and further work is required.

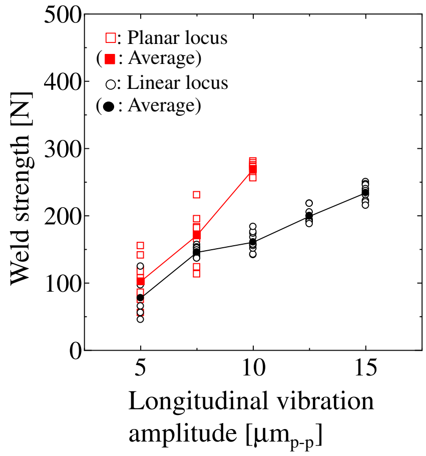


Fig. 15 Relationship between weld strength and longitudinal vibration amplitude. The longitudinal vibration amplitude range is 0–15 μm$_{p\text{-}p}$, static pressure is 100 N, and welding time is 20 s.

5.3. Dependence of Weld Strength on Vibration Amplitude

Figure 15 shows the experimental results obtained by varying the longitudinal vibration amplitude (welding time: 20 s; static pressure: 100 N). In this experiment, the torsional vibration increased as the longitudinal vibration was increased at the rate shown in Fig. 9 for both vibration loci. The vertical and horizontal axes in the figure represent the weld strength and longitudinal vibration, respectively. For both linear and planar loci, the weld strength increased proportionally to the longitudinal vibration amplitude in the measurement range. However, the gradient of the increase was larger for the planar locus than for the linear locus. The higher weld strength was likely owing to the increase in longitudinal vibration with increasing welding area. Furthermore, when the two types of vibration loci were compared at the same weld strength, the value of longitudinal vibration amplitude was smaller for the planar locus than for the linear vibration locus. This indicates that the vibration amplitude required for welding is smaller when using the planar vibration locus and this is thought to cause less damage to the materials being welded.

6. CONCLUSION

In this study, we conducted fundamental research on welding using planar vibration loci. We clarified the longitudinal-torsional vibration characteristics of a vibration source that produces a planar locus of vibration, and we investigated the weld strength of joints between copper and aluminum plates using this vibration source in order to compare the effects of using the planar and linear loci. The following results were obtained.

(a) By driving the vibration source using a signal consisting of the sum of two drive frequencies that give vibration loci of different shapes, a planar vibration locus could be obtained as the sum of the loci at each frequency.

(b) The weld strength of the joint between copper and aluminum plates was higher when using a planar vibration locus than when using a linear vibration locus.

(c) For the same welding time and same static pressure, the weld strength produced when using a planar vibration locus was approximately 1.7-fold that produced when using a linear vibration locus. Furthermore, the planar vibration locus was found to be more energy efficient in this case.

(d) The vibration amplitude needed to obtain a given weld strength was smaller for welding using a planar vibration locus than for that using a linear vibration locus.

In the future, the weld properties should be further investigated by changing the directionality of the weld and the shape of the welding tip. Specifically, we will investigate welding using a larger tip and the design of a vibration source to produce a larger weld area.

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