Effect of tool geometry on ultrasonic welding process

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Abstract. Ultrasonic welding of pure aluminum sheets is performed using two weld tools, one with a knurled surface and one with a cylindrical surface. Relative motion behaviors of each weld tool, with respect to the working materials, during ultrasonic welding tests are analyzed using the digital correlation method. Weld microstructure development is investigated on the basis of transitional weld stages in the context of relative motion behaviors. The dominant relative motion is between the two work materials at the beginning of the weld but changes to be the motion between the weld tool and the work material it is in contact with as weld time increases. Thermo-mechanical effects of the relative motion of the weld tool and the work materials, on the development of weld microstructure, are discussed.

1. Introduction
Ultrasonic welding is a solid-state bonding technique that is widely used to bond electrodes to semiconductors and secondary batteries in automobile industry because of its low temperature and high speed capabilities [1,2]. For ultrasonic welding, a high frequency vibration is applied to the part to be welded using a weld tool attached to an ultrasonic horn. The weld, essentially, is accomplished by friction at the weld interface owing to the relative motion of the working materials. Interfacial phenomena, such as oxide film fracture and adhesion [3,4], material flow near the weld interface [5-6], and changes in weld microstructure [7-9] have been metallographically investigated within the context of relative motion at the weld interface. However, relative motion also occurs between the weld tool and the welding material it is in contact with. It has been reported that weld properties strongly depend on weld tool geometry [10] and anvil geometry [11]. These dependencies can be interpreted as resultant phenomena of relative motion between the weld tool and material. However, this relative motion is not completely understood. The present study aims to investigate the effects of tool geometry on relative motion behavior and weld microstructure.

2. Experimental procedure
Sheets of pure industrial aluminum with thicknesses of 0.5 and 0.8 mm were used as test specimens in this study. Weld process observations were performed on aluminum sheet pieces that were cut to be 50 mm long × 10 mm wide and 50 mm long × 10.5 mm wide along their roll directions (Figure 1(a)). In addition, weld specimens with lengths of 100 mm were prepared for joint strength measurements (Figure 1(b)). The weld areas of the specimens were electropolished.

Ultrasonic welding equipment was operated at a vibrational frequency of 15 kHz, and a power of 2.4 kW. The load-free vibrational amplitude was 53 µm (peak to peak). The equipment consisted of a lateral drive system [1] which applied clamping force to the welding part through an ultrasonic horn as shown in Figure 2. The 0.8 mm thick specimen was placed on the anvil (lower specimen), and the 0.5
mm thick specimen was stacked on the lower specimen (upper specimen) as shown in Figure 2. Vibration was applied perpendicular to the lengths of the specimens. The lower specimen was clamped so as to suppress slippage across the anvil due to applied vibration. Two types of welding tools, shown in Figure 3, were used in this study. A conventional knurled tip tool (K-tip, Figure 3(a)) with a pitch of 0.8 mm, a height of 0.3 mm, and a groove angle of 90° was used as the basis for comparison. Watanabe et al. [10] have demonstrated that using a weld tip with a cylindrical contact surface significantly improves bonding strength. Thus, a tip with a cylindrical surface, having a radius of curvature of 200 mm (C-tip, Figure 3(b)) was used for comparison with the K-tip. The axis of cylindrical curvature was perpendicular to the direction of vibration (x-axis). The welding test was conducted under a constant clamping force of 588 N. In addition, to estimate the temperature near the weld interface, a K-type thermocouple was percussion-welded to the upper specimen as shown in Figure 2. Temperature observations were made simultaneous to high-speed camera observations, discussed presently.

Figure 1. Weld specimens used for (a) high speed camera observation and (b) joint strength measurements.

Figure 2. Schematic of welding test apparatus and observation area of high speed camera.

The motions of the weld tools and specimens during ultrasonic welding were observed using a high speed camera. The observation area was a coupon area that included the tip of the weld tool (weld tip), and the upper and lower specimens, as shown by the broken line in Figure 2. The capture speed of the high speed camera was 100,000 frames per second. Weld tip and the specimen displacements in the direction of vibration were calculated using the digital correlation method discussed previously [12]. Three subset areas were defined in the captured image, the weld tip, the upper specimen, and the lower
specimen. The coordinate of each subset area, during the welding test, was determined based on its intensity array in an 8-bits digital image. The displacements of the two weld tips and the upper / lower specimens in the vibration direction are denoted, respectively, by $u_{K\text{-tip}}$, $u_{C\text{-tip}}$, $u_{upper}$, and $u_{lower}$. Relative displacements between the upper and lower specimens and those between each weld tip and the upper specimen were obtained as follows: $u_{upper} - u_{lower}$, $u_{K\text{-tip}} - u_{upper}$, and $u_{C\text{-tip}} - u_{upper}$.

To evaluate joint strength, welded joints made on 100 mm long specimens were processed into “U-bent shape specimens [7]”. The maximum load in the tensile test was defined as the joint strength in this study. For weld microstructure observations, welded specimens were cut at the center of the welded area, parallel to the vibration direction. The cross-sections were then polished with diamond slurry and electrochemically etched with Barker’s reagent (1 vol% HBF4 solution).

Figure 3. Weld tool geometries used in this study. (a) presents a knurled surface tip (K-tip), and (b) a cylindrical surface tip (C-tip).

3. Results and discussion

3.1 Motion behavior and weld stages of ultrasonic welding

Figure 4 shows typical C-tip and specimen displacements during an 800 ms welding test. The three transitional stages indicated in Figure 4 as I, II, and III were established based on features of the displacement curves. Similar weld stage progressions have been observed in welding tests that used K-tips [12]. In the first stage ($t_w < 50$ ms, weld stage I) upper specimen displacement, $u_{upper}$, rapidly increases to approximately 150 µm more than the vibratory amplitude of the ultrasonic horn. This indicates that vibration causes the upper specimen to slip macroscopically. This macroscopic slippage is likely due to the induction of a bending moment by the clamping force and asymmetric shape of the ultrasonic horn. The slippage distances of C-tips tend to be smaller than those of K-tips, which demonstrate slippage distances of approximately 250 µm [12]. In the second stage ($t_w > 50$ ms, weld stage II), $u_{upper}$ showed displacement. Finally, in the third stage ($t_w > 300$ ms, weld stage III), the welding parts began to be plastically compressed by the clamping force. In this stage, the observation face expanded in the out-of-plane direction, hence $u_{upper}$ and $u_{lower}$ show apparent increases in Figure 4. Displacement analysis was impossible for weld times larger than 600 ms because the captured images were out of focus. Figure 5 shows how temperature changed over the course of a 600 ms welding test and indicates the time ranges of the weld stages, as determined from high-speed camera observations. Temperature monotonically rose during welding, reaching a maximum of approximately 230 °C at the beginning of weld stage III. This temperature should be high enough to initiate aluminum recrystallization. Although the measured temperature indicates an average value for the welding part, it is the compressive deformation associated with the temperature rise of weld stage III that is considered to be responsible for the softening of the upper specimen.
Figures 6 and 7 show the relative motion behaviors, with respect to weld times, that correspond to weld stages I and II. The plots shown in Figures 6 and 7 present relative displacement data, with respect to the upper specimen, for of each weld tip, \( u_{K-tip} - u_{upper} \) and \( u_{C-tip} - u_{upper} \), and that of the lower specimen, with respect to the upper specimen, \( u_{upper} - u_{lower} \). At the beginning of the weld, in the case of the K-tip (Figure 6(a)), the majority of the relative motion occurred between the specimens, \( u_{upper} - u_{lower} \), which vibrated extensively. Smaller amplitude vibration is also observed in the \( u_{K-tip} - u_{upper} \) plot of Figure 6(a). The \( u_{upper} - u_{lower} \) vibrational amplitude decreased to 2–4 µm during weld stage II using the K-tip, as shown in Figure 6(b). Meanwhile the vibrational amplitude of \( u_{K-tip} - u_{upper} \) became dominant, i.e. relative motion occurred predominantly between the weld tip and the upper specimen. It was found that during weld stage I, partially bonded regions formed at the contact surface and suppressed the relative motion of specimens, \( u_{upper} - u_{lower} \). In contrast, compared to that of the K-tip, the vibrational amplitude of \( u_{upper} - u_{lower} \) of the C-tip was relatively small at the beginning of the weld (Figure 7(a)). The cylindrical surface without knurled edges should suppress penetration of the weld tip into the upper specimen and result in greater relative motion of \( u_{C-tip} - u_{upper} \) at the beginning of the weld. However, the vibrational amplitude of \( u_{C-tip} - u_{upper} \) during weld stage II (Figure 7(b)) was smaller than that of \( u_{K-tip} - u_{upper} \) (Figure 6(b)). This may be related to the plastic deformation of the lower specimen, described in the following section.
Figure 6. Relative motions during ultrasonic welding using a K-tip. (a) illustrates the motion observed during weld stage I, and (b) illustrates motion observed during weld stage II.

Figure 7. Relative motions during ultrasonic welding using a C-tip. (a) illustrates the motion observed during weld stage I and (b) illustrates the motion observed during weld stage II.

3.2 Microstructures of weld formations

Figure 8 shows cross-sectional micrographs of K-tip welded specimens. Trapezoidal indentations formed by the penetration of knurled edges were observed on the welding tip side of the upper specimens. Indentation depth increased with increasing weld time and led to thinning of upper specimens. When $t_w = 20$ ms, which corresponds to weld stage I, using the K-tip (Figure 8(a)), almost no change in the microstructure around the weld interface was observed, while the upper side of welding part in contact with the knurled edges was plastically deformed by edge penetration. As
Figure 8. Cross-sectional images of joints welded using a K-tip. Images were obtained at twice the penetration depth reached approximately 300 µm, equal to the height of the knurl, during weld stage I. Figures 8(b) and 8(d), respectively, show high magnification micrographs of the areas indicated by rectangle 2 in Figure 8(b). Figure 8(c) shows a partially bonded region at the weld interface, indicated by a broken line. Figure 8(g) indicates that the partially bonded region observed at the weld interface was relatively small. It is concluded that heating, due to the relative motion of the weld tip and upper specimen, causes the welding part to soften and results in the formation of the severe plastic deformation zone.
In contrast, Figure 9 shows cross-sectional micrographs of joints welded using the C-tip. In the case of the C-tip, the start of weld stage III is observed earlier. The severe plastic deformation zone has already been generated in the upper side of the welding area at the beginning of weld stage III (Figure 9(b), t_w = 300 ms). In addition, the entire welding region, except for the severe plastic deformation zone, was also deformed, giving it a wavy shape. The smaller vibrational amplitude of the weld tip, relative to the upper specimen, observed in weld stage II when using the C-tip probably arose from the fact that plastic deformation of the welding region, including the lower specimen, assisted the motion of the upper specimen. The microstructure of the welding region was more dramatically disturbed as weld time increased (Figure 9(c) and (d)). The changes observed in weld microstructures during weld stage III, Figure 8(d) and Figure 9(d), are mainly attributed to thermo-mechanical effects caused by horizontal vibration and clamping force. It is concluded that the cylindrical surface of the C-tip facilitated the temperature rise caused by weld tip / upper specimen relative motion.

![Cross-sectional images of joints welded using a C-tip. Images were obtained at t_w = (a) 20 ms, (b) 300 ms, (c) 550 ms, and (d) 600 ms.](image)

**Figure 9.** Cross-sectional images of joints welded using a C-tip. Images were obtained at t_w = (a) 20 ms, (b) 300 ms, (c) 550 ms, and (d) 600 ms.

### 3.3 Joint strength

Figure 10 shows how joint strength changed with weld time and indicates the three weld stages observed in the relative motion behaviors of each weld tip at the top. Measurement results for the K-tip were obtained in a previous work [12]. Joint strengths were relatively low for weld times corresponding to weld stage I but increased monotonically, reaching maximum values during weld
stage III. Photographs of the fractured specimens, obtained after tensile tests, are shown in Figure 11. At weld times corresponding to weld stages I and II, fractures occurred at the weld interface, as shown in Figures 11(a) and (b). Dispersed white areas, which indicate partially bonded regions, can be seen in the image of a fracture surface presented Figure 11(a). These areas expand as weld time increases (Figure 11(b)). The increase in joint strength observed in weld stage II of the K-tip curve can be attributed to the expansion of partially bonded regions. In weld stage III, the fracture mode changes to “button fracture” in which the bonded part of the upper specimen remains attached to the lower specimen, as shown in Figure 11(c). The microstructure of the area surrounding the weld interface is intensely disturbed by the relative motion of the weld tip and upper specimen during this weld stage. Disturbance of the microstructure of the weld interface may contribute to the expansion of the bonded area and, hence, lead to increased joint strength during weld stage III. However, longer weld times, $t_w > 700$ ms, lead to compressively deformed welding parts resulting from the clamping force. This phenomenon decreases joint strength, which is due to thinning of the welding part, as shown in Figure 11(d). In addition, uneven surfaces resulting from indentation by knurled edges of the K-tip also result in decreased joint strength and increased joint strength variance. It was found that the strengths of joints produced using the C-tip were higher and varied less than those produced using the K-tip. In the case of the C-tip, concentrated bonded regions were observed at the centers of fracture surfaces (Figure 11(e)). In addition, button fractures were already observed late in weld stage II (Figure 11(f)). The cylindrical surface of the C-tip not only suppresses penetration by the weld tip, it also leads to the formation of concentrated bonded regions because of the high pressures it produces in the contact area at the beginning of the weld. These effects may expedite the onset of weld stages II and III. We attribute the higher joint strengths obtained from the C-tip to its smaller penetration and more significant effect on microstructure.

4. Conclusion

Ultrasonic welding of pure aluminum sheets was performed using two weld tips, a K-tip and a C-tip, and the relative motion behaviors between the weld tip and the specimen, and between the specimens were analyzed. The weld stages defined using features of the displacement curve of the C-tip were similar to those of the K-tip. The relative motion between the weld tip and the upper specimen became dominant after weld stage II (weld time $t_w > 50$ ms). The relative motion between the weld tip and the upper specimen of the C-tip showed a larger vibration at the beginning of the weld compared to that of the K-tip, thus, resulting in greater weld microstructure disturbance during weld stage III. It was found that the difference in weld tool geometry explored affected microstructure growth through differences in relative motion.

**Figure 10.** Evolution of weld stage and joint strength with weld time.
Figure 11. Photographs of fractured specimens. (a) - (d) are joints produced using the K-tip, and (e) - (h) are joints produced using the C-tip.

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