Effect of Buffer Sheets on the Shear Strength of Ultrasonic Welded Aluminum Joints

Experiments showed the buffer sheets reduced sticking and part marking

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WELDING RESEARCH

ABSTRACT

Ultrasonic metal welding is a solid-state joining process that is extensively used by the electronics industry. Other industries also have a strong interest in extending its use in high-strength aluminum alloys, stainless steels, and other advanced materials. In some applications, adhesion between the tooling and parts, and marking of the parts can be issues. To address these issues, a series of experiments were conducted using buffer sheets of copper or zinc between the tool (horn) and the samples to be welded. The main objectives of this work were to reduce sticking between the horn and sample as well as reduce part marking. It was seen that the buffer sheets reduced the tool/part adherence (sticking) and part marking. It was believed that buffer sheets absorbed a portion of the ultrasonic energy reducing part marking. While the copper buffer sheets reduced the ultimate weld strength this effect was not observed with zinc buffer sheets. In addition, part thickness affected the impact of the buffer sheets. For example, thicker samples (3 mm) exhibited a greater loss in weld strength with the use of buffer sheets compared to thinner (2-mm) samples welded with buffer sheets.

Introduction and Background

Ultrasonic metal welding (UMW) — invented more than 50 years ago — is a process that consists of joining two metals by applying ultrasonic vibrations under moderate pressure. High-frequency vibrations (+20 kHz) locally soften the faying surfaces to form a solid-state weld through progressive shearing and plastic deformation. Figure 1A details a typical ultrasonic setup and motion. Preexisting oxides and contaminants are removed by the motion (scrubbing) producing pure metal/metal contact between the parts allowing intermetallic bonds to form. Beyer states that "Ultrasonic welding of metals consists of interrelated, complex processes such as plastic deformation, work hardening, breaking of contaminant films, fatigue crack formation and propagation, fracture, generation of heat by friction and plastic deformation, recrystallization, and interdiffusion" (Ref. 1). Also, it is worth mentioning that "the dominating mechanism for ultrasonic welding is solid-state bonding, and it is accomplished by two different processes: slip and plastic deformation" (Ref. 1).

Because tool/part adhesion (stickage) and part marking can be issues during manufacturing, finding a solution may allow UMW of aluminum fo be further utilized in industry. Copper is known to improve the strength of the aluminum as an alloying element (Refs. 2, 3). It is proposed here, that by increasing the strength of the aluminum alloy, the risk of horn tip penetration in the top part should be reduced. Also, by placing a Cu sheet betqeen the horn tip and the top part prior to ultrasonic welding, the tool/part adhesion should be greatly reduced because if the low/steel,Cu affinity, as well as the strengthening effect of Cu (Refs. 2, 3).

KEYWORDS

Aluminum Alloys
Friction Welding
Ultrasonic Welding
Part Adherence
Part Marking
Buffer Sheets

Figure 1 illustrates the buffer sheet placement and the part marking that can be experienced after UMW. It is seen that part marking is produced on both the horn and anvil sides, but the horn side exhibits relatively more marking. Thus, the focus of this work was to reduce part marking at the horn interface. While it is known that the welding tip and anvil must be designed properly to match the base material and part thickness, part marking remains an issue. For example, Gao (Ref. 4) reports successful welding with similar tip design.

As previously noted, zinc buffer sheets were also studied to reduce the risk of galvanic corrosion in long-term applications (Ref. 5).

In addition, while not reported in detail here, several tip coatings, namely hard-type coatings such as Balinit® C Coating, carbide coatings/insert, and plasma treatments, were also evaluated and found to have adverse effects on part/horn adhesion. That is to say, these coatings either increased sticking/part marking or promoted premature failure of the horn and were thus abandoned.

Objective

The main objective of this work was to characterize the use of buffer sheets to reduce part marking and sticking between the horn and sample. Because buffer sheet placement could be automated as is already done in the plastics industry, the proposed solution would increase productivity by reducing the effort required to separate the horn and part and increase part quality.

Experimental procedure

Experimental design

In order to determine the optimum weld energy value for the various amplitude settings, welds were made at various energy levels ranging between 800 and 5500 J. The weld energy was measured by the power supply in terms of electrical energy. The weld cycle was terminated once

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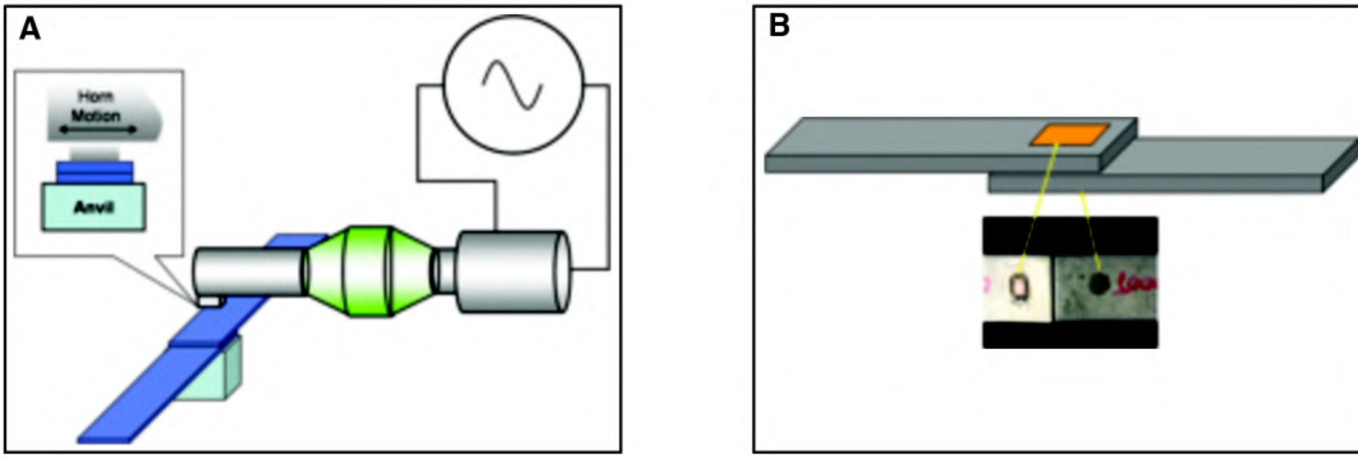

Fig. 1 — A — Illustration of ultrasonic metal welding; B — buffer sheet placement on top and part marking at the bottom.

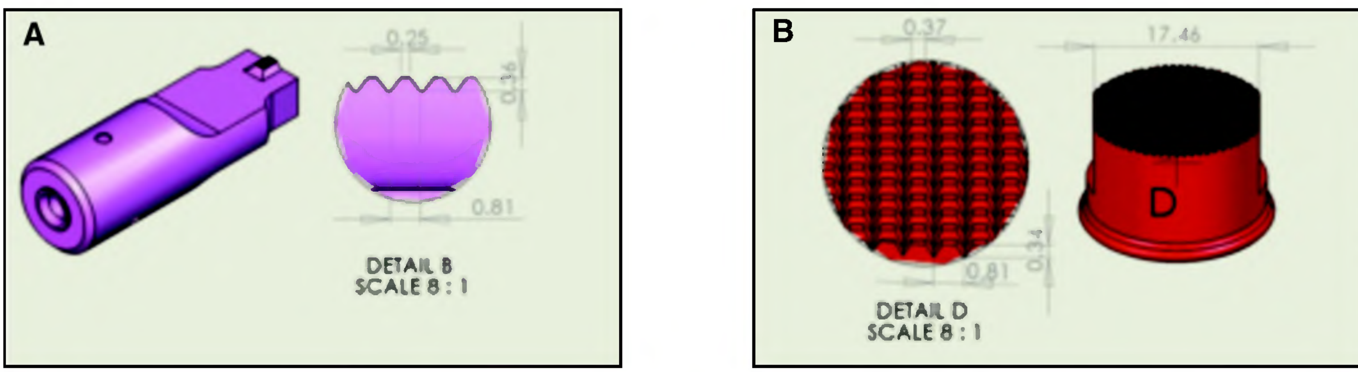

Fig. 2 — Design details (in mm) of the following: A — The welding tip; B — anvil tip.

the preselected value was achieved. This range was selected based on screening experiments that showed values above and below these values resulted in no welds or significant part damage, respectively. The welds were made in increasing order of weld energy level setting with increments of 500 or 1000 J and were not randomized. Ten samples were welded for each energy level setting. The weld amplitudes studied ranged from 43 to 60 μm_{pp} at the various energy values. Additional details of the amplitude settings are defined in the equipment section. The weld force was set to a constant value of approximately 3400 N (90% of the machine maximum capability) based on screening experiments that indicated lower weld force values resulted in inconsistent welding results independent of the amplitude setting.

Table 1 shows the variation of the amplitude and energy values studied in this paper with and without copper and zinc buffer sheets.

Materials

The UMW was completed with aluminum AA5754-H111 coupons with thicknesses of 2 and 3 mm. The samples were used in an "as-received" condition and were purchased from Novelis, Inc. The weld configuration was two 25.4- × 100-mm overlapping coupons, with a 25.4-mm (1-in.) overlap and the weld centered on the overlap. Copper and zinc buffer sheets were cut from approximately 0.1-mm-thick chemically pure sheet and were approximately 5 × 5 mm in size. In screening experiments it was found that thicker buffer sheets greatly reduced weld strength and thus a thickness of ~0.1 mm was selected.

Equipment

In order to ensure optimized conditions, both constant amplitudes (60 and 40 μm_{pp}) and the amplitude profiling (60–43 μm_{pp}) with buffer sheets (Cu or Zn) were studied. Amplitude profiling was included in this study because it has been shown to improve weld strength (Ref. 6). In more detail, with conventional UMW, the amplitude remains constant throughout the entire weld cycle. In contrast, with amplitude profiling the amplitude is adjusted to match the various phases of the weld. For example, initiating the weld with a relatively high amplitude then reducing it as the weld progresses, promotes a fast, relatively uniform weld that undergoes reduced shearing at the later stages of the weld cycle that enhances weld strength.

The weld amplitude was varied using a WPC-1 controller manufactured by Branson Ultrasonic Corp. Based on screening experiments, the switch-over mode was selected as time for amplitude profiling and was held constant at 2.0 s. The switch-over mode is the parameter that defines when the amplitude is switched from an initial value "A" (typically 60 μm_{pp}) to a secondary value "B" (typically 43 μm_{pp}). In this work, only time was evaluated as this is the simplest mode to visualize.

The horn was a standard knurled tip and the anvil was a standard "flex" anvil (designed by SonoBond Inc.). They are detailed in Fig. 2. In screening experiments a rigid anvil was used, but in all cases the resulting welds were extremely weak and thus, this anvil design was abandoned. It was theorized that with a rigid

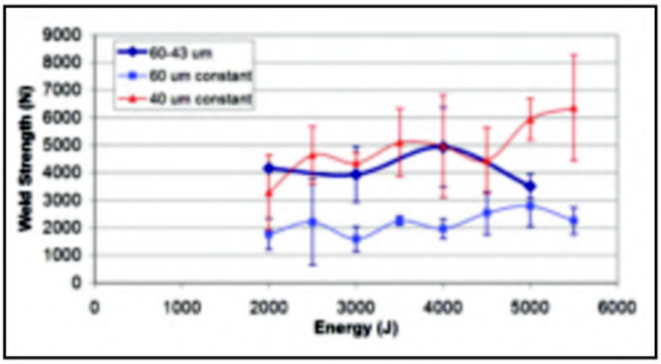

Fig. 3 — Weld strength with Cu buffer sheets for amplitude profiling and constant amplitude for 3-mm coupons.

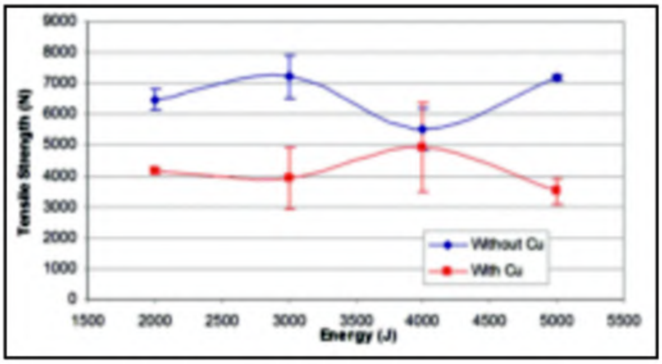

Fig. 4 — Weld strength vs. energy with amplitude profiling with and without copper buffer sheets for 3-mm samples.

anvil the weld was continuously exposed to high shear forces during the entire weld cycle, which fractured the resulting weld in the final phases of the weld cycle when the weld is being formed. In contrast, with a flexible anvil, which had sufficient rigidity to allow motion between the two samples, the relative motion between the anvil and weld tip was reduced as the weld grew in size and became stronger. While not reported here (see appendix) this effect was documented using a laser vibtrometer that recorded the instantaneous displacement of the anvil. A squeeze time of 0.2 s was used to allow the force to fully develop prior to activation of the sonics. The actuator was a specially designed pneumatic linear system that had linear rails to reduce rotation of the stack assembly during welding that had a maximum force of 3700 N, which is consistent with typical optimized weld forces reported by others (Refs. 7–12).

Table 1 — Amplitude and Energy for Coupons with and without Cu and Zn Buffer Sheets

Amplitude ($\mu m_{p\text{-}p}$)	3 mm Energy (J) with Cu Buffer sheet	3 mm Energy (J) w/o Cu Buffer sheet	2 mm Energy (J) with Cu Buffer sheet	2 mm Energy (J) w/o Cu Buffer sheet	3 mm Energy (J) with Zn Buffer sheet	3 mm Energy (J) w/o Zn Buffer sheet
60	2000 2500 3000 3500 4000 4500 5000 5500		2000 3000 4000 5000		2000 2500 3000 3500 4000 4500 5000 5500	
40	2000 2500 3000 3500 4000 4500 5000 5500		1000 1500 2000 2500 3000			
43					2000 2500 3000 3500 4000 4500 5000 5500	
60–43	2000 3000 4000 5000	2000 3000 4000 5000	900 1000 1100 1200 1300 1400 1500	800 900 1000 1100 1200	2000 2500 3000 3500 4000 4500 5000 5500	2000 2500 3000 3500

Characterization

All welds were tested in tension at a crosshead speed of 10 mm/min. The maximum sustained load was correlated to the ultimate strength. Shims were not used in the grips with the sample and thus bending stresses were not minimized. It is important to note that while weld size was generally proportional to weld energy, it was not recorded and only final weld strength was reported in terms of maximum load. Also, it should be noted that although the coupons were tested in tension, the welds were mostly in shear.

Results and Discussion

Study of the 3-mm Aluminum 5754 Coupons Using Cu Buffer Sheets

For those experiments involving Cu buffer sheets, weld strength as a function of the energy graph is seen in Fig. 3. It is seen that at the relatively high amplitude (60 μm_{pp}), the weld strength is relatively low and rarely exceeded 3000 N. This is due to shearing of the weld, which prevented proper joining of the faying surfaces. In more detail, the shearing promoted fracture of the faying surface at the end of the cycle. With the lower amplitude of 40 μm_{pp} and with amplitude profiling from 43 to 60 μm_{pp}, the weld strength was typically over 4000 N, suggesting that lower amplitudes enhance joining as previously reported (Ref. 6). It is important to note that with amplitude profiling a final amplitude of 40 μm_{pp} was not used because of frequent power supply overloads. That is to say that the available power from a power supply is generally proportional to amplitude setting. Thus, at lower amplitude settings, the maximum avail-

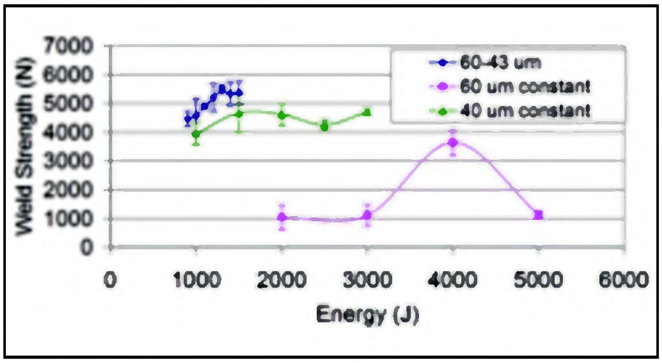

Fig. 5 — Weld strength with Cu inserts. Strength function of energy for amplitude profiling and constant amplitude with 2-mm coupons.

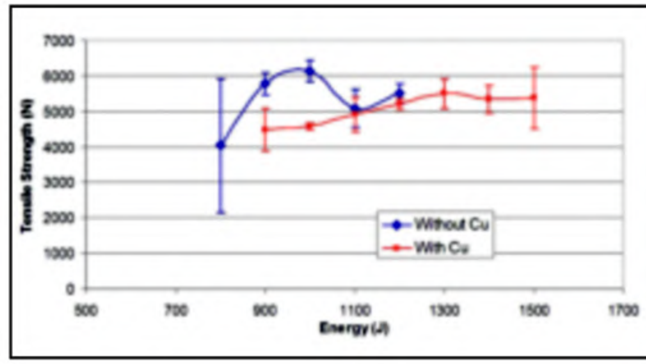

Fig. 6 — Weld strength vs. energy with amplitude profiling with and without Cu buffer sheets for 2-mm samples.

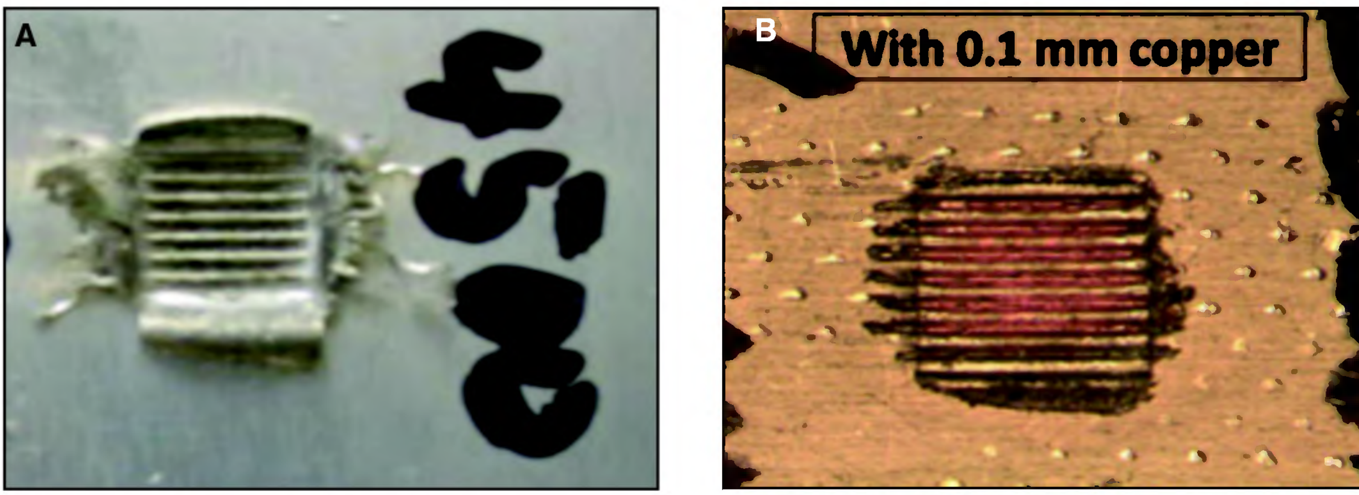

Fig. 7 — Part marking. A — Without, and B — with Cu buffer sheets.

able power is reduced. In more detail it is important to note that the maximum power capacity of the power supply is directly proportional to the set amplitude level. In addition, it is assumed that there is no difference between welds made with 40 and 43 μm_{pp}. It is seen that at the lower amplitude the weld strength exceeded 6000 N with weld energy of 5500 J. This most likely resulted from the lower amplitude at the end of the weld cycle allowing the weld to bond under lower shearing conditions, promoting good joining. In more detail, assuming a constant attenuation, shearing of the weld interface is proportional to the weld amplitude. It is important to note that without amplitude profiling, the cycle times for the welds made with the lower amplitudes were typically two to three times longer.

Because amplitude profiling was seen to have some benefits in the ultrasonic welding of aluminum, such as relatively high weld strength, Fig. 4 shows the weld strength as a function of energy only for welds made only with amplitude profiling. The graph compares the weld strength values of the samples welded with and without copper buffer sheets. It is seen that the maximum weld strength for the samples welded without buffer sheets was slightly over 8 kN. In contrast, the samples welded with copper buffer sheets had a maximum weld strength of ~5 kN. It is important to note that the copper buffer sheets noticeably reduced part marking and the tool/part adhesion as will be detailed later.

Study of the 2-mm Aluminum 5754 Coupons Using Cu Buffer Sheet

For the experiments involving Cu buffer sheets for the welding of 2-mm-thick 5754 coupons, weld strength as a function of the energy graph is seen in Fig. 5. Interestingly, the welds made with thinner samples produced higher weld strengths compared to the previous results with the thicker samples. For example, in the previously detailed experiments with thicker samples, the weld strength rarely exceeded 5000 N. However, with the thinner 2-mm-thick samples, it is seen that for many conditions, the weld strength exceeded 5000 N. With the thicker samples (3 mm), the amplitude is attenuated and inertial effects reduce the true amplitude at the faying surface. In contrast, with the thinner samples, the amplitude is less attenuated and thus welding is more effective. This is supported by the observation that with the thinner samples and higher amplitudes, where shearing of the fused joint promotes failure, the weld strength was typically only 1000 N and never exceeded 4000 N. It is also seen that amplitude profiling produced relatively high weld strengths. For example, with a constant amplitude of 40 μm_{pp}, the maximum weld strength was less than 5000 N. Higher weld energies (>3000 J) with a constant amplitude of 40 μm_{pp} experienced impossible welding due to complete sinking through coupons and were excluded from this study. When amplitude profiling was utilized, the weld strength was as high as 5500 N. In addition, when the copper buffer sheets were used, sticking and marking were reduced. As previously noted, welds made with a constant amplitude had cycle times two to three times longer compared to those welds made with amplitude profiling.

Due to the higher weld strengths that

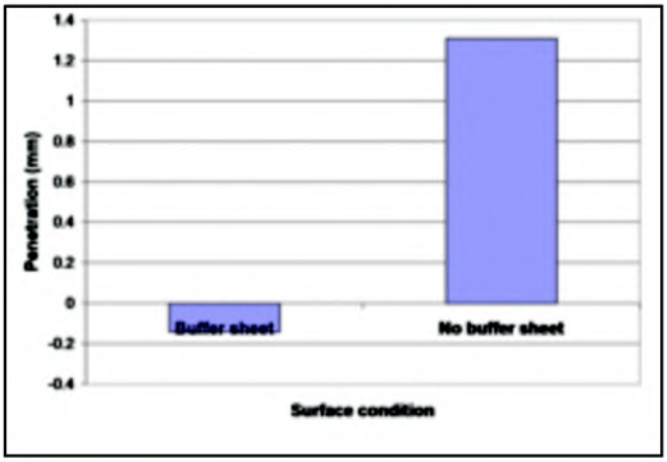

Fig. 8 — Penetration with and without buffer sheets (1200 J, 2-mm sample).

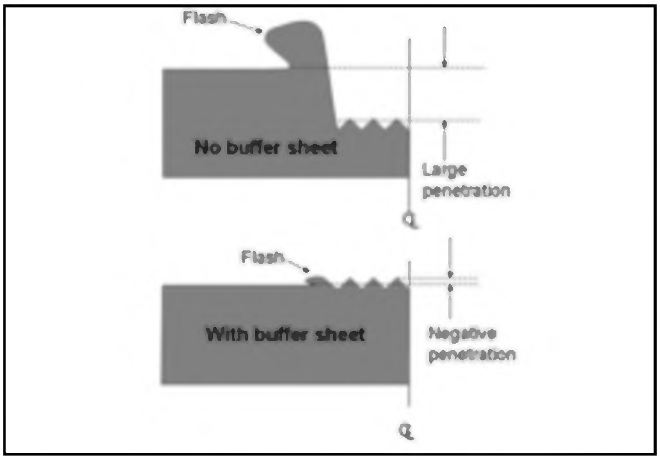

Fig. 9 — Illustration detailing penetration measurements at the weld centerline (CL).

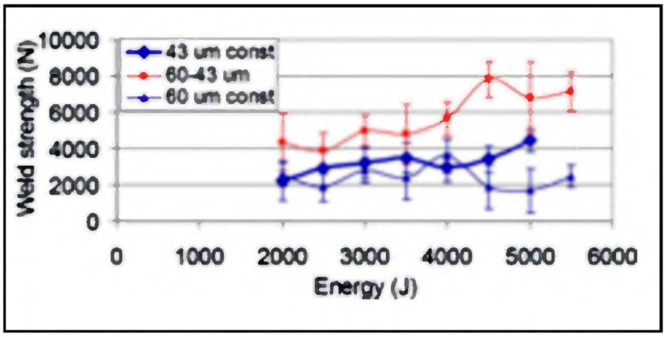

Fig. 10 — Strength vs. energy for amplitude profiling and constant amplitude with Zn buffer sheet.

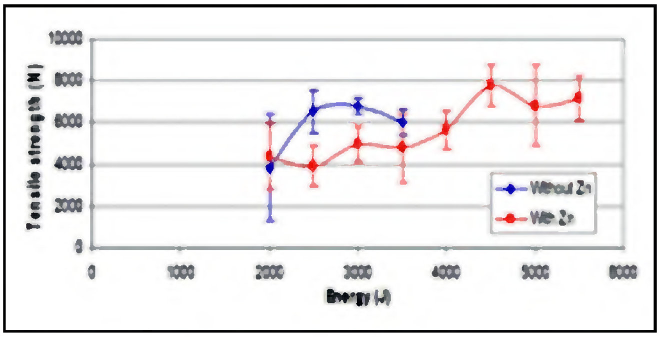

Fig. 11 — Weld strength function of energy (with and without Zn buffer sheet).

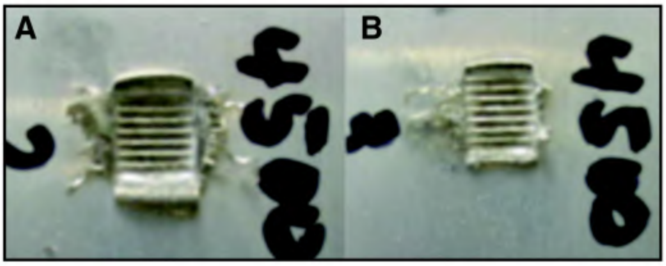

Fig. 12 — Part marking without (A) and with (B) Zn buffer sheets.

were observed from welds made with amplitude profiling, a more detailed study focused only on welding with amplitude profiling with and without copper buffer sheets. Figure 6 shows weld strength as a function of energy for 2-mm-thick samples welded with and without copper buffer sheets. The maximum weld strength achieved without copper buffer sheets was slightly over 6 kN. In comparison, the samples welded with copper buffer sheets had a maximum strength of ~5.5 kN. However, the copper buffer sheets reduced part marking and tool/part adherence. Welding was impossible due to complete sinking through samples beyond 1200 J for samples welded without buffer sheets and beyond 1500 J for samples welded with buffer sheets. Also, it can be seen that the standard deviation is, in general, lower for the samples welded with copper buffer sheets. It is also important to note that with the 2-mm-thick sample, weld strength was not significantly affected.

Figure 7A shows a photograph of part marking without the use of buffer sheets. It is seen that without a buffer sheet there is deep penetration and, consequently, noticeable part marking. In addition, disengagement of the part from the horn required relatively large forces. In contrast, Fig. 7B shows part marking made with the use of a copper buffer sheet. It is seen that the weld made with a buffer sheet exhibited less part marking.

To compare the depth of penetration for the welds made with and without a copper buffer sheet, the depth was measured using a depth gauge. For example, the depth of penetration for welds made with 2-mm-thick samples using 1200 J and an amplitude profile of 60–43 µm is shown in Fig. 8. In this figure, it is seen that the penetration for the sample made without a buffer sheet was much larger compared to the weld made with the buffer sheet. It is important to note that the penetration is negative for the weld made with a buffer sheet because of the displacement of material from the knurled pattern on the horn. In more detail, because the penetration was nearly zero, the knurled pattern "pushed" material above the surface as depicted in Fig. 9.

Study of Aluminum 5754 Coupons Using Zn Buffer Sheet

Figure 10 shows a graph of weld strength as a function of energy with zinc buffer sheets using a constant amplitude (60 and 43 μm_{pp}) and amplitude profiling (60 to 43 μm_{pp}). It is seen that with constant amplitudes of 60 or 43 μm_{pp}, the weld strength is relatively low and rarely exceeded 3500 N. This is most likely due to shearing of the weld, which prevented proper joining of the faying surfaces. With amplitude profiling of 43 to 60 μm_{pp}, the weld strength was typically ~ 8000 N. With amplitude profiling and with the zinc buffer sheets, part marking and tool/part adherence were reduced. Also, the cycle times for the welds made with lower amplitude were typically two to three times longer.

Additional experiments with zinc buffer sheets and amplitude profiling were conducted. For example, Fig. 11 shows weld strength as a function of weld energy with and without zinc buffer (amplitude profiling only). It is seen that in the energy range of 2000–3000 J, the joint shear strength for the coupons welded with Zn buffer sheets is lower compared to the joint shear strength of the coupons welded without the buffer sheets. However, for the energy range beyond 4000 J, a much higher value of the weld strength was noticed; that is, 8000 N, which was never achieved without Zn buffer sheets. It is important to note that there are no data for the weld strength of coupons welded without buffer sheets beyond 4000 J because the weld was impossible due to complete sinking through the coupons.

Part marking was also reduced, as can be seen from the Fig. 12A (without zinc buffer sheets) and Fig. 12B (with Zn buffer sheets). Thus, in summary it is seen that the zinc buffer sheets are more effective in reducing part marking and do not reduce weld strength, which may be due to zinc's relative hardness.

Conclusions

Placing buffer sheets of copper or zinc between the tool (horn) and the top part prior to the ultrasonic welding of aluminum reduced tool/part adhesion and part marking. Also, the use of zinc buffer sheets during the ultrasonic welding of aluminum 5754 alloys resulted in higher maximum weld strength values compared to using copper buffer sheets. It was seen that copper buffer sheets reduced weld strength and this effect is more pronounced with thicker (3-mm) weld samples.

Thus, in summary:

- Buffer sheets significantly reduced part marking and part/tool adhesion.
- Zinc buffer sheets resulted in higher weld strength compared to copper buffer sheets.
- Copper buffer sheets reduced weld strength, especially for thick samples.

Acknowledgments

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Appendix

The chart shown in Fig. 13 follows details motion of the anvil tip as measured with a laser vibrometer. As seen in the figure, the motion of the tip increases as the weld cycle progresses. This confirms that as the weld progresses, there is less relative motion between the weld tip and anvil.

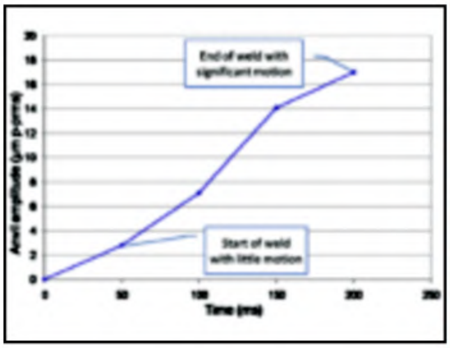

Fig 13 — Motion of the anvil tip as measured with a laser vibrometer

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