Weldability of Thin Sheet Metals during Small-Scale Resistance Spot Welding using an Alternating-Current Power Supply

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The resistance weldability of 0.2-mm-thick sheet aluminum, brass, and copper in small-scale resistance spot welding (SSRSW) was studied. The effects of electrode materials and process parameters on joint strength and nugget size were investigated. The welding current ranges for SSRSW of the sheet metals were determined based on the minimum current that produced a required nugget diameter and maximum currents that did not result in electrode-sheet sticking or weld metal expulsion. A qualitative analysis indicated that resistance weldability of the metals is not only determined by their resistivity (or thermal conductivity) but is also affected by other physical properties (such as melting point, latent heat of fusion and specific heat).

Key words: Small-scale resistance spot welding, weldability, thin sheet metal, joint strength, electrode materials, process parameters

INTRODUCTION

Small-scale resistance spot welding (SSRSW) is one of the microjoining processes, in which a weld is formed between two workpieces through the localized melting and coalescence of a small volume of the material(s) due to the resistance heating caused by the passage of electric current. The heat obtained can be expressed as[1,2]

$$Q = I^2Rt \tag{1}$$

where, Q is the heat generation, I is the welding current, R is the resistance of the workpieces, and t is the duration of the current (weld time). The resistance includes contact resistance at the electrode/workpiece interfaces and at the faying interface between the two workpieces, and bulk resistance of the workpieces and electrodes. These resistance values change during the process and their relative magnitudes control the process. Among them, the contact resistance at the faying interface, which is influenced by material characteristics (such as cleanliness, surface roughness, hardness and plating materials), and electrode force, is believed to be a critical factor affecting the process, especially at the early stages in the heating cycle.[3–7] The formation of a molten metal nugget depends on the interplay of heat generation and heat dissipation in the workpieces. The latter is governed mainly by the material's thermal conductivity and the geometry of the workpieces and electrodes. Since, for most metals, the thermal and electrical conductivities are correlated, it is believed that electrical resistivity is one of the most important materials' properties affecting materials' weldability during resistance spot welding (RSW).[3,7]

Extensive research and development work has been carried out in the area of "large-scale" RSW (LSRSW) of sheet metals for applications in the automotive industry, mainly on relatively thick sheet steels (thicker than 0.6–0.8 mm), and, to a much smaller extent, on sheet aluminum-based alloys.[3,7] In a study of RSW of 0.8-mm-thick steels, Dickinson et al.[4] proposed that RSW comprises a series of stages, namely, (a) surface break down, (b) asperity collapse, (c) heating of the workpieces, (d) molten nugget formation, and (e) nugget growth and mechanical collapse.[4] Similarly, Gould[5] indicated that nugget formation and development could be characterized as a function of welding variables (either weld time or current) by four steps: (a) incubation, (b) rapid growth, (c) steadily decreasing growth rate, and (d) weld metal expulsion. Weld metal expulsion (WME) occurs when the diam-

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eter of the molten metal is larger than the contact diameter and severe WME can reduce the joint strength because of the loss of metal volume.[3–7]

According to the American Welding Society,[7] "weldability is the capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service." There are many ways to define the weldability of a material in RSW (electrode tip life, welding current level and current range, etc.); the current range and the electrode life are two most commonly used tests. The current range is determined by evaluating the minimum and maximum current levels (under certain process conditions) permissible for required joint properties. The automotive experience shows that the strength of resistance spot welded joints can be correlated to the diameter of the weld nuggets; therefore, under certain process conditions, a certain level of welding current is generally required to produce a weld with a minimum nugget diameter.[3–5] However, too high a welding current may result in WME and hence a reduction in joint strength. The electrode deteriorates during welding because of the interactions between electrode tip and workpieces. Electrode tip life may be characterized as the number of welds that can be made before loss of properties of the welds. The current range test is most commonly used since the electrode life test is generally very time consuming. However, there is an increasing research interest on electrode tip life since reduced electrode life becomes one of the major factors affecting resistance weldability of coated steels and aluminum alloys for the automotive applications.[8,9]

Electrode-sheet sticking (ESS) occurs when excessive heat generation produces locally melted areas at the electrode-sheet interface.[8] If the molten metal solidifies before the electrodes separate from the workpieces at the end of the weld cycle, the workpieces may stick to the electrodes and a small force would be needed to separate them. If the molten metal remained molten when the electrodes separated from the workpieces, the welding operator would not experience the electrode-sheet sticking; however, the local surface areas affected by melting (e.g., resultant voids) may be revealed by microscopic examination. If the welding current is increased to beyond the level when ESS occurs, the electrodes might weld to the workpieces. ESS should be minimized because it contributes to reduced electrode tip life.[8]

The application of resistance welding in the fabrication of electronic devices and components (e.g., batteries for implantable pacemaker) is generally termed as micro-, fine, or small-scale resistance welding since the metal sheets to be welded are relatively thin or small in diameter (<0.5 mm).[10–13] Little work has been published in the open literature on small-scale resistance spot welding (SSRSW) despite the ever-increasing applications of the technology. Because of limited information available, it is a common practice for production engineers to "scale down" the welding conditions suggested for "large-scale" RSW (e.g., from Reference 3) to suit their welding requirement. However, there are many differences between SSRSW and LSRSW, e.g., SSRSW uses different welding equipment (with much more precise electrical and mechanical control), and much lower electrode force. Furthermore, materials to be welded in SSRSW are mostly non-ferrous metals.[13] The objectives of this work are to study the weldability of thin sheet aluminum (Al), brass, copper (Cu), and develop practical guidelines for selection of process parameters and electrode materials for SSRSW of thin sheet metals.

MATERIALS AND EXPERIMENT PROCEDURE

Base metals used in this study included 0.2-mm-thick Al (commercially pure 1100-H18, full-hard temper), brass (70 wt.%Cu-30 wt.%Zn, half-hard cold rolled), Cu (commercially pure 110, annealed). Lap-welded joints (Fig. 1) were made using test coupons cut to approximately 40-mm long and 6-mm wide. Joint quality was evaluated using a peel test (Fig. 1) that was performed using a Chatillon Digital Force Gauge DFIS 2 at a speed of 38 mm/min. Nugget

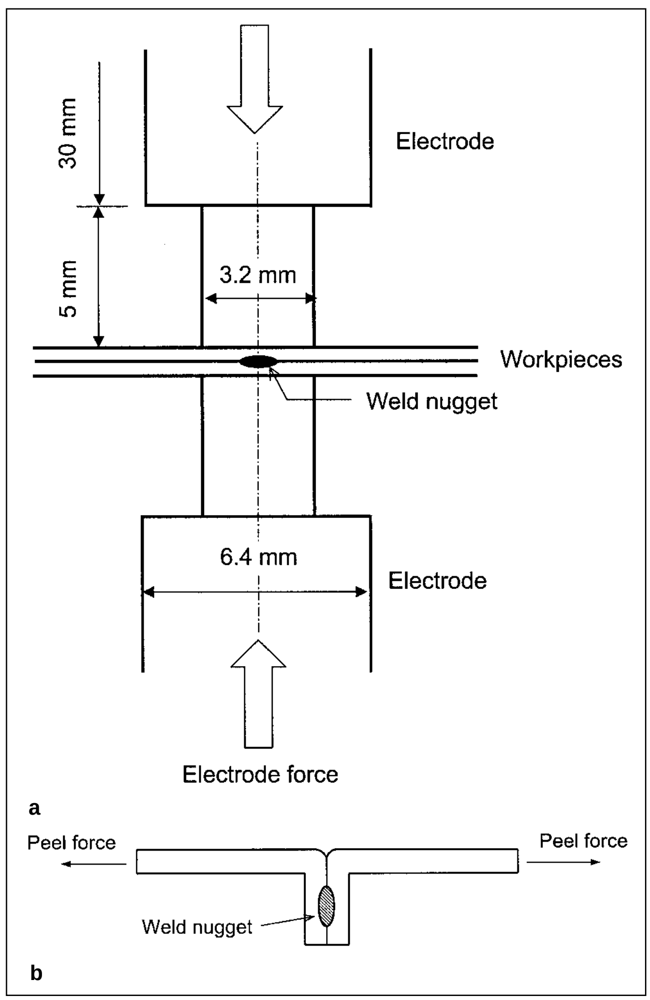

Fig. 1. Schematic of setup for (a) resistance spot welding and (b) peel test

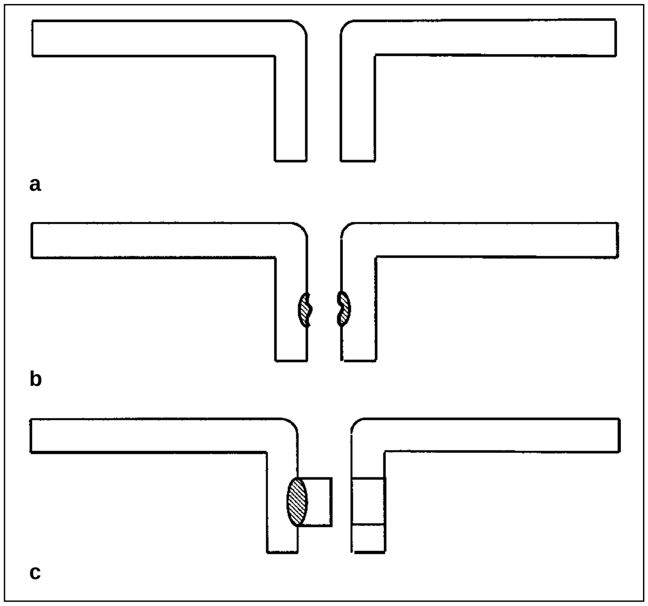

Fig. 2. Schematic showing joint failure modes during peel test: (a) failure along interface, (b) failure through nugget, and (c) failure as a button pullout.

diameter was estimated by measuring the diameter of pullout buttons during the peel test. Peel-tested samples were also examined under stereomicroscopy and scanning electron microscope (SEM) for the existence of expelled metal trapped between the sheets, which is considered to be the result of WME. The weldability of these materials was evaluated by their permissible welding current ranges. Although electrode tip life was not quantified in this work, ESS was monitored through SEM examination of the sheet surfaces that were adjacent to electrodes during welding.

An alternating-current (at 60 Hz) power supply was used for SSRSW; the RMS (Root Mean Square) current values were measured using a Miyachi MM-336A weld checker. Both Class 2 (chromium copper alloy) and Class 14 (molybdenum) electrodes[3] used in this work were commercially available at a tip-face diameter of 3.2 mm and a shank diameter of 6.4 mm (Fig. 1). Unlike LSRSW,[3,7] the electrodes were not water-cooled during SSRSW.

The whole welding process was semi-automatically controlled, i.e., an air-pressure system was triggered by a foot pedal to apply electrode force after two overlapped specimens were manually placed between the opposing electrodes. Welding current was delivered to the stack after the force had reached a preselected value. Welding current, rise time (fixed at 2 cycles in this study), and weld time were all preselected as inputs on the welding controls; however, squeeze time was not measured and, more importantly, cooling time were neither controlled or measured. Prior to welding, the sample surfaces were cleaned using methanol.

RESULTS

Various failure modes were observed during the peel testing of welded joints, namely, interface failure, weld failure, and button pullout (Fig. 2). Interface failure was due to lack of bonding or only weak bonding between sheets (Fig. 2a). Once a weld nugget formed, joints generally failed through the nugget when the nugget diameter was small or by a button pullout when it was above a certain size (Fig. 2b or c).

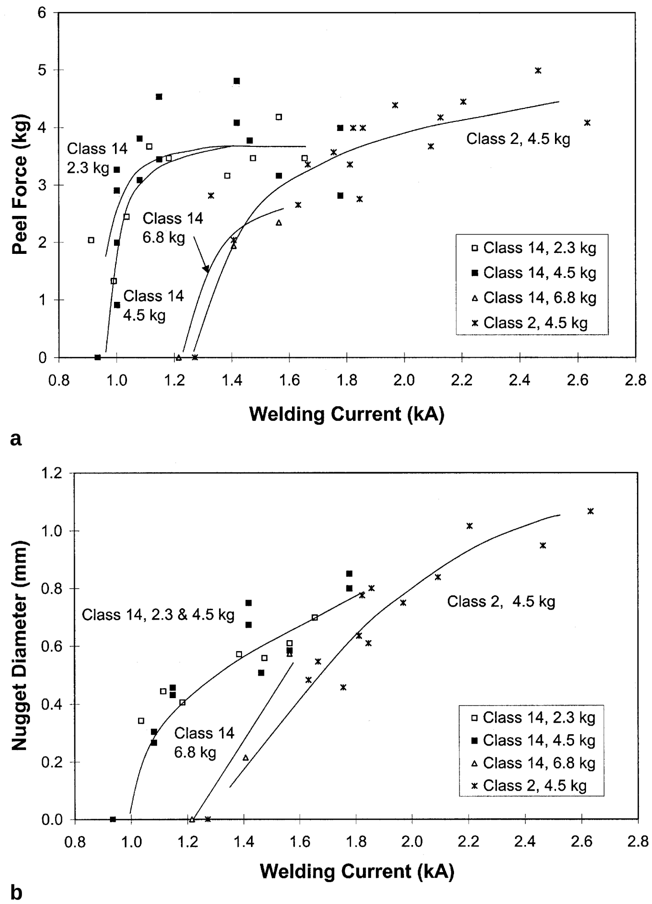

Fig. 3. (a) Peel force and (b) nugget diameter versus welding current using different electrodes (Class 2 and Class 14) and electrode forces (in kilogram) for the brass joints. Weld time is 8 cycles.

Brass

Figure 3 shows the plots of peel force or nugget diameter versus welding current for the brass joints when using Class 2 or Class 14 electrodes, and at a weld time of 8 cycles. Both welding current and electrode force affected nugget size and joint strength. Stereoscopic and SEM observations indicated that weld nuggets generally appeared very porous, which is believed due to the very low boiling temperature of zinc (907°C). Zinc will volatilize from the molten metal even with slight superheat.[14]

When using Class 2 electrodes, WME (Fig. 4) started at a welding current of about 2.0 kA (corresponding to a nugget diameter of about 0.8 mm). ESS was not experienced; however, surface voids were observed when the welding current was 2.6 kA (Fig. 4). If a minimum nugget diameter of 0.4 mm (corresponding to a joint strength of about 3 kg) is required, the minimum current needed is about 1.6 kA. The maximum permissible current can be set at 2.6 kg since

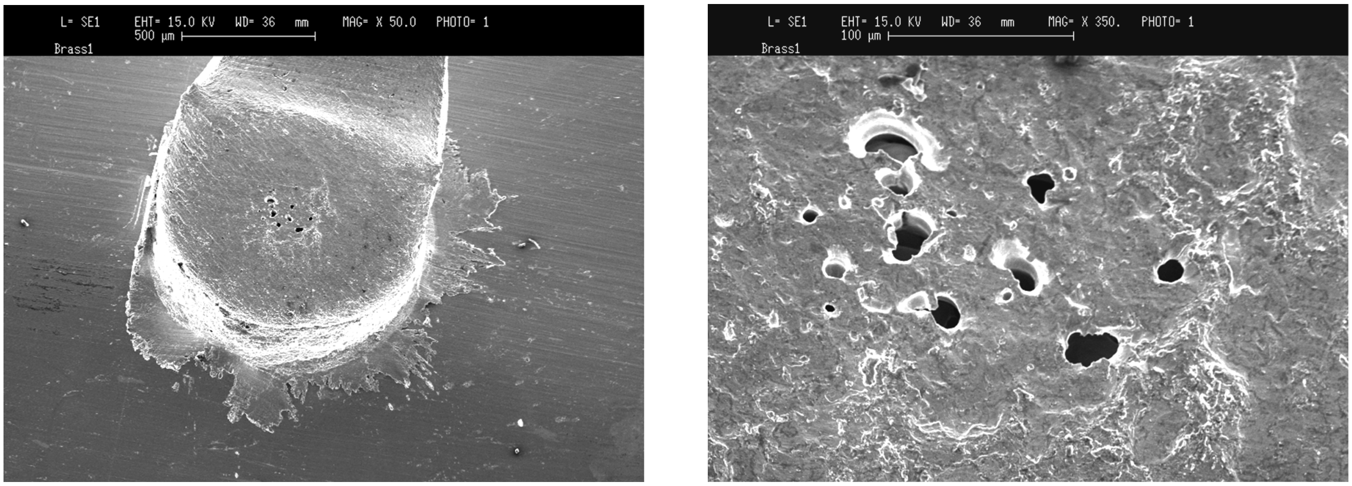

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Fig. 4. (a) An example of a pulled button from a brass joint with 2.6-kA welding current, Class-2 electrodes, 4.5-kg electrode force and 8-cycle weld time. Note the metal that was squeezed out during WME (pointed by arrow) and voids at the button surface; (b) details of the voids at the button surface.

Table I. Welding Current (in kiloamps) for 0.4-mm-Diameter Nugget, WME, and ESS

Sheet Metals	Electrodes	Minimum*	Expulsion	Sticking	Suggested Range
Al	Class 2	1.1	2.0	>2.1	1.1-2.1
	Class 14	0.7	1.0	~1.1	0.7-1.0
Brass	Class 2	1.6	2.0	2.6	1.6-2.6
	Class 14	1.2	>1.8	~1.4	1.2-1.4
Cu	Class 2	≥3.5	3.8	2.8	—
	Class 14	≥2.2	—	2.0	—

* The minimum current is determined to produce 0.4-mm-diameter of weld nuggets. Electrode force is 4.5 kg and weld time is 8 cycles.

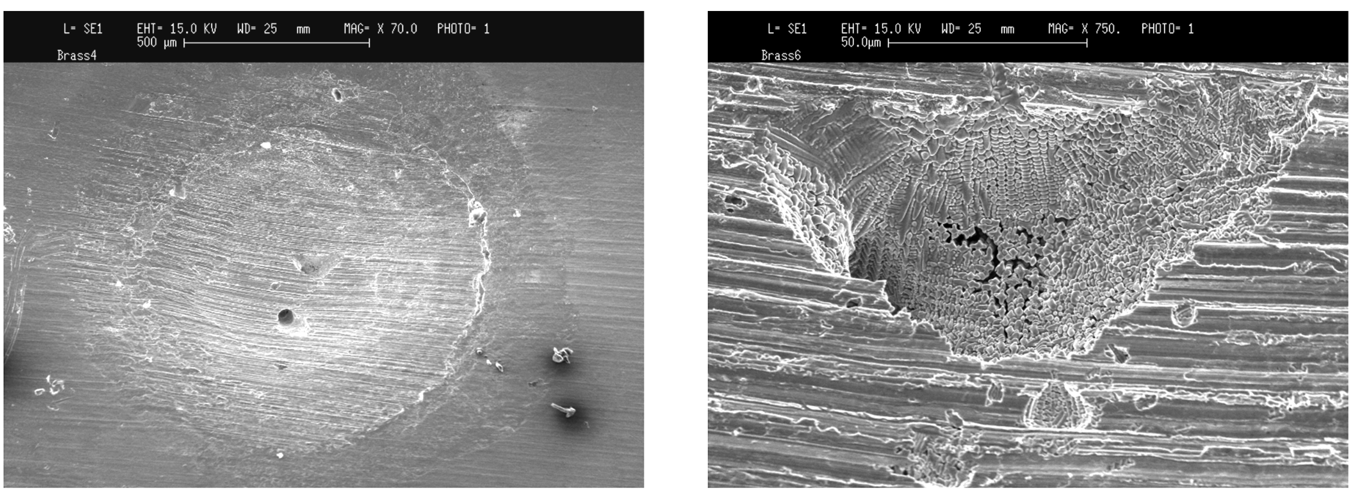

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Fig. 5. (a) SEM micrograph showing a sheet surface that was adjacent to an electrode in a brass joint using Class-14 electrodes, 4.5-kg electrode force, 1.4-kA welding current and 8-cycle weld time. Note a big hole resulting from molten metal and a melted area (pointed by an arrow); (b) Details of the area that is pointed out by an arrow in (a). Note the solidification patterns and many other small melting areas.

WME did not result in a reduction in joint strength and severe ESS reduces the electrode tip life. Therefore, the current range for SSRSW of brass using Class-2 electrode, 4.5-kg electrode force and 8-cycle weld time can be recommended as 1.6–2.6 kA (Table I).

When using Class 14 electrodes, no WME was observed at welding currents up to 1.8 kA. Increasing electrode force from 4.5 kg to 6.8 kg increased the current threshold to form a weld from about 1.0 kA to 1.2 kA (Fig. 3). ESS started at welding current of 1.2–1.6 kA; increasing electrode force appeared to reduce the tendency of ESS. If again a minimum 0.4-mm

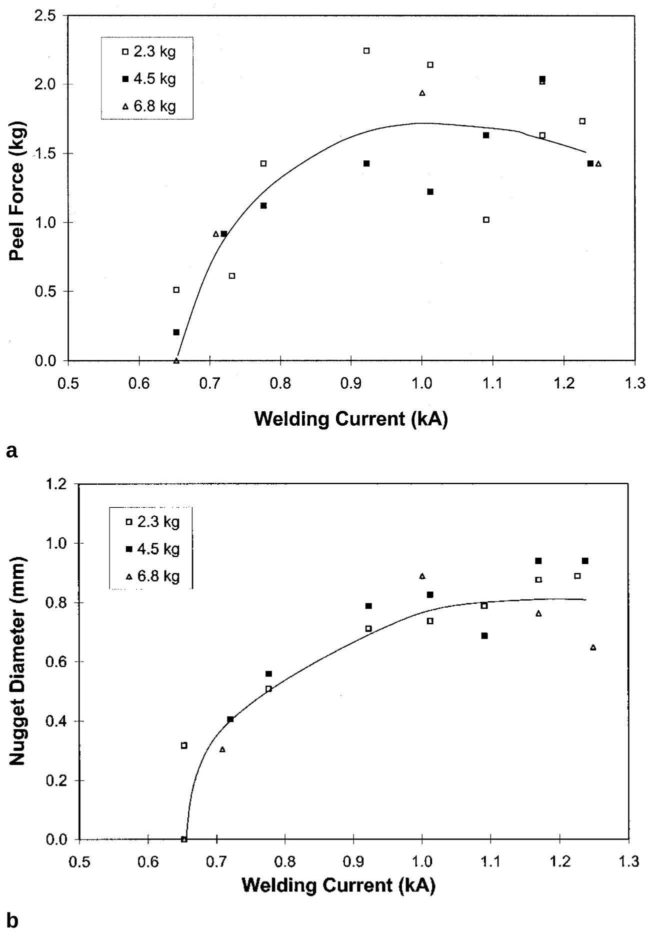

Fig. 6. (a) Peel force and (b) nugget diameter versus welding current for the Al joints using Class-14 electrodes, 8-cycle weld time and different electrode forces (in kilogram).

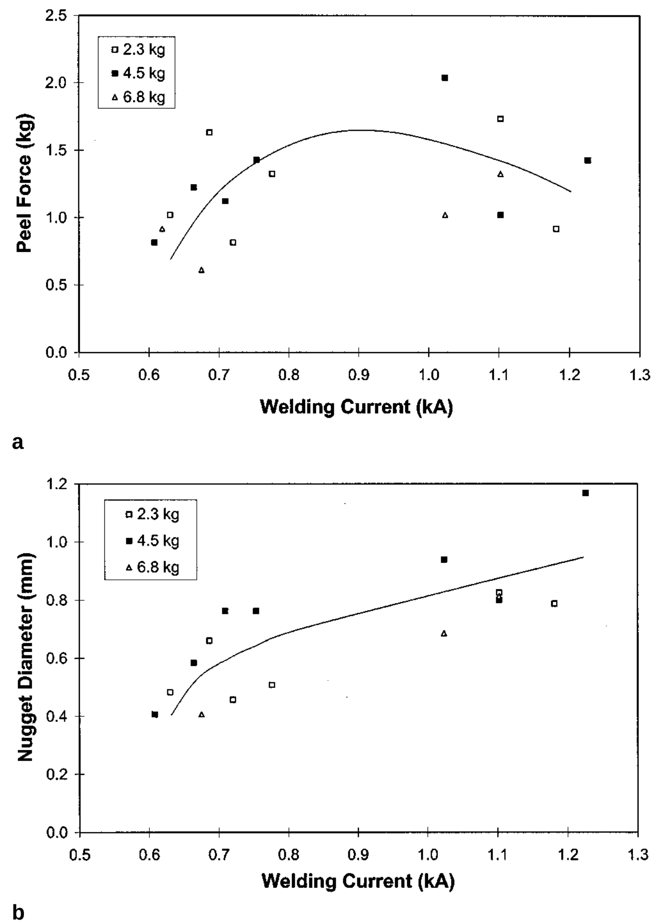

Fig. 7. (a) Peel force and (b) nugget diameter versus welding current for the Al joints using Class-14 electrodes, 13-cycle weld time and different electrode forces (in kilogram).

nugget diameter is required and a severe ESS is to be avoided, the current range for SSRSW of brass using Class-14 electrode, 4.5-kg electrode force and 8-cycle weld time can be selected as 1.2–1.4 kA (Table I).

A comparison of the minimum welding current indicates that a lower welding current was needed to join brass when using Class 14 electrodes compared with that when using Class 2 electrodes (Fig. 3 and Table I). However, ESS was more severe when using Class 14 electrodes. The onset current for ESS is lower than that for WME when using Class 14 electrodes, but higher than that for WME when using Class 2 electrodes (Table I). It is believed that ESS was caused by local melting at the electrode-sheet interface (Figs. 4 and 5). When using Class 14 electrodes, the ESS was worse because higher electrical resistivity and lower thermal conductivity of Class 14 electrodes compared to Class 2 electrodes would result in a higher temperature at the electrode-sheet interface.

Aluminum

Figures 6–8 show the plots of peel force or nugget diameter versus welding current for the Al joints. No effect of electrode force on joint strength and nugget diameter was observed when welding Al, which is different from the welding of brass. The reason may be due to the existence of tenacious aluminum oxide.

When using Class 14 electrodes, increasing welding current increased the joint strength first, and then decreased the joint strength, which may be the result of WME and/or increased softening of the heat-affected zone (HAZ). At 8-cycle weld time (Fig. 6), WME started at a welding current of about 1.0 kA (corresponding to a 0.8-mm nugget diameter approximately); large voids were observed on pullout buttons when WME occurred. ESS was experienced when welding current exceeded 1.0–1.2 kA; increasing electrode force appears to decrease the tendency of ESS. SEM analysis showed the ESS was again caused by Al surface melting (Fig. 9). Increasing weld time decreased the current threshold to form a weld but appeared to reduce the joint strength for the higher current values (comparing Fig. 6 to Fig. 7) and increase the tendency of ESS and WME. The current range would be recommended as 0.7–1.0 kA for SSRSW of Al using Class-14 electrodes, 4.5-kg electrode force and 8-cycle weld time (Table I). The minimum current is determined at a 0.4-mm nugget diameter (corresponding to a joint strength of about 0.8 kg). The maximum current is set at the onset current for WME since the joint strength started to decrease.

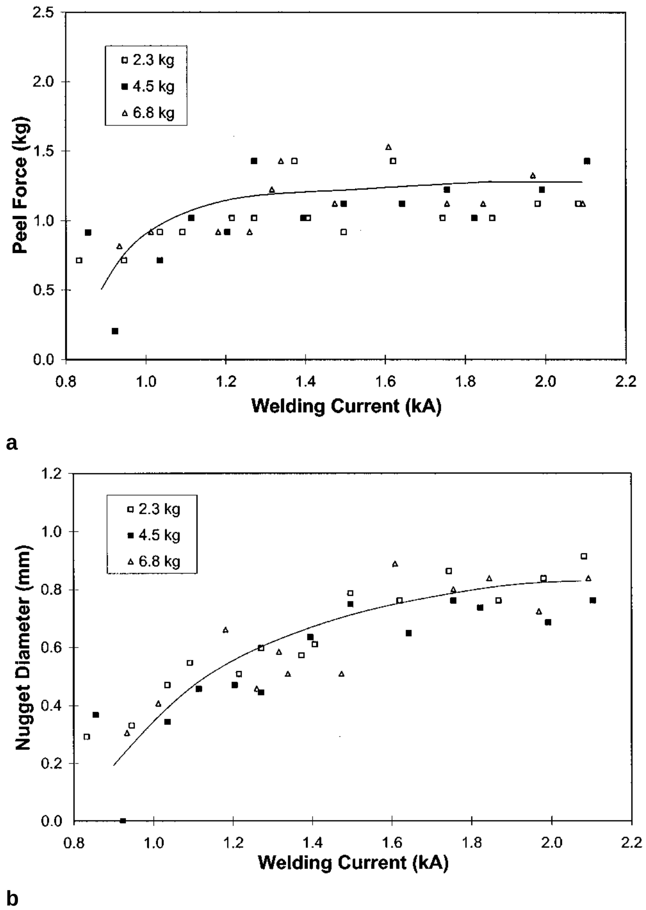

Fig. 8. (a) Peel force and (b) nugget diameter versus welding current for Al joints using Class-2 electrodes, 8-cycle weld time and different electrode forces (in kilograms).

When using Class 2 electrodes, WME started at a welding current of about 1.7 and 2.0 kA (corresponding to approximately 0.7-mm and 0.8-mm nugget diameter) when the electrode force was 2.3 kg and 4.5 kg, respectively. There is no WME observed at welding currents up to 2.1 kA when the electrode force was 6.8 kg. Therefore, increasing electrode force decreased the tendency of WME. No ESS was experienced when welding currents were up to 2.1 kA. Although Fig. 8 appeared to show that increasing electrode force decreases the current thresholds to form a weld, but the data is very scattered and a regression analysis indicated that this effect is not statistically significant (assuming a confidence level of 90%).[15] A limited number of trials also indicated no decrease in joint strength and nugget diameter when the weld time was reduced from 8 cycles to 4-6 cycles.[15] The current range would be recommended as 1.1–2.1 kA for SSRSW of Al using Class-2 electrodes, 4.5-kg electrode force and 8-cycle weld time (Table I). The minimum current is again determined based on a minimum 0.4-mm nugget diameter. The maximum current is set at 2.1 kA since the joint strength did not decrease when the current is larger than the onset current for WME.

Similar to the welding of brass, a lower welding current was needed to join Al when using Class 14 electrodes compared with that when using Class 2 electrodes. However, the permissible current was much smaller when using Class 14 electrodes than that when using Class 2 electrodes (Table I).

Copper

There was only limited success in SSRSW of Cu. The reasons are that the power required is very high due to very high thermal conductivity and low electrical resistance of Cu, and the high heat generation causes severe ESS or even welding between the Cu sheets and electrodes.

When using Class 2 electrodes, the peel force was about 1 kg when welding current was about 2.5–3.0 kA (Fig. 10). Joint strength could be further improved by increasing welding current; however, ESS became increasingly severe as well, and the electrodes and Cu sheets welded together when the welding current was 3.8 kA (Fig. 11). WME also occurred when the welding current was 3.8 kA. The joints produced at this current level achieved a joint strength of 3–4 kg and the diameter of the pullout button was about 1 mm. Limited trials at shorter weld time (4–6 cycles) has shown that weld time has little effect on the nugget size and joint strength;[15] therefore, welding using Class 2 electrodes can be done at a shorter weld time than 8 cycles.

When using Class 14 electrodes, the joint started to form at a welding current of about 2.0 kA and the peel force was about 1 kg (Fig. 10). ESS was observed in all

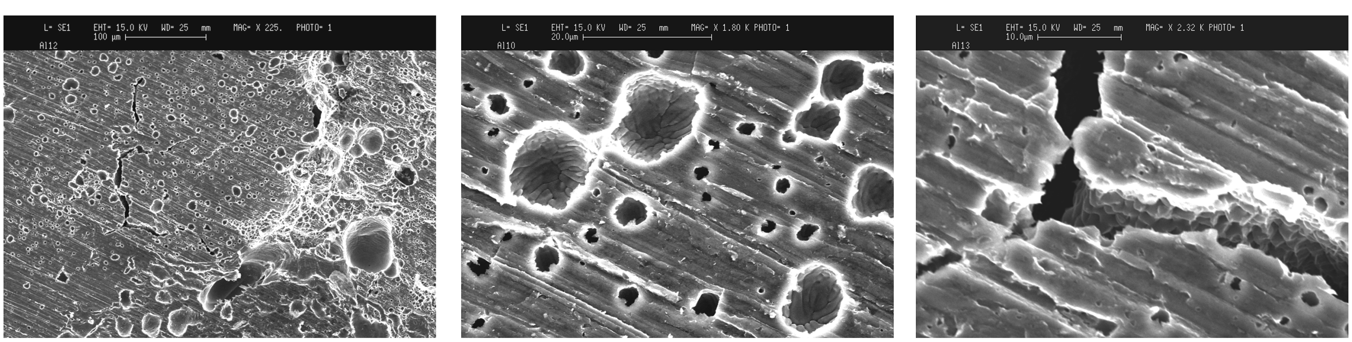

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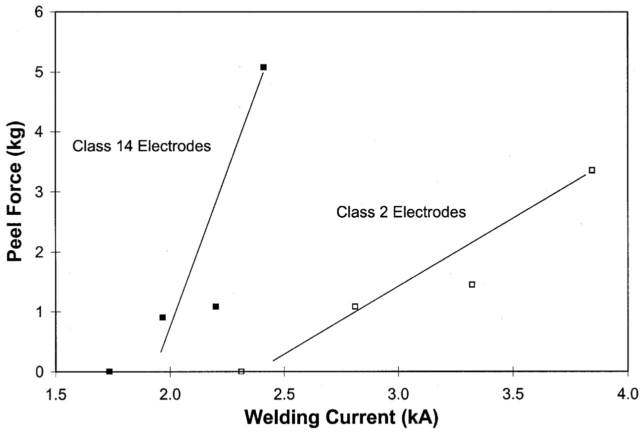
Fig. 9. (a) SEM micrograph showing a sheet surface adjacent to an electrode in an Al joint using Class-14 electrodes, 4.5-kg electrode force, 1.1-kA welding current and 8-cycle weld time. Details of (b) the surface melting holes and (c) the melting at grain boundaries in (a).



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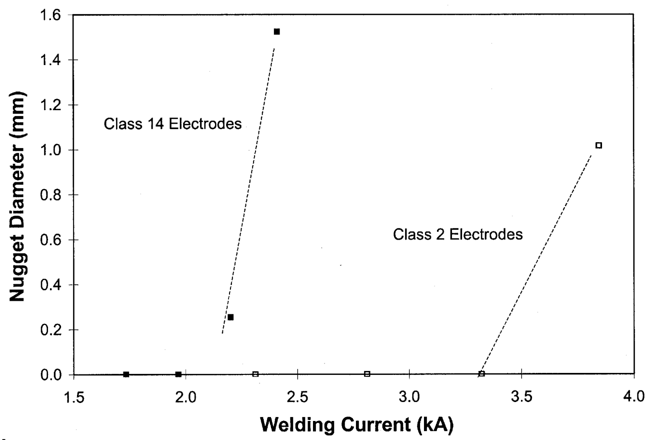

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Fig. 10. (a) Peel force and (b) nugget diameter versus welding current for the Cu joints using 4.5-kg electrode force, 8-cycle weld time and different electrode forces.

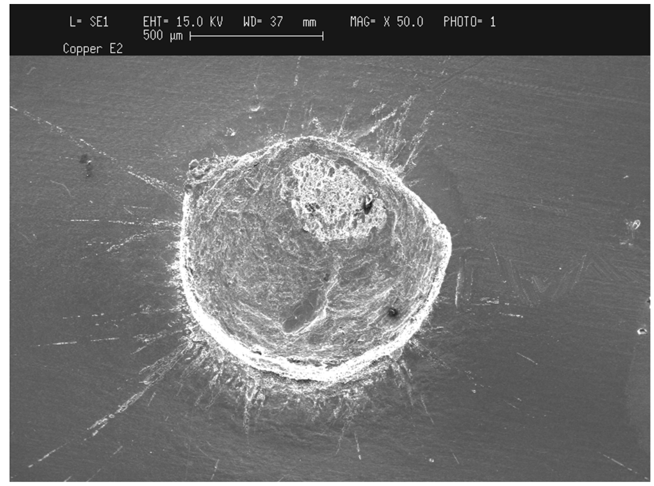
of these joints (Fig. 12). Joint strength was improved to about 5 kg when the welding current was about 2.4 kA. However, it was obvious from the color change at both the electrode tips and Cu specimen that they were over-heated. Joint strengths were decreased to 1–2.5 kg at reduced weld times of 2–6 cycles when the welding current was held constant at 2.4 kA. This indicates that weld time has a much larger effect on the nugget formation and joint strength when using Class 14 electrodes compared to that when using Class 2 electrodes.

Cu is one of those metals that are the least suitable for RSW because of its low electrical resistivity and high thermal conductivity.[3,7] Only limited success was achieved in this study. Observations on WME and ESS when using different electrodes were similar to those for Al and brass. The effect of weld time on nugget formation and joint strength was clearly shown when using Class 14 electrodes. Further work is needed to study the SSRSW of Cu because of its wide use in electronic applications.

DISCUSSION

Weldability of Sheet Metals: Process Parameters

Process parameters (welding current, electrode



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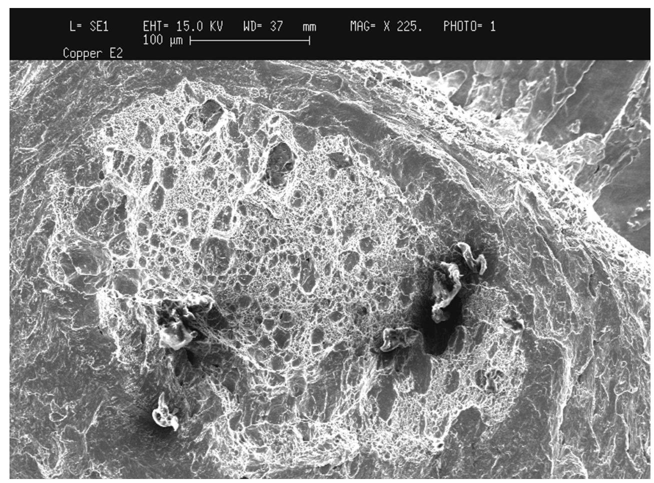

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Fig. 11. (a) Pullout button from a Cu joint using Class-2 electrodes, 4.5-kg electrode force, 8-cycle weld time and 3.8-kA welding current. Note the WME and also a fractured area on the top of the button pointed by an arrow. (b) Details of the area that is pointed out by the arrow in (a). Fractured surface was caused by the weld between the electrode and sheet Cu.

force, weld time, etc.) all may affect the joint strength and nugget size. However, welding current is the most significant variable affecting nugget formation and growth because the power generated is proportional to the square of welding current as indicated in Eq. 1. The requirement for welding current is also related to other process variables, e.g., lower welding current was needed when using Class 14 electrodes compared with that when using Class 2 electrodes because of the higher electrical resistance and lower thermal conductivity of the Class 14 electrodes.

When welding brass, electrode force strongly affects the current threshold to form a weld since electrode force strongly influences the contact resistance by plastically deforming local contact points and breaking down surface contaminant layers.[16] Once a molten metal zone is formed, contact resistance is greatly reduced and its role in nugget development is decreased. Although lower electrode force could reduce the current requirement for forming

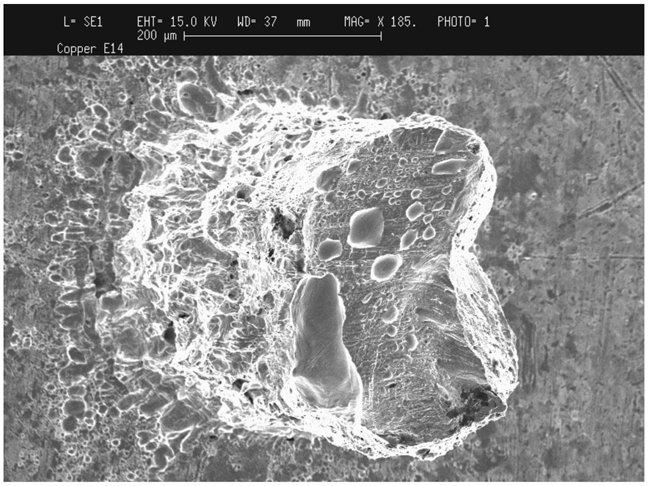

Fig. 12. Pullout button from a Cu Joint using Class-14 electrodes, 4.5-kg electrode force, 8-cycle weld time and 2.2-kA welding current. Note the surface voids that were caused by the ESS.

welds by increasing the contact resistance, it may also lead to unstable/inconsistent resistance values at the contact interfaces,[17] which is undesirable in terms of process control. Very high contact resistance may also cause initial splashing/expulsion at the interface.[18] However, this electrode force effect was not observed when welding Al, which may be due to the existence of tenacious aluminum oxide. It has been shown that the static contact resistance at the room temperature between Al sheets was not affected by the electrode force from 0.5 to 10 kg.[15]

The maximum nugget diameter without WME was about 0.8 mm in this study and was much smaller than the electrode tip diameter of 3.2 mm (although the expulsion did not result in a great reduction of the joint strength). This is very different from the LSRSW in which nugget can generally grow to a size that is similar to the tip diameters of the electrodes without WME.[8] The reason for this difference is due to a much smaller electrode force used during SSRSW. In other words, electrode force determines the maximum nugget diameter without WME when the electrode geometry is kept constant; this aspect has been shown by computer simulation.[6,19] It is thought that this maximum nugget diameter should also be related to materials characteristics, although no such relationship has been observed in this work. It has been reported that higher electrode forces broadened the process window of welding current,[16] which may be because electrode force can increase the onset current for WME more than it can increase the threshold current to form a weld. However, a large electrode force can lead to excessive surface indentation, which is often undesirable during microjoining or precision welding.

The effect of weld time was observed when using Class 14 electrodes in which the higher electrical resistivity and lower thermal conductivity of Class 14 electrodes contributed to the nugget formation and growth. A longer weld time allows more heat to be conducted to the sheet metals. However, longer weld time would increase the softening effect at the HAZ and hence decrease the joint strength when welding cold-worked sheet metals (such as the sheet Al in this study). It has been observed that cold-worked Al (1100-H8) will lose almost 80% of its original strength at 200°C.[14]

ESS was a major problem when using Class 14 electrodes compared with Class 2 electrodes during SSRSW of Al, brass and Cu although using Class 14 electrodes leads to a lower welding current requirement. Higher electrical resistivity and lower thermal conductivity of the Class 14 electrodes would result in a higher temperature at the electrode-sheet interface, which would promote ESS. Higher electrode force usually reduces the contact resistance at the electrode-sheet interface and, hence, would decrease the heat/temperature generated at the interface and hence may reduce the tendency of ESS. Increasing rise time or adding a current pre-pulse are other ways to reduce the ESS because they can gradually reduce the contact resistance between the electrode and the workpiece when the current is low, hence reducing the heat/temperature generated at the interface.[15]

Weldability of Sheet Metals: Base Metal Physical Properties

The weldability of Al, brass, and Cu can be compared based on the welding current required to produce a given nugget diameter (e.g., for a 0.4-mm-nugget, Table I). Cu is included in Table I for comparison although further work is needed to develop the process parameters to efficiently weld Cu. It can be seen that the weldability of these metals can be listed in a decreasing order of Al, brass, and Cu when using both Class 2 and Class 14 electrodes, which is not exactly in the same order of their resistivity or thermal conductivity (i.e., brass > A l > Cu, Table II).[20,21] The current for a given nugget diameter when using Class 14 electrodes for a given metal is always lower than that when using Class 2 electrodes, which is reasonable because of the higher electrical resistivity and lower thermal conductivity of the Class 14 elec-

Table II. Physical Properties Used for Calculations[20,21]

	Al	Brass	Cu	Zn
Melting point (°C)	660	965	1083	—
ΔT (K)	640	945	1063	—
Thermal conductivity (W/m/K)	240	121	393	—
Electrical resistivity ($\mu\Omega$cm)	4.3	6.7	1.7	—
Density (g/cm^3)	2.7	8.55	8.96	—
Specific heat @ 20°C (J/kg/K)	238	388*	386	394
Latent heat of fusion (J/g)	388	177*	205	111
Total heat (q_N) by Eq. 5	1459	4648	5512	—

* The specific heat of brass and latent heat of fusion of brass are assumed to be 70% of that of Cu plus 30% of that of Zn.

trodes compared to the Class 2 electrodes. The following is an attempt to provide a qualitative explanation on the observed weldability order of Al > brass > Cu when using Class 2 electrodes.

Weld nugget formation depends on the interplay of heat generation and heat dissipation in the electrode-workpiece system. Mathematically,

$$Q_G = Q_N + Q_L \tag{2}$$

where, Q_G is the heat generation, Q_N is the total heat required to form a weld nugget, and Q_L is the heat loss by conduction into the workpieces and electrodes, which is determined by the thermal conductivities and geometrical shapes of the workpieces and electrodes. Assuming $Q_L = fQ_N$, Eq. 2 becomes,

$$Q_G = (1 + f)Q_N \tag{3}$$

where f is a ratio determined by the relative magnitude of Q_L and Q_N.

Recall, heat generation can be expressed as,

$$Q_G = I^2 Rt \tag{4}$$

where, I is the welding current, R is the electrical resistance of the workpiece, and t is the weld time. Therefore, the heat generation is determined by both process parameters (i.e., welding current and weld time), and the electrical resistivity and geometrical shape of the workpieces. The heat generated from the electrodes is neglected in this analysis, which is a good approximation since the electrical resistivity of the Class 2 electrodes is very low. The heat generated from the contact resistance at faying interfaces is also neglected to keep the analysis simple and workable, which may be reasonable when the nugget is fairly well developed.

The total heat required to form a weld nugget (Q_N) includes at least two parts: the first to heat the weld metal to its melting point and the second to melt the weld metal to form a molten nugget (other factors, such as the heat to overheat the molten metal, are neglected in this analysis). Therefore,

$$Q_N = q_N\Delta V = (\rho C_p\Delta T + \rho H)\Delta V \tag{5}$$

where, q_N is the total heat to form a weld nugget per unit volume, ρ is the density of the weld metal, C_p is the specific heat, ΔT is the temperature rise from the room temperature to the melting point, ΔV is the volume of weld nugget, and H is the latent heat of fusion per unit volume.

Combining Eqs. 3–5 leads to,

$$I^2t = (1+f)\Delta V \frac{q_N}{R} \tag{6}$$

To compare the welding current required to produce a given nugget diameter at an identical weld time for different sheet metals, the above equation can be arranged to be,

$$I_{Al} : I_{brass} : I_{Cu} =$$

$$\left(\sqrt{(1+f)\frac{q_N}{R}}\right)_{Al} : \left(\sqrt{(1+f)\frac{q_N}{R}}\right)_{brass} : \left(\sqrt{(1+f)\frac{q_N}{R}}\right)_{Cu} \tag{7}$$

Table III. Comparison of Experimental and Calculated Welding Current to Produce 0.4-mm-Diameter Weld Nuggets

	Al	Brass	Cu
Experimental	1.0	1.5	3.2
Calculated	1.0	1.3	2.9

Note: Both experimental and calculated current values were normalized using the current for Al using Class 2 electrodes, respectively.

Since the geometry of sheets and electrodes were identical for Al, brass, and Cu, the resistivity of sheet metals can be used to replace R in Eq. 7. It is also assumed that the ratio of heat loss versus the total heat required to from a weld nugget (i.e., the f value) is identical in the welding of all the sheet metals, so the term (1 + f) can be cancelled out from Eq. 7. With these assumptions, the current values in Eq. 7 are calculated using metal's resistivity and q_N (Table II) and then normalized using the calculated current for Al:

$$I_{Al} : I_{brass} : I_{Cu} = 1.0 : 1.3 : 2.9 \tag{8}$$

All these calculated current values are listed in Table III to be compared with the experimental results.

Table III indicates that the current order of the experiment is the same as that provided by Eq. 8, which implies that weldability is not only affected by metals' electrical resistivity (or thermal conductivity), but also affected by other physical properties (such as melting point, heat of fusion, specific heat). However, it is worth pointing out that the above analysis is just qualitative (or semi-quantitative). While the order is correct, the ratios do not agree quite so well because of the very complexity of heat generation and dissipation in the process. For example, no consideration of contact resistance and electrode resistance, and the latent heat due to Zn vaporization were included in Eqs. 5 and 7. The assumption of an identical ratio of heat loss versus the total heat required to from a weld nugget for the sheet metals is questionable since, in reality, the f value is neither a constant in the process nor a constant for all different materials. However, more detailed and quantitative analysis requires numerical modeling.[6,19]

CONCLUSION

The resistance weldability of 0.2-mm-thick sheet aluminum, brass, and copper in small-scale resistance spot welding (SSRSW) was studied. The effects of electrode materials and process parameters (welding current, electrode force, and weld time) on joint strength and nugget size were investigated. The welding current ranges for SSRSW of the sheet metals were determined based on the minimum current levels that produce a required nugget diameter and the maximum current values that did not result in electrode-sheet sticking (ESS) or weld metal expulsion (WME).

Other major findings from this study can be summarized as follows:

- Al and brass are relatively easier to resistance weld compared with Cu because of their relatively higher electrical resistance and lower thermal conductivity. It was found that resistance weldability of sheet metals is not only determined by resistivity (or thermal conductivity) but also affected by other physical properties (such as melting point, latent heat of fusion and specific heat).
- Welding current, electrode force and weld time all affect joint strength and nugget diameter, with welding current having the strongest effect. Increasing electrode force increased the current threshold to form a weld when welding brass; however, no such effect is observed during welding of Al. Increasing electrode force seems also to increase the onset current for WME and ESS. The effect of weld time was significant when using Class 14 electrodes in which the higher electrical resistivity and lower thermal conductivity of Class 14 electrodes contributed to the nugget formation and growth.
- The maximum nugget diameter that did not result in WME was much smaller than the electrode tip diameter, which is quite different from "large-scale" resistance spot welding in which the maximum nugget diameter is similar to the electrode tip diameter.
- A lower welding current is needed when using Class 14 electrodes compared with that when using Class 2 electrodes. However, the permissible current range is much smaller (0.2-0.3 kA) when using Class 14 electrodes than that when using Class 2 electrodes (1.0 kA) in the welding of sheet Al and brass.

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