Journal of ELECTRONIC MATERIALS, Vol. 30, No. 8, 2001

Weldability of Thin Sheet Metals by Small-Scale Resistance Spot Welding using High-Frequency Inverter and Capacitor-Discharge Power Supplies

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An investigation has been conducted of the weldability of 0.2-mm-thick sheet aluminum, brass, and copper in small-scale resistance spot welding using a high-frequency inverter and a capacitor-discharge power supply. The results have been compared to those of previous investigations using a line-frequency alternating current power supply. The effects of electrode materials and process parameters on joint strength, nugget diameter, weld-metal expulsion and electrode-sheet sticking were studied. This work has also provided practical guidelines for selection of power supplies, process parameters (welding current/pulse energy, welding time/pulse width, electrode forces, etc.) and electrode materials for small-scale resistance spot welding of thin sheet aluminum, brass and copper.

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

INTRODUCTION

Small-scale resistance spot welding (SSRSW) is one of the microjoining processes used in fabricating electrical and electronic components and devices, in which thin metal sheets (<0.2–0.4 mm), mostly nonferrous metals, are joined by resistance heating.[1,2] This application of resistance spot welding (RSW) has many differences compared with "large-scale" resistance spot welding (LSRSW) that is mainly used in the automotive and appliance industries to join relatively thick sheet steels (>0.5–0.7 mm), and, to a much smaller extent, to join sheet aluminum alloys.[3,4] SSRSW is widely used to assemble medical and electronic devices and components (e.g., batteries and sensors).[5]

One of the differences between SSRSW and LSRSW is that various welding controls are commercially available to provide different current waveforms to satisfy most SSRSW applications while 50/60-Hz alternating current (AC) is the dominant current waveform used for LSRSW. There are four types of power supplies used in SSRSW: line frequency AC, capacitor discharge (CD), high frequency (HF) inverter, and direct current (DC). Typical AC, CD and HF current waveforms are shown in Fig. 1.[5,6]

When an AC power supply is used, the heat is controlled by changing voltage and switching off the current for a portion of each cycle. The latter is accomplished through the use of silicon-controlled rectifiers that are made to conduct current in a controlled manner; therefore, the resultant current to the workpieces appears as shown in Fig. 1. The minimum controllable heating unit is 1/2 cycle, that is, 8.3 ms or 10 ms duration, depending on the AC frequency (60 or 50 Hz). The output of a line frequency AC power supply is not compensated for line voltage variations so the repeatability of welding heat input may be poor.

HF inverter systems use switching technology to provide constant current, voltage or power that is achieved regardless of fluctuations in power source voltage or changes in workpiece resistance. The resultant waveform is DC with a superimposed high-frequency, low-amplitude AC ripple (Fig. 1). The actual shape and amplitude of the high-frequency AC ripple depends on the electrical inductance of the secondary welding loop which includes the weld cables, weld head, electrodes, and workpieces. Typical welding time is 10–30 ms and typical control resolution is 1 ms.

When a CD power supply is used, the energy is provided by a charged capacitor bank and the amount delivered is determined by the amplitude and dura-

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(Received March 8, 2001; accepted May 23, 2001

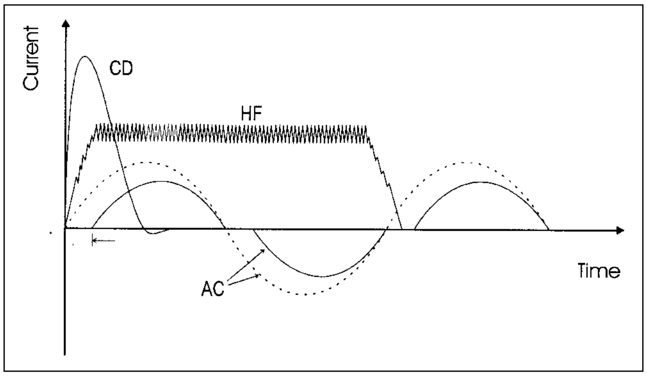


Fig. 1. Schematic of current waveforms of CD, HF, and AC power supplies. The solid AC lines are the result of switching off current for a portion of each cycle, which compares the dashed AC lines with 100% heat ($\Phi = 0$).

tion of the current pulse (pulse width). The heat input can be controlled by varying the voltage on the capacitor bank that changes the amplitude of the current pulse. This type of energy source exhibits good repeatability of the amount of stored energy. Typical pulse width is on the order of 1–5 ms.

SSRSW of aluminum (Al), brass and copper (Cu) with an AC power supply has been investigated in a previous work in which the effects of process parameters (welding current, electrode force and welding time), and the electrode materials (Class 2 and Class 14) were studied.[7] The permissible welding current ranges for SSRSW of these sheet metals were determined based on a minimum current that produced a given nugget diameter and a maximum welding current defined by the onset of electrode-sheet sticking or weld-metal expulsion. It was found that the resistance weldability of the materials was not only determined by their resistivity (or thermal conductivity) but also affected by other physical properties (such as melting point, latent heat of fusion and specific heat). The present work investigates SSRSW of Al, brass and Cu using CD and HF power supplies and compares the effects of all the different power supplies on weldability.

MATERIALS AND EXPERIMENTAL PROCEDURE

The materials 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. 2) were made using test coupons approximately 40 mm long and 6 mm wide. Joint quality was evaluated using a peel test (Fig. 2) performed using a Chatillon Digital Force Gauge model DFIS 2 at a tearing speed of 38 mm/min.

Nugget diameters were estimated by measuring the diameters of pullout buttons during the peel test. The strength of resistance spot-welded joints can be correlated to the diameter of the weld nuggets; therefore, for any set of process conditions, a certain minimum level of welding current is required to produce a weld with a minimum nugget diameter.[3,4] However, excessive welding current may result in weld metal expulsion when the diameter of the molten zone is larger than the contact diameter[7,8] and severe weld metal expulsion can reduce the joint strength because of the loss of metal thickness.[3,4] In this work, peel-tested samples were examined under a stereomicroscope and a scanning electron microscope (SEM) for the existence of expelled metal trapped between the sheets, which is considered to be the result of weld metal expulsion.

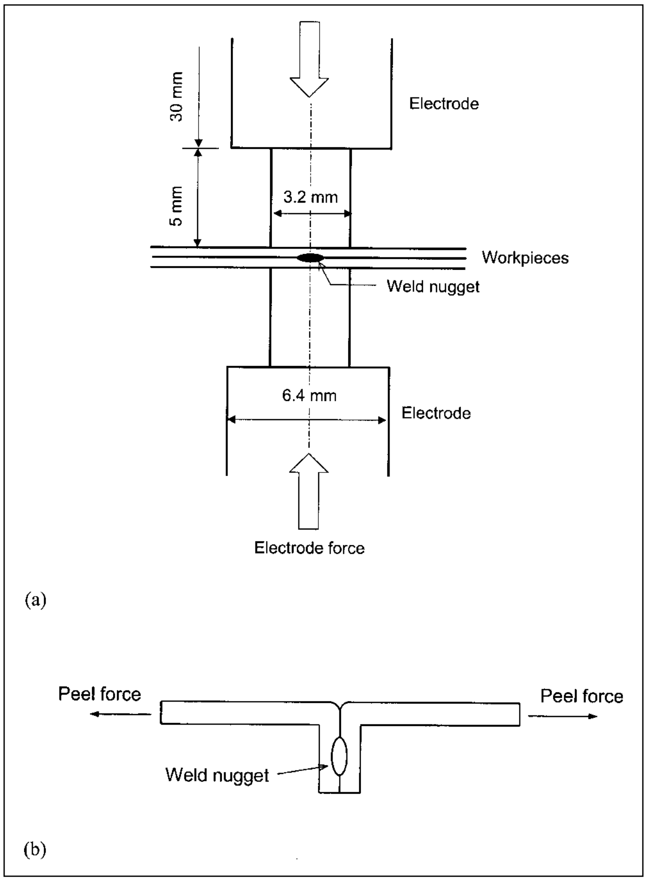


Fig. 2. Schematic of setup for (a) resistance spot welding and (b) peel test.

Electrode-sheet sticking occurs when excessive heat generation produces locally melted areas at the electrode-sheet interface.[7,9] 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 force would be needed to separate them. If the interface is still molten when the electrodes separate from the workpieces, the welding operator would not notice any electrode-sheet sticking; however, the locally melted areas may be revealed by microscopic examination. If the welding current is increased beyond the level of any incipient electrode-sheet sticking, the electrodes can weld to the workpieces. Electrode-sheet sticking should be minimized because it contributes to reduced electrode tip life.[7,9] Although electrode tip life was not quantified in the present work, electrode-sheet sticking was

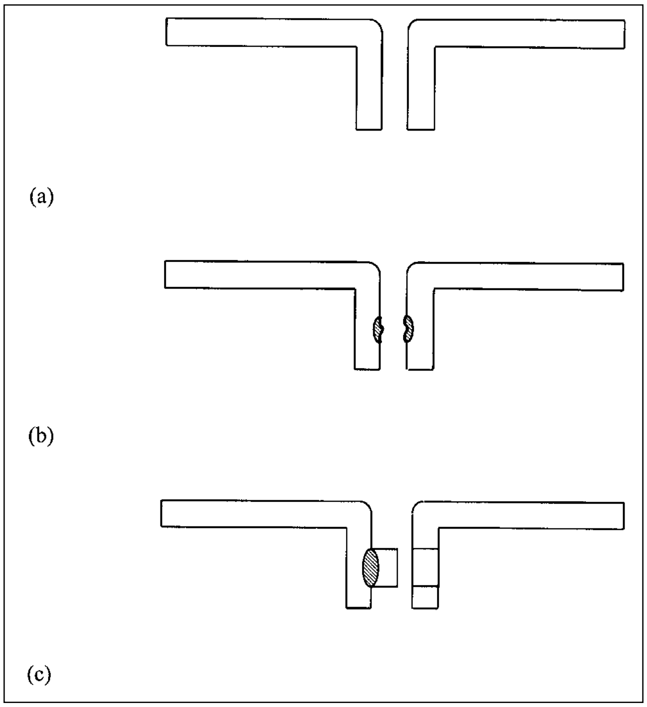


Fig. 3. Schematic showing joint failure modes during peel test: (a) failure along interface, (b) failure through nugget, and (c) failure as a button pullout.

monitored by SEM examination of the sheet surface locations contacted by the electrodes during welding. Once the onset currents for electrode-sheet sticking and weld metal expulsion were determined, the weldability of the materials was evaluated in terms of their permissible welding current ranges based on a minimum current for a given size of nugget diameter and the onset current for weld metal expulsion or electrode-sheet sticking.

A Hughes HCD125 capacitor-discharge power supply and a Unitek HF2 high-frequency inverter power supply were used for SSRSW in this study: the welding current or pulse energy values were recorded from the actual machine settings. Both Class 2 (chromium copper alloy) and Class 14 (molybdenum) electrodes[3] used in this work were commercially available with a tip-face diameter of 3.2 mm and a shank diameter of 6.4 mm (Fig. 2). Unlike LSRSW,[3,4] the electrodes were not water-cooled during SSRSW.

The entire welding process was semi-automatically controlled, i.e., an air-pressure system was triggered by a foot pedal to apply the electrode force after two overlapped specimens were manually placed between the opposing electrodes. Welding current was delivered to the stack as soon as the force had reached a pre-selected value. Welding current/pulse energy, rise time (fixed at 10 ms when using the HF power supply), and welding time/pulse width were all pre-selected as inputs on the welding controls. Total squeeze time was not measured and, therefore, total cooling time after termination of weld current was neither controlled or measured. Prior to welding, the sample surfaces were cleaned using methanol.

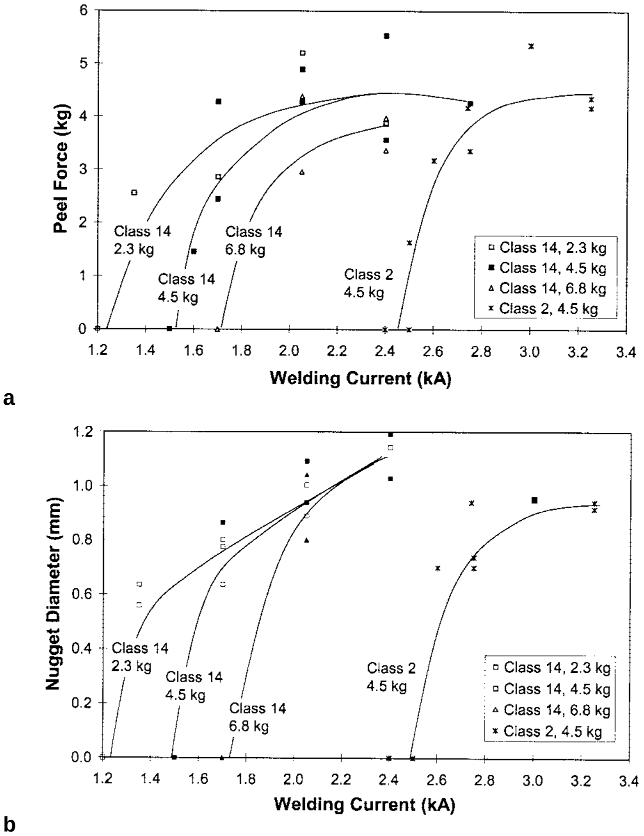


Fig. 4. (a) Peel force and (b) nugget diameter versus welding current at different electrode forces (2.3, 4.5, or 6.8 kg) and when using different electrodes (Class 2 or 14) for the brass joints using the HF power supply at 20-ms welding time.

RESULTS

Three different failure modes were observed during the peel testing of welded joints, namely, interface failure, weld failure, and button pullout (Fig. 3). Interface failure was observed when only weak bonding between sheets occurred (Fig. 3a). 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. 3b or c).

Brass

The variation of peel force or nugget diameter versus welding current is shown in Fig. 4 for three different electrode forces (2.3, 4.5, and 6.8 kg) and two different electrode classes (2 or 14) for the brass joints using the HF power supply. When Class 2 electrodes were used, weld metal expulsion started at a current of about 3.0 kA (corresponding to a nugget diameter of 0.9 mm). No electrode-sheet sticking was experienced with the HF power supply and Class 2 electrodes. For a minimum nugget diameter of 0.4 mm (corresponding to a joint strength of about 2-3 kg), the minimum current needed was found to be 2.6 kA. The maximum permissible current could be selected above 3.2 kA since weld metal expulsion did not result in a reduction in joint strength. Therefore, the current

Table I. Welding Current (in kiloamps) for 0.4-mm-Diameter Nugget, Weld Metal Expulsion and Electrode-Sheet Sticking When Using the HF Inverter Power Supply

Sheet Metals	Electrodes	Minimum*	Weld Metal Expulsion	Electrode-Sheet Sticking	Suggested Range
Al	Class 2	1.9	3.0	>3.0	1.9–3.0
	Class 14	1.2	1.6	1.4	1.2–1.4
Brass	Class 2	2.6	3.0	>3.2	2.6–3.2
	Class 14	1.6	2.0	2.0	1.6–1.0
Cu	Class 2	—	—	—	—
	Class 14	>3.3	—	—	—

* Note: The minimum current is determined to produce 0.4-mm-diameter of weld nuggets. Electrode force is 4.5 kg and weld time is 20 ms.

range for SSRSW of brass using the HF power supply with Class 2 electrodes, 4.5-kg electrode force, and eight-cycle weld time was determined as 2.6-3.2 kA (Table I).

Figure 4 also shows the effects of welding current and electrode force on joint strength and nugget diameter when using the HF power supply with Class 14 electrodes. Electrode force affected the current threshold to form a weld, which is similar to observations using an AC power supply.[7] A lower welding current was needed to join brass using Class 14 electrodes compared with that using the Class 2 electrodes. Weld metal expulsion started at a welding current of 1.7–2.4 kA (corresponding to a nugget diameter of 0.8–1.1 mm) when electrode force was 2.3–6.8 kg; the higher the electrode force, the lower was the tendency to weld metal expulsion. However, it appears that weld metal expulsion has little influence on the joint strength (Fig. 4). Electrode-sheet sticking started at welding currents of 1.7 and 2.0 kA when the electrode force was 2.3 and 4.5 kg, respectively. For different electrodes, the onset welding current for electrode-sheet sticking was similar to or smaller than that for weld metal expulsion using Class 14 electrodes, but higher than that for weld metal expulsion when using Class 2 electrodes (Table I). Therefore, using Class 14 electrode resulted in a higher tendency to electrode-sheet sticking compared with Class 2 electrodes and required more frequent tip dressing. The current range for SSRSW of brass using the HF power supply with Class 14 electrodes, 4.5-kg electrode force and eight-cycle weld time was determined as 1.6–2.0 kA (Table 1) based on a minimum 0.4-mm nugget diameter and the onset current for electrode-sheet sticking.

Figure 5 shows the plots of peel force or nugget diameter versus pulse energy for the brass joints using the CD power supply. Almost identical pulse energy was needed to join brass when using the CD power supply with both electrodes, which is very different from the situation when an HF power supply was used. Weld metal expulsion appeared to start at pulse energy of about 70 J. Electrode-sheet sticking started at 70–90 J when using Class 2 electrodes, but at 40 J when using Class 14 electrodes. Therefore, electrode-sheet sticking was found to be more severe when using Class 14 electrodes. The energy range for SSRSW of brass using the CD power supply with 4.5 kg electrode force and 2.0 ms pulse width was determined as 35–80 J and 35–40 J (Table II) for Class 2 and 14 electrodes based on a minimum 0.4 mm nugget diameter and the onset current for electrode-sheet sticking, respectively.

Aluminum

Figure 6 shows the plots of peel force or nugget

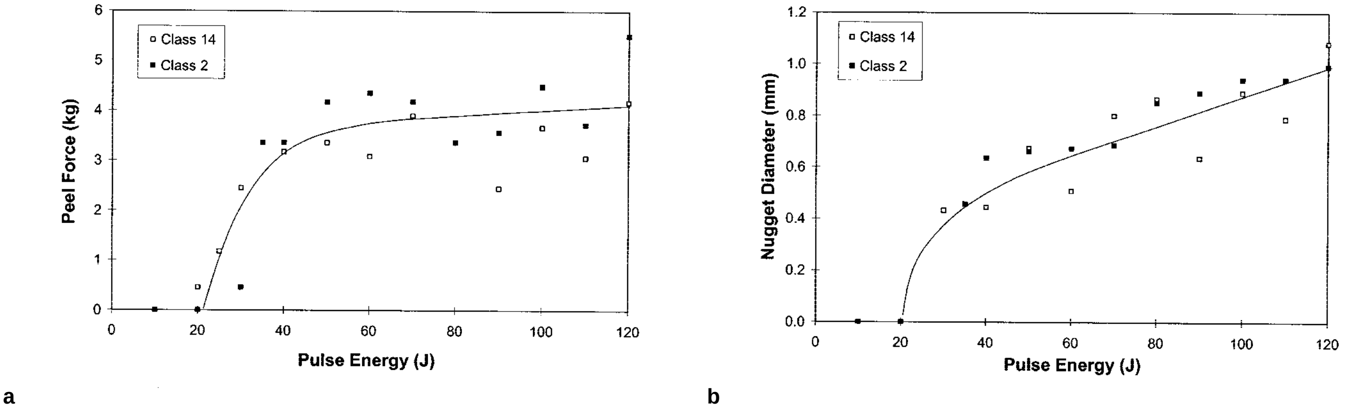


Fig. 5. (a) Peel force and (b) nugget diameter versus pulse energy when using Class 2 or 14 electrodes for the brass joints using the CD power supply at 4.5-kg electrode force and 2.0-ms pulse width.

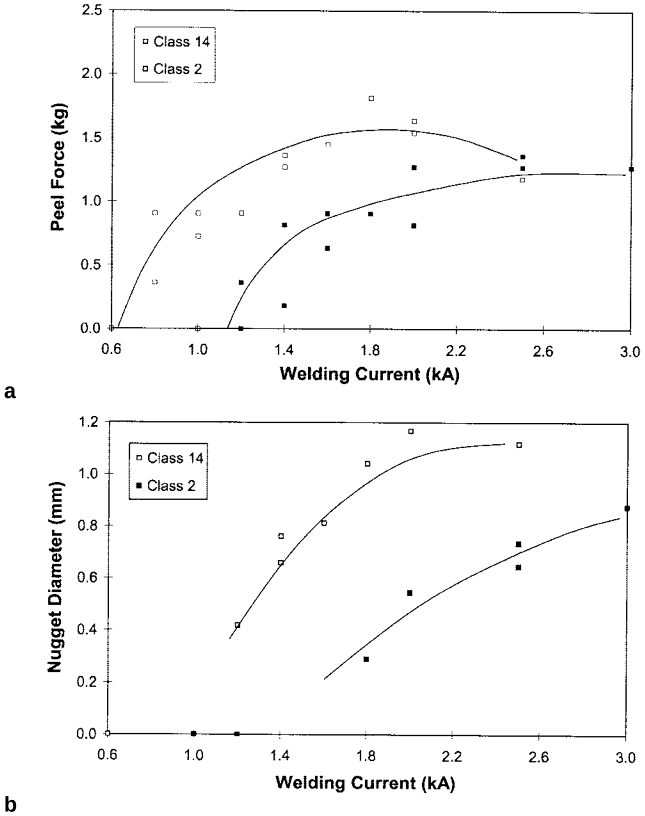


Fig. 6. (a) Peel force and (b) nugget diameter versus welding current when using Class 2 or 14 electrodes for the Al joints using the HF power supply at 20-ms welding time.

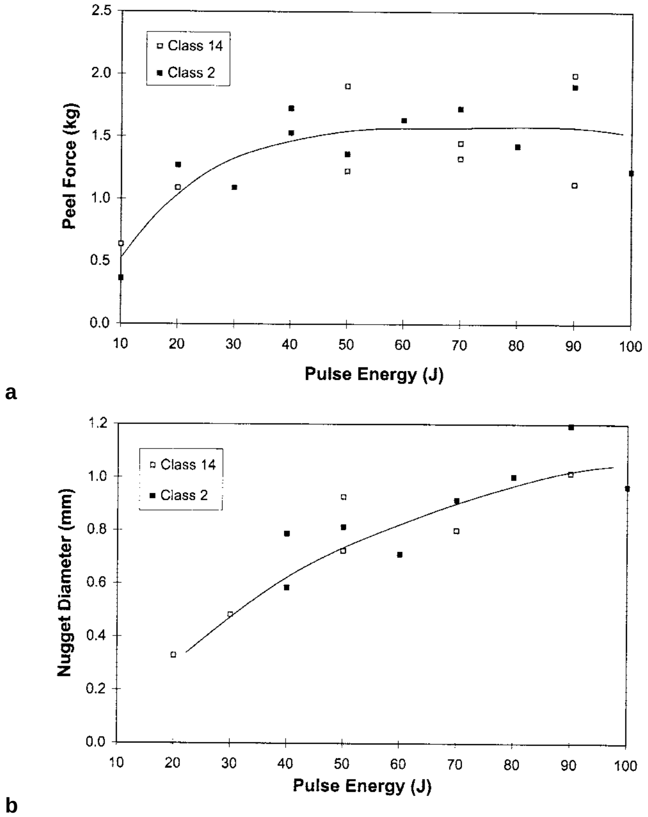


Fig. 7. (a) Peel force and (b) nugget diameter versus welding current when using Class 2 or 14 electrodes for the Al joints using the CD power supply at 2.0-ms pulse width.

diameter versus welding current for the Al joints using the HF power supply. Weld metal expulsion started at welding currents of about 1.6 kA and 3.0 kA (corresponding to nugget diameters of 0.8–0.9 mm) for the joints using Class 14 and 2 electrodes, respectively. Electrode-sheet sticking started at a welding current of 1.4 kA when using Class 14 electrodes. No electrode-sheet sticking was experienced when using Class 2 electrodes. Figure 7 shows the plots of joint strength or nugget diameter versus pulse energy for the Al joints using the CD power supply. Almost identical pulse energy was needed to join Al for both electrodes when using the CD power supply. Weld metal expulsion started at an input energy of 60–70 J (corresponding to 0.8–0.9 mm nugget diameter). Electrode-sheet sticking started at 40–50 J when using Class 14 electrodes and at 100 J when using Class 2 electrodes. For both HF and CD power supplies, electrode-sheet sticking was worse for Class 14 electrodes compared with Class 2 electrodes and more severe at the positive electrode side. The current range for SSRSW of Al using the HF power supply with 4.5-kg electrode force and eight-cycle weld time was determined as 1.9–3.0 kA and 1.2-1.4 kA (Table I), respectively, for the Class 2 and 14 electrodes based on a minimum nugget diameter of 0.4 mm and the onset current for electrode-sheet sticking. The energy range for SSRSW of Al using the CD power supply with 4.5-kg electrode force and 2.0-ms pulse width was determined as 30–100 J and 30–50 J (Table II), respectively, for the Class 2 and 14 electrodes based on a minimum nugget diameter of 0.4 mm and the onset current for electrode-sheet sticking.

Copper

There was only limited success in SSRSW of Cu. The power required is very high due to very high thermal conductivity and low electrical resistivity of Cu. No bonding was achieved using the CD power supply even at the maximum settings (i.e., two pulses at 125 J).

No bonding was achieved with the HF power supply when using the Class 2 electrodes at parameters of 2.3 to 6.8 kg electrode force and 30 to 60 ms welding time with the maximum current setting (4.0 kA) from the HF power supply. When using the Class 14 electrodes, a joint started to form at 30-ms weld time and the maximum current setting (i.e., 4.0 kA although only 3.3 kA was delivered). Joint strength increased from about 3 to 5 kg when the weld time increased from 30 to 80 ms at the same current setting (Fig. 8). The diameters of pullout buttons were 1.1 to 1.9 mm. However, the electrodes and the Cu sheets became overheated when the weld time was above 50 to 60 ms. Surface voids on the Cu sheets at the electrode contact spots were observed in most joints, indicative of melting and incipient electrode-sheet sticking.

Cu is one of the least suitable metals for RSW

Table II. Welding Energy (in Joules) for 0.4-mm-Diameter Nugget, Weld Metal Expulsion and Electrode-Sheet Sticking When Using the CD Power Supply

Sheet Metals	Electrodes	Minimum*	Weld Metal Expulsion	Electrode-Sheet Sticking	Suggested Range
Al	Class 2	30	70	100	30–100
	Class 14	30	70	50	30–50
Brass	Class 2	35	70	80	35–80
	Class 14	35	70	40	35–40
Cu	Class 2	>125	—	—	—
	Class 14	>125	—	—	—

*Note: The minimum current is determined to produce 0.4-mm-diameter of weld nuggets. Electrode force is 4.5 kg and pulse width is 2.0 ms.

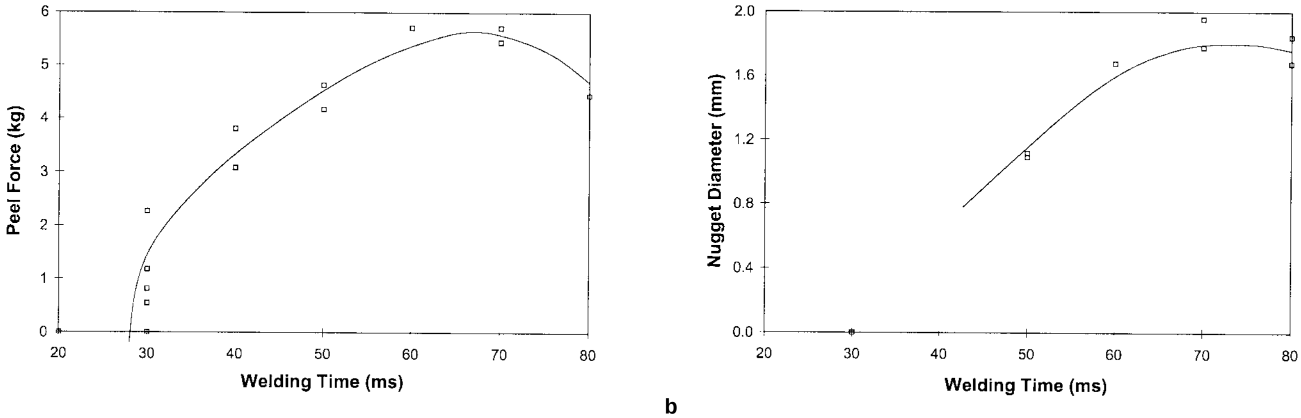


Fig. 8. (a) Peel force and (b) nugget diameter versus welding time for the Cu joints using the HF power supply and Class-14 electrodes at 4.5-kg electrode force and 3.3-kA welding current.

because of its high thermal and electrical conductivity.[3,4] Only limited success was achieved in this study. Observations of weld metal expulsion and electrode-sheet sticking 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 the Class 14 electrodes. Further work is needed to optimize conditions for the SSRSW of Cu, and this will be worthwhile because of its wide use in electronic applications.

DISCUSSION

The Effect of Power Supplies

The magnitude of welding current required to produce a given size of weld nugget was used to compare the weldability of Al, brass and Cu during SSRSW using an AC power supply.[7] Following the same methodology, Table III summarizes the welding current or pulse energy required to produce a pullout button of 0.4 mm diameter using the HF and CD power supplies, along with the results for the AC power supply.[7] It can be seen in Table 3 that the weldability of these metals is ranked in the same order for all three power supplies (i.e., Al > brass > Cu). Electrical resistivity is one of the most important material properties affecting weldability during RSW[3,4] and the resistance weldability of sheet metals is directly related to their resistivity. However, the results of this study have shown a weldability order of Al > brass > Cu, which is different order of their resistivity (i.e., brass > Al > Cu). A semi-quantitative model has been proposed to demonstrate that the resistance weldability is not only affected by metals' electrical resistivity (or thermal conductivity), but is also related to other physical properties (such as melting point, heat of fusion, and specific heat).[7] The estimated current values for a given size of weld nugget for Al, brass and Cu with Class 2 electrodes, when normalized by the current for Al, were $I_{Al}:I_{brass}:I_{Cu} = 1.0:1.3:2.9$.[7] This work (Table III) indicates that the semi-quantitative analysis is still valid when using the HF and CD power supplies.

Table III shows that the required current was higher when using the HF power supply than the RMS current levels from the AC power supply. The difference between the required current level when using different power supplies might be due to the different ways in which current values were determined (machine settings versus the measured RMS values for HF and AC power supplies) and/or due to the difference in weld time (about 20–30 ms versus about eight cycles for the HF and AC power supplies, respectively). However, the plots of peel force or nugget diameter versus RMS welding current for the brass joints in Fig. 8 clearly show the difference between the current requirements when using the HF and AC power supplies. The RMS currents had a rise time of 33 ms and a weld time of 133 ms in Fig. 9. There are a few possible reasons for this difference.

Table III. Welding Current or Pulse Energy Required to Produce Weld Nuggets of 0.4 mm in Diameter

Electrodes	Class 2	Class 14				
Power Supply	**AC (kA)**	**HF (kA)**	**CD (J)**	**AC (kA)**	**HF (kA)**	**CD (J)**
Al	1.1	1.9	30	0.7	1.2	30
Brass	1.6	2.6	35	1.2	1.6	35
Cu	>2.2	—	>125	>2.8	>3.3	>125

Notes: Electrode force = 4.5 kg, Weld time = 8 cycles when using an AC power supply, Weld time = 20 ms when using a HF power supply, Pulse width = 2.0 ms when using a CD power supply. The results with an AC power supply were from Ref. 7.

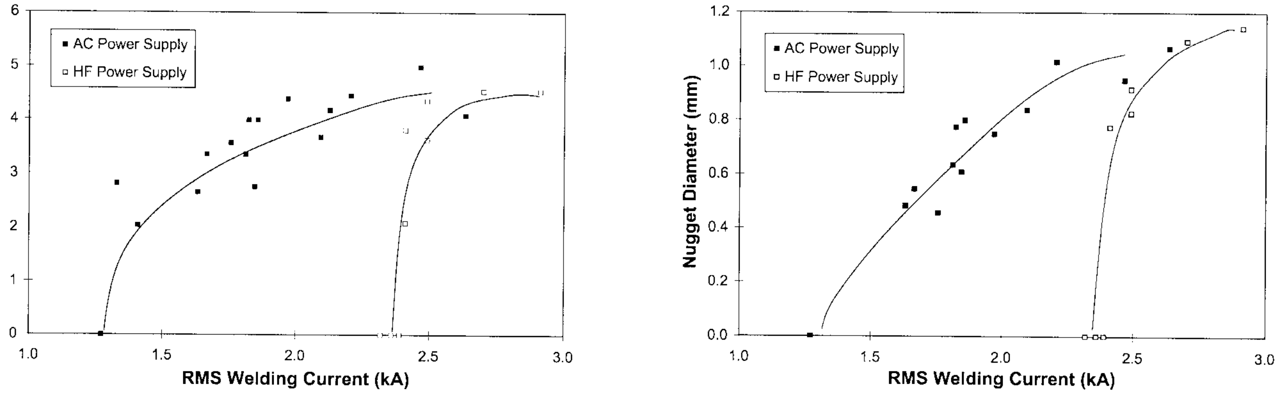
Table IV. Comparison of Power Supplies Used for Micro-Resistance Welding

Power Supply	Equipment Cost	Work Capacity	Ease of Operation	Ease of Control	Maintenance
AC	Low	High	Mid	Low	Low
DC	High	Low	Mid	High	High
HF	High	Mid	Low	High	High
CD	Mid to Low	Low	High	Self Regulating	Low

First, because of the heat generation due to the eddy current and skin effect, etc., the effective resistance in an AC circuit is higher than the resistance of the same circuit carrying only DC.[10,11] Secondly, the shift of the nugget center from the workpiece interface due to the Peltier effect when using DC type of power supplies that might require a higher welding current to achieve the same joint strength compared with that when using AC power supplies. It has been shown that the amount of heat generated at the workpiece surface of the positive electrode is approximately 15% greater than that at the negative electrode.[12] This is consistent with the observation that there was a more severe electrode-sheet sticking at the positive electrode side in the welding of Al using the HF and CD power supplies. Finally, when using an AC power supply the peak current is much higher than the RMS values, which might affect the nugget formation. Further work is needed to quantify these effects.

The selection of power supply also depends on many other considerations (cost, ease of control, ease of operation, etc.) and Table IV lists some comparisons between different power supplies. No single power supply is ideally suited for all SSRSW operations and the selection of one over the others is often due to its availability and cost.

Another difference in the welding of Al using the HF and CD power supplies compared with that using an AC power supply is the finding of more severe electrode-sheet sticking at the positive electrode side. It has been shown that the electrode wear rate is higher at the positive electrode side during LSRSW of Al using rectified three-phase power supplies. The reason for this was a higher temperature rise at the positive electrode due to the Peltier and Thomson effect.[13] The Peltier effect is also dependent on the difference in material characteristics (such as density) between electrodes and workpieces.[12] However, further study would be needed for detailed understanding of how electrode-sheet sticking or electrode wear differs for different electrode/sheet combinations for different power supplies.



a

b

Fig. 9. (a) Peel force and (b) nuggets diameter versus welding current for the brass joints using the AC and HF power supplies with Class 2 electrodes, 4.5-kg electrode force and 33-ms rise time and 133-ms welding time.

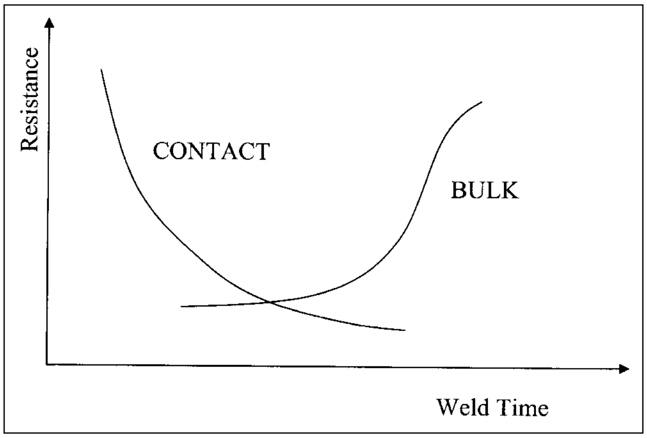


Fig. 10. Schematic showing the change in resistance during resistance spot welding.

The Effect of Electrode Materials

A comparison of the current requirements for different electrodes with the HF and AC power supplies (Table III) indicates that a much lower current is required when using Class 14 electrodes than when using Class 2 electrodes. This is due to the higher resistivity and lower thermal conductivity of the Class 14 electrodes compared with the Class 2 electrodes.[7]

However, for the CD power supply, the pulse energy required to produce a given size of weld nugget was identical for both Class 2 and Class 14 electrodes (Table II, and Figs. 5 and 7). This is due to the relatively short weld time (i.e., pulse width) from the CD power supply compared with those from the HF and AC power supplies (2 ms versus 20 ms or longer). When weld time is very short (such as when using the CD power supply), the heat is generated at the interfaces because at the beginning of the process the contact resistance is high and bulk resistance is low (Fig. 10). Therefore, the nugget diameters at the sheet-sheet interface would mainly depend upon the heat generated from the contact resistance at the interface. Different electrode materials have little influence on the nugget diameters as shown by the similar nugget diameter in the cross sections of two joints made with identical process parameters but different electrode materials (Fig. 11).

Figure 11 shows a more severe electrode-sheet sticking with Class 14 electrodes compared with Class 2 electrodes, also consistent with the observation that the onset energy for electrode-sheet sticking is much lower when using Class 14 electrodes than when using Class 2 electrodes. Large voids, due to the high vapor pressure of Zn, were shown in both metallographic samples. However, the voids in the joint made using Class 2 electrodes were enclosed within the nugget region while the ones in the joint made with Class 14 electrodes were surface voids (Fig. 11). This difference is due to the different temperature profiles experienced in the two samples. In Fig. 11a, the temperature in the nugget center was the highest, and the temperature at the electrode-sheet interface was relatively low because of the high thermal conductivity of the Class 2 electrodes. Therefore, the voids formed at the nugget center were contained by the relatively cold brass shell. On the other hand, in Fig. 11b, the weld nugget extended to both electrode-sheet interfaces because the heat at the electrode-sheet interfaces could not be easily conducted away through the Class 14 electrodes and the high resistivity of the electrodes produces higher heat generation at the interface. There is no difference in pulse energy requirement between the two electrode classes when using the CD power supply, so Class 2 electrodes should be used, rather than Class 14, to reduce electrode-sheet sticking.

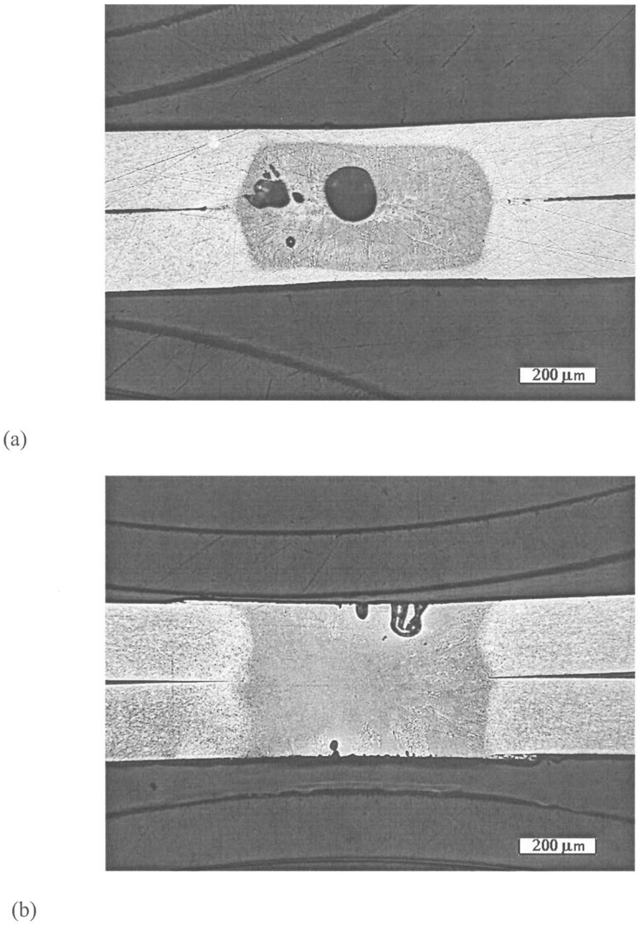


Fig. 11. Cross sections of brass joints using the CD power supply at 4.5-kg electrode force, 60-J pulse energy, 2-ms pulse width, and (a) with Class 2 electrodes and (b) with Class 14 electrodes. Note the central voids at (a) and the surface voids at (b).

SUMMARY AND CONCLUSIONS

Small-scale resistance spot welding (SSRSW) of sheet electronic packaging metals Al, brass and Cu using HF and CD power supplies has been investigated and the results compared with a previous study using an AC power supply. The effects of electrode materials and process parameters on joint strength and nugget size were investigated. The welding current/pulse energy ranges for SSRSW of the sheet metals were determined based on minimum current levels that produce a required nugget diameter and maximum current values that did not result in electrode-sheet sticking or weld metal expulsion. The results of this study indicate that a semi-quantitative analysis proposed in previous investigations [7] to determine the weldability of Al, brass and Cu using an AC power supply is still valid for the results using the HF and CD power supplies.

The current requirement is higher when using the HF power supply than when using the AC power supply; the reason for this needs to be further investigated. More severe electrode-sheet sticking at the positive electrode was observed in SSRSW of Al when using HF and CD power supplies, which is consistent with expectations of a polarity effect. With the AC and HF power supplies, electrode-sheet sticking was more severe when using Class 14 electrodes compared with Class 2 electrodes although a lower welding current was needed when using Class 14 electrodes. There was no difference in pulse energy requirement between different electrodes when using the CD power supply so Class 2 electrodes should be used to reduce electrode-sheet sticking when using the CD power supply.

ACKNOWLEDGEMENTS

The author would like to thank Dr. G. Kelkar at the Edison Welding Institute and Dr. B.H. Chang at the University of Waterloo for their useful discussion and suggestions, and Ms. P. Gorman at the Edison Welding Institute and Mr. Wen Tan at the University of Waterloo for carrying out part of the experimental work.

REFERENCES

1. K.I. Johnson, editor, *Introduction to Microjoining* (Abington, UK: TWI, 1985).
2. C.A. Harper, *Handbook of Materials and Processes for Electronics* (New York: McGraw-Hill, 1970).
3. *Welding Handbook: Vol. 2, Welding Processes* (eighth edition) (Miami, FL: American Welding Society, 1991).
4. *Resistance Welding Manual* (fourth edition) (Philadelphia, PA: Resistance Welder Manufacturers' Association, 1989).
5. Y. Zhou, C. Reichert, and K.J. Ely, *ICAWT'98: Joining Applications in Electronics and Medical Devices* (Columbus, OH: EWI, 1998), pp. 79–90.
6. K.J. Ely, *Proceedings of ICAWT '97: High Productivity Joining Processes* (Columbus, OH: EWI, 1997), pp. 211–223,
7. Y. Zhou, P. Gorman, W. Tan, and K.J. Ely, *J. Electron. Mater*. 29, 1090 (2000).
8. D.J. Browne et al., *Welding Journal*, Welding Research Supplement, 74, 417-s (1995).
9. M.R. Finlay, CRC No. 18 (Silverwater, NSW, Australia: Australian Welding Research, October 1996).
10. B. Hague, *Alternating Current Bridge Methods*, 5th edition, (London: Sir Isaac Pitman & Sons, 1957).
11. H.W. Jackson, *Introduction to Electric Circuits*, 5th edition, (London: Prentice-Hall Int., 1981).
12. M. Hasir, *Schweissen Scheiden* 36, 116 (1994).
13. J. Matsumoto and H. Mochizuki, *Welding Int.* 8, 438 (1994).