Microresistance spot welding of Kovar, steel, and nickel

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Microresistance spot welding of 0·2–0·5 mm thickness Kovar, steel, and nickel using different types of power supply was investigated. The effects of process parameters (welding current/pulse energy, electrode force, and welding time/pulse width) on joint strength and nugget diameter were studied. The maximum values of welding current and nugget diameter that did not result in weld metal expulsion and/or electrode–sheet sticking were determined. The difference between micro- and 'large scale' resistance spot welding was also considered. It was noted that the difference between micro- and large scale resistance spot welding is due not only to the difference in the scale of the joints, but also to the fundamental difference in the electrode forces (pressures) used. Based on the results of the present work, nominal process parameters are recommended for microresistance spot welding of Kovar, steel, and nickel when using different power supplies. STWJ/209

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INTRODUCTION

Resistance spot welding is a complex joining process,[1–3] in which the joint quality depends on many factors, such as the power supply type and its setup, electrode alloy and geometry, electrode force, welding parameters (welding current and time etc.), and characteristics of the metal being welded (alloying elements and surface conditions etc.). In resistance spot welding, the heat required to form a joint between metals is generated by the resistance to the flow of electric current through the workpieces, and can be mathematically described by

$$Q = I^2RT \qquad (1)$$

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 application (welding 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 base material.

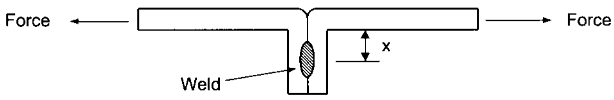
In general, the strength of resistance spot welded joints can be correlated with the diameter of the weld nugget, which is one of the reasons why most qualification procedures for resistance spot welding require a minimum diameter of weld nugget to be formed. Dickinson *et al.*[4] proposed that resistance spot welding comprises a series of stages, namely, (i) surface breakdown, (ii) asperity collapse, (iii) heating of the workpieces, (iv) molten nugget formation, and (v) nugget growth and mechanical collapse. Gould[5] indicated that nugget formation and development could be characterised as a function of welding variables (either welding time or current) by four steps: (i) incubation, (ii) rapid growth, (iii) steadily decreasing growth rate, and (iv) weld metal expulsion. Severe weld metal expulsion reduces the joint strength because of the loss of sheet thickness in the joint region.[3]

There is an increasing demand, in the fabrication of electronic and medical devices, for resistance spot welding of very thin (<0·5 mm) metal sheets, most being combinations of similar and dissimilar non-ferrous metals.[6–9] This application of resistance spot welding (generally termed as micro-, fine, or small scale resistance spot welding) requires much more precise electrical and mechanical control, and uses lower electrode force and current/energy input. However, there is a lack of published work on microresistance spot welding despite the increasing demand. Conversely, extensive research and development work has been carried out in the area of 'large scale' resistance spot welding of relatively thick (greater than 0·6–0·8 mm) sheet steels, mainly for applications in the automotive and appliance industries.[1–3] For example, detailed recommendations have been provided for large scale resistance spot welding of a variety of sheet metals;[1,2] however, no such information is available for microresistance spot welding.

An extensive investigation to study microresistance spot welding of thin metal sheets (including 0·2–0·5 mm thickness aluminium, brass, copper, Kovar, nickel, and steel) was initiated a few years ago. The objectives were to study the difference between micro- and large scale resistance spot welding and the effects of process parameters in microresistance spot welding, and to provide practical guidelines for the selection of process variables (welding current, welding time and electrode force, power supplies, electrode materials, etc.). The work on thin sheet brass, aluminium and copper has been published elsewhere.[10,11] The present paper is intended to summarise part of the results for microresistance spot welding of 0·2–0·5 mm thickness Kovar, steel, and nickel, to provide practical guidelines for the selection of process parameters for these thin sheet metals when using different power supplies, and to investigate the difference between micro- and large scale resistance welding.

MATERIALS AND EXPERIMENTAL PROCEDURE

The base metals used in the present study included 0·2 and 0·5 mm thickness Kovar (annealed), 0·25 and 0·5 mm thickness C1010 cold rolled steel (CRS), and 0·2 and 0·25 mm thickness nickel (Ni200, annealed). The electrodes were straight cylinders of class 2 (Cu–Cr) alloy[1] with a flat tip surface 3·2 mm in diameter and a shank 6·4 mm in diameter, and were not water cooled in microresistance spot welding. Lap welded joints were made using test coupons cut to approximately 40 mm length and 6 mm width. Joint



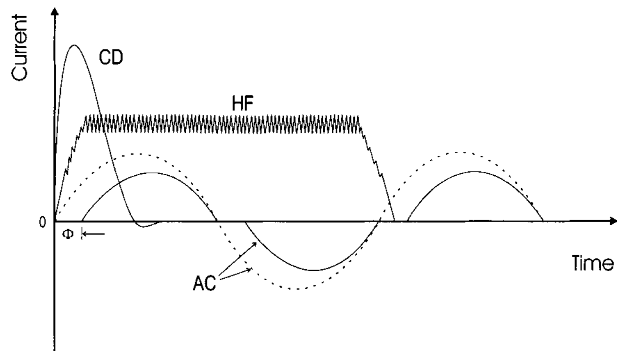
1 Configuration for peel test (x is distance between location of bending point and nugget centre)

quality was evaluated using a peel test (Fig. 1) that was performed using a Chatillon DFIS 2 digital force gauge at a speed of 38 mm min^{-1}. Nugget diameter was estimated by measuring the diameter of pullout buttons during the peel test. The results of peel force or nugget diameter versus welding current/pulse energy were fitted to a curve of the form $y=a+bx^{-2}$, where a and b are constants, although the physics underlying the expression is unknown. Peel tested samples were also examined using stereomicroscopy and a SEM for the presence of expelled metal trapped between the sheet metals, which is considered to be the result of weld metal expulsion.

Surface hardness was measured using a Vickers hardness tester with a load of 1 kg, load time of 15 s, and load speed of 100 mm s^{-1}; each hardness value given in Table 1 was an average of five measurements. The arithmetic mean value R_a of surface roughness was measured using a PocketSurf portable surface roughness gauge with a stylus tip of radius 10 μm and a stylus force of 15 mN; each surface roughness value in Table 1 was an average of 10 measurements and the evaluation length was 4 mm in each measurement. It can be seen from Table 1 that the difference in surface roughness is small for different sheet metals, but the differences in electrical resistivity, thermal conductivity, and surface hardness are significant.[12,13]

Electrode–sheet sticking was studied via SEM examination of the sheet surfaces that were adjacent to the electrodes during welding. Under certain conditions, excessive heat generation at the electrode/sheet interface would produce local melting areas on the sheet surface. If the molten metal solidified before the electrodes were removed from the sheet metals at the end of welding, the sheet metals would stick to the electrodes and a small force would be necessary to separate them. If the molten metal remained molten when the electrodes were removed from the sheet metals, the welding operator might not experience the electrode–sheet sticking; however, local surface areas affected by melting (such as voids) might be revealed by SEM. If the welding current continued to increase after electrode–sheet sticking occurred, the electrodes might weld to the sheet metals. Of course, solid state bonding is another possible mechanism for electrode–workpiece sticking.

Various welding controls are commercially available to provide different current waveforms to satisfy most microresistance spot welding applications, whereas 50/60 Hz alternating current (ac) is the predominant current waveform used for large scale resistance spot welding. There are basically four types of power supply used in microresistance spot welding:[11] ac, capacitor discharge (CD), high frequency (hf) inverter, and direct current (dc). Figure 2 shows the typical ac, CD, and hf current waveforms.



2 Schematic diagram showing current waveforms for capacitor discharge (CD), high frequency (hf), and alternating current (ac) power supplies: solid ac lines are result of switching off current for portion of each cycle, compared with broken ac lines for 100% heat (firing delay angle $\Phi=0$)

When using an ac power supply, the control of heat input is accomplished by changing secondary tap settings (i.e. voltage) and switching off the current for a portion of each cycle. The latter is usually achieved 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. 2. The minimum controllable heating unit is one-half cycle, that is, 8·3 ms since the ac frequency is 60 Hz in the present work. This type of power supply is generally sensitive to line voltage variations, therefore, the repeatability of measurements may be affected.

High frequency inverter systems use switching technology to provide constant current, voltage, or power, which is achieved regardless of fluctuations in power source voltage or a non-uniform workpiece resistance. The resultant waveform is a dc superimposed with high frequency and low amplitude ac pulses (Fig. 2). The actual shape and amplitude of the high frequency ac pulses 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 resolution is 1 ms.

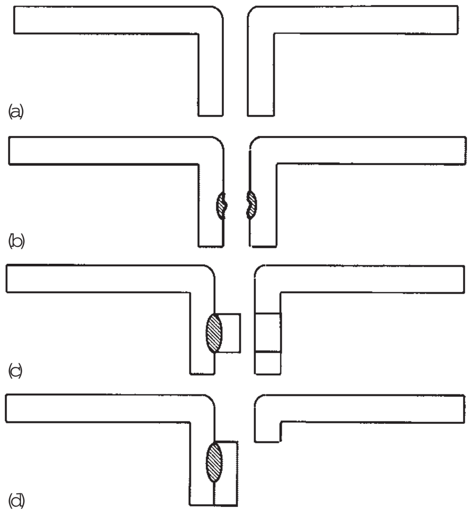
When using a CD power supply, the energy is provided by a charged capacitor bank and the amount of energy (pulse energy) delivered is determined by the amplitude and duration (pulse width) of the current pulse. The heat input can be controlled by varying the voltage on the capacitor bank, hence changing the amplitude of the current pulse. This type of energy source exhibits good voltage control and the amount of stored energy is highly repeatable. Typical pulse width is of the order of 1–5 ms.

When using the ac power supply, the root mean square (RMS) current values were measured using a Miyachi MM–336A weld checker. When using the hf and CD power supplies, the current/energy values were recorded from the actual machine settings. The whole welding process was semiautomatically controlled, i.e. an air pressure system was

Table 1 Physical properties of sheet metals investigated

Material	Thermal conductivity,[12,13] W m^{-1} K^{-1}	Electrical resistivity,[12,13] nΩ m	Surface hardness, HV1	Surface roughness, μm: Thin sheet	Surface roughness, μm: Thick sheet
Kovar	17	500	190	0·13±0·04	0·30±0·07
CRS*	65	120	350	0·17±0·54	0·54±0·05
Nickel	92	68	110	0·38±0·05	0·34±0·09

*CRS cold rolled steel.



a failure along interface; *b* failure through nugget; *c* failure as button pullout; *d* failure in heat affected zone (HAZ)

3 Schematic diagram showing joint failure modes during peel test

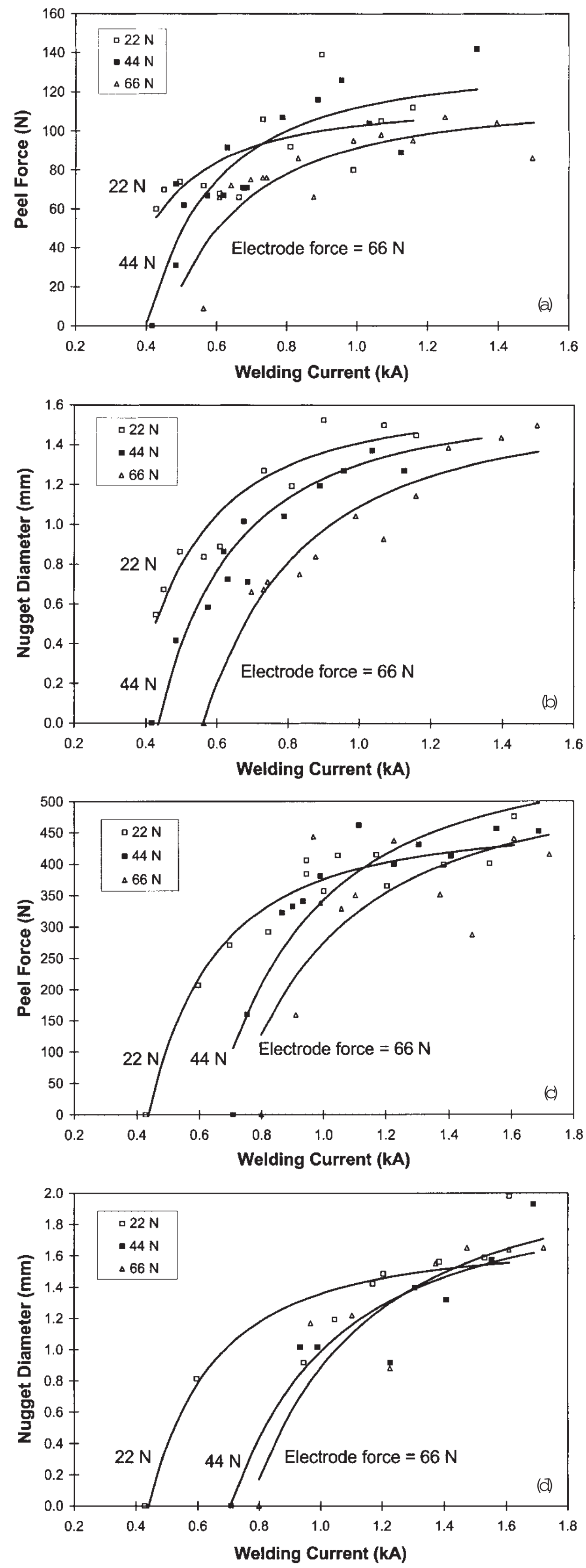
triggered by a foot pedal to apply electrode force after two overlapped specimens were manually placed between the opposing electrodes. Welding current was delivered to the stack after the force had reached a preselected value. Welding current, rise time (fixed at 2 cycles when using the ac power supply and 10 ms when using the hf power supply in the present study), and welding time were all preselected as inputs on the welding controls; however, squeeze time was not measured and, more importantly, cooling times were neither controlled or measured. Before welding, the sample surfaces were cleaned using methanol.

RESULTS

Various failure modes were observed during peel testing of resistance spot welded joints, namely, interfacial failure, weld failure, button pullout, and heat affected zone (HAZ) failure (Fig. 3). Interfacial failure was due to no bonding or only weak bonding formed between metal sheets, as shown in Fig. 3*a*. Once a weld nugget formed, joints generally failed through the weld nugget (when the nugget was small, as in Fig. 3*b*) or by a button pullout (when nugget diameter was above a certain size, as in Fig. 3*c*). However, many of the CRS joints failed at the HAZ (Fig. 3*d*) when the tensile axis direction of the test coupons was transverse to the rolling direction. Other CRS joints failed as a button pullout when the tensile axis direction of the test coupons was parallel to the rolling direction (*see* 'Cold rolled steel' subsection below for further details).

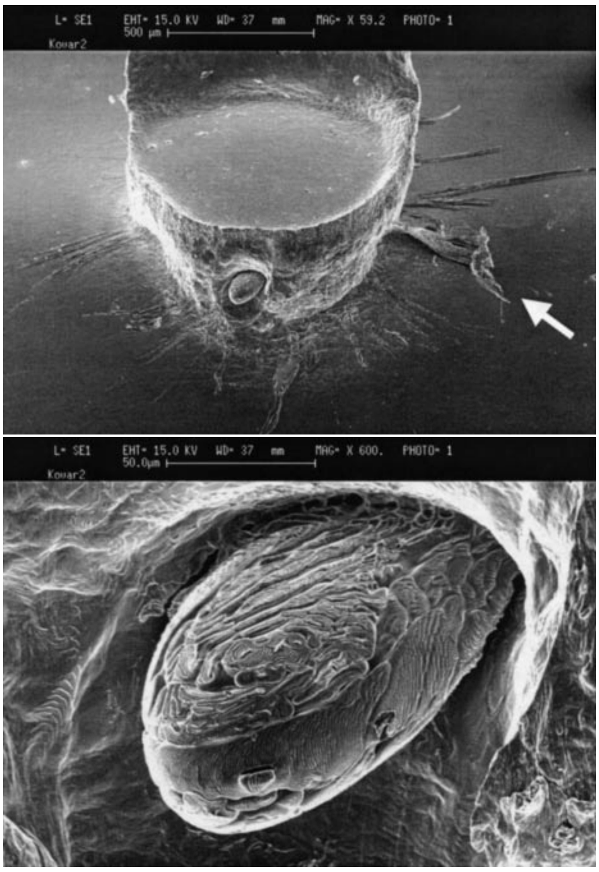
Kovar

Figure 4 shows the plots of peel force or nugget diameter versus welding current at different electrode forces for the Kovar joints produced using the ac power supply. Electrode force mainly affected the current thresholds for weld initiation. For 0·2 mm thickness Kovar, weld metal expulsion (Fig. 5) started at a welding current of 0·6, 0·7, and 0·9 kA (corresponding to a nugget diameter of about 1·0 mm) when the electrode force was 22, 44, and 66 N, respectively. For 0·5 mm thickness Kovar, weld metal expulsion started at a welding current of 0·8, 0·9, and 1·1 kA (corresponding to a nugget diameter of about 1·0–1·2 mm) when the electrode force was 22, 44, and 66 N, respectively. Increasing electrode forces appeared to increase the onset current for weld metal expulsion, but also increased the current threshold for weld initiation (Fig. 4).



a peel force, 0·2 mm; *b* nugget diameter, 0·2 mm; *c* peel force, 0·5 mm; *d* nugget diameter, 0·5 mm

4 Variation of peel force and nugget diameter as function of welding current at different electrode forces for 0·2 and 0·5 mm Kovar joints produced using ac power supply and 8 cycle welding time



a

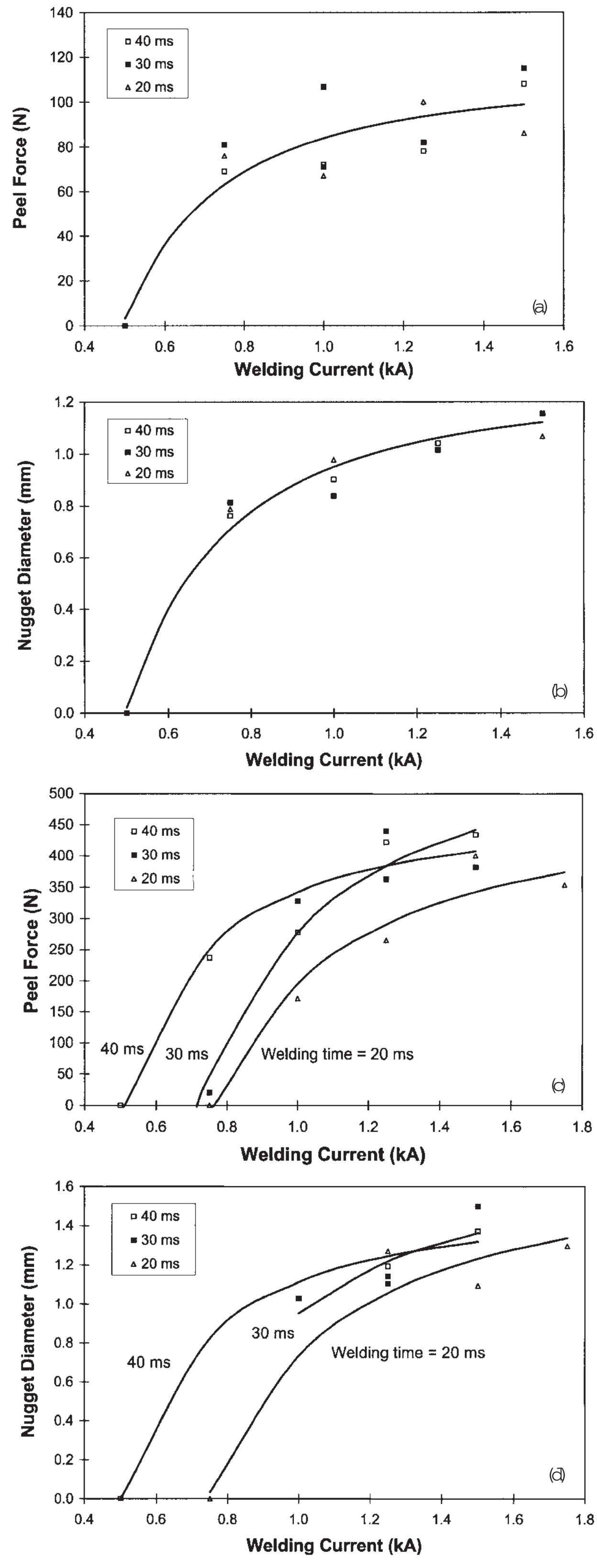
b

5 Weld metal expulsion (arrowed in *a*): *b* shows detail of solidified molten metal being expelled from hole on pullout button in *a* (SEM)

No electrode–sheet sticking was observed during welding. Larger scatter was observed in the peel force data, e.g. *see* Figs. 4*a* and *c*, compared with the nugget diameter data in Figs. 4*b* and *d*, which indicates that the variations in the peel force data are due not only to the variations in nugget diameter. This may be because the distance between the location of the bending point and the nugget (x in Fig. 1) was not very precisely controlled in the present work (about 5 mm); the variations in this distance can cause large variations in the maximum load in the peel test.[3]

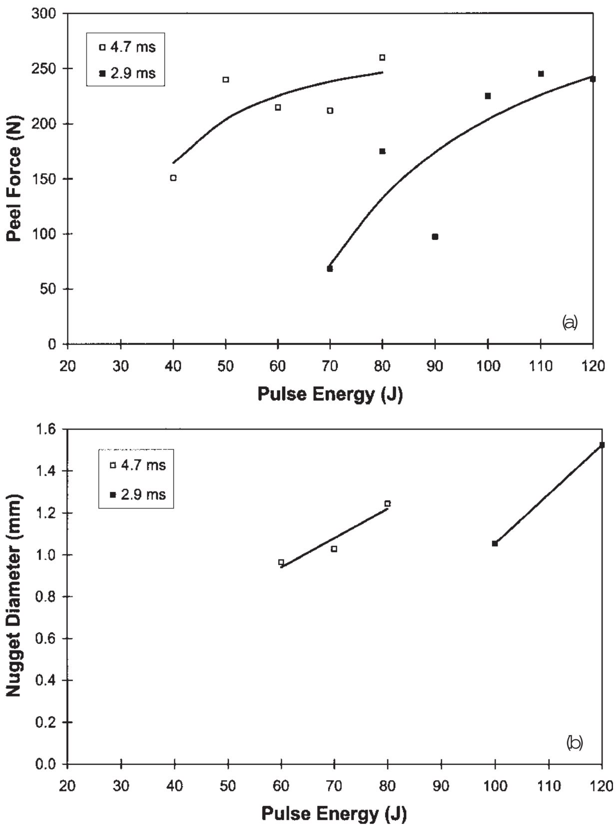
Figure 6 shows the plots of peel force or nugget diameter versus welding current at different weld times for the Kovar joints produced using the hf power supply and 66 N force. Increasing weld times reduced the threshold current necessary to form a weld when welding 0·5 mm Kovar, in contrast with welding of 0·2 mm thickness Kovar (Table 2). For both 0·2 and 0·5 mm thickness Kovar, weld metal expulsion started at a welding current of 1·0–1·25 kA (corresponding to a nugget diameter of about 1·0 mm). No electrode–sheet sticking was observed during welding.

Figure 7 shows the plots of peel force or nugget diameter versus pulse energy at different pulse widths for the Kovar joints produced using the CD power supply and 66 N electrode force. Increasing pulse width reduced the input energy required to form a weld, which is similar to the effect of welding time when welding 0·5 mm thickness Kovar using the hf power supply. For the pulse width of 2·9 ms, weld metal expulsion started at a pulse energy of 100 J (corresponding to a nugget diameter of about 1·0 mm). For the pulse width of 4·7 ms, weld metal expulsion started at a pulse energy of about 60 J (corresponding to a nugget diameter of 0·9–1·0 mm). No electrode–sheet sticking was observed during welding.

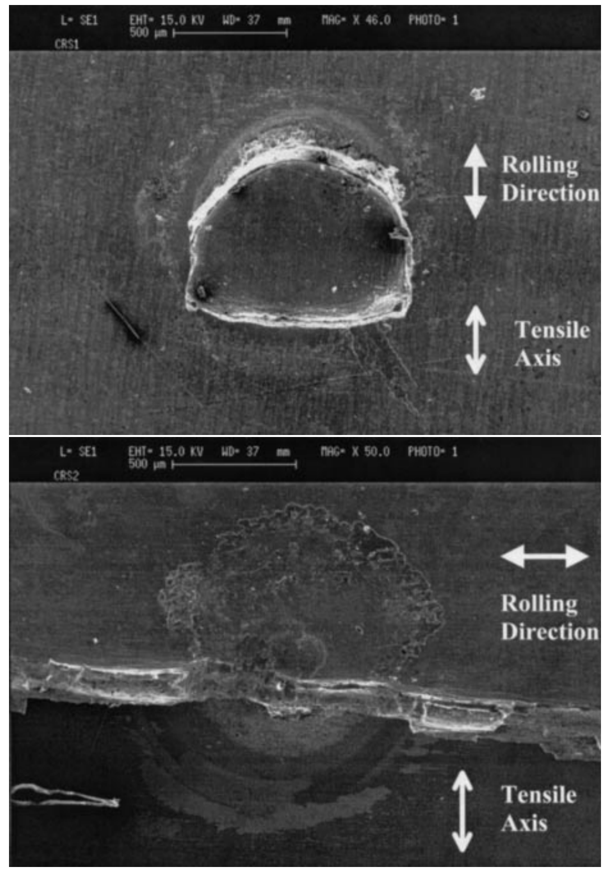


a peel force, 0·2 mm; *b* nugget diameter, 0·2 mm; *c* peel force, 0·5 mm; *d* nugget diameter, 0·5 mm

6 Variation of peel force and nugget diameter as function of welding current at various welding times for 0·2 and 0·5 mm Kovar joints produced using hf power supply and 66 N electrode force



7 Variation of *a* peel force and *b* nugget diameter as function of pulse energy at different pulse widths for 0·5 mm Kovar joints produced using CD power supply and 66 N electrode force



8 Variation of failure mode with specimen orientation: *a* shows button pullout failure when longitudinal direction of test coupons was parallel to rolling direction, and *b* shows HAZ failure when transverse direction of test coupons was parallel to rolling direction (SEM)

Kovar is among those metals that can be readily joined by microresistance spot welding, and the required welding current or pulse energy values were the lowest in the present work. No electrode–sheet (workpiece) sticking was observed during resistance spot welding of Kovar. However, weld metal expulsion readily occurred although it showed little effect on the joint strength. Increasing electrode force increased the onset current for weld metal expulsion, but also necessitated a higher welding current to form a weld. Increasing welding time or pulse width reduced the current or energy required to form a weld for 0·5 mm Kovar when using CD and hf power supplies, but this was not observed when welding 0·2 mm thickness Kovar (Table 2). The reason for this may be greater heat loss during welding into the thicker sheet. It is thought that the fraction of the heat loss into the electrodes will decrease when welding the thicker sheet; however, the total heat loss and the proportion lost to the sheet metal will also be increased owing to the greater heat required to heat the surrounding volumes. Therefore, the thicker sheet would require more heat to form a nugget of a certain size and also a longer welding time to reach thermal equilibrium, compared with the thinner sheet (Table 2). The maximum nugget diameter that did not result in weld metal expulsion was about 0·9–1·0 mm, which is about one-third of the electrode diameter. In comparison, the nugget diameter in large scale resistance spot welding is generally similar to the electrode diameter.[1–3] The reason for this difference will be discussed below.

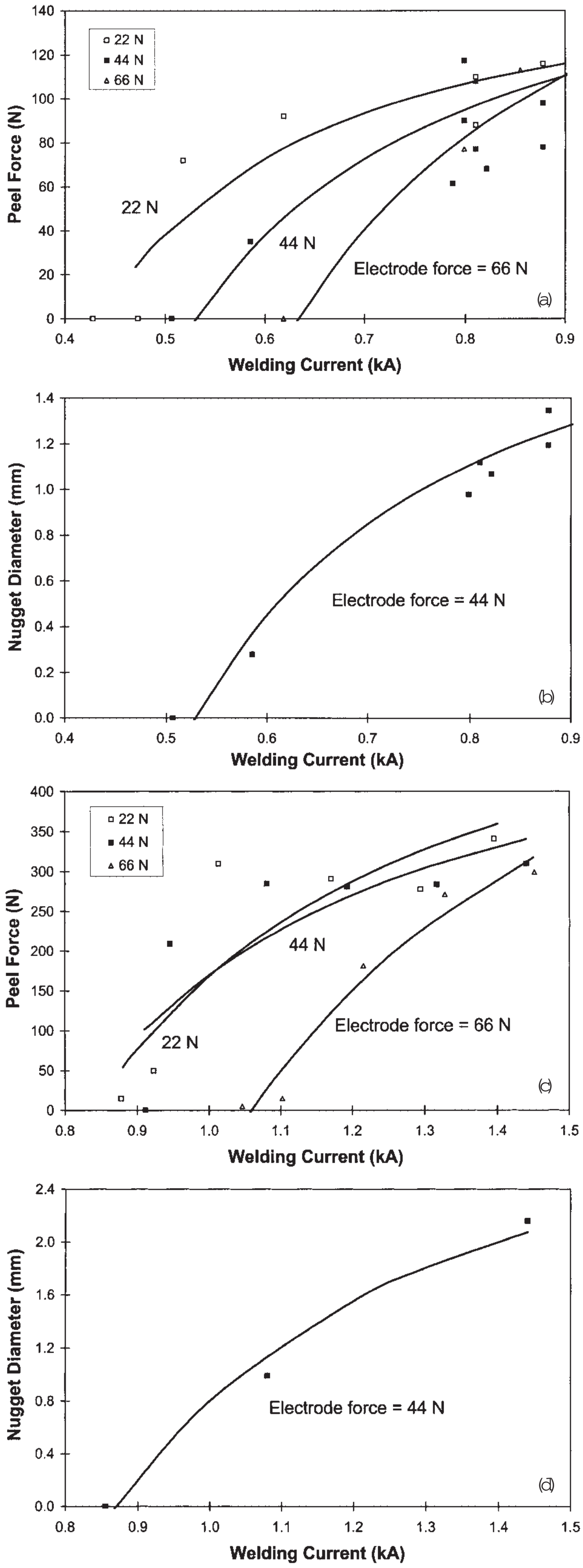
Cold rolled steel

Many CRS joints failed at the HAZ (Figs. 3 and 8) when the tensile axis direction of the test coupons was transverse to the rolling direction, and others showed button pullout failure when the tensile axis direction of the test coupons was in the rolling direction.

Table 2 Summary of welding current (kA) or pulse energy (J) necessary to produce 0·8 mm diameter weld nuggets using alternating current (ac), high frequency (hf), or capacitor discharge (CD) welding*

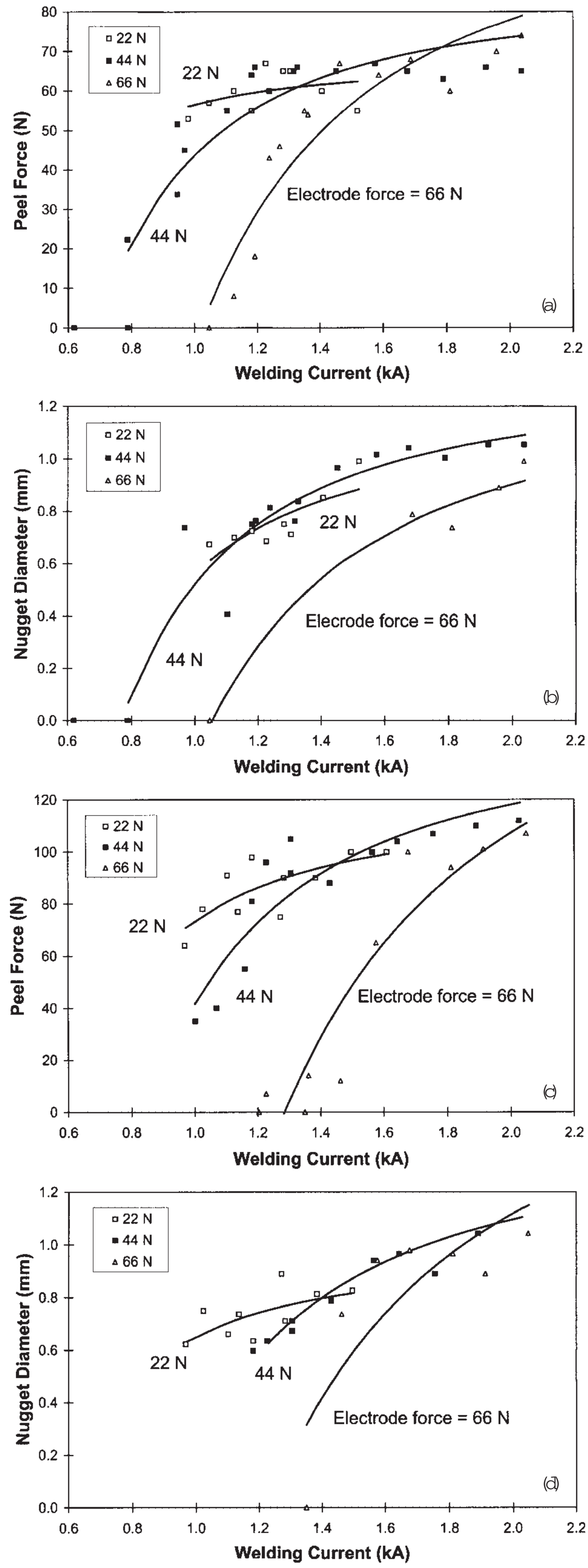
		ac power supply electrode force, N			hf power supply weld time, ms			CD power supply pulse width, ms	
Metal	Thickness, mm	22	44	66	20	30	40	2·9	4·7
Kovar	0·2	0·5 kA	0·6 kA	0·8 kA	0·8 kA	0·8 kA	0·8 kA	…	…
	0·5	0·6 kA	0·9 kA	1·0 kA	1·0 kA	0·9 kA	0·8 kA	50 J	90 J
Nickel	0·2	1·2 kA	1·2 kA	1·6 kA	2·0 kA	2·0 kA	2·0 kA	40–50 J	40–50 J
	0·25	1·3 kA	1·4 kA	1·7 kA	…	…	…	…	…

*Note: weld time is 8 cycles when using ac power supply, and electrode force is 44 N when using hf and CD power supplies.



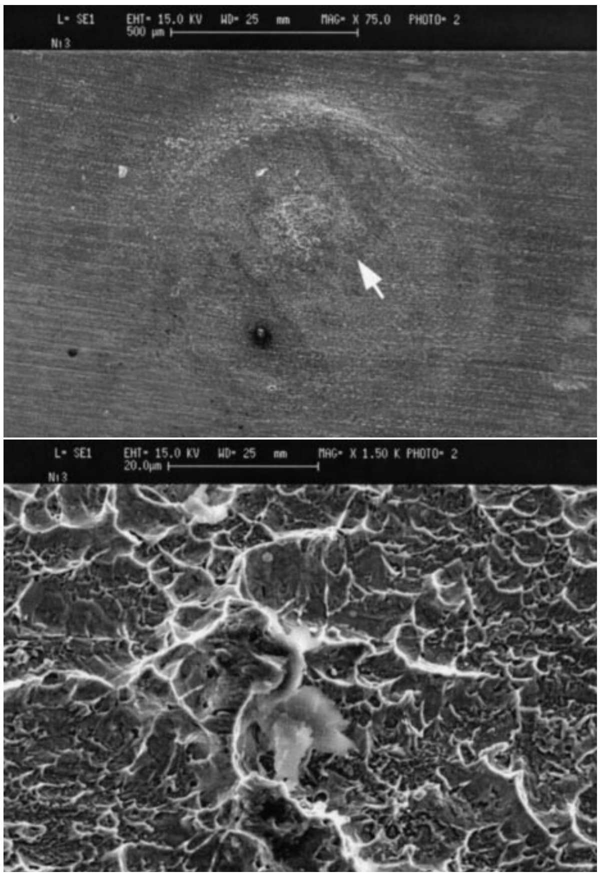
a peel force, 0·25 mm, 6 cycles; *b* nugget diameter, 0·25 mm, 6 cycles; *c* peel force, 0·5 mm, 8 cycles; *d* nugget diameter, 0·5 mm, 8 cycles

9 Variation of peel force and nugget diameter as function of welding current at various forces for 0·25 and 0·5 mm CRS joints produced using ac power supply and 6 or 8 cycle welding time



a peel force, 0·2 mm; *b* nugget diameter, 0·2 mm; *c* peel force, 0·25 mm; *d* nugget diameter, 0·25 mm

10 Variation of peel force and nugget diameter as function of welding current at various electrode forces for 0·2 and 0·25 mm nickel joints produced using ac power supply and 8 cycle welding time



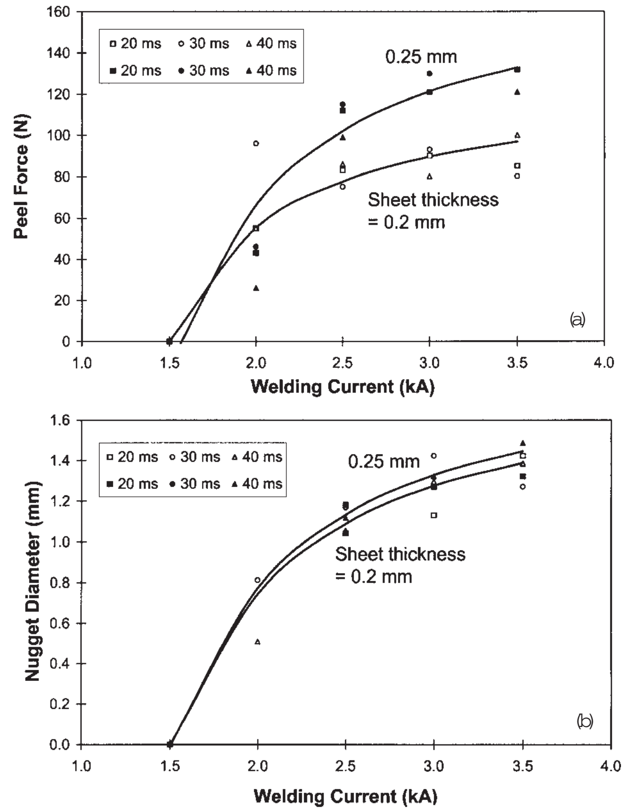
a

b

11 Electrode – sheet sticking area (arrowed in *a*) on sheet surface that was adjacent to electrode (0·2 mm nickel sheet, ac power supply, electrode force 44 N, welding current 1·65 kA, welding time 8 cycles): *b* shows detail of fracture surface in *a* (SEM)

Figure 9 shows the plots of peel force versus welding current at different electrode forces for the CRS joints produced using the ac power supply. Limited trials indicate that reducing weld time from 8 to 4 cycles did not have a significant effect on the joint strength and nugget diameter. Weld metal expulsion started at a welding current of 0·6 kA when the electrode force was 22 N and at 0·8 kA when the electrode force was 44 and 66 N for 0·25 mm thickness CRS. Weld metal expulsion started at a welding current of 1·0, 1·1, and 1·3 kA when electrode force was 22, 44, and 66 N respectively for 0·5 mm thickness CRS. The nugget diameter that corresponded to these onset currents for weld metal expulsion was about 1·0 – 1·1 mm, which is similar to that in the Kovar joints. Increasing electrode force reduced the onset current for weld metal expulsion, but necessitated a higher threshold current to initiate a weld. Electrode – sheet sticking was not experienced during welding although some surface burning marks were observed.

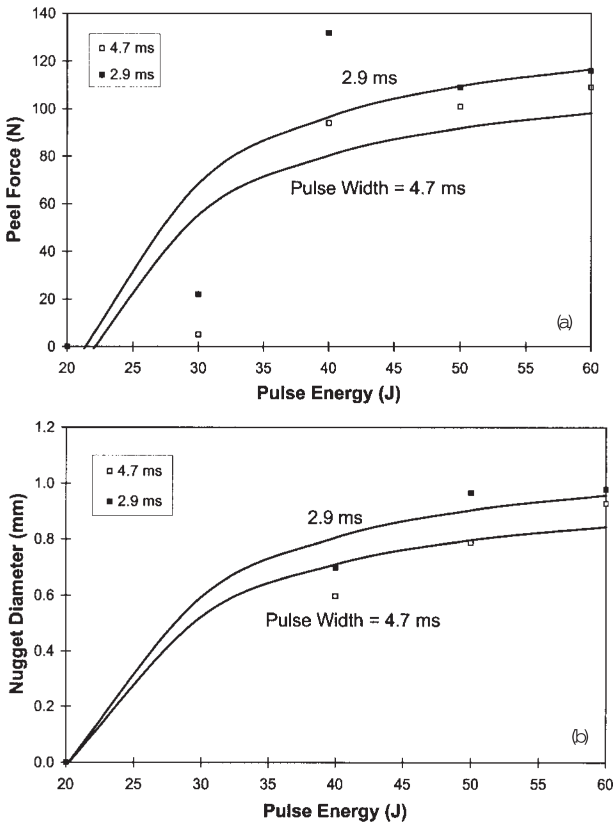
Cold rolled steel is readily resistance spot welded, and the welding current values required were very close to those for Kovar. Also similar to Kovar, electrode – sheet (workpiece) sticking appeared not to be a problem during welding of CRS. Limited trails indicate that the welding of CRS using the hf and CD power supplies was very similar to that for Kovar. For example, it has also been observed that decreasing weld time from 40 to 30 ms reduced the current threshold for weld formation for 0·5 mm thickness CRS, but not for 0·25 mm thickness CRS. The maximum nugget diameter that did not result in weld metal expulsion was again about one-third of the electrode diameter, which is similar to that for welding of Kovar.



12 Variation of *a* peel force and *b* nugget diameter as function of welding current at various weld times for 0·2 and 0·25 mm nickel joints produced using hf power supply and 66 N electrode force

Nickel

Figure 10 shows the plots of peel force or nugget diameter versus welding current at different electrode forces for the nickel joints produced using the ac power supply. Electrode force mainly affected the current threshold for weld initiation. For 0·2 mm thickness nickel, weld metal expulsion started at a welding current of 1·1, 1·3, and 1·8 kA (corresponding to a nugget diameter of about 0·7 – 0·8 mm) when the electrode force was 22, 44, and 66 N, respectively. For 0·25 mm thickness nickel, weld metal expulsion started at a welding current of 1·2 and 1·7 A (corresponding to a nugget diameter of about 0·8 – 0·9 mm) when the electrode force was 22 and 44 N, respectively. No weld metal expulsion was observed for 0·25 mm nickel when the electrode force was 66 N. Increasing electrode force increased the onset welding current for weld metal expulsion but also increased the current necessary to form a weld (Table 2). Electrode – sheet sticking started at a welding current of 1·2, 1·3, and 1·6 kA when the electrode force was 22, 44, and 66 N respectively for 0·2 mm thickness nickel. Electrode – sheet sticking started at a welding current of 1·2, 1·6, and 1·9 kA when the electrode force was 22, 44, and 66 N respectively for 0·25 mm nickel. Figure 11 shows a fractured region on a sheet surface that was adjacent to the electrode during welding, which may be due to electrode – sheet sticking. The electrode and nickel started to weld together at a welding current of 1·4 and 2 kA when the electrode force was 22 and 44 N respectively for 0·2 mm nickel, and at a current of 1·5 kA when the electrode force was 22 N for 0·25 mm thickness nickel. Increasing electrode force appeared to reduce the tendency for electrode – sheet sticking, which may be because the lower contact resistance at the electrode/sheet interface, resulting from the increased electrode force, would reduce the interfacial heating and



13 Variation of *a* peel force and *b* nugget diameter as function of pulse energy at different pulse widths for 0·25 mm nickel joints produced using CD power supply and 66 N electrode force

hence the interdiffusion/interalloying between the copper electrodes and the nickel sheets.

Figure 12 shows the plots of peel force or nugget diameter versus welding current at different welding times for the nickel joints using the hf power supply and 66 N electrode force. The welding time has no effect on the nugget diameter and joint strength for both 0·2 and 0·25 mm thickness nickel. Weld metal expulsion started at a welding current of 3·0 kA (corresponding to a nugget diameter of about 1·2 mm) for both 0·2 and 0·25 mm thickness nickel. Weld metal expulsion appeared to be worse for longer welding times. Electrode–sheet sticking started at a welding current of 3·5 kA for both 0·2 and 0·25 mm nickel. Figure 13 shows the plots of peel force or nugget diameter versus energy at different pulse widths for the nickel joints produced using the CD power supply at 66 N electrode force. Again, the pulse width has little effect on the nugget diameter and joint strength. Weld metal expulsion started at a pulse energy of 60 J (corresponding to a nugget diameter of about 0·8–0·9 mm). No electrode sticking was observed at pulse energies up to 60 J.

Microresistance spot welding of nickel was not as straightforward as that of Kovar and CRS in two respects: the welding of nickel required higher welding current (Table 2) and the electrode–sheet sticking was worse compared with the welding of Kovar and steel, which will be discussed below. Similar to Kovar and CRS, increasing electrode force increased the current threshold for weld initiation, but also increased the onset current for weld metal expulsion. Also similar to Kovar and CRS, the maximum nugget diameter that did not result in weld metal expulsion was about one-third of the electrode diameter.

DISCUSSION

Weldability of sheet metals

Weldability of a material in resistance spot welding is often defined by electrode tip life, welding current level and current range, etc.[1,2] The welding current or pulse energy used to produce a 0·8 mm diameter nugget is given in Table 2 for welding of Kovar and nickel using the ac, hf, and CD power supplies. The welding current or pulse energy requirements for welding CRS are very similar to those for Kovar.

The weld formation in resistance spot welding depends on the interaction of heat generation and heat dissipation in the workpieces. The heat generation is affected mainly by the welding current, the resistance of the workpieces (including contact resistance and bulk resistance), and welding time – *see* equation (1). The contact resistance at the faying interface, which is influenced by material characteristics (such as cleanness, roughness, hardness, and plating materials) and electrode force, is thought to be the most critical factor affecting the nugget formation, at least at the start of the process.[3,4,14–16] For example, an increased surface hardness will increase the contact resistance and hence the heat generation. The heat dissipation is governed mainly by the thermal conductivity of the material and the geometry of the workpieces and electrodes.

When comparing the weldability of different sheet metals in the present work, the electrical resistivity, thermal conductivity, and surface hardness of the workpieces are the main variables since other factors (such as electrodes, electrode force, and sheet thickness and surface roughness) are approximately equal. The relatively high electrical resistivity and low thermal conductivity of Kovar result in a relatively high heat generation and low heat loss during welding, reducing the welding current or pulse energy necessary to produce a weld. Conversely, the relatively low electrical resistivity and high thermal conductivity of nickel indicate low heat generation and high heat loss during welding, which increase the welding current or pulse energy necessary to produce a weld. The properties of CRS are between those of Kovar and nickel. On the basis of its electrical and thermal conductivity, which are lower than but close to those for nickel, it would be reasonable to assume that the current/energy requirements for welding CRS would be lower than but close to those for nickel. However, a much higher surface hardness of CRS compared with those of Kovar and nickel (Table 1) would lead to a higher contact resistance, which may be the reason why the current/energy requirements for CRS were close to those for Kovar (Table 2).

No work was performed on the electrode tip life; however, the electrode–sheet sticking was monitored in the present work since it contributes to reduced electrode tip life. Increased electrode–sheet sticking was observed in the present experiments for welding of nickel compared with Kovar and CRS, which may be because nickel reacts and alloys readily with the Cu–Cr electrodes. It is thought that electrode–sheet sticking is a result of local bonding between the sheet metal and electrode, through either melting or solid state welding. The higher welding current (Table 2), lower surface hardness (Table 1), and higher diffusion coefficient and solubility in the copper electrode of nickel compared with Kovar and CRS would promote interalloying/interdiffusion between the sheet and electrode.[12,13] Therefore, microresistance spot welding of nickel was not as straightforward as that for Kovar and CRS because of the comparatively high welding current and the increased electrode–sheet sticking.

Selection of process parameters

Detailed recommendations have been provided for large scale resistance spot welding of a variety of

Table 3 Recommended nominal process parameters

			ac power supply		CD power supply		hf power supply	
Sheet metal	Sheet thickness, mm	Electrode force, N	Welding current, kA	Welding time, cycles*	Pulse energy, J	Pulse width, ms	Welding current, kA	Welding time, ms*
Kovar	0·2	66	1·0	5	20	2·9	1·1	30
	0·5	66	1·2	7	70	4·7	1·3	40
CRS	0·25	66	1·1	5	25	2·9	1·2	30
	0·5	66	1·3	7	80	4·7	1·4	40
Nickel	0·2	44	1·4	4	35	2·0	2·4	20
	0·25	44	1·5	4	45	2·0	2·6	20

*Welding time includes rise time of two cycles for ac power supply and 10 ms for hf power supply.

metals;[1,2] however, no such information is available for microresistance spot welding. One of the objectives of the present study was to provide practical baselines for selecting process conditions and these baselines could be used as a starting point for further process investigation or process optimisation for specific industrial applications. Based on the present investigation, recommended nominal process parameters for 0·2–0·5 mm thickness Kovar, CRS, and nickel using class 2 electrodes of tip diameter 3·2 mm were determined and are presented in Table 3. The current values in Table 3 were those for which weld metal expulsion started to occur but with little effect on the joint strength.

Welding current (or pulse energy), electrode force, and welding time (or pulse width) may all affect joint strength and nugget size. However, welding current is the strongest of the process variables affecting nugget growth because heat generation is proportional to the square of welding current – *see* equation (1). For each combination of power supply, electrode material, and sheet metal, there can be found a certain current–energy 'window' to form a weld of given nugget diameter without molten metal expulsion and/or electrode–sheet sticking. When using CD and hf power supplies, a longer welding time is required when welding 0·5 mm thickness Kovar and CRS compared with 0·2 mm Kovar and CRS, because more heat dissipates into the sheet metals during welding.

Electrode force affects mainly the current/energy threshold for weld initiation since electrode force strongly influences the contact resistance at the faying interface by plastically deforming local contact points and breaking down surface contaminants.[14] 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/energy threshold for formation of a weld by increasing the contact resistance, it may also lead to unstable or inconsistent resistance values at the contact interfaces,[15] which are undesirable in terms of process control. Very high contact resistance may also cause initial splashing at the interface and promote electrode–sheet sticking.[16] Use of a rise time has been suggested in microresistance spot welding to reduce the contact resistance, and hence initial splashing and electrode–sheet sticking.[16]

A lower electrode force also leads to a lower onset welding current for molten weld metal expulsion. Computer simulation has shown that electrode force determines the maximum nugget diameter without weld metal expulsion when the electrode geometry is kept constant.[17–19] It has also been reported[14] that higher electrode forces broadened the possible range of welding currents, which may be because electrode force can cause a greater increase in the onset current for weld metal expulsion than in the threshold current for weld formation. However, excessive electrode force can lead to excessive surface indentation, which is often undesirable during microjoining or precision welding.[9]

All three power supplies could be used successfully for resistance spot welding of Kovar, CRS, and nickel. However, in welding nickel, the current levels required to produce similar joint strength or nugget diameter when using the hf power supply were higher than the RMS current levels when using the ac power supply. This is markedly different from the results for welding of CRS and Kovar, in which the difference between the two current levels is very small (Table 2). There are a few possible reasons for this difference. First, because of the heat generation due to eddy currents and the skin effect etc., the effective resistance in an ac circuit is higher than the plain resistance of the same circuit carrying only dc.[20,21] Second, the shift of the nugget centre from the workpiece interface due to the Peltier effect when using dc type power supplies might require a higher welding current to achieve the same joint strength compared with that obtained when using ac power supplies. It has been shown[22] that the amount of heat generated at the workpiece surface at the positive electrode side is approximately 15% greater than that at the negative electrode side. This is consistent with the observation that there was more severe electrode–sheet sticking at the positive electrode side in the welding of nickel using hf and

Table 4 Comparison between micro- and large scale resistance spot welding

Parameter	Microresistance spot welding	Large scale resistance spot welding
Sheet thickness	$<0{\cdot}5$ mm	$>0{\cdot}6$–$0{\cdot}8$ mm
Electrode force	<100–200 N	>2000 N
Welding current	<2–5 kA	>5–10 kA
Electrode cooling	No	Yes
Metals to be welded	Mainly non-ferrous metals, such as copper, Kovar, nickel, titanium, and silver (plated and unplated)	Mainly steels, such as carbon steel and stainless steel (coated and uncoated), some aluminium alloys
Plating materials	Silver, gold, nickel, tin, lead, etc.	Zinc, tin, etc.
Applications	Medical devices, electronic components and circuit connections, lamps, batteries, sensors, etc.	Automotive body panels and frames, appliances, furniture, boxes and enclosures, etc.
Published systematic investigation	Little	Extensive

Table 5 Comparison of process parameters for micro- and large scale resistance spot welding of 0·25 mm thickness nickel and steel sheets

Material	Process scale	Electrode diameter, mm	Electrode force, N	Electrode pressure, MPa	Welding current, kA	Current density, A mm^{-2}	Welding time, cycles	Nugget diameter, mm	Source
Nickel	Micro	3·2	44	5·5	1·5	187	4	1·0	Present work
	Large	4·8	1200	66	9·75	539	3	3·0	Ref. 1
CRS	Micro	3·2	66	8·2	1·1	137	5	1·0	Present work
	Large	3·2	900	112	4	497	4	3·3	Ref. 1

CD power supplies. Finally, when using an ac power supply the peak current is much higher than the RMS current, which might affect the nugget formation. However, further work is required to investigate the quantitative contributions of such effects.

Micro- versus large scale resistance spot welding

In comparison with large scale resistance spot welding, microresistance spot welding requires much more precise electrical and mechanical control, and electrode force and welding current are much lower (Table 4). The difference between micro- and large scale resistance spot welding is due not only to the difference in the scale of the joints, but also to the fundamental difference in the electrode forces used. For example, it can be seen from Table 5, in which the nominal process parameters recommended by the present work and by the Resistance Welding Manufacturers' Association[1] for 0·25 mm thickness nickel and CRS are given, that the electrode pressures for micro- and large scale resistance spot welding can differ by a factor greater than 10.

A lower electrode force in resistance spot welding results in a smaller contact area,[17–19] which may be the reason why the maximum nugget diameter without weld metal expulsion is very small in microresistance spot welding (about one-third of the electrode tip diameter in the present work). In comparison, the nugget diameter that can be achieved in large scale resistance spot welding is very similar to the electrode tip diameter (Table 5). However, a higher contact resistance at the faying interfaces because of the very low electrode force (pressure) would reduce the welding current required to initiate and form a weld.

CONCLUSIONS

1. Kovar and CRS are readily microresistance welded because they require lower welding current and show decreased electrode–sheet sticking, which may be due to their high electrical resistivity, low thermal conductivity, and high surface hardness. Microresistance welding of nickel is relatively problematic because the nickel requires higher welding current or pulse energy and shows increased electrode–sheet sticking, which may be due to its relatively low electrical resistivity, high thermal conductivity, and low surface hardness.

2. Welding current/pulse energy, electrode force, and weld time/pulse width all affect joint strength and nugget diameter, with the current/energy having the strongest effect. A higher electrode force increases the onset welding current for weld metal expulsion and electrode–sheet sticking, but also necessitates a higher threshold current to initiate a weld. The maximum nugget diameter that did not result in molten metal expulsion was about 0·8–1·0 mm, which was about one-third of the electrode tip diameter.

3. All three power supplies (ac, hf, and CD) can be used to resistance weld the sheet metals studied; however, the required current when using a hf power supply was higher than the RMS current when using an ac power supply during welding of nickel.

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