Electrode Sticking During Micro-Resistance Welding of Thin Metal Sheets

S. J. Dong, G. P. Kelkar, and Y. Zhou

***Abstract*—The electrode sticking mechanism and factors affecting the sticking, including welding current, weld time, electrode tip coating, electrode force and electrode spacing, were studied during micro-resistance welding of very thin nickel-plated steel to nickel sheets in the assembly of a cell-phone battery package. The results indicated that electrode sticking was caused by local metallurgical bonding between the electrode and the nickel-plated steel sheet. The sticking force was proportional to the total area of the local bonds and to the bonding strength between the electrode and sheet. Reducing welding current and weld time, and increasing electrode force and electrode spacing were found to reduce electrode sticking. Welding electrodes with tips coated with TiC metal matrix composite were tried as an alternative to the regular CuCrZr electrode and were found to be more resistant to sticking.**

***Index Terms*—Cell-phone battery application, electrode sticking mechanism, micro-resistance welding, TiC-composite coating, very thin metal sheets.**

I. Introduction

MICRO- or small-scale resistance welding is a group of microjoining processes (such as resistance spot, parallel gap, series and seam welding) in which micro-joints are formed between two sheets by resistance heating caused by the passage of electric current [1]. These processes are commonly used for applications in electronic and medical packaging, such as lead/pad interconnections and hermetic sealing. For example, micro-resistance spot welding has been used to attach outer shield clips to the plated steel cores of a circuit board during manufacturing of Motorola's MicroTAC cellular telephones [2]. Small-scale parallel gap welding has been used to join high temperature microelectronic interconnects [3] and micro-resistance seam welding has been used to hermetically seal plated microelectronic packages [4].

One of the problems during micro-resistance welding and generally in any resistance welding process is electrode sticking, in which the welding electrodes adhere to the workpieces and a significant force may be needed to separate them from the workpieces after welding [2], [5]–[7]. Electrode sticking slows down production and contributes to the reduction of electrode life and to damage to welded products. A few engineering measures have been proposed to reduce electrode sticking, such as the use of different electrode materials [2], [8], but no detailed work has been performed to study the electrode sticking mechanism and factors affecting the electrode adhesion. In the present work, the details of electrode sticking were studied during small-scale series resistance welding of very thin sheets of nickel-plated steel to sheets of nickel. This project was part of an effort to reduce electrode sticking in the fabrication of a cell-phone battery package.

II. Experimental

Small-scale series resistance welding was performed using a Unitek model HF2 power supply and model 508 weld-head. The experimental setup and basic welding parameters (unless stated otherwise) used are shown in Figs. 1 and 2. When direct-current power supplies are used such as the high-frequency inverter system [5], [6] employed in this work, the Peltier effect (the inverse of the thermocouple effect) can result in a higher heat generation at the anode electrode than that at the cathode electrode [6]. As a result, the weld nugget at the anode can be much larger than that at the cathode. Adjusting the force at each individual electrode (e.g., by reducing the cathode electrode force or increasing the anode electrode force) can normally compensate for the Peltier effect and hence produce similar weld nugget diameters at both electrodes. In this study, three combinations of electrode force were used at anode/cathode electrodes, i.e., 2400/1800, 3600/2400 and 4800/3600 g, under which conditions the cathode nuggets were still smaller than but very close to the anode nuggets. Also at these conditions, the electrode sticking was generally more severe at the cathode; therefore, this work has focussed on the electrode sticking behavior at the latter electrode. The electrode extension (the distance from electrode holder to the electrode tip) is 1.5 mm.

Two types of electrode materials have been used in this work: copper alloy C18200 with a nominal composition of Cu-0.84 wt.% Cr-0.05 wt.% Zr (CuCrZr) and the CuCrZr electrodes with tips coated with a TiC metal matrix composite (TiCap™, which is a trademark of Huys Industries Limited, Ontario, Canada) at about 10–15 μm in thickness [7]. It has been reported that the metal matrix of the electrode coating is mainly Cu and Ni with small amounts of Mo and W and the TiC particles were about 2–10 μm in diameter [7]. Electrodes had a diameter of 1.5 mm and a tip radius of 150 mm. The sheets to be welded were 100 μm thick mild steel with about 7 μm thick pure nickel plating on both surfaces, and 300 μm thick pure nickel (Fig. 1).

Sticking tests were performed on coupons consisting of nickel strips 9 mm wide and 30 mm long and nickel-plated steel

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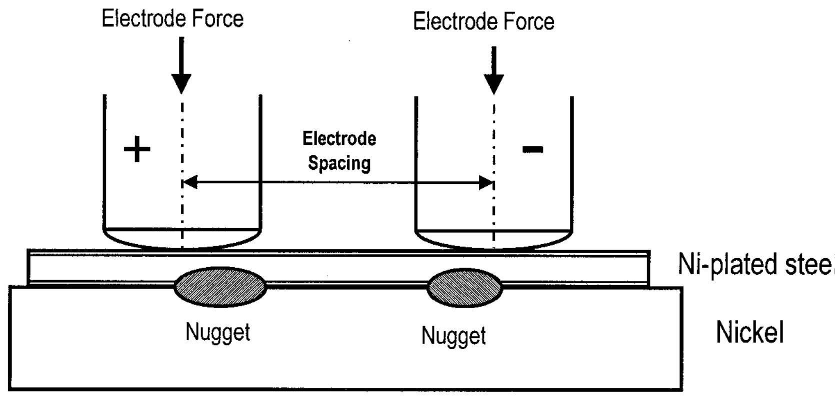


Fig. 1. Schematic of the experimental setup.

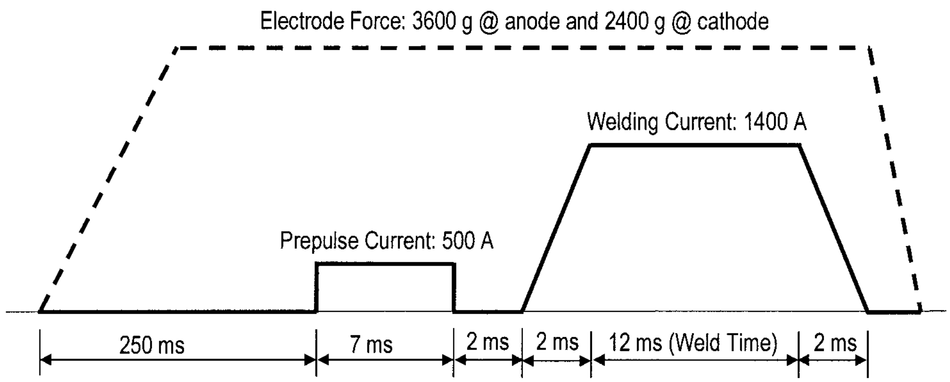


Fig. 2. Schematic of the welding schedule.

strips 4 mm wide and 50 mm long with the nickel-plated steel in contact with the electrodes (Fig. 1). Electrode sticking force was measured when adhesion of electrode to sheet occurred after welding, by using a spring gauge to separate the coupons from the electrodes and the breaking force was recorded as sticking force. The electrode tip surfaces and the sheet areas that were in contact with the electrode tip in welding were analyzed using optical microscopy and scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDX). Joint strength was measured by peel testing using a Romulus Universal Materials Tester.

III. Results and Discussion

A. Electrode Sticking

The relationship of peel force (as an indication of joint strength) and sticking force to welding current is shown in Fig. 3 for a constant weld time of 12 ms. A new pair of electrodes was used for each test current. The joint strength increased as the welding current increased, but leveled off for the currents above 1200 A. For an arbitrarily chosen minimum average acceptable joint strength of about 3 kg, the process window would be 1000–1500 A with the upper bound defined by the onset of electrode sticking. A measurable sticking force between electrode and sheet was not experienced for welding currents below 1500 A and the sticking force increased with further increase of welding current. Both electrode tips and the sheet surface areas that were in contact with the tips during welding were examined using SEM/EDX (Table I). EDX analysis indicated little nickel and iron from sheets was transferred to electrode tip surfaces, but copper was observed on the sheet surfaces (Table I and Fig. 4), which is considered as an indication of transfer of Cu from the electrode tips since there was no Cu in the original sheets. The amount of Cu pickup on the sheet was found to increase with welding current. At the level of welding current corresponding to zero measured sticking force, there was relatively little Cu transferred from the electrode tip (Table II). Fig. 4, including details of the highlighted area in Table I, clearly shows that the Cu pickup on the sheet surfaces was a result of Cu transfer from the corresponding electrode tip surface through fracturing and that this Cu pick up increased as the welding current/sticking force increased. It has been confirmed, even at zero measured sticking force, localized bonding occasionally occurred and the fracturing of these local bonds resulted in Cu removal from the electrode tip surface to the sheet surface [7].

In resistance welding, the heat (H) generated during formation of a joint can be described as

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

where I is the welding current, R is the total resistance of the sheets and interfaces, and t is the duration of the current (weld time) [3]. The total resistance includes contact resistance at three contacting interfaces (two electrode/sheet interfaces and one sheet/sheet interface), and the bulk resistance of the base materials [6]. These resistance values change during the process and their relative magnitudes control the process. Among them, con-

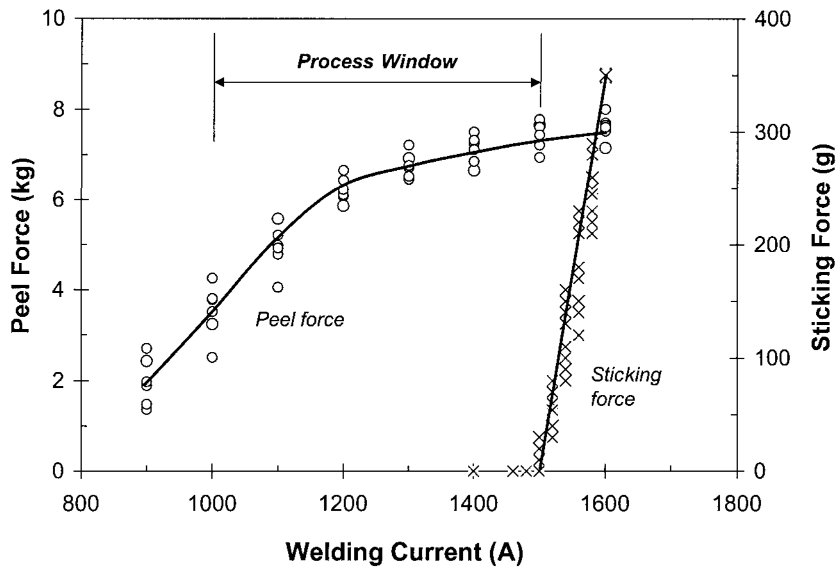


Fig. 3. Peel force and sticking force versus welding current for uncoated electrodes.

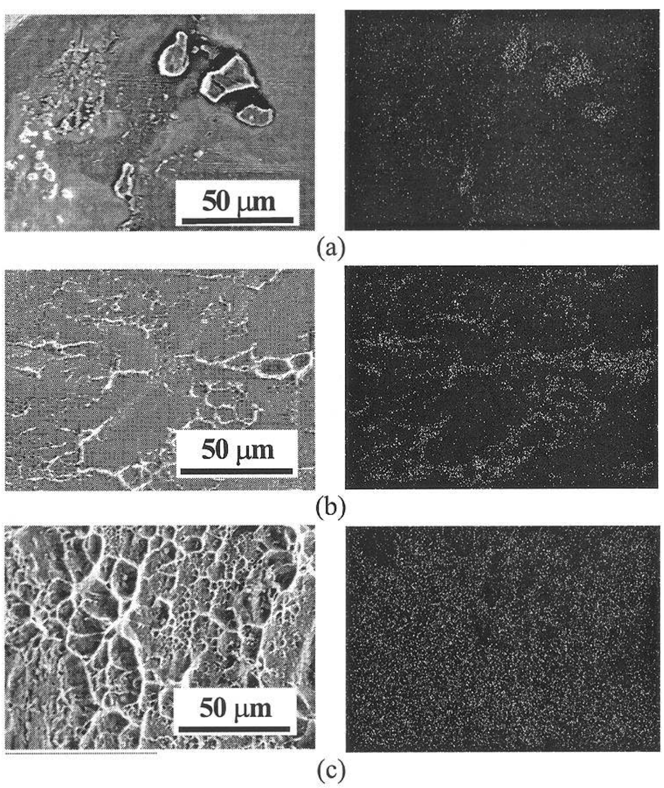


Fig. 4. Details of the highlighted areas on the sheet surfaces in Table I and their corresponding Cu mapping.

tact resistance, which is influenced by material characteristics (such as cleanliness, roughness, hardness and surface coating or plating) at the contacting interface, and electrode force, are believed to be the critical factors affecting the process, especially at the early stages of the heating cycle [6]. The heat generation will be higher at contacting interfaces than in the bulk regions, and if the process is working properly, the temperature will be the highest at the sheet/sheet interface because of the higher contact resistance and poor heat dissipation compared with the other two contact interfaces. Therefore, a molten nugget should generally form first between the sheets. However, the temperature rise at the electrode/sheet interfaces may also facilitate bonding at these interfaces, which is the fundamental cause of electrode sticking. Compared with large-scale (regular) resistance welding where the electrodes are internally water-cooled, electrode sticking should generally be worse in micro-resistance welding because no cooling water is used, hence the electrodes will likely sustain a higher surface temperature [6].

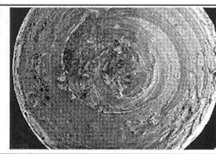
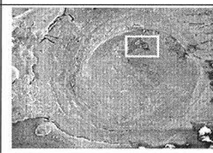
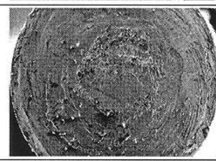
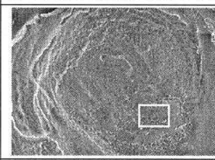
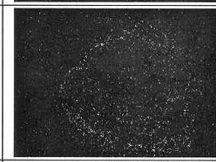
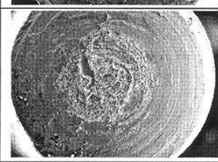
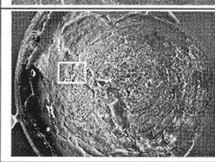
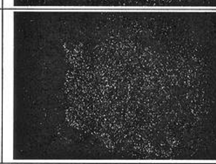
When the bonding between electrodes and sheets is very localized, the sticking force may be too weak to be measured. However, when the local bonds grow in area and/or connect together, the electrode and sheet will remain stuck together after welding and an external force (i.e., sticking force) will be needed to separate them. This force (F_S) is related to the bonding strength (σ) and total area of local bonds (A) between the electrode and sheet, i.e.,

$$F_S = \sigma A. \quad (2)$$

If the bonding strength is constant, the sticking force would be proportional to the bond area. This effect is illustrated in the Cu mapping in Fig. 4 and Table I, in which the area containing adhered copper on the sheet surfaces could be used as an indication of fractured bond area. When the bonding was very localized, the measured sticking force was almost zero. And the sticking force increased with increase in the total area of local bonds. When the bond area covered the whole electrode tip, the sticking force was greater than 350 g. The preference for mainly copper to transfer from electrode tip surface to sheet surface rather than the reverse may be because the copper is the weakest material in the joint region.

It was also observed that electrode sticking occurred mainly at the early stages of utilization for a pair of electrodes (a typical plot of sticking force versus number of welds for a pair of CuCrZr electrodes is shown in Fig. 5). The reason for this effect may be because that the electrode tip face diameter increased and hence the current density decreased as the number of welds increased [7]. When the current density decreases, the rate of heat generation at electrode/sheet interface may decrease below

TABLE I
ELECTRODE TIP SURFACES AND THEIR CORRESPONDING SHEET SURFACES FOR UNCOATED ELECTRODES

Sticking Force (Welding Current)	Tip Surface	Sheet Surface	Cu Mapping on Sheet Surface
0 g (1400 A)			
260 g (1560 A)			
350 g (1600 A)			

Note: Details of the highlighted areas are shown in Fig. 4.

TABLE II
AVERAGE CONCENTRATIONS OF THE SHEET SURFACES IN TABLE I

Sticking Force (g)	Average Concentrations (wt. %)		
	Fe	Ni	Cu
0	36	62	2
260	37	56	6
350	34	37	29

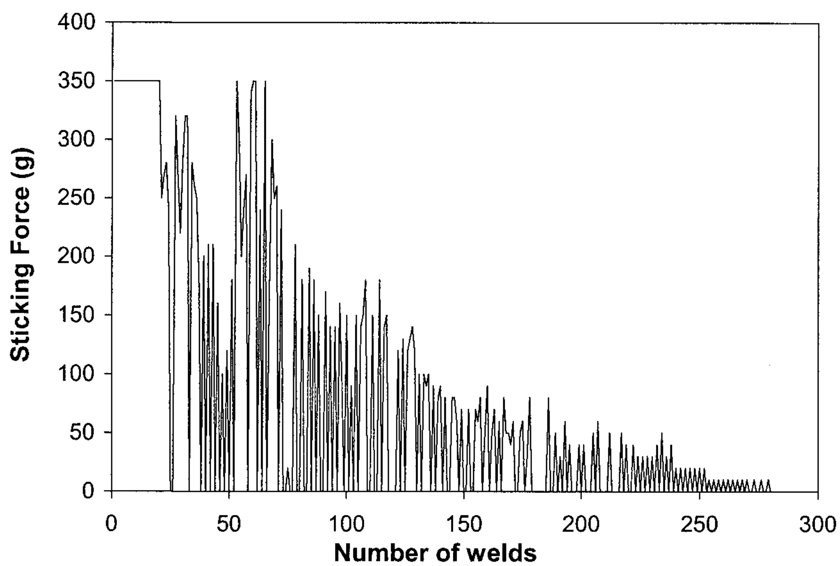


Fig. 5. Sticking force versus the number of welds for uncoated electrodes at 1600-kA welding current.

the level necessary to produce measurable bonding/sticking between the electrodes and sheets.

B. Factors Affecting Electrode Sticking

Equation (1) indicates that increasing welding current, weld time and resistance(s) will all increase the heat generation and hence should increase electrode sticking. Fig. 7 shows the maximum welding current and weld time without electrode sticking (upper limits) and also the minimum welding current and weld time at which a pre-selected joint strength (i.e., 3 kg in this case) will be achieved (lower limits). The regions between the lower limits for a minimum joint strength and the upper limits for electrode sticking is in fact the process window in which the welding

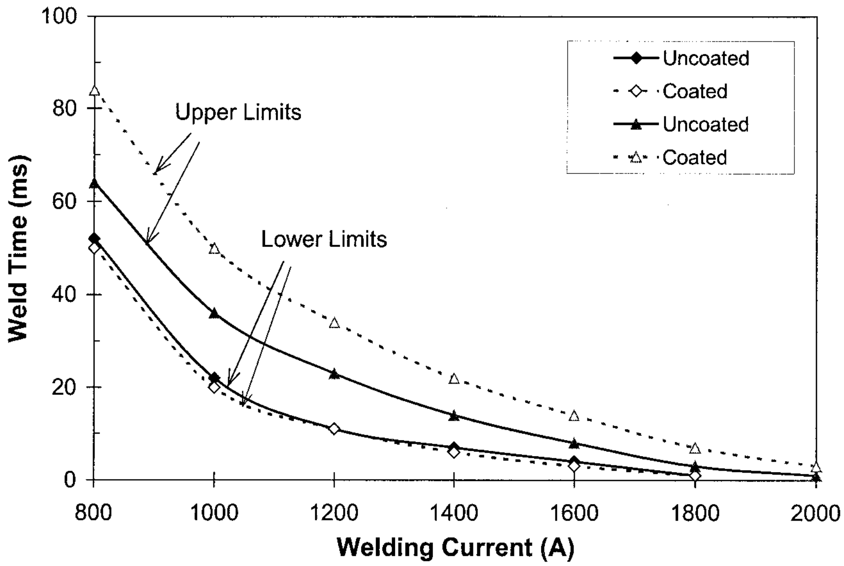


Fig. 6. Effects of welding current, weld time, and electrode coating on electrode sticking.

TABLE III
ELECTRODE TIP SURFACES AND THEIR CORRESPONDING SHEET SURFACES FOR COATED ELECTRODES

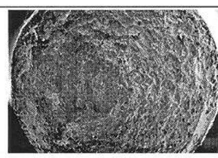
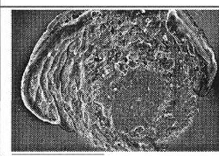
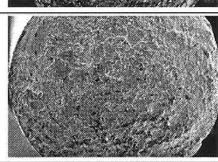
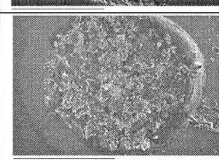
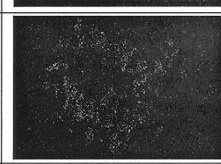
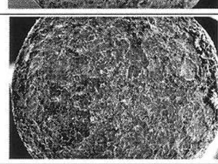
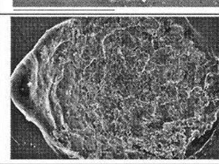
Sticking Force (Welding Current)	Tip Surface	Sheet Surface	Cu Mapping on Sheet Surface
0 g (1400 A)			
0 g (1620 A)			
240 g (1740 A)			

TABLE IV
AVERAGE CONCENTRATIONS OF THE SHEET SURFACES IN TABLE III

Sticking force(g)	Average Concentrations (wt. %)			
	Fe	Ni	Ti	Cu
0	34	61	0	4
0	27	62	2	9
240	27	37	4	32

current and weld time can be used to produce satisfactory welds without electrode sticking.

Fig. 6 also shows that applying the TiC composite coating on the tips has improved the electrode sticking resistance of the CuCrZr electrode, but has little effect on the joint strength. It has been reported that the metal matrix of the electrode coating is mainly Cu and Ni with small amounts of Mo and W and the TiC particles were about 2–10 μm in diameter [7]. It is also observed that TiC particles acted as discontinuities in the bond between the electrode and sheet [7], which was believed to be because TiC particles, with a melting point of 3140 °C, would have poor or no adhesion with metals [8]. In other words, the bond between the electrode and sheet would therefore interrupted by the TiC particles. In other related research, Nadkarni [9] pointed out that Al_2O_3 particles in a composite electrode material can improve sticking resistance

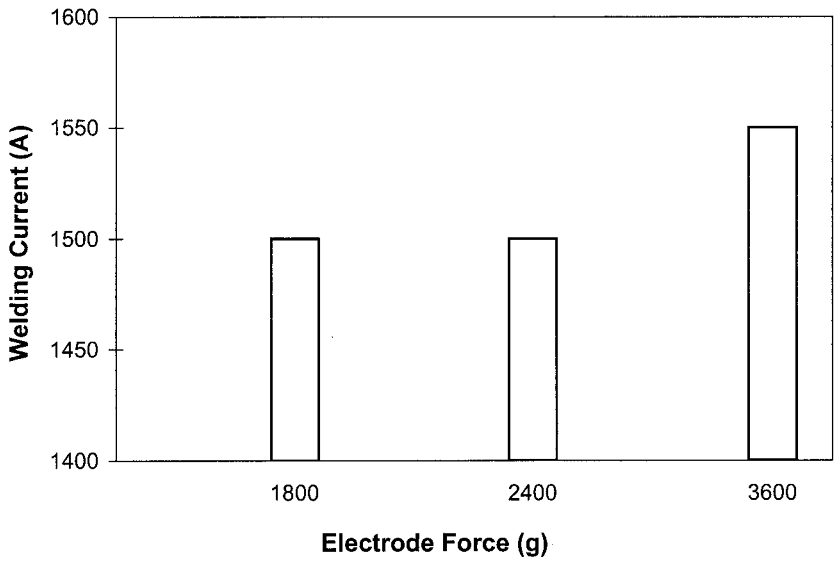


Fig. 7. Effect of electrode force on the maximum welding current without sticking.

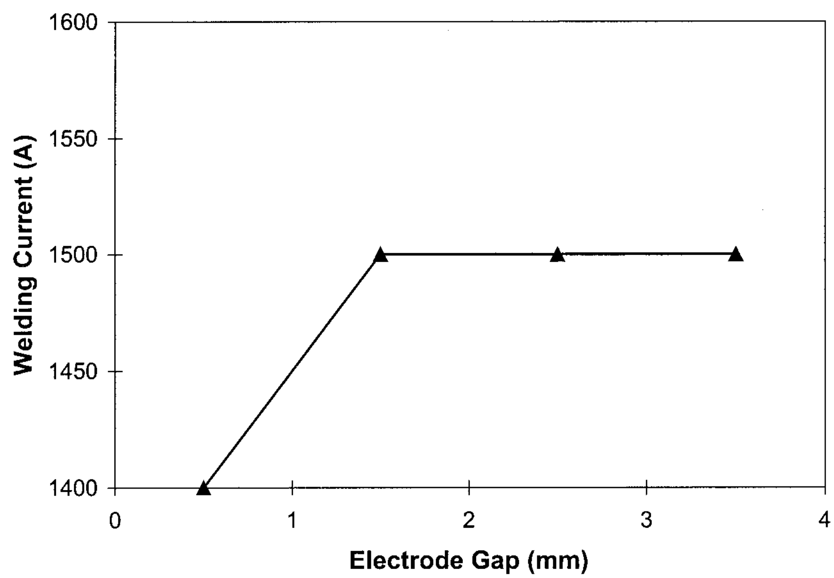


Fig. 8. Effect of electrode gap on the maximum welding current without sticking.

compared to CuCr and CuCrZr electrodes during "large-scale" resistance spot welding of Zn-coated steels. Another reason for the better sticking resistance of the coated electrodes may be related to weak bonding strength between the metal matrix in the coating and the sheet. Based on (2), the sticking force is decided by both bonding strength and bond area. When coated electrodes were used, the amount of copper transferred from electrode to sheet could be up to about 9% before a sticking force could be measured (Table IV); the corresponding copper transfer amount at the onset of measurable sticking force with uncoated electrodes was much lower, at about 2% (Table I). This may suggest that the total area of local bonds between electrode and sheet was correspondingly larger for the onset of measurable sticking force with coated electrodes. Since the TiC particles in the coating apparently did not bond to the sheet, the bonding strength between the sheet and the metal matrix in the electrode coating may be relative low. Further investigation is needed for detailed metallurgical reason for this low strength.

Contact resistance, which is the main part of the resistance term in (1), will be affected by the electrode force: the higher the electrode force, the lower the contact resistance and hence the less severe the electrode sticking. This is confirmed in Fig. 7, in which the maximum welding current without measurable sticking force increased for the CuCrZr electrodes when the electrode force increased from 2400 g to 3600 g. A corresponding reduction in the maximum welding current without sticking was not observed when the electrode force was reduced below 2400 g. This is believed to reflect a change in the mechanism: if electrode force is too low, excessive heat generation may lead to formation of a few local metallurgical bonds early in the welding cycle, which are big enough to limit the contact resistance but not big enough to cause a measurable sticking force.

The maximum welding current without sticking increased as the spacing between electrodes increased from 0.5 to 1.5 mm. However, further increase in the spacing from 1.5 to 3.5 mm produced no change in the maximum current without sticking (Fig. 8). The reason is that, when the electrodes are very close together, the temperature fields of both electrodes will overlap each other on the sheet surface causing the temperatures to increase at the electrode/sheet interfaces. The smaller the electrode spacing, the higher the temperature reached. This overlap will not exist when the electrode spacing is larger than 1.5 mm.

IV. Conclusion

The electrode sticking mechanism and factors (welding current, weld time, tip coating, electrode force and electrode spacing) affecting the sticking were studied during small-scale series resistance welding of very thin nickel-plated steel to nickel sheets. The following are some of the major conclusions.

1) Local metallurgical bonding between the electrode and nickel-plated steel sheet caused electrode sticking. The sticking force was proportional to the total area of the local bonds and the bonding strength between the electrode and sheet.
2) Reducing welding current and weld time, and increasing electrode force and spacing could reduce electrode sticking.
3) An electrode tip coating of TiC metal matrix composite was effective in improving the electrode sticking resistance of CuCrZr electrodes.

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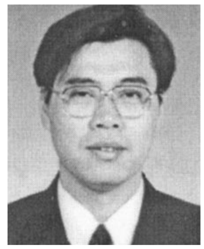

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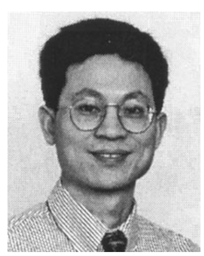

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