

# Effects of TiC Composite Coating on Electrode Degradation in Microresistance Welding of Nickel-Plated Steel

S.J. DONG and Y. ZHOU

Electrode degradation has been studied during series-mode microresistance welding of thin-sheet nickel-plated steel to nickel. The main focus of the study was the effects of a TiC metal matrix composite coating. The results indicated that electrode degradation was caused predominantly by material loss due to pitting (as a result of the fracturing of local bonds between the electrode tip and sheet) and also by microscopic extrusion or plastic deformation (as a result of the softening of electrode tip regions). The composite coating improved tip life by about 70 pct, mainly because the TiC particles contained in the coating discouraged local bonding between the electrodes and sheets, and probably also improved the resistance to surface extrusion. It was also found that the use of an oxide-dispersion-strengthened copper alloy (Cu-Al<sub>2</sub>O<sub>3</sub>) improved tip life by only about 15 pct compared to the conventional precipitation-strengthened Cu-Cr-Zr electrode alloy.

## I. INTRODUCTION

MICRO- or small-scale resistance welding is a group of microjoining processes (such as resistance spot, parallel gap, series, and seam welding). These processes are commonly used for applications in electronic and medical packaging, such as lead/pad interconnections and hermetic sealing.<sup>[1-4]</sup> There are differences between micro-resistance welding and “large-scale” (regular) resistance welding, although the principles of the two processes are similar. For example, lower electrode force (pressure) used in micro-resistance welding results in a relatively smaller contact area and higher contact resistance at the faying interfaces, which, in turn, results in lower welding current required to initiate and form a weld.<sup>[5-8]</sup>

In resistance welding, a weld is formed between two metal sheets through the localized melting and coalescence of a small volume of the material(s) at the faying interface due to resistance heating generated by the passage of electric current.<sup>[5]</sup> However, the welding current will also degrade the electrode tip surfaces due to the resistance heating at the electrode/sheet interfaces. Little work has been published on electrode tip degradation mechanisms and engineering solutions in microresistance welding. In large-scale resistance spot welding of Zn-coated steels for automotive applications, the primary mechanism limiting the electrode life is identified to be growth of the electrode tip face diameter.<sup>[9,10,11]</sup> Enlargement of contact face diameter results in reduced current density/heat generation and hence undersized welds between the sheets.

A number of damage processes that could contribute to the electrode degradation during large-scale resistance spot

welding of Zn-coated steels have been observed or suggested: plastic deformation, alloying, pitting/erosion, cavitation, recrystallization, thermal shock, and fatigue.<sup>[9,10,11]</sup> Holliday *et al.*<sup>[11]</sup> have investigated the relative contributions of plastic deformation, alloying, and wear. The plastic flow (extrusion) of unalloyed material to the tip periphery will cause the formation of “wings” and hence increase the effective tip face diameter, which has been traditionally referred to as mushrooming. Buildup of alloyed product or zinc at the periphery of the electrode contact face can also result in an increase in the effective diameter. The loss of electrode material from the tip face due to the wear (pitting) process will also result in an increase in the effective diameter and a reduction in length of the electrode.

Parker *et al.*<sup>[9]</sup> proposed that, under normal welding conditions (such as at low welding currents), the major damage process contributing to electrode degradation was electrode surface alloying and pitting, which was mainly a function of the type of coating present on the steel. Under such conditions, the use of dispersion-strengthened electrode material (such as Cu-Al<sub>2</sub>O<sub>3</sub>) could not extend the tip life compared to the use of precipitation-strengthened material (such as Cu-Cr-Zr) since the alloying and wear characteristics of both materials are similar.<sup>[9]</sup> On the other hand, the use of dispersion-strengthened material could extend electrode tip life when welding with high currents or when using current stepping programs, because electrode softening and hence plastic deformation becomes a more dominant damage process<sup>[9]</sup> and dispersion-strengthened material provides a better high-temperature strength.<sup>[12]</sup>

Compared to “large-scale” resistance welding where the electrodes are internally water-cooled, the heat build-up at the electrode/sheet interfaces is worse in micro-resistance welding since no water cooling is used and current density is generally higher.<sup>[1-8]</sup> Therefore, the use of dispersion-strengthened electrode material (such as Cu-Al<sub>2</sub>O<sub>3</sub>) could be preferable to precipitation-strengthened material because of its better higher temperature strength. Electrode coatings represent another potential approach to life improvement,

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and in this regard, it has been claimed that a patented TiC-composite-coated electrode (so-called *TiCap\**)<sup>[13]</sup> could

\* TiCap is a trademark of Huys Industries Limited, Weston, ON, Canada.

improve electrode life in large-scale resistance welding. To present, no objective experimental evidence or fundamental explanation as to the validity of this claim has been reported. In the present work, the effect of the TiC composite coating on electrode degradation was studied during series-mode microresistance welding of very thin sheets of nickel-plated steel to sheets of nickel. In order to compare the effectiveness of the composite coating on dispersion-strengthened vs precipitation-strengthened electrode material, electrodes of both types were subjected to controlled welding trials in both coated and uncoated conditions.

## II. EXPERIMENTS

Series-mode microresistance welding was performed using a Unitek (Monrovia, CA) model HF2 power supply and model 508 weld head. The experimental setup and basic welding parameters used are shown in Figures 1 and 2. The electrode extension (the distance from the electrode holder to the electrode tip) was 1.5 mm and the electrode spacing was 2.5 mm (Figure 1). When direct-current power supplies are used such as the high-frequency inverter system<sup>[5,8]</sup> employed in this work, the Peltier effect (the inverse of the thermocouple effect) can result in a higher rate of heat generation at the anode electrode than at the cathode.<sup>[14]</sup> 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, a combination of 3600-g anode electrode force and 2400-g cathode electrode force was used, under which condition the cathode nuggets were just slightly smaller than the anode nuggets. It was also observed that the electrode degradation was generally more severe at the cathode; therefore, this work has focused on the electrode degradation at the latter electrode.

Two electrode materials have been used in this work: copper alloy C18200 with a nominal composition of Cu-0.84 wt pct Cr-0.05 wt pct Zr (Cu-Cr-Zr) and C15760 with a nominal composition of Cu-1.1 wt pct Al<sub>2</sub>O<sub>3</sub> (Cu-Al<sub>2</sub>O<sub>3</sub>). The TiC composite coating was performed using a patented arc coating process (TICAP technology) at Huys Industries Limited.<sup>[13]</sup> The coating process and resulting coated layer are described in more detail in Section III of this article. The electrodes had a diameter of 1.5 mm and a tip radius of 150 μm. The sheets to be welded were 100-μm-thick mild steel plated with pure nickel of about 7-μm thickness, and 300-μm-thick pure nickel. Electrode tip life tests were performed on coupons consisting of nickel strips 9-mm wide and 30-mm long and nickel-plated steel strips 4-mm wide and 50-mm long with the nickel-plated steel in contact with the electrodes. Welding was interrupted after every 100 welds for measurement of peel force using a Quad Romulus IV (Spokane, WA) universal mechanical tester and to measure nugget diameter from pullout buttons (Figure 3). The electrode tip surfaces and the corresponding sheet areas that were in contact with the electrode tip after welding were analyzed using optical microscopy, scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDX). The TiC composite

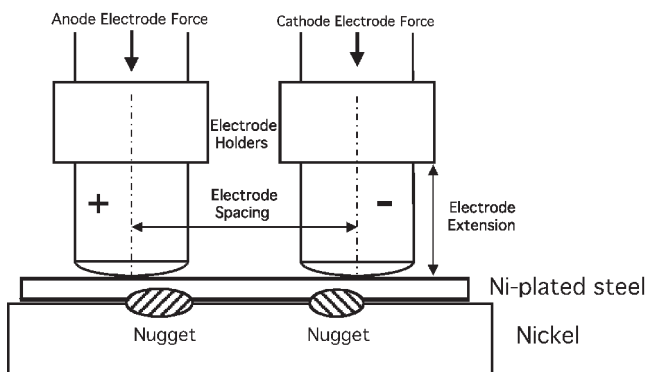


Fig. 1—Schematic of the experimental setup.

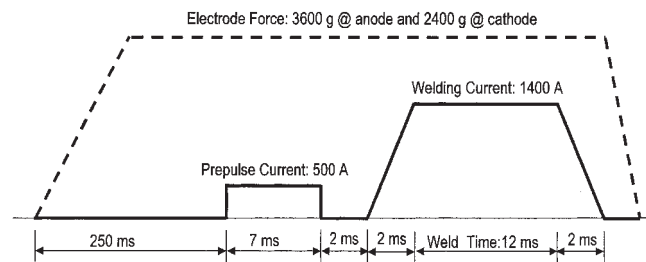


Fig. 2—Schematic of the welding schedule.

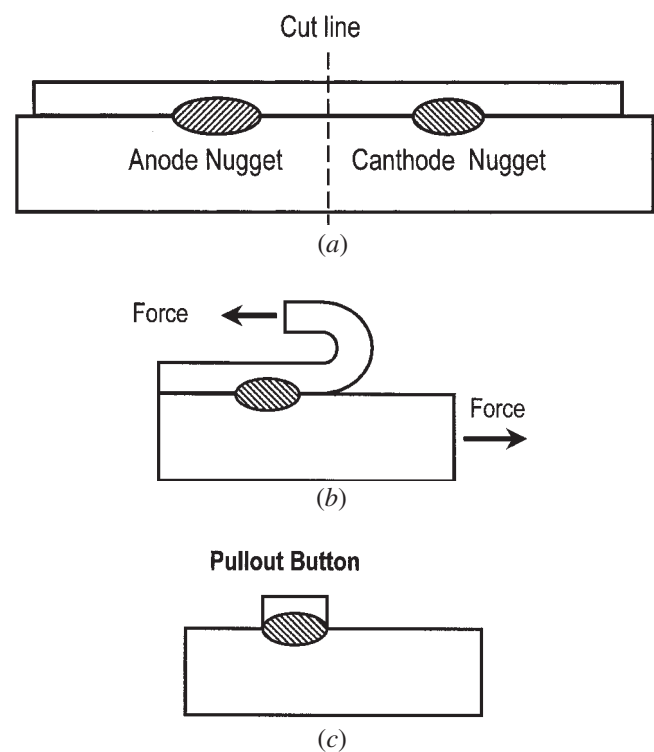


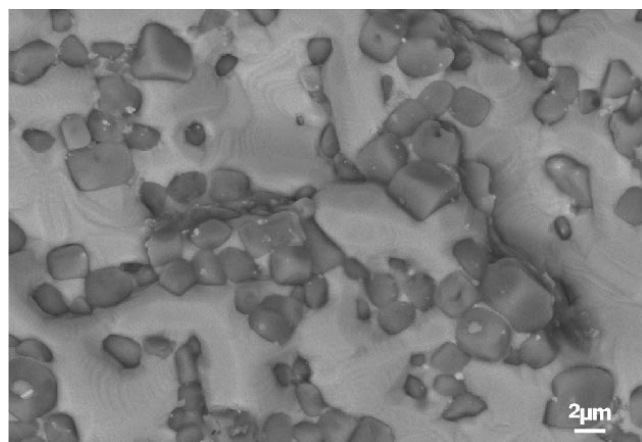
Fig. 3—Schematic of peel test showing (a) cut of welded joint, (b) peel test, and (c) joint failed with a pullout button.

coating was analyzed by X-ray diffraction (XRD) with a Siemens (Karlsruhe, Germany) D500 powder X-ray diffractometer using  $\text{Cu } K_{\alpha}$  radiation. Hardness was measured using a MHT 200 Vickers microhardness tester at 200-g load on prepared metallographic cross sections of each electrode at locations of 0.05, 0.25, 0.5, 1.0, 2.0, and 5.0 mm away from the tip surface.

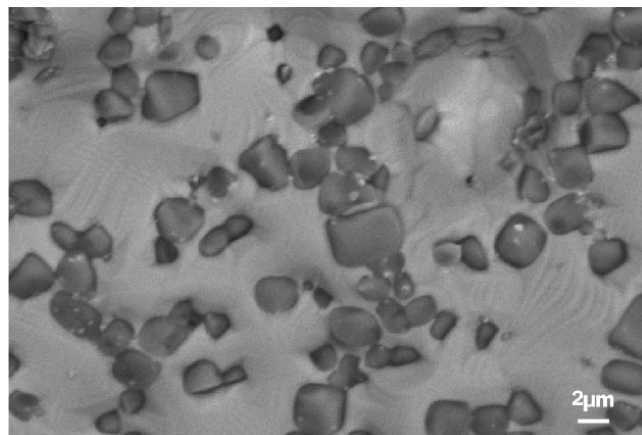
### III. RESULTS

#### A. The Composite Coating

In the arc coating process, the electrode (negative) to be coated and the coating rod (positive) are connected to a low-voltage DC power supply. With the power supply turned on, the coating rod is vibrated to create continual on-and-off contact with the electrode tip surface, generating an intermittent electric arc, which melts and fuses small particles of the coating material onto the electrode tip surface, eventually building up a continuous layer of coating as the point of arcing is manually moved across the surface.<sup>[13]</sup> Both SEM/EDX and XRD were used to investigate the composition and structure of the coating rod, electrode substrate, and coated layer (Figures 4 and 5, Table I). The XRD spectra of both electrode substrates of Cu-Cr-Zr and Cu- $\text{Al}_2\text{O}_3$  electrodes were similar (Figure 5(b)) because the amount of  $\text{Al}_2\text{O}_3$  (about 1.1 wt pct) was too low to be detected in XRD.



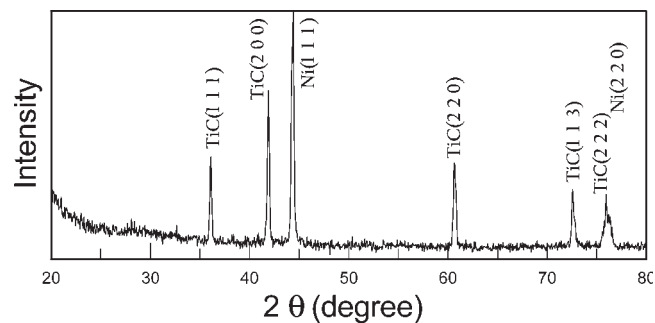
(a)



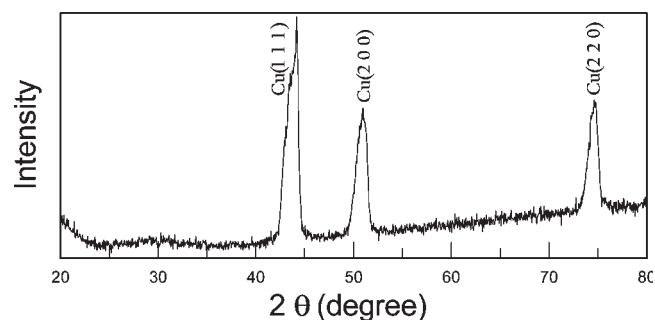
(b)

Fig. 4—Micrographs of (a) coating rod and (b) coated layer.

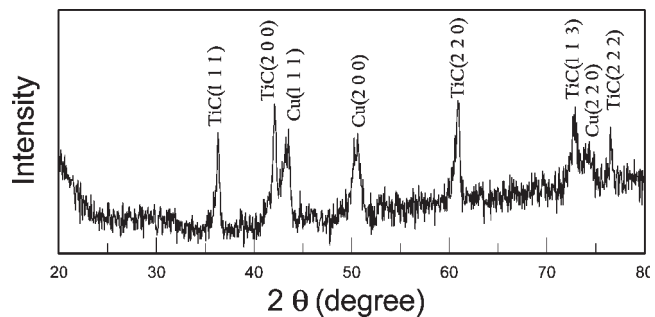
The SEM/EDX and XRD analyses indicated that the coating process did not alter the TiC particle size (2 to 4  $\mu\text{m}$ ), but changed the composition of the metal matrix of the composite and slightly reduced the volume percentage of TiC particles. The metal matrix of the coating rod as supplied was mainly Ni with a small amount of W and Mo, but the coating process introduced Cu to the matrix (Table I), clearly a result of mixing melted Cu from the electrode substrate and melted metal matrix from the coating rod. The volume percentage of TiC particles was about 42 to 50 pct in the rods before coating and 32 to 46 pct in the coated surface (although the coating parameters were kept



(a)



(b)



(c)

Fig. 5—X-ray diffraction spectra of (a) coating rod, (b) electrode substrate, and (c) coated layer.

Table I. Composition (Weight Percent) of the Metal Matrix of Coating Rod and Coated Layer

	Ti	Ni	Mo	W	Cu
Coating rod	14.3	82.6	2.4	0.7	0
Coated layer	13.8	28.6	2.1	0.7	54.5

constant), based on image analysis of cross sections. However, fortunately, this variation in the particle volume percentage, which may result in changes of properties of the coated layer (such as wear resistance), did not result in large scatter in the tip life tests for coated electrodes (details are given in Section B). The coated layer was about 10 to 15  $\mu\text{m}$  in thickness. The hardnesses ( $\text{HV}_{200}$ ) of the coating rod, coated layer, Cu-Cr-Zr, and Cu- $\text{Al}_2\text{O}_3$  electrode substrates were determined to be 2250, 980, 174, and 166  $\text{kg}/\text{mm}^2$ , respectively.

### B. Effects of the Composite Coating on Electrode Life

Figures 6 and 7 show button diameter (as an indication of nugget diameter) and peel force (as an indication of joint

strength) vs the number of welds made with each type of electrode studied. Both button diameter and peel force decreased as the number of welds increased, but the reduction in nugget diameter or peel force was slower for both types of coated electrode than for the respective uncoated electrodes. It also appears that the reduction in button diameter and peel force was slower for Cu- $\text{Al}_2\text{O}_3$  electrodes than those for the Cu-Cr-Zr electrodes.

It has been previously shown that joint strength is mainly determined by nugget diameter: the larger the nugget diameter, the higher the joint strength.<sup>[1,2,3]</sup> For an arbitrarily chosen minimum nugget diameter of 0.1 mm, the tip life was 700 and 1200 welds for uncoated and coated Cu-Cr-Zr electrodes, respectively, and 800 and 1500 for uncoated and coated Cu- $\text{Al}_2\text{O}_3$ , respectively (Table II). The same trend

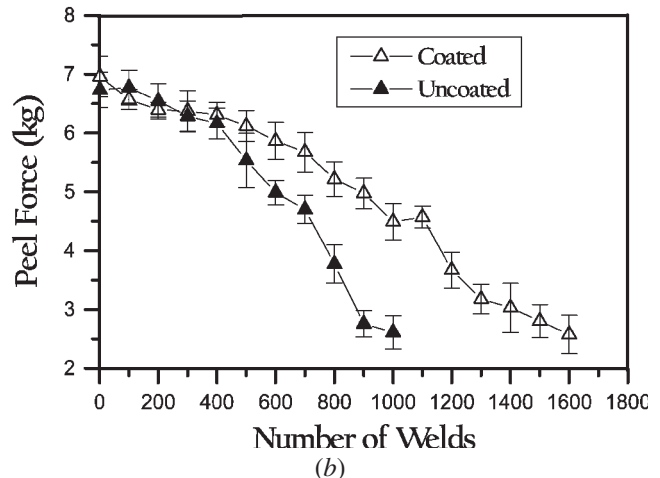
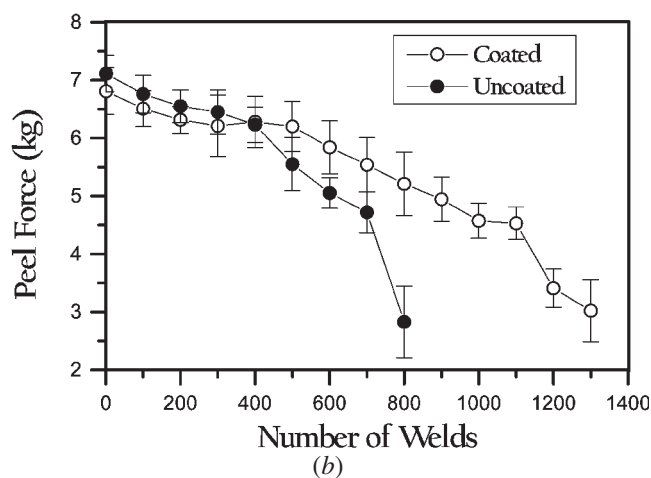
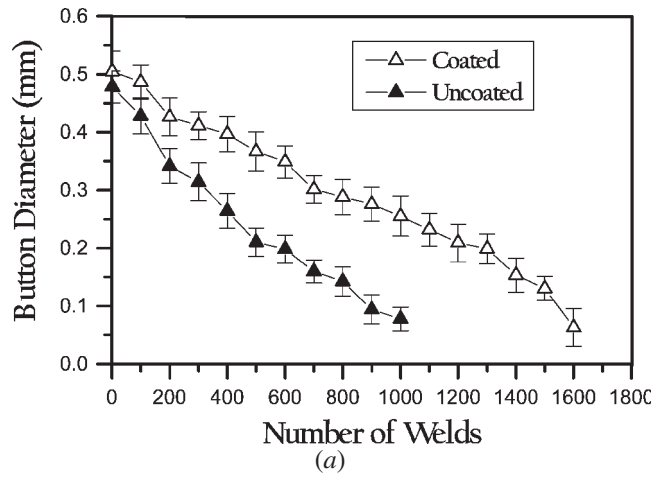
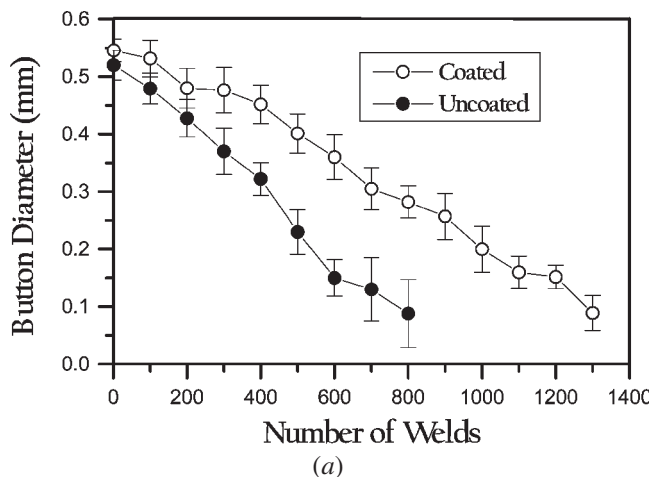


Fig. 6—(a) Button diameter and (b) peel force vs number of welds using Cu-Cr-Zr electrodes.

Fig. 7—(a) Button diameter and (b) peel force vs number of welds using Cu- $\text{Al}_2\text{O}_3$  electrodes.

Table II. Electrode Tip Life in the Number of Welds

Electrodes	Cu-Cr-Zr ( $T_3$ )		Cu- $\text{Al}_2\text{O}_3$ ( $T_4$ )		$(T_4 - T_3)/T_3$
	Button Diameter	Peel Force	Button Diameter	Peel Force	
Uncoated ( $T_1$ )	700	700	800	800	14 pct
Coated ( $T_2$ )	1200	1200	1500	1300	8 to 25 pct
$(T_2 - T_1)/T_1$	71 pct	71 pct	88 pct	63 pct	—

was also found when the peel forces were examined. If an arbitrarily chosen minimum peel force of 3 kg was selected, the tip life was 700 and 1200 welds for uncoated and coated Cu-Cr-Zr electrodes and 800 and 1300 for uncoated and coated Cu-Al<sub>2</sub>O<sub>3</sub> electrodes, respectively (Table II). The use of TiC composite coating increased the tip life by about 63 to 88 pct, while the difference in button diameter or peel force was much less significant (about 8 to 25 pct) between Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes (Table II).

The SEM examination revealed that the surface of the electrode tips was relatively smooth and clean even after a few hundreds of welds. But a flat area on the tip surface was developed during welding and the diameter of this flat face increased with increasing number of welds. The tip face also left an imprint on the corresponding sheet surface during welding (Figure 8) and this imprint could be easily recognized. The diameter of this imprint was used as an indication of the contact areas between the electrode tips and sheets (Figure 9), although the absolute values may be smaller than the real values because they were measured at room temperature after welding. It was obvious that this increase in electrode imprint diameter was due to the increase in tip face diameter (Figure 9). The increase in the imprint diameter was well correlated with the decrease in button diameter (Figures 6 and 7). It is interesting to see, from Figure 9, that the imprint diameter was about 0.95 mm when the tip lives were reached (Table II). This increase in diameter translates into about a 50 pct drop in current density (assuming the initial contact diameter was about 0.65 mm). It is believed

that this reduction in current density is the direct cause of undersized nuggets. Therefore, the enlargement in tip diameter and hence reduction in current density is responsible for the reduction in nugget diameter and joint strength. This is consistent with previous observation in large-scale resistance spot welding of Zn-coated steels.<sup>[9,10,11]</sup> Figure 9 also shows that the increase in contact area was faster for uncoated electrodes than that for coated electrodes. This is in agreement with the observations in Figures 6 and 7 that the nugget diameter or peel force decreased at a faster rate for the uncoated electrodes. The effect of electrode material (Cu-Cr-Zr vs Cu-Al<sub>2</sub>O<sub>3</sub>) on the change in contact area is less significant than that of the composite coating, similar to the effect of electrode material on nugget diameter and joint strength.

#### IV. DISCUSSION

It is clear from the preceding results that the electrodes failed because of increased tip face diameter, which is consistent with observations in large-scale resistance spot welding of Zn-coated steels<sup>[9,10,11]</sup> in that enlarged tip face diameter results in reduced current density/heat generation and hence undersized welds between the sheets. In the following, two mechanisms (pitting and plastic deformation) that have contributed to the increase in tip face diameter in this work will be discussed in terms of interactions between the electrodes and the sheet surfaces.

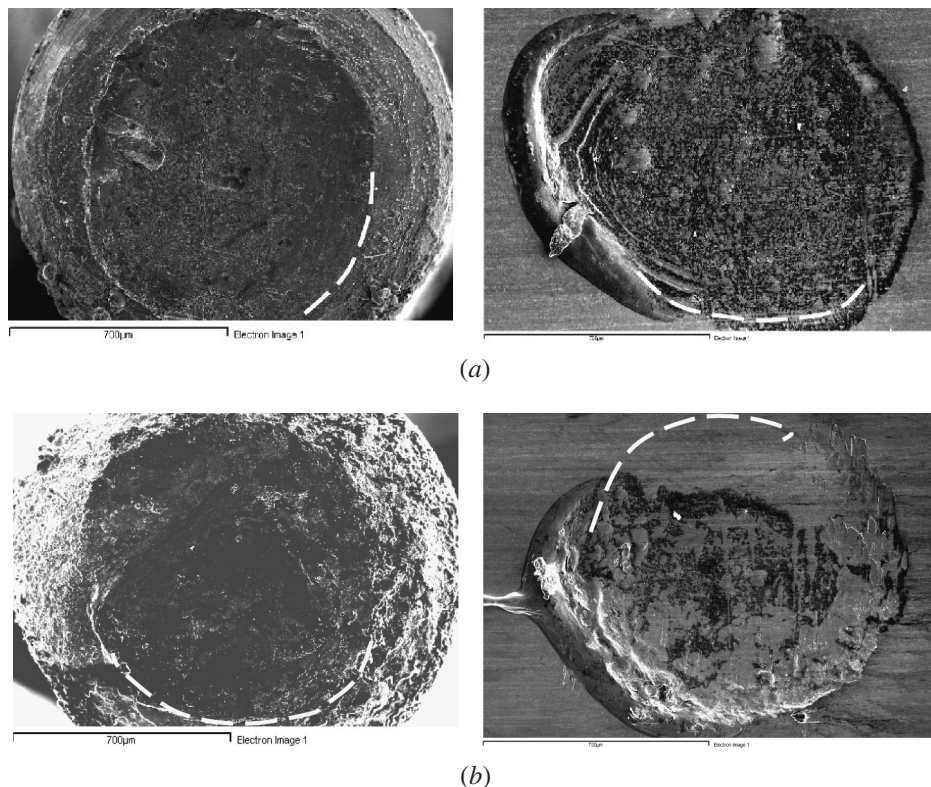


Fig. 8—Electrode tip surfaces and the corresponding sheet surfaces of (a) uncoated Cu-Cr-Zr electrodes after 800 welds and (b) coated Cu-Cr-Zr electrodes after 1300 welds. Dashed lines indicate contact areas.

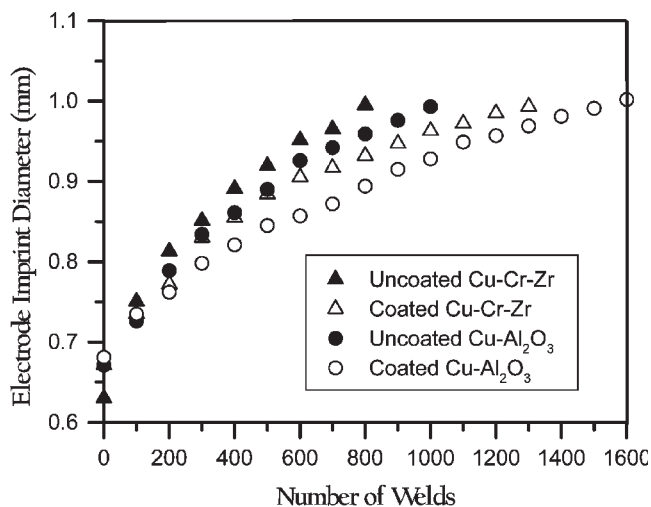


Fig. 9—Electrode imprint diameter vs number of welds.

### A. Metallurgical Interactions

Detailed SEM examination has shown scattered Cu pickup within the electrode imprints on the sheet surfaces after welding. This Cu pickup on the sheet surfaces was clearly transferred from the tip faces since there was no Cu in the original sheets. Figure 10 shows details of the corresponding surface locations on the electrode contact face and sheet surface at the 15th weld for an uncoated Cu-Cr-Zr electrode. This indicates that bonding occurred in isolated spots between the electrode tip face and the sheet surface during welding. The fracture of these local bonds, when electrodes were pulled away from the sheets, resulted in removal of Cu from the tip face (A, B, and D in Figure 10(c)) onto the sheet surface (regions A', B', and D' in Figure 10(b)). The pitting (*i.e.*, the continuous loss of electrode material) during each welding cycle would result in an enlargement of the tip face diameter. This enlarged tip (contact) face diameter would eventually result in an undersized nugget because of the decrease in current density.

Figure 11 shows details of corresponding locations on the electrode tip face and the sheet surface at the 200th weld for a coated Cu-Cr-Zr electrode. Regions A and B on the tip face (Figure 11(c)) contained TiC particles, as shown by the elevated Ti content. Their corresponding regions A' and B' on the sheet surface (Figure 11(b)) contained no Cu transfer. In this case, with coating in place, no bonding occurred at regions containing TiC particles. It could reasonably be inferred that the slower enlargement of the contact face of the coated electrodes (Figure 9) is directly related to the low bonding tendency between TiC particles and sheet surfaces, which would reduce the rate of tip surface removal. It is believed that the TiC particles in the composite coating on the electrode surface, with a melting point of 3140 °C and poor bondability with metals,<sup>[15]</sup> would discourage the bonding between the tip and sheet surfaces and hence decrease the material loss from the tip face.

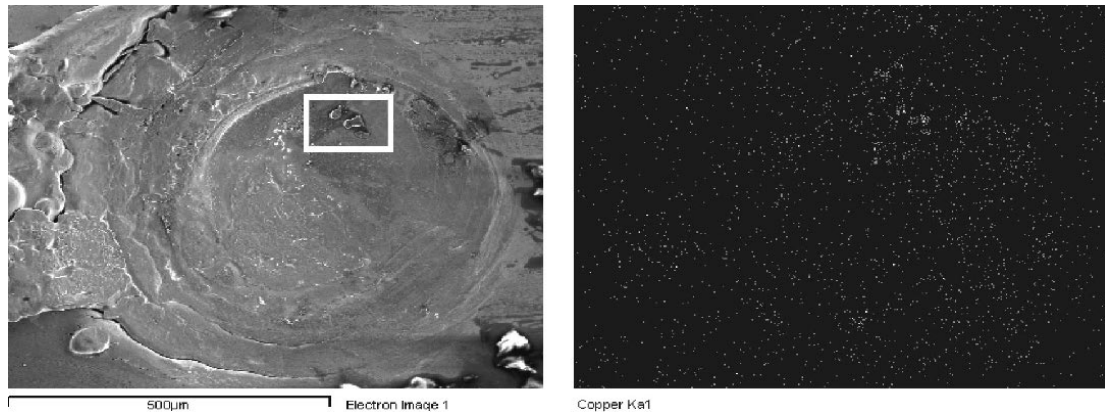
Direct comparison of loss of tip material between uncoated and coated electrodes is difficult since it is not easy

to quantify the material loss. However, rough comparison may be derived from the EDX analysis (Figure 12), which indicated a much higher Cu pickup when uncoated electrodes were used. Figure 12 also shows that, as the number of welds increased, the Cu transfer decreased, which is apparently due to decreased current density as a result of increased tip face diameter. It is also interesting to note that, from Figure 13, which shows Ti content on tip surfaces, a considerable amount of TiC was still retained until the end of the tip life. The EDX analysis showed that Ti pickup on sheet surfaces changed gradually from 0.7 to 0.1 pct from the first weld to the tenth weld, which indicates the major loss of TiC occurred at very beginning of the tip life. A considerable amount of TiC was retained until the end of the tip life, while the metal matrix was continually stripped away.

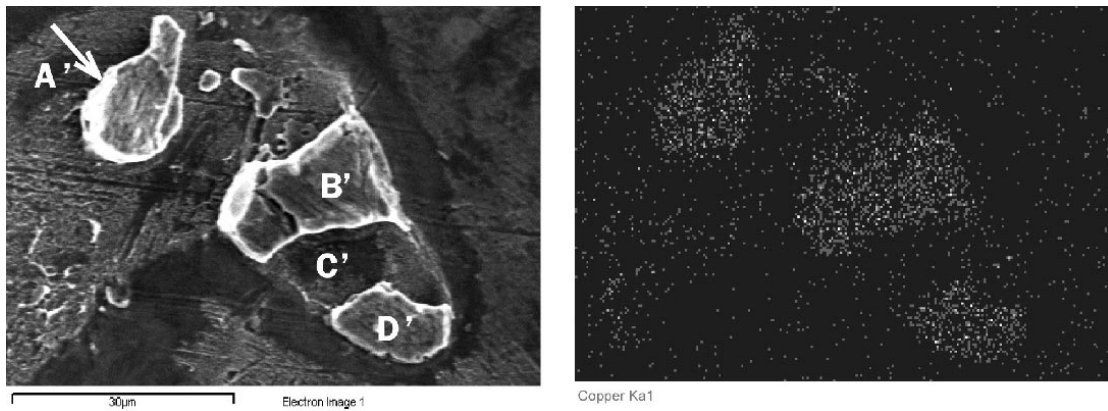
### B. Mechanical Interactions

Little macroscopic plastic deformation (mushrooming) was observed in any of the electrodes (Figure 14(a)). Therefore, the damage process of the increase in tip face diameter by mushrooming (spreading of the tip by large-scale plastic deformation), as observed in large-scale resistance spot welding of Zn-coated steels,<sup>[9]</sup> was not a factor in this work. This may be because of the particular tip shape used: a very large tip radius could increase the resistance to bulk plastic deformation. However, the extrusion of the tip surface layer was observed at a microscopic level in uncoated Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes (Figure 15). It is believed that the extrusion has mainly contributed to material loss, *i.e.*, the increase in tip face diameter through breakoff of these extruded layers. No obvious difference in this microscopic extrusion process was observed between the Cu-Al<sub>2</sub>O<sub>3</sub> and Cu-Cr-Zr electrodes. However, the composite coating improved the resistance to microscopic extrusion, since little extruded material was observed in coated Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes.

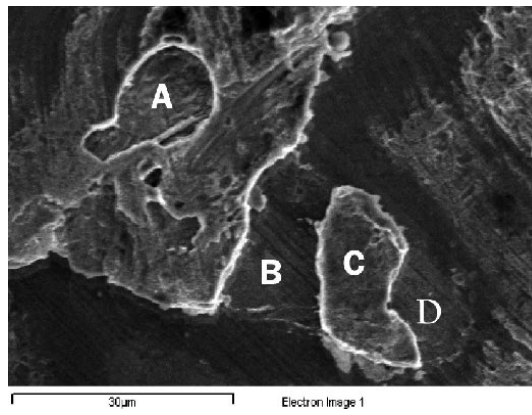
The extrusion of the tip surface layer is obviously a result of softening because of the high temperature that the tip experienced during welding. The softened electrode tip cannot withstand the electrode force when the high-temperature strength drops below the electrode pressure. A layer of recrystallized microstructure, in which the elongated extrusion structure was completely eliminated, was clear at the tip regions in both Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes (Figure 14), although the recrystallized region in Cu-Al<sub>2</sub>O<sub>3</sub> was much smaller. Figure 16 shows the microhardness distribution in the tip surface region of sectioned electrodes that had previously made 400 welds. Both Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes experienced large reductions in hardness (more than 50 pct). It appears that the hardness loss on Cu-Cr-Zr electrodes was slightly larger than that on Cu-Al<sub>2</sub>O<sub>3</sub> electrodes, which agrees with the observation in recrystallized microstructure (Figure 14), but the difference in the hardness drop was quite minor. This is consistent with the tip life test results in which there was no significant difference in tip life when using different electrode materials (Cu-Cr-Zr vs Cu-Al<sub>2</sub>O<sub>3</sub>). New electrodes of both compositions were subjected to 1-hour annealing at a range of



(a)



(b)



(c)

Fig. 10—(a) Sheet surface and its Cu mapping, (b) details of fractured local bonds in a highlighted box in (a) and its Cu mapping, and (c) pits formed on the corresponding tip surface of an uncoated Cu-Cr-Zr electrode.

temperatures to clarify the effect of peak temperature on softening. The results of subsequent hardness testing are shown in (Figure 17). Therefore, the very large drop in hardness at the tip regions of used electrodes (Figure 13) indicated that the temperature at these regions reaches well above 900 °C. Therefore, the use of Cu-Al<sub>2</sub>O<sub>3</sub> material could not improve the tip life, because the temperature experienced

during welding is even higher than the softening temperature of the Cu-Al<sub>2</sub>O<sub>3</sub> electrodes.

## V. CONCLUSIONS

The effects of TiC metal matrix composite coating on electrode degradation were studied during series-mode

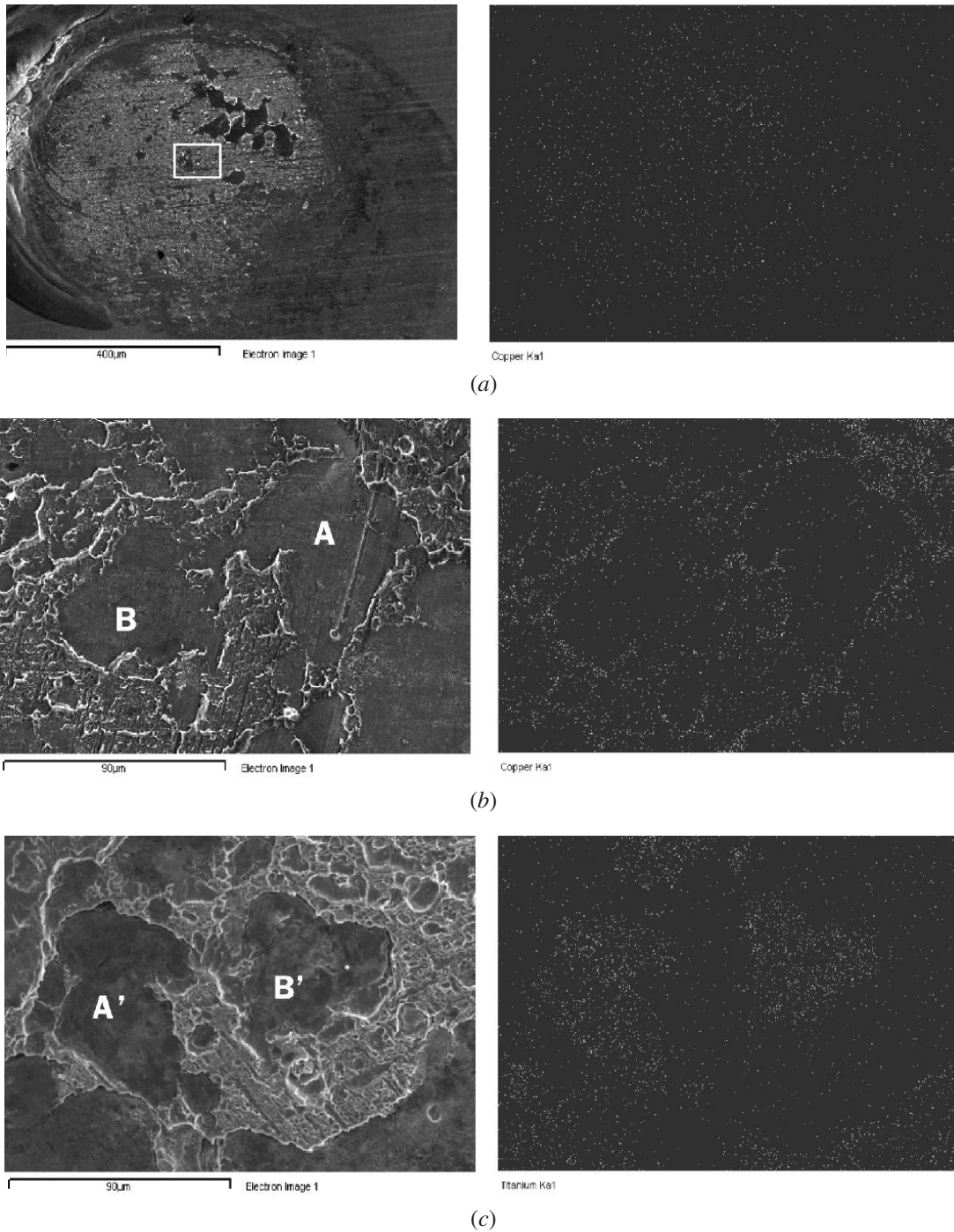


Fig. 11—(a) Sheet surface and its Cu mapping (b) details of fractured local bonds in a highlighted box in (a) and its Cu mapping, and (c) tip surface of the corresponding coated Cu-Cr-Zr electrode.

microresistance welding of nickel-plated steel to nickel. The following are some of the major conclusions.

1. The TiC composite coating increased the tip lives of Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes by about 70 pct. This may be because the TiC particles contained in the coated layer would reduce local bonding between the tip and sheet surface and hence reduce the material loss due to the fracturing of local bonds.
2. Compared to the composite coating, the improvement of tip life due to the use of Cu-Al<sub>2</sub>O<sub>3</sub> electrode was relatively small compared to the Cu-Cr-Zr electrode (only by about 15 pct). This may be due to the very high temperature experienced during welding, well above the softening temperature of the Cu-Al<sub>2</sub>O<sub>3</sub> electrode.
3. Pitting is believed to be the main damage process contributing to the electrode degradation, which results in material loss and hence an increase in tip face dia-



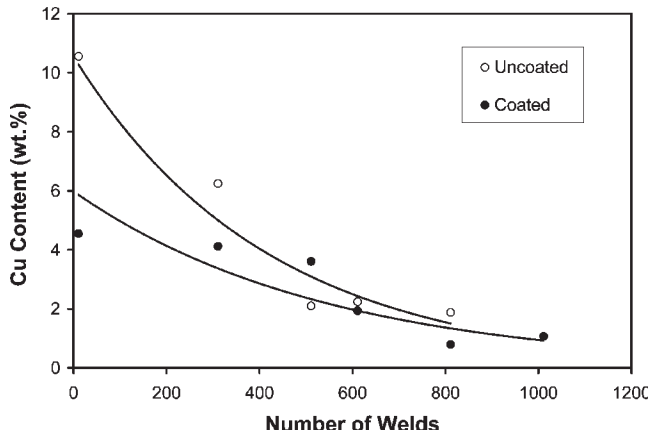


Fig. 12—Copper pickup on the sheet surfaces.

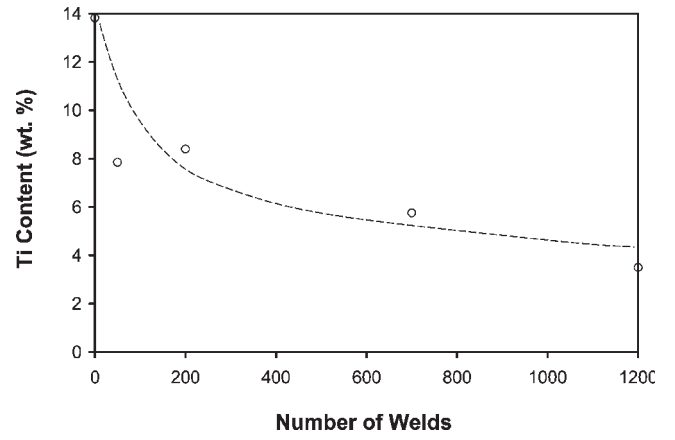


Fig. 13—Titanium content on the tip surface of a coated Cu-Cr-Zr electrode.

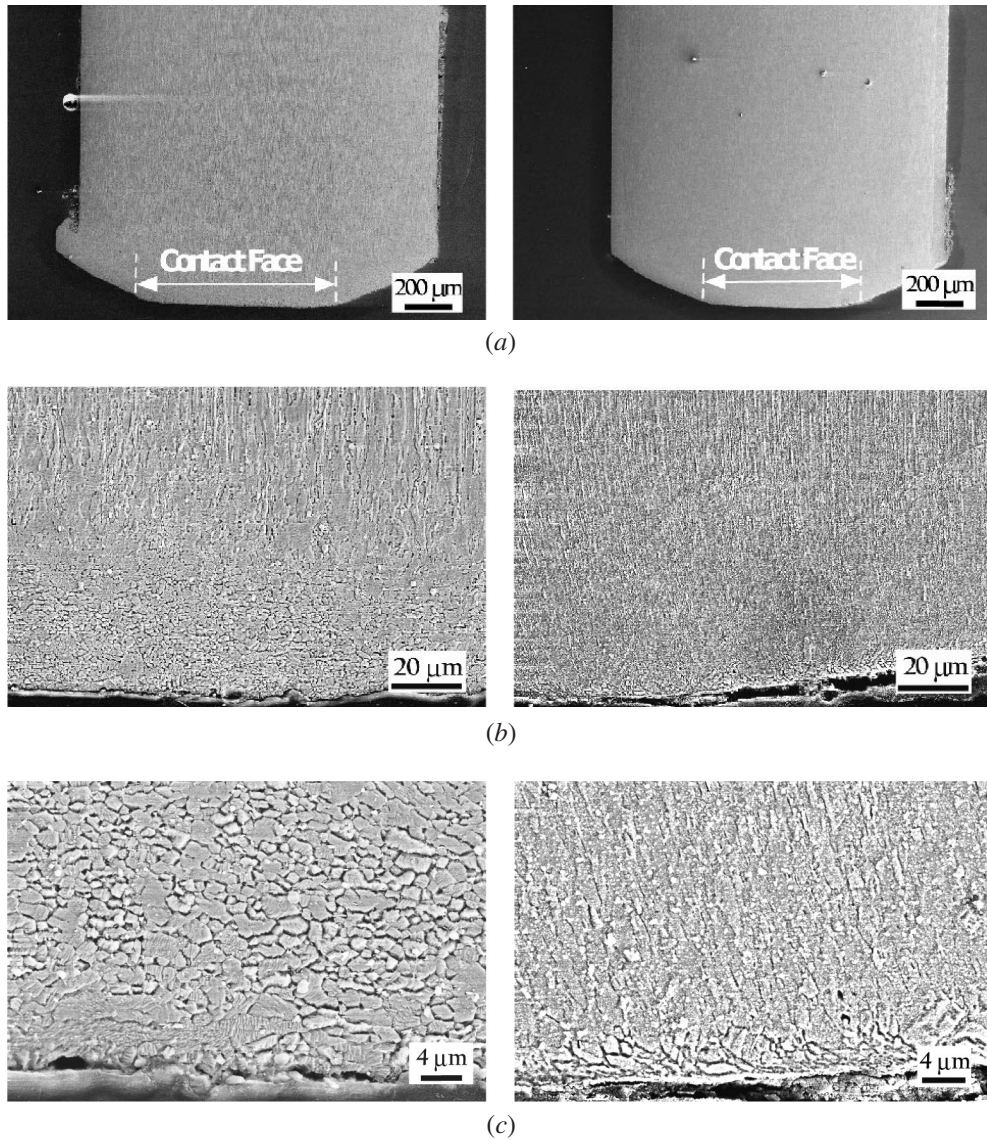
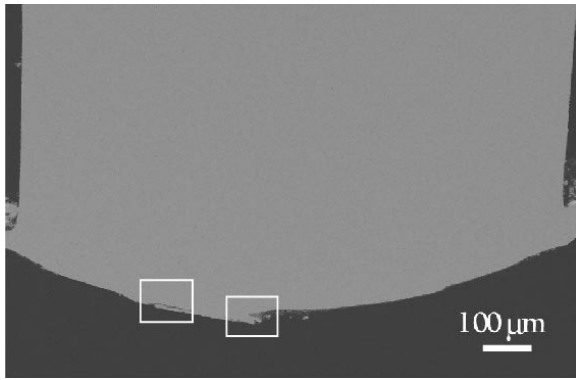
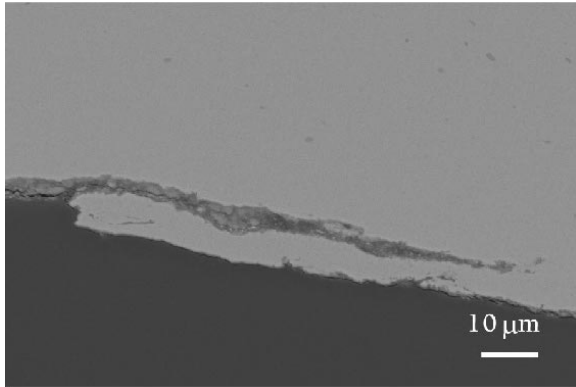


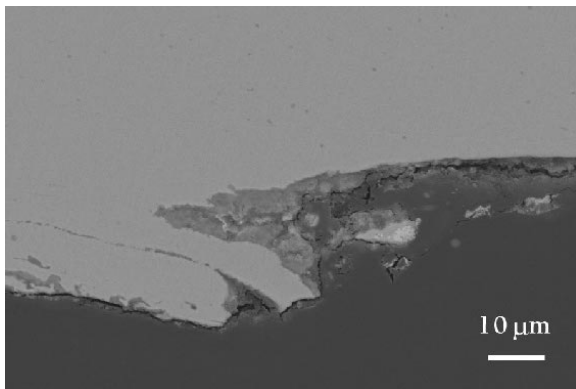
Fig. 14—(a) Cross sections, (b) details of extruded structure in areas away from the tip regions, and (c) recrystallized structure at the tip regions of Cu-Cr-Zr (left series) and Cu-Al<sub>2</sub>O<sub>3</sub> (right series) electrodes, both after 400 welds. Approximate locations of contact faces are labeled in (a).



(a)



(b)



(c)

Fig. 15—(a) Extruded layers on the tip face of an uncoated Cu-Cr-Zr electrode after 400 welds. (b) and (c) Details of the highlighted boxes in (a).

meter. Extrusion of the tip surface layer at a microscopic level may have also contributed to material loss through the fracturing of the extruded layers.

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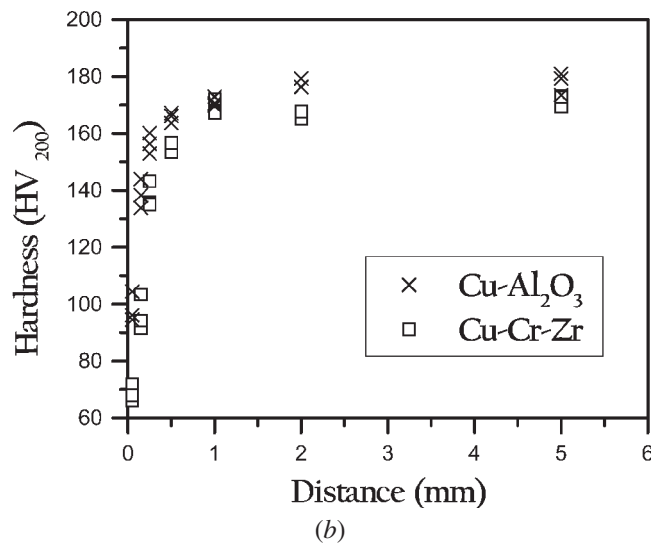
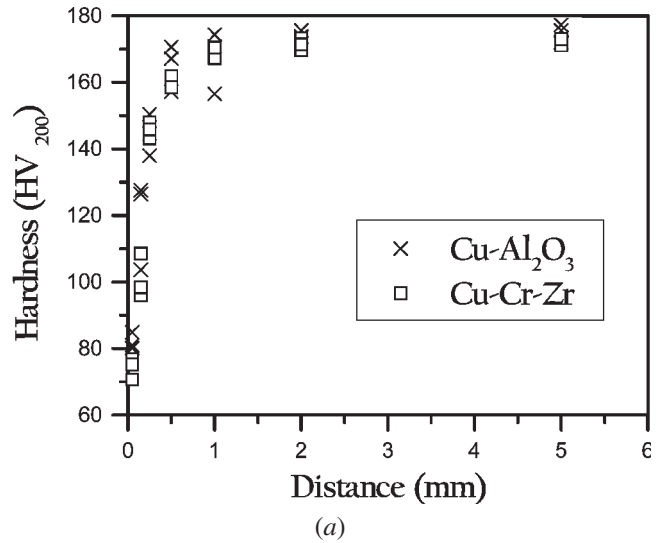


Fig. 16—Microhardness distribution at the tip regions of (a) an uncoated and (b) a coated electrode.

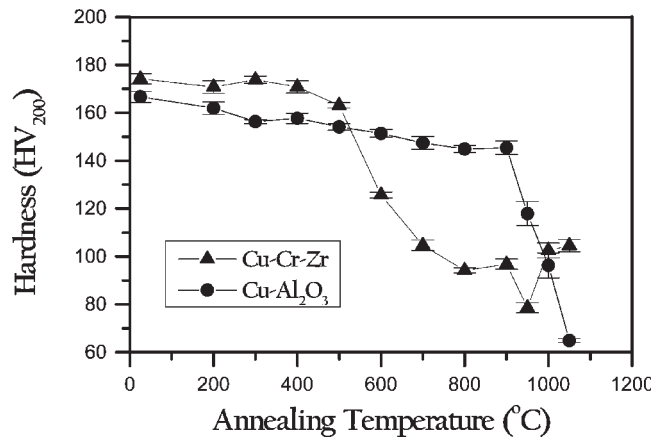


Fig. 17—The hardness of the Cu-Cr-Zr and Cu-Al<sub>2</sub>O<sub>3</sub> electrodes after 1-h annealing.

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