Refractory Metal Composite Tips for Resistance-Spot Welding of Galvanized Steel

A study of electrode life and failure mechanisms, using sintered metal inserts for longer service and more consistent quality

BY J. F. KEY AND T. H. COURTNEY

ABSTRACT. An investigation was undertaken to develop and test refractory metal-copper composites as electrode tips for resistance-spot welding galvanized steel. Powder composites of molybdenum copper and tungsten copper were fabricated by a process that generally produced a discontinuous refractory phase in a copper matrix. Welding tests of electrodes with tips made from these composites indicated that a top of 32 vol.% tungsten and copper was the most successful, lasting an average of 1750 welds. The failure mechanism was shown to involve the melting and displacement of part of the copper matrix during welding as a result of resistance heating. The degraded matrix was not able to adequately support the refractory particles some of which were abraded out of the matrix. The tip diameter thus increased until the current density was insufficient to produce a weld.

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Introduction

Premature electrode deterioration is a problem encountered in resistance welding galvanized sheet steel (Refs. 1, 2). The higher electrode forces, electrical currents and temperatures required for welding coated steel, as compared to uncoated steel, all contribute to shortening the electrode life. The principal cause of reduced life, however, is related to the environment of molten zinc in which the tip must operate. This leads to dissolution of copper from the electrode into the molten zinc. The resulting electrode becomes pitted, but more importantly is also coated with a copper-zinc alloy (Refs. 2, 3, 4). Upon succeeding welds, this layer is melted and discharged from the tip leaving correspondingly larger pits and an increased tip diameter. Progressive deterioration of the tip in this manner causes a decrease in current density until satisfactory welds can no longer be made. Thus, even though standard copper base electrodes (Cu-Zr, Cu-Cr) having high thermal and electrical conductivity are used commercially to resistance-spot weld galvanized steel, the propensity of copper to alloy with zinc inevitably leads to shortened electrode life.

Refractory metal tips, such as copper and tungsten, which do not alloy with zinc, have been considered as possible electrode tips for welding coated steel (Ref. 2). Their lower thermal and electrical conductivities, however, lead to higher tip temperatures and a greater tendency for electrode-workpiece sticking (Ref. 2).

Composite materials incorporating refractory metals into a copper matrix have also been considered as potential electrodes for resistance-spot welding galvanized steel (Ref. 5). The rationale for this is that the presence of copper increases the thermal and electrical conductivities of the electrode, thus alleviating the problem of electrode sticking. The proportion of copper in such a material must be limited, of course, to prevent appreciable alloying of the copper with zinc. Such composites have exhibited improved electrode lives, at least under controlled welding conditions. Most of the composites evaluated in previous work are characterized by microstructures which can be considered suboptimal in the sense that both the copper and refractory phase are continuous (Ref. 6). Hence, a crack in the refractory phase induced by thermal or mechanical shock can propagate appreciable distances within the composite prior to being arrested (Ref. 7), leading to premature "mechanical" failure of electrode tips fabricated from such materials.

The present work is concerned

Table 1 — Microstructural Characteristics of Composites Used in Resistance-Spot Welding Electrode Studies

Series	Refractory phase composition vol %[a]	Sinter-ing time, h	Particle diam[b] average, (μ)	Contacts per particle,[c] avg. no.	Refractory phase [c]
90Mo	70	1	3.6	1.11	Dis-continuous
90Mo	70	64	10.9	1.38	Becoming Continuous
60Mo	47	1	3.7	1.19	Dis-continuous
60Mo	47	64	10.9	1.03	Dis-continuous
90W	59	1	4.1	1.05	Dis-continuous
90W	59	64	6.7	2.21	Continuous
60W	32	1	3.8	0.70	Dis-continuous
60W	32	64	6.7	1.66	Continuous

(a) Ref. 9
(b) Ref. 10
(c) Ref. 8

with the evaluation of refractory metal copper composites in which the refractory phase is generally discontinuous. Additionally, the mechanism of electrode tip failure in such materials was determined. As will be shown, the failure mechanism of electrodes used to resistance-spot weld galvanized steel is fundamentally different from that observed in standard electrodes. Because of this, further development of these materials as electrode tips must proceed along correspondingly different lines.

Experimental Procedure

Composite Fabrications

Composites for electrode tips were fabricated by mechanical compaction followed by liquid phase sintering. Mechanical compaction was achieved by filling precleaned soft copper tubing (0.50 in. OD, 0.032 in. wall thickness) with premixed tungsten copper or molybdenum copper powders. After plugging the ends, the tubing was reduced 45% in cross-sectional area by swaging. The resulting powder mixture, at this point, was approximately 80% dense. The compact was sintered at 1200 C in a dry hydrogen atmosphere for varying periods of time. A 100% dense compact was achieved by capillary flow of the liquid copper within the first half hour of sintering. Subsequent sintering only produced a gradual coarsening of the microstructure and a gradual increase in the continuity of the refractory phase without altering the relative volume fractions of copper and the refractory constituent. The characteristics of the various microstructures are summarized in Table 1. Here, the average number of contacts per particle is a measure of the continuity of the refractory phase (Ref. 8). If, on the average, each refractory particle makes more than 1.50 contacts with other refractory particles on a planar section, the refractory phase is continuous. If the average number of contacts per particle is less than 1.33, the refractory phase is discontinuous in three dimensions. The "series" nomenclature used in this table (e.g. 90W) refers to the weight fraction of refractory constituent present in the powder mixture prior to liquid phase sintering. A complete description of the microstructural evolution during sintering is to be presented elsewhere.

Electrode Tip Fabrication and Welding Studies

Several geometrical configurations of powder composite insert and electrode were evaluated before settling on the design shown in Fig. 1 for the present studies. The filler metal (B Ag-8a; composition 72% Ag, 27.8% Cu, 0.2% Li by weight), in the form of a 0.003 in. x 0.375 in. strip was wrapped around the insert and placed in the tapered hole in the electrode shank. The inserts were then furnace brazed in a hydrogen atmosphere for twenty min at 815 C.

The welding performance of the electrodes was evaluated by first selecting a weld schedule that gave a 0.220 in. diam nugget. The nugget diam, electrode tip diam, and weld current were measured every one hundred welds. When no nugget was formed, the current was increased to again produce a nugget of 0.220 in. diam. Testing was then continued as before until the nugget size again fell to zero. The test was then concluded and the electrode assumed to have failed. Details of, and the rationale for, this procedure are given in Appendix A. In order to compare the composite electrodes to standard electrodes, similar tests were run on inserts of standard Cu-Cr electrode material.

Electrode Failure Determination

The mechanism of electrode tip failure was ascertained by metallographic examination of sections of electrode tips at various stages in their welding life. Each longitudinal section so examined was electroless nickel plated with Enthone NI 415 plating solution in order to preserve edge detail. The sections were prepared for metallographic examination by conventional metallographic techniques and examined by both optical and electron microscopy. Microscopic chemical analysis, utilizing the electron microprobe, was also performed in order to ascertain any chemical compositional changes within the electrode tip.

The above data were correlated with measurements on electrode tip diameter to further substantiate the mechanism of failure of these electrode materials.

Experimental Results and Discussion

Electrode Failure

The progressive deterioration of the electrode tip due to welding is shown in Fig. 2(a-d). Although this figure shows such deterioration only for a 90Mo series composite, qualitatively similar results were obtained on the other series as well. As noted in Fig. 2, a darkened "band" appears in the composite in the vicinity of the electrode tip. After fifty welds, this band extends approximately 0.008 in. into the composite. The band generally thickens as the number of welds increases (Fig. 2a-d); however, erosion of the tip simultaneously occurs during welding so that the total band thickness is the sum of the axial erosion wear and the microscopically evident thickness. Measurements of the axial erosion wear were combined with optical microscopic measurements to determine the total band thickness (Fig. 3). As noted in Fig. 3, the total erosion wear rate and band thickness increase is most rapid at the beginning of welding and these both decrease as the band edge approaches the cooling water jacket in the electrode shank (see Fig. 1).

More detailed microscopic examination of the degraded area of the composite indicates that the boundary between the normal composite microstructure and the darkened band corresponds, in fact, to the position of a solid-liquid interface during the welding cycle. Fig. 4(a) shows the electrode tip in the vicinity of the interface between the normal microstructure and the darkened band. As can be seen, three regions are evident: (1) the normal composite microstructure, (2) a refractory denuded area at the interface between the band and the unaffected composite, and (3) the band which, at this magnification, is seen to consist of refractory particles in a matrix characterized by a very high void content. The microstructural characteristics of the matrix in the denuded zone, Fig. 4(b) are different from that of the matrix in the unaffected composite, Fig. 4(c). Electron microprobe analysis indicated that the matrix in the unaffected area was essentially pure copper whereas the denuded zone contained an appreciable amount of zinc. Not correcting for absorption, the copper to zinc ratio in this area is approximately two to one.

An explanation of the compositional changes that occur at the electrode tip forms a basis for an explanation of the failure mechanism of the tip. A sufficient amount of electrical power is dissipated as heat to raise the temperature of the electrode tip to the vicinity of the melting point of copper. Not only is such a process consistent with the observed metallographic structure as seen above, but calculations (Appendix B) indicate this is a distinct possibility, and visual observations of a red hot band at the electrode tip during a weld also lend credence to this hypothesis. A molten copper matrix in contact with a molten zinc coating on the steel allows the zinc to diffuse rapidly through the matrix until it reaches the solid-liquid interface in the matrix. Thus the interface observed microscopically is actually the solid-liquid interface that existed in the matrix during welding.

The position of the solid-liquid interface is determined by the local temperature in the electrode. As the tip wears during welding, the position of this interface moves further into the electrode. As the interface comes closer to the water cooled jacket, its progression is retarded as has been previously noted in Fig. 3.

The increased volume fraction of the matrix region (i.e. the denuded zone) adjacent to the unaffected composite and the decreased volume fraction of matrix in the band region is a consequence of the matrix reaching the molten state during welding. Since the molten matrix cannot support the high pressures that exist during a weld, part of the molten copper is extruded. Some copper migrates toward the solid-liquid interface and some towards the electrode-workpiece interface. Indeed, copper deposits are visually observed on the workpiece surface after a weld. Starting with a freshly dressed tip, these deposits are most evident in the earlier stages of welding, which correspond to the rapid initial erosion rate.

Because the matrix is molten, erosion of the refractory particles occurs concurrently with, but to a lesser degree than, that of the matrix. The fluid matrix no longer adequately supports the refractory metal particles and they are pulled out of the tip by ad-

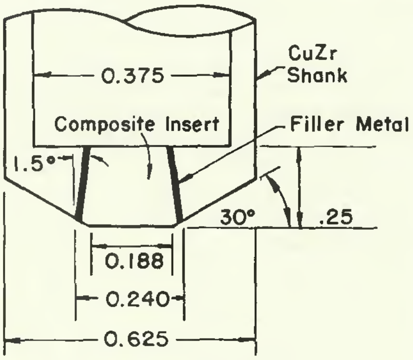

Fig. 1 — Electrode tip design

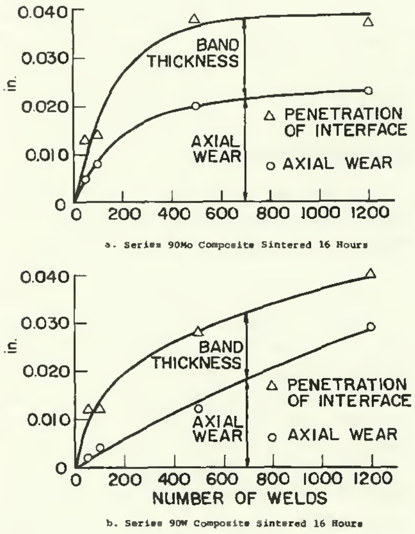

Fig. 3 — Penetration of solid-liquid interface and axial wear of tip. (a) Series 90Mo composite sintered 16 h; (b) Series 90W composite sintered 16 h

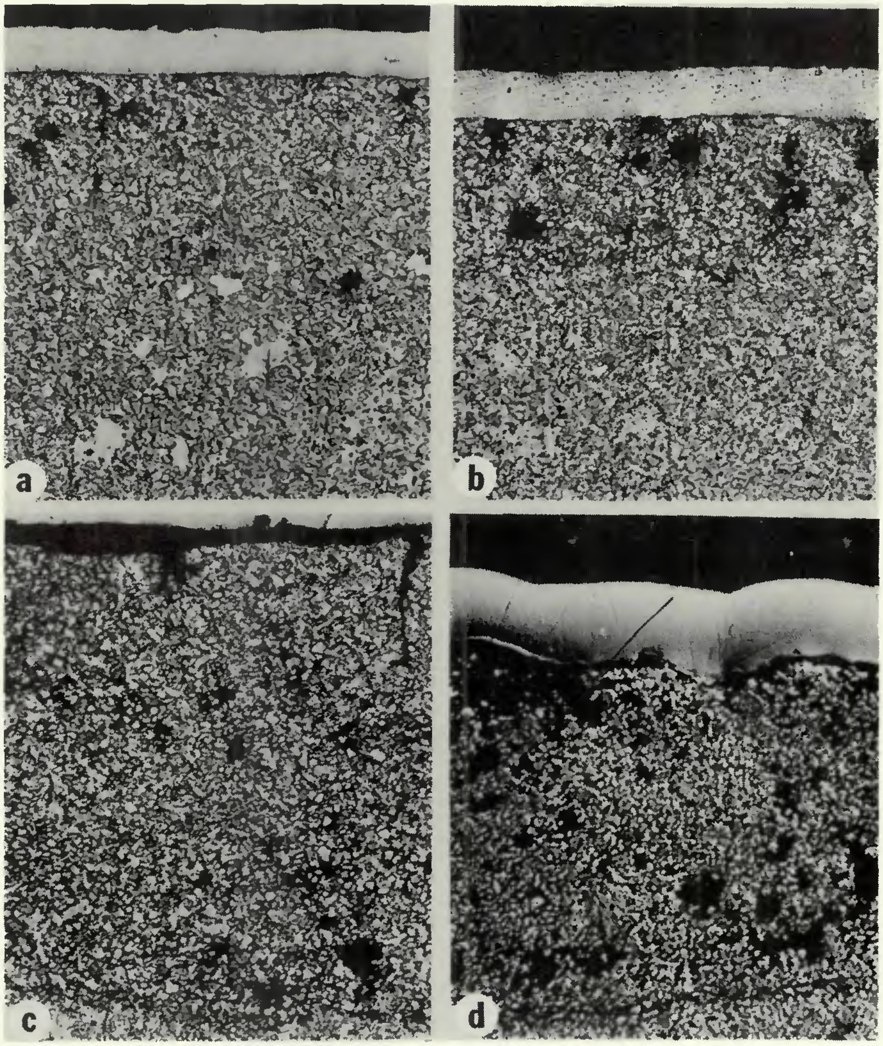

Fig. 2 — Penetration of solid liquid interface into matrix of Series 90Mo composite sintered 16 h: (a) After 50 welds (b) after 100 welds (c) after 500 welds (d) after 1200 welds. (X200, reduced 27%)

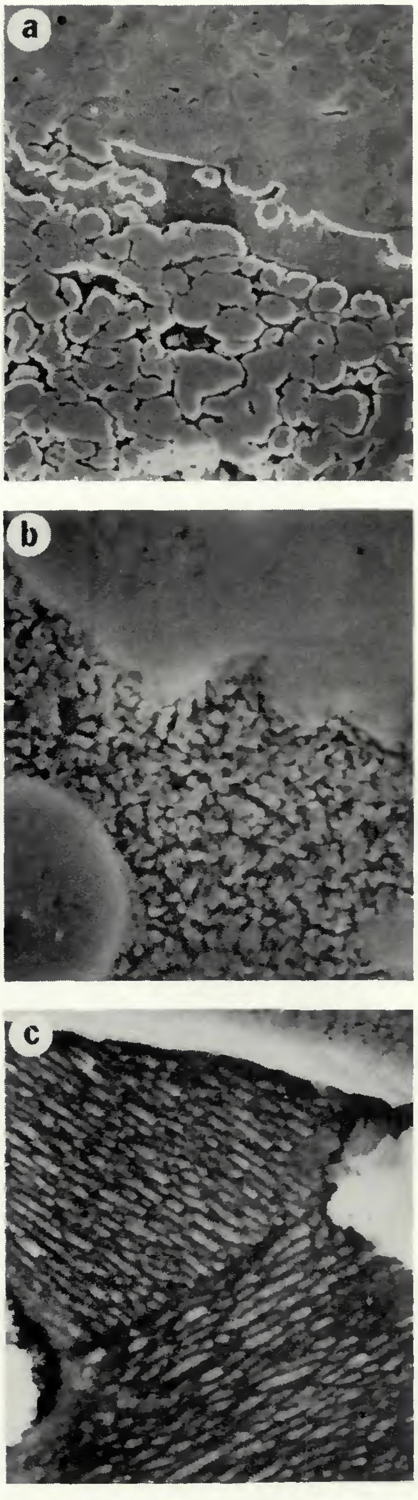

Fig. 4 — SEM photographs of matrix degradation: (a) Solid-liquid interface region (X500, reduced 27%) (b) Degraded matrix in band (X5000, reduced 27%) (c) Normal matrix, etched (X5000, reduced 27%)

hering, in one way or another, to the workpiece. An additional problem occurs if the refractory phase is continuous, for then relatively large pieces of the composite can be pulled out of the tip. Such an area is shown in Fig. 5. Here a region of composite is separated by an almost continuous series of voids in the matrix. This

Table 2 — Electrode Life[a] as Related to Sintering Time

Series	Sintering time (h)	Electrode lives[a] X100	Average life[a]
90Mo	1	13, 10, 9	1070
	16	12, 11, 9	1070
	64	14, 13	1350
60Mo	1	8, 5	650
	16	14, 10	1200
	64	14, 9	1150
90W	1	11, 8, 7, 6	800
	16	14, 14, 14, 9	1280
	64	13, 10	1150
60W	1	21, 19, 17, 13	1750
	16	10, 9, 9	930
	64	8, 7	750
Cu-Cr Std		19, 17, 15, 14	1630

(a) No. of welds produced before failure.

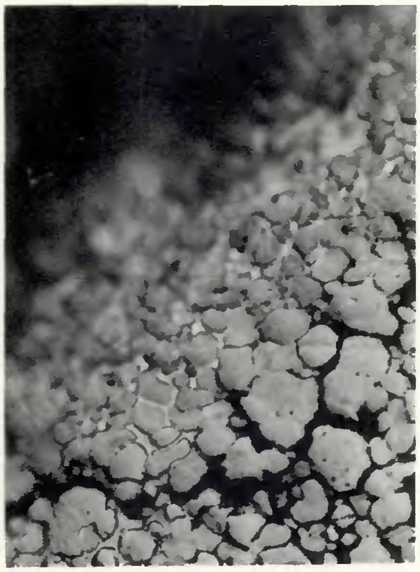

Fig. 5 — Region of Series 90W composite tip prior to incipient pullout permitted by linkage of microcracks. (X1500, reduced 27%)

entire region can stick to the workpiece and be pulled out as a whole during a later weld. As a consequence the tip diameter increases relatively rapidly and pits are concurrently formed.

The eventual failure of the electrode, insofar as its capability to produce a weld is concerned, is due to a combination of the microstructural effects discussed and the geometry of the electrode configuration. As can be seen in Fig. 1, an increase in the electrode tip diameter will occur concurrently with axial wear. Indeed, tip diameter measurements made as a function of the number of welds (Figs. 6 and 7) are similar in form to the corresponding axial wear curves (Fig. 3). When the tip diameter increases to about 0.250 in., a ring of copper in the electrode shank becomes exposed. Due to a combination of the lower resistance of the copper, a larger tip diameter, and the closer proximity of the interface to the water jacket, the tip diameter increases at a lesser rate after this diameter is reached. As noted in Fig. 8, however, the annular ring of copper now shunts current away from the center of the electrode through this ring. Eventual electrode failure occurs when the current density becomes too low to produce a weld.

A word concerning the wear rate of the standard Cu-Cr electrodes (Fig. 7) is in order. In comparison to composite electrodes, wear rates and increases in tip diameter were rapid in this material. However, final electrode "failure" for the standard electrodes generally occurred after a relatively large number of welds. Such "exaggerated" lives of these electrodes are due to the criterion of failure used here; the standard electrodes produced a large number of ring welds prior to "failure" whereas the composite electrodes generally did not.

Electrode Life Studies

The electrode lives of the various electrodes studied here are shown in Table 2. A hierarchial analysis of variance using an F-test shows that there is a greater than 99% probability that a significant difference exists between composition-sintering time combinations. Comparison of the average standard deviation of all the groups with the standard deviation of series 60W-1 shows that there is an approximately 80% probability that 60W-1 is better than the average electrode.

Although a definite explanation cannot be given for the superior performance of the series 60W composites sintered for one hour, several

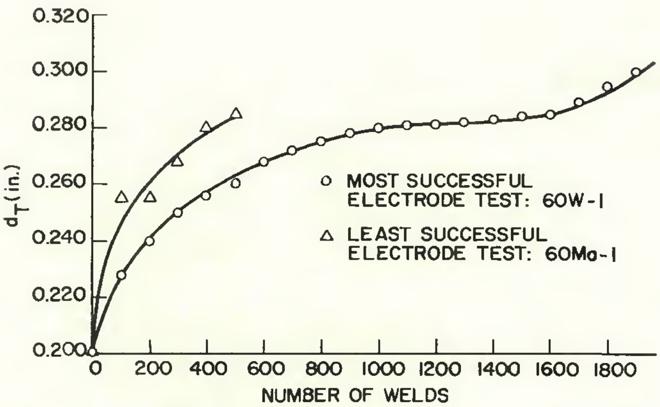

Fig. 6 — Composite electrode tip diameter for most successful and least successful tests

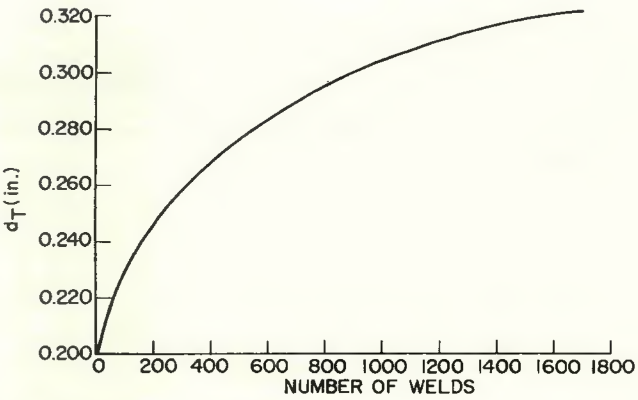

Fig. 7 — Average Cu-Cr electrode tip diameter

possibilities exist. As noted in Table 1, these composites are characterized by a higher volume fraction of copper which leads to less heat generation in the tip (Appendix B); they additionally have discontinuous refractory particles which can account for a lessened wear rate as discussed above. These two factors may, therefore, combine to produce superior welding performance.

As noted in Figs. 6, 7 and 8, the Cu-Cr electrode erodes at a rate almost as fast as the worst composite electrode. However, the reported lives of this material are generally high due to the less severe failure criteria applied to them in this work.

Conclusions

Powder composites with refractory metal bases of molybdenum or tungsten have been tested as tips for spot welding electrodes and their failure mechanisms determined. These composites have microstructures characterized by a continuous copper matrix between discontinuous refractory particles. Exceptions to this occur for 59 and 32 vol. % W composites sintered for 64 h. In these composites the refractory phase, as well as the matrix, is continuous.

A statistical analysis of electrode life indicates that a 32 vol. % W-Cu composite sintered one hour is the most successful of those evaluated in this study. It is hypothesized that the success of these electrodes is due to the lack of continuity of the refractory particles and the relatively high volume fraction of copper contained in them.

Unlike standard Cu-Cr electrodes, operation in an environment of molten zinc is not the fundamental cause of failure of the composite electrodes. The original problem of dissolution of the electrodes into zinc gives way to another mode of failure. In this case, electrode failure is caused by melting of the matrix at the tip. Interfacial temperatures at the tip are high enough to melt a band of the copper matrix. The matrix is then partially extruded from the band, leaving the refractory particles unsupported. As a consequence, a rapid increase in tip diameter occurs until a ring of the relatively pure copper shank is exposed at a tip diameter of approximately 0.250 in. The weld current is then partially shunted through this ring, lowering the current density and consequently the temperature in the composite. The increase in tip diameter is less rapid during this stage. Failure occurs when the current density is insufficient to produce a weld.

Any work concerned with further development, for resistance-spot welding purposes, of composites such as those studied in the present work must take into account the mechanism of failure of these electrodes. In particular, the evidence presented here suggests that microstructures characterized by complete discontinuity of the refractory phase are potentially most useful and such structures may be attainable by variation of sintering conditions. Additionally, the refractory phase should be present in proportions sufficient only to minimize the alloying of the copper matrix with zinc. Increased refractory content, as noted, can lead to direct melting of the copper matrix. It is also felt that optimization of a welding schedule tailored specifically to composite electrode tips and further development of the composite insert-electrode shank joint design will yield significantly longer electrode life.

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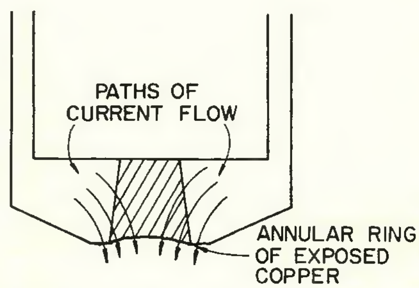

Fig. 8 — Schematic section of severely worn electrode

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Appendix A

Electrode Test Procedure

1. Insert electrodes and precisely align so that axes coincide and tip is flat against workpiece surface.
2. Set cooling water flow rate to 2 gal/min through each electrode.
3. Set electrode force at 575 lb.
4. Set Weld time at 13 cycles; Squeeze time at 30 cycles; Hold time at 30 cycles; Off time at 47 cycles. This schedule gives a welding rate of

30 welds/min.

5. Do not remove any protective oils from the galvanized steel.

6. Condition electrode faces by making 25 welds at least 10% under normal welding current (about 9000 A).

7. Increase current to give a 0.210-0.220 in. nugget diameter as determined by a peel test.

8. Make 100 welds, with approximately 0.75 in. spacing, per pair of 4 in. x 12 in. sheets. After every 100 welds, make one weld per pair on five pairs of 1 in. × 4 in. coupons. Record current, nugget diameter, and tip diameter.

9. When the nugget diameter falls to zero on any two of the five pairs of test coupons, increase the current to again produce a nugget diameter of 0.220 in. (Justification for this procedure is based on the use of a somewhat lower current to totally prevent expulsion. The current increase referred to here is of the magnitude normally used for welding 0.036 in. thick galvanized steel with 0.188 in. diam electrodes. In addition, the condition of the electrodes was still generally good at this point and could not be considered to have "failed" in the sense they were not capable of making further good weldments.)

10. When the nugget diameter on any two of the five test coupons again falls to zero, the test is concluded.

Appendix B

Electrical Power Dissipation in Electrodes

The power dissipation per unit volume, P_O, in a standard electrode is expressed as

$$P_o = I_T^2 \rho_{SE} \frac{L}{A} \qquad (B1)$$

where I_T is the electrode current, ρ_{SE}, the electrical resistivity of a standard electrode, and L, and A are effective electrode length and cross-sectional area for electric current flow, respectively. Assuming that the total current required to effect a weld is the same irrespective of the type of electrode used and assuming the geometry of the individual phases in the composite is that of a parallel circuit, the equation for the current flow is given by

$$I_T = I_{Mo} + I_{Cu} \qquad (B2)$$

where I_{Mo} and I_{Cu} are the currents flowing in the molybdenum and copper, respectively.

For our case,

$$I_{Cu}/I_{Mo} = \frac{\rho_{Mo}/A_{Mo}}{\rho_{Cu}/A_{Cu}} = \frac{\rho_{Mo}}{\rho_{Cu}} \frac{V_{Cu}}{V_{Mo}} \qquad (B3)$$

where the ratio of the cross-section area, A_{Cu}/A_{Mo} is the same as the ratio of the volume fraction V_{Cu}/V_{Mo}.

The power dissipated in the composite electrode per unit volume, is

$$P = I^2_{Mo} \rho_{Mo} \frac{L}{A_{Mo}} + I^2_{Cu} \rho_{Cu} \frac{L}{A_{Cu}} \qquad (B4)$$

or

$$\frac{P}{P_O} = \left[\frac{I_{Mo}}{I_T}\right]^2 \left[\frac{\rho_{Mo}}{\rho_{SE}}\right] \left[\frac{1}{V_{Mo}}\right] + \left[\frac{I_{Cu}}{I_T}\right]^2 \left[\frac{\rho_{Cu}}{\rho_{SE}}\right] \left[\frac{1}{V_{Cu}}\right] \qquad (B5)$$

Substituting from (B2) and (B3) into (B5) and assuming $\rho_{SE} \simeq \rho_{Cu}$ gives

$$\frac{P}{P_O} = \frac{1}{\left[1 + \frac{\rho_{Cu}}{\rho_{Mo}} \frac{V_{Mo}}{V_{Cu}}\right]^2} \left[\frac{1}{V_{Cu}}\right] \left[1 + \frac{V_{Mo}}{V_{Cu}} \left(\frac{\rho_{Cu}}{\rho_{Mo}}\right)\right] \qquad (B6)$$

An estimate on the temperature difference, ΔT, between the electrode tip and the water cooled jacket may be obtained by considering elements of volume (υ) at the workpiece-electrode tip interface

$$\frac{\text{Heat in-Heat out}}{\text{unit time}} = \frac{C_P \upsilon \Delta T}{\text{time}} \qquad (B7)$$

$$\text{Power} - \frac{\text{Heat out}}{\text{time}} = \frac{C_p \upsilon \Delta T}{\text{time}} \qquad (B8)$$

$$P\upsilon \Delta t - \Delta t k A \frac{dT}{dx} = C_p \upsilon \Delta T \qquad (B9)$$

Assuming dT/dx is approximately linear,

$$(P_{\upsilon})\Delta t - \Delta t k A \frac{\Delta T}{L} = C_p \upsilon \Delta T \qquad (B10)$$

Rearranging

$$\Delta T = \frac{P\upsilon \Delta t}{C_P \upsilon + kA \frac{\Delta t}{L}} \qquad (B11)$$

A lower limit estimate on ΔT can be obtained by assuming $\upsilon = AL$, thus

$$\Delta T = \frac{P \Delta t}{C_p + \frac{k \Delta t}{L^2}} \qquad (B12)$$

The extent of temperature rise in a composite compared to a standard electrode is then

$$\frac{\Delta T_C}{\Delta T_O} = \frac{P \; (C_P + k\Delta t/L^2)^{SE}}{P_O \; (C_p + k\Delta t/L^2)^{C}} \qquad (B13)$$

The ratio of the temperature increase can then be estimated between limits. Since $(C_p)_{SE} \sim (C_p)_C$, a lower limit is $\Delta(T/T_O) = P/P_O$ for the case where $C_p >> k\Delta t/L^2$. For $C_p \ll k\Delta t/L^2$, an upper limit $\Delta(T_C/T_O) = k_{SE}P/k_C P_O$ is obtained. At first glance the lower limit seems more appropriate for a resistance-spot welding schedule since Δt is of the order of tenths of seconds. However, if the time scale for thermal equilibrium is much greater than the time between welds, the upper limit may be more appropriate.

In any event the upper and lower limits on temperature rise can be estimated since P/P_O has been obtained previously and $k_C \simeq k_{Cu}V_{Cu} + k_{Mo}V_{Mo}$. For example, for a 70% Mo composite, P/P_O is calculated to be 1.90 and k_{Cu}/k_C is 1.77. Thus $\Delta(T/T_O)$ will range from 1.90 to 3.36. Since a temperature rise of 600 C is not unusual for a standard electrode, it is thus reasonable to expect that the melting temperature of copper is attained in composite electrodes during the welding cycle.