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A New Dimension in Resistance Welding Electrode Materials

Copper electrodes containing Al_2O_3, when compared to RWMA Class II electrodes show less wear, have improved mushrooming characteristics, do not stick to the work and do not show as much pitting

BY A. V. NADKARNI AND E. P. WEBER

ABSTRACT. A dispersion strengthened (DS) copper is described wherein the strengthening is achieved by a uniform distribution of angstrom size particles of Al_2O_3 throughout the copper matrix. Some properties relevant to the performance in resistance welding are given and compared with conventional precipitation-hardened copper alloys.

A cold forging technique was developed to obtain an isotropic equiaxed grain structure in DS copper. Electrodes made by this process were comparatively tested against RWMA Standard Class II electrodes in two different welding tests.

Cold forged DS copper electrodes had less wear after 15,000 welds than did the Class II electrodes after 2500 welds. Mushrooming characteristics also showed a dramatic improvement over Class II electrodes. On galvanized steel, Class II electrodes exhibited a strong tendency toward sticking to the work and pitting of the welding face. DS copper electrodes did not stick to the work and did not show as much pitting.

In short tests dome nose electrodes showed significantly less wear and mushrooming compared to pointed nose electrodes in case of DS copper. Class II electrodes were less sensitive to this change in nose design.

Introduction

Strengthening of metals by fine dispersions of hard refractory materials has been known for over a quarter of a century. Carbides, nitrides, and—most commonly—oxides have been used to strengthen metallic matrices. Composite materials thus produced exhibit excellent creep rupture properties and thermal stability.

Copper, when dispersion strengthened by oxides such as Al_2O_3, ZrO_2, etc., offers a unique combination of high strength and hardness with excellent electrical conductivity. More importantly, a major portion of these properties is retained at and after exposure to elevated temperatures.

The effectiveness of the dispersed particles in matrix strengthening and strength retention depends upon the particle size and interparticle spacing. Among methods known to date, internal oxidation produces the most effective dispersion.[1-3] This study deals with internally oxidized Cu-Al_2O_3 alloys and their merits as welding electrode materials. Properties relevant to qualifying these as welding electrode materials and to their performance in welding tests were also determined.

High strength, hardness and electrical conductivity, and resistance to thermal degradation of these properties should make DS copper an excellent candidate for resistance welding electrodes. However, in actual welding tests the DS copper electrodes were found to mushroom and develop radial cracks in the welding face. This was attributed to the fibrous structure of DS copper resulting from extrusion.

A cold forging technique was developed to change the fibrous structure into equiaxed grain structure. This resulted in dramatic improvements in wear and mushrooming characteristics of the electrodes. Wear and mushrooming relate directly to the electrode life in terms of number of welds that can be obtained with an electrode and with the frequency of redressing

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required. Reduced frequency of redressing minimizes the interruptions (down time) in work schedules which are extremely costly in assembly line production systems. Thus, improved electrode performance translates into lower cost and greater efficiency of the welding operation.

The effects of composition of DS copper, in terms of Al_2O_3 content, and electrode nose design on electrode performance were also studied.

Experimental Procedure

Preparation of Alloys

Two different DS copper alloy compositions were used for this study, *namely*, Cu-1.57 vol.% Al_2O_3 and Cu-2.68 vol.% Al_2O_3.

These alloys were made by first induction melting Cu-0.35 wt.% Al and Cu-0.60 wt.% Al compositions and atomizing them into powder by nitrogen gas stream. These powders were internally oxidized by the method described in U.S. patent 3,779,714.[4] They were then enclosed and sealed in copper containers and hot extruded into fully dense rods.

In some instances, the extruded rods were cold worked by drawing.

Evaluation of Properties

Extruded and cold drawn rods were tested for Rockwell hardness, electrical conductivity and tensile properties. These were checked against the requirements for standard RWMA Class II resistance welding electrode materials.

Since resistance to softening upon exposure to high temperatures is an important requirement for welding electrode materials, the DS copper rods were annealed at temperatures from 400 to 1700 F (204 to 927 C) for 1 hour (h), and hardness and tensile properties were redetermined.

Hot hardness is an important parameter which has a bearing on the performance of an electrode material in welding tests. Hot hardness also bears a strong correlation with stress rupture strength. Since the latter can be determined under more strictly controlled test conditions, the DS copper alloys and a standard RWMA Class II alloy were comparatively tested in stress rupture tests.

Table 1—Welding Test Schedules

	Test 1	Test 2
Sheet materials	SAE 1010 Top: bare Bottom: bare	SAE 1010 Top: bare Bottom: galvanized
Sheet thickness, in. (mm)	Top: 0.044 (1.1) Bottom: 0.044 (1.1)	Top: 0.075 (1.9) Bottom: 0.080 (2.0)
Weld current, amperes	8500	13,000
Weld force, pounds (N)	650 (2893)	1300 (5785)
Weld time, cycles	30	16
Squeeze time, cycles	15	84
Hold time, cycles	10	100
Off time, cycles	15	100
Weld rate, no./min.	32	12
Cooling water, gal/min./electrode	1	1
Cooling water, (liters/min./electrode)	(3.8)	(3.8)

Electrode Fabrication

DS copper alloys were initially machined from ⅝ in. (15.9 mm) diameter rods. However, in subsequent work they were made by cold forging according to the process described in U.S. patent application 4,045,644.[5] The process involved a cold upsetting stage where the fibrous structure of the extruded and drawn rod was converted into equiaxed grain structure.

The standard Class II electrodes were purchased from an electrode distributor. These were made by machining ⅝ in. (15.9 mm) diameter rods. Some electrodes were also made by cold forging to determine the effect, if any, of this process.

Welding Tests

Two types of welding tests were performed on the electrodes under study. The test conditions are given in Table 1.

RWMA Class II Cu-Cr electrodes were used as standard and tested under identical conditions. Tests were conducted on a single station Taylor Winfield ERC-12-150 resistance press welding machine.

The electrode length and welding face diameter were measured at the beginning of the test and at 2500 weld intervals. The changes in length represent wear while the changes in diameter represent mushrooming. The face diameters could not be measured very accurately because of out of roundness of the welding face and, in case of Cu-Cr electrodes, due to excessive peripheral extruded material. Test coupons were tested in tensile shear tests and the loads recorded. Ten coupons were tested in this manner at the end of each 2500 weld interval. The weld nugget cross sections were also observed by etching.

In Test 1 most of the work was done on truncated cone nose (type E)

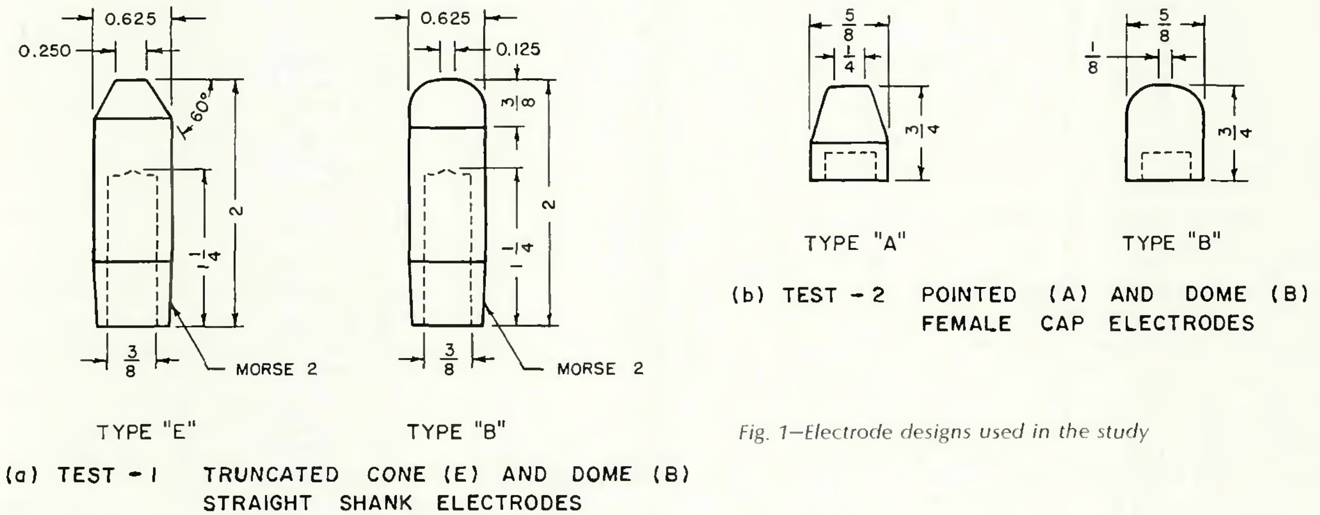


Fig. 1—Electrode designs used in the study

straight shank electrodes made from Cu-1.57 vol.% Al_2O_3 alloy. One 10,000 weld test was run on dome nose (type B) electrodes made from Cu-2.68 vol.% Al_2O_3 alloy. The results showed a combined effect of higher Al_2O_3 content and dome nose design. Both nose designs are shown in Fig. 1(a).

Test 1 was an accelerated test in that the weld time used was almost three times as long as that recommended for this sheet thickness. This was done in order that in relatively small number of welds sufficient wear would be produced in the electrodes for a meaningful comparison of wear rates. Tests with up to 15,000 welds were carried out to determine the stabilized trends in electrode wear.

In Test 2 pointed nose (type A) and dome nose (type B) female cap electrodes shown in Fig. 1(b) were used. Both Cu-1.57 vol.% Al_2O_3 and Cu-2.68 vol.% Al_2O_3 were evaluated. The effect of nose design on a given electrode material was determined in an initial screening test of 2500 welds.

The data indicated that for DS copper alloys dome design was significantly superior to pointed nose design. Therefore, further testing was confined to dome nose electrodes. On the other hand, standard Cu-Cr electrodes did not show any significant difference between the two nose designs. Since pointed nose electrodes are used widely at the present time, the tests on Cu-Cr were confined to this design. In this test a combination of galvanized and bare steels was used and the welding conditions were developed to produce acceptable welds.

Results and Discussion

Properties of DS Copper Alloys

Room Temperature Properties. To qualify for use in resistance welding electrodes a material must meet certain property requirements set by RWMA. Table 2 shows the room temperature properties of Cu-1.57 vol.% Al_2O_3 and Cu-2.68 vol.% Al_2O_3 alloys along with the RWMA minimum property standards for Class II electrodes. The alloys meet all requirements. The work on cold forged electrodes which involved cold upsetting and back extrusion indicated that these alloys have excellent cold formability.

Effect of Annealing on Properties. High strength, hardness and electrical conductivity are not sufficient to make an electrode material perform well in welding tests. Resistance welding electrodes face high temperatures during welding as a result of which the electrode materials undergo certain amount of thermal softening. This type of softening results in rapid wear and mushrooming of the electrodes. Therefore, resistance of an electrode material to softening upon exposure to high temperatures is an important requirement for good performance in welding.

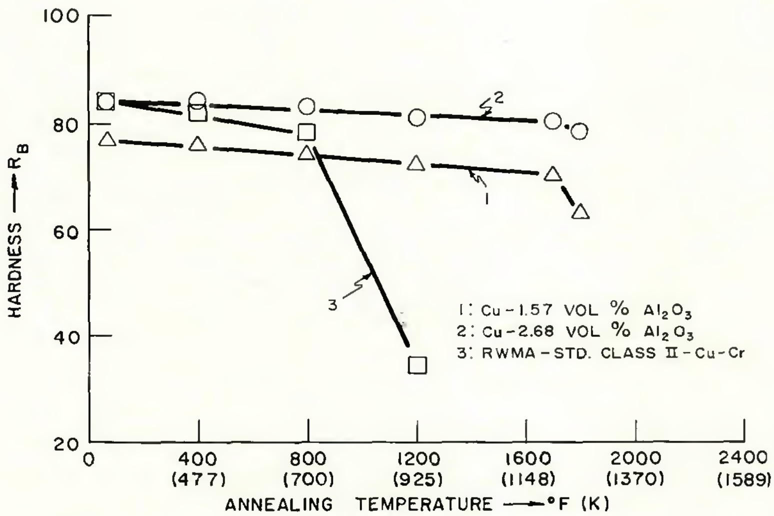
In welding, the exposure of the welding face is not to a constant temperature for a long duration but rather to thermal cycling. At the end of weld cycle the temperature reaches a maximum after which it cools until the next weld cycle starts. Useful indication of the possible electrode behavior under these conditions can be obtained from the effect of annealing on the properties of the material. Therefore, the two alloys were subjected to annealing treatments at temperatures ranging from 400 to 1700 F (204 to 927 C) for 1 h.

Figure 2 shows the effect of annealing temperature on hardness and tensile strength of the two alloys. Similar data on Cu-Cr are also given for comparison. The two DS alloys retain much of their initial hardness and tensile strength after annealing at temperatures up to 1700 F (927 C). However, the Cu-Cr alloy undergoes a

Table 2—Room Temperature Properties of DS Copper Alloys vs. RWMA Class II Min. Standard

Alloy	Hardness, Rockwell 'B'	Conductivity, % IACS	Ultimate tensile strength, psi[a]	Elongation, % in 2 in. (51 mm)
Cu-1.57 vol.% Al_2O_3	77	87	77,000	18
Cu-2.68 vol.% Al_2O_3	84	82	83,000	13
RWMA Standard Class II	75	75	65,000	13

(a) 1000 psi = 6.895 MN/m^2.



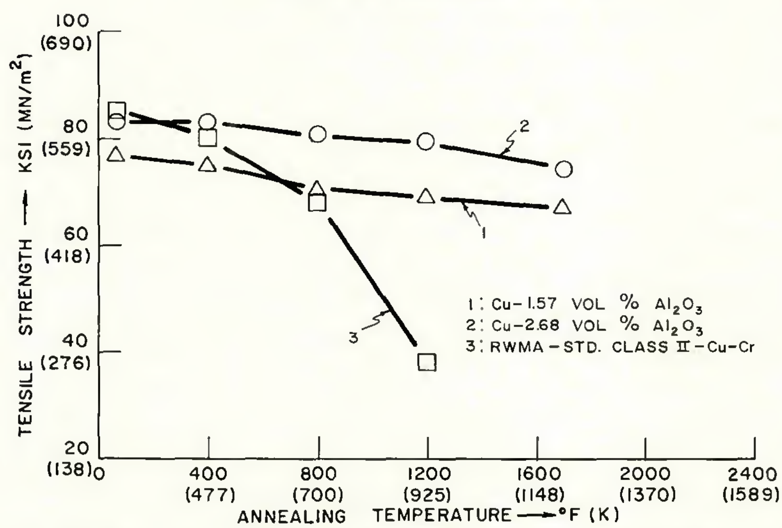


Fig. 2—Effect of annealing temperature on (a) hardness and (b) tensile strength

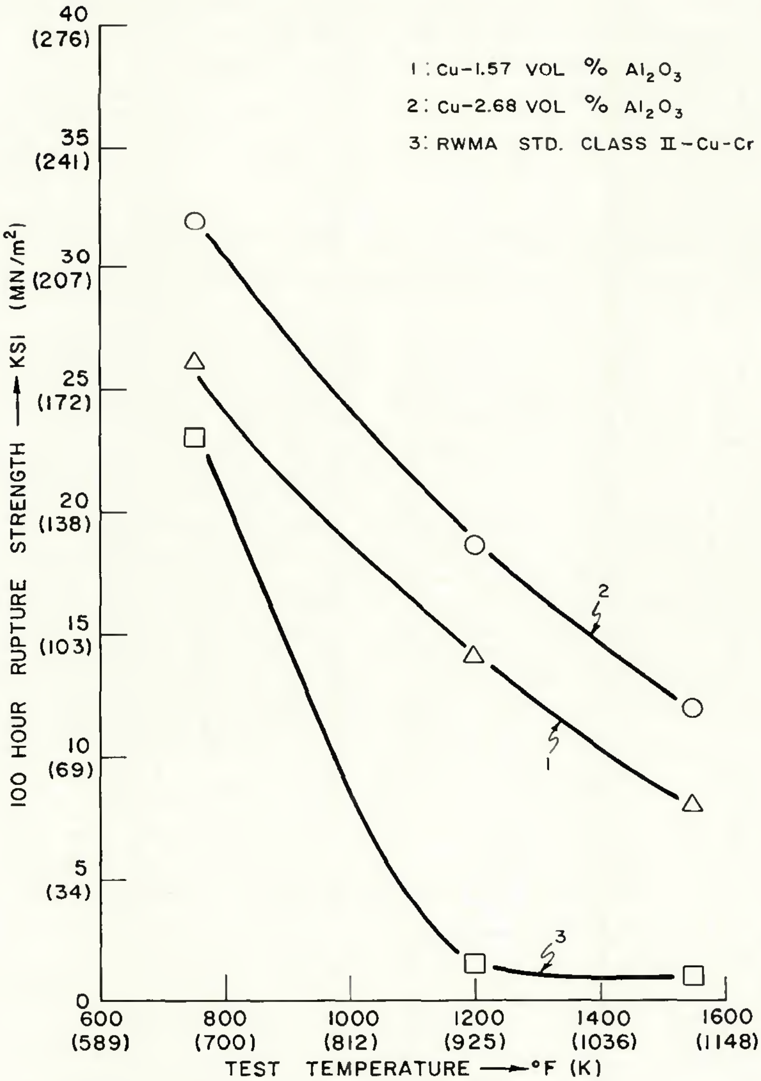


Fig. 3—Effect of test temperature on 100 h rupture strength

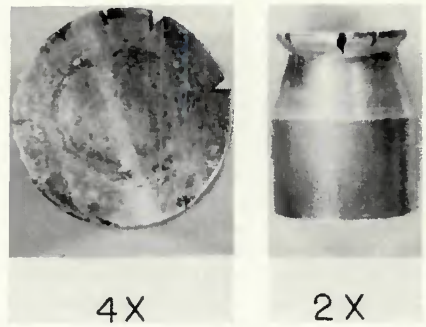


Fig. 4—Mushrooming and peripheral cracking in machined Cu-1.57 vol.% Al_2O_3 electrode

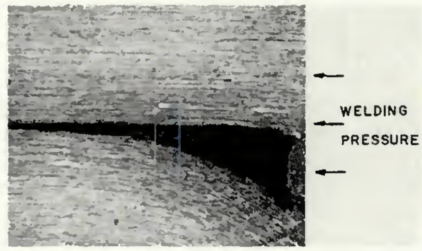


Fig. 5—Fibrous structure and interfiber splitting in Cu-1.57 vol.% Al_2O_3 electrode

tremendous drop in these properties above about 900 F (482 C).

The data show that DS copper alloys have a much greater resistance to thermal softening. The precipitated particles of Cr which are responsible for strengthening Cu-Cr start growing at temperatures above the initial aging temperature and thus lose some of their strengthening effect. The Al_2O_3 particles in DS copper alloys, on the other hand, are more stable and retain their original particle size and distribution up to temperatures in excess of 1800 F (982 C). The dispersed particles impede the motion of grain boundaries and thus resist recrystallization. Consequently, DS copper alloys have a much higher recrystallization temperature than Cu-Cr.

Elevated Temperature Properties. The performance of a material in welding tests also depends upon hardness of the material at temperature experienced at the welding face, i.e., on the hot hardness. The latter bears a strong correlation with stress rupture strength. Stress rupture tests can be performed under strictly controlled conditions and therefore the DS copper alloys and Cu-Cr were stress rupture tested at various temperatures.

Figure 3 shows the 100 h rupture strengths of these materials as functions of test temperature. Clearly the DS copper alloys have exceptional advantage in elevated temperature strength over Cu-Cr. This is even more evident at temperatures above 800 F (427 C). Again, these excellent high temperature properties are attributed to the thermal stability, both structural and morphological, of the dispersed Al_2O_3 phase in DS copper alloys.

Welding Tests

Test 1. The properties described above should make DS copper alloys excellent resistance welding electrode materials. Therefore, some truncated cone straight shank electrodes, as depicted in Fig. 1(a), were machined from extruded and cold drawn Cu-1.57 vol.% Al_2O_3 alloy. These were tested under Test 1 conditions.

Machined Cu-Cr electrodes obtained from an electrode distributor were used as standard for comparison. After 500 welds the DS copper electrodes underwent extensive mushrooming and peripheral cracks were developed. Figure 4 shows the electrode after 500 welds. The tests on this electrode were terminated at this point.

A longitudinal section through this electrode was mounted and prepared. Figure 5 shows the microstructure of this section. DS copper alloy has a highly oriented textured (fibrous) structure which results from hot extrusion of powders. Consequently, there is an anisotropy in properties, i.e., the material has excellent strength in the direction of the fibers (longitudinal) but relatively low strength perpendicular to the fibers (transverse).

The anisotropy becomes even more evident at high temperatures. During welding the compressive weld force on the electrode face develops a tensile stress component in the transverse direction. This combined with the temperature tends to pull the fibers apart in the weaker transverse direction.

Figure 5 shows the interfiber splitting. Once this splitting starts it progresses rather rapidly during further welding thus giving rise to excessive mushrooming and peripheral cracking.

To remedy this problem the fibrous structure must be changed into an equiaxed structure. This would have isotropic properties and still have all the basic structural characteristics of the material such as the Al_2O_3 particle size and distribution. The change from fibrous to equiaxed grain structure was achieved by developing a new cold forging technique. This involved cold upsetting a piece of extruded or cold drawn rod to a larger diameter slug meeting a certain minimum requirement in increase in cross sectional area.

The cold upset slug can be converted into the desired electrode shape by one of three methods:

1. Entirely by cold forging.
2. Partly by cold forging and partly by machining.
3. Entirely by machining.

The first method is of course the most desirable because it eliminates scrap. If the electrode is machined in its entirety, a large amount of scrap is generated. For example, in a female cap electrode as much as 45% material could be scrapped. Thus, cold forging offers a dual advantage in case of DS copper alloy, a desirable metallurgical structure and material savings.

Figure 6 shows a typical microstructure of a longitudinal cross section of a cold forged electrode. The grain structure is equiaxed and in welding tests it was found to eliminate the cracking.

The cold forged Cu-1.57 vol.% Al_2O_3 electrodes were tested in Test 1 and compared with Cu-Cr electrodes. Figure 7 shows the data on wear (ΔL-length change) of upper electrode as a function of number of welds. The

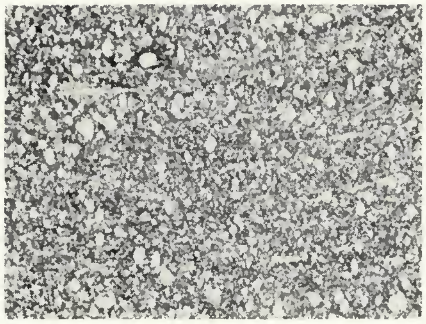


Fig. 6—Cold forging—equiaxed grain structure—no peripheral cracking

lower electrode had similar but somewhat lower wear and, therefore, only upper electrode data were plotted.

The data of Fig. 7 show that after 15,000 welds DS copper electrodes had a wear of 0.030 in. (0.76 mm) while the same wear took place in Cu-Cr after only 3000 welds, i.e., in ⅕ the number of welds. After 15,000 welds Cu-Cr electrodes had more than 2½ times the wear of DS copper electrodes. More importantly, the wear in DS copper leveled off between 12,500 and 15,000 welds while the Cu-Cr electrodes wore at a constant (linear) rate beyond 2500 welds.

Mushrooming (ΔD-diameter change) followed the same trend as wear data in that the Cu-Cr electrodes had a larger diameter after 2500 welds than did the DS copper electrodes after 15,000 welds. As explained earlier these measurements could not be made as accurately as length measurements due to out of roundness of the welding face and the deformed metal hanging on the periphery of the welding face. Therefore, these are not presented in a graphical form here.

Figure 8 shows the tensile shear data on the welds. These were average load values taken from 10 test coupons. The welds were considered acceptable if the load values were above 1400 pounds (6230 N). Both DS copper and Cu-Cr electrodes produced acceptable welds up to 15,000. Figure 9 shows the weld nugget diameter as a function of number of welds. Nugget diameters of 0.180 in. (4.6 mm) or larger were considered acceptable. Both DS copper and Cu-Cr electrodes produced acceptable welds up to 15,000.

The wear and mushrooming characteristics of cold forged DS copper electrodes thus showed a remarkable improvement over Cu-Cr electrodes. Cold forging produced an equiaxed grain structure which was instrumental in eliminating the interfiber splitting observed in machined electrodes. Another possible solution to the splitting problem was to change the triaxial stress distribution in the electrode. This could be done by changing the electrode design.

A dome design was selected for further study because it provided more material in the nose area to support the welding face and thus lower the stress level. Dome nose electrodes are easier to dress than pointed nose electrodes. Their alignment during weld-

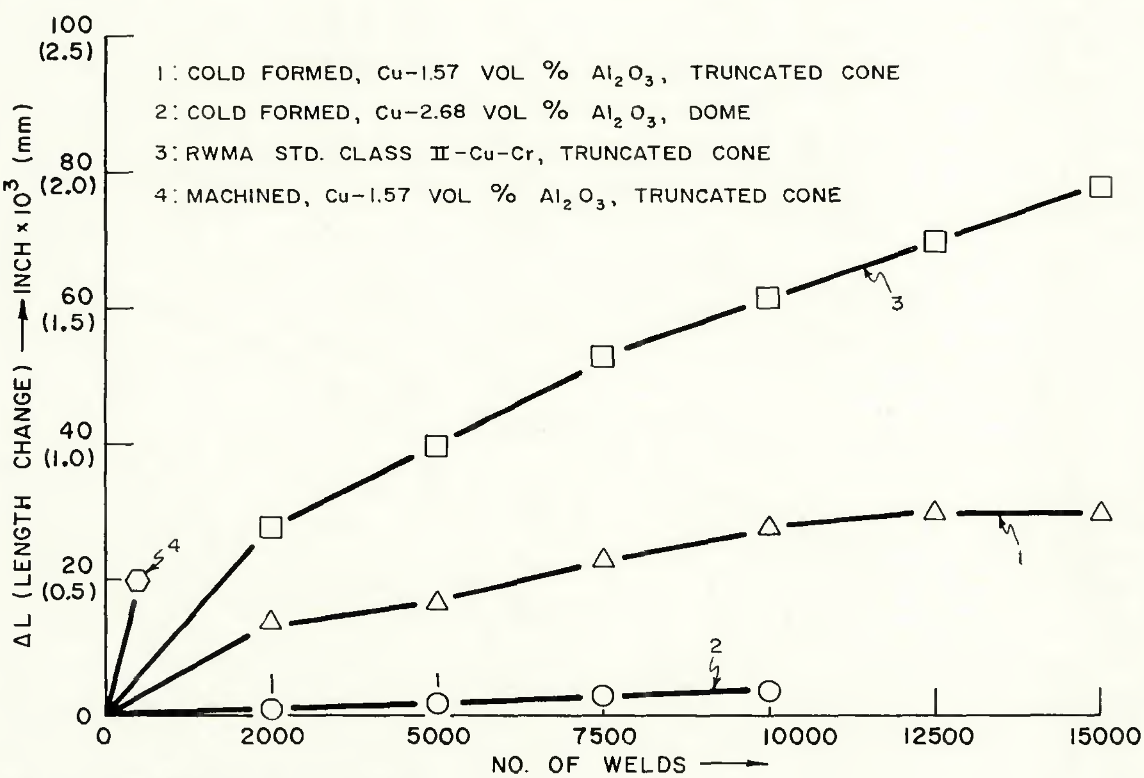


Fig. 7—Upper electrode wear data in Test 1

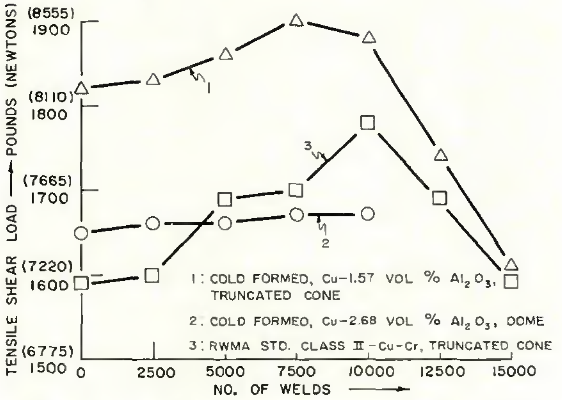


Fig. 8—Tensile shear load data in Test 1

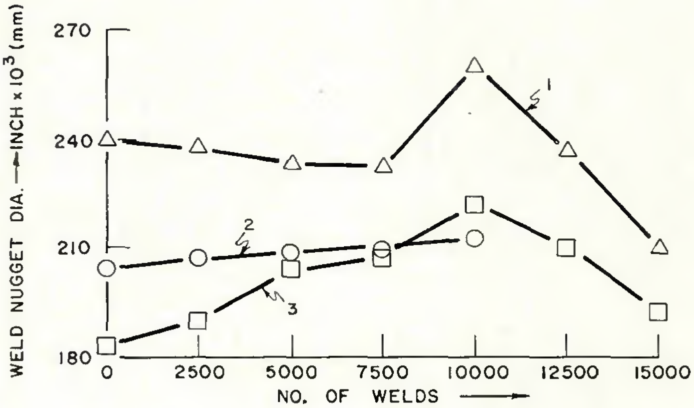


Fig. 9—Weld nugget diameter data in Test 1

ing is also less critical than that of pointed nose electrodes. Yet another possible solution was to increase the transverse strength of DS copper so that the electrode would withstand the tensile stress component in that direction. This could be accomplished by using a DS copper alloy having higher overall strength. Therefore, Cu-2.68 vol.% Al_2O_3 alloy was selected for further study.

Electrodes were made by cold forging Cu-2.68 vol.% Al_2O_3 into a dome nose wherein all three solutions were implemented together. Figure 7 shows the wear data on these electrodes in comparison with other electrodes tested. This test was carried out only up to 10,000 welds because both the electrode length and face diameter were stabilized and showed very little change between 7500 and 10,000 welds.

After 10,000 welds these electrodes had 1/5 as much wear as the Cu-1.57 vol.% Al_2O_3 truncated cone electrodes and 1/10 as much wear as the Cu-Cr truncated cone electrodes. The excellent stability of the electrode face diameter was reflected in extreme consistency in the tensile shear load values and the nugget diameters as shown in Figs. 8 and 9 respectively.

Test 2. This test was done on thicker steel sheets, one of them galvanized, and hence required larger weld current and force. Having already established the desirability of cold forging in DS copper electrodes, all of these were made by this method.

An initial screening test was set up to study the effects of nose design and Al_2O_3 content on electrode wear and mushrooming. Pointed nose and dome nose female cap electrodes were studied with Cu-1.57 vol.% Al_2O_3 and Cu-2.68 vol.% Al_2O_3 alloys. The test involved making a total of 2500 welds and taking the electrode length and face diameter readings after every 500 welds. Tensile shear load values and weld nugget diameter readings were also taken.

Figure 10 shows the electrode wear as a function of number of welds. It is clear that dome nose electrodes have a much lower wear rate than pointed

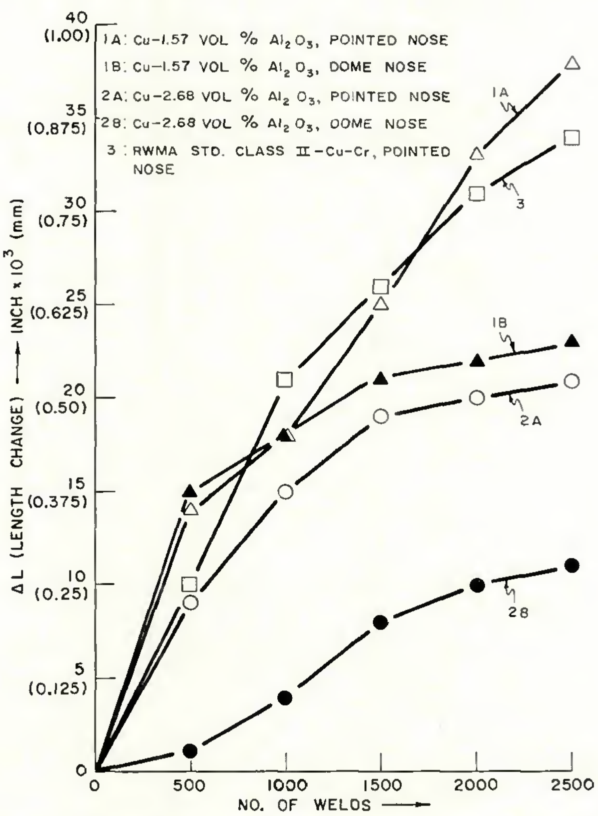


Fig. 10—Upper electrode wear data in Test 2 showing effect of electrode nose

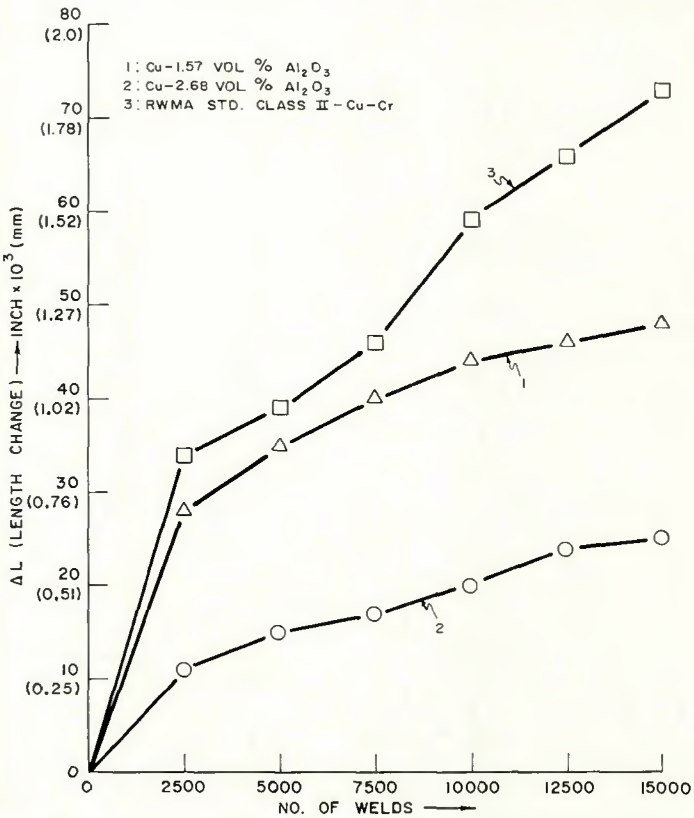


Fig. 11—Upper electrode wear data in Test 2 showing effect of alloy content

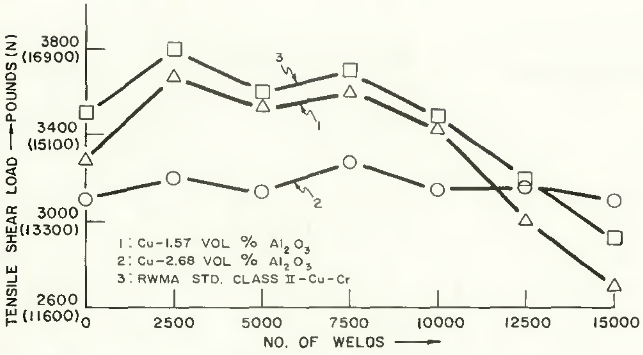


Fig. 12—Tensile shear load data in Test 2

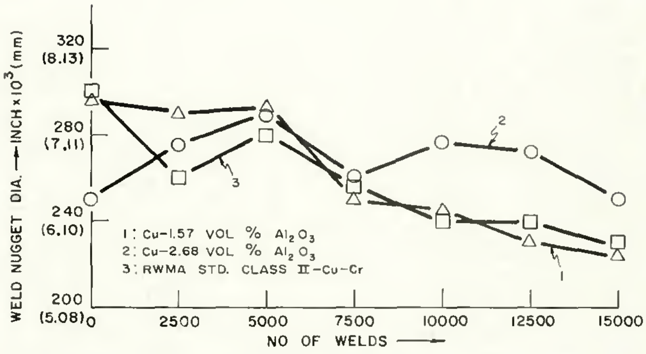


Fig. 13—Weld nugget diameter data in Test 2.

nose electrodes. The Al_2O_3 content exerts an even greater influence on wear in that Cu-2.68 vol.% Al_2O_3 electrodes had significantly less wear than did Cu-1.57 vol.% Al_2O_3 electrodes. Again, a combination of dome design and higher Al_2O_3 content yielded the lowest wear rates.

The electrode face diameter data followed the same trend as the length change data indicating a good correlation between the two. All the electrodes produced acceptable welds having nugget diameters of at least 0.200 in. (5.1 mm) and tensile shear loads of at least 2700 lb (12015 N).

Based on the results of the screening test it was decided to run the following electrodes further beyond 2500 welds:

1. Cu-1.57 vol.% Al_2O_3, dome nose electrodes.
2. Cu-2.68 vol.% Al_2O_3, dome nose electrodes.
3. Standard Cu-Cr, pointed nose electrodes.

These electrodes were tested up to 15,000 welds with all measurements taken at 2500 weld intervals.

Figure 11 shows the wear data as a function of number of welds for the upper electrode which was facing the bare steel. Both DS copper electrodes showed less wear than Cu-Cr electrodes. After 15,000 welds Cu-2.68 vol.% Al_2O_3 electrodes had a wear of 0.025 in. (0.64 mm) while the same wear took place in Cu-Cr electrodes after only 2000 welds, i.e., 1/7 as many welds. After 15,000 welds the Cu-Cr electrodes had about 3 times the wear on the DS copper electrodes.

Electrodes made from Cu-1.57 vol.% Al_2O_3 alloy did not perform as well as Cu-2.68 vol.% Al_2O_3 electrodes but did perform significantly better than Cu-Cr electrodes. Mushrooming characteristics followed the same trend as the wear data.

Figure 12 shows the tensile shear load values as a function of number of welds. Again Cu-2.68 vol.% Al_2O_3 electrodes produced more consistent welds than Cu-Cr as shown by very little fluctuation in the tensile shear loads. This is again attributed to the fact that these electrodes retained their face diameter very well. The weld consistency in case of Cu-1.57 vol.% Al_2O_3 electrodes was not quite as good.

Figure 13 shows the weld nugget diameter data. These data corroborate the tensile shear load data of Fig. 12.

The bottom electrodes in this test were facing galvanized steel. Figure 14 shows the wear data on these electrodes. Cu-2.68 vol.% Al_2O_3 electrodes again had the least wear. After 15,000 welds this electrode had a wear of 0.041 in. (1.04 mm) while the same wear took place in Cu-Cr electrodes after only 5000 welds, i.e., in ⅓ the number of welds.

After 15,000 welds Cu-Cr electrodes had twice as much wear as did the Cu-2.68 vol.% Al_2O_3 electrode. The Cu-1.57 vol.% Al_2O_3 electrode was again superior to Cu-Cr but not quite as good as Cu-2.68 vol.% Al_2O_3 electrode.

The Cu-Cr electrode showed a strong tendency toward sticking to the galvanized steel which both DS copper compositions did not. There was severe pitting on the Cu-Cr electrodes while the DS copper electrodes had substantially less pitting. Thus, the best overall performance was obtained from cold forged Cu-2.68 vol.% Al_2O_3 dome nose electrodes.

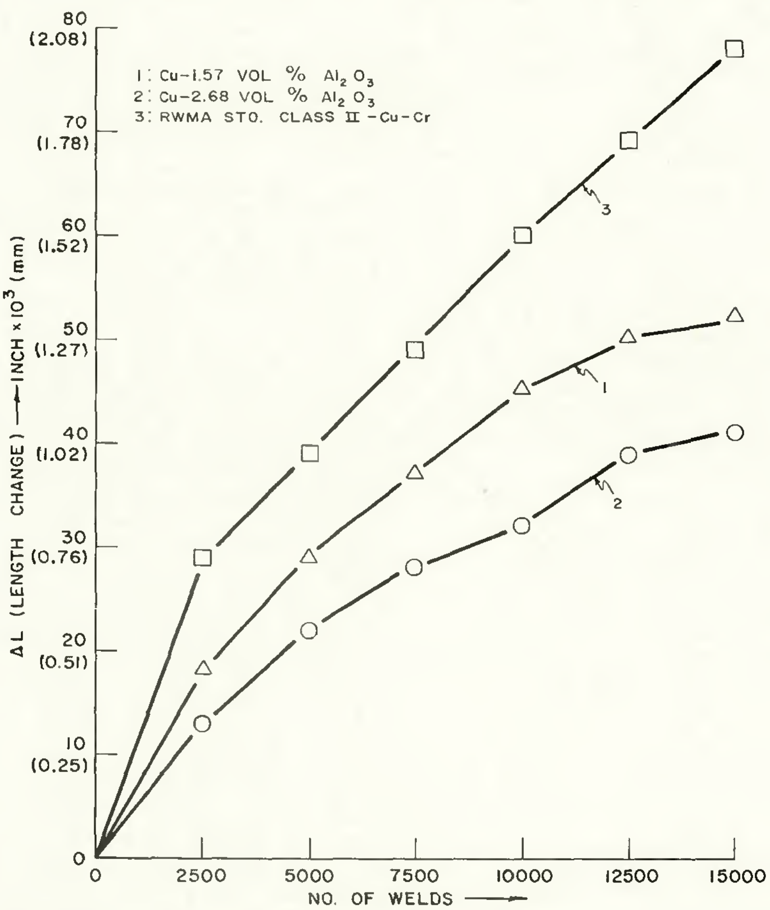


Fig. 14—Lower electrode wear data in Test 2

To study the effect of cold forging and dome design on Cu-Cr electrodes, a pair was fabricated in this manner. These electrodes were tested under Test 2 conditions up to 2500 welds and compared against the standard machined pointed nose electrodes.

Figure 15 shows the wear data on these. Clearly the two electrodes had almost identical wear characteristics. The mushrooming characteristics were also very similar. Therefore, this indicates that Cu-Cr electrodes are relatively insensitive to the method of fabrication and electrode design.

Conclusions

The most significant conclusions of this study were as follows:

1. Interfiber splitting in DS copper electrodes was eliminated by cold forging to obtain equiaxed grain structure; cold forging also minimized the material losses associated with conventional machined electrodes.

2. The higher Al_2O_3 content had a significant beneficial effect on reducing the wear and mushrooming of electrodes.

3. Dome electrodes had substantially less wear than pointed nose electrodes in case of DS copper; 1, 2 and 3 together produced the best electrodes with lowest wear and mushrooming rates. These also produced most consistent welds in terms of weld nugget diameters and tensile shear values.

4. Unlike Cu-Cr electrodes, DS copper electrodes did not stick to galvanized steel sheet during welding; they also showed much less pitting than Cu-Cr electrodes.

5. Cold forging and dome design had no significant effect on the performance of Cu-Cr electrodes.

6. Due to much lower wear and mushrooming the DS copper electrodes made of DS copper; 1, 2 and 3 terms of welds per electrode. More importantly, the frequency of redressing the electrodes is reduced considerably. This results in minimizing undue interruptions (down time) in assembly line production systems, i.e., both welding efficiency and economics are substantially improved.

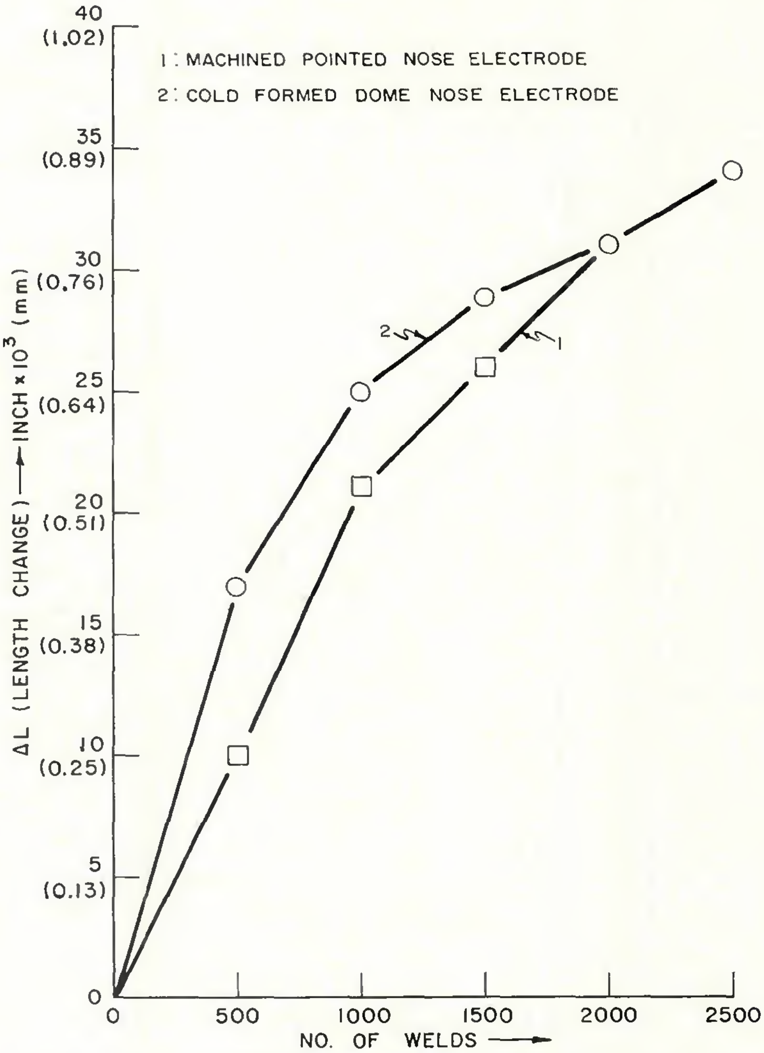


Fig. 15—Wear data on RWMA Std. Class II electrodes, machined pointed nose vs. cold forged dome nose

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