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Coating Weight Effect on the Resistance Spot Weldability of Electrogalvanized Sheet Steels

Current range increases with increasing coating weight, but the relationship between electrode life and coating weight is not clear

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ABSTRACT. The effect of coating weight on the resistance spot weldability of electrogalvanized sheet steel was evaluated using current range tests, lobe tests and electrode life tests to obtain an extensive data base for statistical analysis. Current range and lobe test results indicate that current range increases with total coating weight at the faying interface, regardless of the welding time. This effect appears to be related to the dual ability of the zinc annulus to shunt a portion of the welding current around the developing weld as well as to hinder expulsion by helping to contain the molten steel, which eventually solidifies to form the weld nugget. Variability in current range/lobe test results seems to be primarily due to coating pickup and loss from the electrodes during the test. The relationship between coating weight and electrode life is not clear. Further work with sufficient test duplication to overcome data scatter may yield a clearer picture.

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Introduction

In recent years, designers have called for the incorporation of an increasing amount of coated sheet steel in their products, primarily for corrosion protection. In many industries, one of the steels of choice is electrogalvanized. Since resistance spot welding is a common process used to join sheet, the spot weldability of electrogalvanized steels is of significant interest. Furthermore, since electrogalvanized sheet is available in a wide range of coating weights, typically 10 to 100 g/m^2, it is important to understand the relationship, if any, which exists between weldability and coating weight.

KEY WORDS

Resistance Spot Weld
RSW Weldability
Electrogalvanized
Sheet Steels
Coating Weight
Weight Effect
Current Range Tests
Weld Lobe Test
Electrode Life
RSW Electrode Caps

During the formation of a resistance spot weld between two zinc-coated sheets, the zinc at the faying interface melts and is radially displaced from the weld zone to form a zinc annulus which encircles the weld. This annulus shunts some of the current around the weld zone, leaving less current available for nugget formation. As a result, more current is required to generate a weld in coated sheet. Melting of the zinc coating also occurs at the electrode/sheet interfaces during the welding process. Some of this molten zinc interacts with the copper of the electrode faces and forms a thin layer of brass on the tips (brassing), while additional zinc is oxidized and deposited on the electrode faces. The net effect is to change both the electrical characteristics and the facial topography of the electrodes and, in turn, the resulting weld. As successive welds are made at a constant welding current, the electrode faces become pitted and slowly erode, increasing the face diameter which ultimately reduces the current density to the point where no nugget is formed. These effects are well summarized by Dickinson (Ref. 1). Observations of electrode conditioning and subse-

Table 1—Sheet Thickness and Substrate Composition

Coil	Sheet Thickness, in. (mm)	Substrate Composition (wt-%) C	Mn	P	S	Si	Al	Cr
X	0.032 (0.81)	0.035	0.23	0.010	0.012	<0.010	0.040	0.040
Y	0.031 (0.79)	0.036	0.30	0.012	0.014	0.012	0.045	0.043
Z	0.029 (0.74)	0.030	0.31	0.012	0.018	0.010	0.038	0.034

Table 2—Coating Characteristics and Composition

Code	Coating Weight (g/m²)	Mean Static Surface Resistance (μΩ)	Coating Composition (wt-%) Zn	Fe	Al	Pb
X 8/8	8.4/8.1	26.7+/−3.7	99	–	0.01	<0.01
X 30/30	35.2/35.5	10.3+/−3.1	98.5	1.4	0.01	<0.01
X 60/60	67.1/67.4	10.0+/−2.1	98.6	1.2	0.01	<0.01
X 90/90	100.1/104.9	7.7+/−2.5	99	0.9	0.01	<0.01
X 105/105	100.6/115.5	7.0+/−2.0	99	0.4	<0.01	<0.01
Y 30/30	42.2/42.9	8.5+/−2.8	99.1	0.8	0.01	<0.01
Y 70/70	85.3/83.5	7.7+/−2.1	99.5	0.4	<0.01	<0.01
Y 100/100	103.9/111.2	6.2+/−2.4	99.3	0.5	<0.01	<0.01
Z 100/10	107.4/16.1	–	–	–	–	–

quent electrode life testing would seem to indicate that the "brassing" and coating pick-up mechanisms are responsible for variations in welding behavior early in the life of the electrodes, while the actions of pitting and erosion ultimately result in tip failure.

The objective of this study was to examine the influence of coating weight on the resistance spot weldability of electrogalvanized sheet as quantified by the current range, lobe and electrode life tests. Because the task of gaining a clear understanding of the spot weldability of zinc-coated sheet steel is complicated by the high variability of test results, multiple testing was conducted to permit statistical analysis of the data.

Material and Experimental Procedure

Material

Electrogalvanized sheet steels made from three DQSK substrates, referred to as Coils X, Y and Z, were the subject of the study. Substrate thickness and composition are given in Table 1. As can be seen in the table, all sheet substrates have similar chemistries and thicknesses (0.029 to 0.032 in./0.74 to 0.81 mm), allowing welding parameters and the associated weldability-related data to be directly compared. Table 2 lists property values related to the coatings including measured coating weight, mean static surface resistance, and coating composition. Coating weights were obtained using a fluorescent x-ray coating thickness gauge. Static surface resistance was measured using a low resistance ohmmeter equipped with 0.5-in. (12.7-mm) diameter cylindrical contacts made from RWMA Group A, Class 1 copper and having 3-in. (76.2-mm) radiused faces. Resistance values were read after application of 500 lbf (2220 N) of contact force for ten seconds. Prior to taking measurements, excess oil was removed from the coupons by wiping with a clean paper towel. Coating composition was determined through wet analysis. Inspection of Table 2 reveals that Coils X and Y are coated equally on both sides with nominal coating weights in the range of 8 to 105 g/m². Coil Z is a differentially coated sheet with a nominal coating weight of 100 g/m² on one side and 10 g/m² on the other.

Weldability Testing

All welding was done on a 100-kVA spot welding machine fitted with a solid-state controller. A toroid and current/time analyzer was used to measure the welding current. Table 3 summarizes the welding parameters used for all testing. As indicated in the table, two types of electrodes were employed for the current range and lobe testing. These included "A-nose" (pointed) and 30-deg, truncated-cone, female caps. Although both are made of RWMA Group A, Class 2 copper, the A-nose caps are a zirconium-copper alloy, while the truncated-cone electrodes are composed of chromium-copper plated with cobalt. The cobalt serves as a barrier to the molten zinc during welding, preventing alloying and pitting interactions between the zinc and the electrode material. Electrode life testing was performed with the same A-nose caps referred to above, as well as with 45-deg, truncated-cone, chromium-copper, male caps.

Table 3—Welding Parameters for All Tests

Electrode material	Class II, Zr-Cu	Current range, electrode life and lobe tests
Electrode geometry	A-nose female caps	
Electrode face diameter	0.25 in. (6.35 mm)	
Electrode material	Class II, Cr-Cu	Current range and lobe tests only
Tip plating	Cobalt	
Electrode geometry	30-deg TC female caps	
Electrode face diameter	0.25 in. (6.35 mm)	
Electrode material	Class II, Cr-Cu	Electrode life tests only
Electrode geometry	45-deg TC male caps	
Electrode face diameter	0.25 in. (6.35 mm)	
Electrode adaptors	Open shank	
Min button diameter	0.16 in. (4.06 mm)	
Nom button diameter	0.20 in. (5.08 mm)	
Current range and electrode life, welding time	13 cy (0.22 s)	
Lobe welding times	11 cy (0.18 s), 13 cy (0.22 s), 16 cy (0.27 s), 19 cy (0.32 s)	
Hold time	60 cy (1.0 s)	
Force	500 lbf (2220 N)	
Welding rate	20 welds/min	
Water flow	1.5 gal (5.7 l)/min/electrode	

Current Range Determination

Current range was determined at a nominal weld time of 13 cycles (0.22 s) based on the General Motors Corporation's MDS-247 specification (Ref. 2) for lobe generation. However, in this instance, the tests were performed only at the nominal weld time in order to minimize the effect of electrode face alteration, which is often experienced during the generation of a full lobe. The electrodes were conditioned for 100 welds at a current near the expulsion limit, minimizing expulsion by lowering the welding current as soon as expulsion was encountered during the conditioning process. The minimum welding current (Imin) was then established as that current at which at least three peel tests resulted in the smallest achievable button size above the specified minimum. The maximum current level (Imax) was determined by gradually increasing the welding current until expulsion occurred on both welds of the peel test sample. Finally, the current range was calculated by subtracting Imin from Imax. The above procedure was repeated four times, both with new A-nose caps and with new cobalt-plated caps to determine reproducibility. Because the cobalt prevents the interaction of the sheet coating with the copper electrode face, comparison of the results obtained using the cobalt-plated tips with those acquired using the A-nose caps showed how much of the current range variability typical for current range tests could be attributed to alloying of the zinc with the copper electrode face of the unplated electrodes.

Weld Lobe Determination

The lobe test procedure followed GM's MDS-247 specification (Ref. 2) for lobe generation. Electrode conditioning was as described above for current range testing. Imin was established first for all weld times, then Inom and Imax. This test was performed twice for both the A-nose caps and the cobalt-plated, truncated-cone caps.

Electrode Life Determination

The electrode life procedure followed the guidelines of Ford's BA13-1 specification (Ref. 3). Welding was interrupted every 200 welds to take a tip print and to determine button diameter using a peel test. As the button diameter decreased during the test, the 0.22-in. (5.6-mm) failure point was noted. All tests were terminated when the button diameter fell below 0.16 in. (4.1 mm). Duplicate tests were conducted for each material. To investigate the effect of electrode type and geometry on electrode life, two tests with A-nose, female, Zr-Cu caps (used for all other testing) and two tests with 45-deg, truncated-cone, Cr-Cu male caps were conducted for each material.

Results and Discussion

Coating Composition and Characteristics

As previously indicated, the coatings on the various sheet steels are characterized in Table 2. The composition values show that, except for a small amount of iron, all electrogalvanized coatings are pure zinc. Examination of the table also reveals that the mean static surface resistance decreases slightly with increasing coating weight. The resistance typical of the 8/8 sheet, 26.7 $\mu\Omega$, is approximately four times higher than the 7.0-$\mu\Omega$ value associated with the 105/105 material. Both coils show the same trend, but Coil Y exhibits slightly lower resistance than Coil X for comparable coating weights. This relationship between coating weight and surface resistance may be related to the contact area between the radiused faces of the ohmmeter contacts and the coating. As the coating weight increases so does the coating thickness, allowing the radiused contacts to penetrate the coating to an increasing degree.

Current Range and Lobe Tests

The results for the current range tests and the lobe tests are given in Tables 4 and 5, respectively. The current range testing, done using a nominal weld time of 13 cycles (0.22 s), employed both A-nose and cobalt-plated, truncated-cone caps. Lobe testing was performed for welding times of 11, 13, 16 and 19 cycles, using the same types of elec-

Table 4—Current Range Test Results

		Imax		Imin		Irange	
Code	Electrode Type(a)	Mean (kA)	Std Dev (kA)(b)	Mean (kA)	Std Dev (kA)(b)	Mean (kA)	Std Dev (kA)(b)
X 8/8	1	11.73	+/−0.50	10.32	+/−0.48	1.41	+/−0.28
X 8/8	2	11.96	+/−0.67	10.76	+/−0.41	1.20	+/−0.32
X 30/30	1	12.88	+/−0.26	11.44	+/−0.48	1.44	+/−0.33
X 30/30	2	14.02	+/−0.12	12.56	+/−0.01	1.46	+/−0.12
X 60/60	1	13.50	+/−0.23	11.72	+/−0.15	1.78	+/−0.30
X 60/60	2	14.43	+/−0.21	12.64	+/−0.21	1.79	+/−0.37
X 90/90	1	13.93	+/−0.47	12.06	+/−0.32	1.87	+/−0.23
X 90/90	2	15.43	+/−0.20	13.67	+/−0.10	1.76	+/−0.12
X 105/105	1	14.31	+/−0.12	12.45	+/−0.21	1.86	+/−0.14
X 105/105	2	15.13	+/−0.43	13.24	+/−0.15	1.89	+/−0.36
Y 30/30	1	14.00	+/−0.18	12.63	+/−0.07	1.36	+/−0.12
Y 30/30	2	13.84	+/−0.32	12.56	+/−0.08	1.28	+/−0.36
Y 70/70	1	14.46	+/−0.28	12.70	+/−0.12	1.76	+/−0.33
Y 70/70	2	14.95	+/−0.04	13.31	+/−0.14	1.64	+/−0.16
Y 100/100	1	15.05	+/−0.53	12.92	+/−0.26	2.13	+/−0.27
Y 100/100	2	14.90	+/−0.00	12.67	+/−0.37	2.06	+/−0.11

All results are the means of 4 tests.
(a) 1 = A-nose female caps; 2 = cobalt-plated TC female caps.
(b) One standard deviation.

Table 5—Lobe Test Results

		Irange (kA) for All Welding Times			
Code	Electrode Type(a)	11 cy (0.18 s)	13 cy (0.22 s)	16 cy (0.27 s)	19 cy (0.32 s)
X 8/8	1	0.92	0.85	1.15	1.08
X 8/8	2	1.50	1.17	0.93	0.82
X 30/30	1	0.98	0.98	0.95	1.23
X 30/30	2	1.65	1.72	1.94	1.47
X 60/60	1	1.58	1.70	1.91	1.68
X 60/60	2	1.24	1.16	1.11	1.34
X 90/90	1	1.89	1.90	1.93	1.76
X 90/90	2	2.09	1.69	1.65	1.20
X 105/105	1	1.81	1.70	1.64	1.91
X 105/105	2	1.44	1.79	1.70	1.79
Y 30/30	1	1.40	1.65	1.75	1.40
Y 30/30	2	0.76	0.80	0.94	1.37
Y 70/70	1	1.30	1.50	1.20	1.20
Y 70/70	2	1.58	1.22	1.26	1.58
Y 100/100	1	2.10	1.95	1.80	1.65
Y 100/100(b)	2	1.66	2.36	1.93	1.64
Z 100/10(c)	1	1.23	0.75	0.78	1.28
Z 100/10(d)	1	1.78	1.58	1.47	1.14
Z 100/10(e)	1	2.14	2.12	1.73	1.39

All results are the means of 2-lobe series, except where noted.
(a) 1 = A-nose female caps; 2 = cobalt-plated TC female caps.
(b) One lobe only.
(c) 10 to 10 faying orientation.
(d) 100 to 10 faying orientation.
(e) 100 to 100 faying orientation.

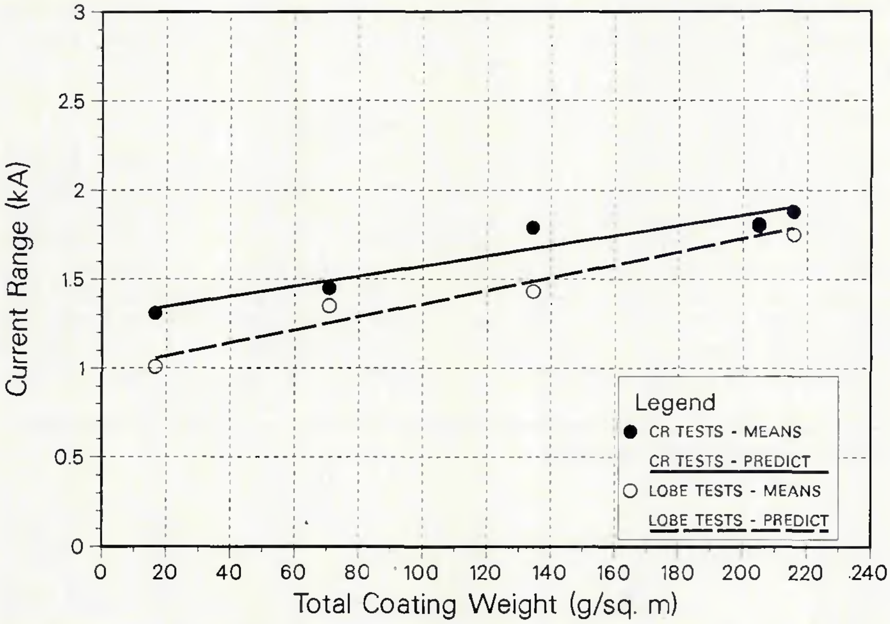

Fig. 1—Coating weight effect on current ranges for Coil X: individual current range and 13-cycle lobe tests

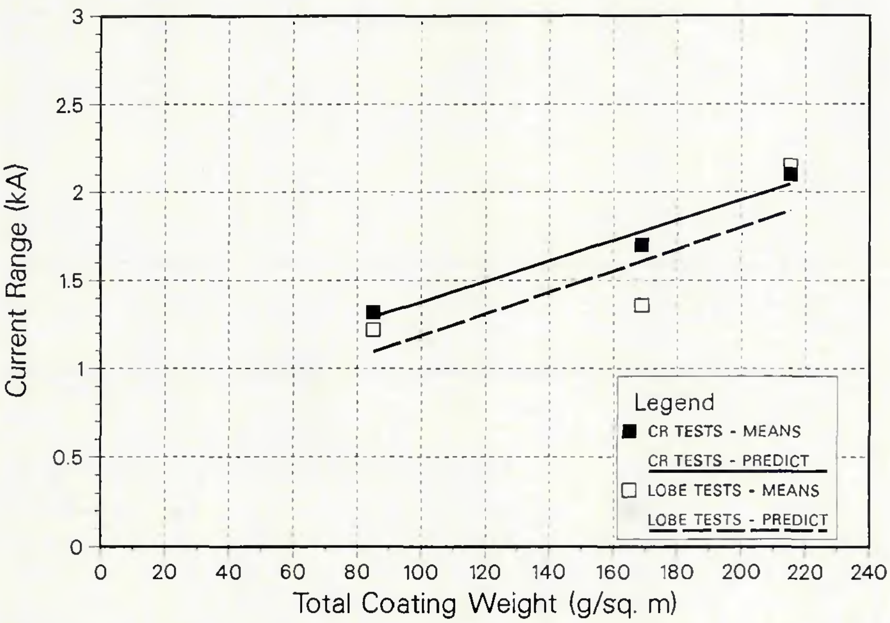

Fig. 2—Coating weight effect on current ranges for Coil Y: individual current range and 13-cycle lobe tests

Table 6—Linear Regression Results for Current Range and Lobe Test Data

Coil	Test Type	R-Squared[a] All Data	R-Squared[a] Means	Equation of Estimate[b]
X	CR	0.33	0.92	CR = 1.29 + 0.003(TCW)
X	Lobe	0.46	0.96	CR = 1.00 + 0.004(TCW)
X	CR + Lobe	0.35	0.96	CR = 1.19 + 0.003(TCW)
Y	CR	0.64	0.97	CR = 0.80 + 0.006(TCW)
Y	Lobe	0.47	0.73	CR = 0.57 + 0.006(TCW)
Y	CR + Lobe	0.55	0.92	CR = 0.72 + 0.006(TCW)
X + Y	CR + Lobe	0.39	0.84	CR = 1.11 + 0.004(TCW)
Z	Lobe	0.73	0.99	CR = 0.56 + 0.008(TCW)

(a) R-squared measures how much variation in the current range data can be accounted for by the fit. The closer R-squared, which can range from 0 to 1, is to 1, the better the curve's fit.
(b) CR = Current range (kA); TCW = total coating weight at faying interface (g/m^2).

trodes as for current range tests. A statistical comparison of current ranges for the two electrode types reveals no consistent difference in the means or the standard deviations as a function of coating weight or substrate. In light of this fact, the current range data for the two electrodes were combined into one population in order to increase the size of the data base for statistical analysis.

Figures 1 and 2 plot current range as a function of total coating weight at the faying interface for Coils X and Y, respectively. As previously indicated, the means represent the combined A-nose and truncated-cone test results. The 13-cycle lobe test means are also included since they are obtained using the same welding time and types of electrodes. The curves shown are derived by linear regression (see Table 6 for curve fit results) and clearly indicate that current range, however determined, is proportional to total coating weight. Furthermore, current ranges determined using the lobe test fall consistently below values obtained using the nominal weld time current range procedure. This difference is believed to be related to the lobe test practice of using one set of electrodes to simultaneously establish the current range at four different weld times. Because of the greater number of welds performed in the lobe test relative to the current range test and because Imax is determined for the maximum and intermediate weld times before the nominal weld time (13 cycles) (0.22 s), significant alterations to the electrode faces' topographical and electrical characteristics frequently occur, resulting in reduced Imax current levels and narrower current ranges.

To compare the current range characteristics of Coils X and Y, the current range test and 13-cycle lobe test data for each coil were combined into a single population and analyzed using linear regression. The resulting fits are described in Table 6 and depicted in Fig. 3. To avoid the confusion resulting from intermingling of numerous data points, only the means for each coating weight are shown. From Fig. 3, it is clear that the two coils exhibit similar current range behavior although the associated curves have dissimilar slopes. Considering the coefficients of variation derived for each fit, the slope difference is probably not significant.

Figure 4 represents an effort to predict current range behavior for an "average" electrogalvanized sheet steel by combining all data, *i.e.*, X and Y data, both from current range tests and lobe tests, into one large data base. The expected trend of increasing current range with total coating weight is obtained and the associated linear regression results can, again, be found in Table 6. Figure 4 also emphasizes the magnitude of scatter, shown by the individual data points, inherent with current range tests on zinc-coated sheets.

Figure 5, which shows the current range behavior of the differentially coated Coil Z, confirms that the total coating weight at the faying interface is the governing factor in determining current range. The three coating weights for which data are shown reflect the three faying surface conditions in which the Coil Z material was welded, *i.e.*, with the 10-wt surfaces touching, with the 10-wt surface in contact with the 100-wt surface, and with the 100-wt surfaces at the faying interface.

Using the combined data for the X and Y coils, Fig. 6 shows that the positive correlation between current range and total coating weight is independent of weld time. Data for weld times of 11, 13, 16 and 19 cycles are shown. The curves fall close to each other and have similar slopes. Based on this data, no clear dependence of current range on weld time is apparent.

A mechanism which may explain the dependence of current range on coating weight concerns the interaction between the zinc displaced from the weld zone, the welding current, and the molten steel involved in the formation of the nugget. As previously described, during the initial portion of the welding cycle, the application of heat and pressure melts the coating at the faying interface and radially displaces it from the weld zone. Forming an annulus or "halo" around the weld, the molten coating shunts current around the fusion zone (Refs. 1–4), lowering the current density and thus increasing the magnitude of current required to induce expulsion. The more coating available, the larger the halo and the greater the shunting effect. Lane, *et al.* (Ref. 5), have indicated that the halo may also serve as a seal or barrier which helps to contain the molten steel in the fusion zone, inhibiting expulsion. Both of these effects result in elevation of Imax at a greater rate than in Imin which, in turn, broadens the current range. Figure 7, which plots Imax and Imin as a function of measured coating weight, illustrates this effect.

The formation of a coating annulus was confirmed by examination of peel test welds. Figures 8A, 8B and 8C show cross-sections of welds made near Imax using the 30/30, 70/70 and 100/100 Coil Y material, respectively. Specifically, the periphery of each weld is depicted. The accumulation of coating in this area is clearly visible and appears to increase with coating weight. To substantiate these conclusions further, several welds with a nominal button diameter (approx. 0.20 in.) were made on peel test specimens. Figures 9A, 9B and 9C show typical areas of halo formation for 30/30, 70/70 and 100/100 Coil Y materials, respectively, as observed with the SEM. In comparing the halo formed on the 30/30 material with that observed on the 70/70 sheet, it is apparent that the 70/70 halo has a greater volume of coating than its 30/30 counterpart. A similar observation can be made when comparing the annulus of 70/70 material with that of 100/100 material, although in this comparison the difference is less obvious except that the annulus of 100/100 material has a wider and more uniform band of displaced coating (the irregular area outside of the smoother annulus band).

Based on coating weight measurements of the zinc annulus as a function of overall coating weight, both obtained using the fluorescent x-ray coating thickness gauge, Table 7 confirms quantitatively that the amount of zinc in the annulus increases with increasing sheet coating weight. This trend appears to hold, in general, for both Coils X and Y. In comparing the coating weight of the annular zinc versus the original coating weight, the data indicate that a greater percentage of zinc is lost by expulsion, displacement, etc., at the heavier coating weights. Also, considerable scatter in results, as indicated by the standard devi-

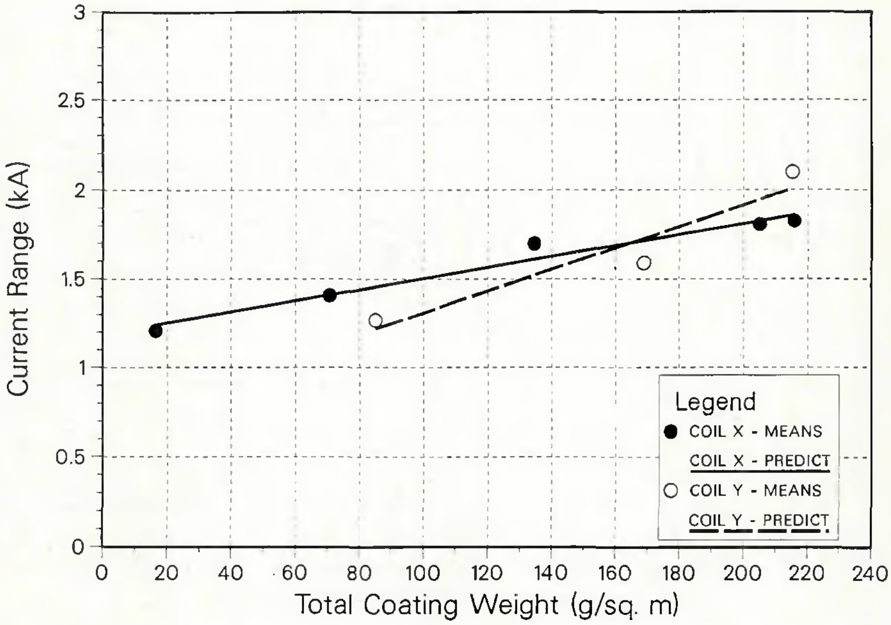

Fig. 3 — Coating weight effect on current ranges for Coils X and Y: current range and 13-cycle lobe test results combined

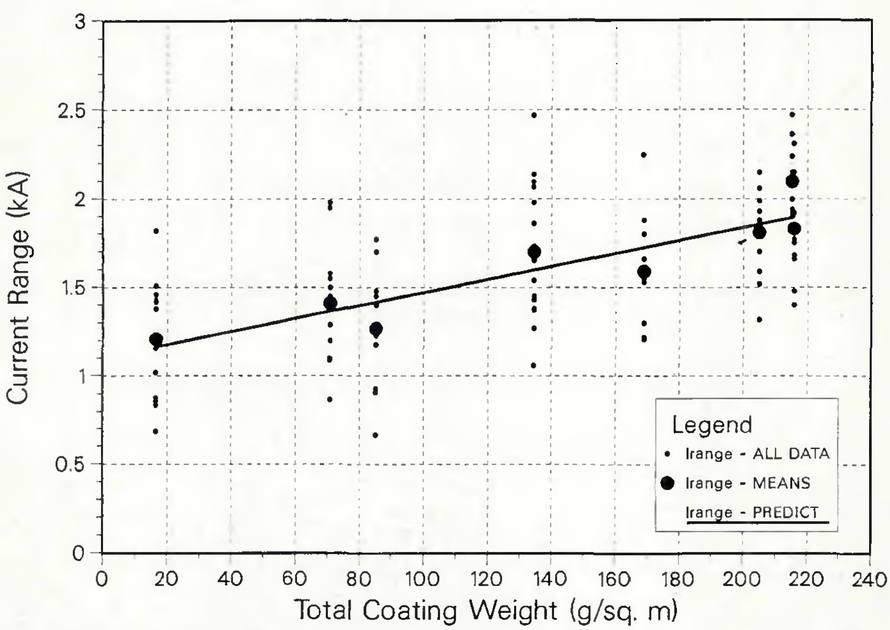

Fig. 4 — Coating weight effect on current range for individual current range and 13-cycle lobe tests of Coils X and Y combined

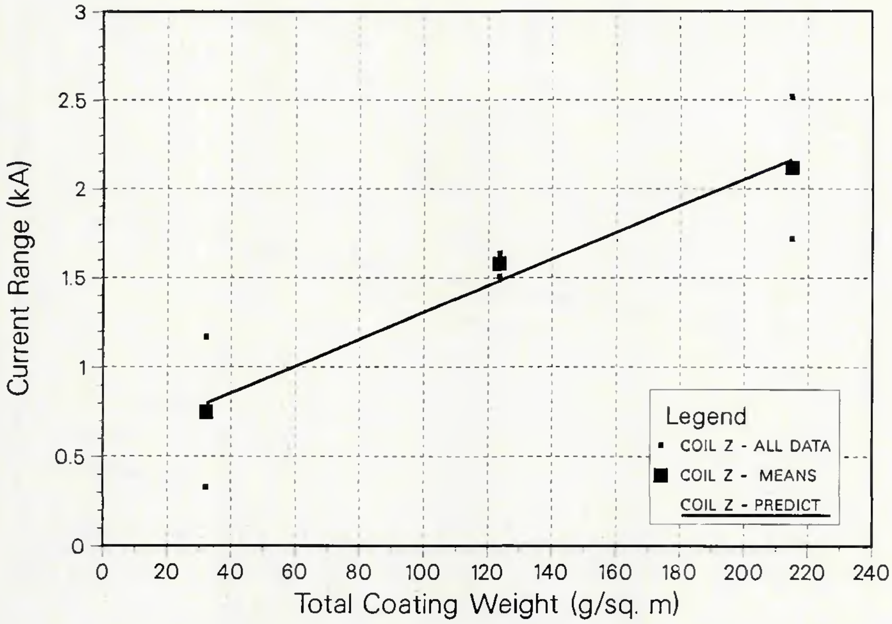

Fig. 5 — Coating weight effect on current range for differentially coated sheet using 13-cycle lobe test results

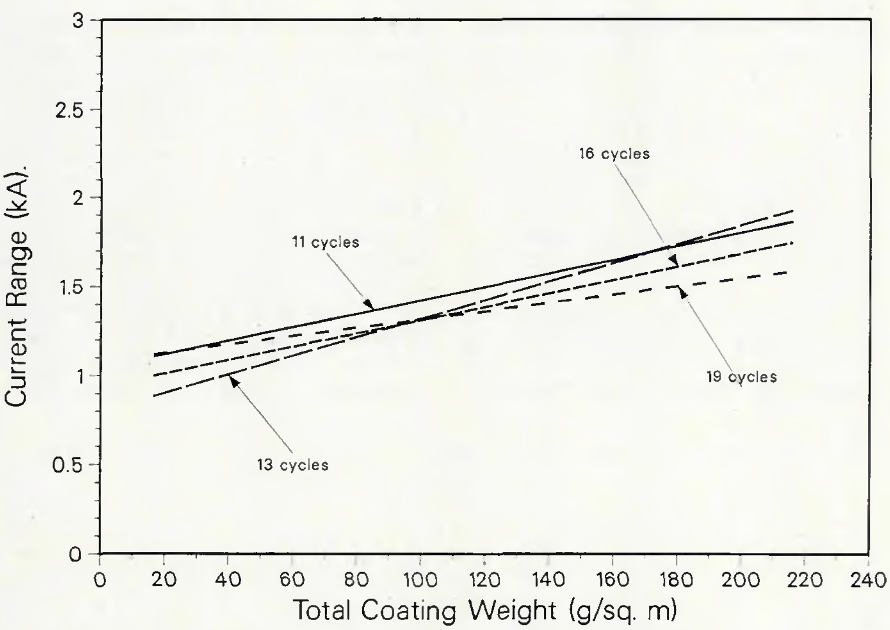

Fig. 6 — Coating weight effect on weld-time lobe current ranges for all coils

Table 7—Base Metal and Weld Annulus Coating Weight

Code	BM Coating Weight: One Side Mean (g/m²)	BM Coating Weight: Std Dev	Annulus Coating Weight[(a)]: One Side Mean (g/m²)	Annulus Coating Weight[(a)]: Std. Dev.
X 8/8	8.2	+/−0.5	11.5	+/−6.9
X 30/30	35.4	+/−1.5	32.7	+/−8.5
X 60/60	67.2	+/−2.4	53.2	+/−16.7
X 90/90	102.5	+/−4.8	58.0	+/−31.2
X 105/105	107.9	+/−5.2	72.3	+/−27.1
Y 30/30	42.5	+/−5.5	33.4	+/−14.0
Y 70/70	84.4	+/−6.5	61.2	+/−8.8
Y 100/100	107.6	+/−8.5	62.0	+/−23.0

(a) Mean of five readings.

ations, is apparent. Such scatter is not unrealistic considering the coating does not displace uniformly around the weld perimeter, nor does it separate equally during peel testing, with equal amounts adhering to each coupon surface.

Reproducibility of Current Range and Lobe Test Results

Current range and lobe test results are typified by a high degree of scatter, a fact well illustrated by the standard deviations found in Table 4 and by the individual data point plots in Fig. 4. This variation is believed to result primarily from the interaction between the electrode faces and the coating, an interaction which is constantly changing the topography and electrical characteristics of the electrode face. During welding, coating is continually being picked up by or removed from the tip faces, the degree depending upon the welding conditions and the characteristics of the coating. The zinc also alloys with the electrode material and/or pits the tip face. Coating pickup/loss, alloying and pitting are all competing processes that operate in an inconsistent manner, the net result being that the pattern of electrode wear seldom repeats itself from test to test.

It was to gain a better understanding of the relationship between the electrode/coating interaction and data scatter that the use of cobalt-plated caps was instituted for some of the current range and lobe tests. The presence of cobalt on the tip face prevents zinc/copper alloying as well as pitting of the copper substrate. As previously noted, the current range test results in Table 4 showed no consistent difference in the data scatter, as quantified by the standard deviations, between the unplated, A-nose Class 2 caps and the cobalt-plated truncated-cone caps. This suggests that, at least over the limited number of welds typical of the current range test, copper/zinc alloying (brassing) and pitting are not responsible for data scatter. With these factors eliminated, it would appear that coating pickup and loss are major contributors to current range test variability. Further investigations of electrode/coating interactions are necessary to gain a clearer understanding of this process and how it affects the variability of test results.

Whatever the mechanisms at work, the great amount of scatter inherent in the current range determination process is significant from the material evaluation standpoint. It is unrealistic to characterize the spot weldability of an electrogalvanized product or any coated sheet steel based on the results of a single current range or lobe test. It is apparent that multiple tests must be performed if one is to obtain an accurate picture of the current range characteristics of electrogalvanized sheet steel.

Coating Weight Effect on Electrode Life

The results for all electrode life tests are listed in Table 8. Linear regression analysis was used to determine the existence of a coating weight to electrode life correlation for Coils X and Y and for each electrode type used. The constants and R-squared values obtained from the analysis are summarized in Table 9.

Figure 10 is a graph of total coating weight at the faying interface versus electrode life for the Coil X material welded using A-nose caps. Two curves, both obtained by linear regression, are shown, one for tip life using 0.22 in. (5.6 mm) as the minimum acceptable button diameter and the other for end of life indicated by a 0.16-in. (4.1-mm) diameter button. Both lines have a negative slope consistent with a decrease in electrode life with increasing coating weight. However, inspection of Table 9 reveals that the associated R-squared values, 0.36 and 0.12, are low, indicating that a straight line does not well describe the data. It should also be noted that the negative slope of the lines is strongly influenced by the long tip life results of the 8/8 coated sheet. Furthermore, if the 8/8 data are not considered, using the argument that 8/8 material falls in a transitional region between bare sheet and heavier coated materials, the resulting curves would have slopes approaching zero.

In contrast, the data obtained for Coil X using truncated-cone caps, as shown in Fig. 11, indicate that electrode life increases with coating weight. Unlike that observed for the A-nose test results, the trend is clear with R-squared values of 0.72 and 0.52, signifying that the data points define a more linear relationship between coating weight and tip life. The fact that the 8/8 test results follow the trend observed for the heavier coating weight sheets either indicates a difference in spot welding behavior for truncated-cone electrodes or suggests that the 8/8 data for the A-nose caps are spurious.

Figures 12 and 13 present electrode life test results for Coil Y sheet welded using A-nose and truncated-cone caps, respectively. As in Fig. 11, the Coil Y data indicate that increasing coating weight is associated with longer electrode life. However, owing to data scatter, the

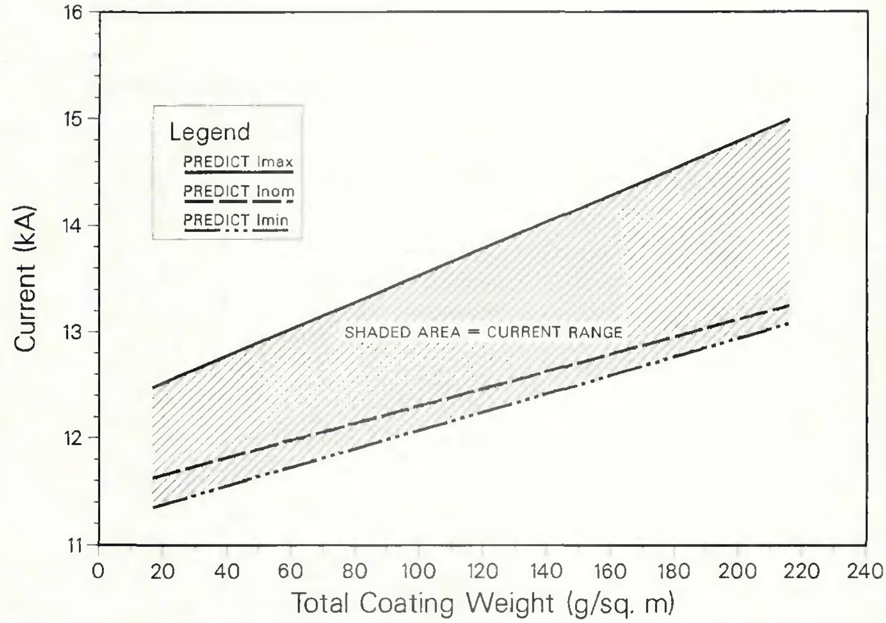

Fig. 7 — Coating weight effect on current levels for combined individual current range and 13-cycle lobe test results of all coils

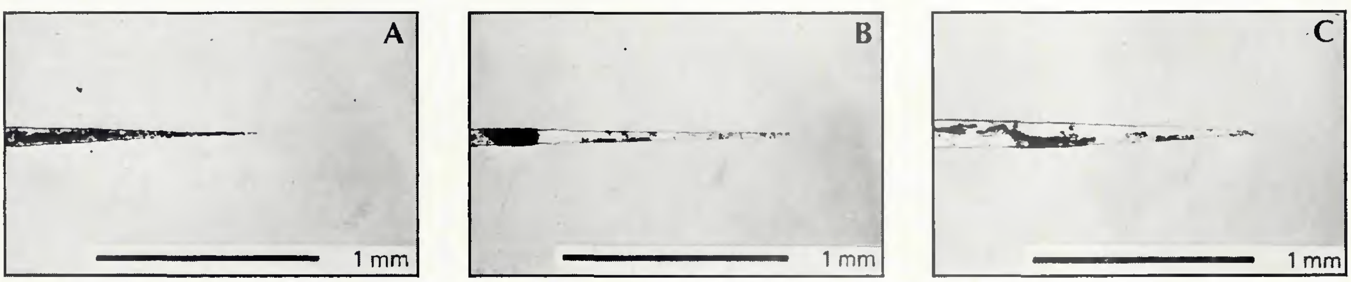

Fig. 8 — Cross-sections of Coil Y welds showing the zinc annulus for: A — 30/30; B — 70/70; and C — 100/100. 50X

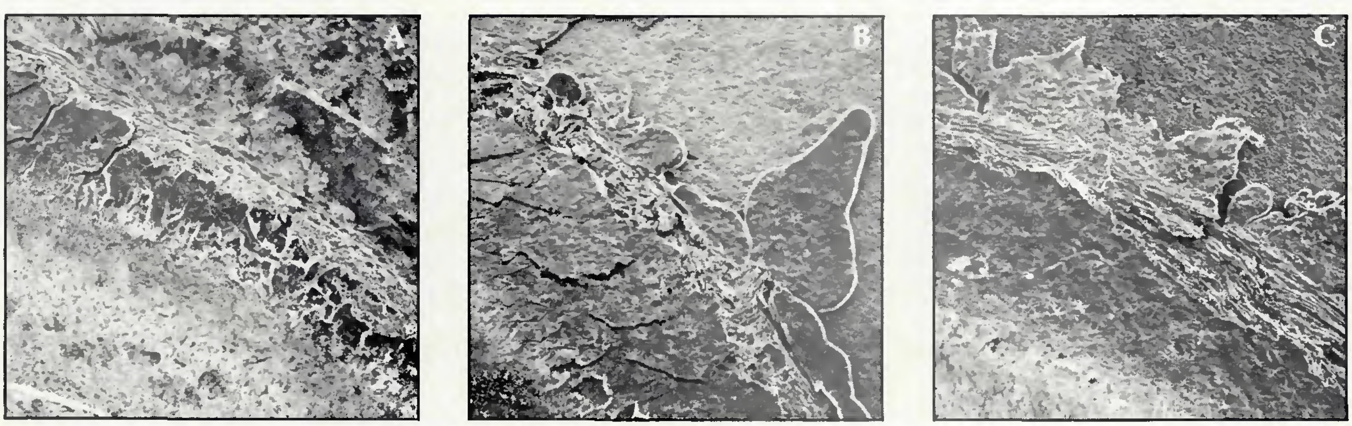

Fig. 9 — Zinc annulus of Coil Y welds at Inom for: A — 30/30; B — 70/70; C — 100/100. 50X, SEM

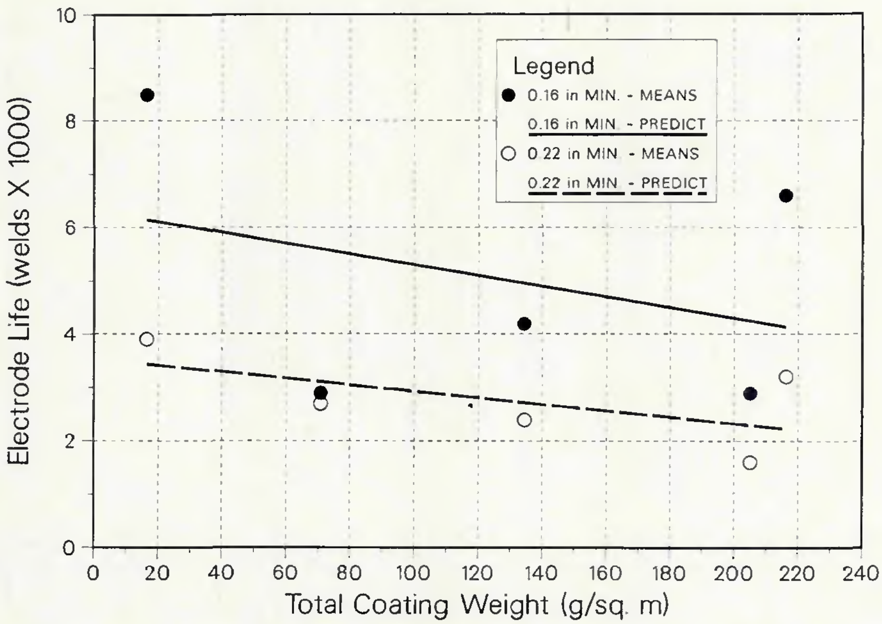

Fig. 10 — Coating weight effect on electrode life for Coil X using A-nose electrodes

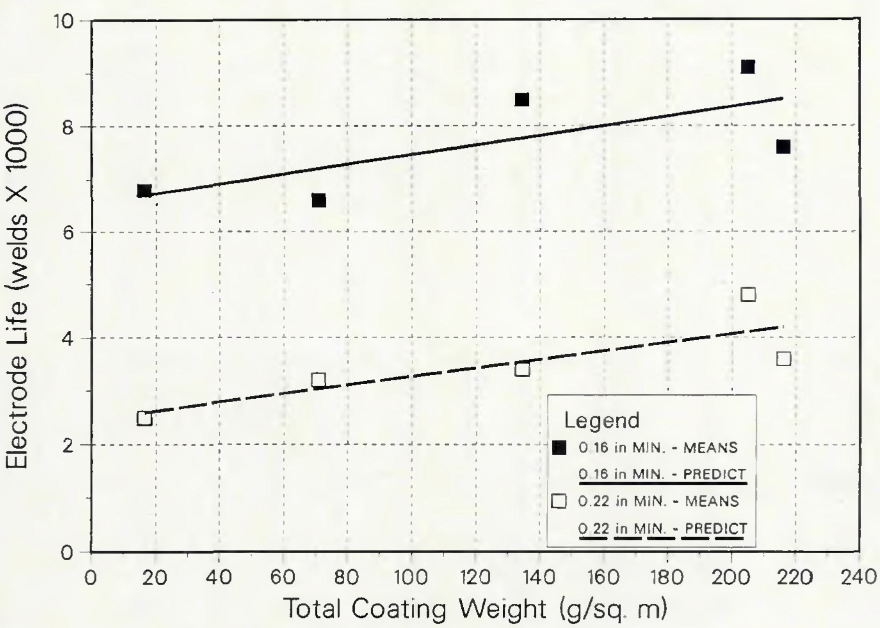

Fig. 11 — Coating weight effect on electrode life for Coil X using truncated-cone electrodes

R-squared values, which quantify the linear correlation between the two parameters, vary significantly. For the A-nose data, R-squared ranges from a low of 0.19 for the 0.22-in. (5.6-mm) minimum button diameter data to 0.99 for the 0.16-in. (4.1-mm) minimum diameter data. A similar spread is observed for the truncated-cone test results.

Thus, test results for three out of the four coil and electrode cap combinations indicate improved electrode life with increasing coating weight. This finding agrees with observations made by Natale (Ref. 6) as well as Kimchi and Gould (Ref. 7). Mathieu and Patou (Ref. 8) have found that, when similar welding currents are employed, more heating of the tip face occurs as the amount of zinc present at the electrode/sheet interface decreases. The higher tip temperatures appear to be more detrimental to the electrode face than the increased alloying and pitting associated with thicker coatings. Alternatively, the poorer electrode life observed for material with lower coating weights may be a consequence of the lower welding currents employed at the lighter coating weights. The lower current levels limit the current range and subsequently, can result in reduced tip life.

The results of the electrode life tests for the differentially coated sheet, Coil Z, appear to conflict with the above, indicating that coating weight has no effect on electrode life. Two coupon orientations were tested for the Coil Z material, *i.e.*, with the 10 g/m^2 sides at the faying interface (100 g/m^2 sides at the electrode/sheet interfaces) and alternatively, with the 100 g/m^2 sides at the faying interface (10 g/m^2 sides at the electrode/sheet interfaces). The corresponding tip lives for these tests, given in Table 8, are 2400 and 2200 welds, respectively, an insignificant difference when considering the factor of a ten difference in total coating weight at the faying interface.

Considering the above conflicting test results, the most that can be said is that the relationship between coating weight

Table 8—Electrode Life Test Results

	A-Nose Female Caps			Truncated-Cone Male Caps		
		Electrode Life (no. of welds)			Electrode Life (no. of welds)	
Code	Current (kA)	0.22 in. (5.6 mm) min	0.16 in. (4.1 mm) min	Current (kA)	0.22 in. (5.6 mm) min	0.16 in. (4.1 mm) min
X 8/8	10.4	3900	8500	10.5	2500	6800
X 30/30	12.6	2700	2900	12.8	3200	6600
X 60/60	13.9	2400	4200	13.4	3400	8500
X 90/90	14.4	1600	2900	14.0	4600	9100
X 105/105	14.7	3200	6600	14.1	3600	7600
Y 30/30	13.3	1500	1900	13.3	1900	3100
Y 70/70	14.8	2900	3000	14.3	3000	5600
Y 100/100	14.8	1900	3700	14.5	3200	4700
Z 100/10[(a)]	14.2	2400	2400	—	—	—
Z 100/10[(b)]	14.8	2200	2200	—	—	—

Two tests conducted, unless otherwise specified. (a) Only one test conducted; faying orientation 10 to 10 side. (b) Only one test conducted; faying orientation 100 to 100 side.

and electrode life is not clear. The fact that three of the four tests conducted on Coils X and Y indicate that electrode life increases with coating weight suggests that further work in which sufficient test duplication is done to overcome the scatter typical of electrode life testing may yield a clearer picture.

A final look at Table 8 and Figs. 10–13 yields two observations. First, the Coil X material exhibits superior electrode life relative to the Coil Y sheet. The reason for this is unknown. Inspection of substrate chemistry, coating chemistry, and surface resistance for the two materials brings nothing obvious to light that might be responsible for the difference. Second, the truncated-cone caps outperformed the A-nose caps in all tests but one, namely in the testing of the 8/8 Coil X sheet. This difference may be related to differences in electrode geometry, composition, or cooling efficiency.

Weldability: Current Range/Lobe Test versus Electrode Life

Two separate measures of resistance spot weldability were used in this study. The current range and lobe tests determine the range of conditions over which an acceptable weld can be made in a particular material. In contrast, the electrode life test quantifies the effect of the coating on electrode wear. Then problem arises in that a material which exhibits desirable properties based on one test does not necessarily perform well in the other test, a point brought out by Natale (Ref. 6). For instance, the Coil X 8/8 sheet had the narrowest current range results, yet had the best electrode life using the A-nose electrodes. On the other hand, the Coil X 90/90 had wide current ranges, yet had relatively poor electrode life using the same caps. From these results, it is clear that neither current range/lobe tests nor electrode life tests can be used as sole indicators of resistance spot weldability of electrogalvanized sheet.

Conclusions

A study to determine the influence of coating weight on the resistance spot weldability of electrogalvanized sheet steel has revealed the following:

1) With respect to current range:
   a) Current range is proportional to coating weight.
   b) The positive correlation between current range and total coating weight appears to be independent of weld time.
   c) The dependence of current range on coating weight appears to be related to the dual ability of the zinc annulus to shunt a portion of the welding current around the developing

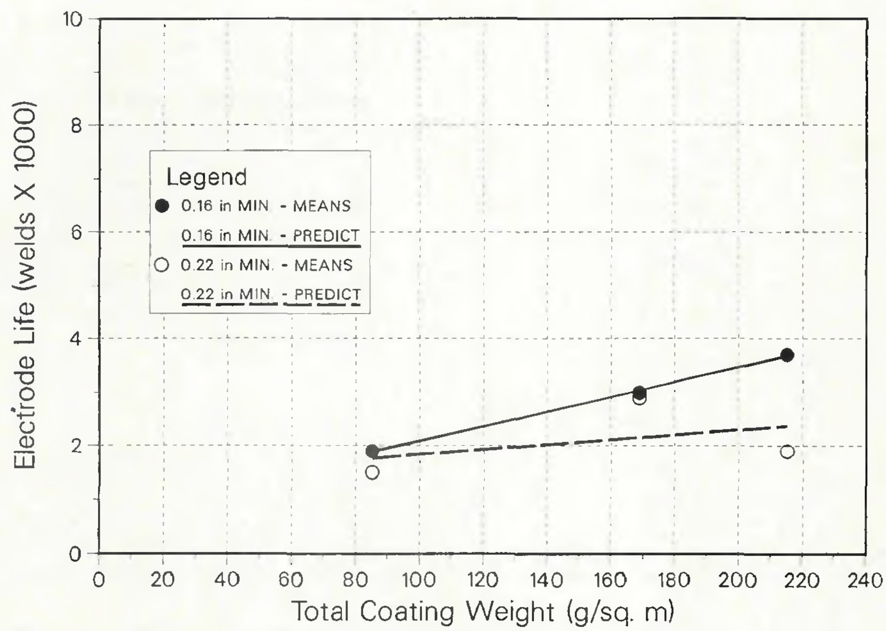

Fig. 12—Coating weight effect on electrode life for Coil Y using A-nose electrodes

Table 9—Linear Regression Results for Electrode Life Test Data

Coil	Electrode Type	0.22 in. (5.6 mm) Min Intercept[a]	0.22 in. (5.6 mm) Min Slope[b]	0.22 in. (5.6 mm) Min R-Squared[c]	0.16 in. (4.1 mm) Min Intercept[a]	0.16 in. (4.1 mm) Min Slope[b]	0.16 in. (4.1 mm) Min R-Squared[c]
X	A-nose	3.53	−0.006	0.36	6.31	−0.010	0.12
X	Truncated cone	2.49	0.008	0.72	6.55	0.009	0.52
Y	A-nose	1.36	0.005	0.19	0.72	0.014	1.00
Y	Truncated cone	1.08	0.010	0.95	2.21	0.014	0.56

(a) and (b) Fit curve for electrode life is L = a + b(TCW) where: L = electrode life; TCW = total faying interface coating weight; a = intercept; b = slope.
(c) R-squared measures how much variation in the electrode life can be accounted for by the fit. The closer R-squared, which can range from 0 to 1, is to 1, the better the curve fit.

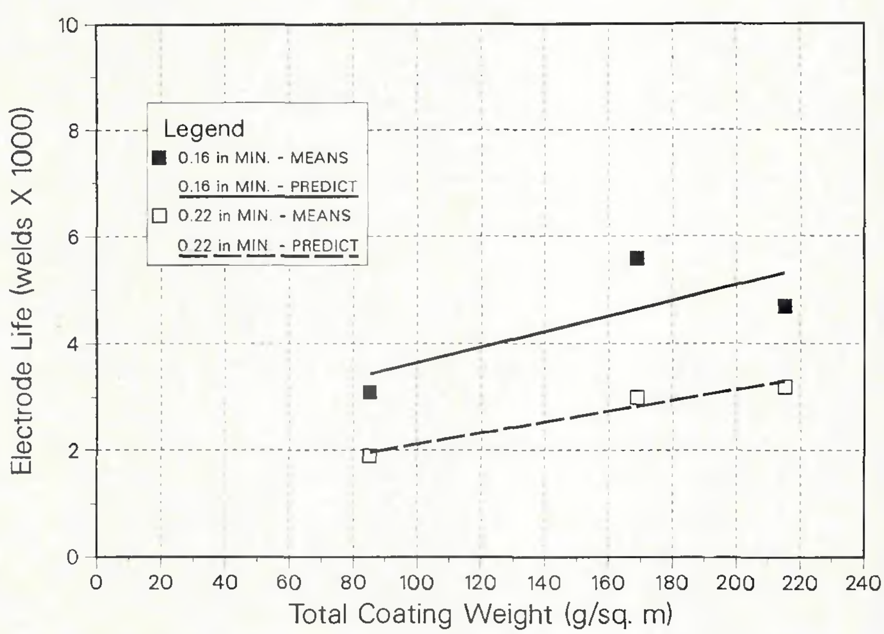

Fig. 13—Coating weight effect on electrode life for Coil Y using truncated-cone electrodes

weld, as well as to hinder expulsion by helping to contain the molten steel which eventually solidifies to form the weld nugget.

2) Nominal weld time current range values determined using the lobe test fall consistently below those obtained using the individual current range procedure.
3) Coating pickup and loss on the electrode faces appear to be the major contributors to current range/lobe test variability.
4) The relationship between coating weight and electrode life is not clear. Further work in which sufficient test duplication is done to overcome data scatter may yield a clearer picture.
5) Truncated-cone electrode caps appear to exhibit superior tip life relative to A-nose electrode caps. The difference may be related to differences in electrode geometry, composition, or cooling efficiency.
6) Neither current range/lobe tests nor electrode life tests can be used as sole indicators of electrogalvanized sheet resistance spot weldability. Furthermore, accurate measures of material current range and tip life characteristics can only be obtained by conducting multiple tests to account for data variability.

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