

Resistance Spot Welding of Galvanized Steel:

Part I. Material Variations and Process Modifications

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Material variations and process modifications have been studied to determine their effects on the acceptable range of resistance spot welding conditions for galvanized steel sheet. The material variations studied include zinc coating integrity, structure, composition, thickness, roughness, oil, and the amount and type of Fe-Zn intermetallics. Process modifications studied include upsloping and downsloping of the weld current, preheat current, postheat current, electrode tip geometry, and applied force. It was found that hot-dipped galvanized materials with coatings which have a very thin Fe-Zn alloy layer have a wider range of acceptable welding conditions than the commercial galvanized products, which have a fully alloyed Fe-Zn coating. The decreased lobe width of the galvanized material is due to the discontinuous Fe-Zn coating structure and morphology. Small variations in the thickness of the coatings studied have no significant effect on the welding current range. Surface roughness of the coating has no effect on lobe width. Upsloping and downsloping of the weld current increase the welding range of hot-dipped products when using truncated cone electrodes, whereas sloped current has no advantage for galvanized or uncoated materials. Radius electrodes can increase the lobe width of hot-dipped products but are not beneficial when using sloped current or when welding galvanized or uncoated materials.

I. INTRODUCTION

VARIATIONS in the spot weldability of galvanized steel sheet have inhibited its widespread use in the major fabrication industries. The acceptable welding current ranges of galvanized steel sheet can vary markedly from producer to producer. Hence, when a steel user mixes heats of steel from different mills, the same welding conditions may produce welds with both acceptable and unacceptable nugget diameters because the weld current lobes do not overlap. Tip life is another important aspect of weldability which varies with material and process changes. However, in the present study, we have focused on lobe width and reasons for its variations in position and width.

In order to determine the cause of and possibly a solution for these variations in required welding current (lobe width), a research program has been established at MIT which concentrates on three main areas:

- (1) Variations in base material or coating which cause variations in weldability and welding current range,
- (2) optimization of the welding process parameters and use of parameter modification to provide the widest range of acceptable welding conditions for a given material, and
- (3) dynamic inspection of the weld current, voltage, resistance, electrode displacement, and force which can be used in a quality control scheme as well as provide information about the mechanisms of weld nugget formation and growth.

Part I of this paper will present the results of the first two areas concerning the material variations and process modifications which affect the weld current lobe width of galvanized steel sheet. Part II will describe the mechanisms of

weld nugget formation and growth which explain these results. Although much work has been performed on the effect of material parameters,^{1,2,3} process parameters,⁴ and electrode composition^{5,6,7} on electrode tip life, little work has been performed on their effects on lobe width, a topic which has recently become increasingly important, especially for galvanized steel. In this paper, the lobe is defined as the envelope of weld time and current conditions which result in a nugget with a minimum diameter of 0.56 cm (0.22 inch) and the absence of expulsion. The minimum acceptable diameter was chosen based on the thickness of the steels being welded.^{8,9} Although the thicknesses varied somewhat (see Table I), they were usually about 16 gauge.

II. MATERIAL CHARACTERIZATION AND EXPERIMENTAL APPROACH

A thorough characterization of each material was performed before any welding was attempted. Ten galvanized steels were studied, including four hot-dipped galvanized, two fully alloyed galvanized coatings, and four Galvalume coatings (Zn-5 pct Al). These steels are listed in Table I. All welding was performed on a single phase 75 kVA Taylor-Winfield spot welder with a Technitron 7000 series synchronous controller.

The material characterization included:

- (1) Measuring the coating thickness and variations across the coil width;
- (2) examining the coating roughness using a profilometer;
- (3) cross sectioning and metallographic examination to determine the thickness of the Fe-Zn alloy layer, the coating integrity, and gain some knowledge of prior heat treatment;
- (4) determining the Fe-Zn alloy phases present in the coating by X-ray diffraction;
- (5) measuring the electrical resistivity of the base metal substrate as a function of temperature after stripping the coating; and

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Table I. Galvanized Steel Composition and Coating Type

Sample Designation	Coating Type	Nominal Coating Thickness (μm)	Substrate Thick (mm)	C	Mn	Si	S	P	Al
G90	hot-dip	22.5	1.5	0.04	0.29	—	0.022	0.005	0.005
A01	galvanized	7.0	1.5	0.05	0.28	—	0.022	0.005	0.063
A40	galvanized	11.0	1.6	0.03	0.29	—	0.019	0.008	0.042
MSR	hot-dip	21.0	0.8	0.027	0.28	0.01	0.015	0.092	0.05
RSR	hot-dip	20.0	1.1	0.020	0.28	0.01	0.019	0.081	0.05
GY	Galfan	30.0	0.57	<0.08	0.25 to 0.45	<0.03	<0.025	<0.035	0.02 to 0.08
GY	Galfan	6.0	0.6	<0.08	0.25 to 0.45	<0.03	<0.025	<0.035	0.02 to 0.08
G5	Galfan	6.0	0.5	<0.08	0.25 to 0.45	<0.03	<0.025	<0.035	0.02 to 0.08
G12	Galfan	6.0	0.6	<0.08	0.25 to 0.45	<0.03	<0.025	<0.035	0.02 to 0.08
USS	hot-dip	20.0	0.72	N/A	N/A	N/A	N/A	N/A	N/A

(6) measuring tensile strength of the stripped material.

From an analysis of the material variations which were measured during the characterization, an experimental program was developed which could effectively examine all of the pertinent variations and determine their effect on weld variations. Primary emphasis was placed on the effect of material variations and process modifications on the weld current lobe width. The welding research program consisted in part of:

(1) Running a very short tip life test for each material, which continued only until the current readings or the nugget size began to fluctuate. This test was used to determine the number of welds needed to break properly in the tips and the time interval between tip redressings. This was not part of a tip life study. This was done to ensure that during the ensuing experiments, any weld variations detected would be due to the material variations being examined and not due to tip wear. Electrodes were typically preconditioned for 50 welds before collecting data, and were not generally used for more than 200 welds before replacement.¹⁰

(2) Making the weld current lobes of the material in both the as-received condition and after cleaning, so that contamination of the material surface could be understood and eliminated as a source of weld variations.

(3) Varying the force and measuring lobes until the greatest lobe width was found. Subsequent lobes were then made using the optimized force for each material.

(4) Selecting thick and thin regions of coating thicknesses from across the coil width. Lobes were then made to determine the effect of minor coating thickness variations on a given steel. The coating thickness at each location was measured with a Deltascop magnetic flux leakage probe.

(5) Removing part or all of the coating in order to determine the overall effect of coating thickness as compared to the uncoated base material. The zinc coating was removed by a mixture of HCl and water (1:3).

(6) Heat treating the hot-dipped material to produce a fully alloyed Fe-Zn coating. This then provided a means of comparing and evaluating the effects of the Fe-Zn alloys in the coating.

(7) Skin passing a material to make it smoother, and artificial roughening of the coating, was used to understand the effect of coating roughness.

(8) Upsloping and downsloping of the weld current as a means of increasing the lobe width, as well as a way to develop a favorable heat generation pattern.

(9) Using preheat current and postheat current to determine if it produced effects similar to sloped current control.

(10) Welding with radiused and domed electrodes and comparing these results to the truncated cone tips normally used in this study.

(11) Stripping of the coating from either the faying surfaces or the electrode surfaces in order to determine which interface may be causing some of the welding phenomena of interest.

(12) Scanning electron microscopy (SEM) and EDAX analysis of the developing weld nugget to generate an understanding of the mechanisms of nugget formation, and how material and process variations affect these mechanisms.

(13) Dynamic inspection monitoring of the weld current, voltage, resistance, electrode displacement, and force on all welds.

(14) High speed photography of the developing weld nuggets was performed to evaluate the effects of process modification, and to obtain visible evidence to support the proposed theories of nugget formation and growth.

Other more specialized tests were then developed to examine the differences noted in the above experiments. The results for items 1 through 10 are now presented in Part I, while the results of items 11 through 13 are presented in Part II of this paper. The high speed photography results (item 14) are now being prepared for publication. It should be noted that some preliminary results of this study were reported at an SAE conference;¹⁰ however, the present paper presents the final results of the entire program. Although ten steels were studied, this paper will focus on three which can be used to describe general trends present for all ten.

III. RESULTS OF THE MATERIAL VARIATIONS STUDIED

Some of the materials used in this study were received with a heavy mill oil finish. Since it was found¹⁰ that the presence of this oil can shift the lobe to lower currents by as much as 2000 amps as well as decrease the width from 1200 amps to 600 amps at 12 cycles, all further tests were

made on degreased samples in order to eliminate the effects of this variable from further studies. This strong variation in lobe location and shape was not seen on lightly-oiled sheets.

The coating thickness can vary as much as 10 microns from spot to spot on the same coil. An example of this is presented in Figures 1(a) and 1(b) which show the coating variations on each side of the sheet for a minimum and a regular spangled hot-dipped coating. This natural material variation was used to help determine the effect of small coating thickness differences on required welding current. The resulting lobes of the above materials are presented in Figures 2(a) and 2(b). These lobes and the data in Table II show that small variations in coating thickness do not have a significant effect on the position or width of the weld current lobe, which is in agreement with some investigations.^{11,12} This material variation was then controlled so that the other material variations could be examined individually.

Parts of the G90 and A01 coatings were removed by etching for various times in HCl and water. The results of this are presented in Figure 3 which shows slices through a welding lobe at 12 cycles for various coating thicknesses. This shows that the presence of the galvanized coating requires increased current for an acceptable weld, but that this effect becomes less significant for thicker coatings.

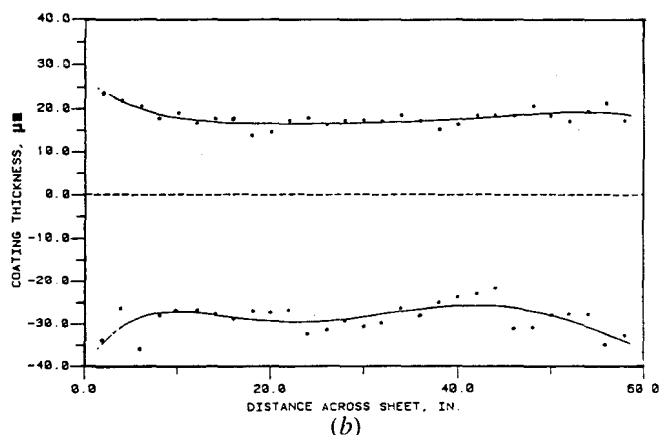
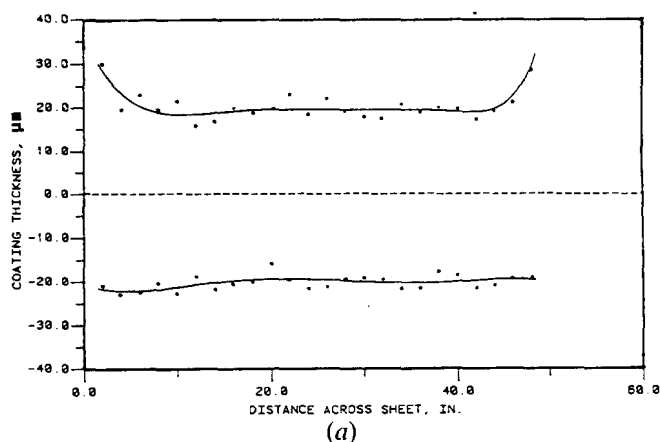


Fig. 1—(a) Coating thickness variation across a coil width of MSR steel. (b) Coating thickness variation across a coil width of RSR steel.

The G90 and A01 materials had identical base metal substrates and electrical resistivity as a function of temperature.¹⁰ This fact enables the direct comparison of the effect of the two different coating types which exhibit very different weldability. Table II shows that the A01 fully alloyed Fe-Zn material exhibits a much narrower lobe width than the hot-dipped G90 coating which is mostly free zinc. This weldability difference can thus be attributed to the coating differences, which are the increased amount of Fe-Zn alloy in A01 as compared with the free zinc in G90, the increased roughness (in terms of frequency of asperities) of the A01

Table II. Effect of Thickness Variation on Weldability Lobe

Sample Designation	Lobe Width at 12 Cycles (amps)	Thickness Variation (μm)	Optimum Force Pounds
G90	1700 ± 100	± 10 — 5	650
A01	600 ± ~0	± 3	650
A40	250 ± 100	± 2	850
MSR	1700 ± 50	± 5	550
RSR	2250 ± 100	± 8	750
GY	1300 ± 75	± 4	1050

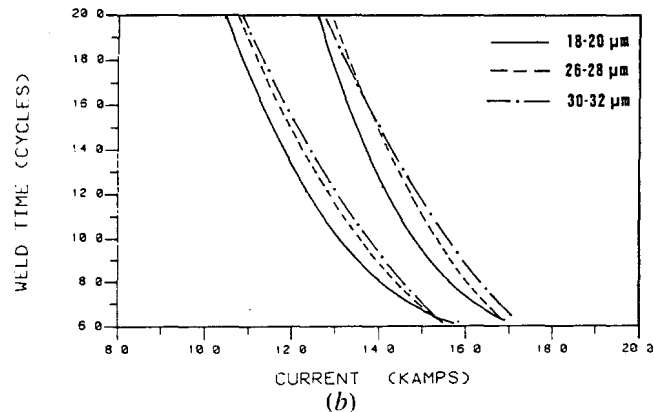
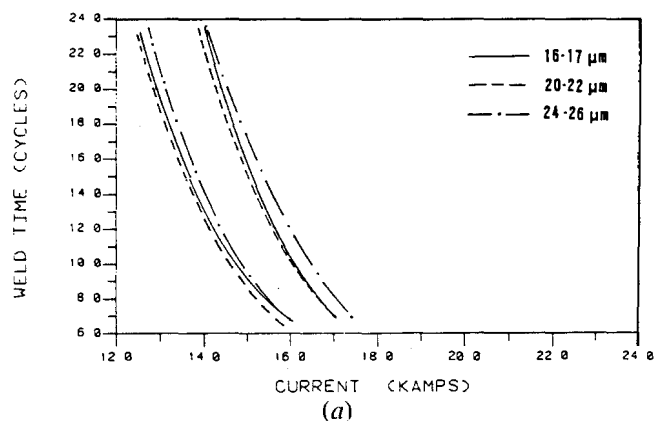


Fig. 2—(a) Weldability lobes of MSR at varying thickness (t. cone, 650 lbs.). (b) Weldability lobes of RSR at varying thickness (t. cone, 650 lbs.).

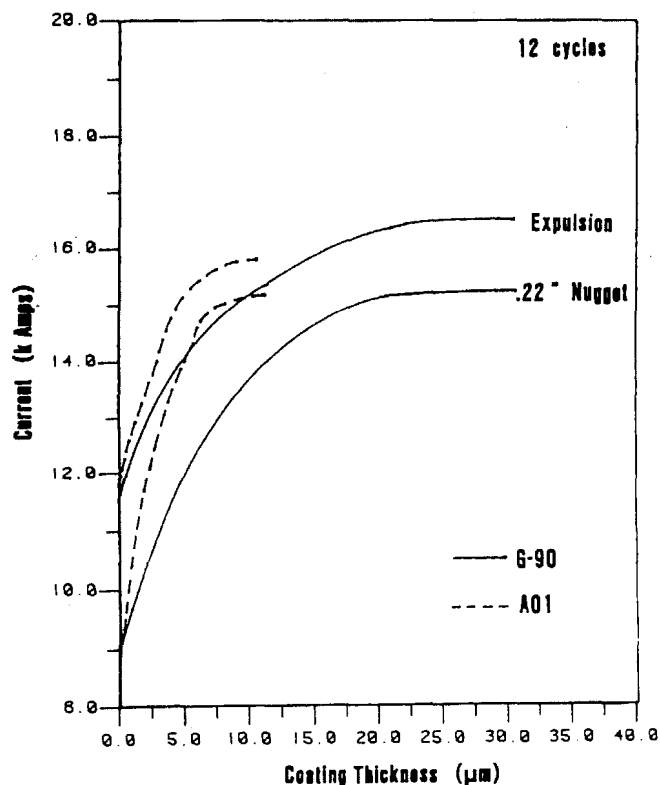


Fig. 3—Current required for minimum sized nugget and expulsion as a function of coating thickness for G90 and A01.

material,¹⁰ or the wide difference in coating thickness (A01 is about 20 microns thinner per side). Some sources have indicated that surface roughness plays a major role in weldability,¹³ whereas others¹⁴ have indicated that the Fe-Zn morphology plays a major role.

In order to determine whether Fe-Zn intermetallics or surface roughness is responsible for the differences in weldability, two specific experiments were performed. The G90



Fig. 5—Photomicrograph of A01 coating morphology. Magnification 732 times.

material which had mostly a free zinc coating with a very thin intermetallic layer was heated for various times and temperatures in an inert atmosphere to grow a thicker Fe-Zn intermetallic alloy layer. These structures were examined with the aid of a scanning electron microscope which had EDAX capabilities, to determine how far the iron and zinc had diffused. The phases which were grown were confirmed through the use of X-ray diffraction, and were in agreement with other sources.^{15,16,17} A photomicrograph of one of the G90 coatings heat treated for 16 hours at 400 °C is shown in Figure 4. Photomicrographs of the A01 and A40 galvanized coatings are shown for comparison in Figures 5 and 6. Even though these materials had about the same surface roughness, the heat treated G90 had a much wider lobe width (1500 amps at 12 cycles as opposed to only 600 for the A01). The remaining difference was the Fe-Zn alloy structure and morphology. As can be seen, the heat-treated coating has smooth continuous layers of alloy, whereas the



Fig. 4—Photomicrograph of G90 heated for 2 h at 400 °C. Magnification 950 times.



Fig. 6—Photomicrograph of A40 coating morphology. Magnification 732 times.

A01 has discontinuous Fe-Zn crystals which were grown in a different manner (from a liquid) than the material grown in our labs (from a solid). The A40 galvanized material had a narrow lobe width (see Table II) due to the poor coating integrity and discontinuous structure.

As a further check on the previous conclusion, the coatings were artificially smoothed, by rolling less than 10 pct, or roughened, by wire brushing or sanding. Ensuing studies showed that the surface roughness had no effect at all on lobe width, even with drastically different profilometer traces of the coating texture.

IV. RESULTS OF PARAMETER MODIFICATION STUDIES

After studying the material variations which change the width of the welding lobe, it was possible to hold these constant in order to study the effect of process modifications. It was found that when using truncated cone electrodes, both upsloping and downsloping widen the weld current lobes of hot-dipped materials which have a mostly free zinc layer. This is shown in Figures 7 and 8 where the vertical axis is weld time not including up or downslope time. However, upsloping and downsloping have shown no

beneficial effects of widening the lobe when welding any of the galvanized materials which have a fully developed Fe-Zn alloy coating, as is evidenced from Figure 9. Up- and downsloping also shows no effect when welding the uncoated substrates, as can be seen in Figure 10. Table III presents a sample of data taken from complete lobes which slows the effects of sloping on other steels.

It was found that preheating/postheating had basically the same effects as upsloping/downsloping, although not quite to the same extent. Some of these results are presented for a regular spangled hot-dip galvanized steel in Table IV.

The use of radiused and domed tip electrodes was then examined. It was found that radiused tips can widen the lobe of hot-dipped materials, but are not beneficial for galvanized or uncoated products. Also, the beneficial effects of up- and downsloping were eliminated when using these tips, as is shown in Figure 11. Table V presents some additional results for several steels. The dome-tipped electrodes studied exhibited substantially decreased lobe width as compared with truncated cone or radiused tips.

In order to explain why up- and downsloping are beneficial only for free zinc coatings when using truncated cone electrodes, other specific experiments have been developed. The use of dynamic inspection monitoring of the displacement, force, and electrical resistivity as well as extensive

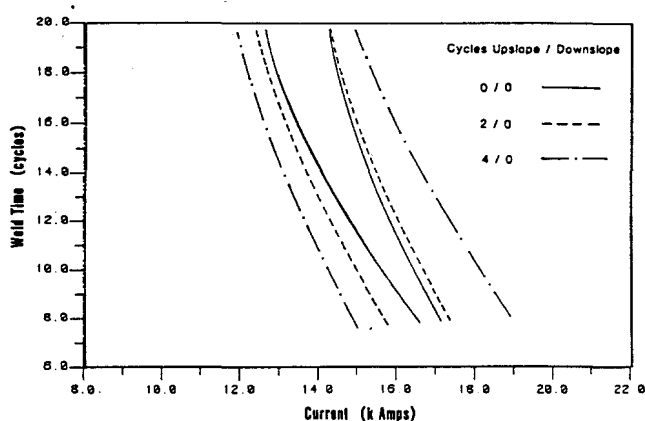


Fig. 7—Weldability lobes of G90 with upsloped current (t. cone, 650 lbs.).

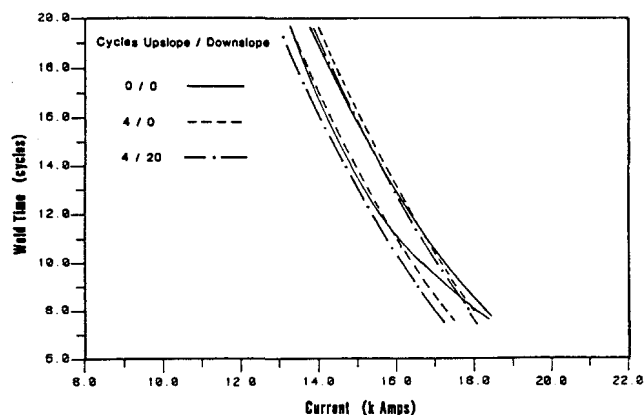


Fig. 9—Weldability lobes of A01 with sloped current (t. cone, 650 lbs.).

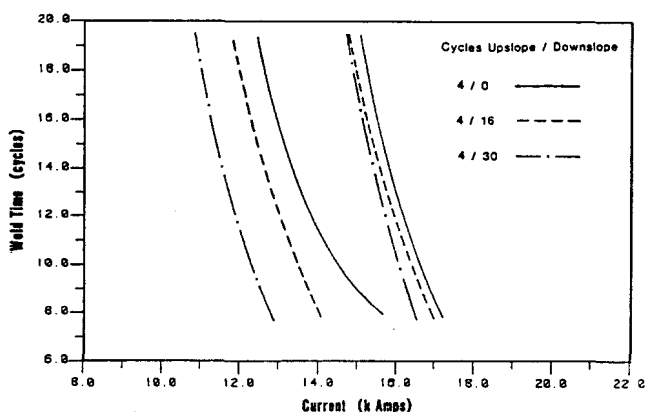


Fig. 8—Weldability lobes of G90 with sloped current (t. cone, 650 lbs.).

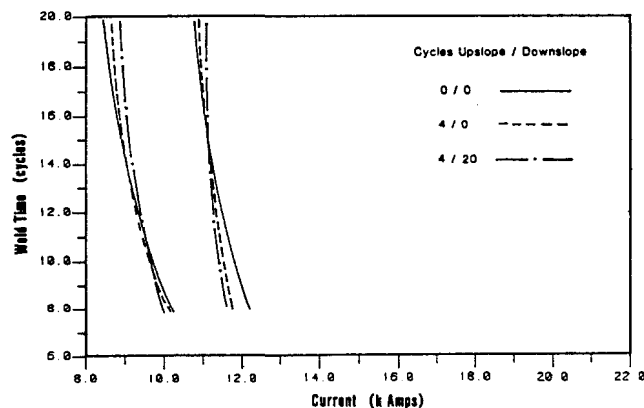


Fig. 10—Weldability lobes of uncoated steel with sloped current (t. cone, 650 lbs.).

Table III. Effect of Sloped Current on Weldability Lobe

Sample Designation	Lobe Width at 12 Cycles with Cycles Upslope/Cycles Downslope (amps)			
	0/0	4/0	0/20	4/20
G90	1700	3000	3000	3500
GY	1300	3500	3500	3700
RSR	2000	3800	2400	3800
A01	600	600	600	600
A40	300	400	600	600
Uncoated	2000	2000	2000	2000

Table IV. Effect of Preheat and Postheat Current on Weldability Lobe

Sample Designation	Lobe Width at 12 Cycles with Cycles Preheat/Cycles Postheat (amps)				
	0/0	4/0	8/0	0/4	8/4
RSR	2000	2200	2600	2000	3400

Table V. Effect of Sloped Current and Radiused Electrodes on Weldability Lobes

Sample Designation	Lobe Width at 12 Cycles with Cycles Upslope/Cycles Downslope (amps)			
	0/0	4/0	0/20	4/20
G90	2500	2600	2400	2600
A01	700	600	N/A	700
A40	500	700	N/A	700
Uncoated	1500	N/A	N/A	1500

scanning electron microscopy of the developing weld nugget were also evaluated in this study, and are presented in Part II of this paper.

V. DISCUSSION

The primary goals of this research program were to investigate the material and process variations which have the greatest effect on lobe width. As shown in Reference 8, a heavy mill oil can have a very significant influence, shifting the lobe as compared with the same oil-free material, such that there is no overlap of acceptable welding current and time for oiled and oil-free surfaces. The presence of oil increases the contact resistance which shifts the welding lobe to lower currents.^{18,19} Thus, if one is still welding at the higher currents required for clean steels, the presence of oil will cause expulsion and extreme overheating of the electrodes which results in decreased electrode life.

Clearly, the end user must be careful to use galvanized steel sheets of relatively uniform surface oil (which usually means degreased). By inference, surface contamination or white rust due to improper storage should probably be removed if consistent weld quality is to be achieved.

As seen in Figure 2 and Table II, rather wide variations in local coating thickness appear to have little influence on

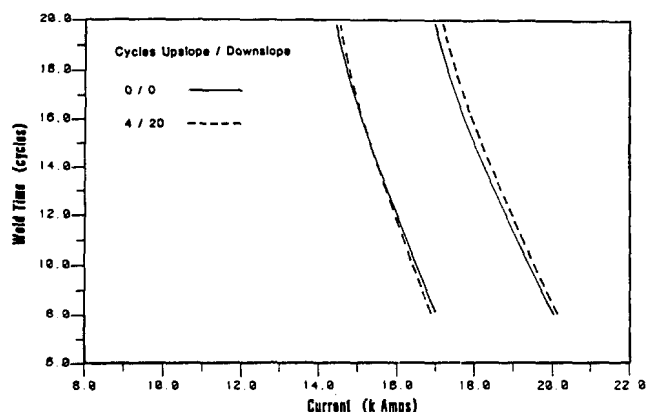


Fig. 11—Weldability lobes of G90 with sloped current (radiused tips, 650 lbs.).

lobe width, at least for the G90 hot-dipped thickness and A01 coatings studied. This result was somewhat surprising as it is well known that zinc coated steels require greater welding current. It was assumed at the outset of this work that local coating thickness variations would be a significant factor in altering the lobe position and width. As seen in Figure 3, this assumption is apparently true for G90 coating thicknesses up to 20 microns and A01 thicknesses up to 5 microns. However, for the thicker coatings such as these steels had initially, the welding current and lobe width do not change much with variations in coating thickness. This is indeed fortunate because closer control of local coating thickness would be difficult to achieve on hot-dipped material. Closer control of local thicknesses can be achieved with electrogalvanized sheet. These electrogalvanized sheets are often used with a thinner coating than G90 and a serious concern suggested by Figure 3 is whether a G30 or G60 coating weight electrogalvanized material will have significant differences in lobe width or current due to local variations in coating thickness. We are attempting to expand our current research to address this question.

The results of this study clearly show that free zinc and alloyed zinc layers have significantly different welding current levels and widths. Hence, indiscriminate mixing of such materials is not advisable. This conclusion, however, can hardly be considered novel.

Another goal of the original study was to evaluate the effect of base steel electrical resistivity on welding current range. In a previous study of uncoated steel in our labs²⁰ such base metal electrical resistivity differences were found to be significant in influencing lobe shape, but, in the current study, not enough information could be obtained to determine the significance of base metal electrical resistivity on weld lobe width. More work needs to be done in this area.

The finding that surface roughness does not have a significant effect on lobe width appears to contradict the work of others;¹³ however, we believe this finding makes physical sense since the zinc coating becomes soft and deforms very early in the welding sequence. As a result, the zinc surface roughness does not exist for more than 90 pct of the total weld time; hence, it is difficult to explain why it should have an effect as others have claimed.

Perhaps the most successful result of this study was the finding that upslope/downslope or preheat/postheat can significantly widen the weld lobe. The reasons for the beneficial effect of these modifications and the reasons why they are not beneficial on Fe-Zn alloy coatings or uncoated steels will be discussed in Part II of this paper.

One reason for describing the use of current modification as the most successful result of this research program is the fact that as a result of this investigation, such process modifications have been introduced in production with good results.²¹ In addition, there is some evidence that these current modifications may extend electrode tip life as well, as will be discussed in Part II.

VI. SUMMARY

Results of this investigation of the spot weldability of galvanized sheet steel have indicated that:

1. Small variations in hot-dipped coating thickness do not significantly affect the acceptable welding range (lobe width).
2. The reduced lobe width of galvanized materials is due to the discontinuous Fe-Zn intermetallic structure and morphology.
3. The surface roughnesses of hot-dipped and galvanized coatings have no effect on lobe width.
4. Upsloping and downsloping of the weld current when using truncated cone electrodes increases the welding range of materials which have a free zinc layer.
5. The use of radius tip electrodes can increase the welding range of hot-dipped materials when using normal current control, but do not improve lobe width when using slope control.
6. Radius-tipped electrodes do not increase the welding range of galvanized or uncoated materials with or without sloped current control.
7. Domed electrodes produce inferior welding current ranges as compared with radius and truncated cone tips.
8. Preheating/postheating exhibit similar effects as upsloping/downsloping of the weld current.

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