The Effect of Electrical Resistance on Nugget Formation During Spot Welding

Applying a higher resistance coating to HSLA steel increases the welding current range to an acceptable level and permits a reduction in electrode force.

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ABSTRACT. Many high strength-low alloy (HSLA) steels are more difficult to resistance spot weld than low carbon steel, due primarily to the narrower welding lobe width. In order to understand the shape of the welding lobe, a comparison was made between HSLA and low carbon steel sheets. Three separate surface conditions on each sheet were studied. These conditions produced surface resistances which varied by approximately an order of magnitude between the lowest and the highest values.

Static resistances were measured with forces of 150 to 1700 Ib (0.67 to 7.56 kN) using test currents of 1 to 1000 amperes. It was found that the static resistance values changed markedly with both force and test current. The contact resistance range for all samples spanned five orders of magnitude. It is shown that the static resistance measurements are controlled by the flattening and melting of surface asperities.

Welding lobes were measured at three or more force levels for each steel and surface condition. The shape and shift of these lobes with welding current can be explained in terms of the heat generated at the faying surface and in the bulk. A model of the local heat generation is proposed that divides a typical lobe into approximately four regimes, depending upon the dominance of either bulk or surface heating. The model provides a qualitative description of the lobe shape, and predictions from the model have been used to increase the acceptable welding current range of HSLA steels.

The initiation of surface melting has been studied in the scanning electron microscope. Three types of surface heating are observed depending upon the current/time parameters which are used.

Each type is explained in terms of local surface conditions, local heat generation rate and heat transport in the metal.

Introduction

There has been great interest for many years in the use of high strength sheet steels, particularly as a means of reducing the weight of automobiles. For a number of reasons, the use of these materials has grown at a slower rate than originally anticipated. One of the limiting factors has been the more restricted range of acceptable welding parameters.

The nature of mass production spot welding requires the ability to make thousands of welds without machine readjustment. This reproducibility is hindered by inconsistencies in metal composition, by variation in surface finish and by electrode tip mushrooming. To allow for these changes during a welding run, it is desirable to use material with the greatest welding current range.

Unfortunately, many high strength steels have very narrow welding current ranges. In some cases, this restricted weldability is due to interfacial failure of the weld nugget (Ref. 1), resulting in an apparently smaller fusion zone. Other investigators have shown that high strength steels may be more susceptible to expulsion due to their higher electrical resistivity (Ref. 2), although the higher resistivity permits welds to be produced at lower currents (Ref. 3), which is considered an advantage. Still other investigators have found significant effects of prior surface preparation on spot weldability (Ref. 4, 5).

The problem addressed in this study is fundamental; it is desired to identify the material properties which control lobe width and to determine the manner in which these properties interact with the welding parameters. The independent process parameters chosen were pressure, time and current; the material properties studied were bulk resistance and surface resistance.

The total welding resistance may be thought of as a series resistance of five loads. These are the two electrode-sheet interface resistances, \( R_1 \) and \( R_5 \); the two bulk material resistances, \( R_2 \) and \( R_4 \); and the faying interface resistance, \( R_3 \). The interface resistances are determined by the thermal, electrical and mechanical behavior of the surface of the material. The faying resistance, \( R_3 \), drops to zero as the nugget is formed. An initial assumption of this work is that it is the dynamic interaction of these five resistances which determines the lobe width.

Experimental

Starting Materials

The compositions of the two steels used in this study are given in Table 1. Both sheets were 1.2 mm (0.049 in.) thick. For each composition, surface conditions of high, medium and low resistance were studied. For both low carbon and HSLA, a
low surface resistance was achieved by degreasing in trichloroethylene followed by pickling in separate baths of sulfuric acid and hydrochloric acid, completed by an alcohol rinse and drying. Several other pickling solutions and rinsing agents, as well as mechanical polishing and sandblasting techniques, were evaluated, but the procedure described above gave the lowest and the most consistent surface resistance. Due to the unprotected nature of the steel surface, the contact resistance increases after exposure to the atmosphere; hence, it was necessary to perform the welding tests immediately after pickling.

An intermediate value of surface resistance was achieved for both compositions by welding in the as-received condition. In this state, mill oil and light oxide were apparent on the steel surface.

A high resistance surface was prepared by either maintaining the sheet at 121°C (250°F) for 96 hours (h) under humid conditions or by application of a phosphate coating.

Welding Procedure

All welds were produced on a 75 kVA pneumatically operated resistance welding machine equipped with synchronous controls. RMS current values were determined, without the use of blanking, on a commercially available current meter (Duffers model no. 273). Dynamic force readings were produced by mounting a full bridge strain gage on the head cross bar of the welding machine. This was calibrated using a 1 in. (25.4 mm) diameter proving ring mounted between the electrode tips. Strain readings of the ring had been calibrated between similar tips using an Instron testing machine in the compressive mode. An electrode tip diameter of 6.3 mm (1/4 in.) was used throughout the study, as was a 30 cycle hold time.

Welding lobes were determined for all six combinations of composition and surface treatment, using 100 by 25 mm (4 by 1 in.) coupons. The maximum current was determined when the shunting effect of a second weld produced the expulsion/no expulsion condition. The minimum welding current was measured by a peel test to determine the minimum acceptable nugget diameter.

Since electrode force directly affects the magnitude and the response of interface resistance, a high, medium (optimum) and low force lobe was constructed for each resistance combination. Thus a 2 X 3 X 3 matrix (composition, surface preparation and electrode force) of conditions was studied.

Static Resistance Measurements

In order to determine the effect of resistance on weld formation, it was necessary to isolate the influence of pressure and current on surface resistance. A DC circuit was constructed which enabled from one to 1000 amperes (A) to be pulsed between the electrode tips in the machine. The secondary circuit of the welding machine was excluded from the DC circuit by seating a specially designed tip in a teflon spacer thus insulating it from the machine. Voltage across the weld pieces was monitored from leads on the sides of the electrodes. Power was supplied by a 2000 A-h battery in series with a graphite plate rheostat.

The average resistance and standard deviation was calculated from approximately 20 measurements for each materi-
results have been obtained at a constant electrode force of 150 lb (667 N).

The bulk resistivity of each steel to 900°C (1652°F) was determined experimentally using a four point probe in a vacuum furnace. In one series of tests, the resistances of the electrode-sheet interfaces, $R_1$ and $R_5$, were reduced to very low levels by placing liquid gallium between the pickled outside surface of the sheet and the electrode. The total resistance values measured with $R_1$ and $R_5$ eliminated in this manner were compared with the values measured without eliminating $R_1$ and $R_5$. $R_2$ and $R_4$ were calculated from the bulk resistivity by assuming a resistive length equal to the sheet thickness and an area equal to the electrode tip. In this way the magnitude of each resistance, $R_1$ through $R_5$, could be estimated.

### Dynamic Resistance Measurements

While it is important to consider the response of resistance to pressure and current, resistance spot welding is truly a dynamic process where few parameters are independent. In order to further understand the mechanisms which determine lobe shape, dynamic resistance was monitored for the matrix of welding conditions. An oscillographic recorder with 5 kHz bandwidth allowed simultaneous recording of current, electrode force and voltage. Dynamic resistance was calculated by dividing the peak voltages by the corresponding peak currents.

### Results

The bulk resistivity of each steel as a function of temperature is shown in Fig. 1. It will be noted that the temperature dependence of both steels is similar but that the HSLA steel has a 40% higher room temperature resistivity. It will be shown subsequently that this difference can be substantial in terms of nugget formation.

The static resistance as a function of test current is shown in Figs. 2 and 3 for the low carbon and HSLA steels respectively. The resistance variation with force is given in Figs. 4 and 5. Estimates of the individual resistances $R_1$ through $R_5$ are

| Table 2—Electrical Resistances of Low Carbon and HSLA Steels |
|------------------|------------------|------------------|------------------|------------------|------------------|
|                  |                  |                  |                  |                  |                  |
| Low carbon:      |                  |                  |                  |                  |                  |
| Pickled          | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ |
| ($\pm 31.8\%$)   | ($\pm 40.5\%$)   | ($\pm 18.8\%$)   | ($\pm 41.1\%$)   | ($\pm 24.2\%$)   |
| As-received      | ($\pm 89.0\%$)   | ($\pm 66.7\%$)   | ($\pm 41.1\%$)   | ($\pm 24.2\%$)   |
| Phosphate        | ($\pm 117\%$)    | ($\pm 47.4\%$)   | ($\pm 41.1\%$)   | ($\pm 24.2\%$)   |
| HSLA:            |                  |                  |                  |                  |                  |
| Pickled          | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ | $R_1$ $R_2$ $R_3$ $R_4$ |
| ($\pm 82.4\%$)   | ($\pm 46.2\%$)   | ($\pm 46.8\%$)   | ($\pm 25.3\%$)   |
| As-received      | ($\pm 52.0\%$)   | ($\pm 32.7\%$)   | ($\pm 25.3\%$)   |
| Oxidized         | N.A.             | N.A.             | N.A.             | N.A.             | N.A.             |

(a) Measured at 250 A search current.
(b) Standard deviation.
posed on a welding lobe

The welding lobes for both steels as a function of surface preparation and electrode force are shown in Fig. 6. A typical set of dynamic resistance curves superimposed on a welding lobe are shown in Fig. 7.

Discussion

Static Resistance

Static resistance measurements indicate that the contact resistance is controlled by both the surface coating and the breakdown of local contact points. It is well known that contact between two smooth surfaces, no matter how finely polished, actually occurs at a few localized points. At high magnification, the apparently smooth surface is found to be very rough. The true contact area may be as little as one to ten percent of the nominal contact area (Ref. 7). Application of pressure causes the contact points to collapse and flatten as the local yield stress is exceeded, resulting in a greater area of contact.

This is readily apparent in Figs. 4 and 5, where the contact resistance is seen to decrease with the applied force. The decrease is roughly linear beyond 600 lb (2.67 kN). The greater yield strength in the HSLA steel produces a higher surface contact resistance for an equivalent surface coating due to the smaller area under the true contact points at equal applied force.

It is felt that electrode force reduces interface resistance primarily by plastically deforming local contact points. However, with increasing surface contamination, contact resistance also becomes dependent on film breakdown. It was observed that the low pressure electrical resistance of pickled material remained constant following the application and removal of a high force, while oxidized and phosphate coated material returned to approximately 90% of the original contact resistance.

The breakdown of contact points with the application of current is apparent from the data in Figs. 2 and 3. Higher currents produce greater local heating at the contact points, which in turn causes softening of metal, resulting in flattening of the contact with a reduction in the overall contact resistance. The greater resistance of the oxide and phosphate coatings results in heating and softening at lower applied currents. At very high currents all surface resistances converge toward a low value, although significant overall differences remain (note that the vertical scale of Figs. 2 and 3 is logarithmic).

Flattening of the contact points was further confirmed by the fact that the measurements were not reversible when the test current was reduced. Once a high current has been used, the resistance remained at this lower value when a lower test current was applied.

Local contacts provide an explanation for the discrepancy between columns five and six of Table 2. Using a low force and a low test current, it can be expected that the current will channel through the bulk of the material due to constriction at the local contact points. This would produce a conducting cross section in the bulk of the material due to constriction at the local contact points. This would produce a conducting cross section in the bulk of the material due to constriction at the local contact points. This would produce a conducting cross section in the bulk of the material due to constriction at the local contact points. This would produce a conducting cross section in the bulk of the material due to constriction at the local contact points. This would produce a conducting cross section in the bulk of the material due to constriction at the local contact points. This would produce a conducting cross section in the bulk of the material due to constriction at the local contact points.

Direct evidence of the softening and melting of local contact points is shown in Fig. 8. A large number of small, brittle fractures may be seen on the surface of a weld which was terminated before the
nugget began to form. These fractures are most likely due to melting of the local contact points. The brittle fracture may be due to very high local oxygen caused by absorption of the surface oxides into the small liquid region; it may also be due to formation of martensite caused by the rapid cooling of these regions. Nonetheless, these features indicate that the welding current is localized at many points during the initial stages of nugget development.

**Dynamic Resistance**

The dynamic resistance measurements also may include reactive components as evidenced by the phase angle between the voltage and the current. Nonetheless, these dynamic resistance (reactance) measurements are related to the formation of the weld nugget. Dickinson noted a peak in the resistance which he designated by the Greek letter B (Ref. 4). It has been observed in this study that the B peak is more pronounced in long time welds than in short time welds. Indeed, in welds of less than five cycles the B peak may not be apparent.

In welds in which the B peak appears, localized melting and surface adhesion may occur several cycles prior to the B peak. The B peak seems to correspond to complete surface melting and to the beginning of nugget growth.

The B peak is caused by the competing effects of increasing bulk resistivity with temperature and decreasing interface resistance. In short time welding, the increases in the temperature of the bulk may be insufficient to produce a B peak.

Higher initial contact resistance produces a more rapid decrease in the faying interface resistance, \( R_3 \), during the weld cycle. Increased bulk resistance causes more rapid heating of the bulk. Both of these changes shift the B peak to shorter times, which is consistent with the hypothesis that the peak is related to competition between increased bulk resistivity and decreased surface resistance.

Shifting of the B peak to shorter times represents an increase in the rate of nugget formation. It follows that the rate of nugget development can be increased by either increasing surface resistance or by increasing welding current. Figure 7 illustrates the shift for increasing currents across a welding lobe. It is observed that increasing the welding current is directly analogous to the dynamic changes found by increasing the surface resistance.

**Modeling of Heat Generation**

In order to qualitatively explain the phenomena caused by variations in bulk and surface resistances, a simplified model of heat generation was constructed. This model did not consider heat loss to the electrodes. Instead, the heat generation at \( R_1 \) and \( R_5 \) was assumed to be zero. While the validity of the model is therefore limited, its qualitative value is considerable. Details of the computer program are available (Ref. 8).

The computer model treated the faying interface resistance as exponentially decreasing with temperature as suggested by Funk (Ref. 9). Bulk resistivity was varied as a function of temperature, in accordance with the data of Fig. 1.

Results obtained using the model are shown in Figure 9; they illustrate how the heating rate is affected by both surface resistance and bulk resistivity. Melting of the interface is shown to vary considerably for various surface conditions. Bulk resistivity controls bulk heating and softening and therefore, expulsion. Bulk heating in HSLA steels was found to achieve a given temperature approximately one cycle faster than in low carbon steels. The higher rate of bulk heating in HSLA steels produces earlier softening of the bulk which leads to earlier expulsion and hence narrower welding lobes.

**Welding Lobe Shape**

For each bulk and surface resistance tested, a low, an optimum and a high electrode force welding lobe was determined as illustrated in Fig. 6. The optimum electrode force is the one which produces the widest welding current range. It appears that the optimum force is related to the mechanical strength of the steel. Since the true area at the localized contact points is proportional to the ratio of the applied force and the
yield strength of the material, it appears that a minimum true contact area is necessary to produce the widest range of welding conditions.

Increased electrode force for all material combinations shifted the lobe to higher currents. It was also noted that increased force extended most lobes to shorter weld times.

Higher electrode forces broadened the possible range of welding currents. This is illustrated by the apparent decrease in slope of the lobes at shorter times as exemplified most clearly by the shift of the pickled HSLA lobe; nonetheless, these trends are general. Since increased electrode force can significantly reduce interface resistance, higher pressure should produce the same trends as lower surface resistance. A comparison of all welding conditions shows this to be true.

Both the minimum and the maximum lines of optimum force HSLA lobes occur at lower current values than were found for similar low carbon materials. This is expected due to the higher bulk and surface resistances of the HSLA steels.

Interestingly, the HSLA lobe width was increased with higher surface resistance conditions. Higher surface resistances shifted the minimum lobe line to shorter times and lower currents. Figure 10 shows that the HSLA expulsion line remains virtually unchanged for both the as-received and oxidized conditions despite the shift of the minimum line.

The lobes of Fig. 6 and the observations made above provide sufficient information to make some general statements concerning the shape of welding lobes.

The lobe shape for any welding condition can be defined in terms of the ratio

![Diagram](image)

**Fig. 11**—Schematic welding lobe illustrating the four regions of nugget formation and expulsion described in the text. The times $t_1$, $t_2$, and $t_3$ are nugget growth parameters. $t_2$ is the time for the nugget to begin to form

![Diagram](image)

**Fig. 12** (right)—Schematic temperature profiles through the sheet thickness at short and long welding times in material of both high and low interface resistance
Mechanics of Nugget Development

In order to further understand the instabilities created in short time welding, the mechanics of nugget growth were studied for high, medium and low welding currents. Scanning electron microscopy revealed that a separate mode of nugget development is associated with each.

At very high currents and short welding times (region D of Fig. 11), the initial melting of the facing surface occurs around the periphery of the electrode - Fig. 13. At these very short times, expulsion occurs either before an acceptable nugget is formed or immediately after. Acceptable nuggets were formed by this mode only for the lower surface resistance conditions of HSLA pickled, and low carbon phosphate treated material. Significant expulsion was always present, although nuggets could be created in HSLA as-received, oxidized and low carbon phosphate treated material. Hence, the slower heating rates of low surface resistance materials are apparently more conducive to stable peripheral melting. The lower rate of surface heating allows time for the bulk material to reach the seal temperature.

It is believed that peripheral melting is due to the fact that the outermost surface of the contact area is under the least triaxial constraint. Therefore, this surface will be most easily deformed and will offer a low resistance current path. The use of domed electrodes may counteract this phenomena and allow for more successful welding at higher currents and shorter times. This can be substantiated by the use of such electrodes in the welding of aluminum where a high ratio of surface resistance to bulk resistance is present.

At lower surface currents, breakdown and current flow become more uniform across the interface. This is shown in Figs. 8 and 14. For these lower current welds, peripheral melting is absent. Figure 8 illustrates early nugget development for a weld below the minimum nugget diameter line at t_1 of Figure 11. The independent points of contact scattered evenly across the interface have been noted previously. Each individual cleavage fracture represents welding between the two sheets. Continued application of welding current would result in the coalescence of these individual welds.

Figure 14 shows the underdeveloped nugget of a low current, long time weld. The entire contact surface has melted on each sheet, however, the actual weld nugget is seen growing radially from the central region. This geometry is believed to be created by the radial temperature gradients which occur at long welding times due to diffusion of heat throughout the bulk. In these situations, heat is flowing radially outward into the sheets, and the center of the weld is the hottest and, therefore, the first region to melt.

Summary

The results of the study presented above suggest that there exists an optimum ratio of surface to bulk resistance, which will produce material with the widest range of welding current. Although little can usually be done to alter the resistivity of the base metal, cleaning or coating the sheet to alter the surface resistance can produce significant changes in the welding performance. In the case of the HSLA steel, a higher resistance coating has increased the welding current range to acceptable limit levels, while it has hardly affected the low carbon steel. A material such as aluminum with a very low bulk resistivity requires a very low surface resistance in order to provide the proper balance between surface and bulk heating. Most expulsion in aluminum spot welding is thought to be of the same form as that observed in Region D of Figure 11.

A further advantage of increasing the surface resistance of HSLA steel is a 20% reduction in electrode force which is permissible without a reduction in the width of the welding lobe. This decrease in force reduces the tendency for tip mushrooming during long production use. Another benefit is a marked reduction in the incidence of interfacial failure of the weld nuggets. Although the cause of this is not known, it may be related to the increased heating and decreased
cooling rates produced by the high resistance interfaces.

Conclusions

The experimental results of this study have disclosed some of the fundamental principles determining lobe shape determination. The following conclusions have been drawn concerning the resistance spot welding of HSLA and low carbon steels:

1. HSLA steels exhibit both higher bulk resistivities and surface resistances than similarly treated low carbon steels.
2. Electrode-sheet interface resistances are comparable in value to faying interface resistances; however, the heat generated at the former interfaces is primarily dissipated into the electrodes.
3. The actual area of current flow may vary markedly from the nominal area of contact. The lower the current or the shorter the weld time, the more this discrepancy will be accentuated.
4. The B peak of the dynamic resistance curve is shifted to earlier times in the weld sequence by increasing either the weld current or the surface resistance.
5. The significance of the B peak is diminished as weld time is decreased.
6. High current, short time welding creates initial melting around the periphery of the contact area. Moderate to low current welding creates more uniform melting across the contact area, causing the nugget to grow radially outward.
7. Higher electrode forces require welding at higher currents but allow for stable welding at shorter times.
8. The trends of lobe shape modification observed for lower surface resistance materials are analogous to the trends observed for higher electrode force welding.
9. HSLA lobe width can be increased by treating the surface with a high resistance oxide coating. Such a treatment also improves nugget failure characteristics and permits the use of lower electrode forces.

The experimental results of this study have only confirmed these conclusions for the welding of low carbon and HSLA steels. Nonetheless, it is believed that the heat generation balance as determined by the relative magnitude of surface resistance and bulk resistivity is generally applicable to all metals.

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