Computer Simulation of Resistance Spot Welding in Aluminum: Part II

Investigation of contact resistance, shunt effects and expulsion indicates the model is in good agreement with experimental results

BY D. J. BROWNE, H. W. CHANDLER, J. T. EVANS, P. S. JAMES, J. WEN, AND C. J. NEWTON

ABSTRACT. A computer-based model has been used to investigate nugget formation in the resistance spot welding of aluminum. As shown in a previous paper, contact resistance at the faying surface is a critical factor in spot welding aluminum. The effect of contact resistance in the presence of a shunt resistance is investigated in the present paper. With contact resistance distributed homogeneously over the area of physical contact at the faying surface, there is an optimum value of contact resistance for efficient nugget formation, depending on the value of the shunt resistance. On the other hand, if contact resistance is not homogeneously distributed over the physical contact area, localized conduction can lead to nugget formation even with high overall contact resistance. In the latter case, a minimum contact resistance is required for efficient nugget formation. Because it incorporates mechanical, as well as thermal/electrical analysis, the computer model is also capable of predicting conditions for the expulsion of weld metal at the faying surface. An example is given of the effect of applied force, acting through domed electrodes, on the conditions for expulsion. A comparison between experimental measurements of nugget growth and an equivalent computer simulation is given.

H. W. CHANDLER, J. T. EVANS, P. S. JAMES and J. WEN are with Department of Mechanical, Materials and Manufacturing Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne, U.K. D. J. BROWNE and C. J. NEWTON are with Alcan International, Banbury, Oxon, U.K.

Introduction

The development of a computer-based model of resistance spot welding, incorporating mechanical deformation, as well as electrical heating and thermal conduction, was described in a previous paper (Ref. 1). Computer-based models of resistance spot welding in steel have been used to develop strategies for process control (Refs. 2–5), but the details of the processes involved in the spot welding of aluminum alloys are not sufficiently understood to adopt the same approach without the development of a specialized model. Key factors in this uncertainty are the high electrical and thermal conductivity of aluminum alloys and the consequent sensitivity of nugget development to the contact resistance at the faying surface. In the present work, we describe how the model was adapted to study some features which are of practical importance in spot welding aluminum alloy sheet. Particular attention is paid to the role of the contact resistance at the faying surface and its interaction with other effects. The computer model also simulates elastic-plastic deformation in a realistic way and this can be used to investigate the effect of applied force on expulsion of weld metal at the faying surface. Four aspects of spot welding were investigated:

1) The effect of the presence of a shunt weld.

2) The optimum faying surface contact resistance for rapid weld nugget development.

3) The effect of an inhomogeneous distribution of contact resistance at the faying surface.

4) The effect of applied force on the conditions for expulsion of weld metal at the faying surface.

KEY WORDS

Computer Simulation
Resistance Spot Weld
Aluminum Alloys
Contact Resistance
Shunt Effects
Expulsion
Applied Force
Nugget Formation
Localized Conduction
Current Density

Modeling the Effect of a Shunt Weld

Preliminary studies made with the model (Ref. 1) showed the importance of the contact resistance at the faying surface in spot welding of aluminum alloys. Because of its low resistivity, ohmic heating is not as intense in the bulk of the aluminum as it is in steel. In addition, the thermal conductivity of aluminum is high, so the heat generated at the faying surface is rapidly conducted away into the electrodes and the cooling water. For these reasons, aluminum is more difficult to spot weld than steel, but to offset the disadvantage of high electrical conductivity, contact resistance at the faying surface can generate additional ohmic heat-

Table 1—Default Parameters Used in Simulations

Parameter	Value
Input current (50 Hz, sinusoidal)	28 kA (peak)
Applied force	5 kN
Cooling water interface, distance from electrode tip	3 mm
Contact resistance	450 μΩ
Shunt weld resistance	50 μΩ
Electrode tip radius	50.8 mm
Sheet thickness	2 mm

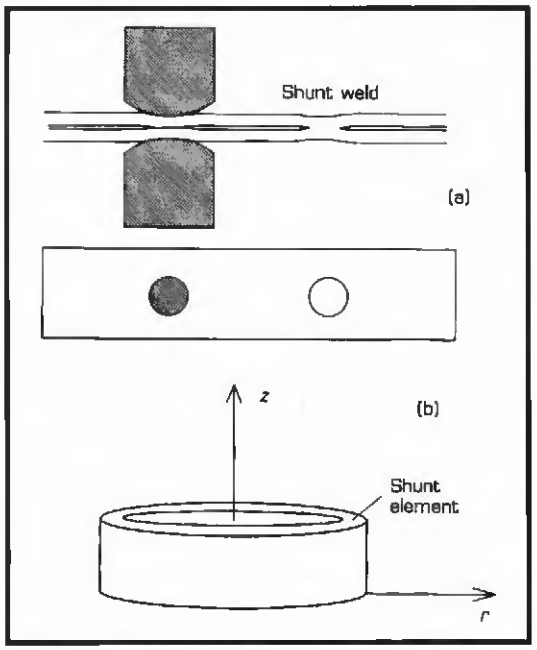

Fig. 1 — A — Schematic illustration of resistance spot welding with a neighboring shunt weld; B — axisymmetric model showing the location of the shunt weld element.

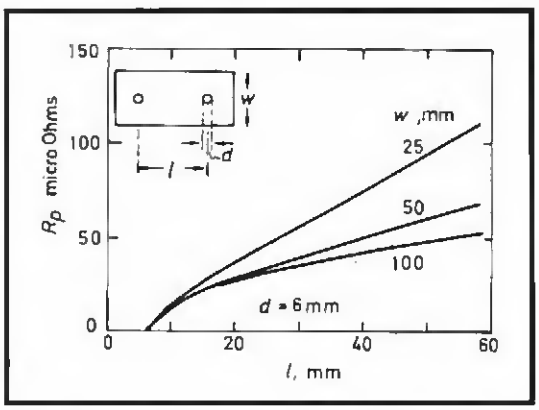

Fig. 2 — The electrical resistance of the path between the electrodes, through the shunt weld, as a function of distance and strip width. The diameter of the contact area and shunt weld was taken to be 6 mm and the thickness of the sheet is 2 mm.

ing. A high contact resistance is thus generally regarded as being favorable to spot welding aluminum. However, in practice, account must be taken of the presence of previously formed welds which form a shunt across the primary circuit of the electrodes — Fig. 1A. In this case, there is likely to be an optimum value of contact resistance for efficient nugget formation, because too large a value of contact resistance will cause current to be diverted into the shunt and too small a value will not give efficient heating at the faying surface (Refs. 6–9). The computer model can be adapted to incorporate the shunt effect, but a fabrication containing a series of spot welds does not possess the axial symmetry that is adopted in the computer model. To incorporate the effect of the shunt resistance in the model, allowance has to be made to interpret the effect of the real geometry of the electrode contact and shunt weld in terms of the axisymmetric model — Fig. 1A and B. Chang and Cho (Ref. 9) showed that the effect of the actual geometry of the arrangement is relatively unimportant unless the shunt weld is very close to the electrode— the important factor is the partition of current between the weld and the shunt. To utilize this finding, a shunt element with a special resistivity ρ_s was introduced into the finite difference mesh — Fig. 1B. The value of ρ_s was adjusted to give a shunt resistance R_s equivalent, in its effect on the partition of current between the electrode contact and the shunt, to those likely to be encountered in practice. In order to assign realistic values to R_s, it is useful to have a method of estimating the range of values of shunt resistance found in a strip. This can be done with the aid of potential theory as now described.

Consider two conducting strips of width w and thickness t and resistivity ρ, where the welds are made in the center of the strip. For a single, preformed weld at a distance l from the electrode, the shunt resistance is composed of the resistance of the weld R_w, which might include the effects of any porosity in the weld, and the resistance of the path R_p between the electrode and the shunt weld, *i.e.*,

$$R_s = R_w + 2R_p \qquad (1)$$

The path resistance between the electrode and a spot weld, diameter d, can be calculated from potential theory (Ref. 10) using the expression

$$R_p = \frac{2}{\pi}\frac{\rho}{t} ln\left[\frac{2}{\pi}\frac{w}{d} sinh\left(\pi\frac{l}{w}\right)\right] \qquad (2)$$

Curves showing the effect of w on the relation between R_p and l are plotted in Fig. 2. In this we assume a weld diameter d = 6 mm (0.24 in.), and a sheet thickness t = 2 mm (0.08 in.). The resistivity of the aluminum alloy is taken to be 48 μΩ mm. From equation 2 and Fig. 2 it can be seen that R_p will depend on the details of the geometry of the arrangement, but for the stated values of d and t, it is likely to lie in the range from 20 to 100 μΩ. The theoretical results for R_p are in line with experimental measurements made on welded aluminum strips, which, in addition, showed that the weld resistance R_w is very small (< 1 μΩ) relative to the path resistance. Thus, the shunt resistance R_s applied in the model can be equated with $2R_p$. Values of the shunt resistance used in the simulations reported below were chosen to be in the range 20 to 100 μΩ.

Effect of Shunt Weld Resistance on Nugget Formation

The efficiency with which a nugget is formed during spot welding depends on a number of interacting parameters, including the electrical current, the distance of the cooling water interface to the electrode tip, the sheet thickness, the applied force, and the electrode tip radius, as well as the contact resistance and the shunt resistance. Of these, the contact resistance is of prime importance, as demonstrated in a previous publication (Ref. 1). In the simulations reported below, the interaction between the contact resistance and the shunt resistance was studied. Unless otherwise stated, the default values shown in Table 1 were adopted for the values of the parameters used in the simulations reported below.

The effect of shunt resistance on nugget formation is shown in Fig. 3, where the nugget profile, representing the boundary between the fusion zone and unmelted aluminum, is shown as a function of time from the start of welding. With alternating current of 50 Hz, nugget profiles after four (0.08 s) and

eight (0.16 s) current cycles are shown in Fig. 3. With no shunt present, the imposed peak current of 28 kA is too great for controlled nugget formation and extensive melting is produced after eight current cycles — Fig. 3C. With shunt resistances of 33 and 83 μΩ (Fig. 3A and B), nuggets of a satisfactory size, contained within the sheet, are produced, although as anticipated, a larger nugget is formed with the 83 μΩ shunt resistance. The results are in good agreement with practical experience of spot welding, and also illustrate the general point that the current required to produce a run of good spot welds in a fabrication do not produce a good result for the first weld in the series (no shunt present).

Optimum Faying Surface Contact Resistance

From the example given in Fig. 3, it can be seen that a decrease in the contact resistance relative to the shunt resistance could have a beneficial effect by directing more current to the weld. On the other hand, less ohmic heating occurs with smaller values of contact resistance. Thus, with a given shunt resistance, the nugget size should reach a peak at some intermediate value of contact resistance. Computer simulations were performed with values of contact resistance varying from 50 to 3000 μΩ (the values of the other parameters are listed in Table 1). Experimental determinations of the contact resistance at the faying surface (Ref. 11) have shown that values in this range could be encountered in practice with coated-aluminum alloy sheet, depending on the surface condition. In order to represent the results in a simple form, the volume of the nugget at different times after the start of welding was calculated from the program output. The nugget volume, plotted as a function of contact resistance at increasing time from the start of welding, is shown in Fig. 4. Clearly, at any time after the start of welding, there is an optimum value of contact resistance for a maximum nugget volume, although the optimum value of this resistance increases with time.

Inhomogeneous Distribution of Contact Resistance

An implicit assumption in the simulations shown in Fig. 4 is that contact resistance at the faying surface is distributed evenly over the area of physical contact. The consequence is that with a shunt present, spot welding becomes difficult when R_c becomes large, and may be impossible when R_c is larger than 3000 μΩ. In fact, this conclusion is at variance with practical experience of spot welding coated-aluminum sheet, which may exhibit measured contact resistances greater than 3000 μΩ and yet still be weldable (Ref. 12). The discrepancy between the modeling results and experience is due to the fact that, in reality, current flow is localized through microscopic spots within the area of physical contact. This can produce intense localized heating, leading to melting on the microscale and breakdown of the high contact resistance. A detailed consideration of the nature of contact resistance (Ref. 13) indicates that it comprises constriction resistance produced by conduction through isolated microscopic areas of metal-to-metal contact, the rest of the physical contact area being effectively insulating. High contact resistance can occur in coated-aluminum sheet when metal-to-metal contact is produced by just a few asperities breaking through the insulating film. Consider an area of physical contact, radius r_0 containing n spots of metal-to-metal contact. If the mean radius of the contact spots is $\bar{a}$, Greenwood's (Ref. 13) equation for the contact resistance is

$$R_c = \frac{\rho}{2n\bar{a}} + \frac{\rho}{2r_H} \qquad (3)$$

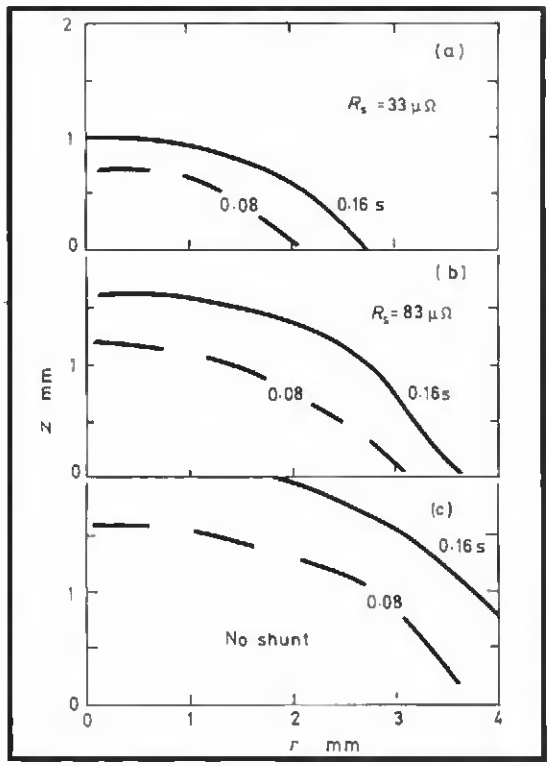

Fig. 3 — Nugget profiles showing the effect of shunt resistance. The default values of other parameters are shown in Table 1.

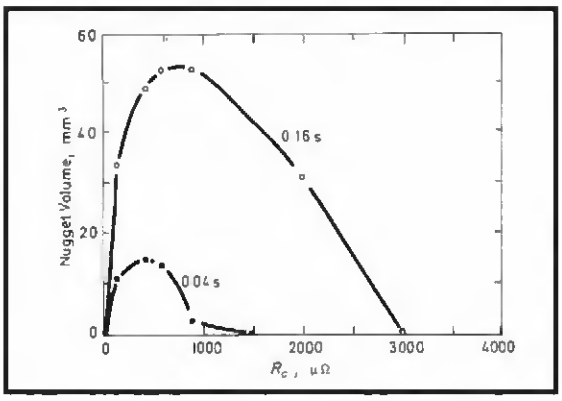

Fig. 4 — The effect of variations in contact resistance on nugget volume (shunt resistance 50 μΩ).

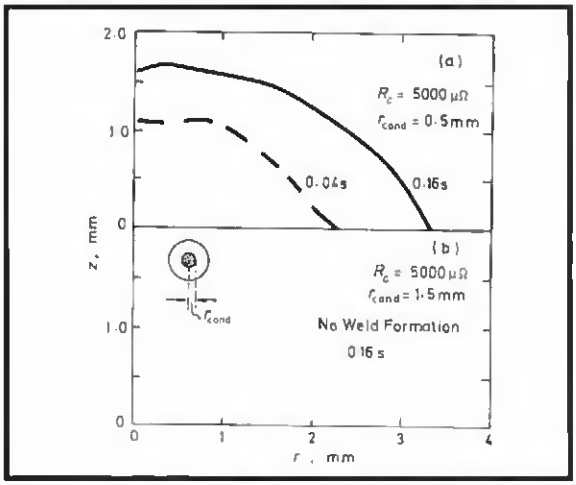

Fig. 5 — Nugget formation with high contact resistance by conduction through a localized patch, radius r_{cond}, within the contact area at the faying surface.

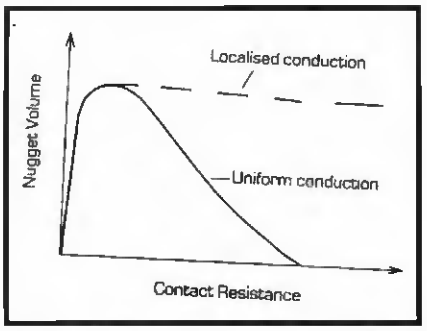

Fig. 6 — Schematic illustration of the effect of faying surface contact resistance on the nugget volume showing the effect of localized conduction at the faying surface.

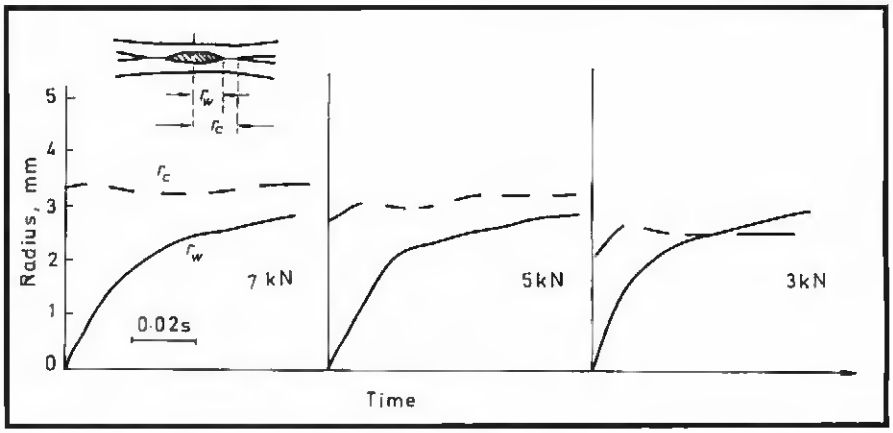

Fig. 7 — The effect of applied force in preventing expulsion of weld metal at the faying surface. The radius of the pool of molten metal r_w and the physical contact radius at the faying surface r_c are shown as functions of time after the start of welding.

where ρ is the resistivity of the material and r_H is the so-called Holm radius of the assembly. When a circular area of physical contact is well filled with contact spots, r_H is approximately equal to r_0. With high contact resistance the second term on the right side of Equation 3 becomes insignificant with respect to the first term. The assumption that contact resistance is spatially uniform is convenient for modeling and is equivalent to having a large number of contact spots evenly distributed over the physical contact area. In fact, as shown by Equation 3, the same overall contact resistance can be achieved in many different ways. For instance, a large number of small spots will give the same contact resistance as a smaller number of larger spots if the product $nã$ is constant. With high contact resistance, there will be relatively few small conduction spots and here microscopic melting occurring early on in the spot welding cycle could lead to a more rapid breakdown in contact resistance than is predicted with a macroscopic model.

To consider this quantitatively, imagine an area of physical contact at the faying surface of radius 3 mm but with a measured contact resistance of 5000 μΩ (experimental studies show that values of contact resistance as high as this can occur with coated alloy strip). Application of Equation 3 to the above example shows that just 10 single metal-to-metal contact spots of 0.5 μm radius contained within the total area could account for the 5000 μΩ contact resistance. In spot welding with this high contact resistance, most of the applied current would be diverted to the shunt weld. But even though a small current passes through the faying surface initially, the current density through the microspots might be high enough to produce microscopic melting, leading to a rapid growth in the size of the contact spots. This may be sufficient to nucleate the process of nugget formation, despite the small initial current passing through the weld. Nugget formation, once nucleated, can be self-sustaining because of the associated increase in resistivity as the temperature rises. Unfortunately, modeling microscopic phenomena of this sort is not feasible with the macroscopic model used to make the present computer simulations. Nevertheless, the trend of the effect of localized conduction at the faying surface can be demonstrated with the following simulation.

A constant nominal contact resistance of 5000 μΩ was selected for the demonstration, together with a shunt resistance of 50 μΩ. As shown by the results in Fig. 4, these resistance values are such that no weld would form if the weld current flowed homogeneously through the whole physical contact area. To mimic localized conduction, the 5000 μΩ resistance was distributed over a reduced number of nodes at the faying surface within a radius r_{cond} from the central axis of the electrodes. The remaining outer nodes at the contact area were then assigned effectively infinite resistances to simulate an insulating coating which has not broken down by mechanical contact. On running the model with this arrangement it was found that, despite the high total contact resistance, good-sized nuggets were formed with values of r_{cond} from 0.1 up to 0.5 mm. These values can be compared with the radius of physical contact, which is 3 mm. Note that 0.1 mm is the smallest value of r_{cond} that can be taken since this covers only two nodes at the faying surface. The results are shown in Fig. 5. When values of r_{cond} greater than 0.5 mm were used, the nugget size became progressively smaller until, at r_{cond} = 1.5 mm (0.60 in.), no nugget was formed at all within 8 cycles of alternating current — Fig. 5B.

The simulation demonstrates that nugget formation is possible even with a high faying surface resistance and a shunt present, provided that localized conduction is confined to a small area within the area of physical contact. Thus, the interpretation of the effect of contact resistance in Fig. 4 should be modified at high contact resistance to allow for the effect of localized conduction within the area of physical contact at the faying surface. A schematic illustration of this possibility is shown in Fig. 6. In this case, contact resistance above a critical value, rather than an optimum value, is indicated for good nugget development.

Expulsion at the Faying Surface

A feature of the computer model is its capability for simulating elastic-plastic deformation in a realistic way, with force applied through domed electrodes. The applied force affects nugget formation through its effect on the area of contact at the faying surface and, as previously reported (Ref. 1), a low electrode force produces larger nugget growth because of the higher current density through a smaller contact area. On the other hand, there is a limit to the extent of nugget growth that can be allowed with low applied forces because of the possibility of expulsion of liquid weld metal at the faying surface. Before expulsion occurs, the pool of weld metal is sealed within surrounding solid material by the pressure exerted at the faying surface by the applied force, as shown schematically in the inset in Fig. 7. A simple criterion for expulsion at the faying surface can be devised using two outputs of the model: the radius of the pool of weld metal at the faying surface r_w and the radius of the cir-

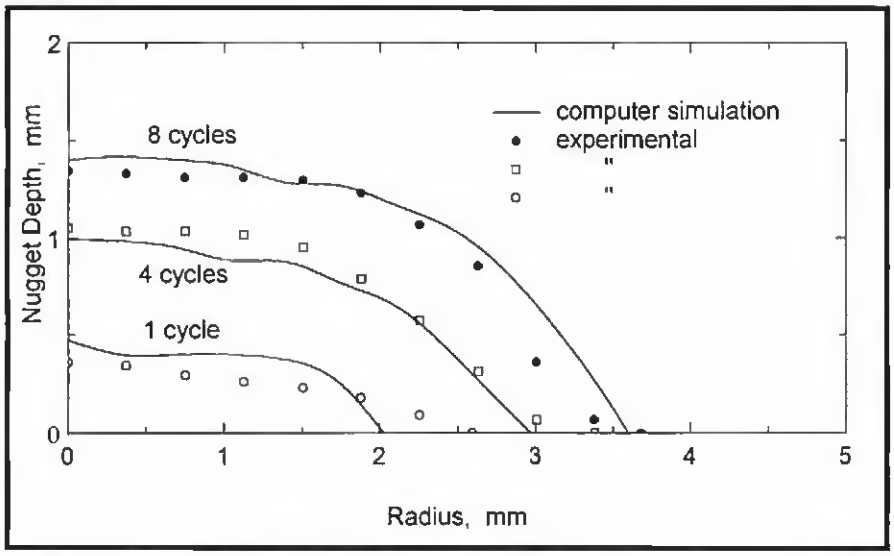

Fig. 8 — Comparison of experimentally observed nugget growth with the computer simulations.

cle of contact between the sheets r_c, where there is a positive pressure acting to compress the sheets. Provided that $r_w < r_c$, the weld metal is contained within the solid, but if r_w becomes larger than r_c, then liquid metal expulsion is judged to have occurred. An example of the relation between both r_c and r_w and time after the start of welding is shown in Fig. 7. With the default values of the various parameters used in the simulation, there is little danger of expulsion with an electrode force of 7 kN for a welding time of up to the equivalent of 8 cycles of alternating current. Application of a lower force of 5 kN brings r_w and r_c closer to the limit for expulsion. Expulsion is predicted to occur within the time of 8 current cycles with a force of 3 kN since r_w grows to be larger than r_c within the time period — Fig. 7.

Comparison of Simulations and Experiment

The most constructive use of computer simulation is for the investigation of the interaction of parameters for circumstances of which there is little prior knowledge. On the other hand, it is also important to know if the computer model is capable of giving results that compare realistically with experience. This point was tested in the present case by performing experiments on aluminum alloy sheet using an instrumented spot welding gun and comparing observed nugget growth with that predicted by the model.

A series of spot welds was made at 30-mm (1.2-in.) intervals along the central axis of a pair of 50-mm (2-in.) wide, 2-mm (0.08-in.) thick aluminum alloy strips. The welds were made using 50 Hz alternating current with a peak value of 28 kA. A clamping force of 5 kN was used, applied through domed copper electrodes (50.8-mm radius). The shunt resistance for these welds was measured to be 60 μΩ. Regular welds were made with 8 cycles of current. Test welds were made with 1 and 4 current cycles and these were interspersed between the regular welds. The welded strip was then sectioned along the central axis and metallurgical sections of the test welds were prepared to observe nugget growth. Measurements taken from the sections showing nugget growth after 1, 4 and 8 current cycles are plotted in Fig. 8. The points shown in the graph represent mean values from the four quarters of the full nugget sections.

The formation of a nugget was also simulated with the computer model using the parameters applied in the experiments. However, since contact resistance is the least well-defined parameter in the simulation, it was measured using a special procedure. Single welds (no shunts) were made in replicate sheets using a reduced current designed to simulate the current passing through the faying surface when a shunt is present. Dynamic contact-resistance values were obtained via the instrumentation fitted to the welding gun. It was found that the contact resistance fell from 520 to 200 μΩ within the early part of the first current cycle. The observed contact resistance/time behavior was then replicated in the computer simulation. Clearly, as shown in Fig. 8, there is generally good agreement between the simulation and the results of the experiment. At 4 and 8 cycles, the predictions are very close to the observations. At 1 cycle, the computer simulation somewhat underestimates the extent of nugget growth at the faying surface, but somewhat overestimates the extent of growth in the axial direction.

Discussion

The results of the modeling studies highlight the contact resistance at the faying surface as a key factor in the resistance spot welding of aluminum. Contact resistance is required in order to spot weld aluminum, but if its value is too high, too much current is diverted to the shunt weld, with a consequent drop in efficiency. However, simulations show that restricting conduction to a localized region within the physical contact area can produce good nugget formation even when the contact resistance is high — Fig. 5. It should be remarked that this effect is analogous to the observation that nugget growth is greatest at low applied loads (Ref. 1). In both cases the current density is higher because of the smaller contact area at the faying surface. The results of the study of the effect of localization of conduction indicates the probability that satisfactory nugget growth is possible with very high overall contact resistance if, despite a high overall contact resistance, there are microscopic areas of good conduction at the faying surface to initiate melting in a localized region. Once initiated locally, further nugget growth is self-sustaining, so that good-sized nuggets can be obtained from a small initiation patch. This result is of practical significance for the resistance spot welding of aluminum alloy sheet with special surface treatments which produce a thin, insulating coating. Such sheets may have large overall contact resistance values at the faying surface, but still may be weldable because of the sharply localized areas of microscopic conduction. In the context of the control of resistance spot welding of aluminum, the results in Fig. 4 should be modified when conduction occurs in localized regions within the contact area — Fig. 6. With localized conduction, contact resistance above a critical level (in the range 500 to 1000 μΩ), rather than an optimum, is required for efficient spot welding of aluminum. Clearly localized conduction is potentially an important feature of spot welding aluminum with insulating coatings and more research is required on the details of the process.

The incorporation of realistic modeling of deformation is a feature of the present model. One effect of mechanical deformation is in controlling the physical area of contact at both the faying and

electrode surfaces so the applied force influences the current density and thus affects nugget formation (Ref. 1). However, a more important effect of applied force is in preventing the expulsion of molten metal at the faying surface. In the example given in Fig. 7, it was found that expulsion is likely to occur with an applied force of 3 kN, but not when it is above 5 kN. These relationships are expected to change with different sheet thickness, electrode tip radius and changes in the other parameters, and can be readily investigated with the present model.

The model has been developed to a stage which can be envisaged to assist process control in future developments. However, since a mathematical model is only an abstraction of reality, the output depends critically on the assumptions, interpolations and extrapolations made in constructing the model. In the present work, it is clear that the results are most sensitive to the assumptions made about the behavior of the contact resistance at the faying surface. The contact resistance can be measured experimentally, as reported elsewhere by the authors (Ref. 8), but even with extensive experimental information on contact resistance, additional assumptions have to be made. For instance, a macroscopic measurement of contact resistance does not provide any information about the distribution of microscopic conduction at the faying surface. However, despite the uncertainties, the assumptions of the present model work, in the sense that good agreement has been found between the predictions of nugget shape and size and experimental data obtained from sectioned welds made in trial studies — Fig. 8.

Conclusions

1) The contact resistance at the faying surface is a key factor in nugget formation.

2) The effect of contact resistance depends on its value in relation to the shunt resistance arising from previously formed spot welds.

3) With a homogeneous distribution of contact resistance at the faying surfaces, there is an optimum contact resistance for efficient nugget formation. Nugget formation can be suppressed with very high values of contact resistance.

4) Nugget formation can occur with high values of contact resistance if conduction at the faying surface is localized, as might occur with an isolated breakthrough of asperities through an insulating surface film. In this case, it is deduced that a minimum, rather than an optimum, value of contact resistance is required for efficient spot welding.

5) The weld force applied through domed electrodes affects nugget formation by controlling the contact area at the faying surface. A small weld force assists nugget formation by increasing the local current density, but larger applied forces are essential to minimize the expulsion of weld metal.

Acknowledgments

The authors are grateful to Alcan International for permission to publish this paper. D. J. Browne and J. Wen gratefully acknowledge the support of Alcan International in the period when the work was undertaken.

References

1. Browne, D. J., Chandler, H. W., Evans, J. T., Wen, J., and Newton, C. J. 1995. Computer simulation of resistance spot welding in aluminum: Part 1. Welding Journal 74(10): 339-s to 344-s.

2. Tsai, C. L., Dai, W. L., Dickinson, D. W., and Papritan, J. C. 1991. Analysis and development of a real-time control methodology in resistance spot welding. Welding Journal 69(12): 339-s to 351-s.

3. Vogler, M. M. 1992. Investigation of spot welding formation, Ph.D. Thesis, Stanford University.

4. Vogler, M. M., and Sheppard, S. D. 1992. A study of temperature histories in resistance spot welding. The 3rd International Conference on Trends in Welding Research, pp. 57–61, Gatlingburg, Tenn.

5. Vogler, M. M., and Sheppard, S. D. 1993. Electrical contact resistance under high loads and elevated temperatures. Welding Journal 72(6): 231s to 238s.

6. Nippes, E. F., Savage, W. F., and Robelotto, S. M. 1955. Measurement of shunting currents in series spot welding 0.036-in. steel, Welding Journal 34(6): 618-s to 624-s.

7. Johnson, I. W. 1960. Spot welding of carbon steel, Welding Journal 39(1): 89-s to 96-s.

8. Blair, R. H. 1947. Shunt circuit impedance in spot welding 1/8, 1/4 and 1/2 in. mild steel. Welding Journal 26(10): 843 to 848.

9. Chang, H. S., and Cho, H. S. 1990. A study on the shunt effect on resistance spot welding, Welding Journal 69(8): 308-s to 317-s.

10. Coulson, C. A., and Boyd, T. J. M. 1979. Electricity. Longmans, London.

11. James, P. S., Browne, D. J., Chandler, H. W., Evans, J. T., and Wen, J. 1993. The effect of mechanical loading on the measurement of contact resistance of aluminum alloys. To be published.

12. Newton, C. J. 1992. Alcan International, Banbury U.K. Private communication.

13. Greenwood, J. A. 1966. Constriction resistance and the real area of contact. Br. J. Appl. Phys. 17: 1621–1632.