Measurement of Transient Temperature Response during Resistance Spot Welding

High-speed cinematography and infrared emission monitoring are used to evaluate heat transfer with various electrodes

BY E. W. KIM AND T. W. EAGAR

ABSTRACT. The transient temperature response during resistance spot welding was measured as a function of various process parameters. The variables include the electrode face thickness, coolant flow rate, welding schedule, electrode force and type of zinc coating.

Two different experimental methods were used. The first one used an infrared emission monitoring method which measures the surface temperature using a Thermovision system. The other method used high-speed cinematography of a cross-sectioned welding setup. The cross-sectioned surface was painted with thermosensitive paint in order to measure the movement of the isotherm during the welding process.

It was found that the slowest step of heat transfer during the axial direction in resistance spot welding is convective heat transfer to the coolant at the electrode/coolant interface. There exists a critical electrode face thickness for which the minimum electrode temperature can be obtained. The critical electrode thickness changes with weld parameters such as welding current, welding time and the heat transfer coefficient at the water cooling surface. A discontinuity in temperature was proven to exist across the electrode/workpiece interface. The heat transfer characteristics across this interface significantly affect the nugget development mechanism in zinc-coated, low-carbon steel. It was also found that galvannealed steel and bare steel induce lower currents in comparison to galvanized steels. Nonetheless, the overall temperature profiles are higher for galvannealed steel and bare steel due to a lower heat transfer rate at the electrode/workpiece interface. These two materials are less sensitive to the electrode force than is the galvanized steel. It was also found that nugget formation initiated at the faying interface with truncated-cone electrodes and at the electrode interface with dome-type electrodes.

Introduction

Since the development of resistance spot welding, a large amount of work has been devoted to understanding the mechanism of nugget formation and electrode wear. As a part of these efforts, various thermal models have been produced (Refs. 1-8). Nevertheless, such modeling work alone is not useful and must be supported by experiments to verify the suitability of the model as a prediction tool. It is felt that the measurement of temperature profiles developed during the welding process is very important in this respect.

In this work, the transient temperature change on the electrode surface was measured using various electrode face thicknesses and coolant flow rates. To see the effect of the electrode force and zinc coating composition on galvanized steel, the temperature distribution during...
welding was monitored in a one-dimensional experimental simulation of the process. The heat propagation into the electrode was also observed on the surface of the cross-sectioned electrode and the workpiece. These experimental observations were then related to the observed welding behavior.

Experimental Procedures

Two different experimental methods were used. The first one used an infrared monitoring method that measures the surface temperature using a Thermovision system (Inframetrics Model 600). The other used high-speed cinematography of the cross-sectioned welding system (Refs. 9-12). The propagation of an isotherm can be traced using cinematography coupled with thermosensitive paints on the flat surface of the sectioned electrodes. Further explanation of these procedures is given below.

Infrared Emission Monitoring

The Thermovision system monitors the emission intensity from the surface of the electrode and the workpiece in the light wavelength range of 8 to 14 micrometers. The experimental apparatus is shown in Fig. 1. The scanning speed of this system is 4 kHz in the horizontal direction and 60 Hz in the vertical direction. The data are displayed in NTSC video format. Data are recorded on videotape and can be analyzed later using a computer interface. The measurement resolution is 8 bits, which is equivalent to 256 steps for a given temperature measuring range.

The most crucial factor in accurate measurement of temperature in this experiment is the emissivity calibration of the emitting surface. As the temperature increases, the surface condition of the electrode and of the workpiece will change; therefore, it is very important to have a known emissivity throughout the experiment. To achieve this, the surface was painted with temperature-sensitive lacquer, which remains solid to 1371°C (2500°F). The emissivity of this lacquer was calibrated by comparing the Thermovision temperature measurement with thermocouple readings on a statically heated sheet held at various temperatures.

Two different experiments were performed using this technique. The first was a measurement of the electrode surface temperature. A series of welds was produced that simulated a robotic welder in an automotive assembly line. Twenty welds were made with 1-in. nugget spacing at a repetition rate of 45 welds per minute followed by a period of 23 s with no welds. This weld-no weld cycle was repeated three times, making a total of 60 welds. The coupon consisted of two strips, each 1 in. (25 mm) wide and 22 in. (56 cm) long. The variables that were evaluated included the electrode face thickness and the coolant flow rate.

The second experiment involved a one-dimensional simulation of the welding process. The setup is shown in Fig. 2. The length of the slender solid cylindrical electrode was 19 mm (0.75 in.) and the diameter was 4.8 mm (0.18 in.). The coupons were made by punching out disks from sheet stock which were then statically pressed at 500 lb (227 kg) to eliminate the shear lips. To keep the temperature low enough during the weld simulation so that the collapse of the disk coupon could be avoided, the welding current was reduced by inserting an electrically resistive material, such as Inconel® or stainless foil, between the electrode shank and the welding machine. The increase of the electrical resistance of the secondary loop was about tenfold, which reduced the secondary current to acceptable levels. This test was used to determine development of the temperature field in the workpiece and in the electrode. The variables studied in this experiment included changes in the electrode force as well as the zinc coating of the steel.

High-Speed Filming

The experimental setup for high-speed cinematography is shown in Fig. 3. The cross-sectioned electrode surface and the workpiece edges were painted with thermosensitive paint, which melted at the relatively low temperature of 371°C (700°F). The propagation of the 371°C isotherm into the electrode can be measured by tracing the melt line of the paint. The pictures were taken at the rate of
1200 pps (pictures per second). The response time of the lacquer is claimed to be a few milliseconds and to have an accuracy of ±1% by the manufacturer (Ref. 13).

Results and Discussion

In general, conductive heat flow across different materials is analogous to flow through a series of thermal resistances. A simple one-dimensional heat flow model of resistance spot welding is shown in Fig. 4. The heat flow in the radial direction for the case of spot welding of steel sheets is considered to be very small and hence is neglected, especially when the thickness of the sheet is small (Ref. 14). If one of the thermal resistances is very much greater than the others, the greatest thermal resistance will control the flow of heat in the system.

Heat flow within the molten nugget is influenced by magnetohydrodynamic convection induced by the welding current. This convection is very strong, which will increase the effective thermal conductivity of the liquid. For simplicity, it is assumed that the convection-enhanced thermal conductivity of the liquid metal is much larger than the thermal conductivity of the solid. The thermal resistance of the workpiece, $R_W$, and of the electrode material, $R_E$, are the reciprocals of the thermal conductivity of each material. The thermal resistance at the electrode interface, $R_{EI}$, acts as a thermal barrier to heat flow from the workpiece to the electrode. Another thermal resistance is included at the boundary layer of the coolant, which is symbolized as $R_C$. The convective heat transfer of the coolant itself is assumed to be very large so that the effective thermal resistance of the coolant, $R_C$, can be neglected. In the following sections, experimental results will be discussed with regard to each of these thermal resistances.

Electrode Temperature

One example of the two-dimensional electrode surface temperature field as measured with the Thermovision system is shown in Fig. 5. The relatively even temperature field in the horizontal direction is clearly seen, and is strong justification for the simplicity of the one-dimensional thermal model. A typical cascade display of a high-speed line scan along the centerline of a similar weld is shown in Fig. 6. The temperature drop at the center is due to the low temperature of the workpiece edge, which is far from the nugget-formation zone. In this experiment, the temperature of the workpiece does not have any significance as the purpose is to measure heat flow in the electrodes. The vertical direction in this figure represents the time axis, and the
Horizontal direction is the geometric position along the electrode axis. The internal geometry of the electrodes was modified by machining conventional RWMA Class 2, A cap electrode shapes to thinner electrode faces. Four different face thicknesses were tested: 2.8, 4.7, 6.6, and 8.5 mm (0.11, 0.18, 0.26, and 0.33 in.). The overall geometry of the electrode that was used is shown in Fig. 7. Welding was performed on 0.8 mm (0.03 in.) electro-galvanized sheet steel, which had 70 g/m² of zinc on both sides. For all cases, the electrode force was 720 lb (327 kg) and the welding time was 12 cycles with two different current settings at the same tap.

Effect of Electrode Face Thickness. Figure 8 shows the maximum temperature observed experimentally on the electrode surface as a function of the number of welds. The welds were made at 10.6 ± 0.1 kA with coolant flow rate fixed at 0.7 gpm (2.6 L/min). These experiments were conducted to investigate the effect of electrode face thickness and the evolution of electrode temperature in successive welding. It is seen that the maximum temperature increases during the first three to five welds and then stabilizes. The temperature rise toward the end of the twentieth weld is due to the heat built up in the workpiece as the welding progresses towards the end of the coupon.

As the face thickness is reduced, the maximum temperature decreases but then increases when the face thickness becomes too thin. Thus, there exists a critical face thickness which minimizes the electrode surface temperature. In this experiment for a weld of 12 cycles, the minimum temperature rise occurs at a face thickness of around 4.7 mm, while the maximum temperature was decreased by about 60 °C (108°F).

Table 1 summarizes another set of experiments wherein the maximum electrode temperature was monitored as a function of various coolant flow rates and electrode face thicknesses. The welding current ranged from 12.5 kA to 12.7 kA. The plots of these data are shown in Fig. 9, which depict the maximum electrode temperature change during the welding cycle. Twenty welds were made in a series. The experimental data were taken from the four welds of these 20 welds for every other cycle. The curves were generated by curve fitting the discrete experimental data with a correlation factor exceeding 0.98 for all cases. The symbols in the graphs were merely inserted to identify each line. Compared with the data in Fig. 8, the temperatures are generally higher due to the increased welding current. It is clear from Fig. 9 and Table 1 that the electrode face thickness has a much greater effect on the maximum electrode temperature than the coolant flow rate. In Table 1, the temperatures for the 6.6- and 2.8-mm (0.26- and 0.11-in.) electrodes at the flow rate of 0.9 gpm seem to be abnormally high. Two possible reasons can be contemplated. The first is the high heat generation rate caused by the contaminated electrode contact surface. The other reason may be the change in the emissivity due to the uneven thickness of the high-temperature lacquer or the smut produced by the contaminated contact surface during welding. Taking the abnormalities into account, it may be said that the lowest temperatures occur in the 6.6-mm electrode of this high-current experiment. The lowest maximum electrode temperature for the 0.7 gpm flow rate occurred in the 6.6-mm-thick electrode. This can be compared with the previous experiment where the lowest temperature occurred in the 4.7-mm-thick electrode with the same coolant flow rate. By increasing the welding current from 10.6 to 12.6 kA, the optimum electrode face thickness had changed.

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**Table 1—Effect of Coolant Flow Rates and Electrode Face Thickness on the Maximum Electrode Surface Temperature**

<table>
<thead>
<tr>
<th>Thickness</th>
<th>0.9 gpm</th>
<th>0.7 gpm</th>
<th>0.5 gpm</th>
<th>0.2 gpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5 mm</td>
<td>460</td>
<td>472</td>
<td>485</td>
<td>481</td>
</tr>
<tr>
<td>6.6 mm</td>
<td>(421)</td>
<td>392</td>
<td>400</td>
<td>420</td>
</tr>
<tr>
<td>4.7 mm</td>
<td>388</td>
<td>413</td>
<td>429</td>
<td>450</td>
</tr>
<tr>
<td>2.8 mm</td>
<td>(487)</td>
<td>466</td>
<td>491</td>
<td>505</td>
</tr>
</tbody>
</table>

(a) Temperatures in Centigrade.
from 4.7 to 6.6 mm. The maximum decrease in the electrode temperature is about 80°C (144°F) for this electrode. For a given flow rate, the effects of the electrode face thickness can be explained below.

The heat diffusion length in a solid body can be estimated by calculating the characteristic heat diffusion length. If the temperature at the electrode interface is assumed constant during each half cycle of weld, this diffusion length, \( L \), is equal to \( 2\sqrt{\alpha t} \) for a temperature rise of 16% of the electrode interface temperature. Here \( \alpha \) is the thermal diffusivity of the electrode material, which is roughly 0.9 cm²/s (5.8 in.²/s), and \( t \) is the welding time, which in this case was 0.2 s (12 cycles). Thus, the estimated characteristic heat diffusion length during the weld cycle is 8.5 mm. This means that the heat generated at the first cycle of welding will diffuse a distance of about 8.5 mm from the electrode interface by the end of the weld cycle. On the other hand, the heat generated at the 12th cycle will propagate only about 2.5 mm before the end of the weld cycle. By decreasing the electrode face thickness, the water-cooled surface area can be increased. If the heat flow at the coolant interface is the rate-determining step, the electrode temperature at the water-cooled surface will increase, thus producing a greater temperature drop across the coolant boundary layer. The increased water-cooled surface area and the larger temperature drop with thinner electrode faces will help reduce the electrode temperature. However, if the electrode face thickness is too thin, heat will build up near the electrode face due to insufficient water cooling. This is pictorially explained in Fig. 10A. The maximum electrode temperature will be determined by the competition of these two factors, i.e., the heat diffusion length and the water cooling at the electrode/coolant interface.

As can be seen in Fig. 8 and Table 1, the 8.5- and 2.8-mm-thick electrodes exhibit the highest temperatures. For the 8.5-mm-thick electrode, water cooling has a very small effect on the electrode/sheet interface temperature during the time of the weld cycle, since most of the heat cannot diffuse as far as the water in the time allowed. This is illustrated in Fig. 9A. In this case, the water cooling merely cools the electrode after the weld is completed. There is a very small effect of the water flow rate on the electrode face temperature during welding, per se. On the contrary, the 2.8-mm-thick electrode experiences cooling by the water during the welding cycle. However, since heat transfer through the water, even in the presence of strong convection, is less than heat diffusion in the copper, heat will build up near the electrode face. For electrodes with thicknesses between these two cases, maximum temperature is lower due to optimization of heat diffusion in the copper and of heat extraction by the water cooling.

For the electrodes with these thicknesses, the effects of the intensity of heat input, the electrode thickness, the heat transfer coefficient at the cooling interface, and the thermal conductivity can be seen as follows. For a simple one-dimensional heat flux equilibrium through the electrode and the cooling water,

\[
k \cdot (T_r - T_c) / L = h \cdot (T_c - T_w) = Q \tag{1}
\]

where \( k \) = electrode thermal conductivity, \( L \) = electrode face thickness, \( h \) = heat transfer coefficient, \( T_r \) = electrode temperature, \( T_c \) = cooling water temperature, and \( T_w \) = water temperature.
transfer coefficient at the cooling interface, $Q = \text{heat flux}$, $T_f = \text{temperature at electrode/workpiece interface}$, $T_c = \text{temperature at the water cooling surface}$ and $T_w = \text{coolant temperature}$. Rearranging these equations,

$$T_f = (A + 1) \cdot T_c - A \cdot T_w \tag{2}$$

$$T_f = T_c + B \tag{3}$$

where, $A = \frac{L \cdot h}{k}$, $B = \frac{L \cdot Q}{k}$.

Equations 2 and 3 are plotted in Fig. 11 with axes $T_f$ and $T_c$. The position of the curves represented by these equations in the $T_f$-$T_c$ plane is determined by the parameters $A$ and $B$. Parameter $A$ is the slope of Equation 2 and is basically a Biot number. For the hypothetical value of $A_2$ and $B_2$, the crossing point, $a$, of these two curves determines the electrode face temperature $T_f$. If the heat input $Q$ is increased, the parameter $B$ increases from $B_2$ to $B_1$, and hence the electrode temperature will increase to the point $b$ in Fig. 11. However, if the electrode face thickness is increased, the temperature drops to the point $c$ by the increase of $A$ from $A_2$ to $A_1$, and then moves in the direction $d$ with additional increases in the parameter $B$, i.e., the final position of $d$ may be either lower or higher than that of the point $b$ depending on the relative positions of the two curves. This suggests the possibility that it may be advantageous to use a thicker electrode for a higher welding current. By the same argument, if the electrode face thickness decreases, the electrode face temperature will follow the path $a$-$b$-$e$-$f$. The final position of $f$ is also dependent on the relative position of the two curves. The thinner electrode may be beneficial or not, depending on the relative values of $A$ and $B$. In this experiment, the lowest temperature was observed in the 4.7-mm electrode for low-current welding, while lower temperatures were found in the 6.6-mm electrode for high-current welding.

The effect of changes in the electrode face thickness, $L$, for a given welding current is the same. The temperature will follow the path $a$-$g$-$d$ or $a$-$h$-$f$, depending on whether the electrode thickness is increased or decreased. An increase in the heat transfer coefficient, $h$, always decreases the electrode temperature from $a$ to $g$.

**Effect of Coolant Flow Rate.** As was discussed in the previous section, the increase in flow rate does not show any significant reduction in the maximum electrode temperature for the 8.5-mm electrode. However, the time held above the threshold is responsive to the flow rate as can be seen in Fig. 9A. By increasing the flow rate, the time above the threshold decreases due to the faster subsequent water cooling. This subsequent cooling is more effective when the electrode face thickness is thinner. This is shown in Fig. 10B. The cooling temperature gradient is steeper for a thinner electrode and the final temperature is generally lower for such an electrode.

It is believed that the electrode wear is related to both the maximum time duration at temperature and the magnitude of the maximum temperature. From this point of view, it is also important to optimize the flow rate and the internal geometry in terms of the coolant flow. It is seen in Fig. 11 that the effect of increased heat transfer coefficient is very important in lowering the electrode temperature. Therefore, thermal optimization of the electrode design should include both the electrode face thickness and also the characteristics of convective cooling behavior of the water. When the electrode is thick enough, the factor controlling the maximum temperature of the electrode depends on the heat diffusion.
characteristics of the electrode body. When the face thickness is less than the longest diffusion distance, convective heat transfer at the coolant interface will control the maximum face temperature during welding. In general, the rate-controlling step for the electrode thermal behavior or the slowest process of heat transfer in resistance spot welding is convective heat transfer of the coolant at the cooling interface.

Effect of the Coating and the Electrode Force

Figure 12 shows a typical temperature profile developed in the one-dimensional simulation. The two vertical lines marked A near the center show the location of the electrode interfaces. Another set of vertical lines marked B is 3 mm (0.12 in.) from the interface where the electrode temperature was monitored. The temperature was also measured at the workpiece center and the electrode interface. The measurement was performed when the highest temperature was reached at the facing interface. As would be expected, the temperature always reached its maximum value at the end of the weld cycle. Specimens of EG (electrogalvanized steel, 70 g/m², both sides), G60 (hot dip galvanized steel), A40 (galvannealed steel) and bare steel (zinc removed by HCl etching from EG 70/70) were used. All were 0.8-mm-thick, low-carbon steel. Welding was done at 450, 550, 650 and 750 lb (205, 250, 295 and 341 kg) with the same current setting in the welding machine. Therefore, differences in electrical properties of the workpieces and of the contact interfaces will induce different welding currents resulting in different temperature profiles. The results are shown in Figs. 13 and 14.

For a given welding machine setting, A40 and bare steel lead to lower currents in comparison to G60 and EG. Nonetheless, the overall temperature profiles are higher for A40 and bare steel. A material with a high electrical contact resistance will produce more heat and will produce higher temperatures provided that the welding current is fixed. But the situation of this experiment is different. The materials that are believed to have higher electrical contact resistance induce lower welding currents and exhibit higher temperatures in the workpieces. The higher temperature may be due to a higher heat generation rate or to a lower heat loss rate or to both. The heat-generation rate is linearly dependent on the electrical resistance and is quadratically dependent on the current. The ratio of the squared current of the low-current materials, A40 and bare steel, to the high-current materials, G60 and EG, is approximately 0.8. This means that the overall electrical resistance of the A40 and bare steel must be about 25% higher than that of the G60 and the EG in order to produce the same temperature profile. The published literature shows the ratio of dynamic resistance of a bare steel or a galvannealed steel to a galvanized steel is roughly 1.3 to 1.5 (Refs. 15, 16). Thus, the heat generation in bare steel or galvannealed steel is higher than that in galvanized steel by approximately 0 to 20%. Considering the large temperature differences in the maximum coupon temperatures compared to the small differences in the electrode temperatures as seen in Fig. 13, it may be concluded that the reason for the higher temperature of A40 and bare steel is more likely due to a higher thermal contact resistance than to a higher rate of heat generation. The higher interface temperatures in these materials are also believed to be due to slower heat dissipation rather than to greater heat generation.

Another observation made from these tests is that the temperature profiles for A40 and bare steel are less sensitive to electrode force than G60 and EG. G60 and EG show sharp overall temperature drops as the electrode force increases. Generally speaking, the temperature decreases as the electrode force increases. However, the induced welding current increases with electrode force as shown in Fig. 14. This may be explained by the decreasing electrical and thermal contact resistances produced with the increasing electrode force. The final temperature field will depend on the combined effect of these two contact resistances. These are believed to be related to the morphology of the contact surface and the deformation characteristics of the sheets. The free zinc on the surface of G60 and EG softens and melts very quickly creating a low electrical and thermal resistance, while the surface of bare steel and the Fe-Zn compound of the A40 resist severe deformation and maintain high electrical and thermal resistance even at elevated temperatures.

As stated previously, the thermal contact resistance will affect the heat distribution in spot welding. The temperature difference between the facing interface and the electrode interface is much larger for A40 and bare steel. The overall temperature in the sheet is also higher for these materials. The low interface heat transfer coefficient may have increased the temperature rise within the coupon even though the induced current level is much lower than that of EG and G60. This illustrates the importance of the thermal contact resistance at the electrode interface in the nugget growth mechanism. This observation may explain the reason why spot welding of galvanized sheets requires a higher current level compared to the bare materials. Previously, the formation of a zinc halo surrounding the weld nugget has been an explanation for the effectively larger nugget size and consequently the higher current requirement for welding of galvanized materials (Refs. 15, 17, 18). In addition to this halo effect, the enhanced heat transfer char-

![Fig. 12 - Temperature profile of a high-speed line scan during one-dimensional simulation of the spot welding process](image-url)
characteristics at the electrode interface of the zinc coated steel is also seen to be important. As the nugget size increases, the heat loss to the electrode becomes greater and will demand higher heat input. Figure 15 shows the lobe curve for these coated materials. The relative positions of the lobe curve qualitatively matches the thermal behavior observed in this experiment (Ref. 19).

Heat Generation and Propagation

Figure 16 is an example of the heat propagation pattern observed during the high-speed cinematography experiment. As described in the experimental procedure section, the melting propagation front of the thermosensitive paint matches the 371°C isothermal line. This figure shows two different combinations of weld time and weld current. The heat generation and propagation pattern is quite different for these two cases. The heat propagation front in the electrode is more convex when long time and low current are used. In this case, the heat propagation pattern is symmetric. Weld B in Fig. 16, which used high currents and short weld times, shows localized heating in the early stages of the process. Due to a larger change in the current amplitude for high-current welding, the fluctuation in the temperature is also greater and is more localized. This is the usual case for higher current welding, i.e., there is less symmetry and much more localization of the heating pattern. In both cases, the temperature builds up in the workpiece first and then propagates into the electrode. This also confirms that there is a significant thermal discontinuity at the electrode interface.

Table 2 shows the effect of the different zinc coatings on the heat propagation and generation pattern. The times shown in the first two columns indicate the starting frame of the high-speed movie at which a phase change was observed in the thermosensitive paint. The third column indicates the time at which a visible red glow in the workpiece started. The time was measured from the onset of the welding current. The distance between the isotherms indicates the distance between the 371°C isotherms in the upper electrode and the lower electrode after the completion of the weld cycle. These were measured at the center of the cross-sectioned electrode on the projected image. Thus, the units in this column are only relative. The incipient phase change of the thermosensitive paint occurs in the workpiece. A40 shows an early buildup of temperature and glow in the workpiece as compared to G60 and EG, but the temperature rise in the electrode is slower. This is manifested by the shorter distance of heat diffusion into the electrode in the last column of Table 2. This phenomenon is thought to be related to the difference in the contact heat transfer characteristics of these materials as discussed in the previous section. This result is another example of the importance of the thermal characteristics of the electrode interface as a heat transfer barrier in developing the weld nugget.

Another observation from the high-speed cinematography experiment is the effect of the electrode outer geometry. The nugget starts to melt at the faying interface for truncated-cone electrodes, but with the dome-type electrode, melting begins at the electrode interface. The smaller contact area for heat and current
transfer with the dome-type electrodes results in a concentrated heat generation pattern at the electrode interface. This may explain the poor wear behavior of domed electrodes (Ref. 15).

Conclusions

Based on these observations and discussion, one can conclude the following:

1) There exists a critical electrode face thickness above which heat conduction in the electrodes controls the maximum electrode surface temperature, and below which convective heat transfer at the water coolant interface is rate determining.

2) For a given welding machine setting, A40 and bare steel induce lower currents in comparison to G40 and EG steel; nonetheless, the overall temperatures are higher for A40 and bare steel and are less sensitive to the electrode force.

3) A discontinuity in temperature exists across the electrode interface. The heat transfer characteristics across this interface significantly affect the nugget development mechanism in zinc-coated, low-carbon steel.

4) Nugget formation initiates at the faying interface with truncated-cone electrodes and at the electrode interface with dome-type electrodes.

5) The slowest step in heat transfer in the axial direction in RSW is convective transfer to the water at the electrode/coolant interface.

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