G. Long-Life Electrodes for Resistance Spot Welding of Aluminum Sheet Alloys and Coated High-Strength Steel Sheet (ORNL)

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Objective

- Understand the mechanisms of copper electrode wear used in spot-welding of high-strength steel sheets used in automotive industries.
- Evaluate the fundamentals of physical processes that lead to deformation and chemical attack, and model the same using thermo-mechanical-metallurgical models.
- Apply the models to design new electrode material—geometry—process parameter combinations that may mitigate excessive electrode wear.
- Characterize the mechanical properties of electrodes at high temperatures as input to the computational models and also to evaluate the softening resistance of different electrodes.
- Explore the possibility of electrode softening on the overall electrode wear characteristics.
- Provide support to the team lead by automotive industries in the implementation of these new computational models.

Approach

- Perform critical review of literature to evaluate the conditions that determine the mode of electrode wear, that is, either deformation or chemical attack due to zinc coating present on the coated steel sheets.
- Develop simple and phenomenological models that can capture the electrode wear characteristics by welding engineer in the automotive industry.
- Measure the stress-strain characteristics of candidate copper electrode materials at different temperatures, and describe them using well-established analytical equations.
- Measure the spatial hardness variations in copper electrodes at different stages of their useful life during a typical resistance welding operation.

- Measure the extent of chemical attack by molten zinc by isothermal exposure test on candidate copper electrode materials.

Accomplishments

- Identified the conditions at which either deformation or chemical attack can occur during resistance spot-welding through exhaustive review of the literature. The hypotheses were validated with results from sequential life test experiments performed at Edison Welding Institute.
- Identified the spatial softening of copper electrodes as a function of electrode life in conventional electrodes due to metallurgical changes.
- Developed a simple, but powerful, phenomenological model that captures the sequential deformation of copper electrodes as a function of electrode mechanical properties and resistance spot-welding process parameters.
- Applied computational thermodynamic and diffusion-controlled growth models to describe chemical attack of copper electrode by zinc. The modeling results successfully identified that the copper electrodes will wear at rapid rates when they are exposed to molten zinc due to dissolution of copper.
- Both deformation and chemical model results were in agreement with experimental results from Edison Welding Institute and Oak Ridge National Laboratory.
- Based on the above modeling work, possible concepts for improving the life of copper electrodes were devised in collaboration with an industrial team.
- Published the results in a internationally reputed sheet metal welding conference, which is attended by a wide range of automotive industry personnel, including original equipment manufactures and suppliers. The paper was well received, and the audience agreed with the findings and indicated the applicability of the computational models to their industrial setting.

Future Direction

- The deformation model will be made accessible to the automotive industries for plant-specific applications after rigorous validation with the new industry data.
- Participate in the “beta-site” testing and evaluation of the results from new sets of experimental electrode materials and different geometry.
- Disseminate the knowledge to a wide range of audiences by publishing in international welding journals.

Introduction

The introduction of galvanized high-strength steels has led to increased demands on the performance of copper electrodes used in resistance-spot welding of these steel sheets. Resistance spot welding relies on rapid generation of heat due to resistive heating. The heating is proportional to I^2R, where I is welding current, and R is the electrical resistance of the steel. When the steel sheets are galvanized, the zinc coating provides a very low resistance compared to the bare steel. Consequently, resistance spot welding of galvanized steels requires higher welding currents. The higher welding currents produce higher temperatures and temperature gradients in the copper welding electrodes (shown schematically in Figure 1). As a result, the electrodes deteriorate by both deformation and chemical reactions**.** These deteriorations slowly increase the diameter of the copper electrode until it reaches a critical value after making 1000–2000 welds. At this critical diameter, the current density becomes too low to make an acceptable weld between the zinc-coated steel sheets. This condition signals the end of life for the electrodes. In general, the life cycles of copper electrodes used in coated steels are lower than electrodes used on bare steels.

Until now, the above problem has been addressed by trial and error experiments with different types of electrodes (geometry and

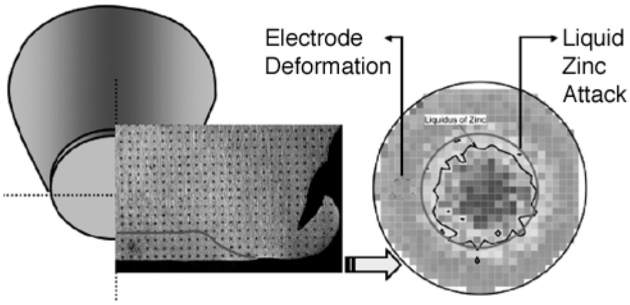

Figure 1. Schematic illustration of copper electrode wear mechanisms through deformation and chemical attack.

composition) and zinc coatings (composition and thickness), and by modification of resistance spot welding parameters. However, there is a need to develop a more systematic framework for evaluating various candidate electrode materials and accelerating the selection of improved electrodes for the various requirements of the automotive industry.

The goal of this collaborative research project with Edison Welding Institute (EWI), automotive industrial members, and electrode suppliers was to develop a mathematical model to describe the deterioration of copper electrodes as a function of electrode properties and welding process parameters.

Earlier Research

In earlier research, Oak Ridge National Laboratory (ORNL) and EWI, through a collaborative project, developed a coupled thermal, electrical, mechanical, and metallurgical model to evaluate the weld formation, deformations in both electrode and sheet, microstructure formation in welds and performance of welds, in bare steels.[1–3] The model was able to consider the complex interplay between welding loads, welding current, contact resistance, and strength of materials. It was able to capture all the physical phenomena that occur within the time scale of one spot weld. In principle, this finite-element-based model can be extended to simulate electrode deterioration by repeating the procedure as a function of 1000 or 2000 welds. However, there are major issues with doing this. One is that the simulation for each spot weld takes up to 10 h of computing time on average. Consequently the simulation of 2000 spot welds will take 833 d! Another problem is that the electrode shape will change with each successive weld. The new electrode shape will require a new mesh. This is another time-consuming activity. Therefore, the existing model, and others like it, was not an efficient solution in terms of both time and cost for optimizing electrode materials and geometries over wide ranges of process conditions. This was the challenge posed to ORNL at the beginning of the research project.

Experimental Measurements of Electrode Wear

The results from an electrode life test conducted according to the American standards are shown in Figure 2. The data show that as the number of spot welds increases, the electrode face diameter also continuously increases. Because the welding current is kept constant in these tests, the increase in electrode face diameter leads to a reduction in current density. Eventually the current density is reduced below the critical value needed to produce the required minimum weld button size. This event signals the end of electrode life.

Figure 2 illustrates the importance of current density on electrode life. It is well known that the current density is directly related to the peak temperatures achieved at the sheet/sheet and electrode/sheet interfaces. The electrode face temperatures will decrease with increasing electrode face diameter for a fixed current level. The face temperature will determine the rates of deformation and chemical attack at the electrode/sheet interface. Therefore, an analytical model was needed to relate the electrode face diameter to electrode face temperature.

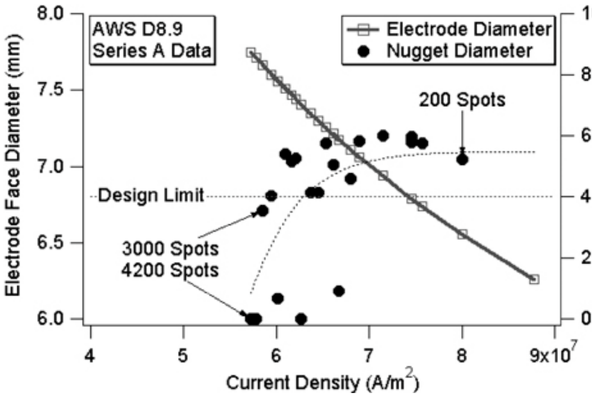

Figure 2. Experimentally measured electrode face diameter of a standard electrode tip and weld nugget diameter as a function of current density.

Localized Softening of Copper Electrode During Welding

For the model development, it was speculated that the regions of the electrodes near their faces would soften during welding operations. This softening may be related to metallurgical changes that cumulatively occur due to thermal cycling experienced during each spot weld. The spatial variation of Vickers microhardness of the CuCrZr electrode alloy was also measured at various stages of electrode life, and microhardness maps are presented in Figure 3. The maps were done on only one-half of the sectioned surfaces because of axial symmetry. Figure 3(*a*) shows that the hardness of the electrode alloy near the tip was 120 kg/mm^2 after 100 welds, while the bulk of the electrode exhibited a hardness of 180 kg/mm^2. This confirms that softening occurs fairly rapidly in the cold-worked, precipitation-hardened electrode alloy as has been observed in other work. The hardness distributions after 500 welds and at the end-of-life stage are shown in Figure 3(*b* and *c*). As life testing proceeded, microhardness values near the electrode tip fell to as low as 70 kg/mm^2. However, the hardness distribution did not change significantly after 500 welds. These results demonstrate that an assumption of constant room temperature strength is not valid, and the model to be developed in this work needs to consider this phenomenon.

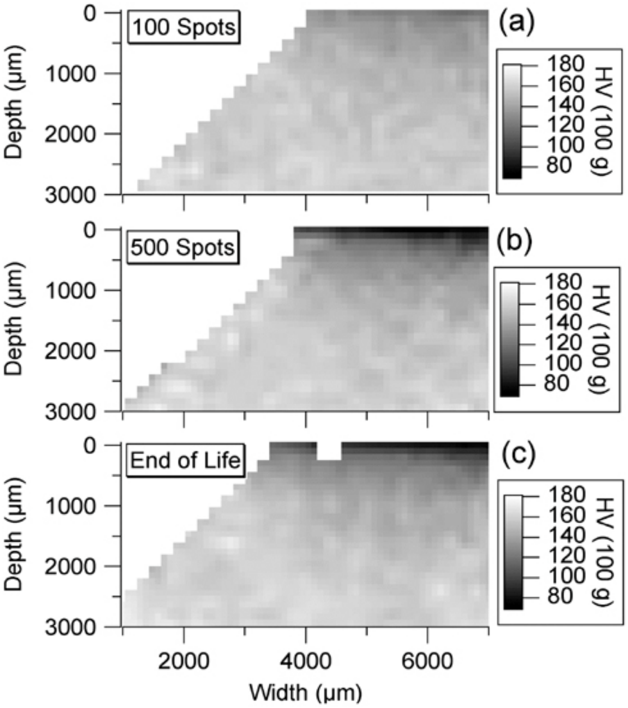

Figure 3. Measured spatial variation of hardness in copper electrodes after (*a*) 100 welds, (*b*) after 500 welds, and (*c*) at the end of life showing progressive softening at the electrode face.

Model for Predicting the Electrode Deformation

The deformation model must consider the physical processes as follows: (1) thermal cycles at the copper electrode—steel sheet interface; (2) stress-strain characteristics as a function of temperature, (3) softening characteristics as a function of weld numbers; and (4) progressive electrode deformation. The methodologies to describe each of the four phenomena are briefly outlined below.

(1) Thermal cycle prediction: Although sophisticated finite-element or finite-difference methods can be used to estimate these temperatures, to allow for rapid calculations, an empirical sigmoidal equation was used to relate the electrode face temperature (T, in Kelvin) to electrode face diameter (d, in mm).

(2) Stress-strain characteristics: The tensile properties of CuCrZr class 2-electrode alloy were measured as a function of temperature to provide input for the deformation analysis. The specimens had gage dimensions of 6.35-mm diameter by 31.75-mm length. They were tested at a nominal strain rate of 6.7×10^{-4} s^{-1}. All of the elevated temperature tests were conducted in still air. The data were then represented in the form of a simple analytical equation.

(3) Electrode softening: The softening characteristics measured (see Figure 3) were represented in the form of an analytical equation. Ability to change the softening resistance was considered in this equation.

(4) Progressive deformation: The descriptions of temperature variation at the electrode face, temperature-dependent tensile properties, and softening behavior were then combined into a simple model of electrode deformation. The model assumes that the deformation is confined to a disc of material at the electrode tip. The deformation of the disc will

eventually cease when the pressure associated with welding equals the yield strength of the alloy. At that point, mechanical equilibrium is achieved at the electrode face.

The model was calibrated to a set of experimental data. The comparisons of measured and predicted data are shown in Figure 4 and demonstrate the validity of the model. There is no question that this model greatly simplifies the mechanical and metallurgical issues associated with the electrode deformation process. However, as details are added to improve technical precision, the complexity of the analysis and the demand for computation time increases.

Our intention was to provide an engineering tool that would be capable of guiding electrode alloy development efforts and selecting welding parameters and one that was relatively accessible to a wide range of potential users. This personal-computer-based deformation model satisfies that objective.

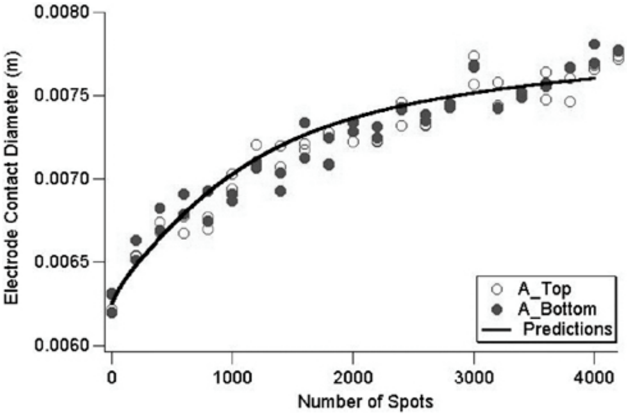

Figure 4. Comparison of predictions using Eq. (4) and experimentally measured face diameters from top and bottom electrode as a function of number of welds.

Methodology for Predicting the Chemical Attack by Zinc Coating on Steel

Clearly any general model of resistance spot welding electrode deterioration must account for chemical attack mechanisms. This aspect of electrode deterioration is being addressed through application of diffusion-controlled growth analysis. One-dimensional diffusion (analogous to the axial direction in an electrode tip) in a material couple between copper and zinc is being considered. The chemical activity of zinc at the copper/zinc interface is held constant at unity, which is equivalent to assuming there is an infinite reservoir of zinc . This is reasonable for describing conditions over typical electrode lives of 1000s of welds.

Two simulation conditions are considered: (1) a peak temperature close to the melting point of zinc, and (2) a peak temperature above the melting point of zinc. The analyses are based on somewhat arbitrary temperature profiles with durations of 0.5 s. The calculations were performed with DicTra™ software[4] assuming a diffusivity of copper in liquid zinc of 10^{-8} m^2/s.

The results are presented in Figure 5. The case where the zinc does not melt was based on the thermal cycle shown in Figure 5(*a*) in which the temperature increases from room temperature to near the melting point of zinc (693 K) in 0.4 s and cools back to room temperature in 0.1 s. Because zinc does not melt, only solid-state diffusion occurs across this copper/zinc interface and the profile of zinc concentration in the copper is shown in Figure 5(*b*). For these conditions, the diffusion distance for zinc into the copper is less than 1 nm, a miniscule amount.

The thermal cycle for the case where zinc melting is permitted is shown in Figure 5(*c*). The initial temperature is just above 693 K. It increases to a maximum of 1000 K in 0.4 s, and then decreases back to 693 K in 0.1 s. For these conditions copper dissolves into the zinc and the copper/zinc interface rapidly penetrates into the copper. The profiles for zinc penetration into the copper are shown in Figure 5(*d*) for this case. The maximum extent of the zinc penetration was about 500 nm.

These results are consistent with the conclusion that it is the reaction of liquid zinc with copper alloy electrode tips that dominates the chemical attack process. Subsequent solidification of the copper-rich liquid at the copper/zinc interface will result in the formation of brass layers on the electrode tip.

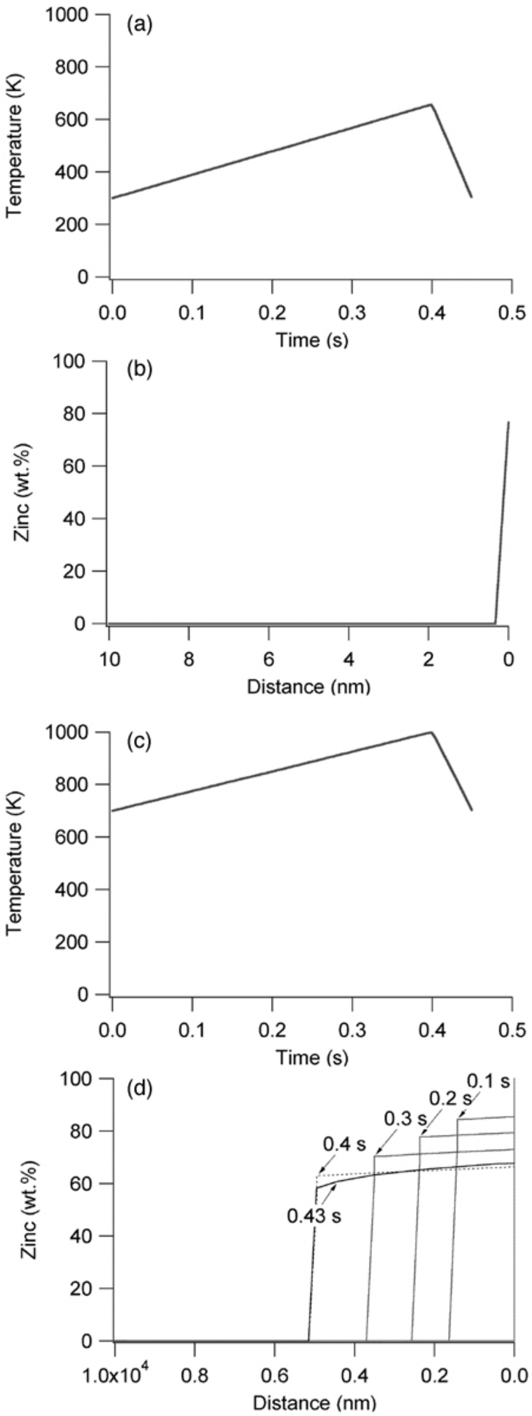

Figure 5. Predictions of a model that considers chemical attack by zinc: (*a*) assumed temperature profile with a peak temperature less than melting point of zinc, (*b*) calculated solid-state diffusion profile in the copper block, (*c*) assumed temperature profile with a peak temperature higher than melting point of zinc, and (*d*) calculated penetration depth of liquid zinc into copper block.

Experimental Evaluation of Chemical Attack by Molten Zinc

A simple melting experiment was done to illustrate the rate of reaction between liquid zinc and copper. An OFHC copper specimen with dimensions of 12 × 12 × 3 mm was heated in high-purity argon atmosphere to 440°C on a hot plate with digital temperature control. A 0.25-g pellet of high-purity zinc was then placed on the copper. The zinc melted within several seconds, and then the specimen was removed from the hot plate and rapidly cooled to room temperature. The total contact time between the liquid zinc and copper could not be accurately determined, but it was very brief, less than 30 s. An optical micrograph of the zinc droplet that solidified on the copper surface is shown in Figure 6(*a*). Reaction of the zinc with the copper surface is illustrated in Figure 6(*b*) where the original position of the copper surface is indicated by the line. Penetration of the liquid zinc into the copper surface is evident. Also, the yellow layer of α-brass indicates diffusion of zinc into the copper. Identical results were obtained when this experiment was repeated using CuCrZr rather than OFHC copper.

Ongoing Work

Analyses of the chemical aspects of electrode deterioration are continuing with one objective being development of a predictive capability similar to the deformation model. Whether deformation or chemical attack dominates, deterioration is not clear. Certainly both deterioration mechanisms are operating in resistance spot welding electrodes, and either could be dominant under specific welding conditions or during different periods of the typical electrode life behavior.

For instance, in the early period of life, electrode diameters are relatively small resulting in relatively high current densities and contact pressures. The higher current densities will increase temperatures at the electrode/sheet interfaces, and this will promote deformation. Higher contact pressures will also make deformation at the electrode tip more likely. In later life, as face diameters enlarge, current densities and contact pressures will decrease, thereby reducing the probability of further deformation. In contrast, the formation of liquid

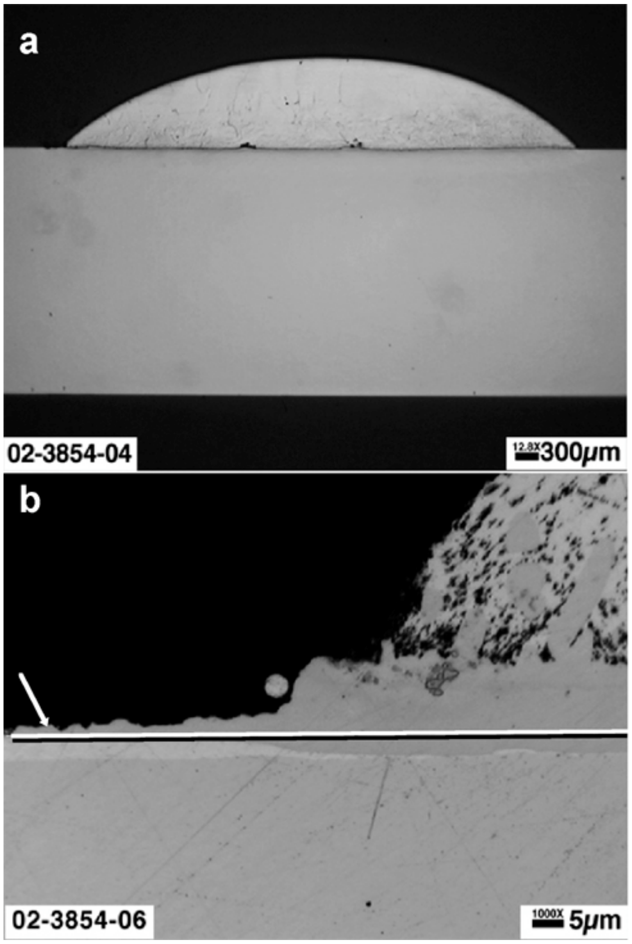

Figure 6. (*a*) Optical macrograph showing the presence of solidified zinc layer on top of the copper electrode and (*b*) high-magnification micrograph showing the presence of different brass layers with different shades indicating different zinc concentrations. The horizontal line shows the original position of the surface before the chemical attack.

zinc at electrode/sheet interfaces is likely to occur irrespective of electrode tip diameter.

Consequently, it may be that deformation is more important as an electrode deterioration mechanism in the early stages of life, while chemical attack is nearly constant throughout. Developing an improved generalized model of electrode deterioration, even of a simplified variety like the present case, will require a better understanding of the deterioration mechanisms and their interrelationships.

Conclusions

An analytical model that relates the electrode face diameter, welding load, welding current, mechanical properties as a function of temperature, and material degradation to electrode wear was developed. The model suggested that the life of resistance spot welding electrodes can be increased by enhancing their softening resistance rather than their absolute strength. A diffusion-controlled growth model showed that if the electrode face temperature is higher than the melting point of zinc, there is a probability of significant penetration of liquid zinc into copper. The predicted rate of liquid zinc penetration into copper was 500 times more than the rate of solid-state diffusion. Melt drop experiments confirmed that liquid zinc penetration into copper readily occurs and will lead to the formation of different brass reaction layers.

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Presentations and Publications

1. S. S. Babu, M. L. Santella, and W. Peterson, “Modeling Resistance Spot Welding Electrode Life,” *Proc. of Sheet Metal Welding Conference XI, Sterling Heights, Michigan, May 11–14, 2004*.
2. S. S. Babu, M. L. Santella, W. Peterson, and J. E. Gould, “Modeling resistance spot welding electrode life,” AWS Welding Show, April 2004, Chicago, Illinois.