E. Long-Life Electrodes for Resistance Spot Welding of Aluminum Sheet Alloys and Coated High-Strength Steel Sheet (AMD 302[i])

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Objective

- Survey the currently available technology for achieving long electrode life.
- Comparatively test a broad selection of existing and developmental electrode technologies that have technical merit.
- Investigate the electrode wear process through a combination of testing, metallography, and computer modeling.
- Evaluate a “best practice” electrode(s) through beta-site automotive production testing. The goal of these tests is to demonstrate the potential to double electrode life in a production environment through changes to electrode materials and/or geometry.

Approach

- Conduct benchmarking (Phase 1). A review of the open literature, available corporate literature, and interviews of industry experts produced a state-of-the-art report on electrode wear. This phase has been completed.
- Conduct testing (Phase 2). Candidate electrode technologies were screened and in-depth testing of electrodes was performed to help define the mechanism(s) of electrode wear. “Best practice” electrodes for beta-site testing were produced as part of this phase. This phase is complete, except for completion of the beta-site tests.
- Computer modeling (Phase 3). Computer models of the electrode metallurgical and mechanical changes that occur as a result of electrode wear were developed. These models helped to investigate the mechanism(s) of electrode wear and define the best practice electrodes. This phase is complete.

Accomplishments

Accomplishments that have been completed since the last reporting period:

- Completed beta-site tests at the DaimlerChrysler Windsor assembly plant on galvannealed steel.
- Developed procedures for establishing stepper procedures evaluating comparative stepper-based electrode testing in a production environment.
- Established optimum production stepper schedule for "best practice" electrodes – able to double and triple electrode life on actual application.
- Developed procedures for comparing "best practice" electrodes for the DiamlerChrysler beta-site tests.

Future Direction

- All work completed.

Introduction

Resistance spot-welding (RSW) has been heavily adopted by the automotive industry due to its relatively low capital and operating costs and the capacity to support high production rates. RSW is commonly used to weld high-strength steel and aluminum (Al) in vehicle construction. These materials are commonly selected to reduce vehicle weight and thus improve fuel economy and reduce greenhouse gas emissions. However, electrode wear of coated steels and Al continues to be a significant issue. Electrode wear adversely affects the cost and productivity of automotive assembly welding due to reduced weld quality, reliability, and robustness. This mandates increased inspection rates and greater control of welding parameters. Consequently, large potential cost savings and quality improvements are expected from substantial improvements in electrode life.

As technology has developed, few engineering solutions have been successfully introduced into the manufacturing process to manage electrode wear. Weld-current steppers and electrode-cap dressers have been used for many years, but these techniques do not resolve the underlying causes of electrode degradation. More recent efforts to remedy electrode wear have resulted in innovative electrode technologies, such as new material compositions, material inserts at the electrode face, surface-coated electrodes, and nontraditional electrode geometries (P-, G-, and S-nose). The scope of the present investigation is to objectively evaluate existing and developmental electrode material and geometry technologies to improve electrode life in production.

Review of Previous Work on AMD 302

The overall program organization is schematically illustrated in Figure 1. Prior work in AMD 302 covered most of Phases 1 to 3. The current work activities cover the beta-site testing (Phase 2) of electrodes developed from Phases 1-3. The scope of work in AMD 302 has focused primarily on the influence of electrode materials on the electrode life of both Al and high-strength galvanized steels. However, after completing several electrode life tests on Al using a number of electrode materials, no demonstrable plan based on electrode composition was clearly highlighted. Electrode wear in Al occurs through deposition of Al onto the face of the electrode. The factors that contributed to reduce sticking of the tip to the Al sheet during electrode

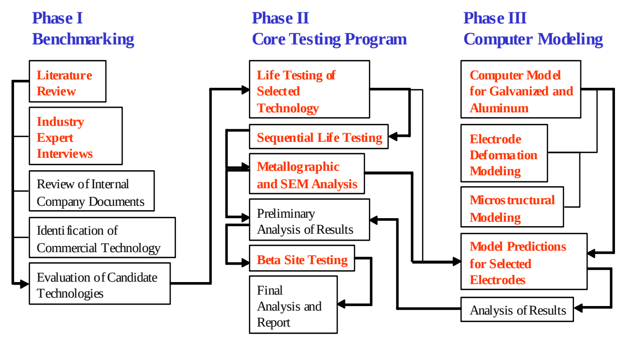

Figure 1. Current activities include production of targeted electrodes and beta-site testing in Phase 2. Work completed in previous phases include: benchmarking, core testing, and computer modeling.

retraction were opposite to those which improved weld-nugget stability. Additionally, this work showed that the solutions to electrode wear involved much more than just a study of alternate electrode materials. As a result, this part of the program was curtailed and additional efforts were focused on the electrode wear mechanism on steel.

Achievement of the program objectives for galvanized steel required a fundamental understanding of how electrode wear occurs. In prior phases of this work, three key processes responsible for electrode wear in RSW have been identified, namely, electrode-face extrusion, gamma-brass deposition onto the steel sheet, and weld-nugget stability. In this program, these three processes have been integrated into a coherent mechanism to describe the weld-nugget failures associated with electrode wear. In summary, the first two wear processes act to enlarge the contact area at the electrode face. This reduces current density and results in an inherent loss of weld-nugget stability in galvanized steels. This mechanism also addresses the phenomenon of pitting and electrode sticking associated with the metallurgical phenomena occurring during electrode wear.

The electrode wear mechanism developed in this program was based on interpretation of standard electrode life and stepper tests performed on several common electrode geometries that were produced from standard and developmental electrode materials. Computer modeling of the two electrode-enlargement processes described above were developed to better understand significant aspects of the phenomenon, such as edge extrusion rate, electrode surface temperature, and brass evolution. This was coupled with information from a detailed metallographic examination of the electrodes at several stages of electrode wear. The metallographic work identified the development, formation rate, and composition of brass alloys and parting layers on the face of the electrodes throughout electrode life. Altogether, this work formed the foundation of the electrode wear mechanism that described spot-weld behavior during electrode life in galvanized steel.

Electrodes Studied in the Beta Test Phase

Two beta-site test locations were identified. The work performed at General Motors has been previously reported. The present report focuses on the beta-site evaluation at DaimlerChrysler. Both sites used the best-practice electrodes based on either reducing the electrode surface temperature or maintaining a high current density by promoting a protrusion, or narrowed conduction path through the workpieces. These two approaches are summarized below:

- **Low Face Temperature Approach** (reduce rate of electrode face enlargement)
  - Internal fins and reduced face thickness
  - Conductive electrode material
  - Balance conductivity, electrical surface resistance, thermal conductance, and high-temperature strength

- **Sacrificial Electrode Approach** (maintain current density by protrusion formation)
  - One-dimensional heat flow, face must be hot to maintain protrusion
  - Selective sticking, deformation, and chemical erosion occur sacrificially to maintain protrusion
  - Protrusion formation produces a high current density in the center of the electrode that promotes nugget stability

The latter approach uses either P-cap or G-cap sacrificial electrode-nose geometry with appropriate material to reduce electrode sticking and maintain the protrusion under high heat conditions.
The candidate electrode materials and geometries considered for beta-site testing are listed in Table 1.

Table 1. Candidate Beta-Site Test Electrodes.

Material	Electrode Design	Beta Site Test Material	Approach
CuZr	E-cap w/internal fins	HDG	Low Temperature
CuZr	B-cap w/internal fins	GA, HDG	Low Temperature
M material	E-cap	GA, HDG	Low Temperature
M material	B-cap	GA, HDG	Low Temperature
M material	G-cap	GA, HDG	Sacrificial
Al_2O_3 ODS	P-cap	GA, HDG	Sacrificial

GA = Galvannealed
HDG = Hot-Dip Galvanized

Due to corporate preferences, the electrode geometries used in the beta-site tests were limited to 16-mm body diameter B-nose cap designs with 4.8-mm flat faces. Both conventional CuZr and an experimental alloy, Alloy M, were evaluated in these tests. The CuZr electrodes incorporated fins to increase surface area and facilitate heat transfer at the water cooling channel. The electrodes made from both materials used reduced face thickness (6-7 mm) to further enhance heat flow.

DaimlerChrysler Windsor Assembly Plant Beta-site Test Results

The DCX beta-site tests were performed on a non-safety-critical part with easy equipment access and good plant support. The joint combination was 0.66- mm galvannealed DQ steel welded to 1.2-mm galvannealed 350-MPa steel. A stationary pedestal-type AC welder was used with robotic part manipulation. 11 welds are made per part at a welding rate of about 30 welds per minute (wpm). The electrodes were replaced once per shift. The initial stepper schedule produced about 3400 welds before electrode replacement. The standard electrodes were composed of dispersion-strengthened copper (DSC) core with a CuZr body and used a similar B-nose design with standard face thickness (10 mm).

The original stepper-based weld schedule at the DaimlerChrysler Windsor Assembly Plant was:

- Electrode force: 330 lbf
- Weld time: 14 cycles
- Hold time: 2 cycles
- Initial Current: 9000A
- Stepper Slope: 2A/weld for 1000 welds, 1.5A/weld for 1500 welds, 1A/weld for 1500 welds

This schedule produced a current of approximately 15.5 KA after one shift. Initial observations of the standard production processing of the beta-site test application showed that every weld was made at expulsion for at least the first 2500 welds.

Weld quality during the beta-site trials was primarily monitored through periodic component teardowns. Ultrasonic testing was available, but the equipment was out of service during many of the early weld trials at the facility. Without frequent non-destructive testing, visual detection of expulsion was the method used to verify the presence of a weld.

However, maintaining expulsion accelerates electrode wear and increases the stepper slope rate. Thus, with greater expulsion frequency, higher stepper slopes are expected, limiting the effective electrode stepper life. Alternately, lower current-stepper slopes reduce the rate of electrode face enlargement, but endanger weld quality if the stepper slope is insufficient to maintain the minimum weld size. While undersized welds are acceptable in the laboratory to determine the need to increase weld current, they are unacceptable for assembly operations. Additionally, operating current values vary due to differences in materials, prior processing, and setup practice. Therefore, production weld currents must be maintained high enough to produce acceptable welds under most normal production conditions. These factors tend to favor high operating weld-current levels and steeper stepper slopes.

Selection of the appropriate stepper slope also involved operating below the upper limit of the transformer and scheduling the opportunities to exchange electrode sets. At the DaimlerChrysler site, the opportunities to change the electrodes for this part occurred during lunch breaks and shift changes. Historically, electrode changes for this application have been made on each lunch break. The goal of the AMD 302 project was to double electrode life in production. However, doubling the electrode life in a 3-shift operation would result in changing the electrodes every other shift. In order to reduce confusion, DCX personnel suggested changing the electrodes twice daily or every shift and a half. Alternately, the electrodes could be changed once per day.

The maximum stepper rates to achieve a 1½- and a 3-shift electrode change are 0.75 amp/weld and 0.35 amp/weld, respectively. This is based on 3400 welds per shift, initial current, and upper operating current limit of the transformer. Based on the initial trials, a decision was made to change the electrode sets twice daily. This meant that the electrodes should be fully capable of reaching two shifts during the weld set-up testing.

The first stage of stepper development during these trials was to reduce the initial operating current and stepper slope. A weld schedule suitable for producing welds over 1½ shifts (average 0.75 amp/weld) during the beta-site testing with the M electrode material was:

- Electrode force: 380 lbf
- Electrode geometry: B-cap with 4.8-mm flat face on 16-mm body diameter
- Electrode material: M electrode
- Weld time: 10 cycles
- Hold time: 2 cycles

Different combinations of stepper slopes were evaluated to extend these results through a full second shift. The stepper rate was divided into three portions:

- 0.65 amp/weld for 2500 welds
- 0.76 amp/weld for 2500 welds
- 0.85 amp/weld for 2500 welds

The increasing stepper slope values maintained the appropriate current density as the electrode face size increased.

Acceptable electrode life performance was based on maintaining weld quality during the stepper campaign using the prescribed stepper schedule developed for doubling electrode life.

Experience on this project showed that if the weld-current was able to sustain low numbers of expulsions per part, then weld quality was significantly improved compared to the original welding practices. Conversely, if the number of expulsions per part decreased using the prescribed stepper schedule, then weld quality deteriorated.

DCX Beta-site Production Trials

A graphical summary of the 12-hour production weld trials performed on the M Alloy, CuZr Finned, and original DSC electrodes are given in Figures 2 to 4. These plots show moving averages of the number of welds exhibiting expulsion per 11 welds made per part. This expulsion rate is plotted against the number of assemblies made during the trials. While the numbers of assemblies per shift varied, the average number of assemblies between electrode changes was approximately 550.

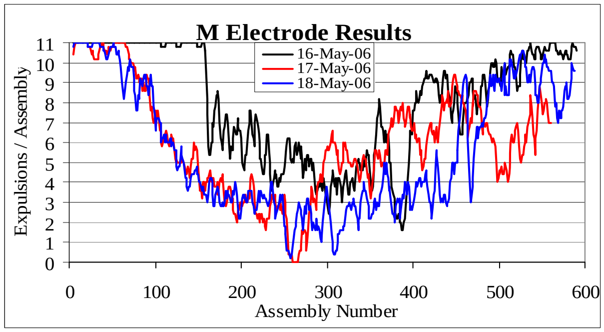

Figure 2. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) made for the 12-hour trials on the reduced face thickness B-cap M electrode.

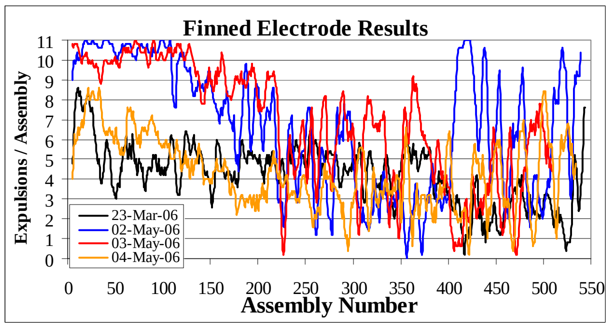

Figure 3. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) made for the 12-hour trials on the reduced face thickness B-cap CuZr Finned electrodes.

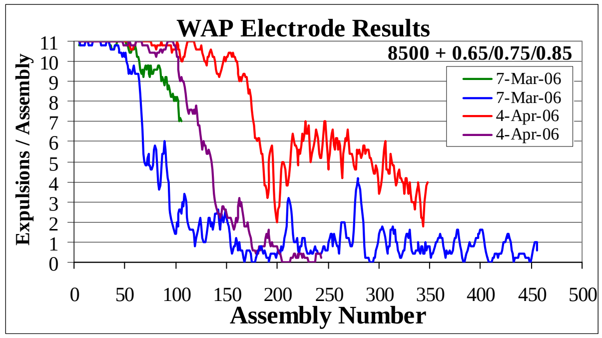

Figure 4. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) for the 12-hour trials on the original DaimlerChrysler electrodes.

The M Alloy and the CuZr Finned electrodes successfully passed weld-quality requirements using the prescribed stepper schedule during six 12-hour production weld trials. The original DSC electrodes were unable to maintain consistent weld quality during the 12-hour trials and these tests were terminated. This demonstrated the improvement in electrode life using the best-practice electrodes.

The success of the finned caps at the DCX beta-site promoted a further reduction in stepper slope in an effort to produce a 24-hour weld trial. The stepper rate was divided into three portions:

- 0.35 Amp/weld for 5000 welds
- 0.40 Amp/weld for 5000 welds
- 0.45 Amp/weld for 5000 welds

This stepper schedule was successfully used on the finned caps over three shifts as shown in Figure 5.

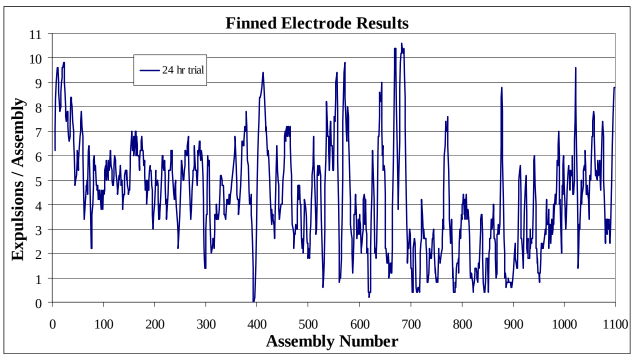

Figure 5. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) made for a 24-hour trial on the reduced face thickness B-cap CuZr Finned electrodes.

Metallographic Evaluation of the Electrodes

The working surface of the electrodes was photographed prior to metallurgical sectioning to examine the electrode surface and cross-section in a manner similar to that done in previous phases. Similar to other phases of the program, these results showed that recrystallization occurred at the face of the CuZr electrodes producing softening at room temperature. Conversely, the M Alloy and DSC (original DCX) electrodes maintained a fibrous grain structure with slight softening occurring on the M Alloy electrode at room temperature.

Observations of the electrode face showed that the CuZr electrodes had a smooth surface appearance with minor pitting. Conversely, the M Alloy and DSC electrodes exhibited rough surface appearances with extensive central pitting. In addition, the M Alloy electrode showed surface cracking. The brass alloy distribution and layer thicknesses were similar to those from the GM tests with exception of the original DSC and the 24-hour finned electrodes. These two electrodes had much thicker parting layers at test termination.

These observations confirmed that chemical erosion (dissolution and deposition of brass onto the workpiece) is a very significant component of the electrode wear process.

Benefits of Improved Electrode Life

Improvements in electrode life reduce the number of electrodes and labor associated with electrode replacement. Improved electrode life improves process robustness and can result in a reduced-frequency weld-quality inspection. In addition, the lower stepper rates associated with improved stepper schedules require less energy on a per-day basis. This latter point is illustrated in Figure 6 showing total energy for the M Alloy and Finned electrodes relative to the original DSC electrodes. The M Alloy reduces energy consumption by 6% while the Finned electrodes provide an 18% reduction relative to the DSC electrodes.

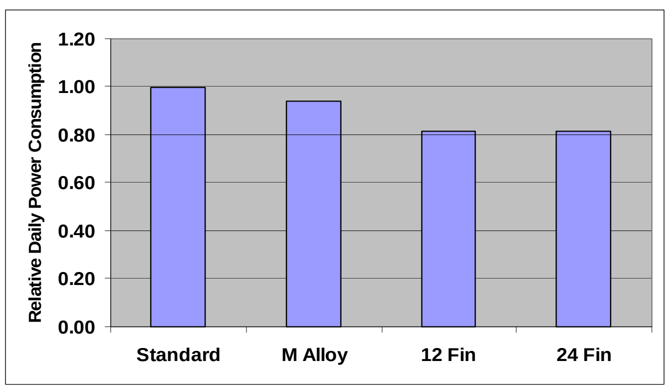

Figure 6. The relative daily power costs for the M Alloy and Finned electrodes relative to the original DSC electrodes used on the beta-site application plotted against the number of number of hours.

Conclusions

The work performed in the beta-site phase of AMD 302 has shown that the stepper performance of the "best practice" varieties of electrodes met the project expectations of doubling and potentially tripling electrode life on galvannealed steel in a production environment. Significant results from the beta-site tests include:

1. The stepper slope for galvannealed steel is much lower and more repeatable than the slopes produced on hot-dip-galvanized steel.
2. The "best-practice" electrodes developed from previous phases of this work may be machine and application dependent. Specifically, these electrodes are strongly influenced by the volume of cooling water.
3. Increasing stepper-slope schedules maintain current density as the cap face increases in size.
4. Evolutionary operation-type experimental plans were used to develop optimized stepper schedules in production.
5. The CuZr Finned electrode provided up to 24-hours (3 shifts) of electrode life under production conditions.
6. The M Alloy electrode provided 2 shifts of useful electrode life under production conditions.
7. The original electrodes at the DCX beta-site were unable to maintain a consistent performance for a 2-shift extension of electrode life.
8. The significant role of chemical erosion was shown in electrode face enlargement for specific electrode materials.
9. Improved electrode life results in significant cost savings due to power reduction, improved process robustness, and electrode replacement costs.

Presentations/Publications/Patents

2003. Gallagher, M. "Electrode Wear in Resistance Spot Welding of Galvanized Steel Sheet". M.A. Sc. Thesis, University of Windsor, Windsor, ON.

2004. Peterson, W.A., Gould, J.E., Bowers, R., Santella, M., Babu, S. "Evaluation of Electrode Design and Materials for Improving Electrode Life," Sheet Metal Welding Conference XI, Paper 1-6. Sterling Heights, MI (May 11-14). AWS - Detroit Section.

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