D. Long-Life Electrodes for Resistance Spot-Welding of Aluminum Sheet Alloys and Coated High-Strength Steel Sheet

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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.
- Beta-site testing of best-practice electrodes in a production environment. This phase of testing is currently in progress.

Accomplishments

Accomplishments that have been completed since the last reporting period:

- Produced “best-practice” electrodes for beta-site testing
- Completed laboratory verification testing of “best-practice” electrodes
- Completed beta-site testing at General Motors on hot-dip-galvanized (HDG) steel
- Initiated beta-site tests at the DaimlerChrysler Windsor assembly plant on galvannealed (GA) steel
- Developed procedures for establishing stepper procedures evaluating comparative stepper-based electrode testing in a production environment
- Established the production stepper schedule for the reduced-face-thickness B-cap M electrode material
- Proposed procedures for comparing “best-practice” electrodes for the DaimlerChrysler beta-site tests

Future Direction

- Complete beta-site tests on the best-practice electrodes at DaimlerChrysler Windsor Assembly Plant on galvannealed steels.
- Complete final report on project.

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 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 aluminum 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 project organization is schematically illustrated in Figure 1. Prior work 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 primary scope of work focused on the influence of electrode materials on the electrode life of both aluminum and high-strength galvanized steels. However, after completing several electrode life tests on aluminum using a number of electrode materials, no demonstrable plan based on electrode composition was clearly highlighted. Electrode wear in aluminum occurs through deposition of aluminum onto the face of the electrode. The factors that contributed to reduce sticking of the tip to the aluminum sheet during electrode 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.

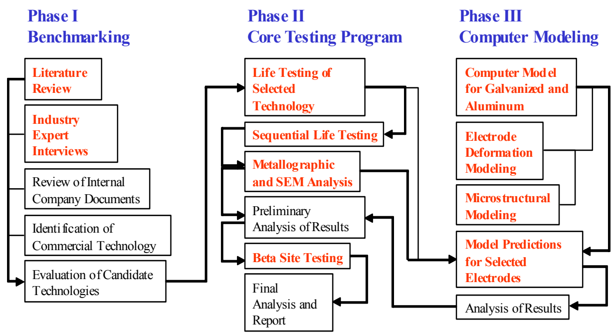

Figure 1. Schematic outline of workscope. Current activities include production of targeted electrodes and beta-site testing in Phase II. Work completed in previous phases include: Benchmarking, core testing, and computer modeling.

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 resistance-spot-welding (RSW) have been identified, namely, electrode face extrusion, gamma-brass deposition onto the steel sheet, and weld-nugget stability. These three processes have been integrated into a coherent mechanism in this program 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 describes the phenomena of pitting and electrode sticking that is 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 Present Phase

The approach used to define the best-practice electrodes for beta-site testing is 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 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 electrode materials and geometries defined for best practice electrodes are listed in Table 1.

Table 1. 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

The electrode geometries used in the present phase are based on 16 mm-body-diameter with 4.8-mm-flat faces on the B-nose cap designs and 6-mm-flat faces on all other caps. All of the B-cap and E-cap electrodes used a 6- to 7-mm face thickness that increases heat flow to the cooling water channel. The P-cap or G-cap needs high surface temperatures on the electrode face to maintain the protrusion; therefore, no reduced face thickness (10 mm) was incorporated into these designs.

These electrode materials are standard alloys, except the M alloy. This alloy was identified from the previous phases of work. It characteristically produced good welds over a longer numbers of welds compared to the conventional CuZr alloy.

Laboratory Stepper Test Approach

Two sites were selected for beta-site testing, namely the GM Technical Center and DaimlerChrysler's Windsor Assembly plant. The welding parameters, materials, and procedures used in the simulative laboratory tests were replicated as closely as possible to the beta-site application. These tests were used to validate the best-practice electrodes and provide initial welding conditions for the beta-site tests. To better understand the conditions used in the laboratory tests, a description of the GM Technical Center and DaimlerChrysler beta-site tests is provided in the paragraphs that follow.

The GM beta-site tests used the GM WS 5A stepper test. GM performs this test as a standard procedure prior to introducing a new steel, electrode, etc. into production. They compare the stepper to a standardized stepper schedule to determine suitability for production. The same stepper test procedure was used on the prior and present laboratory tests at EWI. The GM test data will provide a separate investigation of electrode performance on the same materials used in previous phases of work. These tests will evaluate selected best-practice electrodes on a different welding machine, operating conditions, and technical staff. They will also use the GM test-termination criterion. The steel used for the GM beta tests will be taken from the 1.1-mm HDG 350 MPa steel remaining from the previous phases of work

The standard GM welding parameters for 1.1-mm 350 MPa HDG steel welded to itself are:

- Weld Time: 16 cycles
- Electrode Force: 670 lbf
- Hold Time: 2 cycles
- Min Button Size: 4.0 mm
- Weld rate: 30 wpm

The DaimlerChrysler beta-site tests are performed on a non-safety-critical part with easy equipment access and plant support. A stationary, rocking-arm AC welder is used in these trials with robotic part manipulation. The electrodes are normally replaced once per shift. Eleven welds are made per part at a welding rate about 30 wpm. This schedule produces about 3400 welds on the electrode at the time the electrodes are replaced.

The materials used for the laboratory tests were donated by DaimlerChrysler. This part welds 0.66-mm DQ galvannealed steel to 1.2-mm DQ GA steel. A weldable sealant is also used at the welding interface.

The standard welding parameters for the 0.66-mm/1.2-mm DQ GA steel application at DaimlerChrysler are:

- Weld Time: 14 cycles
- Electrode Force: 480 lbf
- Hold Time: 2 cycles
- Min Button Size: 3.0 mm

The welding parameters and steels used on both beta-site tests were incorporated in the laboratory tests on hot-dip-galvanized and galvannealed steels. Female electrodes are used at both beta-site tests locations; therefore, female caps were studied in the laboratory tests. However, all of the work performed in previous phases used male electrode designs. The laboratory work validated the targeted electrodes in a female cap design. The laboratory results were compared to the performance of similar electrode design and materials from previous phases of work on this project.

Additionally, both beta-site locations use weld current steppers. Consequently, only stepper testing was used in the laboratory evaluation of the best-practice electrodes. The GM WS-5 stepper test procedure used in previous phases was again used. A summary of this test procedure is provided below:

- Ensure proper electrode installation in electrode holders
- Begin testing without electrode break-in
- Starting at a low current, increase current in 100 A increments until a minimum button size is established
- Add 500 A to the current required to establish minimum button size
- Weld 98 welds on large test panels to simulate electrode wear
- Make 1 peel test sample, peel test the 100th weld
- Check weld size
- If weld size is greater than minimum button size:
  - Continue at present current level for next electrode wear increment and perform peel test
  - Otherwise, increase current to get minimum button size, add 500 A, and repeat the electrode-wear and peel tests steps listed above

Continue to maintain minimum button size using this procedure until test termination

Examples of stepper test results from a previous phase of the program are shown in Figure 2.

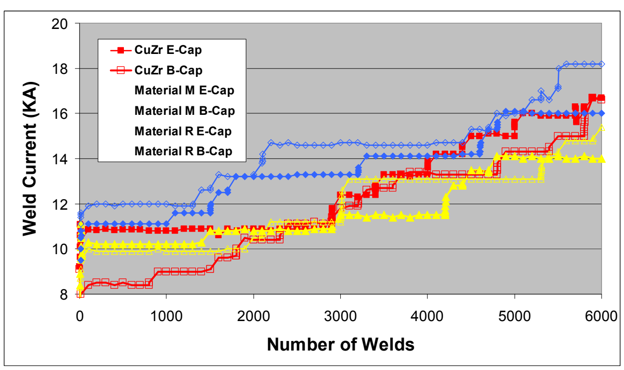

Figure 2. GM WS 5A stepper test results from developmental electrodes studied previously in Phase II. The M electrode is used in the beta-site tests in the current work.

Summary of Laboratory Stepper Test Results

The stepper test results for the electrodes tested in the laboratory in the present phase are summarized in Figure 3. The electrodes and weld schedules tested in the laboratory are summarized in Table 2 below.

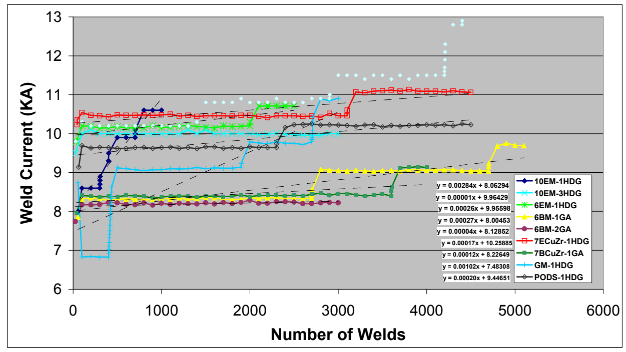

Figure 3. Comparison of limited laboratory tests performed on targeted electrodes in preparation for beta-site testing. The electrodes are listed in Table 2.

Table 2. Electrode designs, electrode materials, sheet materials, and weld schedules for the electrode studies in the laboratory phase of the beta-site testing.

Test	Face Thickness (mm)	Electrode Geometry	Electrode Material	Trial	Steel	Weld Time (cyc)	Electrode Force (lbf)
10EM-1HDG	10	E	M	1	HDG	16	950
10EM-2HDG	10	E	M	2	HDG	16	670
10EM-3HDG	10	E	M	3	HDG	16	670
6EM-1HDG	6	E	M	1	HDG	16	670
6BM-1GA	6	B	M	1	GA	14	480
6BM-2GA	6	B	M	2	GA	14	480
7ECuZr-1HDG	7	E	CuZr	1	HDG	16	670
7ECuZr-1GA	7	B	CuZr	1	GA	14	480
GM-1HDG	9	G	M	1	HDG	16	670
PODS-1HDG	10	P	ODS	1	HDG	12	670

Notes:
Test 1 (10EM-1HDG) was terminated due to use of welding machine with poor cooling. This test had unusually fast electrode wear – very limited analysis. All other trials used original welding machine from previous work.
Test 2 (10EM-2HDG) was terminated quickly due to lack of cooling water. No analysis
Test 6 (6BM-2GA) was performed with sealant.
Test 7 (7ECuZr-1HDG) used internally-finned electrodes
Test 8 (7BCuZr-1GA) used internally-finned electrodes
Test 10 (PODS-1HDG) was performed with a P-cap on top and a CuZr finned B-cap on bottom.

The galvannealed steels in these trials were always tested using the B-nose electrodes while the hot-dip-galvanized steels were always tested using E-nose electrodes. This was done to maximize the work with the limited budget available for the laboratory testing in this phase.

The laboratory tests on the electrodes were limited to verifying the similar performance of the best-practice electrodes to the characteristics observed previously. This provided the least impact on the budget for this phase. After validating the electrodes in the laboratory, selected electrodes were released for beta-site testing at GM and DaimlerChrysler.

GM Technical Center Beta-Site Test Results

A summary of the beta-site weld trials performed at GM is provided in Figure 4. The maximum electrode face diameter criterion in GM WS 5A was used to terminate each of these tests. The face diameter measurements are made from carbon impressions taken every 500 welds. Testing was stopped when these measurements exceeded 10 mm. The test termination criterion ranked the performance of the standard GM cap (10-mm face thickness CuZr) first at 8000 welds; the 6-mm reduced-face-thickness M electrode second at 7500 welds; and both 7-mm reduced-face-thickness CuZr B-cap and E-cap electrodes, at third with 7000 welds.

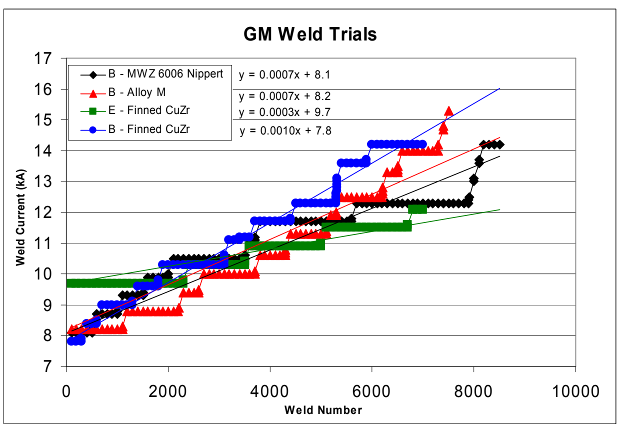

Figure 4. Summary plot showing GM beta-site current stepper test results on 1.1-mm HDG 350 MPa Steel.

Besides the maximum-face-diameter criterion, the maximum current, stepper slope, and other characteristics of the test are also important production considerations. The 7-mm reduced-face, internally-finned CuZr E-cap electrode had the least weld current at 7000 welds compared to the other electrodes and also had the lowest stepper current slope value. Conversely, the 7-mm reduced-face, internally-finned CuZr B-cap electrode had the largest maximum current at 7000 and the highest stepper slope of the beta-site electrodes. The average current and slope values for the GM standard electrode and the 6-mm reduced-face M electrodes were identical. Interestingly, only the standard GM cap did not have indications of boiling behind the cap, as evidenced by a white residue at the water jacket/electrode interface. This suggested that the reduced-face-thickness caps required better water cooling than provided in these trials. Additionally, the weld buttons were more stable for the GM standard CuZr B-cap and the finned CuZr E-cap in this beta-test compared to the other two electrodes. This is contrary to the laboratory testing performed previously, which showed that the M electrode maintained button size until the end of life.

DaimlerChrysler Windsor Assembly Plant Beta-Site Test Results

The stepper-based weld schedule at the DaimlerChrysler Windsor Assembly Plant specifies both a starting current and stepper slope.

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.

The initial weld schedule was:

- Electrode force: 330 lbf
- Electrode geometry: B-cap with 4.8-mm flat; 16-mm body diameter
- Electrode composition: Composite electrode: Al_2O_3 ODS core with CuZr Body
- Weld time: 14 cycles
- Hold time: 2 cycles
- Initial Current: 9000 A
- Stepper Slope: 2A/weld for 1000 welds, 1.5A/weld for 1500 welds, 1A/weld for 1500 welds

This schedule met the maximum transformer current of approximately 15.5 kA after 1 shift.

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 a non-destructive test method, visual detection of expulsion was the method used to verify the presence of a weld between teardown testing. 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 welds under most normal production conditions. These factors tend to increase the operating weld current level, promoting higher initial currents and stepper slopes.

Selection of the appropriate stepper slope also involves operating below the upper limit of the transformer and acknowledging 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 had been made at each lunch break. The goal of the project is 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, Windsor personnel suggested changing the electrodes twice daily or every shift and a half. Alternately, the electrodes would have to be changed once per day.

The maximum stepper rates to achieve a 1½- and a 3-shift electrode change is 1.4 amp/weld and 0.7 amp/weld, respectively. This is based on 3400 welds per shift, three shifts (6 break points), and 7000 A maximum difference between initial current and upper limit of the transformer. The actual stepper current slopes would have to be at least less than these average values. Based on the initial trials, it was decided to work toward changing the electrode sets twice daily. This means that the electrodes should be capable of reaching 2 shifts during the weld setup testing. The 2-shift aim indicates that the average maximum stepper rate should be less than 1.0 amp/weld.

The stepper rate for the trials involving the 6-mm reduced-face-thickness B nose M electrodes were based on minimizing the average numbers of expulsions per part. A graphical summary of some of the setup trials performed on this electrode at DaimlerChrysler is shown in Figure 5. This plot shows a moving average of the number of expulsions that occurred out of 11 welds per part made on this application. This expulsion rate is plotted against the number of assemblies made during the trial. While the numbers varied, the traditional average number of assemblies made between electrode changes was approximately 310 assemblies.

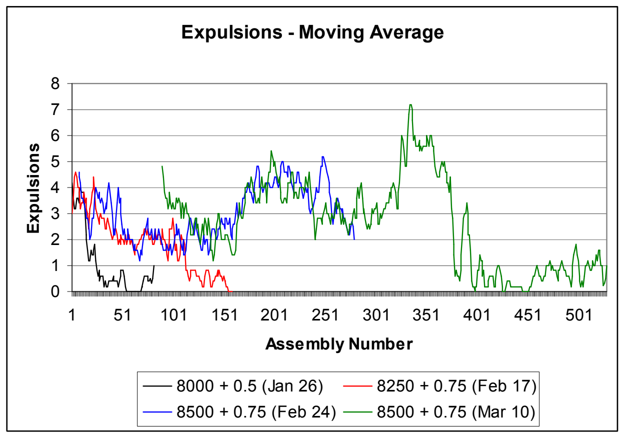

Figure 5. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) made for selected trials of the reduced-face-thickness B-cap M electrode during DaimlerChrysler beta-site testing. The individual weld trials show the stages of stepper schedule development. Legend shows the starting current and stepper rate. 11 welds are made per assembly. Approximately 310 assemblies are made each shift.

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

The expulsion frequency for this stepper is shown in Figure 6. The expulsion frequency for the early part of the stepper was not monitored, but it exactly overlapped the pattern from the previous trials.

Different combinations of stepper slopes were trialed 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

This stepper schedule better maintained the appropriate current density as the electrode face size increased. An example of a weld trial using this stepper schedule is shown in Figure 7. Welding in this trial extended to approximately 2 shifts. Again, the first part of the trial was not monitored, but the average numbers of expulsions in the latter stages of wear was relatively low and weld quality was maintained as verified in teardown tests.

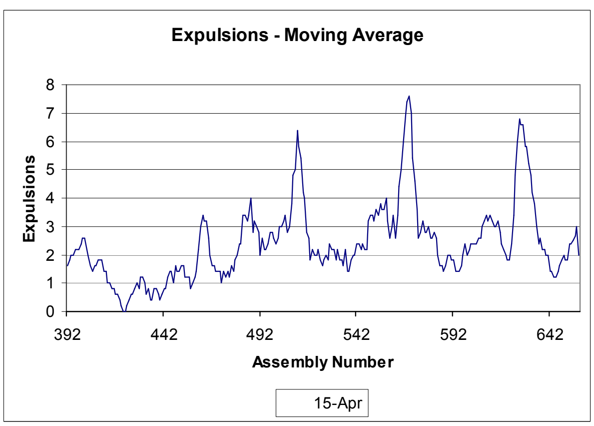

Figure 6. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) using reduced-face-thickness B-cap M electrodes during DaimlerChrysler beta-site testing. This trial extended weld quality to 1½ shifts using a three-stage linear stepper schedule. 11 welds per assembly. Approximately 310 assemblies are made each shift.

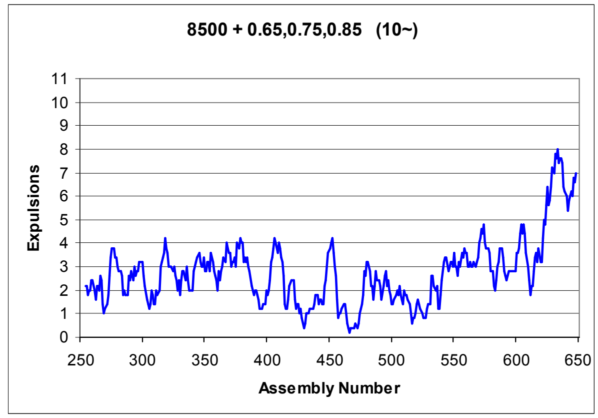

Figure 7. The average number of expulsions per part (11 welds maximum) plotted against the number of assemblies (parts) using reduced-face-thickness B-cap M electrodes during DaimlerChrysler beta-site testing. This trial extended weld quality to 2 shifts using a three-stage linear stepper schedule. 11 welds per assembly. Approximately 310 assemblies are made each shift.

The next stage in the program is to test the reduced-face-thickness B-cap M electrodes in an extended production trial with 2 electrode changes per day over several days of production (at least 12 contiguous shifts).

In an effort to expedite the completion of this work, the work plan to compare the performance of the different best practice electrodes will be based on the minimum stepper rates determined for the M electrode. After adjusting the starting current, weld quality and expulsion frequency will be monitored for a trial up to 2 shifts. If the electrode passes, then a 12-shift weld trial will commence.

Comparison of electrode performance for the alternate electrodes listed in Table 1 (and the current production electrode) will be based on the ability to follow the stepper slope developed for the reduced-face-thickness B-cap M electrode. Experience has shown that if the electrode performance is better than that of the M electrode, then the number of expulsions per part will increase. Conversely, if the performance is worse, then the number of expulsions per part will decrease. A number of other comparisons are also proposed to distinguish between electrodes that can achieve 2 production shifts.

Conclusions

The work performed to date in this phase of the project has shown that the stepper performance of the "best-practice" varieties of electrodes identified in the earlier phases of the program have performed reasonably well in the beta-site tests. Significant results include:

1. Male electrodes appear to provide slightly better stepper-based electrode life compared to female electrode designs.
2. The stepper slope for galvannealed steel is much lower and more repeatable than the slopes produced on hot-dip-galvanized steel.
3. The "best-practice" electrodes developed from the previous phases of this work which incorporate reduced face thickness may be machine- and application- dependent. Specifically, these electrodes may be strongly affected by the lack of cooling water.
4. Stepper slope should increase with increasing numbers of welds to better maintain current density as the cap face increases in size.
5. A plan has been developed to generate stepper schedules in production and efficiently compare different electrodes under production conditions.

Presentations/Publications/Patents

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.

2004. Gallagher, Athwal, K.S.B., Bowers, R., "Evaluation Wear Characterization in Resistance Spot Welding," Sheet Metal Welding Conference XI, Paper 1-5. Sterling Heights, MI (May 11-14). AWS - Detroit Section.

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