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

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Objectives

- 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.

Approach

- Conduct benchmarking (Phase 1). The open literature and available corporate literature will be reviewed along with interviews of industry experts in an effort to produce a state-of-the-art report on electrode wear. This phase has been completed.
- Conduct testing (Phase 2). This involves screening of candidate electrode technologies, in-depth testing of electrodes, and beta testing of selected electrode technologies in a production environment.
- Conduct computer modeling (Phase 3) of the electrode metallurgical and mechanical changes that occur as a result of electrode wear. The models will be used to define the mechanism(s) of electrode wear.

Accomplishments

- Completed screening of standard electrode compositions and designs. The influence of electrode geometry was determined from this work.
- Examined the metallographic changes that occur after completion of electrode life.
- Evaluated five developmental electrode material compositions (using a standard electrode design). Two materials were selected for a detailed sequential electrode wear examination.
- Continued metallographic investigation of the wear process through a sequential examination of electrode wear for three electrodes using two standard electrode geometries.
- Continued to develop and improve computer models to predict electrode life. This includes wear due to both electrode deformation and chemical attack.
- Continued initial beta site test planning.

Future Direction

- Complete sequential life testing.
- Integrate results with computer modeling to produce an electrode for beta site testing.
- Complete planning and execution of beta site test(s).
- 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 its potential for high production rates. However, electrode wear of coated steels and aluminum has been a continuing and significant problem. Electrode wear adversely affects the cost and productivity of automotive assembly welding because it reduces weld quality reliability and robustness. This requires additional inspection and mandates more strict control of the welding parameters. Electrode life potentially becomes especially problematic for high-strength steels. Ultimately, worn electrodes result in deteriorated weld performance. Consequently, large potential cost savings and quality improvements are expected from substantial improvements in electrode life.

As technology has developed during years of use, few engineering solutions have been successfully introduced into the manufacturing process to manage the issues caused by electrode wear. Weld current steppers and electrode cap dressers have been used for many years to address electrode wear, 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 objective evaluation of existing and developmental electrode material and geometry technologies is one of the aims of AMD project 302.

The AMD 302 project team is composed of representatives of General Motors, Ford, and DaimlerChrysler, as well as electrode manufacturers, an automotive supplier, a steel company, and researchers from Oak Ridge National Laboratory (ORNL), University of Windsor, and Edison Welding Institute (EWI).

A flowchart of activities included in AMD 302 is given in Appendix A. The activities in

Phase I and the electrode screening in Phase II have been completed. Sequential life testing and beta site testing of Phase II are under way. The computer models in Phase III are nearly ready to accept data from the sequential life testing and screening results. Each activity will be reviewed as follows.

Initial Electrode Screening Tests on HDG Steel

The initial screening tests for seven 6.4-mm face diameter, RWMA 5 electrodes using 1.1-mm, 350-MPa hot dip galvanized (HDG) steel have been completed. These tests include AWS D8.9-97, a single-current electrode life test, and GM WS5A, Part 3, a stepper electrode life test. The electrodes were largely composed of standard or commercially available electrode materials, namely:

- CuZr, 45° E-cap
- Al_2O_3 (Al60) dispersion strengthened copper (DSC), 45° E-cap and P-nose
- TiC coated CuCrZr, 30° E-cap
- DSC core, CuZr body composite electrode, 45° E-cap
- CuCd (with internal cooling fins), 45° E-nose electrode
- W insert brazed to CuZr, 45° E-nose electrode

These electrodes were tested in E-nose geometry with the DSC material also tested in P-nose geometry as shown in Appendix B. The CuCd was a full-length electrode. All of the E-cap electrodes had a 45° taper except for the 30° TiC coated electrode. Screening of developmental electrode materials was accomplished using a standard E-nose and B-nose geometry.

The initial screening tests were performed using both test procedures; however, the screening of the developmental electrodes was done using AWS D8.9-97. Depending on performance, the developmental electrodes were further tested using a B-nose design; and, both E-cap and B-cap electrodes were sequential life tested, followed by testing using the GM stepper test.

Single-Current Electrode Life Tests on HDG Steel

As provided in the last annual report, the results from the initial electrode life tests using AWS D8.9-97 are shown in Figure 1. The electrode life for DSC material in a P-nose electrode produced 5800 welds before

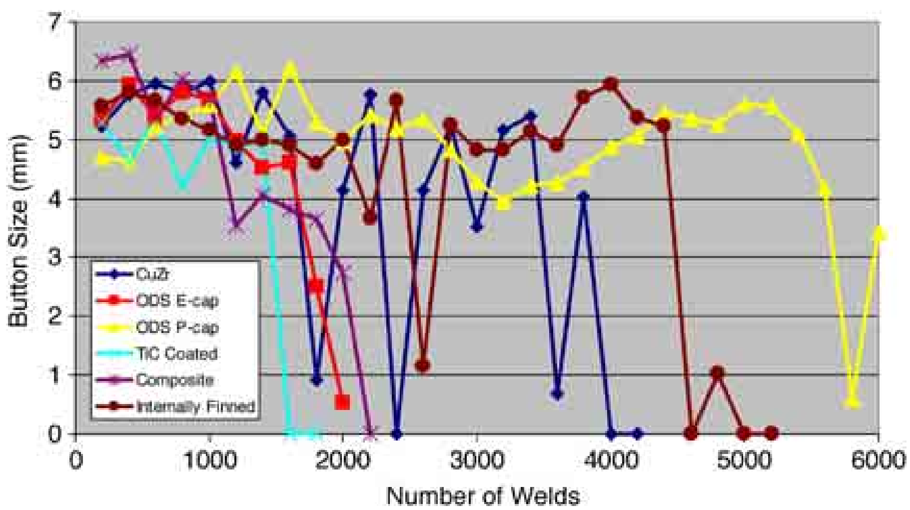


Figure 1. Summary of single-current electrode life (AWS D8.9-97) data for several electrodes on 1.1-mm 70/70 HDG 350-MPa high-strength steel. All of the electrodes were 45° E-cap designs, except the P-cap and the 30° TiC-coated electrode.

failing the test specification requirements, while the E-nose electrode produced only 1800 welds. Electrode geometry appears to play an important role in improving electrode life for the DSC electrode material.

Internal electrode cooling was also effective in extending electrode life, producing 4600 welds before test termination.

The performance of the other electrode materials, with exception of the W faced electrodes, was comparable and provided between 1800–2200 welds of electrode life. The two DSC E-nose electrodes had very similar performance. The W faced electrode had excessive sticking to the galvanized coating that caused it to catastrophically fail during electrode conditioning. These results are not shown on the graph.

Stepper-Current Electrode Life Tests

The GM WS-5A test results are shown in Figure 2. Most of these electrodes were studied in the AWS D8.9-97 test series. Not all of these tests had been completed at the last reporting period. In this test, ideal stepper electrode life test performance was noted by both low-current stepper slope and predictable current step frequency. The test represents the current required to maintain an above minimum sized weld button.

Nearly all of the electrodes had similar performance in this test; however, the P-nose electrode and the 30° E-cap TiC-coated electrodes produced notable responses. The P-cap electrode had half of the stepper slope compared to the best of the other electrode materials. The TiC-coated electrode also performed well due to its lower slope and regular stepping current frequency. The other materials performed similarly in overall stepper slope, except for the W-faced electrodes, which encountered sticking problems similar to that experienced in single-current electrode life tests. The DSC composite electrode did not have a current step until 4000 welds.

Role of Current Density in Electrode Life Testing

Both the single-current and stepper-current electrode life test results had similar current density characteristics during life testing for welds that produced subminimum sized welds. The current densities from the single-current and stepper tests are shown in Figures 3 and 4, respectively.

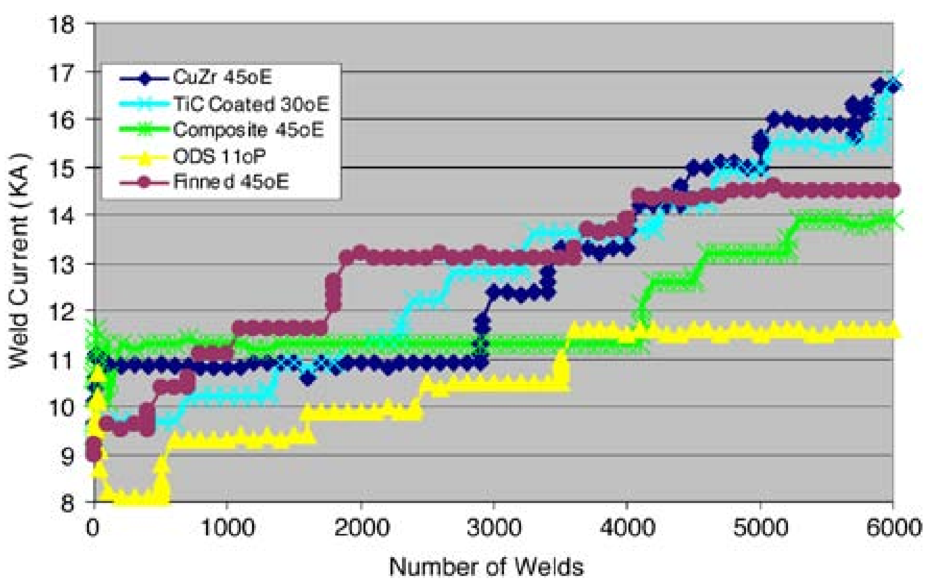


Figure 2. Summary of stepper-current electrode life (GM WS-5A Part 3) data for several electrodes on 1.1-mm 70/70 HDG 350-MPa high-strength steel.

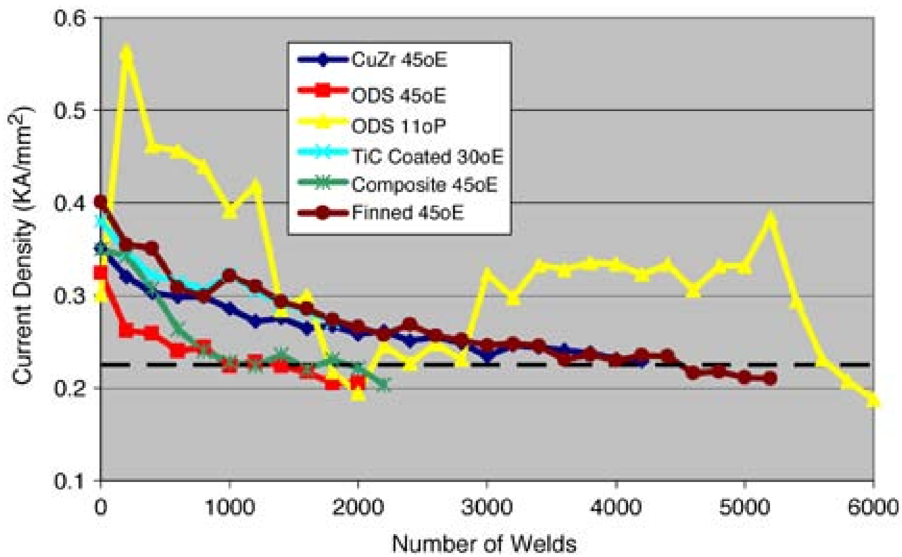


Figure 3. Summary of current density for single-current electrode life (AWS D8.9-97) data for several electrodes on 1.1-mm 70/70 HDG 350-MPa high-strength steel.

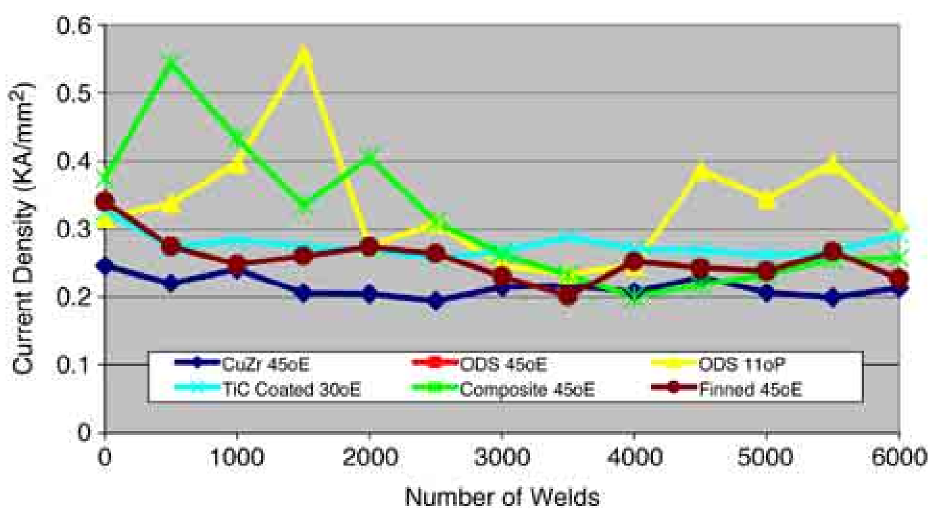


Figure 4. Summary of current density for stepper-current electrode life (GM WS 5A) data for several electrodes on 1.1-mm 70/70 HDG 350-MPa high-strength steel.

Both of these figures demonstrate that the minimum weld size occurred at a current density of approximately 0.225 KA/mm^2 for the HDG steel tested. Current density below this value tended to produce button failure in these two tests. This is a result of electrode face enlargement during testing.

Generally, the bottom electrode did not wear as fast as the top electrode and tended to control the current density needed to establish an above minimum sized weld nugget. The button size is of interest in the stepper test in conjunction with the current densities shown in Figure 4. These welds often exhibited very large button sizes while still producing minimum sized weld buttons. These large welds were shown to suddenly produce near no-weld conditions once the current density fell below the critical value.

Spot Weld Metallographic Evaluation

To better understand the rapid loss in weld button diameter in the GM stepper test, metallographic sections of spot welds made in HDG steel were made before and after the current step increases for the internally finned electrodes. This electrode provided the best demonstration of this effect. These cross sections are shown in Figure 5.

The nugget penetration is relatively stable prior to the production of a weld with subcritical current density. As the current density neared the critical level, the nugget penetration became shallower, changing from about 80% to 70% penetration. Additional wear failed to produce melting, causing the nugget to disappear in some conditions. Weld nugget penetration was reestablished after subsequently stepping the current level to a weld current set at 500 A above that required to produce a minimum weld size.

Metallographic Evaluation of Electrodes Tested on HDG Steel

Each of the electrodes tested were metallographically examined after completion of the AWS and GM tests. A summary of the electrode hardness profile through the centerline of the electrode for the AWS test is given in Figure 6. This plot show that the oxygen-dispersion-strengthened (ODS) materials retained their hardness up to electrode face while the non-ODS materials were substantially softened by the repeated welding operations.

Three optically distinct alloy phases were present at the electrode face. These were noted as a soft inner yellow layer composed of beta brass, a hard intermediate white layer composed of delta brass, and a dark outer layer with a variable composition and hardness. The relative thickness of these layers are shown in Figures 7 and 8 for the AWS and GM stepper tests, respectively. These figures show that the higher heat input from

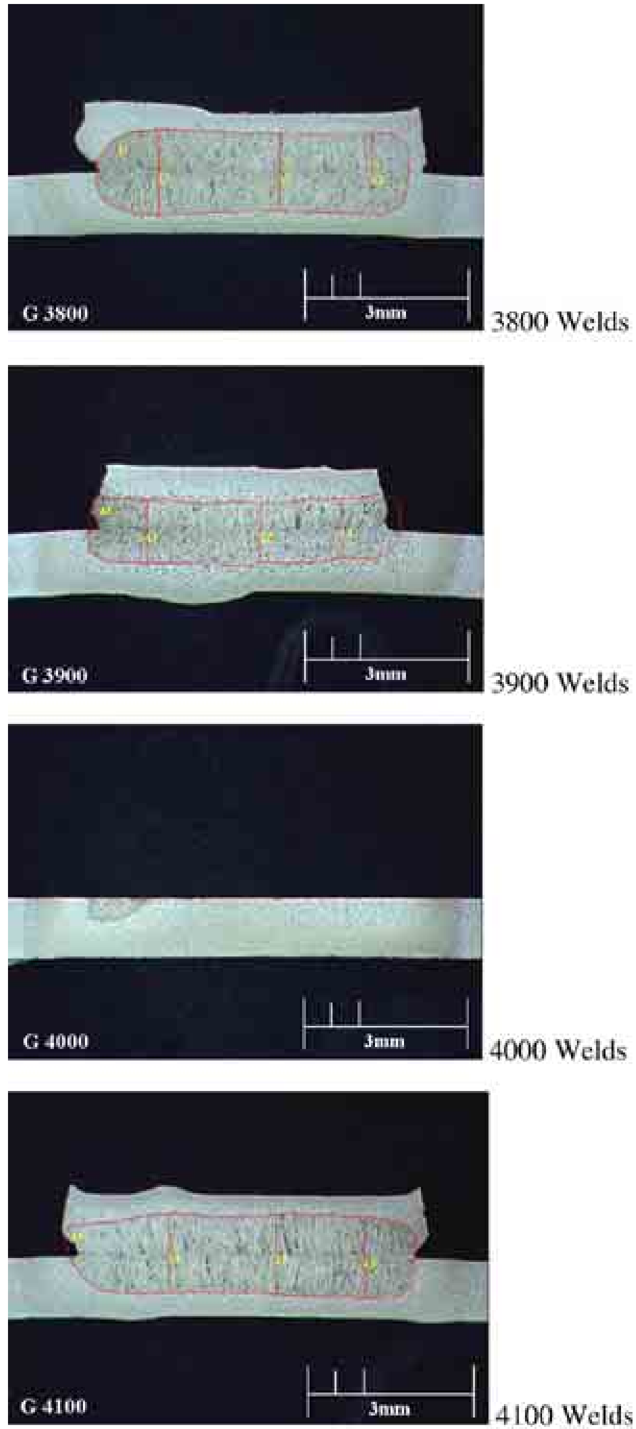


Figure 5. Weld button cross sections from welds 3800, 3900, 4000, and 4100 from stepper test (GM WS 5A) with internally finned electrodes on 1.1-mm 70/70 HDG 350-MPa high-strength steel. Nugget penetration decreases before button failure.

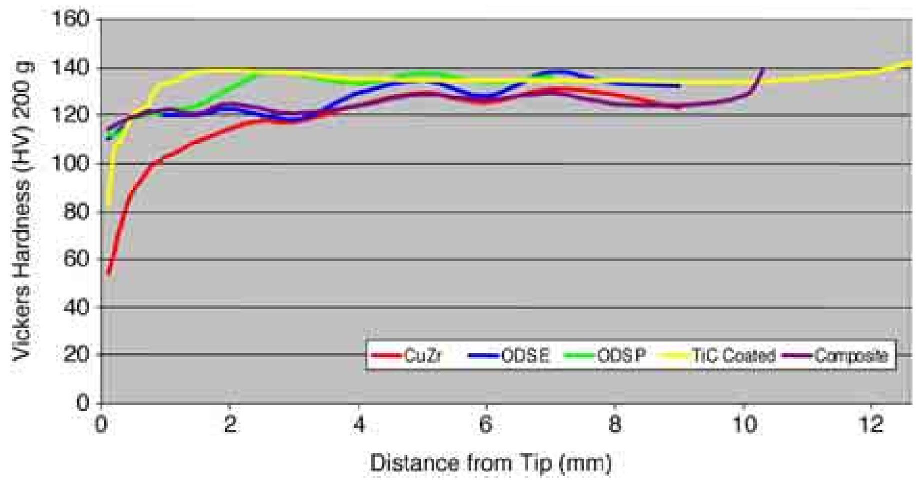


Figure 6. Summary of hardness profile at the centerline of the electrode for several electrodes after the AWS D8.9-97 test on 1.1-mm 70/70 HDG 350-MPa high-strength steel.

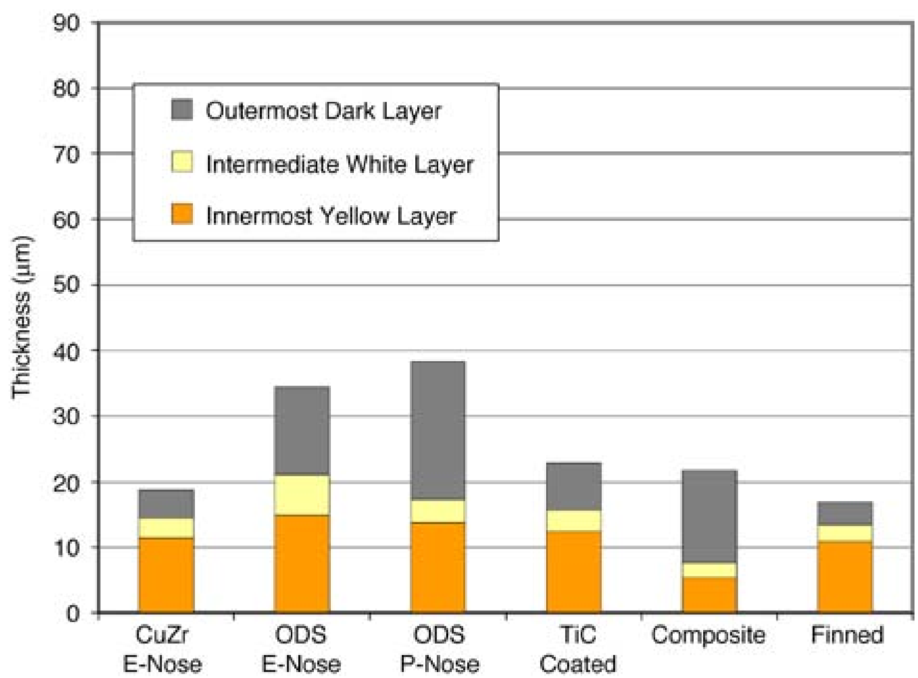


Figure 7. Alloy layer thickness at the electrode surface after AWS D8.9-97 testing 1.1-mm 70/70 HDG 350-MPa high-strength steel.

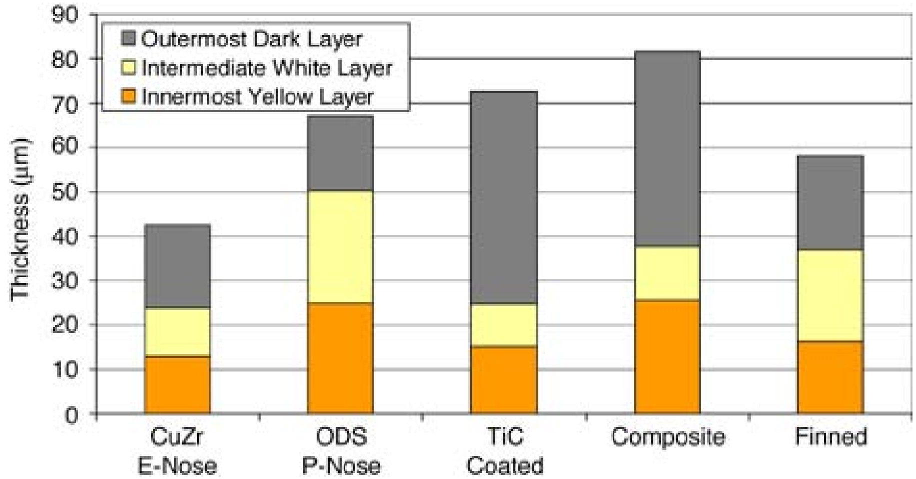


Figure 8. Alloy layer thickness at the electrode surface after GM WS 5A testing 1.1-mm 70/70 HDG 350-MPa high-strength steel.

the GM test increased the total alloy thickness and increased the thickness of the two layers near the electrode surface. The outer layer was found to fill pits and probably acted as a parting layer to the electrode surface.

Electrode Life Testing of Aluminum

The electrode life test performed on uncoated 1-mm Al5754 sheet used a modification of the Ford BA113 specification for assessing electrode wear in aluminum. The frequency of button size assessments were modified to peel test nearly every weld made in this program. Weld button size and quality were recorded. The electrodes for testing aluminum used a similar E-nose geometry as used in the HDG wear study. The electrode materials tested were

- CuZr
- CuCd (internally finned)
- C107 oxygen-free copper (OFC)

These electrodes were tested with a large pedestal welder. The mass of the ram in this machine is characterized by a slow electrode followup characteristic. A spring pack was alternately employed to isolate the mass and accelerate the electrode followup. This is needed to avoid excessive weld metal expulsion. Graphs of typical electrode life observed in this study are illustrated for the C107 electrode tested using both fast and slow electrode followup characteristics, as shown in Figures 9 and 10.

Electrodes on a slow followup welding machine generate more heat at the electrode-sheet interface resulting in excessive sticking. Ultimately, sticking was manifested by adherence of large chunks of aluminum from the sheet onto the electrode during electrode retraction. Additional welds with this adhered material would have produced massive expulsion, severely damaging the electrodes and putting a hole in the sheet. This event signals the end of electrode life without a fast followup head.

Besides the catastrophic sticking event observed for the welding machine configured with a slow followup characteristic, electrode life was largely governed by weld button quality and scatter in the button size results. The average weld button size did not decrease during electrode life as observed during testing HDG steel. Rather, the consistency of weld size from weld to weld became an issue, together with other weld quality indications.

The welds produced using slow electrode followup had less button size variability compared to welds produced with a fast followup head assembly. Conversely, the welds made using a fast followup head assembly

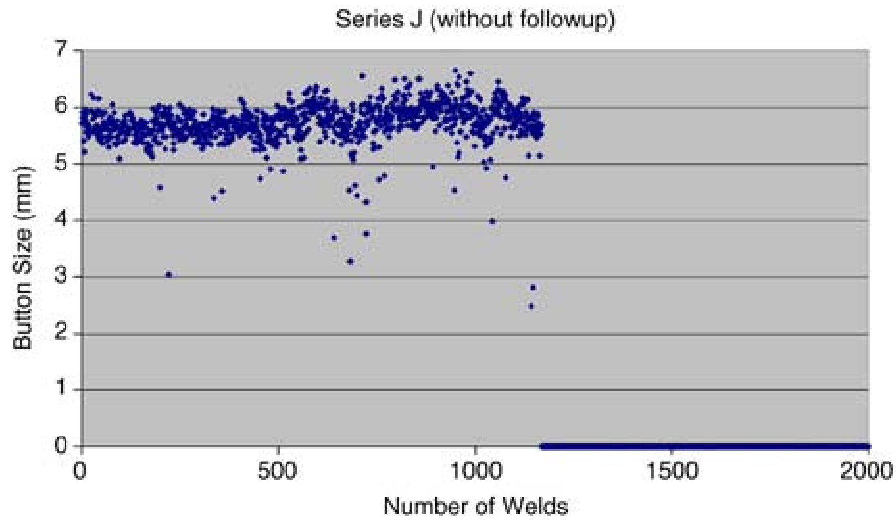


Figure 9. Summary of single-current electrode life (Ford BA 113) data without fast followup head on E-nose C107 electrodes on 1.0-mm Al 5754.

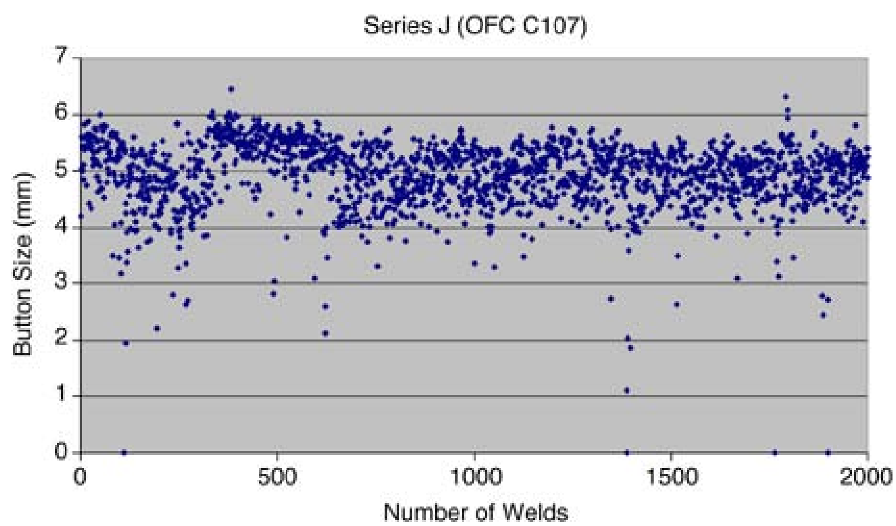


Figure 10. Summary of single-current electrode life (Ford BA 113) data with fast followup head on E-nose C107 electrodes on 1.0-mm Al 5754.

were much more likely to produce sudden losses in peel button size early in electrode life compared to welds made without a fast followup head. Overall, welds made with a fast followup head had greater variability in average weld size but were less likely to produce weld button failures and other button quality problems later in electrode life compared to welds made without a fast followup head.

A summary of weld quality indication rates for the electrode life tests in the aluminum is given in Figure 11. This plot shows the frequency of occurrences for undersized welds, partial interfacial and full interfacial fractures, cracks, holes on top surface of button, and porosity visible on button fracture face. As can be seen, all of the electrodes had different weld quality issues. However, the more conductive electrode materials

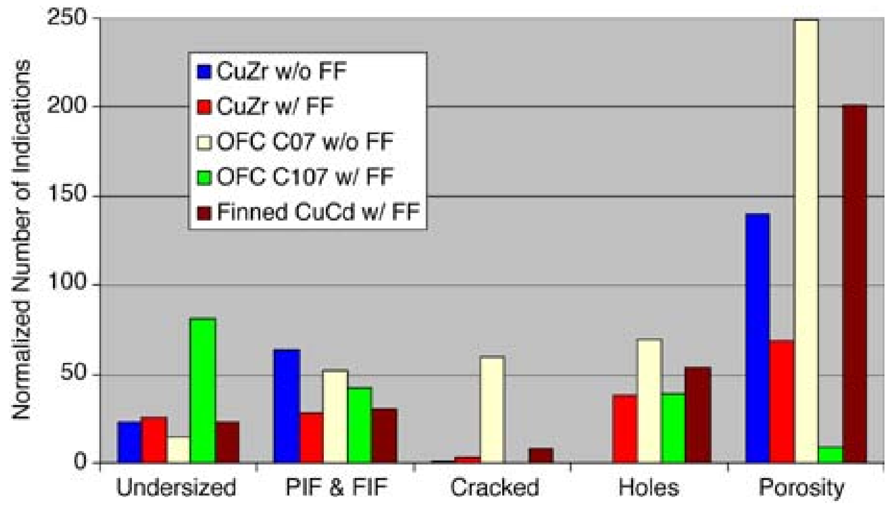


Figure 11. Summary of button quality problems for various electrodes during electrode life testing (Ford BA 113) on 1.0-mm Al 5754.

generally produced the least number of significant weld button quality problems.

The reason for this relates to the manner of electrode wear in aluminum. Much of the heat used to initiate and grow the weld nugget comes from the breakdown of the oxides at the electrode-sheet and sheet-sheet interfaces. Because of the high thermal conductivity of aluminum, heat generated at the electrode-sheet interface can be quickly diffused to the weld nugget. Welds made without a fast followup electrode system increase resistive heating at the electrode-sheet interface. This heat is diffused to increase and maintain a more consistent weld size. However, the large weld size also exaggerates the severity of expulsion of weld metal, which causes porosity. The location of nugget porosity is important to random nature of the sudden loss in weld button size, which is the result of fracture propagation across a weld nugget through adversely positioned porosity distributions.

Excessive heating of the weld nugget generally promotes the poor weld quality indications, as noted in Figure 11. Thus, the more conductive electrode materials appeared to produce better overall weld button quality results as a result of electrode wear. This is because greater conduction of heat from the electrode face results in less overheating the weld nugget and fewer severe weld metal expulsions.

No clear direction in electrode material composition was established for welding aluminum as a result of this testing because those factors that improved weld button stability also contributed to poorer weld quality. Additionally, the test results in aluminum appear to be machine specific.

Changes to the Program

As a result of the testing on aluminum, the AMD board chose to focus the remainder of the program on improving the performance of electrode materials for welding HDG steel. This effort will concentrate on E-nose and B-nose electrode geometries for testing developmental electrode materials. While the P-nose electrode geometry produced good results, the performance of electrode materials needed to be addressed separately. In addition, there was concern with implementation of P-caps in production. Normally, the P-nose electrodes have been used in conjunction with a B-nose electrode. It is thought that the B-nose electrode performance could govern the performance of the electrode pair.

Electrode Wear Computer Modeling

Computer models describing both electrode deformation and surface chemical attack are being developed at ORNL and are nearly complete. The deformation model is based on deformation of disks of material at the electrode face. These should be ready in time to accept the sequential life test results. Additionally, high-temperature electrode material properties are being developed at ORNL to support the modeling effort.

An analytical model is also being formulated at EWI. This will be based on previous work and will also describe the thermo-mechanical deformation aspect of electrode wear. Both models will support each other and strengthen the overall data interpretation effort.

Sequential Life Testing

A sequential study of the stages of the progression in electrode wear is under way for CuZr and two developmental electrodes selected from screening tests performed on developmental electrodes. Five developmental electrode materials using the E-cap design were screened using AWS D8.9-97. The results of these screening tests are shown in Figure 12. The M and R electrode materials were selected for further evaluation in the sequential life testing program. Additionally, these electrode materials were AWS D8.9-97 tested in a B-cap design. Furthermore, both E-cap and B-cap designs for these materials were GM stepper tested for comparison with previous screening results. A summary of the GM stepper test results are presented in Figure 13.

The sequential life testing phase involves the production and metallurgical evaluation of progressively longer electrode lives. The electrodes were removed at set intervals using standard life testing procedures. These electrodes are currently being metallurgically sectioned and examined to show the progression and stages of electrode wear. Chemical evolution of electrode surface will be tracked. Additionally, microstructural and phase changes will be tracked as a function of depth from the electrode face.

Electrode samples for the CuZr, M, and R electrode materials with both E-nose and B-nose electrode geometries have been produced. A plot of button size vs number of welds for the E-nose electrode is shown in Figure 14. The electrodes were removed after 25, 50, 100, 250, 500, 1000, and 2000 welds. The electrodes from the standard AWS D8.9-97 test were used as the end-of-life condition.

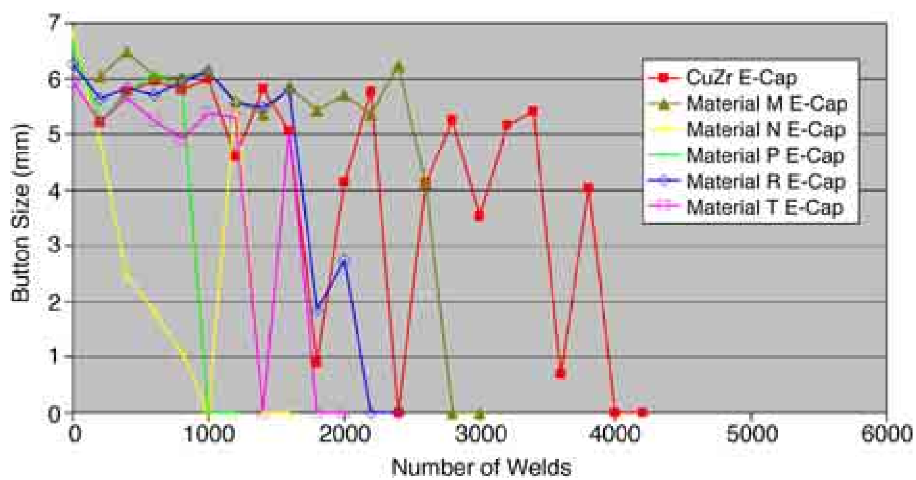


Figure 12. Summary of screening tests for CuZr and five developmental electrode compositions tested in 45° E-cap design using AWS D8.9-97 on 1.1-mm 350-MPa HDG steel.

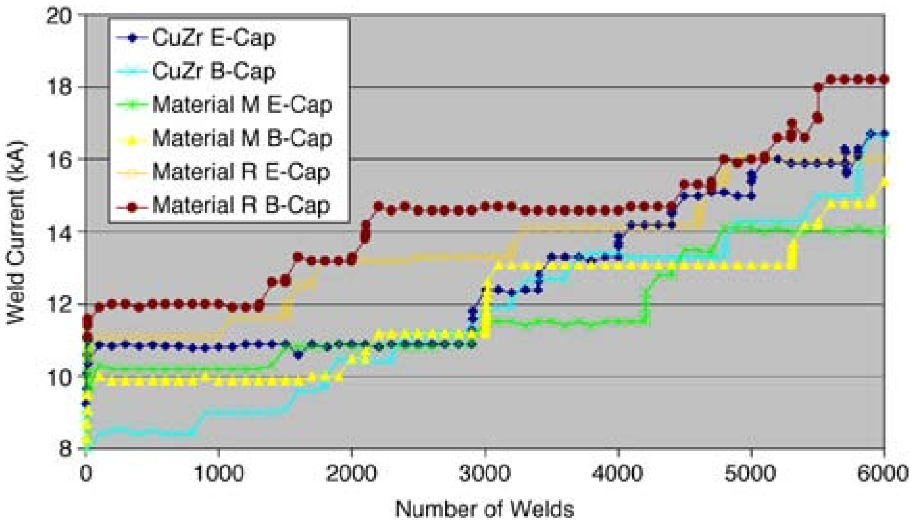


Figure 13. Summary of GM WS 5A Stepper Test results for CuZr, M, and R electrode materials in 45° E-cap and B-cap designs on 1.1-mm, 350-MPa HDG steel.

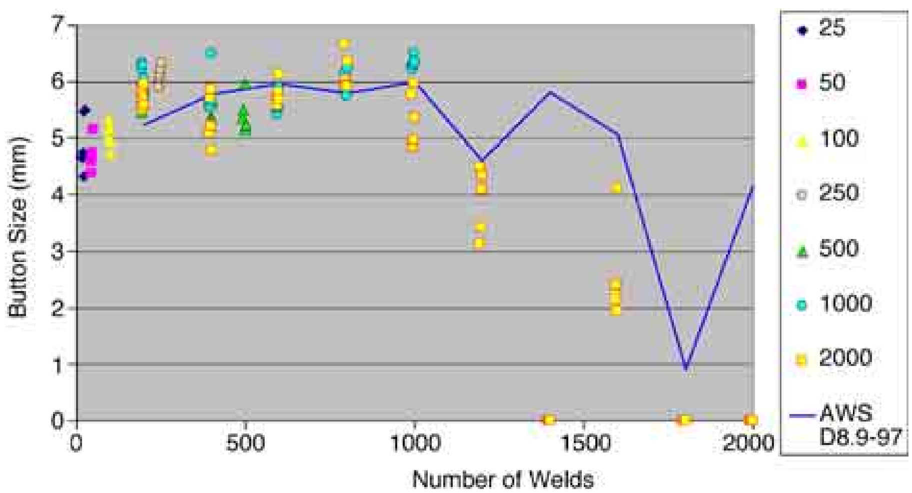


Figure 14. Button size measured during interrupted electrode life tests with CuZr electrodes on 1.1-mm, 350-MPa HDG steel (solid line indicates standard AWS D8.9-97 results).

The button size, welding parameters, electrode face diameter, and electrode C-imprint data from the screening and sequential life test data will be combined with the computer models to interpret and evaluate the surface and microstructural changes that describe electrode wear in electrode life for HDG steel. This information will be used to predict the "best practice" electrode material and electrode design to be evaluated during the beta site test(s).

Planning Beta Site Testing Activities

Possible beta site test locations have been identified at DaimlerChrysler and other automotive companies. These locations need to be further evaluated. Additionally, initial experimental plans have been sketched for the trials. These plans include standardized "optimization" procedures, the list of requested and required measurements and observations needed to analyze the results, etc. These plans will be developed quickly in preparation as the beta site test phase of the program initiates.

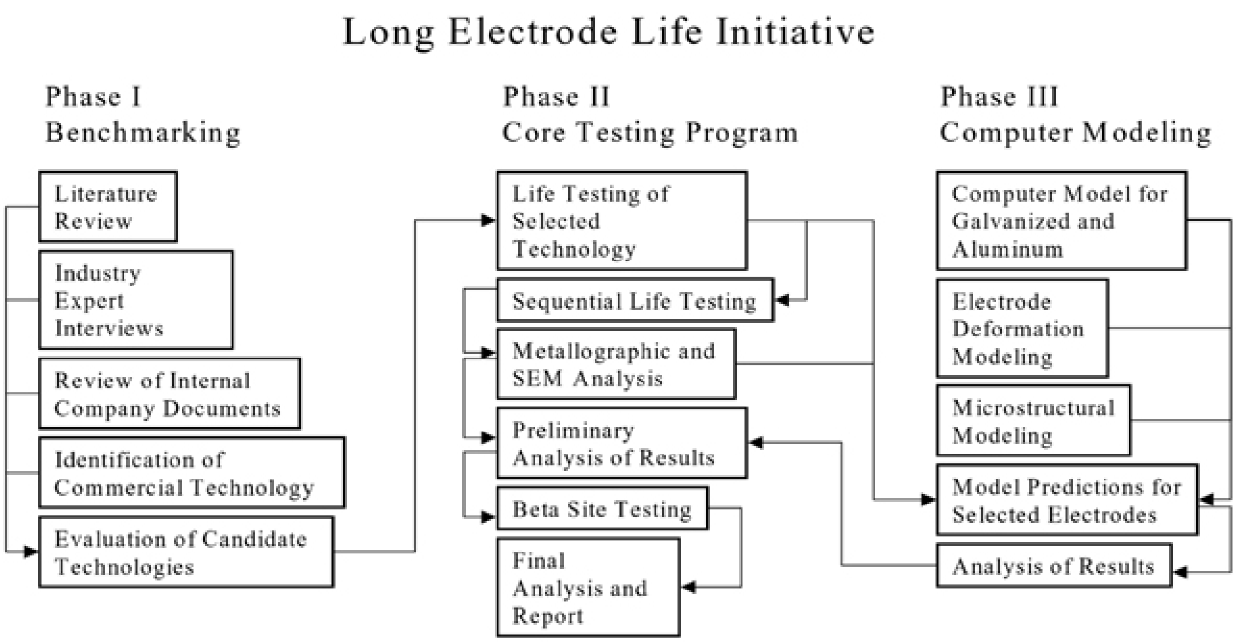
The beta tests will occur after the sequential life testing has been completed and "optimized" electrodes have been produced for testing. Two sessions are expected. The first session will indicate deficiencies between laboratory and production conditions, and the second iteration is expected to demonstrate the electrode life improvements under production constraints. The data gathered during the first beta site evaluation will be coupled with the computer and analytical modeling to produce an updated electrode for evaluation during the second beta site test. The specification of the electrode geometry for these electrodes will need to be worked out in conjunction with the beta test site.

Future Work

Future work on this project should lead to a more effective, accurate, and efficient electrode development effort. New copper alloys, with targeted material properties, can be produced and evaluated using the predictive capabilities provided by the models developed during this program. The alloys thus developed should show deliberate improvement in electrode life.

Additionally, the computer models can be adapted to improve schedule development for stepper and electrode dressing techniques. This will further improve electrode performance, improve weld quality and productivity, as well as reduce setup costs in automotive production.

Appendix A



Appendix B