K. Joining of Dissimilar Metals for Automotive Applications: From Process to Performance

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Objective

- Develop and evaluate different technologies for joining dissimilar aluminum alloys and aluminum to steel.
- Characterize the performance of these joints.
- Develop a unified modeling procedure to represent these joints in vehicle structural simulation. The steel materials include mild, high-strength low-alloy, and dual-phase steels.

Approach

- Further develop and/or enhance self-piercing rivets (SPRs) and resistance spot welding (RSW), with and without adhesives, for joining dissimilar metals.
- Develop a database for the static, dynamic, fatigue, and corrosion behavior of dissimilar material joints, consisting of different material selections and different joining techniques.
- Incorporate and represent the joint performance data into current computer-aided engineering (CAE) codes for evaluation of impact and fatigue performances of joint components.
- Develop design guidelines in the forms of tables and charts for use in joint structural and crash design.

Recent Accomplishments

- Developed a complementary experimental and analytical approach that results in a more thorough understanding of the effects of different joining methods on vehicle structural integrity and long-term performance.
- Provided knowledge regarding the selection of appropriate materials and provided the know-how for joining of dissimilar materials.
- Optimized the rivet strength by examining the effects of different manufacturing and in-service factors on the peak load and energy absorption levels of different joint configurations:
  - Effect of rivet length

  - Effect of riveting direction
  - Effect of dissimilar materials combination
  - Effect of adhesive
  - Effect of loading rate

- Investigated experimentally the static, fatigue, and dynamic behavior of the following dissimilar joints:
  - Joint ID 13A: SPR DP 600 (1.6 mm) and 5182-O (2 mm) with DOW Betamate 4601
  - Joint ID 13B: SPR DP 600 (1.6 mm) and 5182-O (2 mm) with DOW Betamate 1480
  - Joint ID 13D: SPR DP 600 (1.6 mm) and 5182-O (2 mm) exposed to 500-h salt spray
- Investigated the influence of "weld ductility" on component crash behaviors.
- Applied the fatigue analysis procedure to 14 different combinations of joined dissimilar materials.
- Conducted sequentially coupled corrosion-fatigue test on one joint population.
- Compared the influences of different structural adhesives on the strength of the bond-riveted joints.
- Documented the results of our project in terms of six topical reports and disseminated the information to the automotive industry through the U.S. Council for Automotive Research (USCAR) Web site: https://secure.uscarteams.org/VROOM/
- Completed current test populations.
- Completed validation of the proposed failure criterion.
- Transferred joint performance database to members of the joining team.
- Conducted final workshop/presentation summarizing results to the joining team.
- Completed final report.

Introduction

This project is a collaborative effort between the Department of Energy (DOE), Pacific Northwest National Laboratory, and the Metals Joining Team of the U.S. Council for Automotive Research (USCAR). The work started in April 2001.

The automotive industry envisions that an optimized vehicle, in terms of performance and cost, can be achieved only by using different materials at different vehicle locations to utilize the materials' functionalities to the fullest extent. Currently, aluminum and steel are the most important construction materials for the mass production of automotive structures. High-volume, nonsteel joining is a significant new problem to the industry. For joining dissimilar aluminum alloys, the leading candidate joining methods are spot welding and self-piercing rivets (SPRs) with or without adhesives. The major concerns with aluminum spot welding are its high-energy consumption, low electrode life (see report 7G), and structural performance concerns related to weld porosity. For joining aluminum to steel, the industry is currently comfortable with SPRs (with and without adhesives). However, there are a number of barriers to the widespread exploitation and high-volume production of the riveting technology. One of these barriers is the limited performance data relative to automotive applications.

In contrast, to shorten the vehicle development cycle, more and more computer-aided engineering (CAE) analyses are performed before the actual prototype is built. The question that the CAE researchers ask most often is how to represent the structural joints in crash simulation and fatigue simulation. Currently, there is no unified approach to representing the structural joints that works for different material combinations under multiaxial loading. This is particularly true for dissimilar material joints, where even basic performance information on the joint coupon level does not exist.

Project Summary

In this project, we have developed a complementary experimental and analytical approach that results in a more thorough understanding of the effects of different joining methods on vehicle structural integrity and long-term performance. We have experimentally investigated the static, fatigue, and dynamic behavior of several dissimilar material joint populations (current joint studies are underlined):

- Joint ID 7: SPR 5182-O (2 mm) and 5182-O (2 mm)
- Joint ID 8: SPR 5182-O (1 mm) and 5182-O (2 mm)
- Joint ID 9: SPR 1008 (1.4 mm) and 5182-O (2 mm)
- Joint ID 10: SPR 5182-O (2 mm) and HSLA 350 (1 mm)
- Joint ID 10A: SPR 5182-O (2 mm) and HSLA 350 (1 mm) with Betamate adhesive
- Joint ID 11: SPR HSLA 350 (1 mm) and 5182-O (2 mm)
- Joint ID 11A: SPR HSLA 350 (1 mm) and 5182-O (2 mm) with Betamate adhesive
- Joint ID 12: SPR 5182-O (2 mm) and DP 600 (1.6 mm) with 6.0-mm rivet
- Joint ID 12A: SPR 5182-O (2 mm) and DP 600 (1.6 mm) with Betamate 4601 adhesive and 6.5-mm rivet
- Joint ID 12L: SPR 5182-O (2 mm) and DP 600 (1.6 mm) with 6.5-mm rivet
- Joint ID 13: SPR DP 600 (1.6 mm) and 5182-O (2 mm)
- <u>Joint ID 13A</u>: SPR DP 600 (1.6 mm) and 5182-O (2 mm) with DOW Betamate 4601
- <u>Joint ID 13B</u>: SPR DP 600 (1.6 mm) and 5182-O (2 mm) with DOW Betamate 1480
- <u>Joint ID 13D</u>: SPR DP 600 (1.6 mm) and 5182-O (2 mm) exposed to 500-h salt spray
- Joint ID 14: RSW 5182-O (2 mm) and 5182-O (2 mm)
- Joint ID 15: RSW 5182-O (2 mm) and 6111-T4 (2 mm)
- Joint ID 16: RSW 1008 (1.4 mm) and 5182-O (2 mm) with aluminum-clad steel interlayer (1.5 mm)

In characterizing the performance of these joints, we investigated the effects of different manufacturing and in-service factors on the peak load and energy absorption levels:

- effect of rivet length,
- effect of riveting direction,
- effect of dissimilar materials combination,
- effect of adhesive, and
- effect of loading rate.

We have also developed an overload failure and fatigue failure criterion from the experimental results utilizing CAE. A joint overload failure criterion was derived from the static and dynamic test results of different joint coupon configurations. Frontal and side impact simulations were performed to evaluate the impact performance of spot-welded aluminum and steel hat sections. Failure functions were monitored for each weld during the deformation processes.

Component-level joint fatigue analysis was developed using experimentally obtained master stress intensity factor (SIF) life curves. In this project, SIF was chosen to be used as the single parameter to consolidate the fatigue performance curves of different joint populations and different coupon geometries into the fatigue master SIF-life curves. The SIF was chosen because of its accuracy and computational simplicity in vehicle simulation.

The goal of this project is to provide automotive designers with more performance data for light-weight and dissimilar material joints of different choice, provide knowledge regarding the selection of appropriate materials and the joining of dissimilar materials, and to provide CAE engineers with more reliable joint properties and modeling techniques to realistically represent these structural joints in crash and durability simulations.

The following sections describe the research conducted during this reporting period.

<u>Effects of Corrosion Damage on Joint Strength</u>

Previously, salt spray corrosion tests were conducted on SPR and RSW populations evaluated (with the exception of Joint ID 13 and 16). Specimens were exposed to salt spray/fog for 500 h according to the American Society for Testing and Materials (ASTM) B117. Scanning electron microscopy (SEM) and electron dispersive x-ray spectroscopy (EDS) were performed to determine whether corrosion was observed in the joints after being exposed to salt spray.

No pitting or crevice corrosion was observed in any of the populations analyzed. However, chloride and increased levels of oxygen were present in all SPR populations tested without adhesive in the joint. No chloride was present in the RSW joints or the SPR joints with adhesive.

Lap shear, cross tension, and coach peel coupon geometries of DP 600 and 5182-O joints (ID 13D) were exposed to 500 h of salt spray to determine the effects of corrosion on the performance of the joints; (the increased levels of oxygen observed in aluminum/steel joints are possibly due to formation of rust, Fe_2O_3). Experiments were performed to investigate the effect of salt exposure on the static and fatigue performance of the joints.

The static performance of Joint ID 13 and 13D are compared in Figures 1 and 2. It was observed that the joints exposed to salt spray yielded comparable strength characteristics for the same joint not exposed. The average peak load for lap shear coupons exposed to salt spray was approximately 9% lower than lap shear joints not exposed to salt

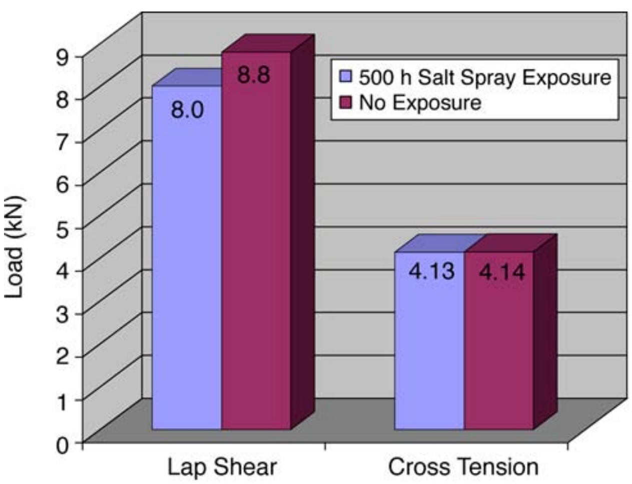

Figure 1. An illustration of static peak load results for Joint ID 13 and 13D. Results shown are representative of the average peak load observed for the specimen designs tested in each joint population.

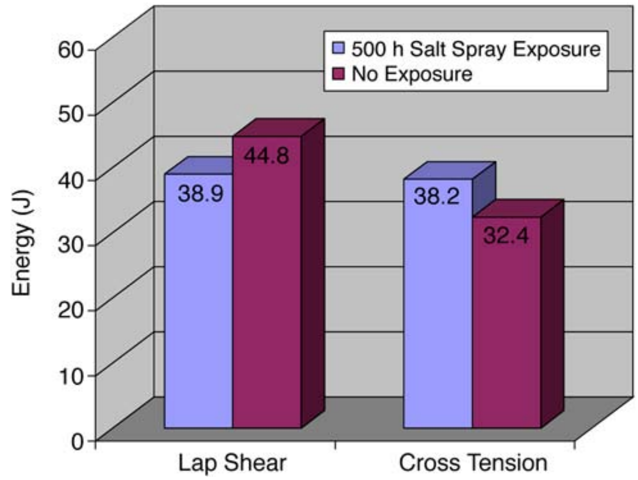

Figure 2. An illustration of the static tests energy absorption results for Joint ID 13 and 13D. Results shown are representative of the average energy absorption for the specimen designs tested in each joint population.

spray. The cross-tension joints were comparable regardless of exposure.

Cyclic fatigue tests were also performed on the joints under a tension-tension ratio of R = 0.1 for lap shear and cross-tension specimen designs. Figure 3 compares the fatigue strength of the joints. Comparable and slightly greater fatigue strengths were observed in the joints exposed to salt spray. It is thought that the corrosion products formed between the rivet and material substrates are making the joints tighter. Further investigation of the tightness of the joint and correlation of fatigue life are both needed.

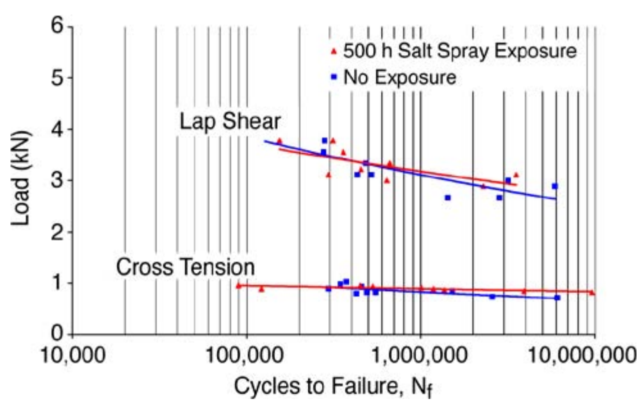

Figure 3. Fatigue test results of Joint ID 13 and 13D.

Effects of Different Structural Adhesive on Joint Strength

The effects of different structural adhesives on the static strength of two bonded-riveted populations are investigated:

- Joint ID 12A: SPR 5182-O (2 mm) and DP 600 (1.6 mm) with Dow Betamate 4601 adhesive and 6.5-mm rivet
- Joint ID 13B: SPR DP 600 (1.6 mm) and 5182-O (2 mm) with DOW Betamate 1480 adhesive

The purpose of this study is to evaluate the different adhesion levels for different adhesive systems on dissimilar metals substrates; namely, DP600 and AA5182-O. Dow Betamate 4601 is the structural adhesive currently being used in the U.S. automotive industry. Dow Betamate 1480 is currently only commercially available in the European market. Therefore, our study helps the domestic automotive industry to evaluate the structural behaviors of these two different adhesive systems. Figures 4 and 5 compare the static performance of Joint ID 12A and 13B for lap shear and cross-tension specimen designs. It was observed that the two different adhesives yielded similar strengths (first peak on load-displacement graphs).

The mode of failure for the samples was also similar. Figure 6 is a photo representative of the joints with adhesive. Both adhesive (separation at adhesive-substrate interface) and cohesive (failure within adhesive) failure modes are observed.

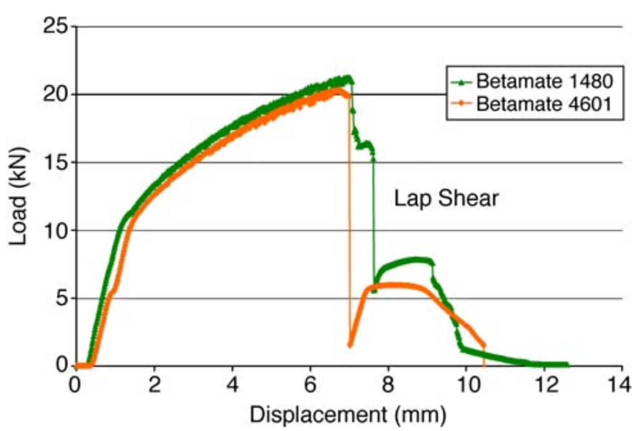

Figure 4. Static test results of ID 12A and 13B. Results shown are representative of the average peak load observed in each joint population.

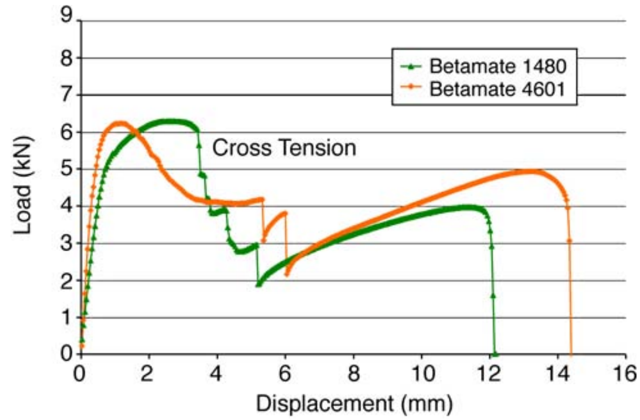

Figure 5. Static test results of ID 12A and 13B. Results shown are representative of the average peak load observed in each joint population.

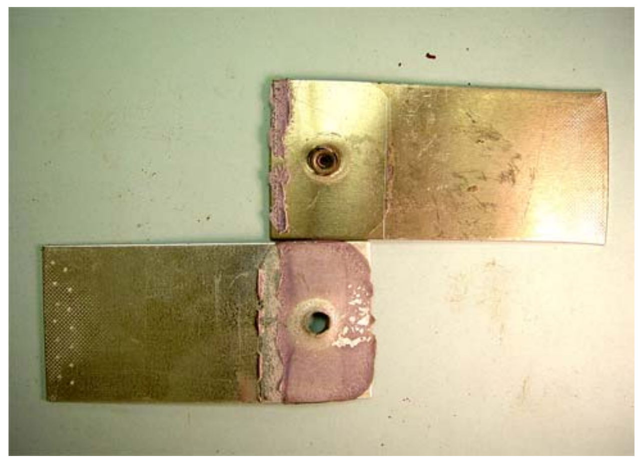

Figure 6. Typical static failure mode of joints with adhesive.

Conclusions

Through the course of this project, many observations and accumulated knowledge have been documented in terms of eight topical reports. Further conclusions and technical details are documented in the following reports:

- *Joining of Dissimilar Metals for Automotive Applications—From Process to Performance* (final report)
- *Dynamic Joint Strength Evaluation under High Rate Impact Loading*
- *Characterization of Fatigue Behaviors of Dissimilar Metal Joints Part I—Experimental Studies*
- *Performance Comparisons through Weibull Analyses of Self-Piercing Rivets and Resistance Spot Welds Joining Dissimilar Metals*

- *Resistance Spot Welds of Aluminum Alloy to Steel with Transition Material: From Process to Performance*
- *Effect of Failure Modes on Strength of Aluminum Resistance Spot Welds*
- *Analytical Strength Estimator for Self-Piercing Rivets*
- *Lap Shear Coupon Design Sensitivity Study for Self-Piercing Rivets and Resistance Spot Welds*

Through experimental investigation and analytical study, the following conclusions are derived from this research:

1. The joint strength remains relatively unchanged from static to dynamic 10-mph and 20-mph tests for the dissimilar metal joint populations studied.
2. The total energy absorption for the joint samples decreases with increasing testing velocity.
3. For certain material and thickness combinations and die design, the rivet strength can be optimized through different rivet length.
4. Different piercing directions yield different strength characteristics for SPR joints. Static strength can be improved if failure occurs on the side of the stronger material.
5. Softer, more formable material at the tail end allows a better mechanical interlock between the rivet and the base material. A fatigue strength improvement is observed.
6. A mechanics model developed in this project may be used to predict SPR static joint strength given the materials and thickness combinations.
7. Application of a structural adhesive increases the static strength of riveted joints. A significant increase is observed in lap shear joints (3 ~ 5 times) and a modest increase is observed in cross tension and coach peel joints (up to 20%).
8. Application of a structural adhesive increases the static energy absorption of rivet joints, particularly, in lap shear and cross tension joints. The increase is marginal in coach peel joints.
9. Two distinct, uncoupled peaks are observed for static SPR joint samples with adhesive. The first peak is the adhesive failure; the second peak is the rivet failure.
10. Static strength of rivet bonding/weld bonding can be estimated. The rivet failure peak load is not affected by the presence of adhesive and the adhesive, failure peak load is not affected by the presence of rivets.
11. Application of a structural adhesive significantly increases the joint fatigue strength.
12. Joints exposed to salt spray yielded similar strength characteristics compared with the same joint not exposed.
13. Among the different overload failure criteria, the force based model (#2 in DYNA 970 material 100) is recommended for representing joints in vehicle crash simulation.
14. Among the different fatigue failure criteria, the stress intensity factor K-based and the structural stress-based models are recommended for representing joints in vehicle performance/ durability simulations.

A project compact disk (CD) including all topical reports, raw data, summary data, and presentations has been distributed to the Joining Task Force Team. Reports and all data have been made available to all members through the USCAR Web site: https://secure.uscarteams.org/VROOM/

Presentations and Publications

1. X. Sun, E. V. Stephens, M. A. Khaleel, H. Shao, and M. Kimchi, May 2004, “Resistance Spot Welding of Aluminum Alloy to Steel with Transition Material—From Process to Performance,” *Proceedings of the Sheet Metal Welding Conference XI.*
2. X. Sun, E. V. Stephens, M. A. Khaleel, H. Shao, and M. Kimchi, June 2004, “Resistance Spot Welding of Aluminum Alloy to Steel with Transition Material—From Process to Performance, Part I: Experimental Study,” *Welding Journal*, **83**(6), 188s–195s.
3. X. Sun and M. A. Khaleel, July 2004, “Resistance Spot Welding of Aluminum Alloy to Steel with Transition Material—From Process to Performance, Part II: Finite Element Analyses of Weld Nugget Growth,” *Welding Journal*, **83**(7), 197s–202s.

4. X. Sun, E. V. Stephens, and M. A. Khaleel, July 2004, *Characterization of Fatigue Behaviors of Dissimilar Metal Joints Part I—Experimental Studies*, Technical Report prepared for DOE-EE-OFCVT.

5. E. V. Stephens, X. Sun, M. A. Khaleel, and R .W. Davies, September 2004, *Joining of Dissimilar Metals for Automotive Applications—From Process to Performance*, Technical Milestone Report prepared for DOE-EE-OFCVT.

6. X. Sun, E. V. Stephens, and M. A. Khaleel, September 2004, *Dynamic Joint Strength Evaluation under High Rate Impact Loading*, Technical Report prepared for DOE-EE-OFCVT.

7. X. Sun, E. V. Stephens, R. W. Davies, M. A. Khaleel, and D. J. Spinella, 2004, "Effects of Fusion Zone Size on Failure Modes and Static Strength of Aluminum Resistance Spot Welds," *Welding Journal*, **83**(11), 308s–318s.

   X. Sun, E. V. Stephens, M. A. Khaleel, H. Shao, and M. Kimchi. "Resistance Spot Welding of Aluminum Alloy to Steel with Transition Material—From Process to Performance," *Sheet Metal Welding Conference XI*, *Sterling Heights, Michigan; May 12, 2004.*

   M. A. Khaleel, E. V. Stephens, X. Sun, and R. W. Davies, "Joining of Dissimilar Metals for Automotive Applications—From Process to Performance," DOE-OFCVT Project Review Meeting to the USAMP Steering Committee, Southfield, Michigan; July 28, 2004.