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Project Title: Collision Welding of Dissimilar Materials by Vaporizing Foil Actuator: A Breakthrough Technology for Dissimilar Metal Joining

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Signature of Submitting Official (electronic signatures (i.e., Adobe Acrobat) are acceptable)

Glenn S. Daehn, PI

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Executive Summary

This work demonstrated and further developed Vaporizing Foil Actuator Welding (VFAW) as a viable technique for dissimilar-metal joining for automotive lightweighting applications. VFAW is a novel impact welding technology, which uses the pressure developed from electrically-assisted rapid vaporization of a thin aluminum foil (the consumable) to launch and ultimately collide two of more pieces of metal to create a solid-state bond between them. 18 dissimilar combinations of automotive alloys from the steel, aluminum and magnesium alloy classes were screened for weldability and characterized by metallography of weld cross sections, corrosion testing, and mechanical testing. Most combinations, especially a good number of Al/Fe pairs, were welded successfully. VFAW was even able to weld combinations of very high strength materials such as 5000 and 6000 series aluminum alloys to boron and dual phase steels, which is difficult to impossible by other joining techniques such as resistance spot welding, friction stir welding, or riveting. When mechanically tested, the samples routinely failed in a base metal rather than along the weld interface, showing that the weld was stronger than either of the base metals. As for corrosion performance, a polymer-based protective coating was used to successfully combat galvanic corrosion of 5 Al/Fe pairs through a month-long exposure to warm salt fog. In addition to the technical capabilities, VFAW also consumes little energy compared to conventional welding techniques and requires relatively light, flexible tooling. Given the technical and economic advantages, VFAW can be a very competitive joining technology for automotive lightweighting. The success of this project and related activities has resulted in substantial interest not only within the research community but also various levels of automotive supply chain, which are collaborating to bring this technology to commercial use.

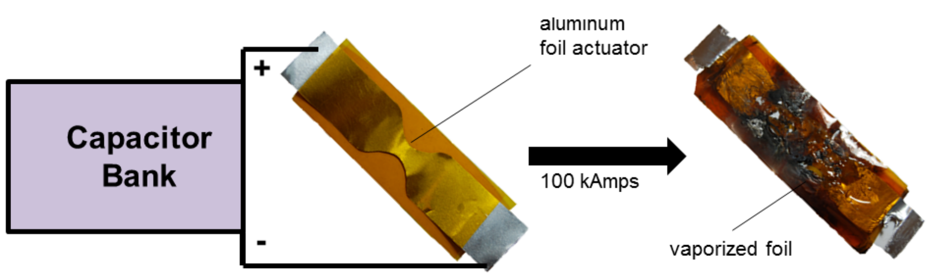


Figure 1: Electrically driven vaporization of foil actuator used for VFAW.

Actual Accomplishments vs Project Objectives

The overall objective of the project was to, through an early screening process, determine the material pairs to be focused upon and then to develop coupon scale welds under optimal conditions to test them for corrosion resistance, strength, and failure mechanisms. During the execution of specific tasks, scale up and commercialization was an underlying theme. The accomplishments matched the original goals and objectives of the project. A new method was developed to create welds between alloys between pairs of two out of three alloy systems which are relevant to commercial and military vehicles: magnesium, aluminum, and steel. Alloy selection was conducted based on industrial relevance. Optimal welding parameters were identified for select metal combinations, and numerous weld coupons were tested for strength and corrosion performance. Through high resolution microscopy, hypotheses related to failure mechanisms and weld strength were validated. A list of practical considerations for commercialization was included in the 11th quarterly report. The final year of the project also focused on developing working relationships with different levels of the automotive industry supply chain including OEMs, Tier 1 suppliers, equipment builders, and material suppliers. A strategy for industrial adoption of VFAW has been developed and is now being executed.

Project Activities

Introduction

Impact welding (as often accomplished through explosive or magnetic pulse welding) has long been known for its ability of joining drastically different metals in a nominally solid-state process with minimal heat effect. Vaporizing foil actuator welding (VFAW) (*Figure 2*) brings impact welding to a scale that is conducive to scientific study in a laboratory setting and eventual deployment in a common manufacturing environments.

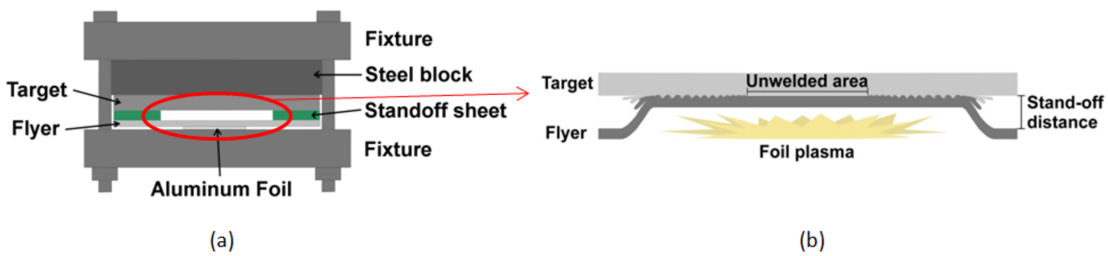


Figure 2. (a) VFAW setup, (b) welding event

Unlike conventional fusion-based welding, VFAW does not involve external heat input, thus avoiding a number of potential problems that could be brought on by heat. Such problems include distortion, the formation of brittle phases along the weld interface and weakening of base materials surrounding the weld. Instead of applying heat, VFAW welds metals by means of a high-speed impact. Such an impact clears off oxides from the mating surfaces of the materials being joined and brings nascent materials into intimate contact, thus forming a metallurgical bond. Between the two members to be welded, typically one is held stationary against an anvil, and the other member is propelled to a high speed to collide with the stationary member. The stationary member is called the target, and the moving member is called the flyer.

While there are other forms of impact welding, VFAW is set apart by its driving mechanism by which flyers are accelerated. While other techniques use chemical explosives and electromagnetic forces, VFAW accelerates flyer sheets by a high pressure pulse derived from rapid electrical vaporization of a consumable thin metal foil. This rapid vaporization is capable of generating an instantaneous pressure on the order of 1 GPa using input energies of no more than 10 kJ, and this makes VFAW a capable and agile tool for impact welding and a number of other impulse metalworking tasks.

Optimizing welding parameter and weld strength

Throughout this work, 18 combinations of dissimilar structural alloys, listed below, were attempted for welding by VFAW. The selection of alloys was based on their potential usefulness in the design and manufacture of automotive structures.

1. AA6061-T4/HSLA a588 †
2. AA5052/HSLA a588
3. AA5052/HSLA a656 *
4. AA6061-T4/AM60B *
5. AA5052/AM60B *
6. AA6061-T4 and -T6/ DP780 †
7. AA6061-T4/JAC270F (galvannealed with Zn coating)
8. AA6061-T4/JAC270F (ground) †
9. AA6061-T4/boron steel †
10. JAC270F/AM60B
11. JAC270F/AA3003/AM60B
12. AA6061T4/AZ31B
13. JAC270F/AZ31B
14. AA5052/AZ31B
15. AA5052/JAC980 †
16. AA5052/JSC1500 †
17. AA6111-T4/JAC980 †
18. AA6111-T4/JSC1500 †

A robust and rapid screening method was established to help identify the optimal welding parameters which produce the best interface morphology for a given pair of materials (*Figure 3*). This method involved measuring flyer speed, using photonic Doppler velocimetry (PDV), and controlling the angle of impact using grooved plates. 3 material combinations were characterized by this method, and favorable microstructures were obtained in all 3 cases (marked with "*"). In other trials, weld coupons were made using flat metal sheets. The flat weld coupons were sectioned for mechanical testing in lap-shear and 90° peel configurations. Very strong welds were obtained for 8 material combinations (marked with "†"), where either the 90° peel strength exceeded 30 N/mm or the lap-shear strength exceeded the strength of a base metal (Figure 4).

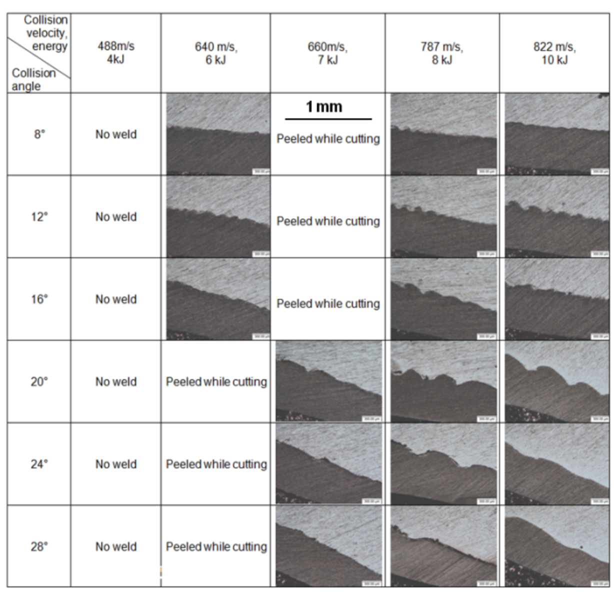
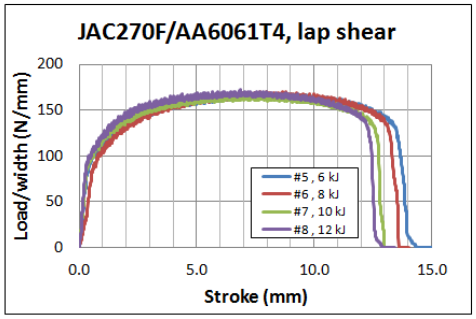


Figure 3: Weld morphology map of AA6061-T4/AM60B, obtained by PDV and grooved target plates



Sample	Peak shear load (N/mm)	Site of failure
#5, 6 kJ	169.39	Fe
#6, 8 kJ	169.86	Fe
#7, 10 kJ	167.34	Fe
#8, 12 kJ	172.31	Fe

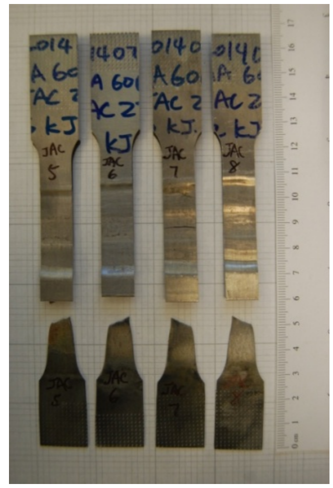


Figure 4. (Left) load vs. stroke curves of lap-shear test of AA6061-T4/JAC270F; (right) tested samples, with failure occuring consistently in base JAC270F

All of the very strong combinations were of the Al/Fe kind, which is a popular material pair in automotive lightweighting. Some Al/Mg pairs also welded decently, with good microstructures and strengths (*Figure 5*), but none of the Fe/Mg pairs welded successfully, largely due to the lack of toughness of Mg alloys (*Figure 6*).

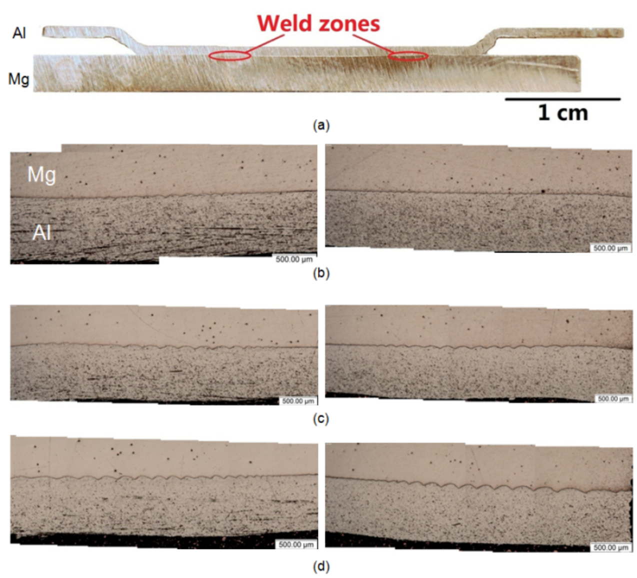


Figure 5. Cross section of AA6061T4/AM60B welds: (a) macroscopic view, showing the left and right weld zones. Both weld zones are shown for samples welded at (b) 6 kJ, (c) 8 kJ, and (d) 10 kJ input energy.

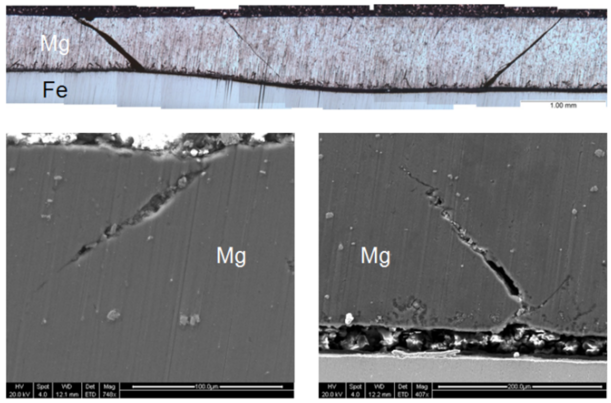


Figure 6. Sheared Mg target in a JAC270F/AZ31B joint.

Pivot in screening methodology

During the latter part of the first year of this work, there was a pivot in screening methodology. The original plan was to screen 15 metal combinations for optimal welding parameters using photon Doppler velocimetry (PDV) and grooved plates. The method worked well initially with Al/Mg pairs; however, AA6061-T4/HSLA 588a and AA5052/HSLA 588a failed to weld in the grooved-plate configuration (*Figure* 7). It was possible to get the grooved target method to work by implementing a vacuum between target and flyer sheet and providing an escape route for jetted material and air through a slit in the target plate.

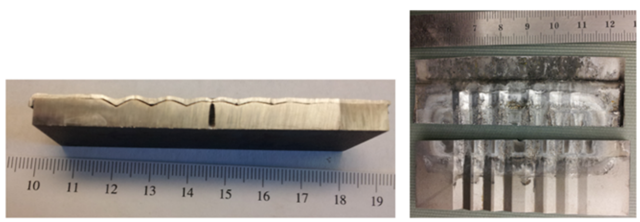


Figure 7. Unsuccessful sample of AA6061-T4/HSLA 588a and AA5052/HSLA 588a in grooved-plate configuration

It was observed that even the material pairs that were difficult to weld with the grooved target method welded relatively easily with a flat target geometry. After some internal discussion and with permission from DOE, it was decided that the focus of the project would be shifted to welding a wider range of materials using flat target sheets and mechanically testing the welding coupons in the manner illustrated in *Figure 8*. This yielded fruitful results, and many mechanically strong welds were obtained. The following material combinations were selected for further investigation: the high strength steels were obtained from Honda, and the alloy names follow Japanese nomenclature.

1. DP780/AA6061-T4
2. JAC270F/6061-T4
3. AM60B/AA6061-T4
4. AA5052/JAC980
5. AA5052/JSC1500
6. AA6111-T4/JAC980
7. AA6111-T4/JSC1500

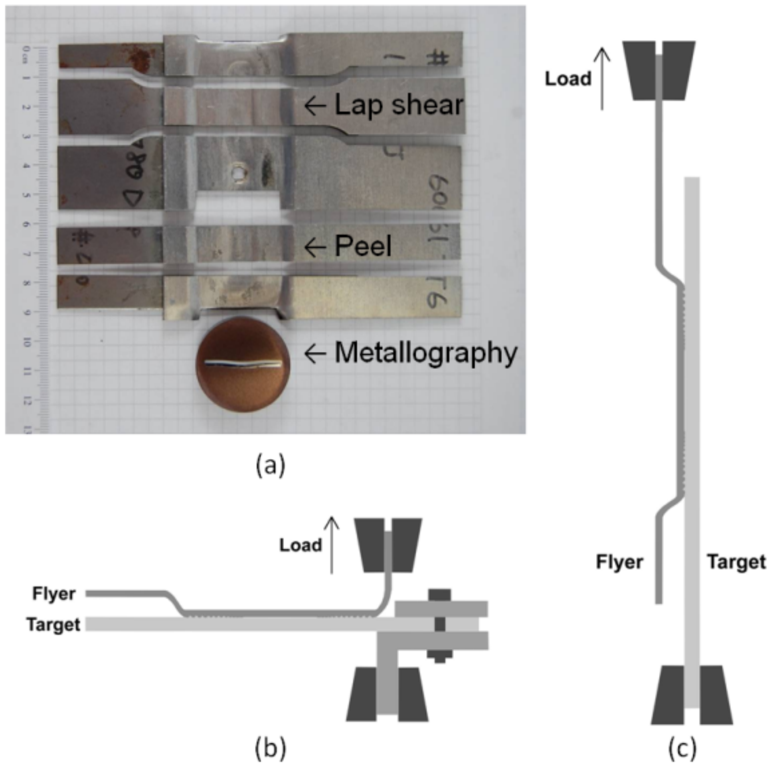


Figure 8. (a) Sectioned sample for mechanical testing, (b) peel testing setup, (c) lap shear testing setup

Investigating high-strength Al/Fe welds

Four Al/Fe combinations consisting of very strong alloys were welded successfully with high weld strength: AA5052/JAC980, AA5052/JSC1500, AA6111-T4/JAC980, and AA6111-T4/JSC1500. Favorable interfacial microstructures were obtained for all four (*Figure 9*); all interfaces contained regions that were free of voids and intermetallic compounds (IMCs). Such regions, which contain direct, continuous metal-metal bonds, represent areas that were strong and tough. These favorable microstructures gave rise to good mechanical strength. When tested in lap-shear, the majority of the samples of all four combinations failed in the base Al instead of the weld, indicating that the weld was even stronger than a base metal.

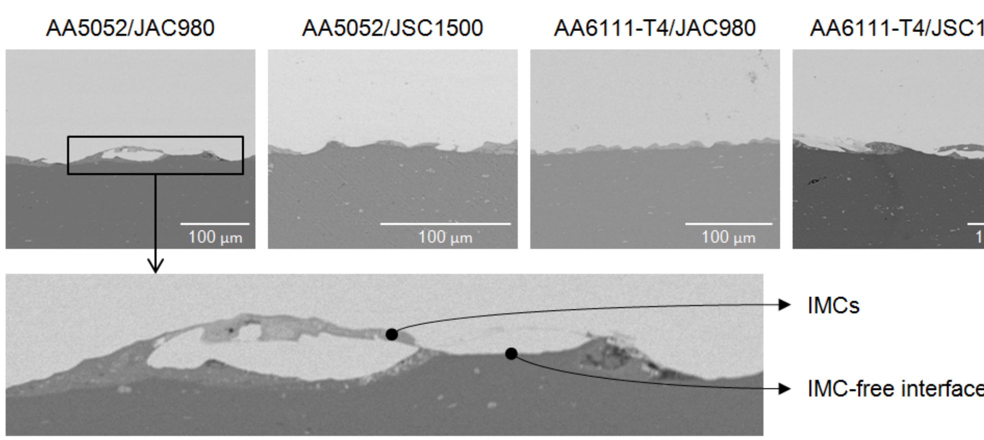


Figure 9. Backscattered electron images of weld cross sections

Figure 10: A lap shear tested AA5052/JAC980 weld sample showing failure in base material (aluminum).

While most of the samples failed in the base Al, a few failed along the weld interface. One such case was AA6111-T4/JAC980, where at least one test sample had sustained interfacial failure in both lap-shear and peel testing. Scanning electron microscopy (SEM) images of the Fe side of such a fracture surfaces showed small chunks of Al (*Figure 11*). It appeared that the Al was torn out of its base material in a ductile fashion and transferred over to the Fe side. It was then hypothesized that the Al/Fe bond of this area must be exceptionally strong, such that it even exceeded base material strength. *Figure 11* shows both (a) shear-type and (b) tensile-type ductile failures. The latter was selected for further study by transmission electron microscopy (TEM).

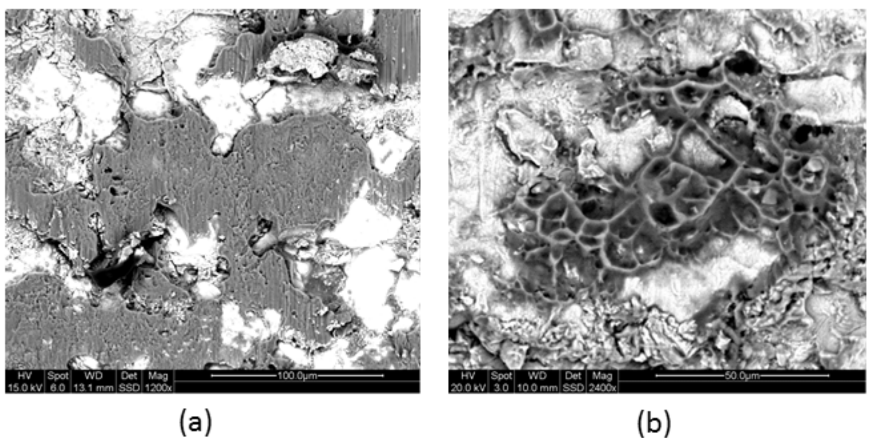


Figure 11. Steel side of ductile fracture surfaces of AA6111-T4/JAC980 from (a) lap-shear mechanical testing and (b) peel mechanical testing. Darker areas represent aluminum.

A TEM foil was extracted by focused ion beam (FIB) by milling directly into the area of interest and revealing the presumed strong Al/Fe bond interface. In TEM, microscopic wavy features were observed as shown in *Figure 12*. Some areas along the interface had IMCs, and some areas did not. These microscopic wavy features (less than 1 micron in height) resemble the mesoscopic wavy features (some 30 microns in height) often observed in optical microscopy, but on a much smaller scale. These resemble fractal-like patterns in Kelvin-Helmholtz instability, where self-similar features can be found at different length scales (*Figure 12*(c)). An EDS line scan across an IMC-free interface showed a very sharp transition between Al and Fe.

Most of the interface was covered with a very thin layer of Al-Fe intermetallic compounds (IMC) of types FeAl, Fe_3Al, Fe_2Al_5, and $FeAl_3$. The thickness of the IMC layer ranged from 0 nm to 100 nm (*Figure 12*(a), (b)). This indicated that very little diffusion or mechanical mixing had taken place.

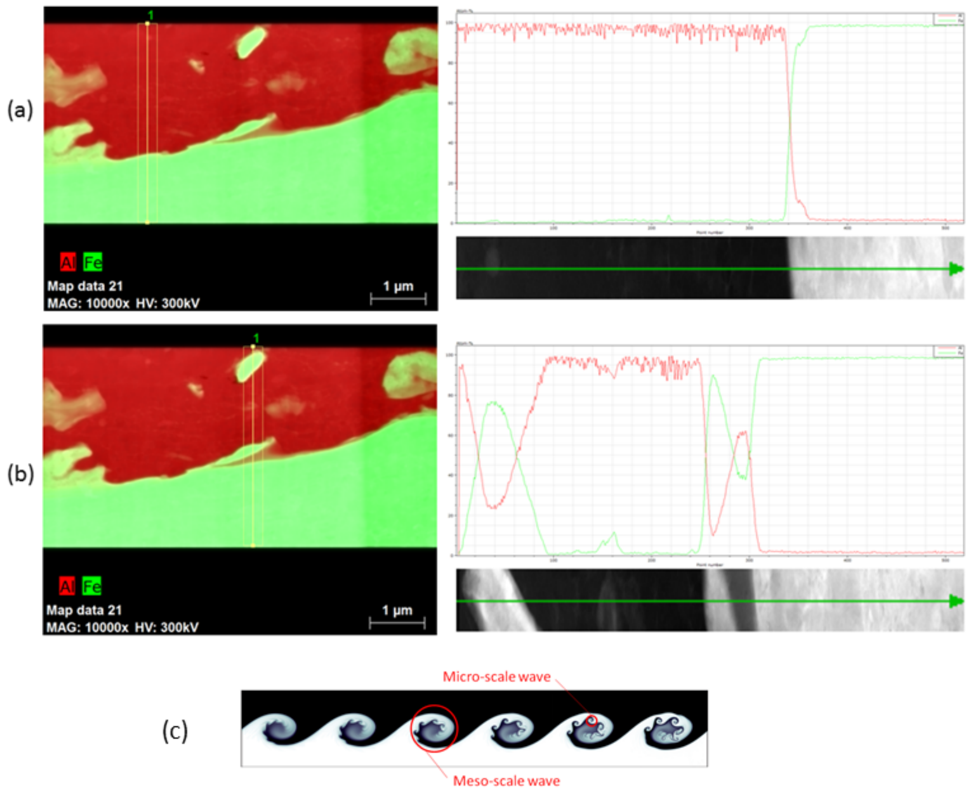


Figure 12. (a) Microscopic wavy features at the weld interface and EDS line scan across an IMC-free area of the weld interface, (b) EDS line scan across an IMC layer, (c) Kelvin-Helmholtz instability waves with self-similar waves on different scales (http://oatao.univ-toulouse.fr/606/1/Joly_606.pdf)

Within 2 microns of the interface, the grains on both sides of the interface are very refined, with some grains as small as 50 nanometers. XRD revealed that the weld interface is fully crystalline, as shown in *Figure 13*.

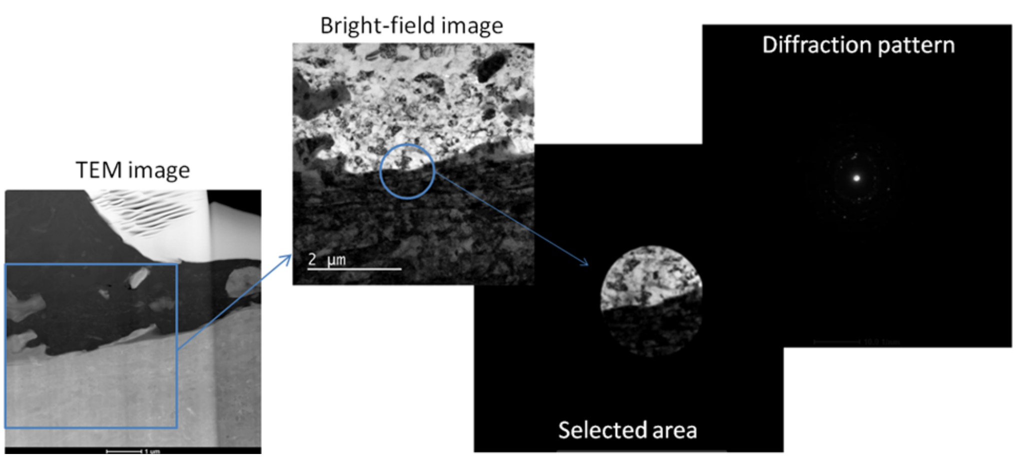


Figure 13. TEM bright field imaging and diffraction showing crystalline nature of the interface

The findings here validate the hypothesis about a strong bond interface, that it is free of large or continuous IMC phases, continuously bonded between two base *metals with little diffused region in between, strengthened by grain refinement, and reinforced by mechanical interlocking of waves (on both meso- and microscopic levels).*

The TEM work was conducted in collaboration with Dr. Michael Presley of the Center for Accelerated Maturation of Materials (CAMM) at the OSU Center for Advanced Microscopy and Analysis (CEMAS).

Modifying welding configurations

Modified welding configurations were used to improve weldability or weld morphology. Vacuum and venting slots dramatically improved the welding of AA5052/HSLA a656 by eliminating the negative effects of entrapped air and jetted materials. Based on this work, a new welding configuration was developed: countersink spot welding (*Figure 14*), which miniaturized spot welds by ~50% while maintaining mechanical performance. Interlayers were used to improve weldability of poorly welding pairs. The weldability of JAC270F/AM60B was slightly improved by insertion of an AA3003 interlayer, and that of AA6061-T4/HSLA 588a was improved by insertion of an AISI 1018 interlayer.

Figure 14. (a) Weld cross sections of spot weld with countersink target. (b) Top view of peeled sample with three weld spots.

Corrosion testing

The corrosion behaviors of 7 material combinations were studied by ASTM B-117 warm salt-spray testing in both bare and protection-coated conditions (*Figure 15*, *Figure 16*). The driving force for galvanic corrosion between a given pair of metals was evaluated based on open cell potential (OCP) measurements. Four Al/Fe combinations were identified where the differences in OCP were small, meaning that they should be less prone to galvanic corrosion. Protective coating proved to be an effective way to combat corrosion. 5 coated Al/Fe pairs retained >80% of their strength through a 30-day long corrosion test.

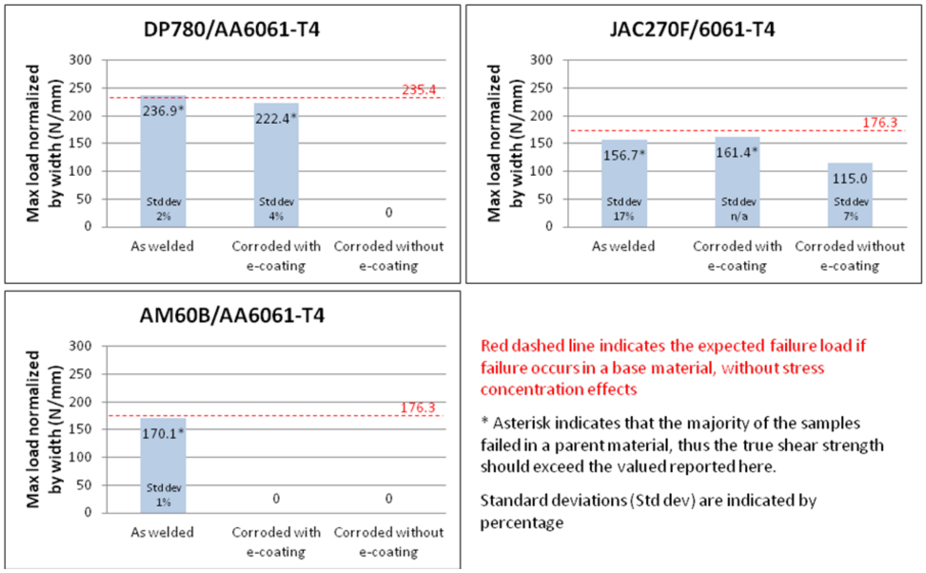


Figure 15. Lap-shear testing data of AA6061-T4/DP780, AA6061-T4/JAC270F, and AA6061-T4/AM60B under various corrosion conditions

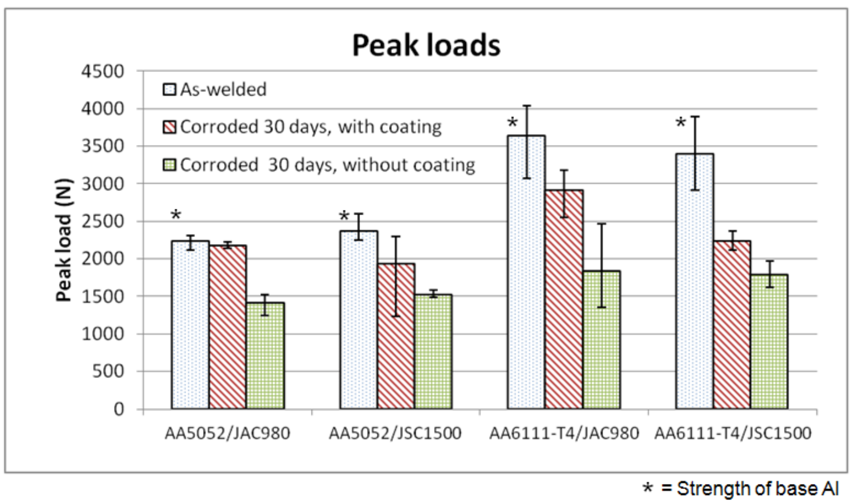


Figure 16. Lap-shear testing data of four Al/Fe combinations of high-strength alloys under various corrosion conditions

The failure mechanism of the corroded samples was investigated for the four Al/Fe combinations shown in *Figure 16*, using AA5052/JSC980 as a representative and AA5052/AA5052 as a non-galvanic control group for comparison. It became clear that the weakening by corrosion is mainly due to the thinning and pitting of base Al near the Al/Fe junction of the weldment (*Figure 17*). Galvanic corrosion played an important role in accelerating this process, and the rough morphology of the Fe corrosion product also helped attract an accumulation of salt and moisture, which also exacerbated the corrosion problem.

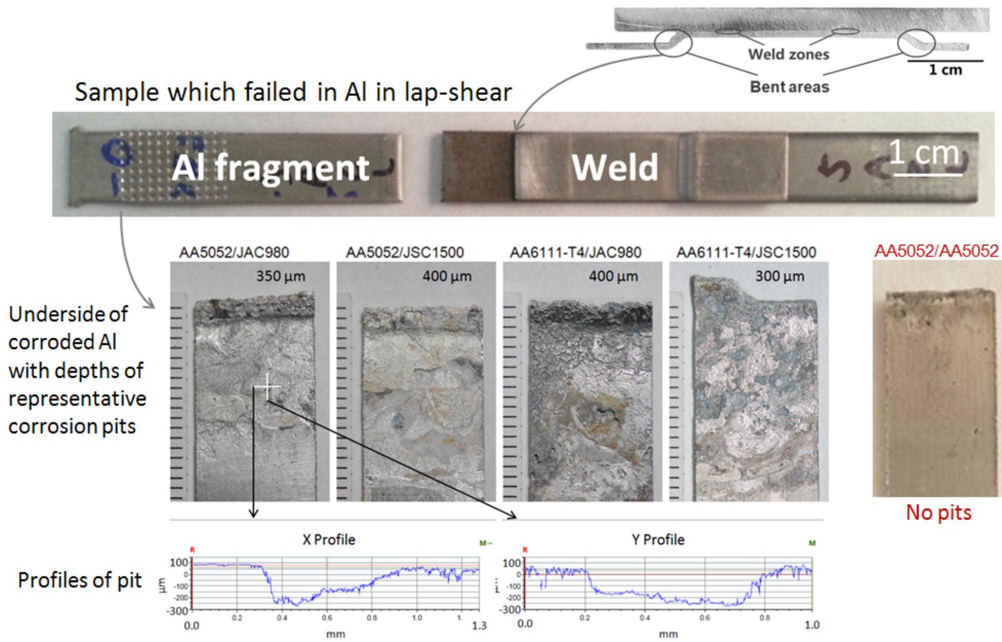


Figure 17. Aluminum fragments from uncoated, corroded Al/Fe samples, along with depths (µm) of representative corrosion pits. An aluminum fragment from a comparable AA5052/AA5052 sample is shown on the right for comparison

Products

a. Publications:

Liu, Bert, A. Vivek, and G. S. Daehn. "Impact Welding Structural Aluminium Alloys to High Strength Steels Using Vaporizing Foil Actuator." 7th International Conference on High Speed Forming, April 27th-28th 2016, Dortmund, Germany. 2016.

Vivek, Anupam, Scott M. Wright, Taeseon Lee, Geoffrey A. Taber, and Glenn S. Daehn. "Low-Energy Impact Spot Welding of High-Strength Aluminum Alloys." *WELDING JOURNAL* 95, no. 2 (2016): 32-34.

Liu, B., et al. "Solid-State Dissimilar Joining of Ti-Fe with Nb and Cu Interlayers." Welding Journal 94.7 (2015): 219-224.

Vivek, Anupam, et al. Impact Welding of Aluminum Alloy 6061 to Dual Phase 780 Steel Using Vaporizing Foil Actuator. No. 2015-01-0701. SAE Technical Paper, 2015.

Liu, Bert, Anupam Vivek, and G. Daehn. "Use of vaporizing foil actuator impact welding of aluminum alloy sheets with steel and magnesium alloys." Light Metals (2015): 463-468.

Liu, Bert, Joining Dissimilar Structural Alloys by Vaporizing Foil Actuator Welding: Process Conditions, Microstructure, Corrosion, and Strength, Ph.D. Dissertation, The Ohio State University, 2016.

b. Web site or other Internet sites that reflect the results of this project:

The research group maintains a website: https://iml.osu.edu that is updated monthly.

In November, 2015, there was considerable press activity on VFAW based on a release from Ohio State's communications office (https://news.osu.edu/news/2015/10/29/vfaweld/). This resulted in much media coverage, including being featured on the front page of Reddit and a very fruitful Reddit "Ask Me Anything" discussion hosted by Dr. Glenn Daehn. See: https://redd.it/3s4j5o.

c. Networks or collaborations fostered:

The research team has been earnestly pursuing the commercialization aspect of this technology, including through the I-Corps Ohio program, which entailed 100 interviews with relevant persons in the industry and developing a viable business model to get this technology through to production.

As a result of the success of this DOE breakthroughs project and the networking through I-Corps Ohio, a coalition of leaders from different levels of the automotive supply chain (Magna, Honda, Coldwater Machine Company, Alcoa, Ashland Chemicals, Jefferson Industries Corporation), national lab experts (PNNL), and academicians (process innovation, corrosion, numerical modeling, characterization) has come together to commercialize VFAW.

Ohio Development Service Agency awarded a $500k grant to the team to develop and commercialize a pedestal-style VFAW system. The team has also been awarded a $3M, 4 year grant from DOE for prototype level production of an aluminum/steel hybrid component using VFAW as the primary joining technology.

d. Technologies/Techniques:

A method was established for quickly determining the optimized process parameters for a given metal combination.

A new spot welding technique was developed, which reduced spot weld sizes by ~50% while delivering excellent mechanical strength.

e. Inventions/Patent Applications, Licensing Agreements:

N/A

f. Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment:

The research group disseminates knowledge to the general public through a Youtube channel (www.youtube.com/channel/UCKwMnasGKA-n9PK74kIfJ1Q), mainly featuring VFAW and related technologies. The channel has had >25,000 views since its release in 2014.