II Lightweight Materials

II.4 Joining of Dissimilar Materials

II.4.1 Joining Core Program

II.4.1.5 Extending Ultrasonic Welding Techniques to New Material Pairs (Oak Ridge National Laboratory)

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Start Date: October 1, 2020 End Date: September 30, 2023
Project Funding (FY 2022): $584,000 DOE share: $584,000 Non-DOE share: $0

Project Introduction

Modern multimaterial vehicles require joining of various lightweight materials, such as aluminum (Al) and magnesium (Mg) alloys and carbon fiber reinforced polymers (CFRP), with advanced high-strength steels together to form a high-performance and lightweight body structure. A variety of joining methodologies (e.g., resistance spot welding, adhesive bonding, linear fusion welding, hemming, clinching, bolting, riveting) have been attempted by the automotive industry to join different materials. Often, these joining techniques are limited to only certain material combinations. For capital and operational cost, automobile original equipment manufacturers need to limit the number of joining technologies implemented on an assembly line.

In Phase I of the Joining Core Program, we investigated the versality of ultrasonic-based spot-joining (UJ) processes to join different material combinations [1, 2]. Ultrasonic spot welding (USW) is one of the major UJ processes which is a solid-state joining method that produces weld joints by localized high-frequency tangential vibration under moderate clamping pressure. The temperate rise during a USW process is generally not sufficient to melt the material. Instead, the high-temperature and pressure at the interface induce rapid diffusion between the substrates to form the joint. In Joining Core Program Phase I, we successfully demonstrated the ability of joint DP590 steel and AZ31B Mg alloys with a reasonably high-strength, including bare steel to Mg that were considered to be unweldable as they are metallurgically immersible, through USW process innovations assisted by extensive physics-based process modeling.

However, a number of technical challenges still remain in the prevention of successful application of USW for automotive body structures. They include challenges to produce consistent joint quality for many welds to assemble large metal body structures. This is particularly challenging due to the lack of understanding of complex ultrasonic wave propagation and interaction with other spot welds in a large structural assembly. In addition, further research is required to extend the USW to other material combinations for further lightweighting of multimaterial auto-body structures.

Objectives

The primary objective of this project is to further explore, understand, and extend the unique characteristics of UJ—the ability to metallurgically bond immiscible material pairs and the acoustic softening phenomenon—to various lightweight material combinations in an assembly of a lightweight multimaterial vehicle. The targeted outcomes will be a versatile, ultrasonic-based solid-state spot joining technology to join representative component level coupons in which multiple UJs are required. The outcome will include extending the joining technology to join a variety of lightweight dissimilar material stack-ups including Al, CFRP, Mg, and steel.

Approach

The project is divided to three major tasks to ensure risk mitigation and successful completion. These main tasks are:

- **FY 2021:** Making multiple USW joints in large steel-Mg coupons and obtaining an average joint strength at least 80% of that is obtained in single-joint coupons.
- **FY 2022:** Extending USW method to join large Al-steel and Al-Mg coupons consisting of multiple joints and obtaining an average joint strength at least 80% of that is obtained in single-joint coupons.
- **FY 2023:** Using one UJ variant to join polymer-metal structural stack-ups.

The following sub-tasks were planned to meet FY 2022 milestones:

- **Sub-Task 1:** Feasibility study to extend USW to join Mg-Al and Al-steel in single-joint lap-shear coupons.
- **Sub-Task 2:** Perform microstructural analysis and mechanical tests on single Mg-Al and Al-steel coupons.
- **Sub-Task 3:** Apply thermal-mechanical and model-based numerical tools to assist the process development to join multiple Mg-Al and Al-steel joints in component level structures.

Results

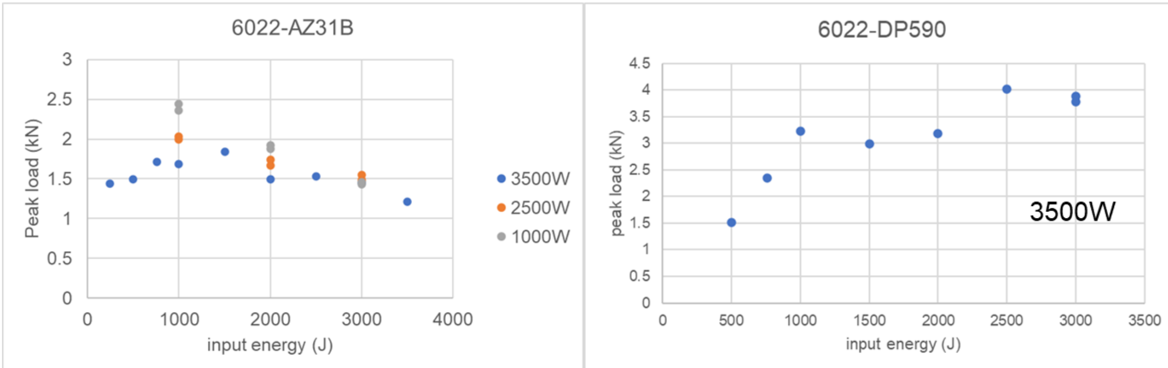
In Phase II, we developed an innovative strategy to join large coupons with consistent weld quality and strength. We identified that different welding energy levels were required depending upon the part geometry and joint location. Hence, a wide range of welding energy was systematically investigated to join single-joint lap-shear Al-steel and Al-Mg coupons in FY 2022. For the study, Al was 1-mm-thick 6022, steel was 1-mm-thick DP590 with a galvanized surface coating, and Mg was 2-mm-thick AZ31B.

Plots of the peak lap-shear tensile strength as a function of ultrasonic energy for the single-joint Al-Mg and Al-steel coupons are shown in Figure II.4.1.5.1(a) and (b) respectively. Al-Mg USW coupons were made using three welding power levels (e.g., 1000W, 2500W, 3500W). The welding energy varied from 250–3500 joules (J). The maximum value of the peak strength occurred at ~1000J welding energy regardless of which power was used. On the other hand, for Al-steel USW coupons, only one welding power was used, where the welding energy varied from 500–3000J. The peak lap-shear strength monotonically increased from 1.6–4kN.

(a) (b)

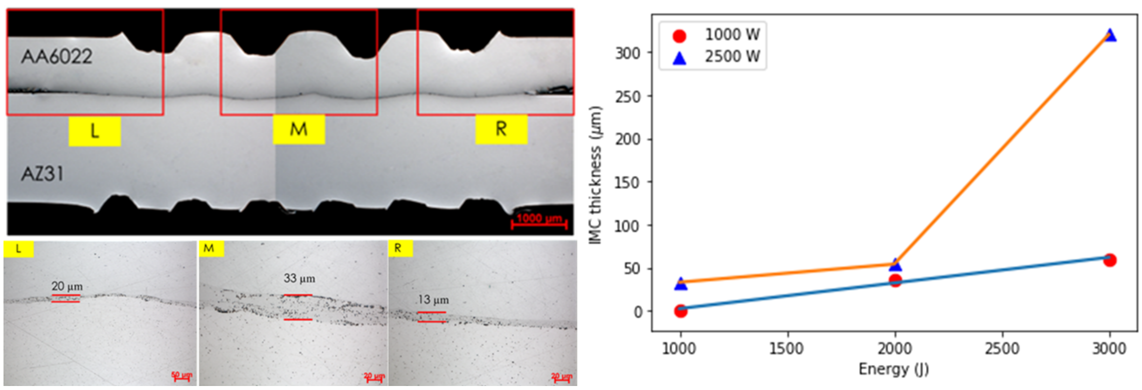
Figure II.4.1.5.2(a) shows the optical micrograph of a representative Al-Mg USW joint interface. A layer of Al/Mg intermetallic compound (IMC) was formed at the faying surface. The average thickness of the IMC layer for USW joints made with different energy under 1000W and 2500W was compared as shown in Figure II.4.1.5.2(b). These results suggest that a thin layer of an Al-Mg IMC layer is critical to obtain a strong lap-shear strength. Overgrowth of the IMC layer would deteriorate the mechanical performance. Figure II.4.1.5.3

shows the micrographs of the Al-steel USW joint interface and the chemical composition at the center of the joint interface. A layer of Al-Fe-Zn ternary phase was observed.



(a) (b)

Figure II.4.1.5.1 Peak lap-shear tensile load as a function of ultrasonic energy on single-joint (a) Al-Mg and (b) Al-steel coupons. Source: ORNL



(a) (b)

Figure II.4.1.5.2 (a) **Representative microstructure at the Al-Mg USW joints showing IMC at the interface and (b) the average IMC thickness as a function of welding energy of Al-Mg USW joints. Source: ORNL**

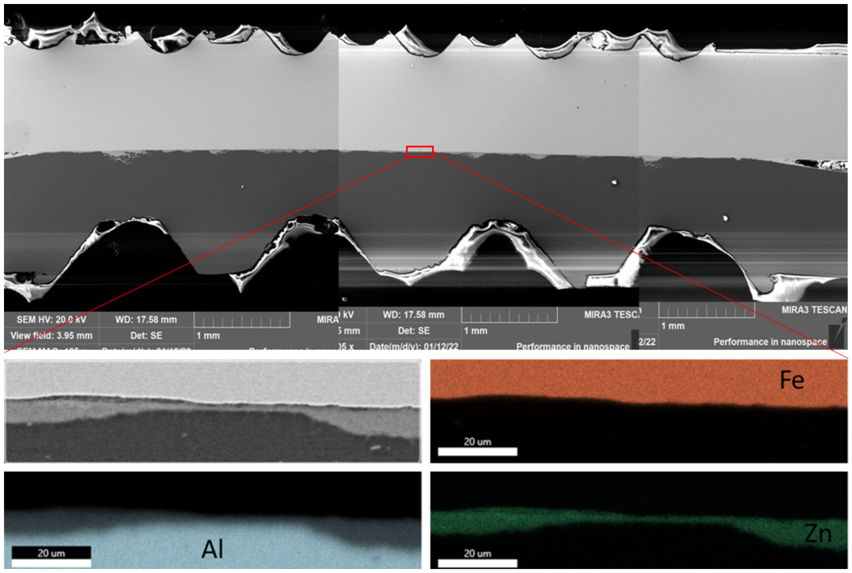


Figure II.4.1.5.3 Chemical composition of Al-steel joint interface at the center of the joint. Source: ORNL

Computational modeling of ultrasonic wave propagation in a metal sheet were utilized to assist the process development for joining large coupons consisting of five USW joints. Both elastic linear modal and thermal-mechanical finite element analyses suggest that the mechanical and thermal responses are different when making joints at different locations. The linear modal analysis suggests that the amplitude of actual contact force between the sonotrodes and metal sheets varied with joint locations, even though a constant static clamping force (i.e., 1000N) was applied when making all five joints. For instance, they were 1748N versus 1530N for the first and third Al-Mg USW joint. As a result, the resistance force at the first joint was higher, while the actual sonotrode vibration amplitude was smaller, which is consistent to the experimental measurement using a vibrometer, as shown in

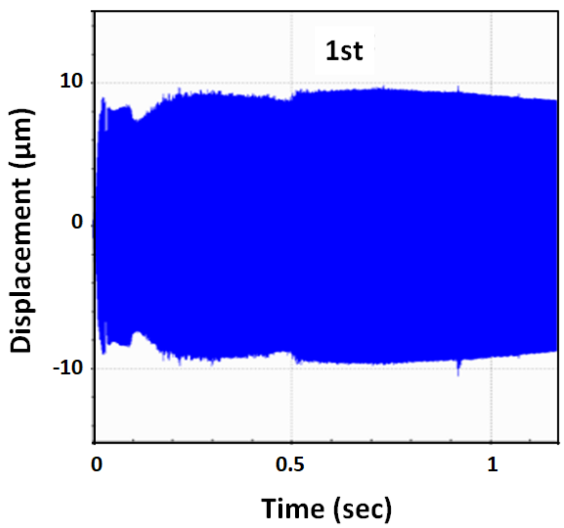
(a) (b)

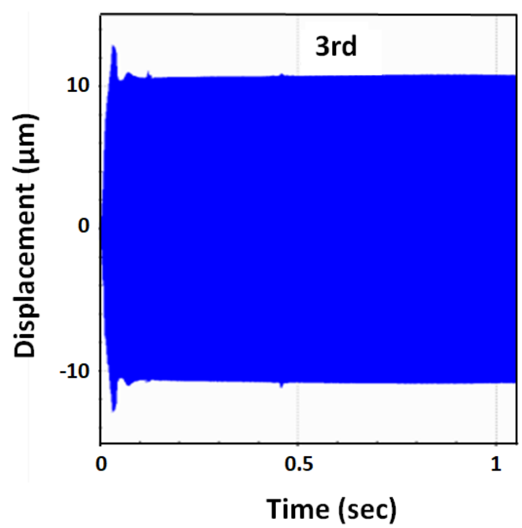
(a) (b)

Figure II.4.1.5.4(a) and **Figure II.4.1.5.4**(b). Further non-linear thermal-mechanical modeling shows a higher heat generation when making the first USW joint versus the third joint, as observed in

(a) (b)

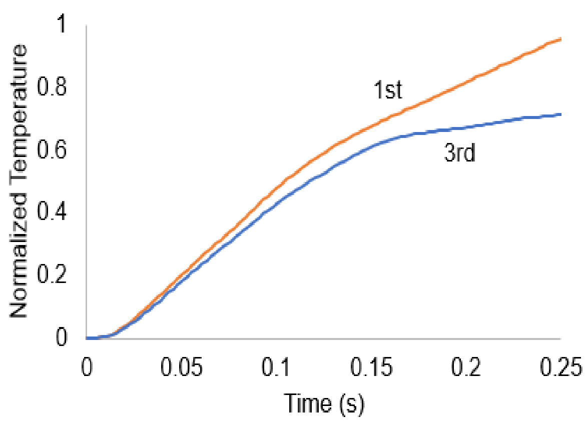
Figure II.4.1.5.5(a), which is also consistent with the experimental measurements using an infrared camera shown in Figure II.4.1.5.5(b).

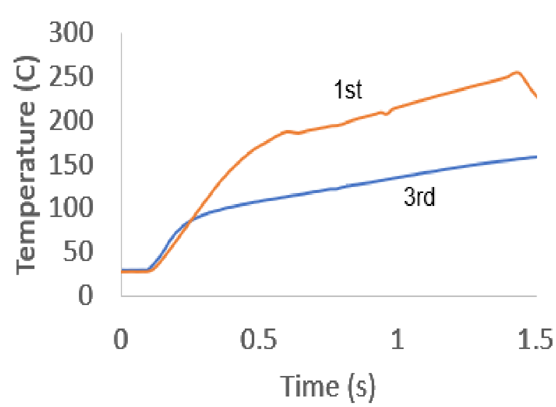




(a) (b)

Figure II.4.1.5.4 Measured sonotrode vibration amplitude during the (a) first and (b) third USW although the power setting was identical. Source: ORNL





(a) (b)

Figure II.4.1.5.5 (a) Predicted and (b) measured temperature history showing a higher temperature occurred when making the first USW joint. Source: ORNL

Before utilization of the model, the trial-and-error experimental processes resulted in inconsistent weld quality at different weld locations for joining large coupons. Particularly for Mg-Al coupons, no effective joint was formed in the middle of the coupons (e.g., third joint). Great success has been achieved after adoption of the numerical models for better design and optimization of the process parameters. Figure II.4.1.5.6 and Figure II.4.1.5.7, respectively, plot the lap-shear mechanical strength results for each joint in the large coupons and the comparison with the reference joint strength obtained from the single-joint coupons. For Al-Mg, an overall average strength of 1.92 kN of the large coupons was achieved, which was 83.5% of the reference strength 2.3 KN obtained on the single-joint coupon. For Al-steel, the average joint strength of the large coupons was almost identical to what was obtained on the single-joint coupons.

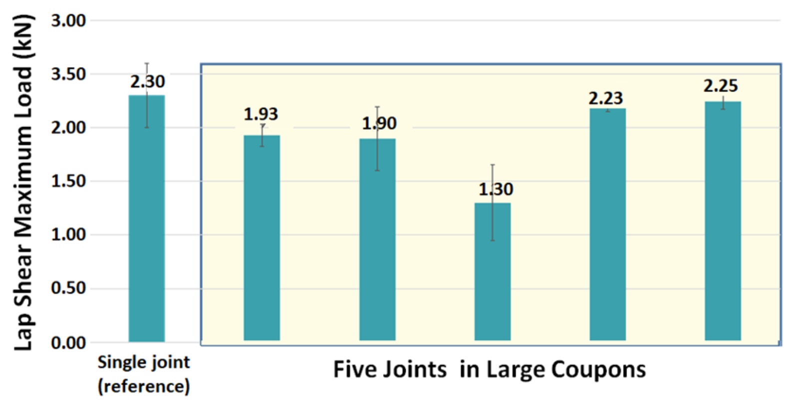


Figure II.4.1.5.6 Reference single joint strength and strength of each joint in large coupons of Al-Mg. Source: ORNL

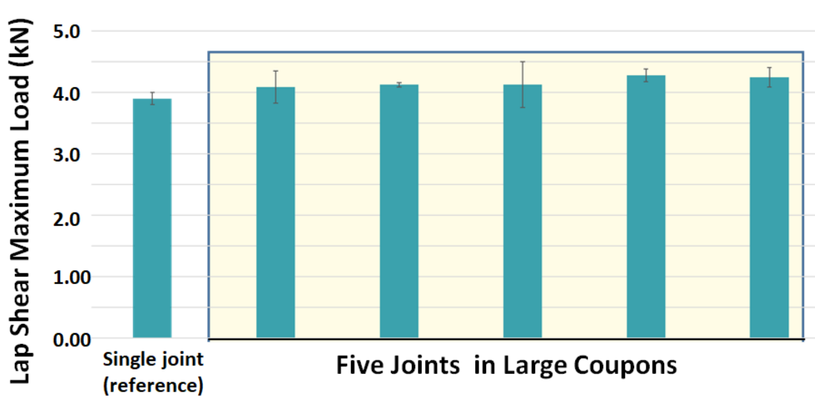


Figure II.4.1.5.7 Reference single joint strength and strength of each joint in large coupons of Al-steel. Source: ORNL

Conclusions

The research and development in FY 2022 led to the following major achievement and findings:

- USW process is not only material-dependent, but also geometry-dependent. A process parameter set developed on single-joint small coupons cannot be readily applied to join large structures consisting of multiple joints.
- Numerical models can be adopted for better design and optimization of the process parameters.

- USW is feasible to join large dissimilar metal coupons (e.g., Mg-steel, Al-steel, Mg-Al).

Key Publications

Chen, J., Y.-C. Lim, H. Huang, Z. Feng, and X. Sun, 2019, "Ultrasonic welding of AZ31B magnesium alloy," *MRS Bull.*, Vol. 44, No. 8, pp. 630–636. https://doi.org/10.1557/mrs.2019.182.

Chen, J., Y.-C. Lim, H. Huang, and Z. Feng, 2019, "Ultrasonic welding of AZ31B magnesium and DP590 steel," *American Welding Society Annual Conference*, 11–14 November 2019, Chicago, IL, USA.

Chen, J., Y. C. Lim, D. N. Leonard, H. Huang, Z. Feng, and X. Sun, 2020, "In situ and post-mortem characterizations of ultrasonic spot welded AZ31B and coated dual phase 590 steel joints," *Metals*, Vol. 10, No. 7, Art. 899. https://doi.org/10.3390/met10070899.

Chen, J., R. W. Davies, Z. Feng, X. Hu, H. Huang, and X. Sun, 2020, "Ultrasonically assisted self-piercing riveting," U.S. Patent Application No. 16/585,754, filed 2 April 2020, UT-Battelle, LLC.

Chen, J., Y. Li, H. Huang, J. Cheng, Y.-C. Lim, X. Hu, Z. Feng, 2022, "Ultrasonic spot welding of immiscible mg/steel: bonding mechanisms and approach to weld multi-joint components," *Advances In Welding and Additive Manufacturing Research (AWAMR) Conference*, 13–16 June 2022, Virtual (Invited).

Huang, H., J. Chen, Y.-C. Lim, X. Hu, J. Cheng, Z. Feng, and X. Sun, 2019, "Heat generation and deformation in ultrasonic welding of magnesium alloy AZ31," *J. Mater. Process. Technol.*, Vol. 272, pp. 125–136. https://doi.org/10.1016/j.jmatprotec.2019.05.016.

Huang, H., J. Chen, Y.-C. Lim, Z. Feng, and X. Sun, 2019, "Enhance heat generation and joint strength in dissimilar metal ultrasonic welds by surface engineering," *American Welding Society Annual Conference*, 11–14 November 2019, Chicago, IL, USA.

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Lim, Y.-C., Z. Feng, J. Chen, X. Sun, and R. W. Davies, 2022, "Ultrasonic rivet joining of dissimilar materials," U.S. Patent 11,253,908 B2, Awarded 22 February 2022. Available at: https://www.osti.gov/servlets/purl/1892631 (last accessed 17 March 2023).

Xiong, L., A. Chuang, D. Singh, J. Chen, Y.-C. Lim, and Z. Feng, 2020, "Synchrotron x-ray diffraction and computed tomography studies of ultrasonic welding dissimilar Mg-Fe metals," *TMS Coatings and Surface Engineering for Environmental Protection II Conference*, 23–27 February 2020, San Diego, CA, USA.

Pending patent: Chen, J., Y.-C. Lim, H. Huang, Z. Feng, A method to consistently produce high-quality ultrasonically welded spot joints in large metal structures. (US Patent application. 63/358,250, 2022).

References

1. Upadhyay, P., H. Das, J. Chen, Z. Feng, H. Huang, Y. C. Lim, Y. Li, D. N. Leonard, X. Sun, L. Xiong, C. A. Chuang, and D. Singh, 2021, *Solid-State Joining of Magnesium Sheet to High-Strength Steel*, ORNL/SPR-2021/1836, Oak Ridge National Laboratory, Oak Ridge, TN, USA. https://doi.org/10.2172/1772623.

2. Chen, J., R. W. Davies, Z. Feng, X. Hu, H. Huang, and X. Sun, 2020, "Ultrasonically assisted self-piercing riveting," U.S. Patent Application No. 16/585,754, filed 2 April 2020, UT-Battelle, LLC.

Acknowledgments

The authors acknowledge the contributions from the following ORNL team members: Y. Li, H. Huang, Y. C. Lim, Y. Wang, J. Cheng, and D. Kyle.