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Friction Stir Welding of Thick Section Aluminum for Military Vehicle Applications

by Brian Thompson, Kevin Doherty, Craig Niese, Mike Eff, Tim Stotler, Zak Pramann, John Seaman, Roger Spencer, and Perry White

ARL-RP-417 **December 2012**

A reprint from the *9th International Symposium on Friction Stir Welding (9ISFSW)*, Huntsville, AL, 15–17 May 2012.

NOTICES

Disclaimers

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14. ABSTRACT

This report will highlight the work conducted in developing production-level, single-pass friction stir welding (FSW) parameters for thicknesses ranging from 0.5 to 1.6 inches in aluminum alloys 5083, 5059, and 2139. This includes developing welding procedures to meet ballistic shock requirements, extending tool life greater than 500 in without loss in weld properties, and maximizing travel speeds. Phased array ultrasonic testing (PAUT) was selected as the primary inspection method due to its flexibility, portability, and accuracy in detecting common FSW defects. The high automation of the FSW process led to an inherently stable process, ensuring that the incidences of welding defects were limited. As such, the PAUT development effort focused on refining techniques for inspecting defects most likely to occur in a production environment over the range of expected FSW joints. This collaborative effort between the U.S. Army Research Laboratory, EWI, and General Dynamics Land Systems (GDLS) culminated in the construction and inspection of a military vehicle demonstrator hull at GDLS facilities in Lima, OH. The successful fabrication of this demonstration article represents a significant step forward in accepting FSW technology as a viable joining method for aluminum hulled military vehicles.

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Friction Stir Welding of Thick Section Aluminum for Military Vehicle Applications

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Abstract

Under a U.S. Army Research Laboratory (ARL) cooperative agreement, EWI has been developing thick section aluminum Friction Stir Welding (FSW) for use in aluminum military vehicle applications. The primary objective of this work was the successful transfer of developed technology into the General Dynamics Land Systems (GDLS) production facility, Joint Systems Manufacturing Center (JSMC), in Lima, Ohio. Spanning multiple years, work on a number of 5xxx series and 2xxx series aluminum alloys over an array of joint geometries, alloy combinations, and thicknesses have led to the development of robust FSW procedures. The ballistic shock testing associated with these FSW procedures demonstrated an improved performance over traditional Gas Metal Arc Welding (GMAW) and offer a step forward in vehicle integrity.

This paper will highlight the work conducted in developing production level single pass FSW parameters for thicknesses ranging from 0.5 to 1.6 in. in aluminium alloys 5083, 5059, and 2139. This includes the development of welding procedures to meet ballistic shock requirements, extend tool life greater than 500 in. without a loss in weld properties, and maximization of travel speeds. Both tool material selection and tool feature designs had a large impact on process forces, tool life, and achievable travel speeds. It was also found that overall tool design depended on both the material to be welded and the target thickness. These procedures were documented in an easily transferable electronic Welding Procedure Specification (WPS) format and were used to fabricate relevant test articles for further testing, the results of which will be briefly discussed. These structures incorporated several different joint designs including butt-joints, butt corner-joints, and rabbet corner-joints.

Phased Array Ultrasonic Testing (PAUT) was selected as the primary inspection method for this work due to its flexibility, portability, and accuracy in detecting common FSW defects. The high automation of the FSW process led to an inherently stable process, ensuring the incidences of welding defects were limited. As such, the PAUT development effort focused on refining techniques for the inspection of the defects most likely to occur in a production environment over the range of expected FSW joints. PAUT modeling was performed to develop initial inspection procedures for examining wormhole and lack-of-penetration (LOP) defects. Calibration and setup samples were then manufactured from defect-free FSW coupons. The procedures developed under the modeling program were used to scan the calibration samples and develop finalized procedures. These procedures were then used to inspect all articles containing a friction stir weld over a range of thicknesses.

This collaborative effort between ARL, EWI, and GDLS culminated in the construction and inspection of a military vehicle demonstrator hull at GDLS facilities in Lima, Ohio. Using the production-optimized FSW tools and parameters and the refined PAUT techniques on GDLS equipment, EWI successfully transitioned all developed techniques to the JSMC production facility. The successful fabrication of this demonstration article represents a significant step forward in the acceptance of FSW technology as a viable joining method for aluminum hulled military vehicles.

Introduction

In a number of militaries around the world, a significant emphasis is placed on deploying highly mobile armored vehicles. A key characteristic of these military vehicles is their ability to absorb multiple threats while maintaining their structural integrity and protecting their occupants (MacGregor, 2012). Due to their highly mobile nature, weight is often sacrificed for the benefits of speed. However, a reduction in weight cannot come at the price of crew survivability or compromise vehicle integrity. With the proliferation of Improvised Explosive Devices (IEDs) throughout the world, today's militaries face an easily accessible, inexpensive, and extremely effective tool for use against military vehicles (Singer, 2012). This proliferation represents and enduring threat to military vehicles around the globe and technologies must be developed to address this threat (Singer, 2012). Constructing vehicles out of materials with ever increaseing strength is one way to provide significant blast and ballistic protection.

Higher strength often means constructing vehicles that are comprised of high density materials such as steel. While affording a high level of protection to both the vehicle and occupants, the overwhelming weight of these materials placed limits on their mobility and speed. The challenge then is to effectively balance increased protection while reducing weight (Dauer, 2011). In recognition of this critical balance, research has and is currently being conducted on a wide variety of materials with high strength to weight ratios to achieve the proper balance. Of particular focus has been a variety of higher strength aluminum alloys. For example, some 7xxx series alloys have comparable strength to that of mild steel, however with about one third the density (Ghaziary, 2011).

Due to the extensive ballistic and blast evaluation of these materials, aluminum alloys 5083, 5059, 7039, 2519, 2139, and 2195 in their monolithic form have all been registered as armor plate by the United States Department of Defense (Ghaziary, 2011). Aluminum-Lithium (8xxx series) alloys have also been investigated for potential use in military combat vehicles (Holmes, Chin, Huang, & Pasternak, 1992). The different aluminum alloys from each series offer different mechanical properties and therefore different protection levels. Care must be taken to ensure that the proper alloy is selected for correct areas on a military vehicle hull design. For example, in the lower hull of a military vehicle, blast resistance is often a high priority. In this location alloys which have demonstrated a particular ability to resist blast events, such as 5xxx series alloys, would be must suitable. In other locations higher on the vehicle, ballistict impact testing has suggested higher strength aluminum alloys such as 2xxx or 7xxx series would be better suited for these locations (Ghaziary, 2011). Because of their varied properties, no single alloy can meet the varied demands of a military vehicle. However, when properly designed and employed in their most useful locations, a lightweight and highly protective military vehicle can be manufactured.

With such a variety of aluminum alloys registered for use on a military vehicle, the manufacture of such a structure can be a challenge. Generally speaking, while 5xxx series aluminum alloys are readily welded using traditional arc welding, some 2xxx and 7xxx series alloys are more difficult to join with GMAW or Gas Tungsten Arc Welding (GTAW) (Meister &

Martin, 1967). Certain alloys in these two series suffer from hot crack susceptability, making joining by traditional arc welding a challenge (The Aluminum Association, 1997). Additionally, with multiple componenets of a vehicle using different aluminum alloys, dissimilar joints can be quite prevelant. These dissimilar aluminum joints can be difficult to join using tradtional arc welding methods due to the care that must be taken in selecting the proper filler material in order to achieve the desired weld quality and properties. This selection becomes particularly important when joining a crack sensitive alloy to a non-crack sensitive alloy. A robust, cost-effective welding method is needed that can join these high-strength aluminum alloys while also withstanding the demanding conditions of a combat environment.

Since its invention by The Welding Institute (TWI) in 1991 (Wayne, et al., 1991), one of the main benefits of Friction Stir Welding (FSW) has been its ability to join difficult to arc weld materials such as the aluminum alloys described above. Due to the predominately solid-state nature of this process, hot cracking susceptibility in 2xxx and 7xxx series aluminum alloys is of little concern. These same benefits make FSW an attractive option for the joining of dissimilar aluminum alloys (Rajiv S. Mishra, 2007). The defense industry, aware of these benefits, has begun to investigate the joining of aluminum hulled military vehicles using FSW. Previous work has been conducted demonstrating the feasability of using FSW to fabricate aluminum hulled military vehicles (Colligan, Konkol, Fisher, & Pickens, 2003) (Arbegast, 2007). Of primary concern in the use of this welding technology has been the ballistic and blast performance of the FSW joints in the aluminum alloys of interest (Ghaziary, 2011).

In order to address this concern, EWI has been working under a U.S. Army Research Laboratory (ARL) cooperative agreement in an effort to advance the FSW process for acceptance as a viable joining method for military vehicles within the defense industry. Additionally, Phased Array Ultrasonic Testing (PAUT) procedures were developed in parallel to ensure high quality in the fracture stir welds. The primary objective of this work was the successful transfer of developed technology into the General Dynamics Land Systems (GDLS) production facility, Joint Systems Manufacturing Center (JSMC), in Lima, Ohio. Multiple years of development on 5xxx and 2xxx series alloys has led to the development of robust FSW procedures for a variety of joint geometries. The ballistic shock performance of the friction stir welds demonstrated improved performance over welds made with GMAW. These benefits help position FSW as a joining method of choice for the fabrication of aluminum hulled combat vehicles that offer maximum protection to their crews while reducing gross vehicle weight and maintaining high vehicle mobility.

Friction Stir Welding Procedure Development

While work was conducted on a variety of 2xxx and 5xxx series aluminum alloys over the course of this program, final development focused primarily on two aluminum alloys: AA2139 and AA5059. AA2139 T8 is a heat treatable aluminum alloy with copper as the primary alloying element (Meister & Martin, 1967). AA5059 H131 is a non-heat treatable aluminum alloy with magnesium as the primary alloying element (Meister & Martin, 1967). A comparison of their base metal mechanical properties, take from material used in this study, is displayed in Figure 1. All FSW trials were conducted at EWI on a General Tool Company (GTC) AccuStir machine. This gantry style machine has a vertical force capacity of 60,000 lbf and produces 1,800 ft*lbs of maximum torque. All static tensile testing during development followed ASTM E8 and bend tests followed ASTM E290. Development of the welding procedures for all alloys followed a general path of tool design, initial parameter development, parameter down-select, tool life trials, and ballistic shock panel fabrication.

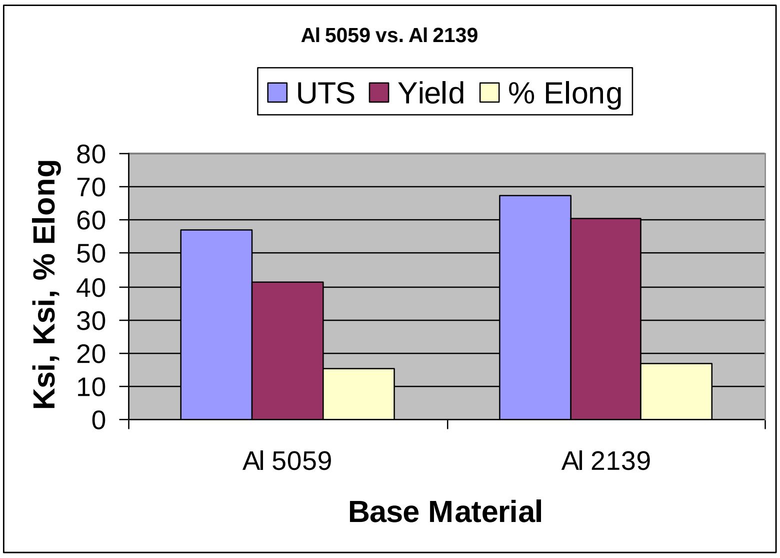

Figure 1. Comparison of Base Metal Mechanical Properties between AA5059 H131 and AA2139 T8

FSW of AA5059

For the AA5059 material, single pass FSW procedure development was conducted on plates with thicknesses ranging from 0.25 to 1.5 in. However, the ultimate goal for this work was to achieve production viable procedures for the joining of 1.5-in.-thick AA5059 in a single pass. With this in mind, the tool designs were quickly scaled up to 1.5-in. thick after demonstrating success on thicknesses between 0.25 and 1.0 in. The tool designs (51316-T05 and 51316-T06) fabricated during the first round of 1.5-in.-thick welding trials are summarized in Table 1.

FSW Tool Design	Style	Tilt	Shoulder Diameter (in)	Threads	Flats
AA5059 Round 1					
51316-T05	Monolithic	3°	2.40	Left Hand	Four
51316-T06	2-Piece	3°	2.00	Left Hand	Four
AA5059 Round 2					
51969-T05	2-Piece	3°	2.00	Left Hand	Five
51969-T08	2-Piece	3°	2.00	Left Hand	Eight
AA2139					
51611-T02	2-Piece	0°	1.25	Left Hand	Four
51611-T03	2-Piece	3°	1.625	Left Hand	Four

Table 1. FSW Tool Designs

Welding trials were then conducted using these tools to identify the outer bounds of a welding parameter window. Prior to welding, each plate sample was milled to remove the oxide layer and chemically cleaned with acetone. Once the outer edges of the parameter window were established, the parameters were further refined using PAUT inspection, visual inspection of weld cross-sections and mechanical test samples. A summary of the static tensile properties of the welds made in AA5059 are displayed in Figure 2. These properties summarize single pass welds made in 1.0-in. thick and 1.5-in.-thick AA5059 as well as double-sided welds made in 1.5-in.-thick AA5059. It should be noted that the cross weld properties stayed fairly consistent across the different thicknesses; however an increase in ductility was observed during the double-sided welding, most likely due to an overall larger heat input.

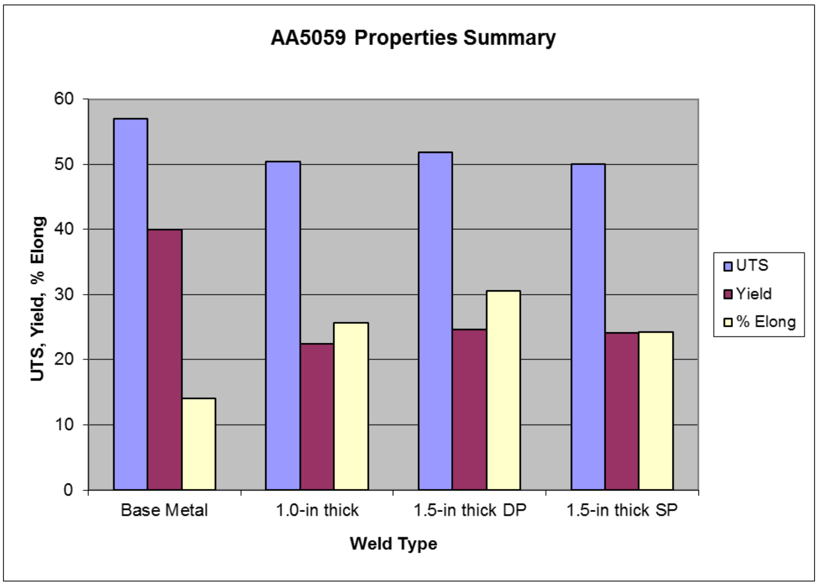

Figure 2. Cross Weld Static Tensile Properties

Based upon the evaluation of the mechanical test data and the weld cross-sections, the final parameters down-selected for both of the Round 1 tool designs were 75 RPM and 2 ipm. These tools were then run in an extended tool life test to determine overall tool robustness. The target length for these tool life tests was set at 500 in. of total weld length divided into a series of seven 65-in.-long welds and one 45-in.-long weld. In between each weld, the wear condition of the tool was documented with a series of images. Both tool designs from Round 1 achieved a total weld length of 500 in. without catastrophic failure. However, abrasive wear did occur on each tool, primarily near the pin and shoulder interface (Figure 3). Despite this wear, weld quality remained consistent along the entire 500 in. as demonstrated by weld cross-sections and mechanical test properties evaluated in the first 20 in. and the last 20 in. of weld length (Figure 4). This consistency in quality suggests that these tools could travel to greater lengths beyond 500 in. After the tool life tests, tool number 51316-T06 was selected for further evaluation in ballistic panel fabrication based upon visual examination of the weld cross-sections and a lower traverse welding force of 4,500 lbf.

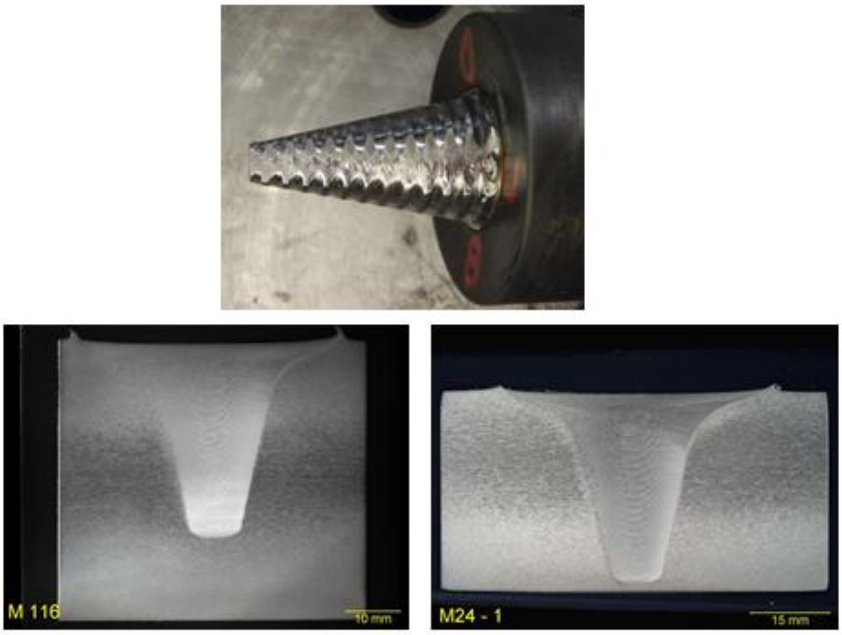

Figure 3. Tool Wear and Weld Cross-Sections from the Tool Life Test using Tool No. 51316-T06

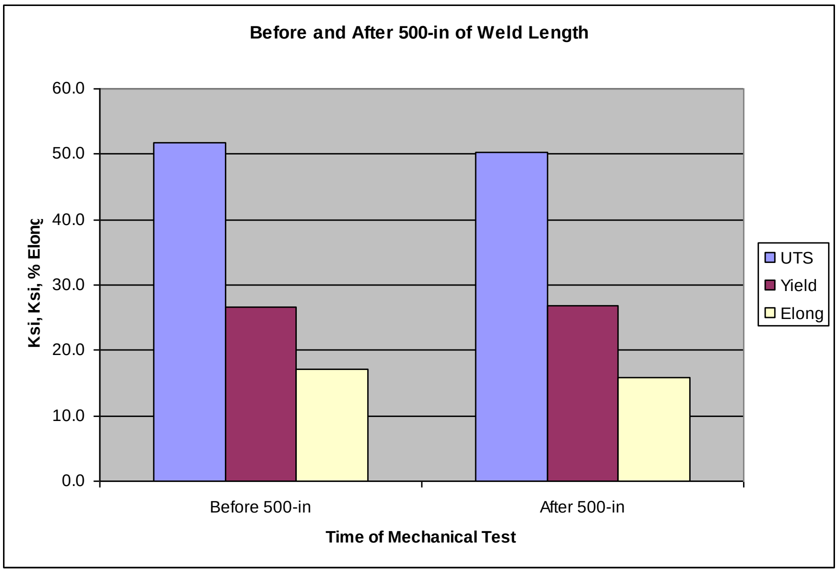

Figure 4. Static Tensile Properties from the Tool Life Test using Tool No. 51316-T06

Despite the success in achieving a total tool life of 500 in. with both Round 1 tool designs, the travel speed remained too slow for a production environment. In light of this, a second round of tool development was initiated to develop tool designs that could double the travel speed without sacrificing tool life. This resulted in the development of FSW tools that could weld at faster travel speeds with lower traverse forces. Previous studies conducted on FSW tool designs in open literature have indicated that one method to reduce traverse weld forces is to increase the number of flats on the tool (Colligan, Xu, & Pickens, Welding Tool and Process Parameter Effects in Friction Stir Welding of Aluminum Alloys, 2003). The two tool designs created for Round 2 incorporated this principle in both five flat and eight flat designs (Table 1).

Early parameter development trials with these two new tool designs indicated that the eight flat tool design (51969-T08) was ineffective at reducing the traverse weld forces. However, the five flat design (51969-T05) did result in a reduction of the welding forces when traveling at 2 ipm. The welding speed was then steadily increased until a 4 ipm travel speed was achieved. The final welding parameters for the 51969-T05 tool were 75 RPM at 4 ipm carrying 4,500 lbf of traverse welding force. Using these parameters, the 51969-T05 tool successfully achieved the stated goal of 500 in. of total weld length without catastrophic failure or severe tool wear during the tool life trials. Weld quality was again confirmed through mechanical testing and visual inspection of weld cross-sections in the beginning 20 in. and the final 20 in. of weld length.

FSW of AA2139

For the AA2139 material, FSW procedure development was conducted on only two thicknesses of material: 1.0- and 1.5-in. thick. Two tool designs (Table 1) were selected in order to compare how different tilt angles may affect tool life and traverse forces. Both tools had a pin length of 0.970 in. allowing for full penetration in the 1.0-in.-thick material. For the 1.5-in.-thick material, a double pass welding technique was used with these same tools creating a joint overlap of approximately 0.440 in.

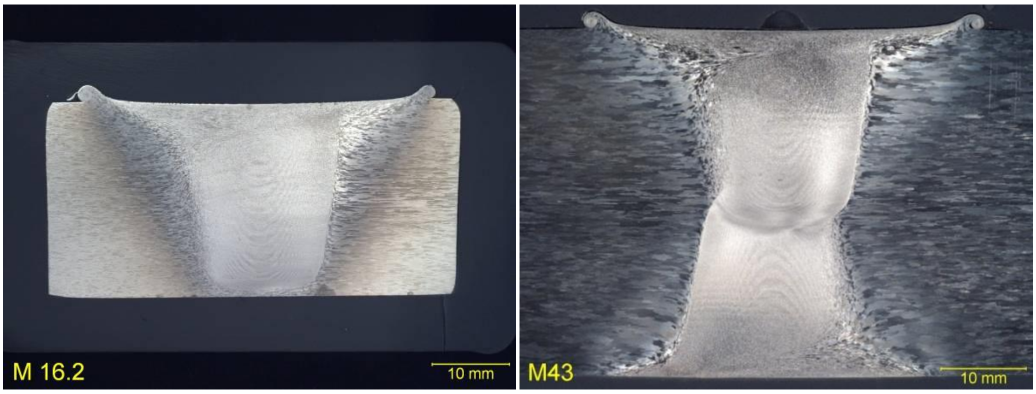

Figure 5. Macrographs of Single Pass and Double Pass Weld Cross Sections

Parameter development for this alloy followed a similar path as that for the AA5059 material. Prior to welding each plate sample was milled to remove the oxide layer and chemically cleaned with acetone. The outer bounds of a parameter window were identified for each thickness using PAUT inspection, visual inspection of weld cross-sections, and mechanical tests. Evaluation of the mechanical test results did not reveal significant property variation for significant changes in welding parameters (Figure 6). This result suggests a wide and robust welding window for these particular tool designs and material.

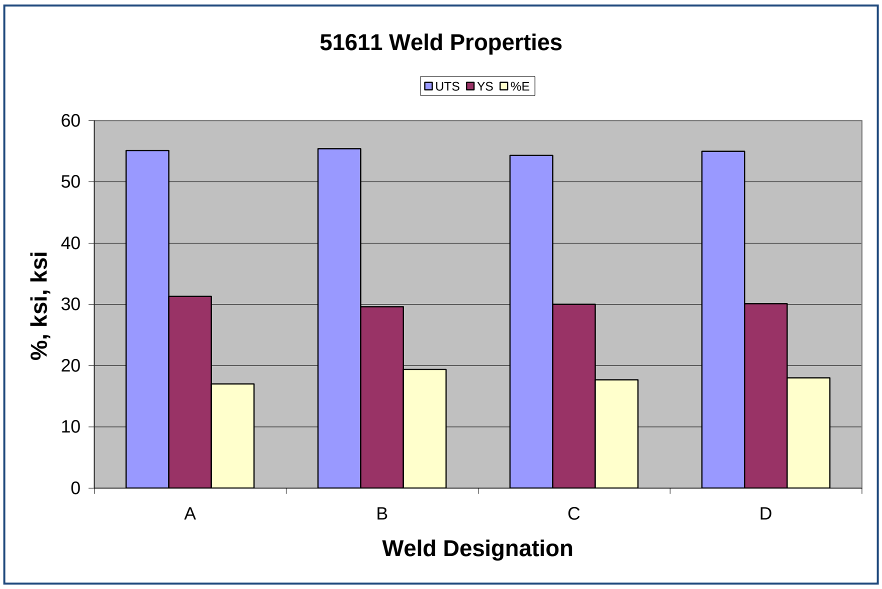

Figure 6. Cross Weld Static Tensile Properties of AA2139 Across Various Weld Parameters

Similar to the test performed in AA5059, these tools were then run in an extended tool life test to determine overall tool robustness. The target length for these tool life tests was also set at 500 in. of total weld length and was divided into a series of seven 65-in.-long welds and one 45-in.-long weld. In between each weld, the wear condition of the tool was documented with a series of images. During the tool life test, tool number 51611-T02 was run at 150 RPM and 4 ipm. Using these parameters, the pin of the T02 tool was sheared off approximately 200 in. into the tool life test. Tool number 51611-T03 was run at 150 RPM and 2 ipm over the course of the tool life test and was able to meet and exceed the goal of 500 in. Additionally, minimal wear was observed on this tool and weld quality remained consistent as confirmed by visual inspection of the weld cross sections.

Ballistic Shock Testing

Ballistic shock testing is just one of many methods available for assessing the performance of welds under impulse. An admittedly oversimplified description of the process includes the use of a non-penetrating 75-mm soft aluminum cylinder impacting a test sample known as an “I-Panel”. These I-Panels are composed of a material of interest in an approximately 4-ft by 4-ft square (Figure 7). As this test is comparative in nature, all results are base lined against the impact performance of a monolithic plate of material. In this case, monolithic plates of both AA5059 and AA2139 were tested and their performance quantified based upon the acceptance criteria. These performance values were then used to judge the performance of the welded samples made with FSW and GMAW. For the welded samples, an I-Panel consists of two 2-ft by 4-ft aluminum panels joined together to form the requisite 4-ft by 4-ft square. The weld is placed along the 4-ft long edge and stood vertically in the test stand. The aluminum cylinders are targeted to impact directly onto the weld joint.

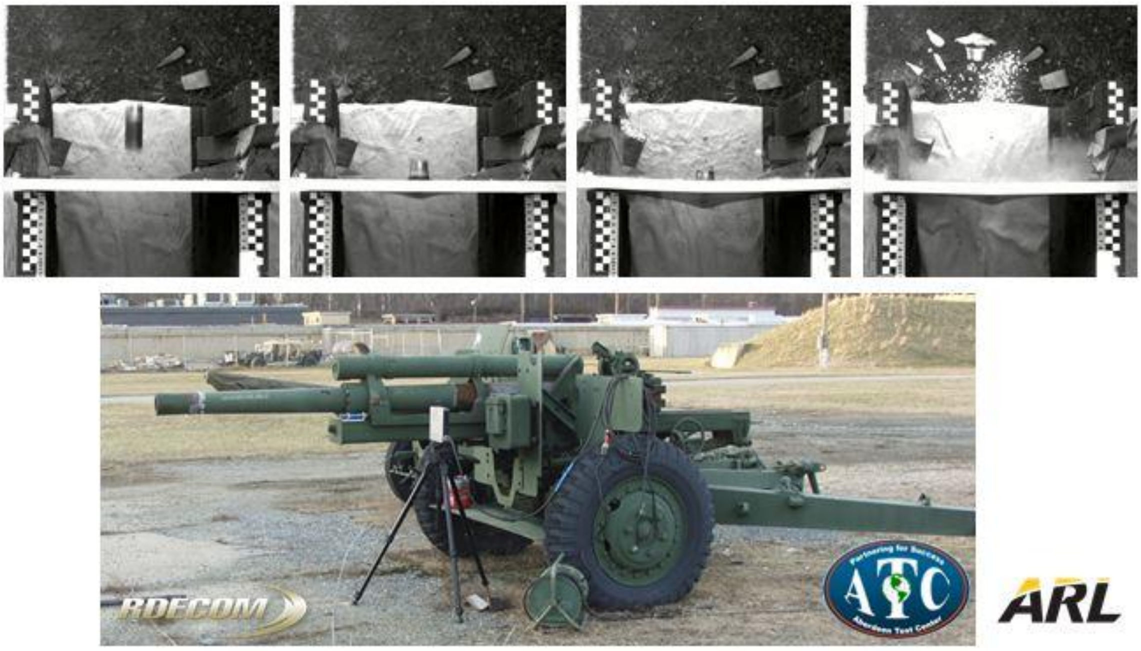

Figure 7. Ballistic Impact Testing

Using the down selected parameters from the AA5059 development, several I-Panels were made using the 51316-T06 and 51969-T05 tools at 1.5-in. thick. These friction stir welded I-Panels were tested against the performance of 1.5-in.-thick I-Panels constructed using GMAW. The performance of the GMAW I-Panels approached 93% of the AA5059 monolithic plate performance while the FSW I-Panels approached 100% of the AA5059 monolithic plate performance. In an ideal situation, the weld should appear “invisible” during impact loading, behaving as close to the monolithic plate behaviour as possible. In this case, the friction stir welded panels performed closer to this goal than the GMAW I-Panels.

Similarly, several I-Panels were constructed out of AA2139 using the 51611-T03 tool. Due to the difficulties in arc welding AA2139, no I-Panels were constructed using GMAW. The 1-in.-thick single pass FSW I-Panel approached 90% of monolithic plate performance while the 1.6-in.-thick double pass FSW I-Panel was greater than 90% of the monolithic plate. While these panels did not achieve 100% of monolithic plate performance, their performance is still considered to be excellent in terms of a welded 2xxx series aluminum alloy. Due to the complex nature of this aluminum alloy, fusion welding processes such as GMAW would struggle to perform to this level due to the processes susceptibility to defects such as hot cracking and an appreciable knockdown in strength due to the high heat input. The results of these ballistic shock tests in both aluminum alloys suggest that friction stir welds would better resist cracking under ballistic shock and therefore offer better protection to the war fighter inside a friction stir welded aluminum vehicle.

Phased Array Ultrasonic Testing Development

In parallel to the development of FSW procedures, work was conducted to evaluate and develop PAUT for inspection of the friction stir welds. This program did not allow for the execution of a full Probability of Detection (POD) study. Instead, work focused on developing PAUT inspection parameters to detect two defects that were determined to most likely occur within a Welding Procedure Specification (WPS). The two defect types selected for this study were a planar defect and a volumetric defect. More specifically, these included a Lack of Penetration (LOP) type defect and a wormhole type defect (Figure 8).

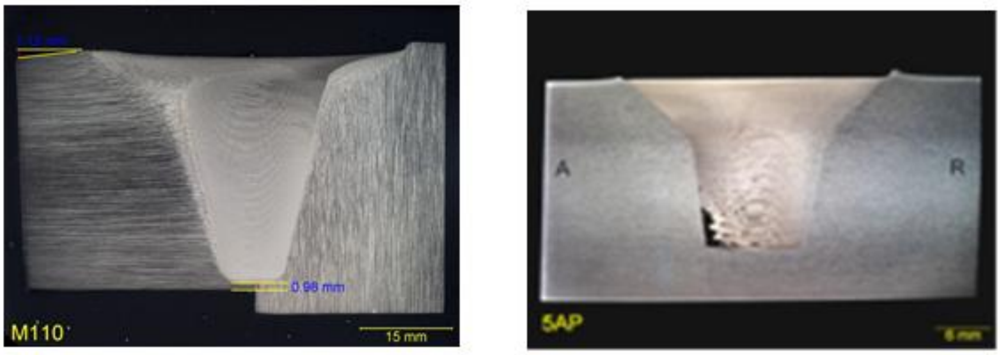

Figure 8. Lack of Penetration Type Defect (Left) and a Wormhole Type Defect (Right)

The first step in developing PAUT inspection techniques was to use a modelling program to evaluate different probes for their effectiveness at inspecting the different weld joint geometries. Among other parameters, this software allowed for the evaluation of different element arrays, frequencies, focal distances, and active elements. By starting with a modelling exercise, the overall cost of the development phase was reduced due to the software's ability to narrow down the probe choice selection prior to actually inspecting a weld sample.

After determining the proper inspection probes and initial inspection parameters, a calibration block was created. This calibration block consisted of a friction stir welded corner joint using objective geometries, the down selected FSW tool design, and down selected FSW parameters. One calibration block was created for each material. Several notches (0.04-in high x 0.25-in long), contoured to the stir zone profile, were then machined into each calibration block to simulate different defect locations through the thickness of the weld (Figure 9). These notch locations helped ensure the developed PAUT parameters would cover the full range of anticipated defects and locations.

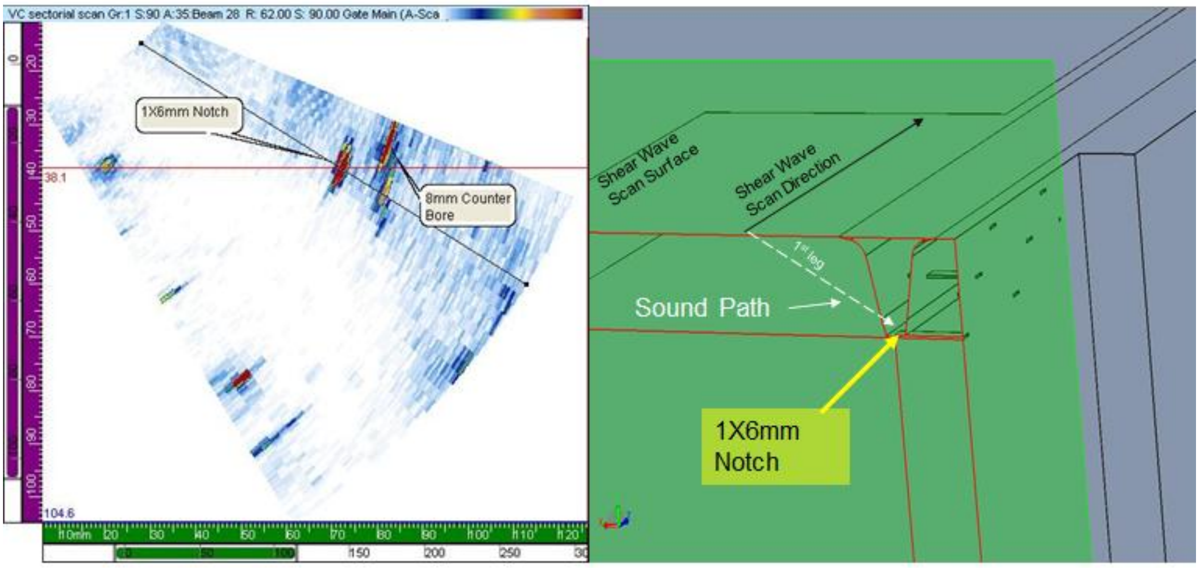

Figure 9. Sectorial Scan of the Calibration Block (Left) and a Model of the Calibration Block (Right)

Using the calibration blocks to dial in the procedures identified by the modelling software, open trials were conducted on friction stir weld samples throughout the development of the FSW procedures on both materials. Development welds were first inspected using PAUT and then areas of indications were cross-sectioned to confirm the presence of the indications. These open trials confirmed the capabilities of the PAUT inspection parameters were capable of detecting defects down to 0.040-in. high. The fully developed PAUT inspection techniques were used throughout the course of this project to ensure weld quality in the development welds, tool life tests, and ballistic shock I-Panels. Additionally, these inspection techniques were transferred to the GDLS production facility in Lima, Ohio, where they were used to ensure weld quality on a military vehicle demonstrator.

Technology Transfer and Demonstration

Per the direction of the U.S. Army, the ultimate objective of this work was to transfer all developed technology to General Dynamics Land Systems to aid in the production of military vehicles. These technologies were to support their Joint Systems Manufacturing Facility (JSMC) in Lima, Ohio, where they recently installed a large gantry style FSW machine. To demonstrate the successful development and transition of these technologies, two military vehicle demonstration structures were fabricated at JSMC.

To aid in technology transfer, all of the developed FSW parameters were documented in the electronic WPS data management software WeldEye©. Tool designs used on the GTC AccuStir machine at EWI were then modified and fabricated to integrate with the FSW machine at JSMC. These procedures were then used in conjunction with procedures developed at JSMC by GDLS to fabricate two military vehicle demonstration structures. These structures were comprised of AA5059 aluminum and were designed with multiple butt and corner joint weld geometries. The basic design of the structure was a rectangular five-sided box. The FSW process was used to join the bottom of the box onto the accompanying four sides. The final welds on the bottom of the box are displayed in Figure 10 along with an image of the welding in process at JSMC.

Figure 10. Military Vehicle Demonstrator during Welding (Left) and Fully Assembled

PAUT inspection of these two demonstrators was accomplished by a team of inspection personnel comprised of both EWI and GDLS personnel. Each demonstrator was inspected post-welding while it remained in the fixturing. During the inspection of the first demonstrator, a LOP defect was observed in one of the corner joint welds (Figure 11). The cause of this defect was traced back to an under-designed anvil underneath of that particular section. The anvil in this section was subsequently improved and the defective section re-welded. Inspection of the re-weld confirmed the elimination of the LOP (labelled as LOF in Figure 11) defect detected previously. The second demonstrator was similarly inspected in the fixture after welding and was found to be free of weld defects.

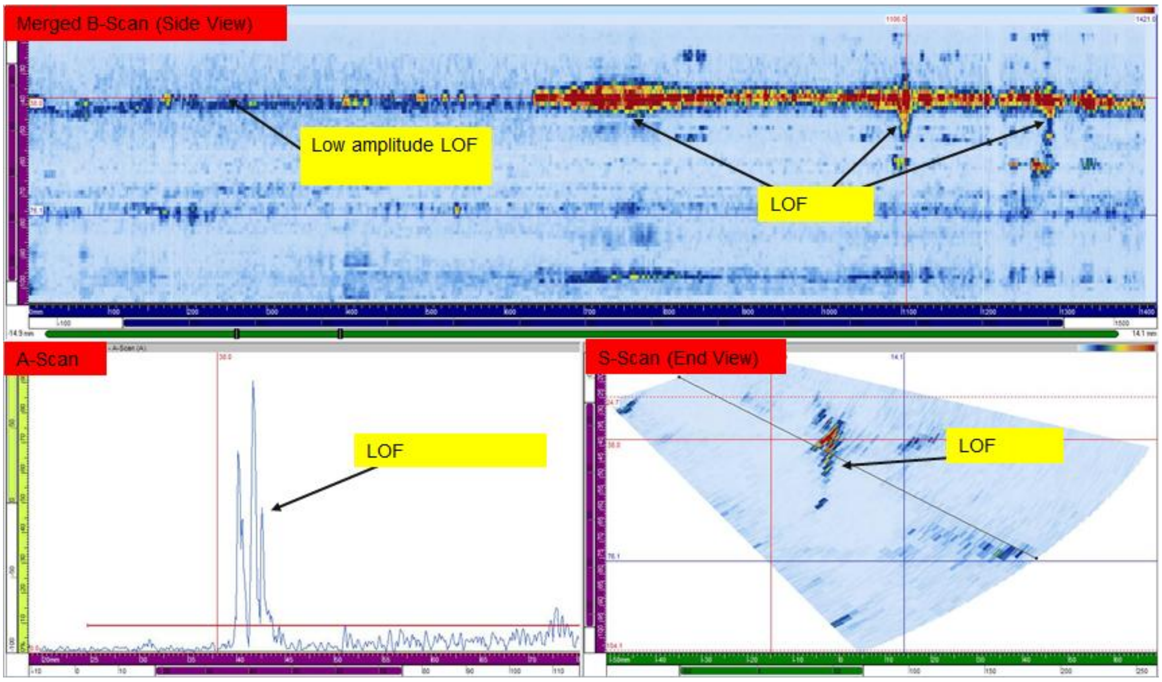

Figure 11. PAUT Inspection Results from a Corner Joint on the First Demonstrator

Summary

A team comprised of U.S. ARL, GDLS, and EWI successfully developed FSW procedures for a number of aluminum alloys over a range of thicknesses including 1.5-in.-thick aluminium plate in aluminum alloys 5059 and 2139. These procedures were evaluated by PAUT inspection, static tensile properties, and extended tool life tests. Over the course of the development, it was found that tool design depended largely upon the alloy to be welded and the anticipated production conditions. The parameters were optimized for a production environment and the tools developed achieved the stated goal of 500 in. of total weld length without failure. Most importantly, weld quality did not suffer over the total length of weld produced.

The best welding parameters found during development were used to construct ballistic shock I-Panels in order to evaluate their impact performance. AA5059 outperformed comparable panels joined with GMAW while AA2139 performed roughly 90% of the monolithic plate performance. All of the welds made in this program were inspected using the developed PAUT parameters. The use of this inspection technology ensured a high degree of weld quality in all joint configurations. Finally, all of the developed technology was transferred to the JSMC operated by GDLS in Lima, Ohio. This technology was used to successfully fabricate two military vehicle demonstration articles. In fixture PAUT inspection of the first demonstrator allowed for quick and effective correction of tooling ensuring the second demonstrator was free of weld defects.

While considerable work remains to fully develop FSW for military vehicle applications, this work adds to the existing body of knowledge advocating its use. Of particular importance is the ballistic shock performance of the friction stir welds versus that of traditional arc welding methods. This performance allows for future military vehicles to be constructed that are light weight and highly mobile while still providing the necessary protection to both crew and vehicle.

References

Arbegast, W. J. (2007). Application of Friction Stir Welding and Related Technologies. In R. S. Mishra, & M. W. Mahoney, *Friction Stir Welding and Processing* (pp. 273-308). Materials Park: ASM International.

Colligan, K. J., Konkol, P. J., Fisher, J. J., & Pickens, J. R. (2003). Friction Stir Welding Demonstrated for Combat Vehicle Construction. *Welding Journal*, 34-40.

Colligan, K. J., Xu, J., & Pickens, J. R. (2003). Welding Tool and Process Parameter Effects in Friction Stir Welding of Aluminum Alloys. In K. V. Jata, M. W. Mahoney, R. S. Mishra, S. L. Semiatin, & T. Lienert, *Friction Stir Welding and Processing II* (pp. 181-190). Materials Park: ASM International.

Dauer, C. (2011, 11 11). *Military Vehicles Must Balance Weight, Protection Considerations.* Retrieved from IDGA: http://www.idga.org/vehicles/articles/army-vehicles-must-balance-weight-protection-consi/

Ghaziary, H. (2011). *Application and Performance Characteristics of Aluminum Armor Plate for the Hull Construction of Current and Future Military Tactical Vehicles.* SAE Technical Paper: doi: 10.4271/2011-01-0536.

Holmes, T. M., Chin, E. S., Huang, P. J., & Pasternak, R. E. (1992). *Evaluation of 8090 and Weldalite-049 Aluminum-Lithium Alloys.* Watertown: U.S. Army Materials Technology Laboratory.

MacGregor, D. (2012, February). Don't Waste a Drawdown. *Armed Forces Journal*, pp. 24-26, 38-39.

Meister, R. P., & Martin, D. C. (1967). *Welding of Aluminum and Aluminum Alloys.* Columbus: Battelle Memorial Institute.

Rajiv S. Mishra, M. W. (2007). Introduction. In M. W. Rajiv S. Mishra, *Friction Stir Welding and Processing* (pp. 1-6). Materials Park: ASM International.

Singer, P. W. (2012, February). The Evolution of the IED. *Armed Forces Journal*, pp. 32-33.

The Aluminum Association. (1997). *Welding Aluminum: Theory and Practice.* Washington D.C.: The Aluminum Association, Inc.

Wayne, T. M., Nicholas, E. D., Needham, J. C., Murch, M. G., Templesmith, P., & Dawes, C. J. (1991). *Patent No. 9125978.7.* United Kingdom.

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