OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Final Report

Friction Stir Welding of Lightweight Vehicle Structures

CRADA No. ORNL-04-0693
with
Ford Motor Company

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Table of Contents

Purpose and Background

The purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, LLC and Ford Motor Company was to establish friction stir welding (FSW) and friction stir processing as viable options for use in construction of lightweight substructures for trucks and cars, including engine cradles, suspension sub frames, instrument panel supports, and intake manifolds.

Background

Friction stir technology, both welding and processing, appears to be an important enabling technology for the construction of aluminum and magnesium lightweight vehicle substructures with accurate dimensional control and high joint strength. Suspension subframes (as illustrated in Figure 1) and engine cradles of light trucks and passenger cars are traditionally made from stamped steel component parts. However, analysis results indicate that these structures can be made lighter while maintaining strength and stiffness if they are constructed from cast or wrought aluminum alloys. In addition, the subassemblies can be constructed of simply-shaped castings and extrusions which would help minimize material costs. Besides subframe assemblies, components such as instrument panel and radiator supports (as illustrated in Figure 2) are being made of Mg alloys. Magnesium structures are usually either one-piece castings or they are fabricated from castings and extrusions by bonding with adhesives, mechanical fasteners, or fusion welding. All these bonding techniques have disadvantages: adhesives require cure cycles, mechanical fasteners add additional weight, fusion welding causes distortion and heat-affected zones with varying properties in base metals. Fully realizing the potential benefits of Al and Mg alloys in these applications depends directly on developing improved joining techniques.

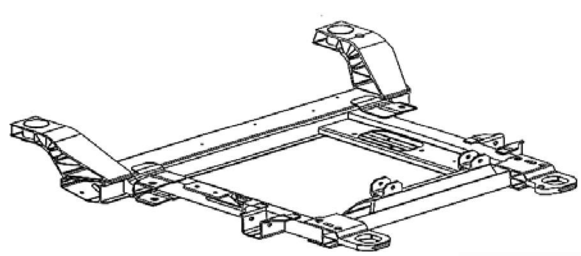


Fig. 1. Aluminum subframe concept made from extrusions

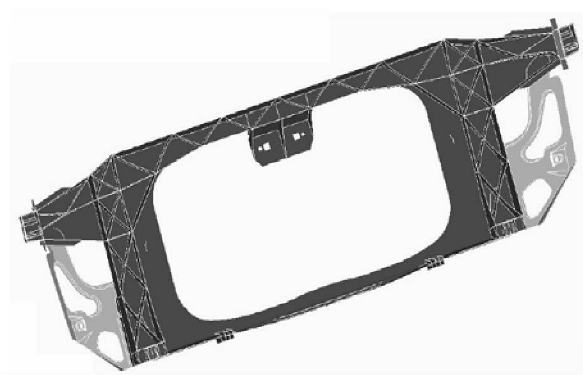


Fig. 2. Magnesium radiator support in new Ford F-150.

Traditionally, the most widely used processes for welding automotive components are gas metal arc welding (commonly known as MIG) and resistance spot welding (RSW). Both of these processes have well-documented issues (e.g., weld porosity, low weld strength, excessive distortion) associated with using them on Al and Mg alloys in vehicle assembly operations. The friction stir processes avoid melting and typically distribute heat over wider areas than traditional welding processes. This minimizes distortion and contributes to higher strength in FSW joints. FSW has been implemented in shipbuilding, military and aerospace applications in joining mainly flat Al panels. Its potential benefits in truck and automobile construction and on Mg in particular are just beginning to be explored.

Objective

The objective of the CRADA project was to establish friction stir welding (FSW) and processing as viable candidates for construction of lightweight substructures for trucks and cars, including engine cradles, suspension subframes, instrument panel supports, and intake manifolds.

The approach was to conduct welding trials to establish acceptable process parameters for producing quality joints that maximize mechanical performance appropriate for specific applications (strength, fatigue, etc.). The work was conducted primarily on castings and flat-rolled stock of aluminum and magnesium alloys. The project was structured in three phases where coupon testing would be used to establish basic behaviors, concept testing would be used to demonstrate commercial viability, and component testing would used to verify that the processing was developed sufficiently for deployment in production.

Proposed Tasks

The first three tasks, as originally anticipated, embodied a coupon testing phase that was meant (1) to establish the basic characteristics of the friction stir processes as they might be applied to cast and extruded Al and Mg, (2) to define parameter ranges for acceptable application of the processes, and (3) to determine baseline properties. Tasks 4 & 5 were to be used to establish that the overall concept of using friction stir welding to build lightweight automotive structures was feasible in terms of joint configurations, component designs, and tooling requirements. Tasks 6-7 would verify that production-type parts could be constructed with FSW and that component properties were acceptable.

Task 1. Process Parameters (effort: 50% ORNL, 50% Ford)

Various trials would be conducted to establish process parameter windows for the product forms and thicknesses of interest. This would be done using a combination of equipment that included the MTS Systems Corporation Intelligent Stir Welding for Industry and Research (ISTIR) Process Development System (PDS) FSW machine at ORNL and a robotic friction stir system built by Kawasaki and installed at the Scientific Research Laboratories at Ford. Specific proposed activities included:

1. Producing joints of both butt and lap configurations
2. Producing joints with both the customary friction stir tooling that requires back-up support for welding, and with self-reacting tools that do not require support.
3. Evaluation of techniques for elimination of entry and exit holes.
4. Use of the design-of-experiments (DOE) approach to assist in the selection of experimental conditions and in the analysis of results.

Task No. 2 - Analysis of Temperature and Stress Fields (effort: 80% ORNL, 20% Ford)

An analysis would be performed of the temperature and stress fields of acceptable FSW joints to provide input for joint design, component design, and the selection of stir tooling.

Task No. 3 – Microstructure-Property Analysis (effort: 60% ORNL, 40% Ford)

A detailed microstructure-property analysis would be conducted on a selection of joints prioritized according to Ford's anticipated needs. At a minimum, butt joints would be subjected to bend and tensile testing and lap joints would be subjected to torque and tensile testing. Microstructures would be examined to establish the general characteristics of stir zones and heat-affected zones for the configurations, product forms and alloys of greatest interest. Microstructure analysis would include determining grain structure and second phase identification and distribution parameters.

Task No. 4 – Assessment of Component Design Requirements (effort: 70% Ford, 30% ORNL)

It was anticipated that Tasks 1-3 would permit specification of process parameter and tool loading limits that would be appropriate for designing purpose-built tooling for construction of lightweight automotive components. The information from those tasks could then be communicated to MTS for use in machine design. Also, an assessment of component design requirements specific to FSW would be conducted with Ford engineers in designing automotive components with friction stir technology.

Friction stir trials would be conducted on prototype parts (rather than flat coupons) using Ford equipment to verify the acceptability of optimized processing parameters on actual automotive component parts. Tool loading conditions would also be verified and process parameters would be documented.

It was also anticipated that high-speed impact/crush testing of friction stir welded components would be done using facilities available at the National Transportation Research Center.

Task No. 5 – Prototype Parts Trials (effort: 50% Ford, 50% ORNL)

Friction stir trials would be done on prototype parts (rather than test coupons) using the Ford equipment to verify the acceptability of optimized processing parameters on actual automotive components parts. Tool loading conditions shall also be verified and process parameters would be documented.

Task No. 6 – Construction and Testing (effort: 70% Ford, 30% ORNL)

Construction and testing of prototype subsystem components would be done using newly-designed stir tooling that was optimized for the specific conditions under consideration.

Task No. 7 – High-Speed Impact/Crust testing (effort: 60% ORNL, 40% Ford)

High-speed impact/testing of friction stir welded components would be done using facilities available at the National Transportation Research Center.

Summary of Activities

Once this project began, three types of automotive components were addressed in the technical activities: structural subframes, exterior panels, and castings. The structural subframes were primarily associated with manufacturing interests in Ford business units, where aluminum alloys and various welding/bonding strategies were under consideration. Activities related to exterior panels were focused on improved manufacturing capabilities for aluminum alloys. For castings, there was interest in the use of friction stir processing for local mechanical property improvements and for welding to other product forms for subframe constructions.

During the period of 2005-2006, monthly conference calls were held which included participation of Ford, ORNL, and the University of Warwick. These calls were used for a wide range of discussions related to friction stir technology. The topics that were typically discussed included the alloys of most interest, experimental plans, stir tool designs, data analysis, business opportunities for the technology with Ford operations, and strategies for targeting specific components for production trials.

Progress by Task

Task 1

The majority of the welds were lap welds because these are much more common in automobile construction than butt welds. Linear welding was primarily confined to surface modification of castings. The emphasis on these types of welds meant that there was no need for evaluation of self-reacting tooling. Consequently, none was done. Similarly, there was no compelling need to address issues related to the elimination of entry and exit holes in linear welds. It was thought that exit holes in surface modification could be avoided by exiting at features built into castings or at locations that would require subsequent drilling or machining. Some DOE experimentation was done at Ford when friction stir spot welding was under consideration for construction of aluminum hood assemblies.

Task 2

No significant effort was devoted to analysis of temperature and stress fields. Several discussions were devoted to outlining a process analysis strategy. Ultimately, it was judged that this type of effort was too resource intensive for the funds available and the utility of the results within the framework of the project was too uncertain. An original goal of this task was to use process modeling as an aid to design of stir tooling. Instead, tooling was designed based on experience and on guidance available from private discussions and published works. Some of the stir tool design considered are presented in Appendix A7 which indicates the range of variation considered in attempts to optimize the stir tooling for the application of friction stir spot welding structural frame members. This activity was done in collaboration with University of Warwick staff.

Task 3

Considerable effort was devoted to microstructure and property characterizations as outlined in the appended publications.

Task 4

A considerable amount of early experimentation was directed to characterizing loading conditions on tooling during friction stir spot welding. The bulk of this work was done at ORNL using the MTS friction stir equipment. Tool loading conditions were measured for various stir tool configurations, stack-up conditions (2 mm-to-2 mm, 3 mm-to 3 mm, etc.), and welding cycle times. An iterative process was used to adjust processing conditions to obtain joint strength within the desired range while also keeping the machine/tool loading conditions within a range tolerable to existing robotic equipment. Once confidence was established that joints of acceptable strength could be made with acceptable loading conditions, making welds robotically began to be emphasized. This would be a step toward implementation in an assembly plant environment.

Task 5 & 6

Prototype parts were produced to simulate use of friction stir spot welding to fabricate hood assemblies from aluminum. Test results indicated that joint strengths and weld cycle times met the constraints required for assembly plant construction.

Task 7

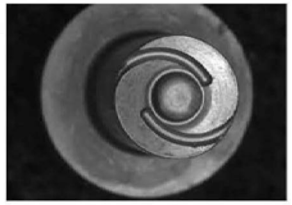
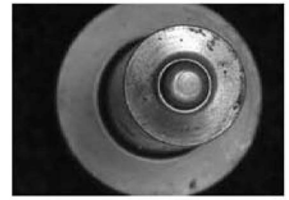
No high-speed impact testing was conducted.

Accomplishments

Accomplishments are summarized in the appended documents labeled as Appendix A1-A7.

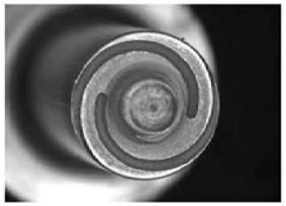
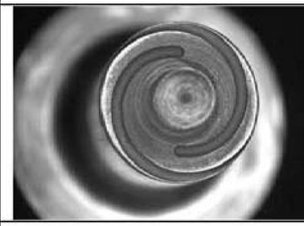
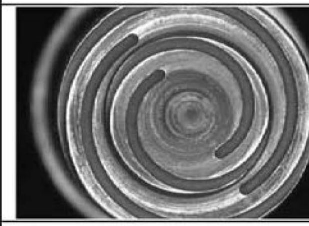
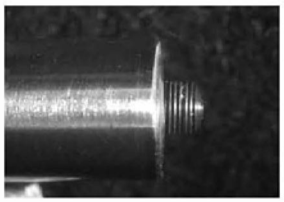
Appendix A7

SFW tools made by Warwick, 12/2005

Tool Names	War-1	War-2	War-3	War-4	War-5
					
					
Concavity	14	14	14	14	14
Shoulder D(mm)	10	10	10	10	10
Pin D (mm)	3.6	3.6	3.6	3.6	3.6
Pin L (mm)	2.8	2.35	2.8	2.4	2.4
					
Comments	Thread damaged	For 2mm/2mm SFW	For 2mm/2mm SFW	For 2mm/2mm SFW	For 2mm/2mm SFW

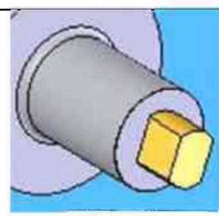
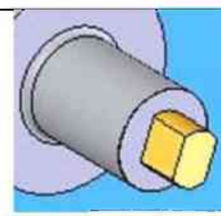
Photos taken and compiled by Tsung-Yu Pan, 313-322-6845, tpan@ford.com, 8/22/2006

SFW tools made by Ford-MicroFixture (War-6 to War-9), 5/2006. War-10 to War-13, proposed 8/21/2006

Tool Names	War-6	War-7	War-8	War-9	War-10
					
					
Concavity	2	14	2	2	2
Shoulder D(mm)	10	10	10	Two steps 16 / 10	Two steps 16 / 10
Pin D (mm)	3.6	3.6	3.6	3.6	4.0
Pin L (mm)	2.8	4.2	4.2	Two steps 1.0 / 2.8	Two steps 1.4 / 3.0
					
Comments	For 2mm/2mm SFW	For 3mm/3mm SFW	For 3mm/3mm SFW	For 3-t 2mm/2mm/2mm. Broken 7/17/2006	

Photos taken and compiled by Tsung-Yu Pan, 313-322-6845, tpan@ford.com, 8/22/2006

War-10 to War-13, proposed 8/21/2006

Tool Names	War-11	War-12	War-13		
Concavity	14	14	14		
Shoulder D(mm)	14	14	14		
Pin D (mm)	4.0	4.0W x 8.0L	4.0W x 8.0L		
Pin L (mm)	4.2	4.2	4.2		
		 No tread	 with tread on two long ends		
Comments	For 3mm/3mm SFW	For 3mm/3mm SFW	For 3mm/3mm SFW		

Photos taken and compiled by Tsung-Yu Pan, 313-322-6845, tpan@ford.com. 8/22/2006