D. Friction-Stir Spot Welding of Advanced High-Strength Steel

Principal Investigator: Michael L. Santella
Oak Ridge National Laboratory (ORNL)
1 Bethel Valley Road, Oak Ridge, TN 37831-6096
(865) 574-4805; fax: (865) 574-4928; e-mail: santellaml@ornl.gov

Principal Investigator: Glenn J. Grant
Pacific Northwest National Laboratory (PNNL)
902 Battelle Boulevard, P.O. Box 999, Richland, WA 99352
(509) 375-6890; fax: (509) 376-6034; e-mail: Glenn.Grant@pnl.gov

Principal Investigator: Zhili Feng
OR NL
1 Bethel Valley Road, Oak Ridge, TN 37831-6096
(865) 576-3797; fax : (865) 574-4928; e-mail: fengz@ornl.gov

Principal Investigator: Yuri Hovanski
PNNL
902 Battelle Boulevard, P.O. Box 999, Richland, WA 99352
(509) 375-3940; fax: (509) 376-6034; e-mail: Yuri.Hovanski@pnl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov

Expert Technical Monitor: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

---

Contractor: Oak Ridge National Laboratory & Pacific Northwest National Laboratory
Contract No.: DE-AC05-00OR22725 & DE-AC06-76RLO1830

Objective

- The primary objective of this project is to develop friction-stir spot welding (FSSW) as a superior method to join advanced high strength steels (AHSSs).
- Phase 1 activities will address the critical questions of whether there are tool materials available that have potential for reasonable life, and whether FSSWs made in high-strength steels are feasible and can develop similar or better mechanical performance than welds made by conventional processes like resistance spot-welding (RSW).
- Phase 2 activities will seek to increase joint strength through a more through investigation into weld process parameters and tool design. This will be accomplished both explicitly using new tools and refined operating parameters and by means of modeling both the process and fundamental conditions applicable to FSSW.

Approach

- The project is a collaborative effort between ORNL and PNNL, and includes an advisory committee with representatives from DCX, Ford, GM, two automotive steel suppliers, and a friction-stir welding tool supplier.
- Lap joints are made and used to correlate tensile shear strength with processing parameters and microstructures.
- Tool durability is evaluated by measuring tool wear after and during test programs and by characterizing the tool strength with changing welding conditions.
- Process modeling will be developed to help define optimum processing conditions and tool geometries.

Accomplishments

- Test programs fabricating spot-welds in DP780 and hot-stamped boron steel (HSBS) were initiated and a wide range of scoping weld parameters was investigated.
- Fabricated coupons were subjected to metallographic examination, hardness testing, and lap-shear tests.
- Metallurgically-bonded areas in the weld nuggets were measured, characterized, and found to be smaller than expected, thus indicating the need for more development work on weld process parameter and tool design.
- Two tool materials, tungsten 25% rhenium (W25Re) and polycrystalline cubic boron nitride (PCBN), and three tool geometries were initially investigated.
- Initial trials show that tool wear in PCBN is low, but tool wear in W25Re is high; however, tool wear and durability are strongly related to weld process conditions.
- Mechanical testing of phase-1 lap-shear coupons in DP780 and HSBS indicate that, while overall strengths weld parameters are in the range of acceptable values defined by the Draft AWS (American Welding Society) Specification for RSW of steel, the specific strength of nearly any condition exceeds the minimum stress condition.
- As tool geometry was found to have a profound effect on joint performance, four new tools were designed, procured and tested for the onset of phase-2 work.
- Several optimum and exploratory weld conditions were used with each of the four new tool designs with marked increase in lap-shear performance.

Future Direction

- Initial phase-1 study has shown joint strengths are at and just below the parameters set in the Draft AWS Specification for RSW of steels. Phase-2 activities will develop higher-strength joints through a more thorough investigation into weld process parameters and tool designs.
- Other factors critical to industrial implementation will be investigated including total spot cycle time, tool wear and robustness as a function of changing weld parameters, tool life, and the process of transferring optimized process parameters to a robotic system.
- Both process and fundamental models will be developed to predict weld performance with changing process conditions.
- Assess the potential for in-process NDE.

Introduction

The technology for implementing friction-stir spot welding (FSSW) of aluminum (Al) in automotive manufacturing environments exists. C-gun-type FSSW heads have been developed and adapted to robotic systems that are now commercially available for FSSW of Al alloys. This project addresses the questions of whether the FSSW process is viable for advanced high strength steels (AHSSs) and whether FSSW has advantages over conventional processes like resistance spot-welding (RSW). Preliminary work on FSSW of AHSS suggests that several features of the process (fine-grained microstructure in the nuggets of AHSS, potentially higher-strength joints and higher energy absorption in crash, low energy consumption and environmental emissions during manufacturing) may give FSSW cost and energy-saving advantages over RSW. In addition, the process may be viable for lightweight materials that currently have joining problems using conventional techniques (DP1000, Martensitics, hot-stamp boron steels, etc). If this can be accomplished, the FSSW process may be an enabler for more widespread use of the lightweight, advanced and ultra-high-strength materials.

- Important questions remain about effective, economical application of FSSW to AHSS. Critical unknowns to be addressed in this study include:
- Are tool materials available that have potential for reasonable life?
- Are joint strengths comparable to or better than conventional processes?
- Are manufacturing issues appropriate (cycle time, tool wear, process robustness and sensitivity to production variation)?
- Do FSSW joints have any advantage for NDE, or for real-time process control over RSW?
- Are total-life cycle costs appropriate?
- Can the process be modeled and predictive tools developed to aid designers?

If FSSW of high-strength steels can be demonstrated and its advantages over RSW identified, then it may help to accelerate the insertion of lightweight, high-strength materials into automotive body construction to help meet FreedomCAR goals.

Approach

The primary objective of this project is to characterize the responses of AHSSs to FSSW. The project is organized into two phases. Phase-1 activities addressed the critical questions of whether there are tool materials available that have potential for reasonable life, and whether FSSWs made in high-strength steels could develop strengths comparable to those made by conventional processes like RSW. Phase 2 encompasses activities including development of a more detailed process model including weld performance prediction, evaluation of joint microstructures and mechanical properties, assessments of the potential for in-process NDE and establishment of the framework of a design database for spot-friction-welded structures. The project is a 50/50 collaboration between ORNL and PNNL, and it includes an advisory committee with representatives from DCX, Ford, and GM.

Three uncoated high-strength steels were selected for the Phase-1 study: 1) dual-phased steel, DP780; 2) a steel with transformation-induced plasticity, TRIP780; and (3) a hot-stamp boron steel (HSBS) sourced from a Swedish supplier. It was agreed to acquire the material in a thickness of 1.5 mm based both on easy availability from the steel suppliers (Mittal Steel Corp. and Gestamp US Hardtech, Inc) and on the level of interest among OEMs.

Two materials were selected for the friction-stir tools: polycrystalline cubic boron nitride (PCBN) and an alloy of tungsten containing 25 wt% rhenium (W25Re). Both materials are commercially available. Initially, four tool designs, shown in Figure 1, were selected using input from the industry supplier of the PCBN, MegaStir, Inc. The tool design shown in the upper left corner of Figure 1 is considered relatively conventional, having a pin that protrudes from its main body. The main body is referred to as the shoulder region with a diameter of 0.4 inches. The pin itself is a truncated cone with three flats.

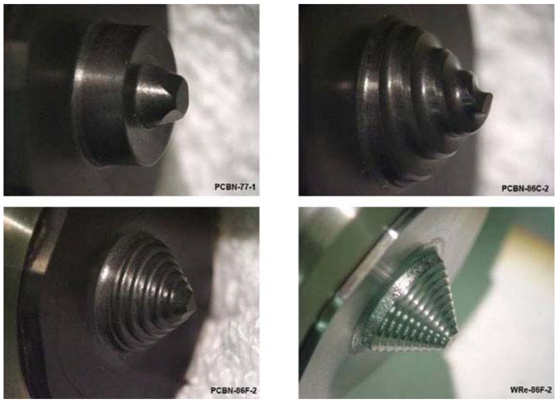

Figure 1. Tool geometries investigated in Phase 1.

The remaining three tools in Figure 1 depict 'shoulderless' tools. The tool in the upper-right corner is designated a coarse spiral and the two lower tools are fine-spiral designs. Both of these tools do not engage the shoulder with the workpiece. This geometry was recommended by MegaStir based on their exploratory work on FSSW. Two tools of each design and material were made and tested during Phase 1 of this study.

Lap joints were made to measure tension-shear strength, and to correlate strength with processing parameters and microstructures. Spot-welds were made by varying the parameters of tool plunge depth and tool plunging rate. In addition to these control parameters, a number of other process variables were recorded for each weld including weld time, spindle torque, normal force, and temperature on the back side of the two-sheet stack-ups.

Joint strength, as measured by lap-shear load, was correlated with these parameters. Joint strengths were also compared with those of resistance spot-welds using data from the Draft AWS Specification for RSW of Steel.

Correlations between weld process parameters, joint strengths, and bonded-area measurements developed throughout phase 1 were used to design new tools for phase-2 initiation. These optimized tools were subjected to similar testing to determine the effect of tool design on joint strength, bonded area and tool life.

Results and Discussion

Published data indicate the variables of plunge depth and weld cycle time are important for determining spot-weld strength in Al alloys. Based on this information, the initial testing plan for the AHSSs was meant to probe this parameter space by plunging to predetermined depths at constant rates, and by including a dwell at the end of each spot-weld program.

The friction-stir machine was used in displacement control during the spot-welding. The plunge depths were selected by considering the geometry of the conventional pin tool and the thickness of the two-sheet stack-ups being used for the welding. The pin extends beyond the plane of the shoulder by about 2.33 mm. The two-sheet stack-up is about 3 mm thick. Consequently, plunging to a depth of 2.3 mm would insert the pin entirely into the stack-up and just start to engage the shoulder of the tool on the surface of the top sheet. Plunging to a depth of 2.9 mm would insert the end of the pin nearly to the bottom surface of the bottom sheet. Based on this reasoning, the plunge depths were varied from 2.3-2.9 mm in 0.1 mm steps. Operating the machine in the displacement mode ensured that the desired final plunge depths were achieved.

Because the friction-stir machine was operated in displacement control, the dwell portions of the welding control programs required special consideration. Using a fixed-position dwell in displacement-control mode would permit the normal load on the tool to decrease due to temperature rise at the dwell position. It was believed that maintaining the loading conditions at the dwell position would promote better bonding. Consequently, incorporation of a dwell was accomplished by creating a two-step welding program that involved first plunging to nearly the full desired depth followed by further plunging the final 0.2 mm of depth at a slower rate. Three initial plunging rates were used: 0.4 mm/s, 2 mm/s, and 3 mm/s. The two secondary plunge rates used were 0.07 mm/s and 0.20 mm/s. These secondary plunge segments produced 'quasi-dwells' of either 1 s or 3 s at the end of each weld program.

Examples of two weld programs are shown in Figure 2. This procedure resulted in 14 individual welding programs at each plunging rate for 42 individual welding conditions. These 42 sets of conditions encompassed total welding times of 1.70-9.75 s. Spot-welds were made using both the conventional tool and the shoulderless tool. Six parameter sets were chosen to produce plunge depths of either 2.3 or 2.9 mm and weld times of 1.70, 2.05, 3.90, 4.35, 6.25 and 9.75 s.

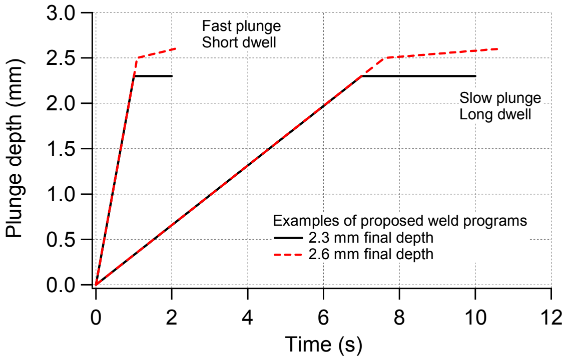

Figure 2. Illustration showing examples of conditions using for friction-stir spot-welding.

Figure 3 shows a representative micrograph of two friction-stir spot-welds in cross-section. These welds show the effects of different plunge depths at the extremes of the test matrix. The key feature of a high-strength joint is the width of the bonded area on each side of the exit hole. The bonded area is that part of the weld where the original surface between the two sheets disappears into the recrystallized and transformed stir zone on each side of the exit hole. Figure 3a shows a weld with a bonded area that is very narrow, due to an insufficient plunge depth. In Figure 3b, the bonded area is much wider indicating a significantly larger area of the joint was transformed, recrystallized, and plastically deformed. The original surface between the sheets has become a fully-mixed interface. Maximizing the bonded area is the goal of the process-parameter development because there is a strong correlation between bonded area and lap-shear strength. This is somewhat different from a resistance spot-weld where outer diameter of the spot is the key feature correlated with strength.

Figure 4 illustrates the shape of the bonded area in a FSSW. If the dimension W_w, the width of the annular bonded area, becomes too thin, then even large-diameter nuggets will fail at low loads because of lack of load-carrying section. This concept may require a different way of evaluating the quality of FSSW on the production floor. Joints that easily meet strength minimums may fail across this annular bonded area, and not by conventional nugget pullout. Inspecting and qualifying FSSW joints will be addressed in phase 2.

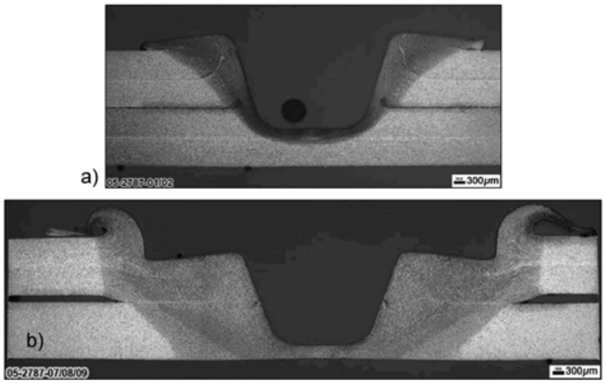

Figure 3. Bonded area is a function of tool design, plunge depth, tool material, shoulder heating, and process parameters (RPM, plunge rate, dwell).

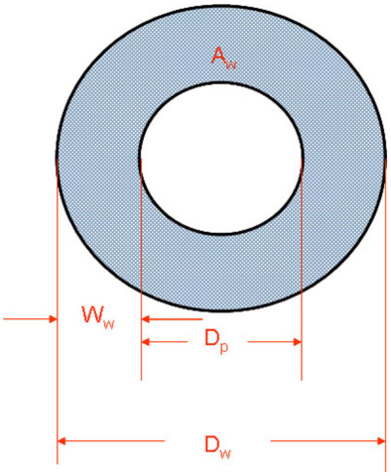

Figure 4. Geometry of the bonded area of a FSSW.

Figure 5 shows the correlation between lap-shear strength and total annular area of the bonded region. The area was calculated by measuring (by optical comparator) the dimensions of the sheared, or pulled-out, weld metal on the surface of a weld coupon after testing. It was assumed that these areas represent the bonded area, although in material cases where the heat-affected zone (HAZ) is weaker than the stir zone, the pull-out or sheared area will include more than just "nugget" material.

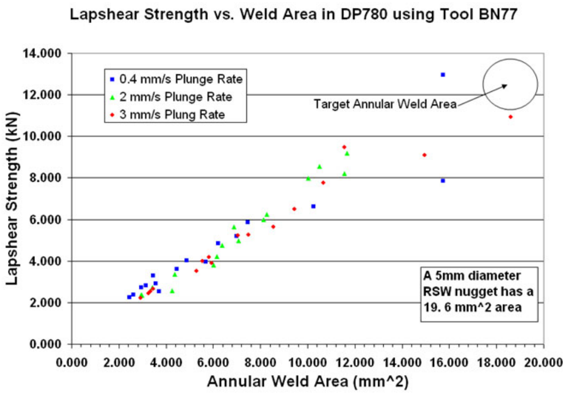

Figure 5. Lap-shear strength vs. annular weld area showing linear relationship.

Data in Figure 5 show a logical linear correlation between bonded area and lap-shear strength. For comparative purposes, a RSW joint with a nugget diameter of 5 mm will have an annular area of 19.6 mm^2. While the data in this graph are from a wide range of process parameters, only a single tool design (smooth-shouldered, smooth pin with three flats) was used. Plots like this allow for process optimization by pointing to operating parameters that lead to larger bonded areas and higher strengths. For example, lap-shear tests that resulted in loads above 10kN occurred in cases where plunge rates were on the high side of tested conditions (3mm/sec) and dwell times were longer (3 sec).

Figure 6 shows the relationship, for a single tool design, between lap-shear strength and total weld time, as defined by the time from tool touch down to retraction. (Also shown is the relationship between strength, plunge rate and dwell time). The figure shows there are process parameters where joint strength over 10 kN can be achieved at weld cycle times of 4 seconds.

Figures 7 and 8 demonstrate unique differences between FSSW and traditional RSW. According to the Draft AWS Specification for RSW of Steel, D8.1M:200X, minimum lap-shear strengths for spot-welds of overlapping 1.5 mm sheets in 780 MPa materials should be 10.4 MPa with an applicable minimum spot size of 19.6 mm^2. While several acceptable FSSW parameters produced lap-shear

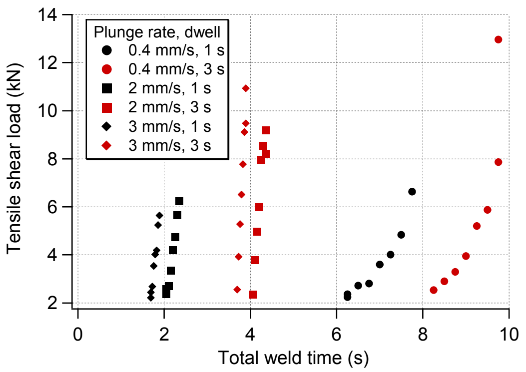

Figure 6. Lap shear strength vs. total weld time for a BN77 three-flat tool.

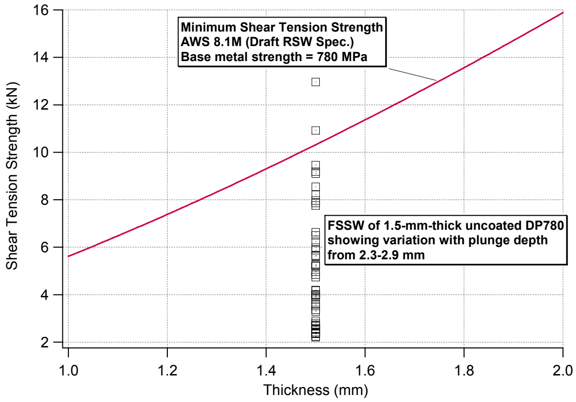

Figure 7. Graph represents data for all process parameters and a single conventional tool superimposed on a minimum strength standard for RSW welds (Draft AWS D8.1M:200X).

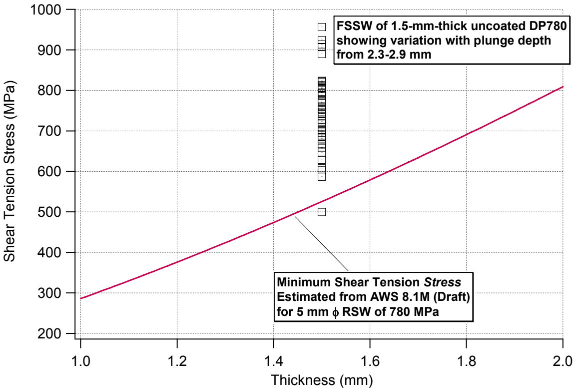

Figure 8. Graph represents specific strength data for all process parameters and a single conventional tool superimposed on a minimum strength/minimum area criteria (Draft AWS D8.1M:200X).

strengths exceeding such a requirement, bonded areas of the friction-stir spot-welds were below the required minimum spot size.

In order to compare the lap-shear response of friction-stir spot-welds to the Draft AWS Specification minimums, specific strengths of each FSSW specimen in DP780 were compared to the standard minimum requirement for 780 MPa steel with 1.5 mm thicknesses. Figure 8 more clearly demonstrates the lap-shear strength comparison of friction-stir spot-welds by factoring in the bonded area data into the specific-strength calculations. While these data shed a positive light on the ability of FSSW to retain a great percentage of the base metal strength, it also illuminates the need for developing tools and parameters that produce a larger bonded region in FSSW joints.

Four new tools were designed with the intent of increasing the overall bonded area of the FSSW. Pin lengths were shortened to force the shoulder to engage deeper into the top sheet, and pin geometry was altered to enhance the mixing characteristics of the tool. Additionally, one tool was chosen with a convex shoulder and short, threaded pin with the intent of mixing a larger region in a shorter duration.

Initial weld trials using the four redesigned tools shown in Figure 9 have provided marked increases in lap shear strengths and bonded areas.

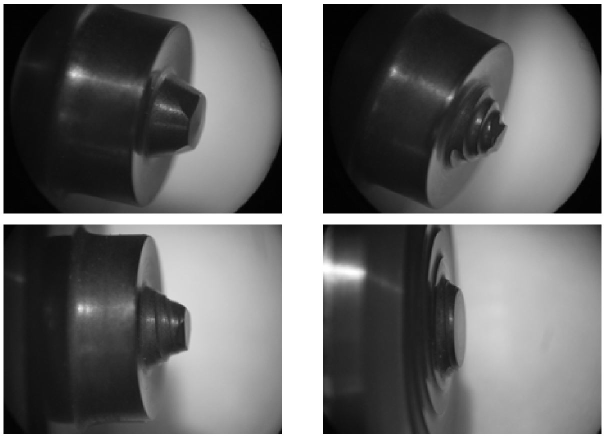

Figure 9. Initial phase 2 tools.

Tool Wear

Several hundred welds have been performed on the PCBN tool shown in the upper left part of Figure 1. No visible wear has occurred on the tool. More detailed and quantified wear studies are currently underway. Tungsten 25% rhenium tools, however, have shown significant wear. It is not yet clear if this is due to incorrect process parameters for this tool material (overload due to different thermal conditions) or if some kind of surface reaction or high friction condition is occurring between the W25Re and the steel base materials. The W25Re is under study for surface reactants currently to see if tool interaction with the work piece is at the core of the wear problem.

Conclusions

Friction-stir spot-welds were made on a two-high stack-up of DP780 and some initial trials on HSBS steel using polycrystalline cubic boron nitride tools. Three tool geometries were initially used, that of a conventional pin tool and two tools with a shoulderless geometry and differing thread pitches. Tool wear appeared negligible. Lap-shear results indicate that reasonable strengths can be obtained and that strength is highly dependent on tool design and process parameter. Phase 2 of this work will continue to investigate new tool designs and parameter development in an effort to increase the bonded area and increase the lap-shear strength. Phase 2 will also include the following scope:

- Other factors critical to industrial implementation will be investigated including total spot cycle time, tool wear and robustness as a function of changing weld parameters, tool life, and the process of transferring optimized process parameters to a robotic system
- Both process and fundamental models will be developed to predict weld performance with changing process conditions
- Assess the potential for in-process NDE
- Establish the framework of a design database for spot-friction-welded structures.