G. Friction Stir Joined Aluminum Sheet Materials for Heavy Vehicle Cab Structures

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Objective

- Develop and deploy friction stir joining (FSJ) as a weight and cost-saving manufacturing technology for heavy vehicle cab structures.

Approach

- Demonstrate the use of aluminum tailor-welded blanks (TWBs) for heavy vehicle applications.
- Develop weld process parameters to lower manufacturing cost, increase joint reliability, and explore dissimilar material blanks that can afford additional weight savings.
- Develop and prototype lightweight, cab-in-white structures including door inners, door opening panels, back-wall, and floor structures for Class 7-8 trucks using FSJ technologies.
- Address manufacturing issues to lower blank fabrication cost and other barriers to implementation of Al TWBs.

Accomplishments

- Developed process parameters and joining conditions to fabricate blanks in several similar and dissimilar aluminum alloys that were subjected to stamping trials.
- Characterized the local mechanical properties of the weld metal and surrounding region of AA5052-H32 and AA5182-O TWBs to understand the effect of the welding process on the ductility of the weld metal.
- Investigated new part configurations, using thin-gage heat-treatable alloys and dissimilar alloy combinations (5000 and 6000 series aluminum TWBs).
- Constructed three, full-scale Class 8 truck cabs using friction stir welded TWBs for the door inners, door opening panels, backwall, and floor.
- Passed full scale crash and durability testing for the constructed cabs (no weld related structural failures were observed).

- Investigated the interaction between the weld in the TWB and the joining method used to assemble the blank into the vehicle and determined how this interaction influenced long-term vehicle durability and crashworthiness.
- Developed welding process parameters to minimize cost and maximize performance of truck components.

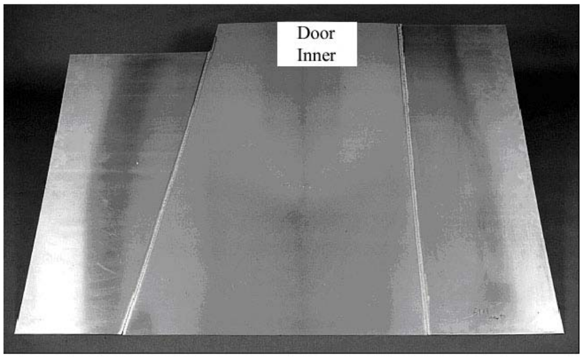
Future Direction

- Continue with the weld process and tool development for dissimilar alloy combinations and hard alloys (6xxx, 5xxx H3x, etc.) that would employ greater cost and weight savings.
- Develop and optimize the welding process parameters of dissimilar aluminum alloys of different thicknesses (5182-O and 6022 aluminum alloys).
- Conduct a design of experiments on tool development and process design for high speed welding (+150 inches per minute) to decrease cost parity with monolithic sheet stampings.
- Focus on friction stir joining as a low-cost enabler of lightweight, low-cost vehicle assembly (non-TWB).

Introduction

This work is a collaborative effort between Pacific Northwest National Laboratory (PNNL), Freightliner, LLC, Advanced Joining Technologies, Inc., Drive Automotive, and Alcoa. This project aims to develop and deploy FSJ as a weight and cost-saving manufacturing technology for heavy vehicle cab structures. To date, the project has focused on 1) developing the appropriate FSJ process parameters to create high-reliability joints that survive stamping operations; 2) prototyping full cabs using FSJ technologies and testing for durability and crash performance; and 3) addressing manufacturing issues including lowering blank fabrication cost and other barriers to implement the technology. The challenge is to develop stamped panels that can meet the unique strength and durability requirements of heavy vehicle cab structures.

Aluminum TWBs consist of multiple-thickness and multiple-alloy sheet materials welded together into a single, variable-thickness blank. Figure 1 shows a typical fusion-welded TWB before and after a stamping application. A TWB is assembled as a series of flat sheets joined together, which are then submitted to a stamping process. The technology allows production of a weight-optimized, variable-thickness vehicle body component. TWB technology gives automotive and truck designers the ability to selectively vary body panel thickness to optimize the use of material. Successful use of the technology ultimately results in reducing vehicle weight without compromising final strength, stiffness, and durability. The manufacture of TWBs and their application in body panels requires that the weld material deform under biaxial loading during sheet metal stamping. The deformation of weld materials and their limits of formability are important aspects of TWB technology.



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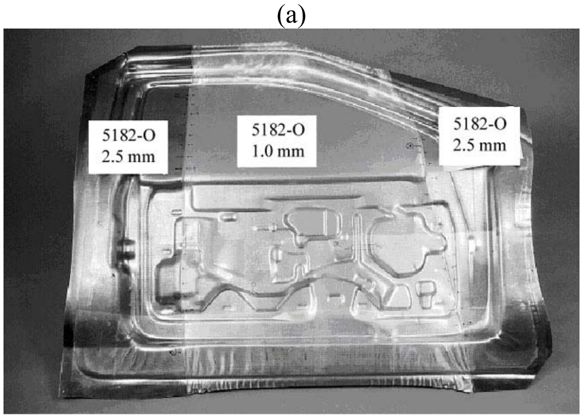


Photos courtesy of Reynolds Metals Company and Ogihara America Corp.

(b)

Figure 1. (a) A TWB viewed in the as-welded condition, ready for submission to the stamping process. The shape shown is typical for a door inner stamping operation. (b) Aluminum TWB after stamping to produce a door inner panel.

The primary challenge of using aluminum TWBs in the past has been the relatively low ductility of aluminum fusion welds, which often results in premature fracture or lack of reliability of weld materials during stamping. Improving aluminum weld quality, understanding and describing the formability of the weld region, and predicting its formability are the primary technical challenges in using aluminum TWBs.

FSJ is a revolutionary joining technology that employs severe plastic deformation to create solid state joints between wide varieties of different materials. Invented by TWI, Ltd., about 12 years ago, FSJ is capable of producing aluminum alloy welds as good as (or significantly better than) fusion welds in terms of joint efficiency, mechanical properties, and environmental robustness. The advantage of using this solid state joining technique is the ability to avoid liquid metal during joining, where aluminum has low molten viscosity, high reflectivity, and a relatively high propensity to form internal porosity because of the high solubility of hydrogen in liquid aluminum.

Friction stir welding (FSW) can also eliminate hot cracking and minimize heat-affected-zone (HAZ) issues in 6000-series heat-treatable aluminum alloys. Avoiding the liquid phase of the materials also avoids the formation of various large eutectic constituent particles or other undesirable intermetallic particles that develop in particular alloys or with certain types of weld or materials contamination.

The use of FSW also better facilitates welding of heat-treatable materials, since the HAZ is normally smaller or less pronounced compared with fusion welding. The use of solid state joining enables a variety of types of dissimilar aluminum alloy joining not normally possible using fusion welding methods. The goal of producing a highly formable weld joint may be achievable with friction stir welding because of the wide range of weld heat, plastic work, and weld metal grain size manipulation that is possible.

FSJ Process Parameter Development

In a previous feasibility study, some alloy combinations were successfully stamped from TWBs fabricated by FSJ. However, weld line failures occurred in many other alloy combinations. The main thrust of this program is to better understand the weld process, forming parameters, and performance characteristics of TWBs and to apply them to a wider range of cab components. The use of FSJ to produce TWBs may result in dramatically improved weld quality and formability of aluminum TWBs —thereby enabling this weight and cost-saving technology.

In order to develop and use FSJ to make high-quality aluminum TWBs for intermediate- and high-volume truck applications, the FSJ process must be competitive with laser welding and other fusion welding technologies from a production rate perspective. The target weld speeds are 2–5+ meters/minute. The friction stir welds must also be significantly higher in formability compared with conventional fusion welds.

This project will develop process parameters to make successful welds in the following weld combinations, as they are representative of typical truck alloys and material thicknesses:

- 5182-O 2 mm to 5182-O 2 mm
- 6022-T4 2 mm to 5182-O 1.6 mm
- 6022-T4 2 mm to 5182-O 2 mm
- 5182-O 2 mm to 6022-T4 1.6 mm
- 5182-O 2 mm to 5182-O 1.6 mm
- 6022-T4 2 mm to 6022-T4 1.6 mm
- 6022-T4 2 mm to 6022-T4 2 mm
- 5052-H111 1.27 mm to 5052-H111 1.27 mm
- 5052-H32 1.6 mm to 5052-H32 1.6 mm

This project will determine, within the "defect-free" process window, where a set of parameters exists that produces a TWB with the best formability (see Figure 2). Within that process window, an optimum set of parameters exists for forming and stamping, and those conditions may not necessarily be the best for other properties (ultimate strength, etc.). The process and forming parameters are being developed by FSW test coupons at a range of weld conditions, which are then subsequently tested for strength and formability to establish optimum weld conditions for each material and thickness combination of interest.

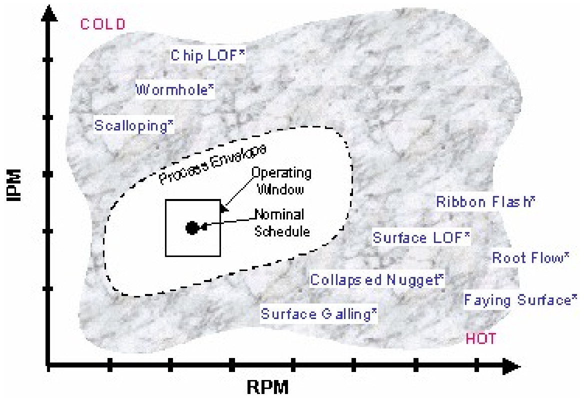


Photo courtesy of Bill Arbegast, SDSMT

Figure 2. An illustration of the process parameter window to determine the optimum set of parameters that produce a TWB with the best formability.

Limited Dome Height Testing

Limited dome height (LDH) testing and miniature tensile testing has shown that welded blanks with the highest dome heights can be correlated with those that have minimal property gradients across the weld zone. Minimal property gradients delay the onset of necking instability. Changes in process parameters will change the local mechanical properties and provide a way to "customize" the weld to the parent sheet. Picking process parameters that match flow stresses between the sheet and the weld zone may be a strategy to increase stamping performance.

A typical process parameter matrix is shown in Table 1. In this case, data is shown for a TWB with 5182-O, 2mm thick material on one side of the weld, and 6022-T4, 1.6mm thick on the other. Similar matrices were compiled for other material combinations but are not presented here. This data is sorted on decreasing LDH height at failure, and includes notes on the failure style. It can be seen that for this material combination at a weld travel speed of 75 inches per minute (ipm), the tested LDH height was 0.583 in. Higher dome heights were achievable with increasing traverse speeds up to 150 ipm, however, above 150 ipm, the dome heights dramatically decreased. At a travel speed of 275 ipm, the weld split easily at low load indicating a very poorly consolidated weld. From this data, based on LDH testing, 150 ipm at 2000 rpm are inferred to be the optimum welding parameters for this tool and welding conditions.

Table 1. Example test matrix – 5182-O 2mm joined to 6022-T4 1.6mm

	Travel Speed (IPM)	*Rotation Speed (RPM)*	*LDH Height (in.)*	*Failure Type*
Weld 4.2	150	2000	0.624	Failed in thin sheet (6022), parallel to weld, right on weld
Weld 4.4	100	2000	0.598	Failed in thin sheet (6022), parallel to weld, 0.1" from weld
Weld 4.1	125	2000	0.589	Failed in thin sheet (6022), parallel to weld, 0.1" from weld
Weld 4.3	75	2000	0.583	Failed in thin sheet (6022), parallel to weld, 0.15" to 0.2"
Weld 4.5b	175	2000	0.533	Failed in weld, parallel to weld, off centerline on retreating side
Weld 4.6b	200	2000	0.510	Failed in weld, parallel to weld, on centerline
Weld 4.7b	250	2000	0.428	Failed in weld, parallel to weld, on centerline
Weld 4.8b	275	2000	N/A	Failed early in test, "unzipped" on centerline at low load
Weld 4.9b	300	2000	N/A	Failed early in test, "unzipped" on centerline at low load

From the LDH data, process maps can be constructed like that shown in Figure 3. For welded blanks with 5052-H111 on both sides of the joint (and similar thicknesses), good LDH performance relative to an unwelded blank is achievable at generally higher tool rotation speeds. Also, welded blank dome heights 90% as high as monolithic (unwelded) sheets can still be achieved at traverse speeds up to 130 ipm.

In a manufacturing environment, high weld traverse speeds are important for good throughput. One objective of the process parameter development program was to see how LDH results varied with increasing weld speeds up to the limits of the experimental setup or process. Maximum weld traverse speed is very much a function of tool design, so the results obtained in this study only reflect the maximum weld speeds for the single tool used in this study. Figure 4 shows that for 5052-H111 a region exists where enhanced LDH results can be achieved if some tradeoff in ductility can be tolerated. The best dome heights are found at the slower traverse speed for welds made at both

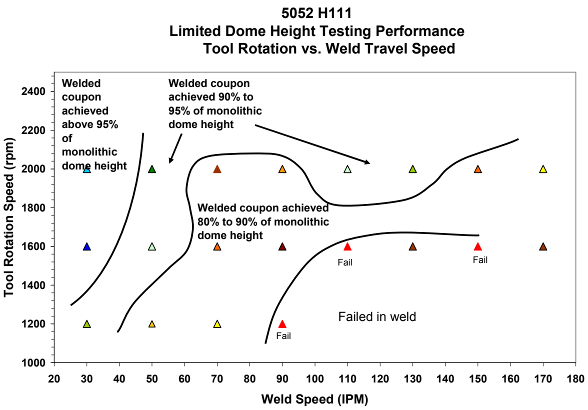
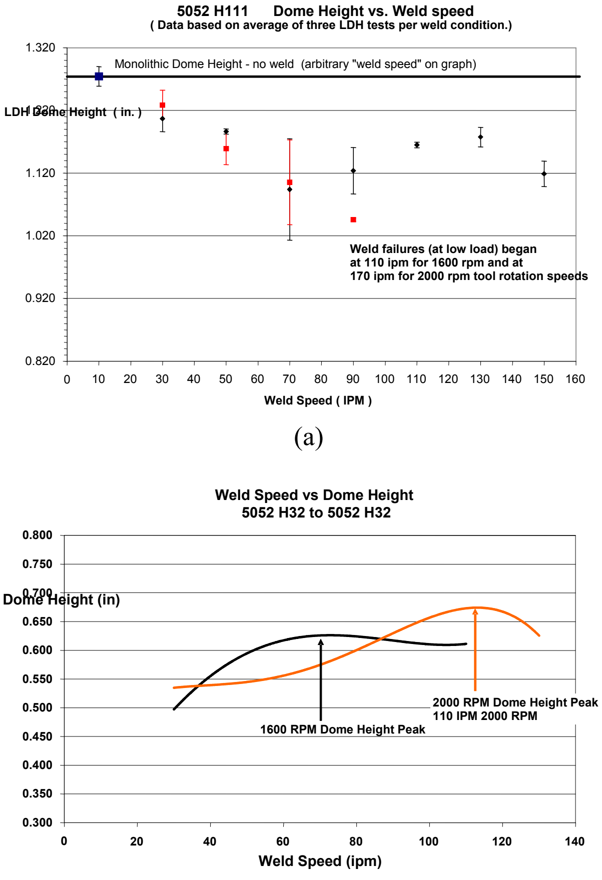


Figure 3. Process parameter map showing how a welded blank with 5052-H111 material on each side of the weld compares to a monolithic (unwelded) sample of the same material. The data is grouped by the percentage of monolithic dome height achieved by the welded assembly.



(a)

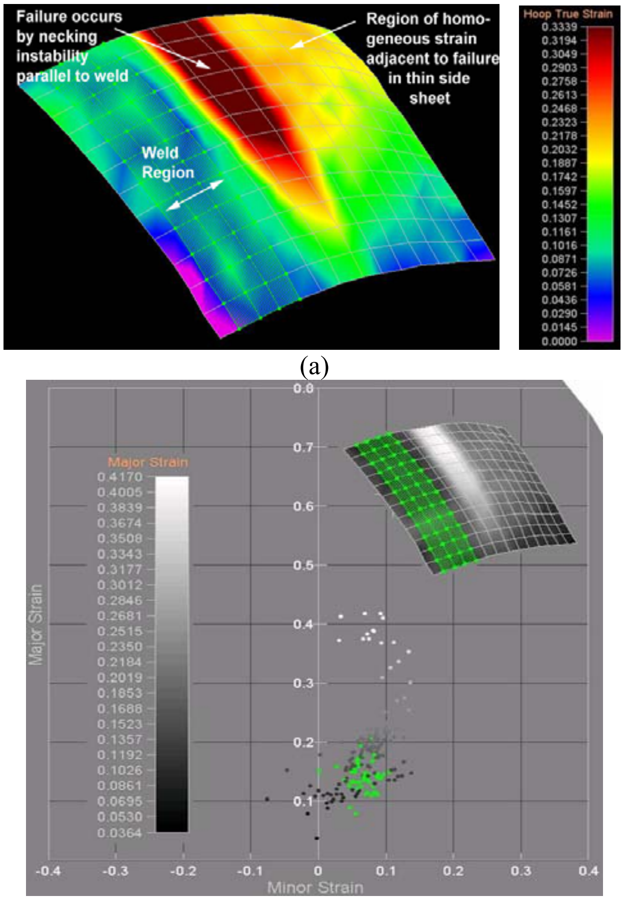
(b)

Figure 4. Dome height vs. weld speed for 5052 alloys. (a) Results of 5052 in an H111 temper, and (b) results for a H32 temper. Both tempers show enhanced ductility at high weld speed.

1600 rpm and 2000 rpm. However, for 2000 rpm a region exists around 120 to 130 ipm where ductility again increases. The reason for this is not clear, but it occurs in 5052-H111 as well as 5052 when it is in a work hardened, H32 temper. These formability “sweet” spots indicate some favorable balance of input heat, time at temperature, conduction, HAZ development, and nugget microstructure can combine to create favorable ductility, even at high process speeds. This study was limited to a maximum rotation speed of 2000 rpm, but the process maps suggest even higher rotation speeds may produce favorable results.

Once process parameters are established, maximum strains can be analyzed using optical techniques. In order to help predict the stamping performance of a FSW joined TWB, surface strains can be measured and midplane strains can be calculated for LDH specimens tested to failure. Post test strains developed in the specimen can be measured in the weld, the heat affected zone, and the parent sheet. The specimens tested during this study were full width LDH that undergo approximately equal biaxial stretching near the top of the specimen, and a complex and changing strain history in the region between the punch and the circular lockbead. A post-test strain analysis reveals only the final strain distribution from a sample that has had each material point follow a complex strain path. However, strain analysis of LDH specimens can provide data that correlates well with stamping trials and gives an indication of the maximum strains that will be achievable during biaxial stretching.

Figure 5 shows results from typical strain analysis. These results are from an LDH specimen taken to failure that has 5182-O 2mm on the left side of the FSW joint and 5182-O 1.6 mm on the other. The failure occurred by necking instability parallel to the weld about 0.2 inches from the weld edge in the thin side sheet. The region immediately adjacent to the necked zone showed a uniform major strain of about 18 to 21%. This is the maximum homogeneous strain to which this welded blank can be subjected at failure. This data and the Forming Limit Diagram in the lower part of Figure 5 can be used to estimate limit strains for finite element analysis of different die designs, and can help in part design and joint placement for stamping trials.



(a)

(b)

Figure 5. **(**a) Optical strain grid analysis of an LDH specimen of 5182-O 2mm joined to 5182-O 1.6 mm. FSW weld region is cross hatched on left side of specimen. (b) Forming limit diagram showing the distribution of strain near the failure.

Mechanical Property Gradients

Optical strain analysis on tested specimens can only provide data on the final strain distribution in the assembly. In order to effectively model the performance of a blank in a die design, data is needed on local property variation. Microhardness variation in cross section can be used to infer property gradients, but requires assumptions on the relationship between microhardness and yield stress. Miniature tensile testing is a useful, although time consuming, technique to determine the flow curves for each region of a heterogeneous assembly.

Tensile testing of miniature specimens produces the flow curves seen in Figure 6. Figure 7 illustrates the specimen design. For blanks with 5182-O on both sides of the FSW joint, the flow stress of the weld metal is very close to the flow stress of the parent sheet and displays a similar hardening profile. There is a slight increase in flow stress in the weld metal especially on the top side of the weld, but it is not large. The similarity of the flow curves is due to the fact the parent metal is already in a soft condition (O temper) and additional weld heat did not create additional softening.

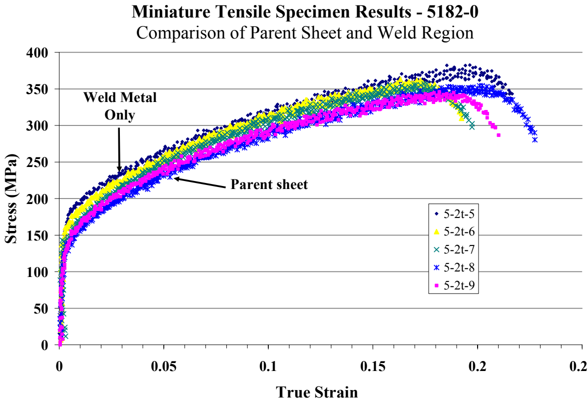


Figure 6. Flow curves for miniature specimens taken from weld metal and parent sheet at increasing distance away from the weld edge in 5182-O.

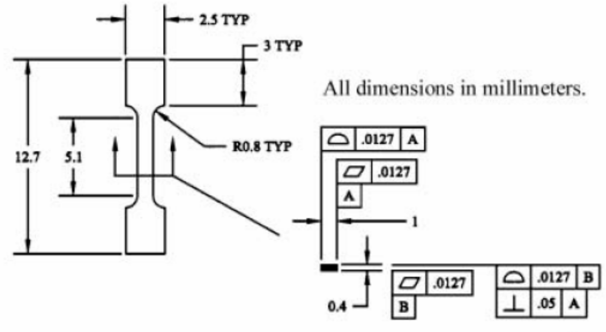


Figure 7. Miniature tensile specimen dimensions.

These results illustrate there is little effect on ductility due to the welding process. This feature is very important for producing a homogeneous distribution of strain in response to stress during stamping. Minimizing strain gradients is an important strategy to prevent early flow localization and failure during stamping.

In contrast, friction stir (or any joining process that introduces heat) can be challenging for later forming if the mechanical properties of the weld metal differ significantly from the parent material. Figure 8 shows the results of miniature tensile tests on specimens taken from a FSW joined blank of 5052 in a work hardened condition (H32). The weld metal has a significantly lower flow stress than the parent sheet due to the recrystallization in the nugget. The effects of partial annealing of the work hardened condition in the thermal mechanical affected zone can also be seen by the slight decrease in yield as the weld edge is approached from the parent sheet. Interestingly the ultimate strength of the weld nugget is higher than the parent sheet, and the ductility is, of course, significantly higher than the harder H32 material (Figure 9).

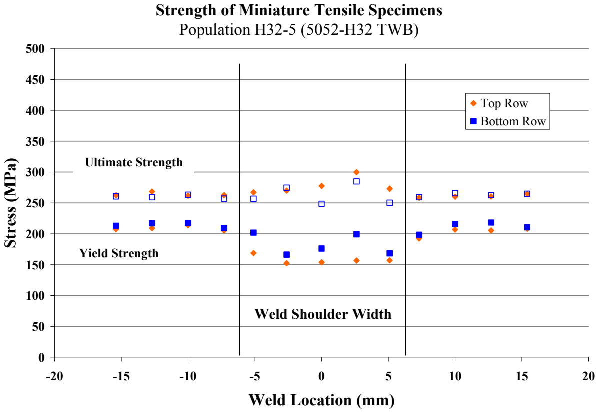


Figure 8. Yield and ultimate strength variation across a FSW in 5052-H32.

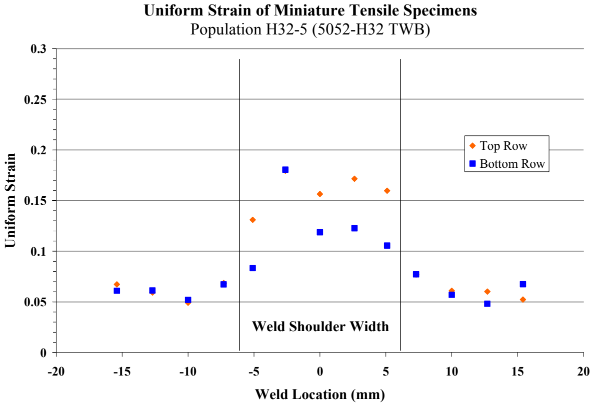


Figure 9. Local ductility of weld metal and adjacent parent material in a 5052-H32 welded assembly.

Stamping Trials and Assembled Cabs

When the weld process parameters were optimized for the material combinations investigated in this project, Advanced Joining Technologies, Inc. fabricated the blanks and the FSJ welded blanks were subsequently stamped by Magna utilizing conventional dies. Figure 10 illustrates several of the cab-in-white structures fabricated.

While many material combinations were successfully stamped, others, which would have had strong manufacturing arguments (cost and weight savings), were not successfully stamped. During stamping, some were less robust, especially hard alloys and some dissimilar material joints. For

(a)

(b)

Figure 10. Photos of stamped friction stir welded TWB cab structures. (a) Door inner panel. (b) Door opening panel.

example, joints in 5182-O had excellent formability performance, but joints in 5052-H32 sheet failed in the stamping trials. The weld metal in 5052-H32 has a significantly higher strain at failure (from the fine-grained, recrystallized nature of the nugget) than the parent sheet, leading to early localization in the weld metal. More process development is needed for 5052-H32 to enhance its stamping reliability.

For the successfully fabricated blanks in several similar and dissimilar aluminum alloy sheet combinations, the friction stir welded TWB stamped panels were shipped to Freightliner and assembled into three full-sized Class 7-8 cabs. Cabs were tested for durability (shaker table) and crash performance by Freightliner. The assembled cabs passed full scale crash and durability testing with no weld related structural failures observed.

Manufacturing Concerns

Ultimately, these TWBs need to be assembled into a vehicle, and the interaction between the weld in the TWB and the joining method used for assembling the blank into the vehicle needs to be understood. Automotive designers need to know whether these joints are within the target joint strengths for a particular application. In this project, the interaction of a friction stir welded 1.6 mm 6022-T4 and 2mm 5182-O TWB joined to 2mm 5182-O monolithic sheet material by a self-piercing rivet was investigated to determine how the interaction between the rivet and the friction stir weld in the TWB may influence long-term vehicle durability and vehicle crash worthiness.

First, a preliminary evaluation to determine the position of the rivet in the joint that yielded the weakest joint strength was conducted. Then, a more thorough investigation of the weakest joint configuration to determine the structural integrity and performance of the joint was conducted. Figure 11 illustrates the joint assembly and Figure 12 shows the cross section of one of the joint configurations investigated. Uniaxial tension tests were performed on lap shear and cross tension coupon assemblies to characterize the joint strength and the total energy absorption capability of the friction stir welded TWB/monolithic sheet self-pierce riveted joints.

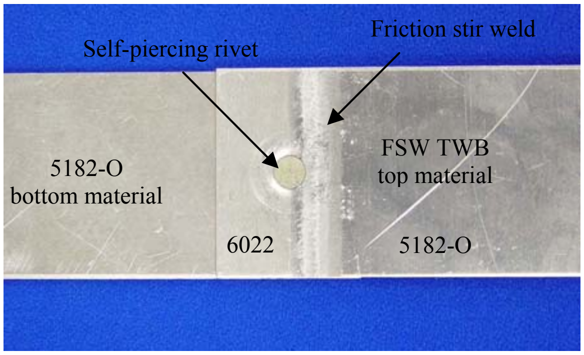


Figure 11. Photo of a friction stir welded AA6022-T4 and AA5182-O TWB (top material) joined to AA5182-O (bottom material) by a self-piercing rivet.

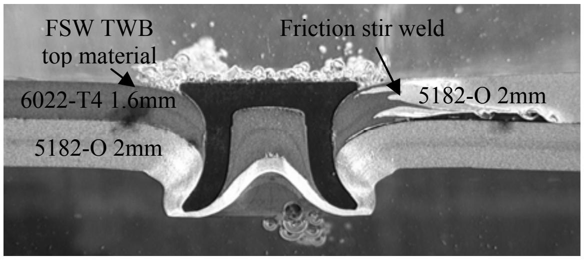


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Figure 12. Photograph illustrating the cross section of the joint assembly where the SPR is piercing through the 6022-T4 sheet in the HAZ region of the TWB.

In this investigation, piercing through the heat-affected zone in the friction stir weld and through the thinner material (1.6mm 6022-T4) of the tailor welded blank exhibited the weakest static strength in comparison to piercing through the weld center and weld edge through the 2mm 5182-O sheet of the TWB. The heat-affected zone region in the 6022 sheet in the blank also had a dominant affect on the fatigue failure and failure location of the TWB/ monolithic sheet joints. In addition, the significant difference in sheet thickness of the blanks (20% thickness difference) is a contributing factor to the performance results observed. Essentially, this study suggests that it is best to avoid the weld region, particularly the HAZ in the thinner material of the TWB, if possible, during the assembly process. Details of this study are presented in *SAE Special Publication SP-1959*.

Conclusions

From this investigation, the following conclusions were derived:

- Friction Stir joining is suitable for fabricating aluminum TWBs.
- Weld speeds can be very high (up to 130 inches per minute using the tools in this study) and still produce good performance in LDH testing. Process maps suggest higher rotation speeds may allow even higher travel speeds (this study was limited to 2000 rpm rotation speed).
- Process parameters can be established through experimental programs that lead to joints that show up to 96% of the unwelded parent metal ductility.
- The FSJ process is "customizable" for mechanical properties and the weld process parameters can be optimized for formability.

Presentations and Publications

1. "Evaluation of the Mechanical Performance of Self-Piercing Rivets in Friction Stir Welded Structures" presented at Society of Automotive Engineers 2005 World Congress, Detroit, MI, April 13, 2005.

2. "The Formability of Friction Stir Welds in Automotive Stamping Environments" presented at Society of Automotive Engineers 2005 World Congress, Detroit, MI, April 13, 2005.

3. "Friction Stir Joined Aluminum for Heavy Vehicle Cab Structures" presented at 21st Century Truck Partnership Project Review Meeting, Oak Ridge, TN, September 14, 2005.

4. Grant, GJ, et al. 2005. "The Formability of Friction Stir Welds in Automotive Stamping Environments." SAE Special Publication SP-1959, SAE International, 141-151.

5. Stephens, E.V., et al. "Evaluation of the Mechanical Performance of Self-Piercing Rivets in Friction Stir Welded Structures." SAE Special Publication SP-1959, SAE International, 153-158.