B. Forming Limits of Weld Metal in Aluminum Alloys and Advanced High-Strength Steels

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Objective

- Develop, validate, and disseminate a combined experimental and numerical method to statistically describe and systematically quantify the forming limits of welded aluminum (Al) alloys and advanced high-strength steels (AHSSs).

Approach

- Develop a standard tool for weld process development that will systematically quantify failure probabilities during forming.
- Provide accurate and standardized methods of experimentally characterizing weld-metal formability using unique, but simple, test methods available on the shop floor.
- Provide predictive models for more accurate forming simulations of tailor-welded blanks (TWBs) and hydroforming operations. Predict parts-per-thousand failure rates during production from finite-element analysis (FEA).
- Characterize static/fatigue properties and forming behavior of several weld populations and correlate with statistically-based tool.

Accomplishments

- Incorporated digital image correlation (DIC) or speckle pattern interferometry strain evaluation method to study the details of localization in uniaxial and biaxial testing.
- Completed uniaxial experiments of welded material populations (friction-stir-welded (FSW) AA5182-O to AA5182-O, FSW AA5182-O to AA6111-T4, laser-welded (LW) DP600 to DP600, and LW DQ to DQ steel).
- Completed biaxial experiments of welded-material populations.
- Completed metallography and weld-microhardness measurements of welded-material populations.

- Completed miniature tensile tests of specimens removed from the FSW weld zones of the 5182 and 5182 to 6111 welded-alloy populations.
- Completed probabilistic-based forming-limit predictions for DP600 and AA5182-6111 welded alloys.

Future Direction

- Further investigate a combined forming-limit prediction for DP600 and AA5182-6111 welded alloys.
- Increase focus on biaxial experiments.
- Quantify the combined forming-limit diagram (FLD) using the statistical approach.
- Implement new testing approach for AA5182-O to AA5182-O welded alloys to biaxial limited-dome-height tests.

Introduction

This work is a collaboration effort between DOE, Pacific Northwest National Laboratory (PNNL), a USAMP team of the U.S. Council for Automotive Research (USCAR), US Steel, Olympic Controls and Alcoa. This project will develop, validate, and disseminate combined experimental and numerical methods that systematically quantify the forming limits of weld materials in Al alloys and AHSSs through a combination of experimental and deformation-modeling analyses. This work will enable high-volume, robust deployment of tailor-welded blanks (TWBs), seam-welded tubes, and tailor-welded tubes in emerging materials. Figure 1 is a schematic of the project.

The deformation of weld materials and their limits of formability are important aspects to both TWB and hydroforming technologies. The conventional low-carbon steels used in automotive applications are easily fusion welded using conventional technologies, and suffer no appreciable strength degradation near the weld. Al alloys are more difficult to weld than low-carbon steels due to high conductivity and reflectivity, and low molten viscosity. They have a high propensity for porosity to form during fusion welding, as well as hot cracking and heat-affected-zone (HAZ)-related issues in heat-treatable Al alloys. Many of the AHSSs that are finding increasing application in the automotive industry suffer from degradation of

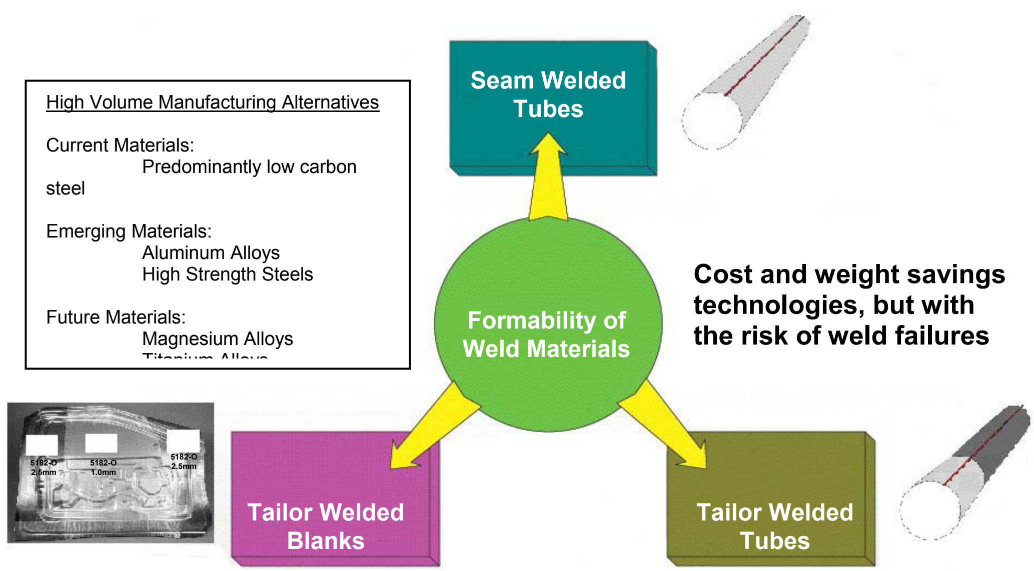

Figure 1. A schematic of the formability-of-weld-materials project.

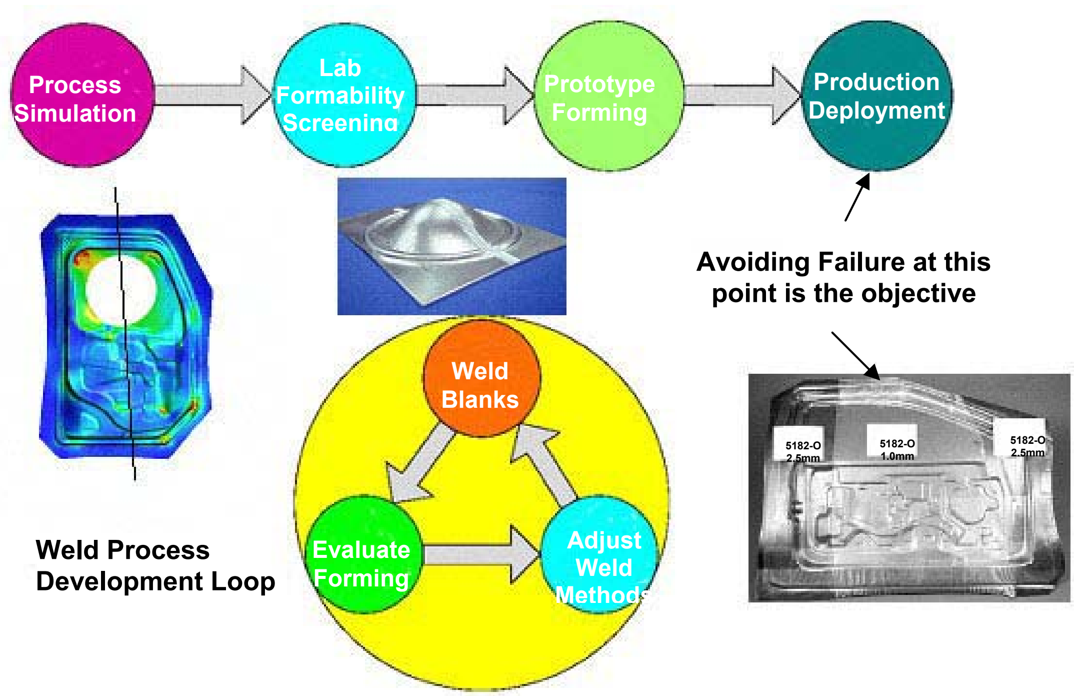

Figure 2. A schematic of the typical manufacturing process development.

strength in the HAZ. Furthermore, nearly all fusion welds suffer from irregular geometries and elevated levels of surface roughness compared to the parent materials, which also influence formability and component performance.

This project will focus on developing a generalized numerical method to predict material-forming limits in weld materials and verifying deformation and forming-limit predictions. The approach will rely on developing standardized test methods for weld-material populations to establish a statistical description of material imperfection and mechanical properties in their weld region, and developing statistically-based forming-limit diagrams or continuum damage models that predict material failure in the weld region.

The project will include numerical model development, validation, and supporting experiments. A number of candidate weld methods will be examined in combination with selected Al alloys and AHSSs. The project materials will include 5000 series and 6000 series Al alloys and relevant AHSSs including high-strength low-alloy (HSLA), transformation-induced plasticity (TRIP), and dual-phase steels. The selection of sheet materials and welding methods will be coordinated with the participating OEMs and will be representative of high-volume, commercially-viable materials and processing technologies.

The deliverables will include a standard procedure for weld-material evaluation coupled with a numerical approach for establishing weld-region forming limits. The results will also allow evaluation and development of candidate weld processes and the interaction between materials and weld parameters. The overall objective is to develop test methods and experimental results to enable wide-spread deployment of weight-optimized TWB and tube hydroforming and to avoid weld failures during production. Figure 2 is a schematic of the typical manufacturing process development.

Experimental Characterization

The experimental characterization of the second program year has focused on incorporating digital image correlation as a strain-evaluation method, continuation of uniaxial testing with the simple geometric specimen design, and biaxial testing. The TWB material combinations evaluated were LW DP600 to DP600, LW DQ to DQ, FSW AA5182-O to AA5182-O, and FSW AA5182-O to AA6111-T4 with greater emphasis on the DP600 and AA5182-6111 welded alloys.

Strain Characterization Utilizing Digital Image Correlation

During this reporting period, digital image correlation (DIC), or speckled pattern interferometry, has been applied for use with uniaxial tests and biaxial limited dome-height formability tests. DIC is a data-analysis method which uses an algorithm to analyze digital image data taken when a sample is subjected to mechanical strain. Displacement and strain are measured. This technique uses white-light speckle correlation, where two similarly speckled images captured by a video camera represent the state of the object before and after deformation. Consecutive images are captured during testing and the image correlation will register a change in surface characteristics as the specimen is affected by stresses imposed upon it. The actual object movement is measured and the Lagrangian strain tensor is available at every point on the surface.

This technique will help us further understand strain localization in a non-homogenous gage such as a weld. We are able to track strain localization and strain variation of the welded parts during forming. For example, Figure 3 illustrates the strain rate results from the DIC analysis during uniaxial testing of a LW DP600 longitudinal specimen. Four levels of deformation are shown. The faint line in the illustrations is the weld. Localization occurs when the local strain rate is much greater than the overall specimen strain rate. In this specimen, as in all the other longitudinal DP 600 specimens, we observe the strain rate localizing in the weld just prior to failure.

Uniaxial Experimental Testing

Continuation of the uniaxial tests occurred this reporting period where rectangular specimens were designed with the weld oriented either longitudinal or transverse to the tensile axis as shown in Figure 4. Thirty longitudinal and thirty transverse specimens were made for each welded TWB material combination. All specimens were etched with square grids to determine the incipient necking condition utilizing optical strain grid analysis (a more

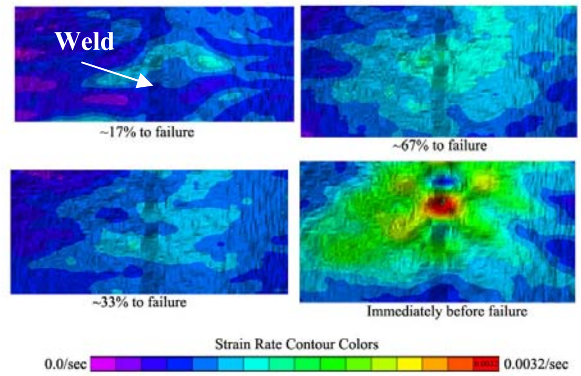

Figure 3. The strain-rate results from the DIC analysis of a longitudinal LW DP600 specimen at four different levels of deformation during uniaxial testing.

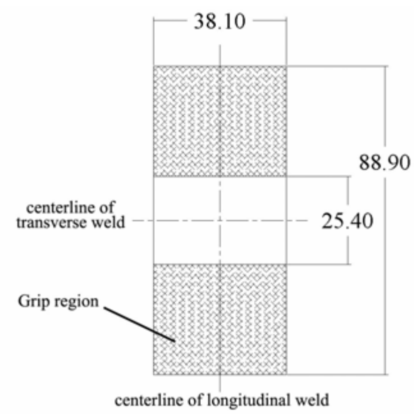

Figure 4. Uniaxial specimen design for longitudinal and transverse specimens. Measurements in millimeters.

conventional method in addition to DIC). All tests were stopped after an 8% drop in load.

Microhardness testing was performed on a cross-section of the LW DP600 weld. The microhardness test measurements show that the weld is considerably harder than the parent sheet with a minimum HAZ (Figure 5). All thirty uniaxial DP600 longitudinal specimens failed in the weld. All thirty of the transverse specimens failed in the thin sheet away from the weld and weld region (HAZ). Localization occurs in the weaker thin sheet. Failure is determined by the weld properties in the longitudinal DP600 welded specimens, where as failure is determined by the properties of the thin parent sheet material in the transverse specimens.

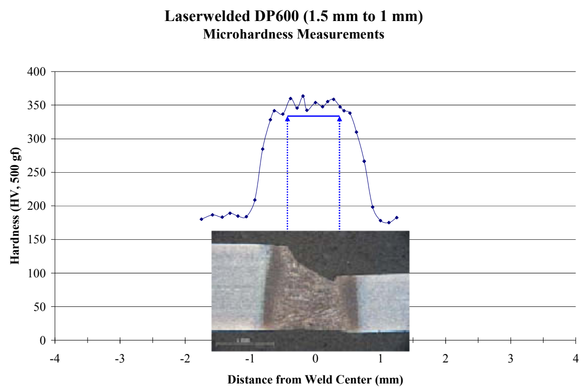

Figure 5. Microhardness test measurements of the DP600 welded alloy.

For the 5182-6111 friction-stir-welded alloys, all thirty longitudinal specimens failed in the weld and twenty-nine of the thirty transverse specimens failed in the HAZ of the thin sheet 6111 material. Miniature tensile tests performed on specimens removed from the weld and weld region indicated the weld material to be a strong, yet less ductile, material in comparison to the parent sheets (Figure 6) and weaker in the HAZ. A depression in strength was observed in the HAZ

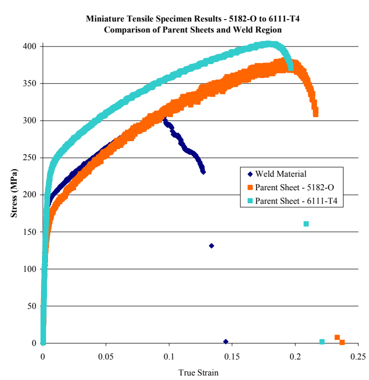

Figure 6. The stress-strain curves of the parent materials and weld material of the 5182-6111 TWB.

In this welded-alloy combination, failure is determined by the weld properties in the longitudinal specimens, where as failure is determined by the HAZ of the thinner 6111 material in transverse specimens.

For the FSW 5182 welded alloys, twenty-nine of the thirty longitudinal specimens failed in the grip region and all thirty transverse specimens also failed in the grip region. Miniature tensile tests performed on specimens removed from the weld and weld region indicated the weld material to be just as ductile and strong as the parent sheet. Minimal mechanical property gradients across the weld and weld region were observed. Further testing approaches need to be investigated.

Biaxial Experimental Testing

Biaxial limited dome-height tests were performed on the DP600 and 5182-6111 welded alloys. Both full domes and 4-inch-wide domes were tested, with a minimum of five specimens tested for each condition. Full dome tests were also conducted on the parent sheet materials for the two TWB combinations. Both optical strain grid analysis and DIC was used to evaluate the specimens. Figure 7 is an illustration of the DIC analysis for a full- dome DP600 welded specimen.

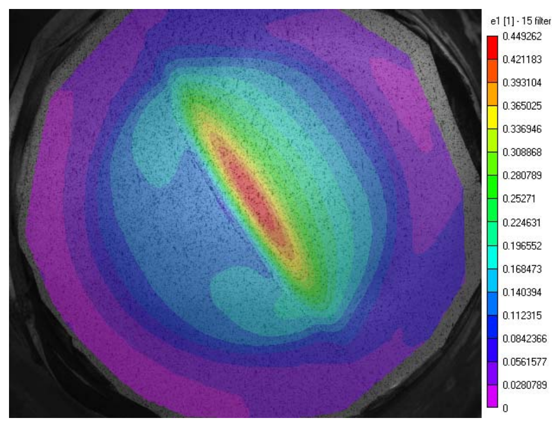

Figure 7. An illustration of the DIC strain data just prior to fracture on a LW DP600 limited dome-height test.

For the DP600 welded specimens, all full-dome biaxial tests failed in the thin sheet parallel to the weld. All 4-inch-width domes failed in the weld, transverse to the weld.

For the 5182-6111 welded specimens, all full-dome biaxial tests failed in the weld; however, two different failure modes were observed. The specimens either failed in the weld, longitudinal to the weld, or failed in the weld, transverse to the weld with the crack propagating into the thin sheet 6111 material. In the 4-inch-width dome tests, all specimens failed in the weld, transverse to the weld.

M-K Method to Predict Formability

Forming-limit diagrams for the DP600 and 5182-6111 TWBs were generated using a Marciniak-Kuczynski (M-K) method approach. The M-K model can track the development of plastic strains in the monolithic sheet and the weld materials under applied external loading. The model also tracks the evolution of imperfections and predicts localization and failure of the specimens.

Theoretical FLDs are generated based on uniaxial tensile results and statistical probability. The level of imperfection *f* that must exist in the specimens in order to describe the formability for each of the thirty longitudinal specimens is determined. A Weibull probability distribution is then applied to describe the longitudinal specimen imperfections and the predicted FLD for the TWBs is generated.

The LW DP600 full-dome biaxial test experiments were compared to the theoretical forming-limit diagram generated. Discrepancies of the model and biaxial experiments were observed, so all test results were combined in a FLD where the strain longitudinal to the weld and the strain transverse to the weld was plotted (Figure 8). The FLD of the parent sheet material (from literature) was also plotted. Figure 8 shows that there is a region in the FLD where the weld will always fail and a region where the sheet will fail. In between is a “gray area” where either the weld or sheet will dictate the failure. A similar methodology was applied to the 5182-6111 welded-alloy population and a similar “gray area” was observed where the weld or HAZ of the thin sheet 6111 material will dictate the failure.

Further investigation of how the FLDs will be suppressed in these “gray areas” is needed including further modification to the forming-limit prediction.

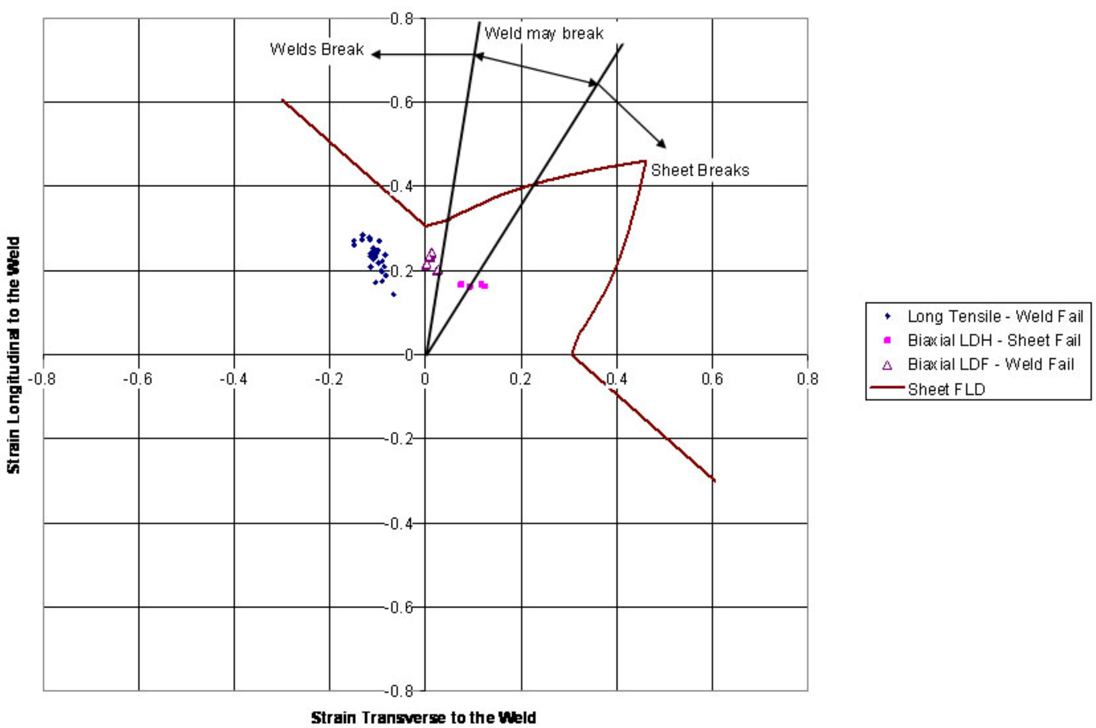

Figure 8. DP600 laser-welded materials combined test results. The FLD for DP600 monolithic sheet is also shown.

Conclusions

From this investigation, the following conclusions were derived:

- In uniaxial tests of LW DP600 specimens, failure is determined by the weld properties in the longitudinal specimens, where as failure is determined by the properties of the thin parent sheet material in the transverse specimens.
- In uniaxial tests of FSW 5182-6111 specimens, failure is determined by the weld properties in the longitudinal specimens, where as failure is determined by the HAZ of the thinner 6111 material in transverse specimens.
- The tensile approach for the FSW 5182 to 5182 welded alloys appeared to be limited for the higher quality welds and a change in testing methodology is needed, possibly to biaxial limited dome height only.
- Further investigation of a combined forming-limit prediction of DP600 and AA5182-6111 welded alloys is needed where the combined FLD is quantified using the statistical approach.

Presentations and Publications

- Davies, RW, et al. 2006. "Forming Limits of DP600 TWBs during Biaxial Stretching." In *IDDRG '2006.*
- "*Forming Limits of DP600 TWBs during Biaxial Stretching*" presented at International Deep Drawing Research Group 2006, Porto, Portugal, June 2006.
- *"Forming Limits of Weld Material in Aluminum Alloys and High-Strength Steels"* presented at United States Automotive Materials Partnership AMD Offsite Annual Review Meeting, Detroit, MI, October 2005.
- *"Forming Limits of Weld Material in Aluminum Alloys and High-Strength Steels"* presented to Industrial Team Advisory Committee, Detroit, MI, October 2005.