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

Project Manager: Richard W. Davies
Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352-0999
(509) 375-6474; fax: (509) 375-5994; e-mail: rich.davies@pnl.gov

Principal Investigator: Frode Stavehaug
Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352-0999
(509) 372-4766; fax: (509) 375-4448; e-mail: frode.stavehaug@pnl.gov

Principal Investigator: Glenn J. Grant
Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352-0999
(509) 375-6890; fax: (509) 375-4448; e-mail: glenn.grant@pnl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Participants
Elizabeth Stephens, Xin Sun, Siva Pilli, Pacific Northwest National Laboratory
USAMP, US Steel, Alcoa, Olympic Controls

Contractor: Pacific Northwest National Laboratory
Contract No.: DE-AC06-76RL01830

Objective

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

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 blank (TWB) 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 tools.

Accomplishments

- Evaluated competing weld specimen designs by FEA for their suitability in providing statistical information on a given weld methodology or population.
- Experimentally validated specimen designs that produced nearly plane-strain deformation across a welded sample from a simple sample geometry and load-frame test set-up.
- In conjunction with the USAMP steering committee, outlined initial weld populations to be studied to test validity of statistical and predictive methodologies.
- Completed uniaxial tensile testing of laser-welded DP600 to DP600 (1.5 mm to 1 mm thickness) TWBs.
- Constructed theoretical forming-limit diagram for laser-welded DP600 to DP600 TWBs.

Future Direction

- Finish the experimental characterization and validation on select weld populations including friction stir welded and laser-welded specimens.
- Continue development of continuum damage models to create predictive failure tools that can be used to estimate the robustness of a given weld population based on plane-strain performance, microstructural features, and other properties.
- Continue development of Digital Image Correlation for TWBs.
- Commence biaxial testing of TWBs.

Introduction

This work is a collaborative effort between DOE's Pacific Northwest National Laboratory (PNNL), 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 aluminum alloys and high-strength steels through a combination of experimental and deformation modeling analysis. This work will enable high-volume, robust deployment of tailor-welded blanks (TWB), seam-welded tubes, and tailor-welded tubes in emerging materials.

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. Aluminum alloys are more difficult to weld than low-carbon steels due to high conductivity and reflectivity, and low molten viscosity. Aluminum also has 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 aluminum alloys. Many of the high-strength steel alloys that are finding increasing application in the automotive industry suffer from degradation of 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 (FLDs) or continuum damage models that predict material failure in the weld region.

The project includes numerical model development, validation, and supporting experiments. A number of candidate weld methods will be examined in combination with selected aluminum alloys and advanced high-strength steels. The project materials will include 5000 series and 6000 series aluminum alloys, and relevant high-strength steel alloys, including high-strength low alloy (HSLA), transformation-induced-plasticity (TRIP), and dual-phase (DP) 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 widespread deployment of weight-optimized TWB and tube hydroforming and to avoid weld failures during production. Figure 1 is a schematic of the typical manufacturing process development.

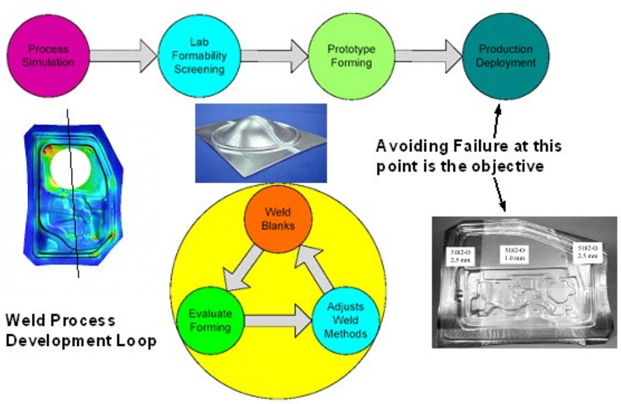


Figure 1. A schematic of the typical manufacturing process development.

Numerical Modeling

During this reporting period, finite element analysis began by first evaluating the forming limits of TWBs. Modeling of TWBs, both aluminum alloys and high-strength steels, is done to aid in the experimental analysis of the deformation of weld materials and their formability limits. A series of tensile tests were modeled and experimentally tested. Initially, a standard ASTM specimen was modeled. The model predicted failure in the thin side of the specimen as expected.

Next, a parametric study was conducted to design a tensile test specimen in which failure would occur in the plane-strain condition. Various length- to-width ratios (not shown here) and several grip dimensions, starting from a regular straight grip to a novel semi-circular grip, were modeled to achieve failure in the plane-strain condition. Figure 2 illustrates the tensile specimen design considered and varying grip design test cases modeled.

Figure 3 illustrates the predicted strain, ε_z, along 'z' in the HAZ prior to failure. It can be seen that an almost plane-strain condition can be achieved with this new tensile test specimen design and with radius grips. Figure 4 shows the stress, σ_y, for grip designs case 'a' and for the regular straight grip design, case 'g'. Note that the stress concentration is lower for case 'a'.

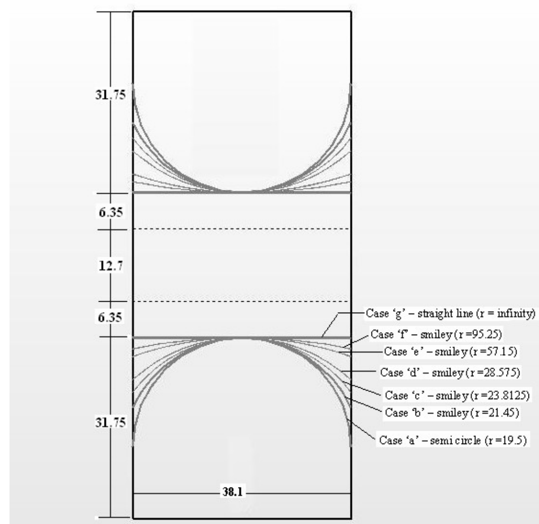


Figure 2. Tensile test specimen design and various grip cases modeled to achieve plane-strain. Dimensions are in millimeters.

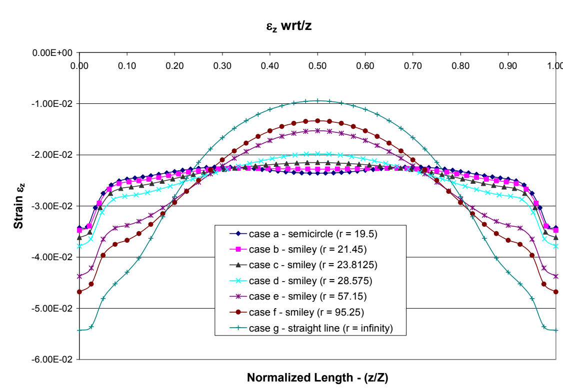
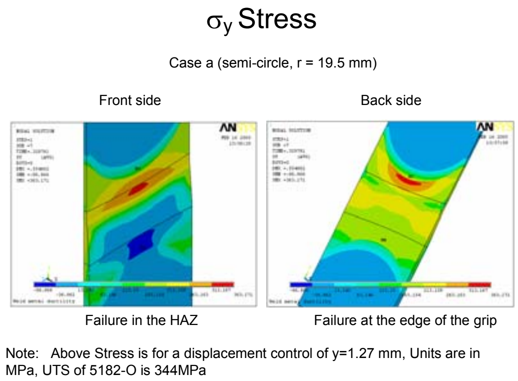
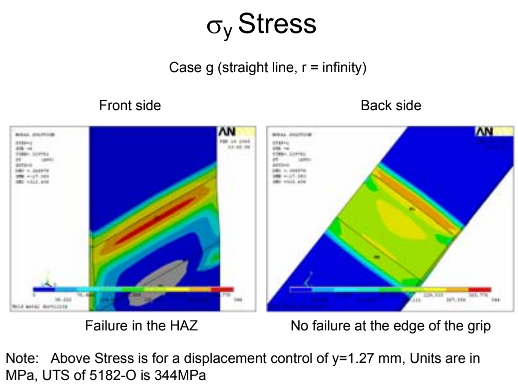


Figure 3. An illustration of the predicted strain, ε_z, with respect to 'z'.



(a)



(b)

Figure 4. Predicted stress results for: (a) Case 'a'. (b) Case 'g'.

Experimental Characterization

The experimental characterization during the first program year has consisted of verifying the grip design, testing of two weld populations and evaluating one alternative method to strain grid analysis, namely, Digital Image Correlation, also known as Speckle Pattern Interferometry.

Tensile Specimen Design

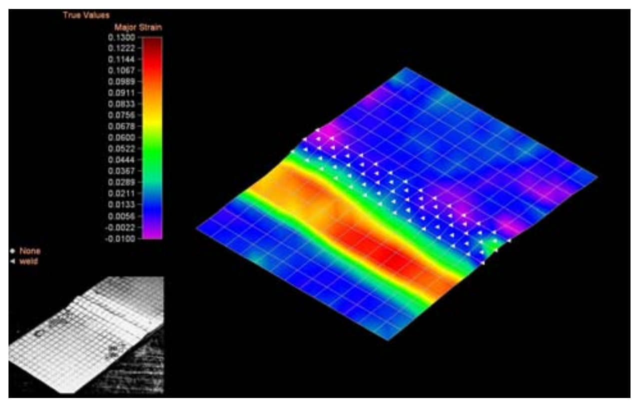
Experimental characterization began with validating the modeling results for the tensile specimen design with case 'g' grips shown in Figure 2. Case 'g' predicted an almost plane-strain condition with no failure at the edge of the grip. Tensile tests were conducted on 5182-O, 2-mm- thick, monolithic sheet specimens. The straight-line grip design had slippage problems due to material flow at the grip edges. A 45^{o} neck was observed in the gage consistent with tensile failure and not plane-strain.

The experimental investigation then continued with the same specimen design, but with the semi-circular grip (case a). Initially, similar necking was observed as in the previous specimens, but with little slippage. The specimen length was then increased to 5 inches (12.7 cm) to ensure a better grip of the specimen. A neck perpendicular to the gage was observed in the center of the longer monolithic sheet specimens, indicative of a plane-strain condition.

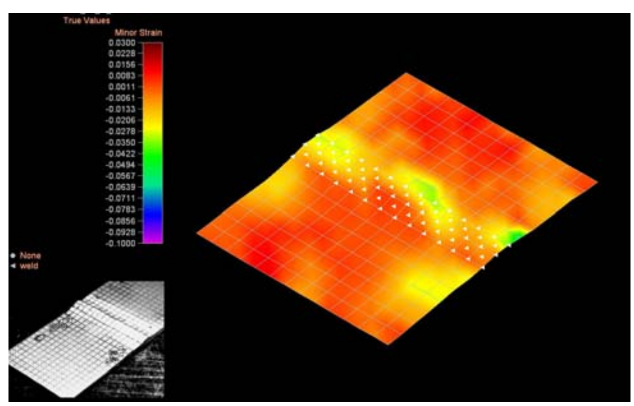
GTAW 5182-O TWB's (2 mm to 1 mm)

A population of gas tungsten arc-welded (GTAW) 5182-O TWB's (2 mm to 1 mm) were prepared to verify the plane-strain condition observed in the monolithic sheet specimens. Thirty specimens were gridded and tested.

In this population, there was only one weld failure. The other 29 specimens failed in plane- strain. The specimens were characterized for surface strains via strain-grid analysis. Figure 5 is representative of the



(a)



(b)

Figure 5. Typical strain-grid analysis results. (a) Major strain. (b) Minor strain.

typical strain results observed. The experimental results to date have shown good correlation with the modeling predictions.

DP600 TWB's (1.5 mm to 1 mm)

Laser-welded DP600 to DP600 TWB's (1.5 mm to 1 mm) were also tested. The total width of the laser-welded zone is small, less than 0.125 inch (3.2 mm).

Sixty samples were tested, 30 samples with a transverse weld orientation and 30 samples with a longitudinal weld orientation. No failures in the weld zone were recorded for the transverse weld samples. All failures were due to localization in the thin sheet (1 mm) far away from the weld and HAZ. Thus, for the transverse weld orientation, failure is determined by the properties of the 1-mm-thick parent sheet material.

In contrast, all longitudinal weld samples failed in the weld and the failure mode is therefore determined by the properties of the longitudinal weld.

Forming-Limit Diagrams

After the completion of the tensile testing, the data were compiled and theoretical FLDs were constructed for both GTAW 5182-O and laser-welded DP600 materials.

The first step in the construction of the FLD is to determine the amount of strain prior to the onset of localization via strain-grid analysis as previously discussed. Figure 6 shows the results of the strain-grid analysis of a representative sample. The data are divided into two groups, safe and localized (necked). From these two data sets, the plane-strain value for the onset of localization can be determined.

The plane-strain values for the onset of localization from all 30 samples in each data set are thereafter used as input into the Marciniak-Kuczynski (M-K) method to predict the theoretical FLD. The theoretical FLD for both GTAW 5182-O and laser-welded DP600 materials based on Weibull distribution of imperfection limits are shown in Figure 7.

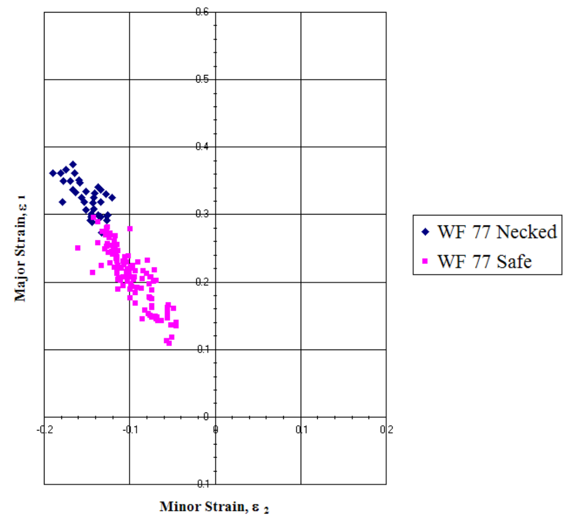


Figure 6. Representative FLD constructed from the strain-grid analysis for one specimen.

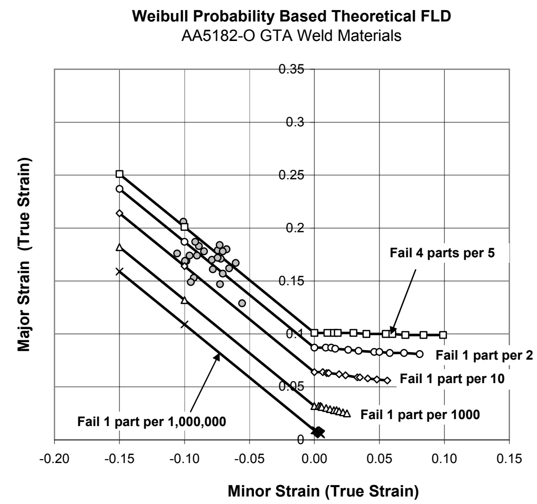
The theoretical calculation of FLD is a powerful tool to predict sheet-metal formability, starting with simple mechanical tensile testing results. This concept will be evaluated during FY 2006.

Digital Image Correlation

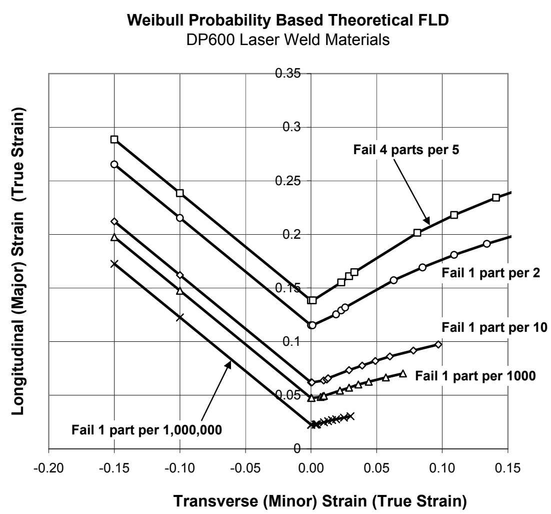
Strain-grid analysis is both time consuming and prone to subjective determination of the onset of localization. In order to address these two issues, we have just begun assessing another strain evaluation method, Digital Image Correlation or Speckle Pattern Interferometry.

Using Digital Image Correlation, a speckle pattern is painted on the sample. Two cameras then record a stereo image of strain accumulation throughout the entire deformation event. The experimental setup is shown in Figure 8.

Digital Image Correlation has very high resolution and non-homogeneous deformation is tracked locally. Since local strains can be tracked, Digital Image Correlation seems ideally suited for non-homogeneous gage areas like welds. Results to date have been very encouraging and Digital Image Correlation will be utilized for the the next material combinations to be tested.



(a)



(b)

Figure 7. Theoretical forming-limit diagrams of (a) GTAW 5182-O. (b) Laser-welded DP600. Both FLD's are based on a Weibull distribution of imperfection levels.

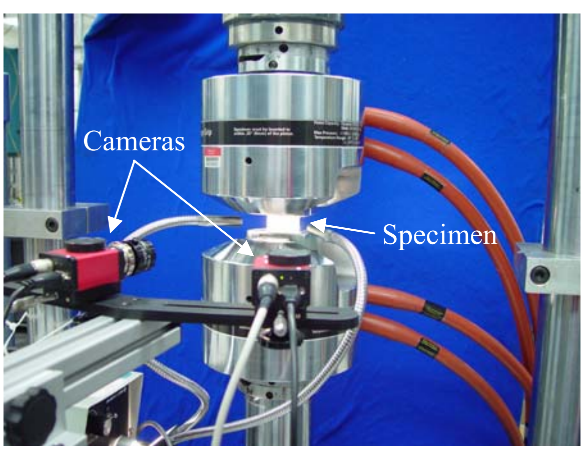


Figure 8. Digital Image Correlation set-up.

Conclusions

From this investigation, the following conclusions were derived:

- FEA can be utilized to evaluate competing weld specimen designs and determine their suitability in providing statistical information on a given population.
- A simple, sample geometry specimen design produced nearly plane-strain deformation across a welded sample.
- In laser-welded DP600 to DP600 TWBs, the properties are determined by the properties of the longitudinal weld.
- Theoretical FLDs can be predicted starting with simple mechanical tensile testing results.
- Digital Image Correlation, or Speckle Pattern Interferometry, has potential to be a more accurate tool to characterize local strain variation than current strain-grid analysis.