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## 2014 Annual Merit Review

# High Speed Joining of Dissimilar Alloy Aluminum Tailor Welded Blanks

YURI HOVANSKI

Pacific Northwest National Laboratory

June 18, 2014



Project ID #LM075

# Project Overview

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## Project Timeline

- Start: FY2012
- Finish: FY2014
- 85% complete

## Technology Gaps/Barriers

- Capacity to rapidly join Al sheet in dissimilar thicknesses and alloys is not developed.
- Supply chain doesn't exist for high volume joining of automotive aluminum sheet.
- Characterization of post-weld formability must be tied to the process to allow the entire supply chain to successfully integrate the technology.

## Budget

- Total project funding
  - DOE – \$0.9 M
  - Industrial cost share >\$1.5M
- FY12 Funding - \$300k
- FY13 Funding - \$300k
- FY14 Funding - \$300k

## Partners

- OEM
  - GM
- Tier I Supplier
  - TWB Company LLC
- Material Provider
  - Alcoa



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# Relevance: Project Motivation

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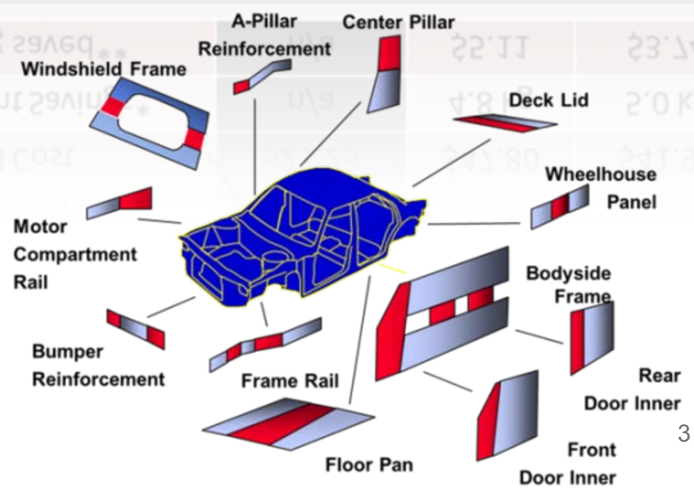
- By 2015, demonstrate a cost-effective 50% weight reduction in passenger-vehicle body and chassis systems
  - Critical technology gaps in all advanced materials systems must be overcome to meet the multi-material lightweight vehicle challenge
  - Multi-material joining was identified as a key technology gap
    - Aluminum is a near-term material solution for lightweighting
    - Aluminum welded panels provide further potential for weight reduction

| Front Door Inner Example | Steel –TB 1.4 / .7 mm | Al – Assembly | AL – TB 2.0 / 1.1 mm |
|---|---|---|---|
| Gross Weight | 14.5 kg | 9.0 kg | 7.4 kg |
| Net Weight | 11.6 kg | 6.8 kg | 6.6 kg |
| Material cost ($1.25/kg vs $4.50/kg) | $18.13 | $40.50 | $33.30 |
| Blanking & Welding | $3.12 | $.70 | $5.85 |
| Stamping | $2.00 | $3.60 | $2.80 |
| Assembly | $0 | $3.00 | $0 |
| Total Cost | $23.25 | $47.80 | $41.95 |
| Net Weight Savings* | n/a | 4.8 kg | 5.0 kg |
| Cost / kg saved** | n/a | $5.11 | $3.74 |



# Relevance: Goals and Objectives

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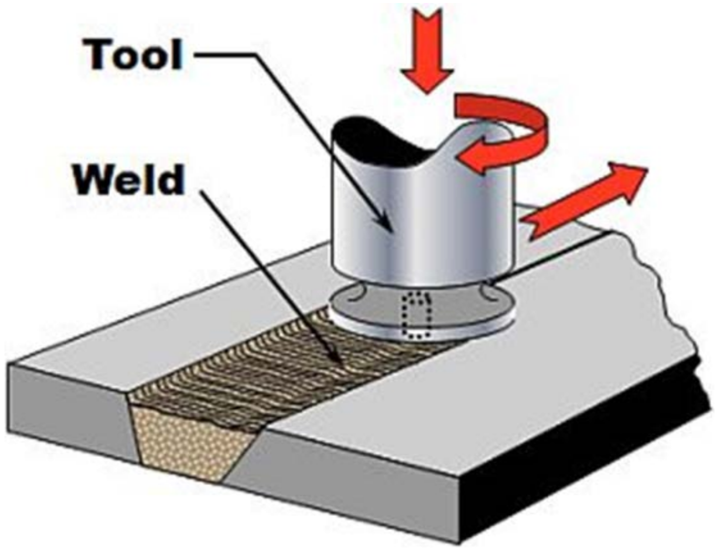
- Enable more wide-spread use of mass-saving aluminum alloys.
- Develop joining technology needed for high speed fabrication of Al-TWBs.
- Introduce Al TWBs into the high volume automotive supply chain.




Evaluating Laser – single spot & double spot, laser-hybrid, and friction stir welding

# Project Schedule and Progress

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| | | FY2012 | | | | FY2013 | | | | FY2014 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quarter | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| | **Task 1: Weld development of dissimilar aluminum alloys** | | | | | | | | | | | | |
| | 1.1. Dissimilar thickness 5XXX series weld development | | | | | | | | | | | | |
| | 1.2. Dissimilar alloy 5XXX series to 6XXX series weld development | | | | | | | | | | | | |
| | 1.3. Dissimilar alloy 5XXX series to 7XXX series weld development | | | | | | | | | | | | |
| | **Task 2: Formability screening of dissimilar aluminum alloys** | | | | | | | | | | | | |
| | 2.1. Coupon Production | | | | | | | | | | | | |
| | 2.2. Formability Screening | | | | | | | | | | | | |
| FY13 Go/No-Go | **Decision Gate** | | | | | | | | | | | | |
| | **Task 3: Production readiness and technology deployment** | | | | | | | | | | | | |
| FY13 Milestone | 3.1. High speed weld development | | | | | | | | | | | | |
| | 3.2. Technology transfer | | | | | | | | | | | | |
| FY14 Milestone | 3.3. Probabilistic evaluation of alloy/thickness combinations | | | | | | | | | | | | |
| | 3.4. Component forming Model | | | | | | | | | | | | |
| | **Task 4: Prototype Development and Component Testing** | | | | | | | | | | | | |
| FY14 Milestone | 4.1. Component production | | | | | | | | | | | | |
| FY14 Milestone | 4.2. Formability validation & stamping | | | | | | | | | | | | |
| | 4.3. Production durability testing | | | | | | | | | | | | |

# Relevance: Project Milestones

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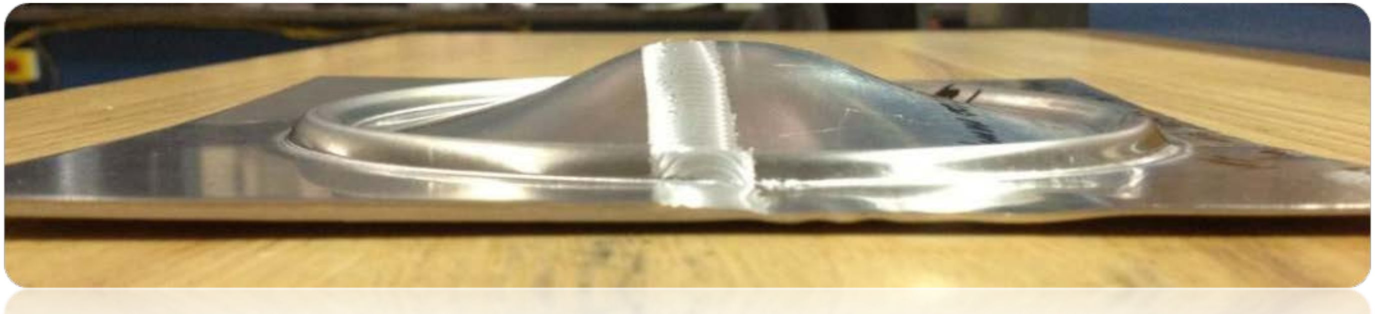
| Month/Year | Milestone or Go/No-Go Decision |
|---|---|
| Sept. 2012<br>*Progress Milestone* | **Complete Initial Joining Comparison**<br>Evaluate the performance of best in class laser, laser/hybrid and FSW for joining dissimilar thickness aluminum TWBs. |
| May 2013<br>*Decision Gate* | **Down-select Joining Method** |
| Sept 2013<br>*Progress Milestone* | **Initiate high speed weld development**<br>Develop weld parameters demonstrating a 30% increase in weld speed with reduction in formability or other quality criteria. |
| March 2014<br>*Formability limits* | **Probabilistic formability evaluation**<br>Evaluate post-weld formability to determine statistically modeled formability limitations for use in FEA models. |
| June 2014<br>*Tech Transfer* | **Produce welded door panels at GM and TWB for component welding and demonstration**<br>20 door stampings in AA5182 and AA6022 (2mm to 1mm) |
| Sept 2014<br>*Validate FEA models* | **Validation of component forming**<br>Utilizing statistical formability limits validate FEA models with strain data obtained from actual stampings |

# Technical Approach

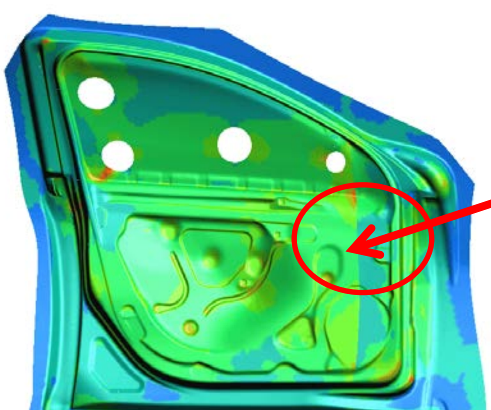
- **Task 1: Weld development of dissimilar aluminum alloys**
  - Task 1.1. Dissimilar thickness 5XXX series weld development
    - Evaluate current welding methods for welding dissimilar thickness
  - Task 1.2. Dissimilar alloy 5XXX series to 6XXX series weld
    - Evaluate current welding methods for welding dissimilar alloy
  - Task 1.3. Dissimilar alloy 5XXX series to 7XXX series weld development
    - Evaluate FSW for high strength alloy combinations
- **Task 2: Formability screening of dissimilar aluminum alloys**
  - Task 2.1. Coupon Production
  - Task 2.2. Formability Screening
    - **Decision Gate:**
      - **Determine the appropriate welding method from laser, laser-hybrid, laser-plasma, & FSW**



# Technical Approach (con't)



- **<u>Task 3: Production readiness and deployability</u>**
  - Task 3.1. High speed weld development
  - Task 3.2. Technology transfer
    - Transfer welding technology into the supply chain (TWB Company)
  - Task 3.3. Probabilistic evaluation of alloy/gauge combinations
  - Task 3.4. Component forming Model
    - Feed forward probabilistic bounds into the forming model to more accurately predict weld failures in the stamping process
- **<u>Task 4: Prototype Development and Component Testing</u>**
  - Task 4.1. Component production
  - Task 4.2. Formability validation & stamping
  - Task 4.3. Production durability testing



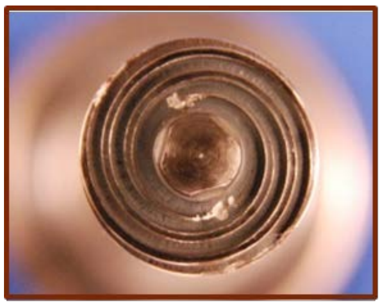
Split Predicted

No Split, Actual

# Technical Accomplishments: High Speed Weld Development



- Design of Experiment approach to high speed FSW
  - 36 tool designs (3 pin lengths, 3 pin features, 2 shoulder features, 2 shoulder to pin diameters)
  - Control Variables (3 plunge depths, 2 tool tilts, 2 anvil tilts, 3 RPMs



Pin with 3 Flats
Double scrolled shoulder,
Shoulder to pin ratio (S/P) =3

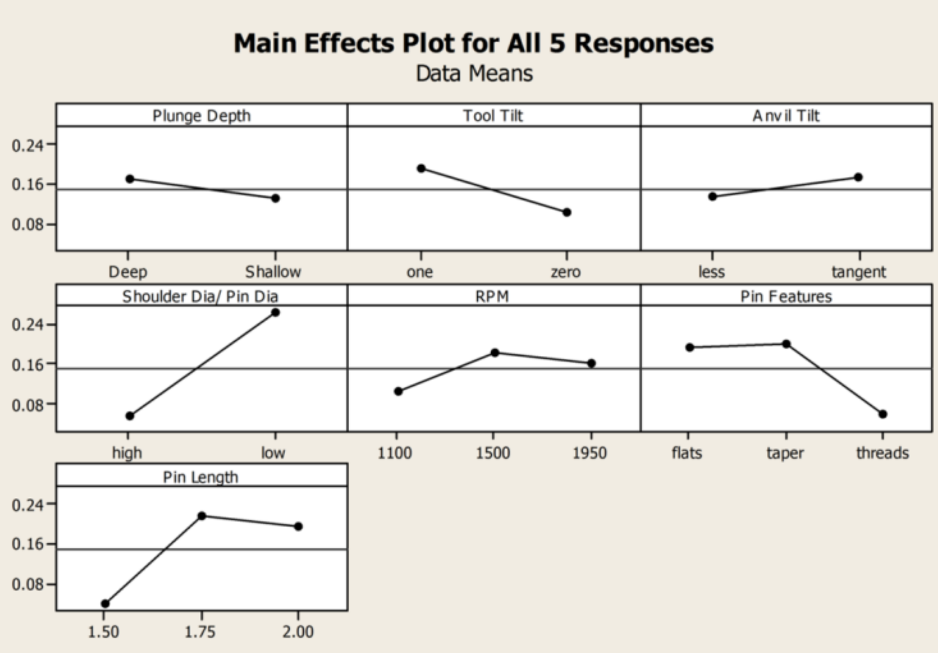
Pin with 3 Flats
Single scrolled shoulder,
Shoulder to pin ratio (S/P) =2.5

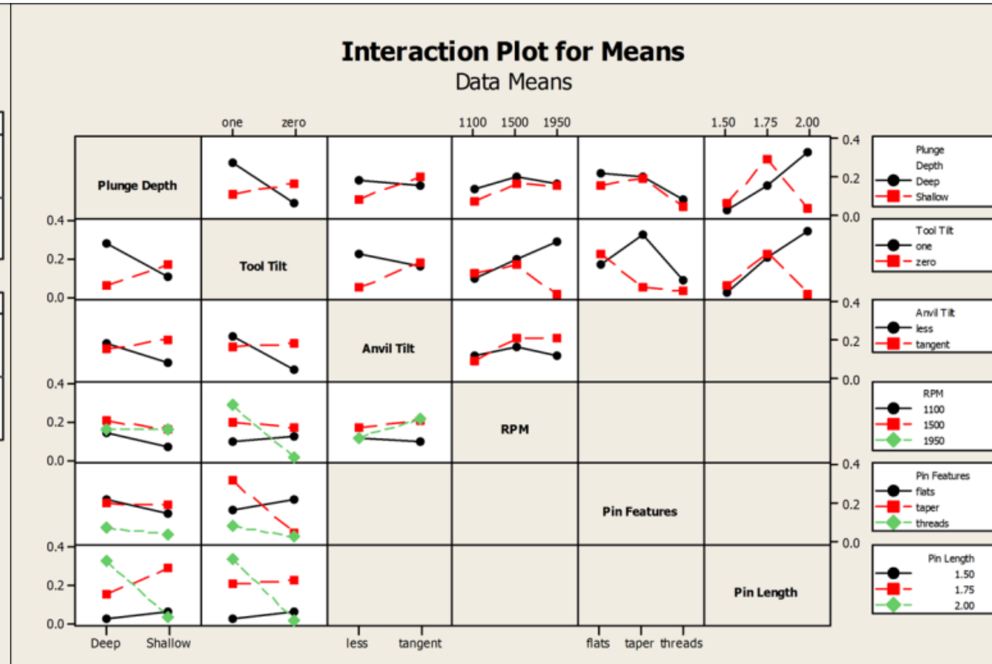
| # | Plunge Depth | Tool Tilt | Anvil Tilt | Shoulder /Pin Ratio | Scroll | RPM | Pin Feature | Pin Length | Strength, MPa | % Elong. | LDH, mm | Ra, Rmax |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Deep | one | tangent | low | 2 | 1950 | flats | 2 | 297.7 | 12.4 | 20.8 | 29.4, 33.7 |
| 2 | Deep | one | less | low | 1 | 1500 | taper | 2 | 297.5 | 11.9 | 20.90 | 36.3, 47.8 |
| 3 | Shallow | zero | tangent | low | 1 | 1500 | flats | 1.75 | 294.4 | 11.2 | 18.0 | 87.8, 96.3 |

# Technical Accomplishments: High Speed Weld Development



- Normalized plots weighted based on tensile strength, post-weld formability, surface quality, and weld flash
- Shoulder to pin diameter ratio had the largest single effect
- Pin length & features showed specific favorable regions
  - Interaction show pin length and plunge depth linked
- Tool tilt was critical for higher RPM welds
- Evaluation completes FY13 milestone



# Technical Accomplishments: Probabilistic Formability Limits

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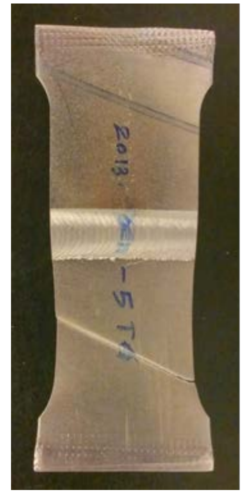
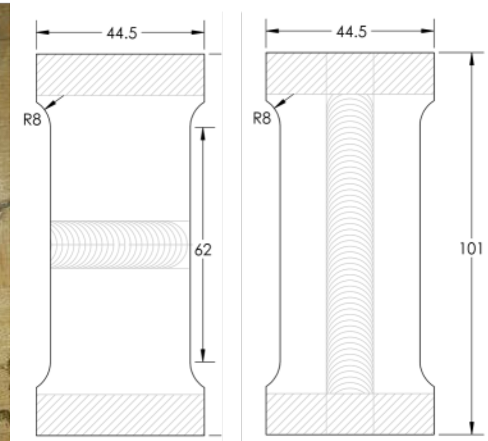
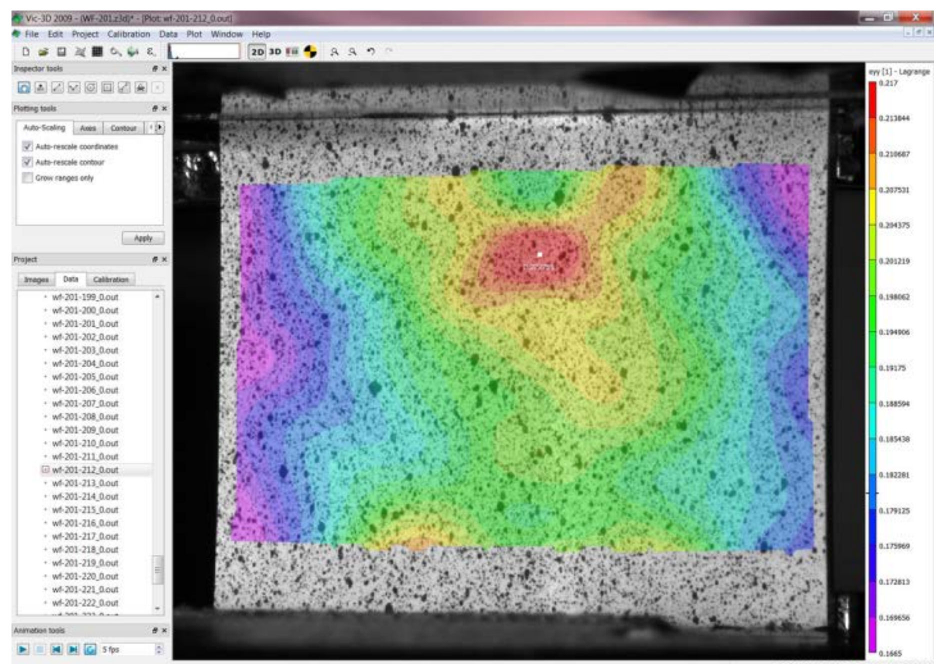
- 30 sets of tensile coupons prepared to evaluate available strain in dissimilar thickness welded aluminum blanks
  - Transverse & longitudinal
- Speckle pattern interferometry
  - Strain evaluation
  - Determines maximum safe strain available to each specimen
  - Max $e_{yy}$ and corresponding $e_{xx}$ are recorded
    - Lagrangian strain conditions
- Completes FY14 milestone



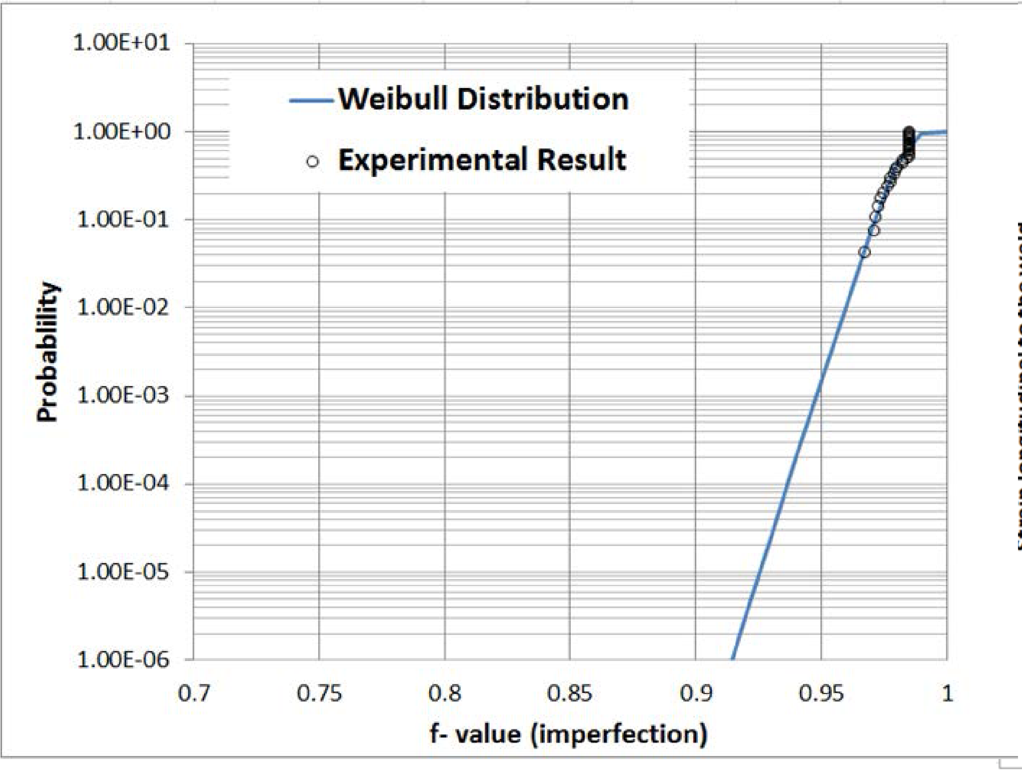


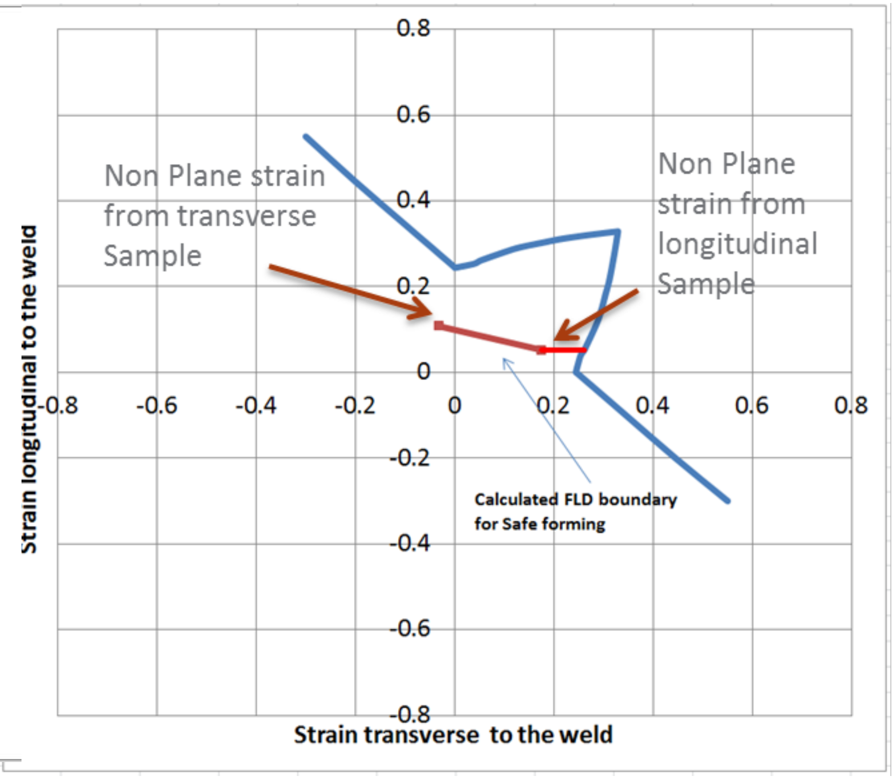



# Technical Accomplishments: Probabilistic Formability Limits



- Calculated statistical distribution for the level of imperfection associated with the weld and geometric discontinuity
  - Level of imperfection corresponds with f value for each $e_{xx}$
- Weibull analysis established for the f-values of each specimen
- Probabilistic formability limit established for safe strain in the production of TWBs (FY14 milestone)

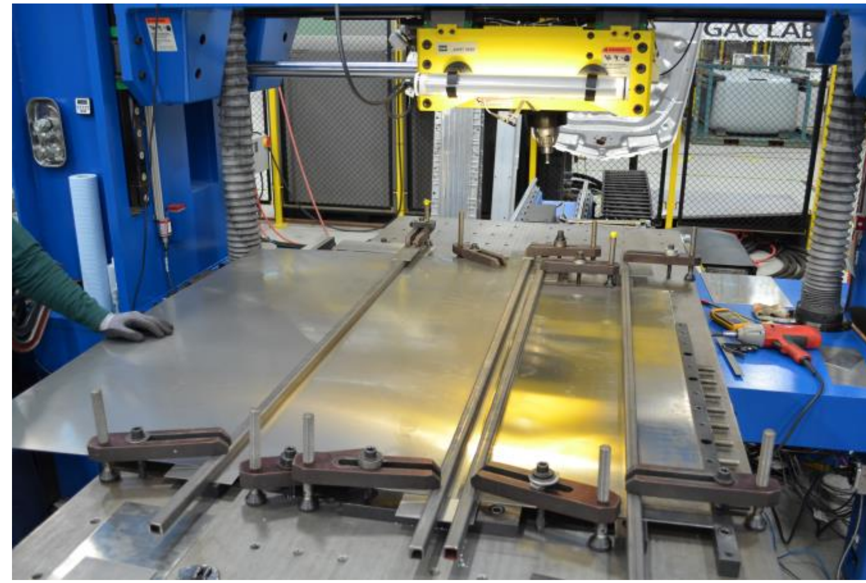


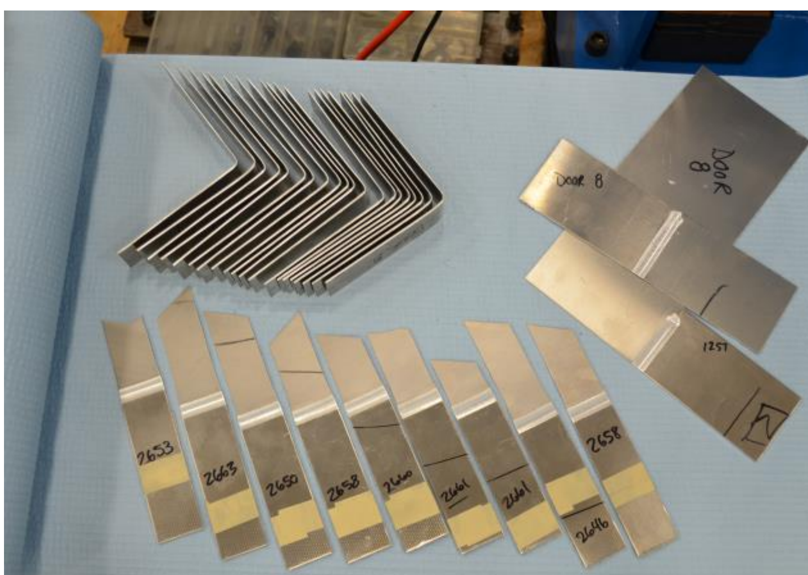



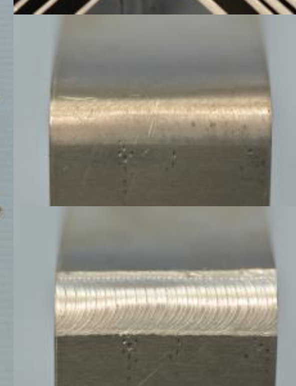
# Technical Accomplishments: Component Production at General Motors

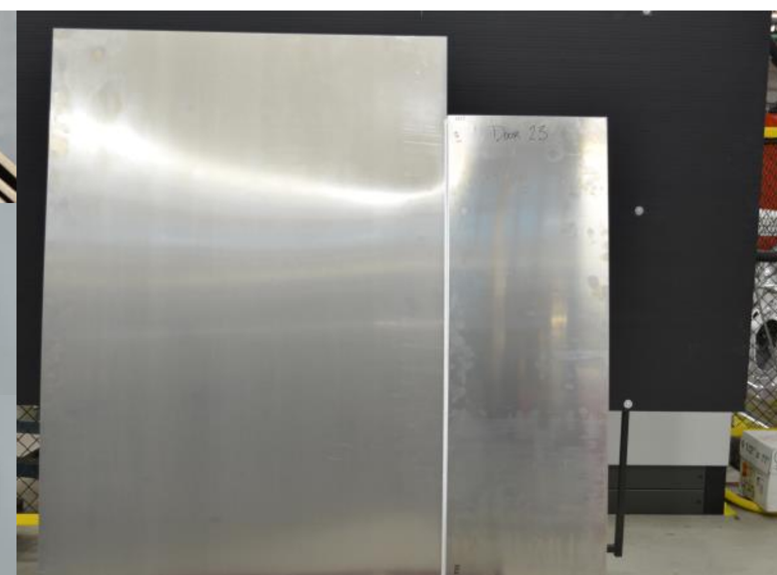


- Door panels produced
  - AA5182 (2.0mm to 1.1mm)
    - All at 3m/min
  - AA6022 (2.0mm to 1.0mm)
    - At 3m/min & 6m/min
- Welds tested and passed tensile and bend tests
- Shipped for stamping trials







# Technical Accomplishments: Technology Transfer & Component Production



- TWB (supplier) preparing for full production
  - Tool drawings, database, and production chain established
  - Equipment purchased, on-site, & welding
  - Production fixtures for linear welding in place
    - 4 meter lengths at speeds up to 10 meters/min

# Responses to Previous Year Comments



- **Question 2: Technical accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made, measured against performance indicators and demonstrated progress toward DOE goals.**
  - *"the project looks very good; hopefully, in the next phase the team can try to move beyond lab specimens and onto more production representative geometries. "*
    - Task 4 was specifically designed to demonstrate the technology at full scale at the OEM and in simulated production at the suppliers facility. Full-size door panels have been produced at each site (FY14)
- **Question 4: Proposed future research –**
  - *"the project team had an ambitious schedule, and the reviewer hopes that all of the associated characterization is also going to be performed. "*
    - The project team concurs, but with the possibility of actual vehicle implementation in 2015, the success of the project demands ever increasing input from the team members.
- **Question 5: Does this project support the overall DOE objectives of petroleum displacement? Why or why not?**
  - *"tailor welded Al blanks are a key enabler to further weight reduction in automotive body and closure stampings. "*
    - The project was designed to support specific shortcomings related to joining lightweight materials in high volumes, such that implementation could meet the 2015 weight reduction targets.
- **Question 6: Resources: How sufficient are the resources for the project to achieve the stated milestones in a timely fashion?**
  - *"the match is growing, which implies that the project team underspecified the budget."*
    - The agreed upon match of the suppliers was a minimum of 50/50 with the DOE. The understanding from the beginning was that marked successes would lead to increased investment by the team partners.

# Collaborations



- University Collaborators
  - Washington State University
    - Characterization and analysis of process on properties
- Private Collaborations (complete automotive supply chain)
  - General Motors
    - Laser Welding Evaluation, Formability Modeling & Durability
    - High Speed FSW Feasibility
  - TWB Company, LLC.
    - Welding, stamping evaluation, high volume production,
  - Alcoa
    - Material provider, high temperature material properties, formability

# Remaining Challenges and Barriers



- Successful handoff to the supplier
  - Capability & know-how to succeed with a variation of alloys and thicknesses
- Predictive design tools to OEMs to accurately design for welded and stamped aluminum components
- Validation of modeling efforts based on actual parts

# Proposed Future Work

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- Spring 2014: Formability & Stamping (FY14 milestones)
  - Stamp full size door inner panels produced at GM & TWB in dissimilar thickness AA5182 & AA6022 welded at 3 m/min
  - Stamp full size door inner panels produced at GM & TWB in dissimilar thickness AA6022 welded at 6 m/min
- Spring 2014: Complete Technology Transfer
  - Supplier kick-off and demonstrations for OEMs
  - Ready for high volume production of aluminum TWBs
- Summer 2014: Component Forming Model (FY14 final milestone)
  - Feed data from probabilistic forming limit established for AA5182 and AA6022 dissimilar thickness welds into component forming models
  - Validate stamping results from stamping trials
  - Supply predictive forming guide for future design needs
- Propose follow-on work in high speed joining of dissimilar aluminum alloys
  - Joinability and forming challenges of dissimilar alloy welded blanks

# Project Summary



- Project developed high volume supply chain for aluminum tailor welded blanks
  - Successful technology transfer from National Lab to automotive supplier
  - Supported from OEM and material provider to assure success & support
  - Millions invested from project partners based on measured & staged demonstrated success of the project
- Demonstrated high speed friction stir welding of dissimilar thickness combinations in various aluminum alloys
  - Weld speeds to 6 m/min in dissimilar thickness
  - Higher speeds demonstrated by supplier in similar thicknesses
  - Pushed the technology beyond the previous state-of-the-art to facilitate high volume production needs
- Predictive tools and weld development were completed for similar alloy welding; however, dissimilar alloy development remains a significant challenge.

# Technical Back-Up Slides

# Initial Taguchi DOE: Welds at fixed 3 m/min



- Plunge Depth
  - High (1.85-mm), Low (2.00-mm)
- Tool Tilt
  - High (1º), low (zero tilt)
- Anvil Tilt
  - Tangent (3.82º), less (3.00º)
- Pin Diameter
  - High (2.5:1 S/P ratio), Low (3:1 S/P ratio)
- Number of Shoulder Scrolls (2 or 1)
- Rotational Velocity
  - High (1950), Med (1500), Low (1100)
- Pin Features
  - Taper, Flats, Threads
- Pin Length
  - 1.5-mm, 1.75-mm, 2.0-mm

# Technical Backup: Limited Dome Height Testing

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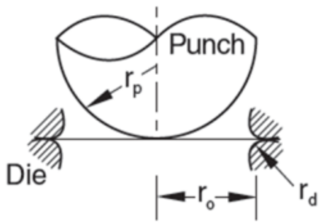
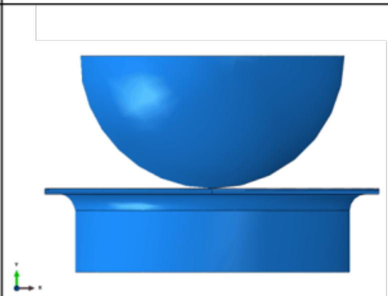
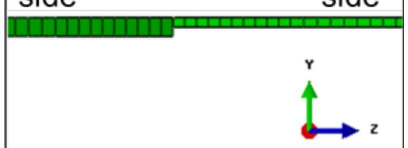
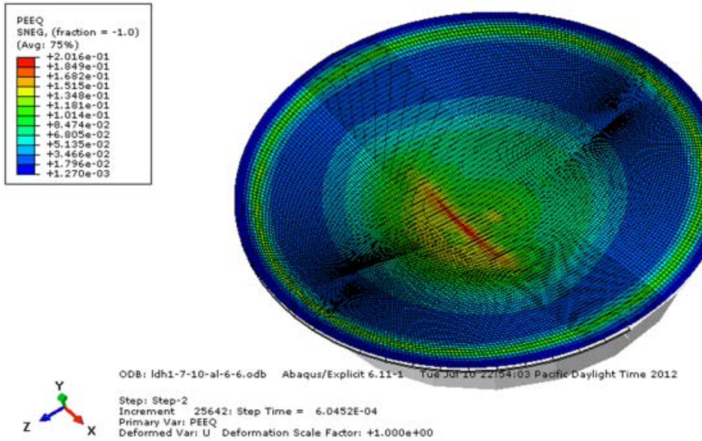
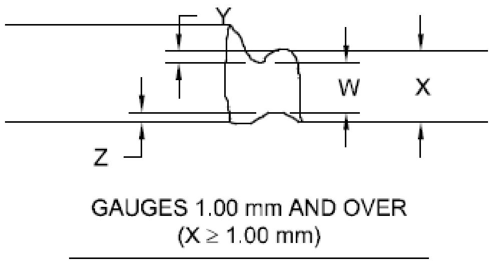
- Formability Screening of dissimilar thickness welded blanks
  - Height & load at failure measured
  - Predicted failure was outside weld in the thin sheet for 2-mm to 1-mm joints
    - Failure related to geometric discontinuity rather than the weld


| Model Schematic | FE Model | "Al" Sheet Details |
| --- | --- | --- |
|   $r_o$ = 59.18 mm<br>$r_p$ = 50.8 mm<br>$r_d$ = 6.35 mm |  |   |




# Technical Backup : Applying Weld Quality Specifications



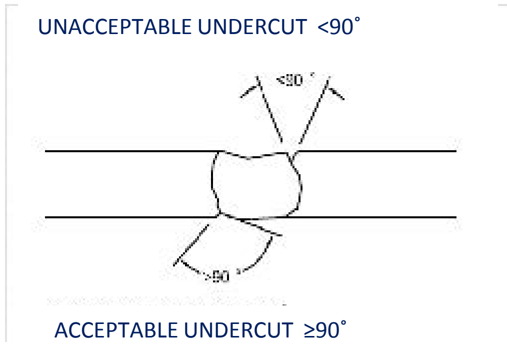


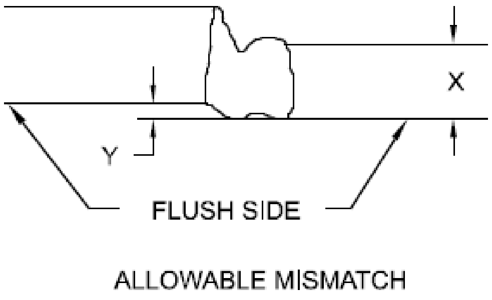

$\frac{Y}{X} \leq 0.20$

$\frac{Z}{X} \leq 0.20$

$\frac{Y+Z}{X} \leq 0.20$

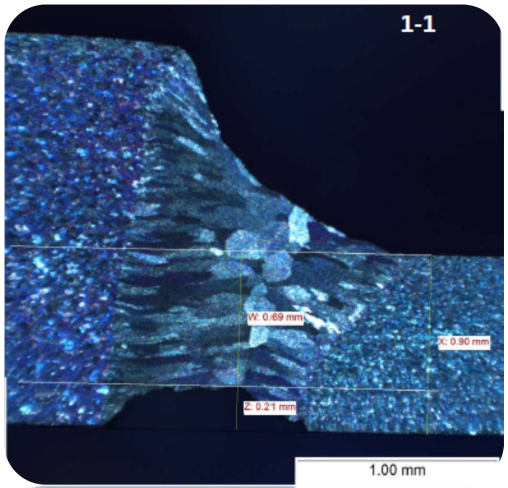
$W \geq 0.80$ OF X



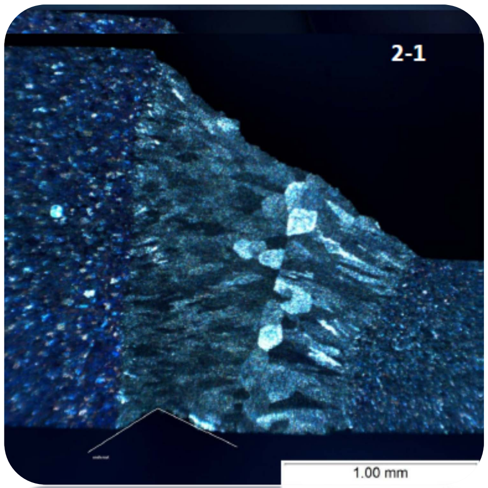




$\frac{Y}{X} \leq 0.10$

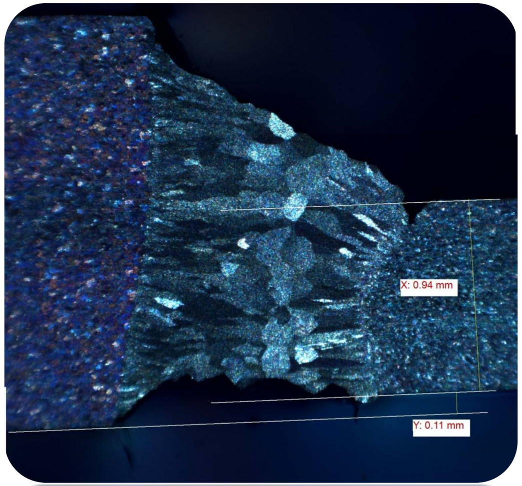
## Single Spot - Concavity




## Twin Spot - Undercut




## Twin Spot - Mismatch



# Technical Backup :
# Down Selecting a Joining Technology

- FSW maintained the highest formability in LDH screening tests
  - Laser twin spot (across the joint) performed similarly at higher weld speeds
  - Weld materials
    - 2.0-mm 5182-O to 0.9-mm 5182-O
- LDH screening tests alone were insufficient to determine most suitable welding method

| Weld Process | Dome Height (mm) | Concavity (Z/X ≤ 0.2) | Convexity (Z/X ≤ 0.1) | Mismatch (Y/X ≤ 0.1) | Undercut (Angle ≥ 90˚) |
|---|---|---|---|---|---|
| Single Spot | 11.7 ± 0.3 | 0.22 – 0.23 | / | / | / |
| Twin Spot (across weld) | 15.1 ± 0.4 | / | / | 0 – 0.21 | 116 - 180 |
| Twin Spot (along weld) | 14.3 ± 1.0 | 0.19 – 0.36 | / | 0.12 – 0.25 | 51 - 180 |
| Laser-Plasma | 11.9 ± 4.0 | 0 – 0.28 | 0.31 – 0.69 | / | / |
| FSW | 15.4 ± 0.5 | / | / | / | / |

# Technical Backup : Numerically Driven Evaluation

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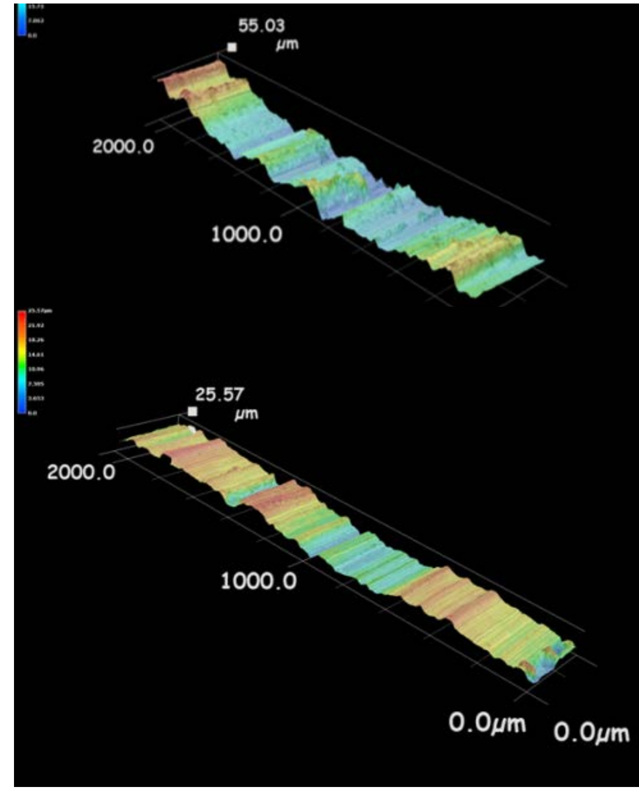
- DOE designed to evaluate the statistical effects of 8 factors
  - Quantify the responses to the following:
    - Surface roughness & Flash
      - Weld #29 (  25µm)
      - Weld #36 (  15µm)
    - Formability
    - Mechanical Properties
      - Repeatability, failure mechanism, values




Weld # 36 – Start of weld