2016 Annual Merit Review

High Strength, Dissimilar Alloy Aluminum Tailor-Welded Blanks

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Pacific Northwest National Laboratory

June 2016

Project ID #LM099

Project Overview

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Project Timeline

- Start: FY2015
- Finish: FY2017
- 43% complete

Technology Gaps/Barriers

- Capacity to rapidly join dissimilar alloy Al sheet is not developed for high volume production.
- Scientific understanding to enable thermal stability of work-hardenable and precipitation hardenable alloys during welding is lacking
- Supply chain for curvilinear geometries in dissimilar thickness and alloy combinations is non existent.

Budget

- Total project funding
  - DOE – $1.2 M
  - Industrial cost share >$1.2M
- FY15 Funding - $400k (received)
  - Industrial In-kind > $400k
- FY16 Funding - $400k (received)
  - Industrial In-kind > $500k
- FY17 Funding - $400k

Project Partners

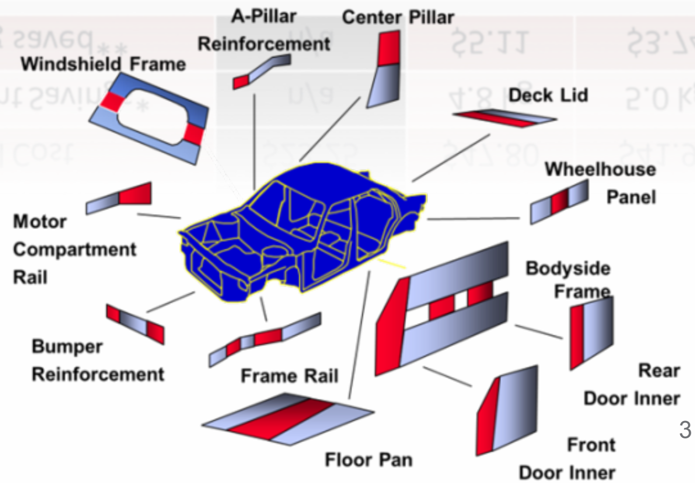
- National Laboratory
  - PNNL (lead)
- Automotive OEM
  - GM
- Tier I Supplier
  - TWB Company LLC
- Material Provider
  - Alcoa

2

Relevance: Project Motivation

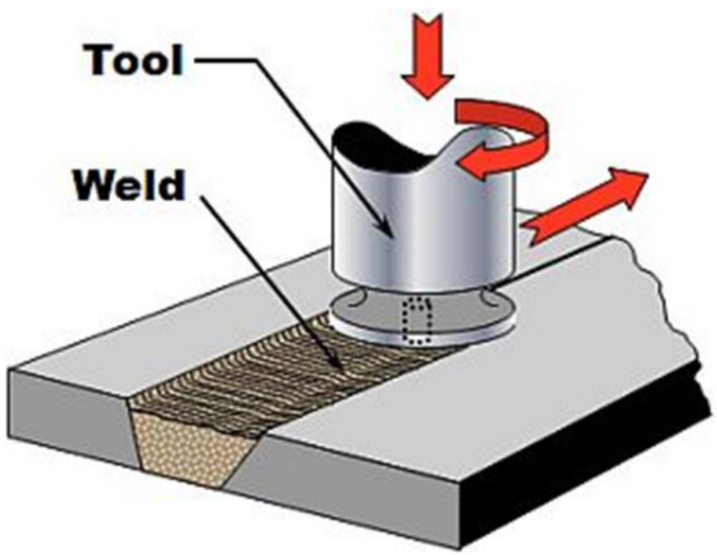
- EERE–VTO Goal:
  - By 2025, demonstrate a cost-effective 35% weight reduction in passenger-vehicles compared to 2010 model (<$2.16 / lb saved)
- VTO - Challenges and Barriers:
  - Improving understanding and manufacturability of lightweight materials
  - "Joining thin sheets or sheets with different thicknesses is difficult…new joining and forming technologies…will need to be developed."
- Project designed to address each of these issues as related to the production of Al-TWBs
  - Increase supplier base
  - Develop and validate predictive modeling tools
  - Develop new joining technique with lower cost and simplified assembly
- Early projections showed weight savings at $1.70 cost/lb saved ($3.74 cost/kg)

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

- Enable more wide-spread use of mass-saving aluminum alloys.
- Develop joining technology needed for high speed fabrication of high strength, dissimilar alloy Al-TWBs in linear and curvilinear geometries.
- Introduce curvilinear Al TWBs into the high-volume automotive supply chain.



Relevance: Project Milestones

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Month/Year	Milestone or Go/No-Go Decision
March 2015 ***Complete*** ✔	**Establish Predictive Formability** Establish FE modeling for predicting LDH height in welded sheet using Barlat coefficients
June 2015 ***Complete*** ✔	**Characterize Influence of Heat Input** Characterize HAZ relationships in 5x, 6x, and 7x aluminum alloys as a function of welding speed
Sept 2015 *Progress Milestone* ***Delayed***	**Disseminate Information** Submit a publication on relationships of high speed FSW parameters on the magnitude & location of HAZ in welded blanks **(publication delayed to await public release of data)**
Sept 2016 *Go/No-Go* ✔ ***Complete***	**High Speed Dissimilar Alloy** Demonstrate high-speed, friction-stir welded dissimilar alloy welded blanks between 5x & 6x alloys in linear and curvilinear geometries
April 2017 Progress Milestone	**High Strength Dissimilar Alloy** Demonstrate high-speed, friction-stir welded dissimilar alloy welded blanks between 5x & 6x alloys to 7x alloys in linear and curvilinear geometries
June 2017 Progress Milestone	**Validate Formability Model for Dissimilar Alloy and Thickness** Account for anisotropy across multiple alloys, dissimilar alloy welds, and heat affected regions.

Approach: Project Schedule and Progress

- FY15 Milestone
- FY16 Go/No-Go
- FY17 Milestone
- FY16 Milestone
- FY15 Milestone
- FY17 Milestone

	FY2015				FY2016				FY2017			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Relating weld parameters and material properties												
1.1. Sheet Characterization												
1.2. FSW properties												
1.3. HAZ relationships												
1.4. Effects of Coatings												
1.5. Dissimilar Joint Properties												
Task 2: Dissimilar Alloy FSW Development												
2.1. 5xxx to 6xxx												
Decision Gate:												
2.2. 6xxx to 6xxx												
2.3. 5xxx & 6xxx to 7xxx												
2.4. Curvilinear weld development												
Task 3: Production readiness and deployability												
3.1. Repeatability - Linear												
3.2. Repeatability - curvilinear												
3.3. Durability - tools												
Task 4: Weld formability modeling and validation												
4.1. Barlet Coefficients												
4.2. Dissimilar Thickness												
4.3. Dissimilar alloy & thickness												
4.4. Prototypical validation												

Technical Approach

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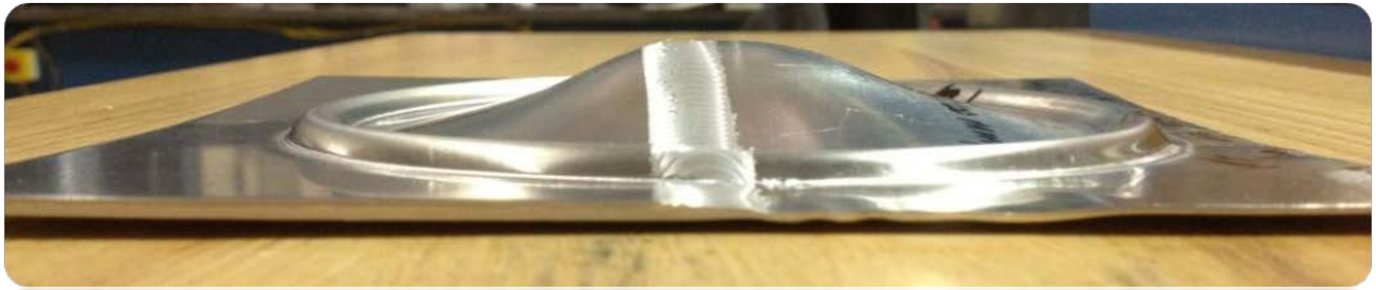
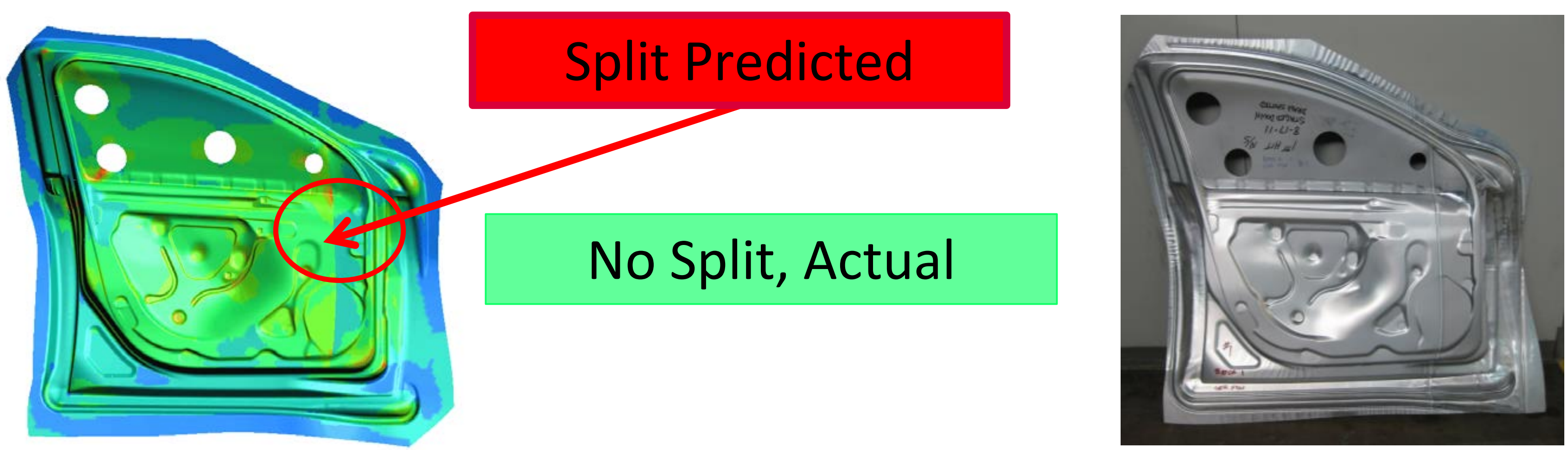
- **<u>Task 1: Relating Weld Parameters & Material Properties</u>**
  - Task 1.1. Base-metal sheet characterization
  - Task 1.2. FSW material characterization & properties
  - Task 1.3. Heat affected zone characterization and relationships
  - Task 1.4. Effects of sheet coatings on properties of weld and HAZ
  - Task 1.5. FSW characterization & properties of dissimilar alloy joints
- **<u>Task 2: Dissimilar Alloy Friction Stir Welding Development</u>**
  - Task 2.1. Dissimilar alloy weld development of AA5xxx and AA6xxx
    - Decision gate
  - Task 2.2. Dissimilar alloy weld development of precipitation strengthened alloys
  - Task 2.3. Dissimilar alloy weld development of 5x and 6x alloys to 7x
  - Task 2.4. Curvilinear high speed FSW development



Technical Approach (con't)

- **<u>Task 3: Production Readiness and Deployability</u>**
  - Task 3.1. Repeatability of high speed dissimilar alloy FSW
  - Task 3.2. Repeatability of high speed curvilinear FSW
  - Task 3.3. Tool durability
- **<u>Task 4: Weld Formability Modeling and Validation</u>**
  - Task 4.1. Developing Barlat Coefficients
  - Task 4.2. Simulating formability of dissimilar thickness Al TWBs
  - Task 4.3. Simulating formability of dissimilar alloy & thickness Al TWBs

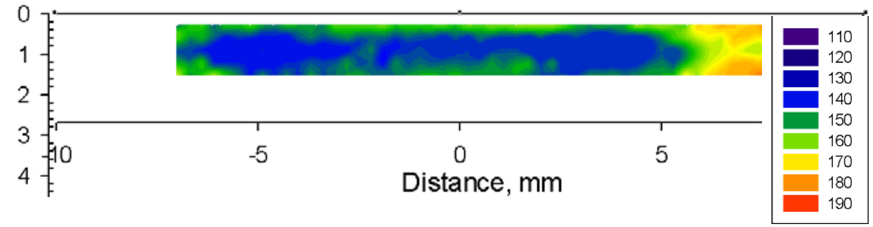


Technical Accomplishments: Task 1 - Relating Weld Parameters & Material Properties

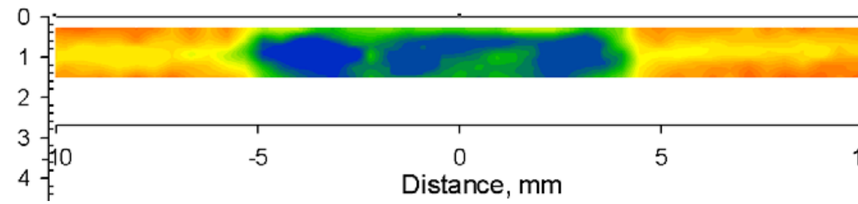
Previously reported work preparing for progress in current reporting period

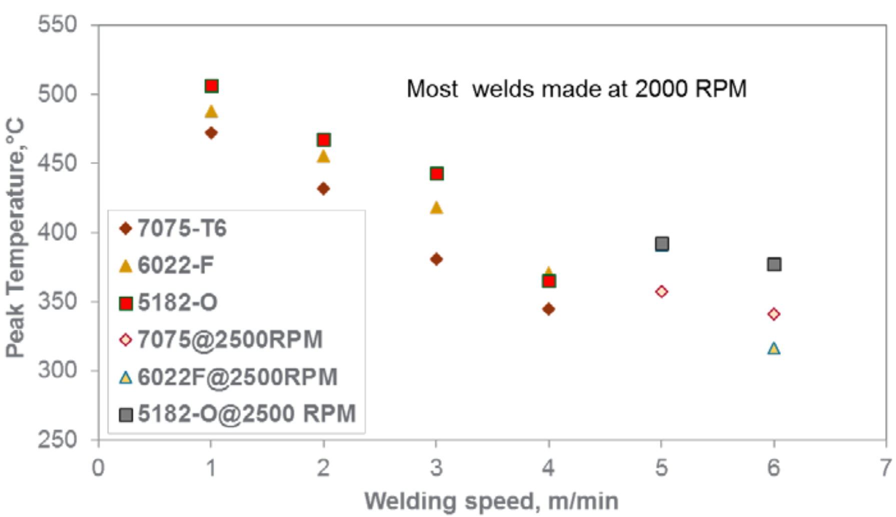
- Thermal monitoring during FSW from 1m/min to 6m/min in various alloys
  - 7075-T6, 6022-T4, 5182-O
  - Increased linear speed demonstrated
    - grain refinement
    - Peak temperature reductions
    - HAZ reductions
- Goal: Mapping the thermal history and effects of heat on material properties in appropriate aluminum alloys

2m/min, 2000 RPM, Tool T= 423°C

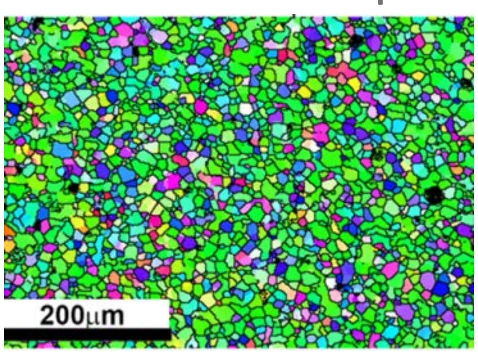


3m/min, 2000 RPM, Tool T= 375°C

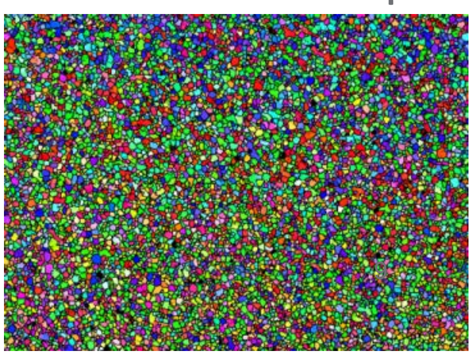




1m/min @ 1500 RPM
T_{max}=470°C
Average Grain Size: 8.7 μm,
Grain size variance: 27 μm

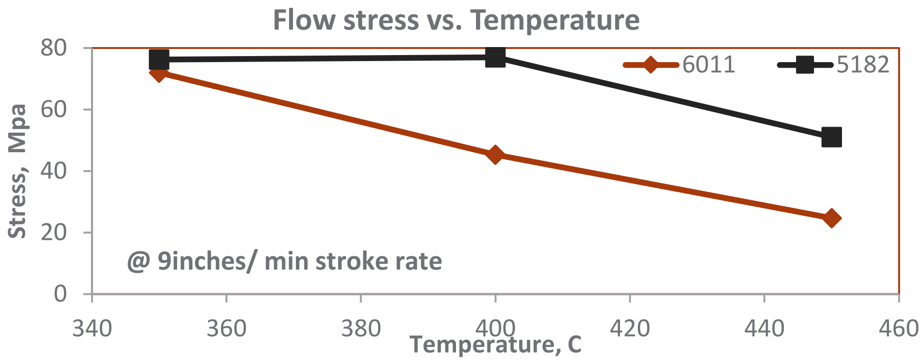


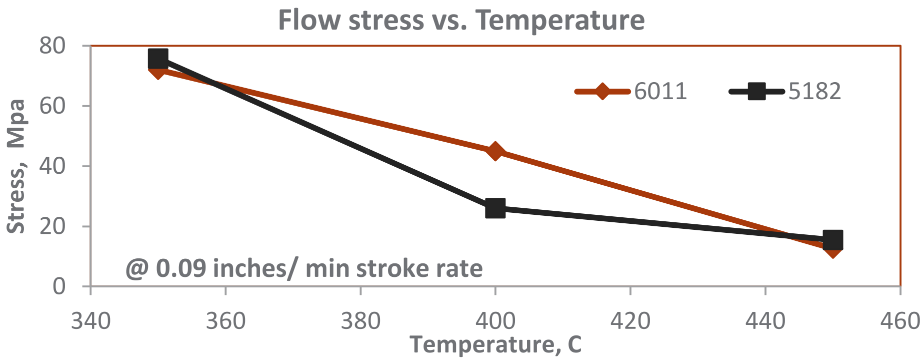
3m/min @ 1500 RPM
T_{max}=355°C
Average Grain Size: 5.6 μm,
Grain size variance: 8.3 μm



Technical Accomplishments: Task 1 - Relating Weld Parameters & Material Properties

- Goal: Prescribe the appropriate thermal window in which dissimilar alloys can be effectively joined in the solid-state (supporting 2016 Go-No-Go)

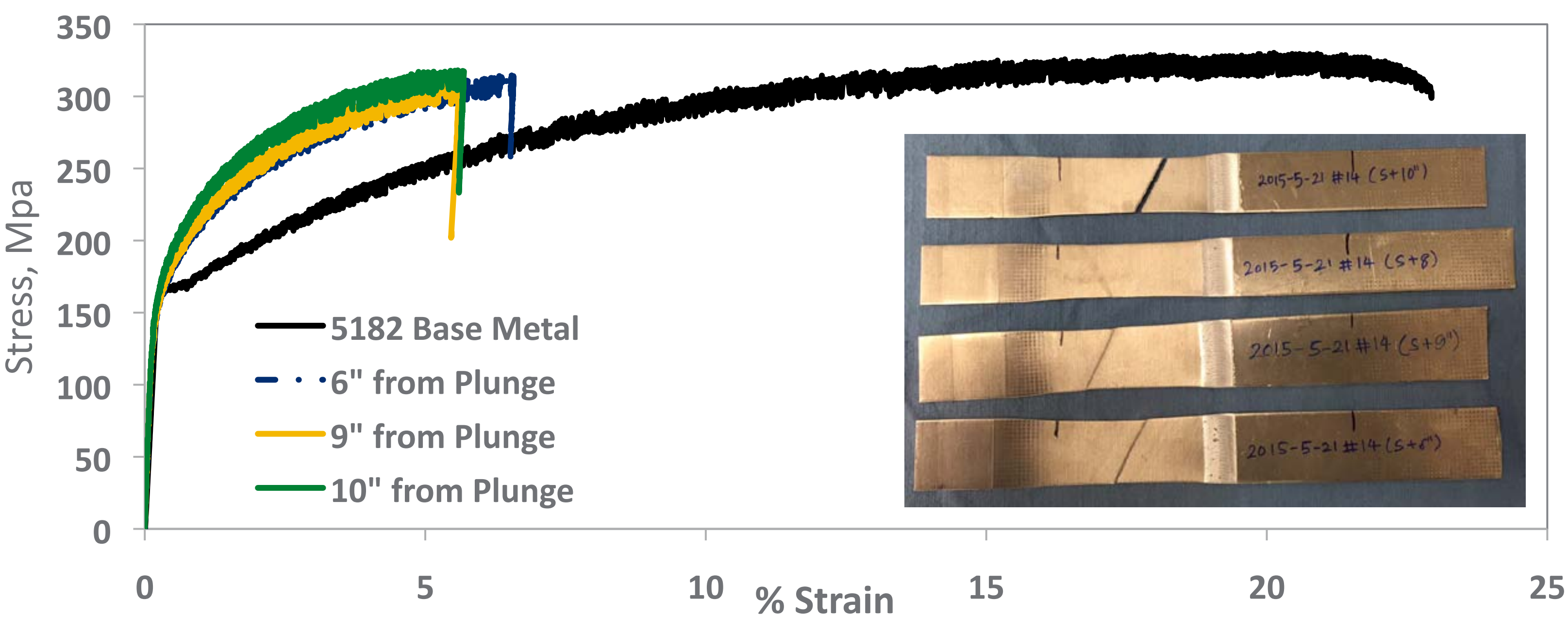




- Different alloys exhibit unique high temperature flow stress
  - *Resistance to thermal softening*
- In the event that one alloy experiences a drop in high temperature flow stress below the high temperature yield stress of another, the two become incompatible for FSW
- We see that at high and low strain rates different thermal regimes demonstrate compatible flow regimes
  - Lower temperature options are compatible with both alloys

Technical Accomplishments: Task 2 - Dissimilar Alloy Friction Stir Welding Development

- Goal: Demonstrate high-speed, friction-stir welded dissimilar alloy welded blanks between 5x & 6x alloys in linear and curvilinear geometries (FY16 Go-No-Go)
- Developed process parameters for effective joining of work hardenable and precipitation strengthened alloys
  - 1.1 mm - AA5182-O to 2.0 mm - AA6022-T4
- Established process development rules to enable rapid development across thickness variations and alloy combinations



Technical Accomplishments: Task 2 - Dissimilar Alloy Friction Stir Welding Development

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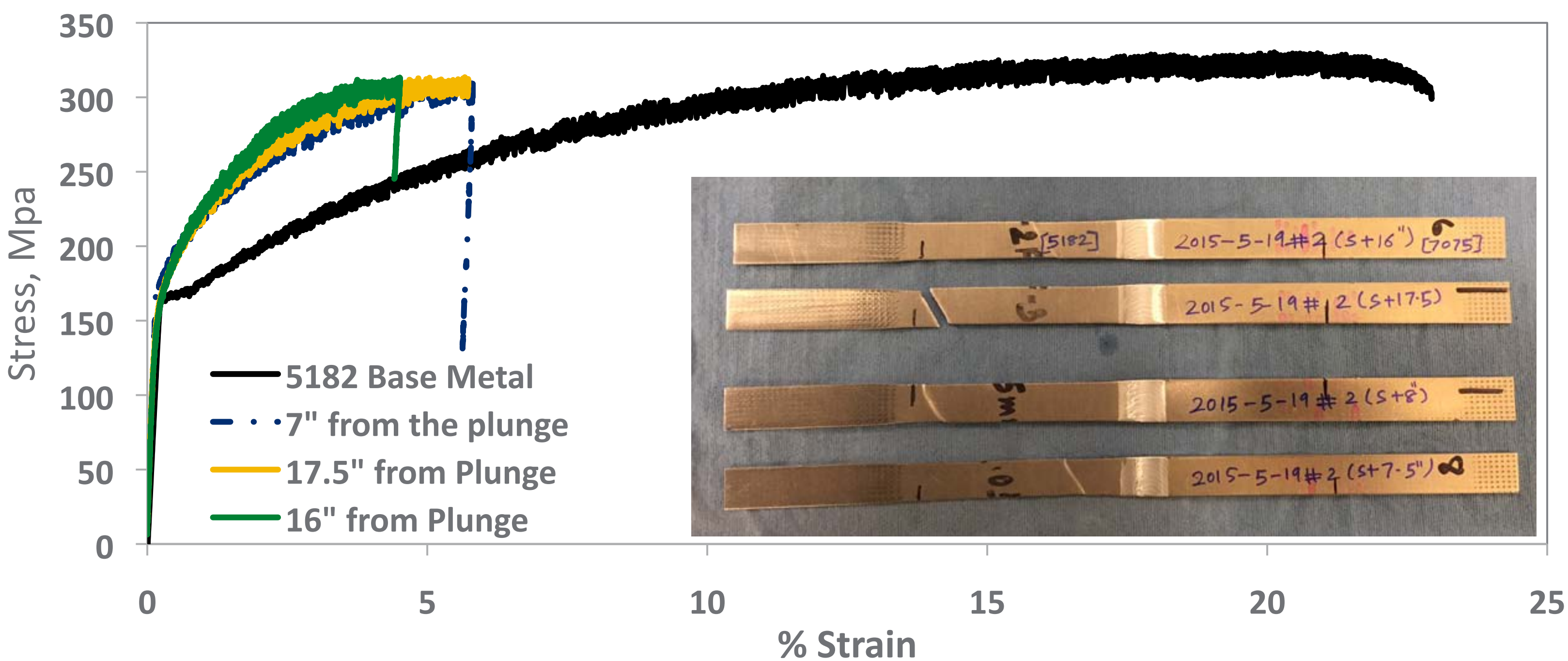
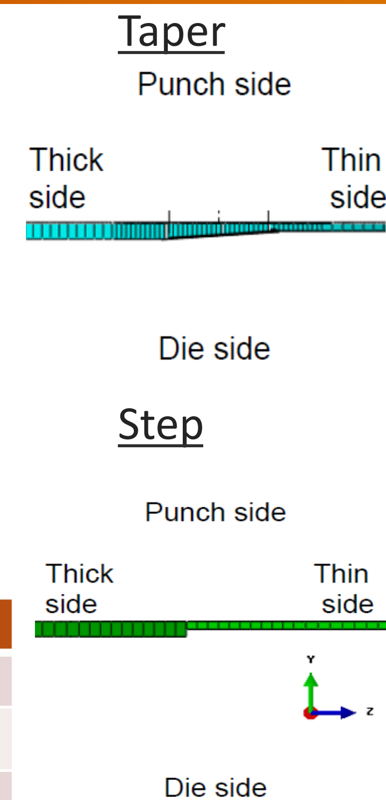
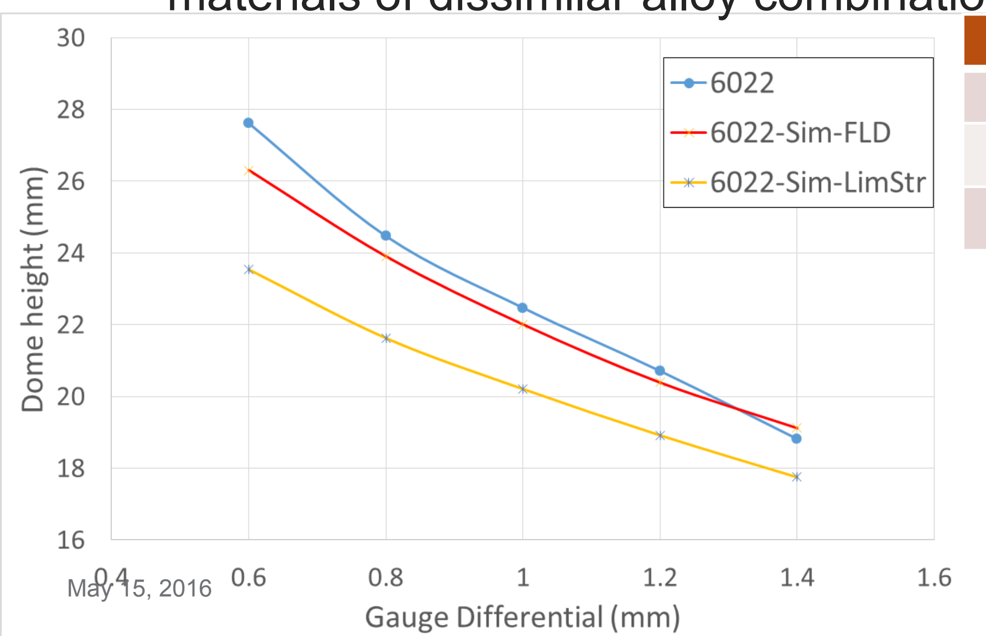
- Goal: Demonstrate high-speed, friction-stir welded dissimilar alloy welded blanks between 5x & 7x alloys (FY17 milestone)
- Developed process parameters for effective joining of work hardenable and ultra-high strength alloys
  - 1.1 mm - AA5182-O to 2.0 mm – AA7075-T6
- Established process development rules to enable rapid development across thickness variations and alloy combinations



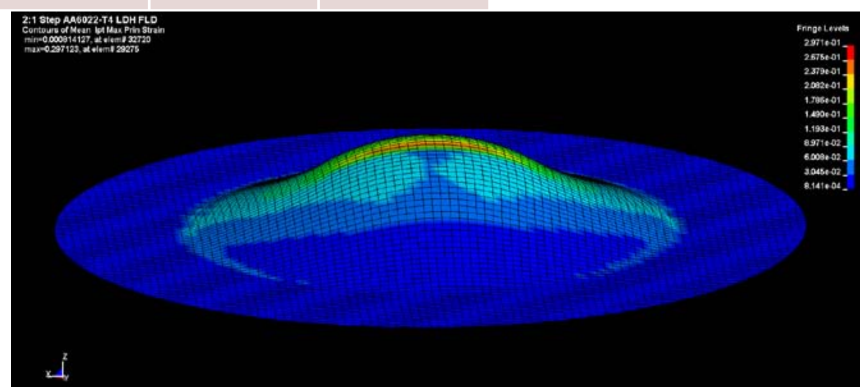
Technical Accomplishments: Weld Formability Modeling

- Introducing Barlat 2000 Coefficients to account for anisotropy and strain sensitivity precipitation strengthened alloys (AA6022-T4)
- Evaluated strain limits based on FLD and tensile data
  - Limiting strain based on tensile data was much more conservative than using the FLD as the limiting case
  - Validation of the model for base materials across varying gauge differentials was performed to prepare for welded materials of dissimilar alloy combinations



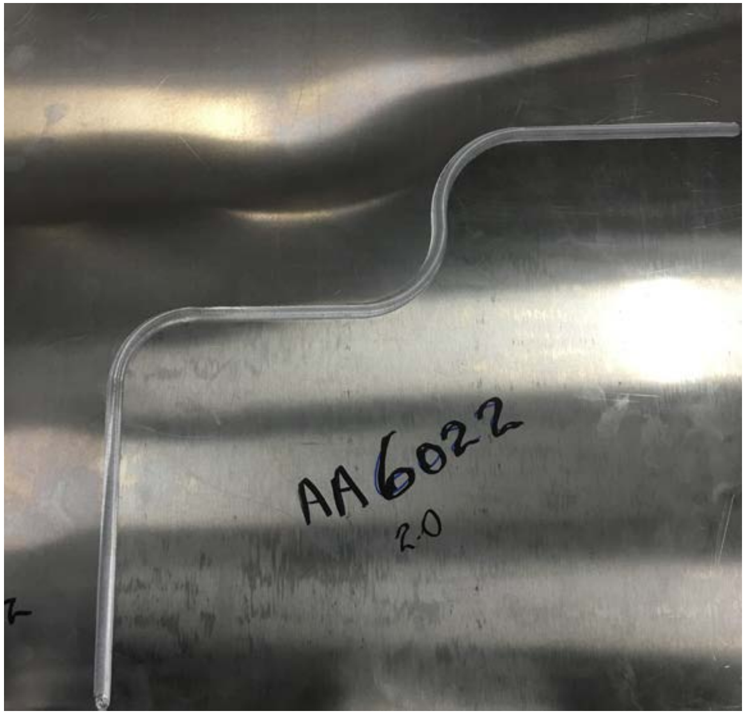


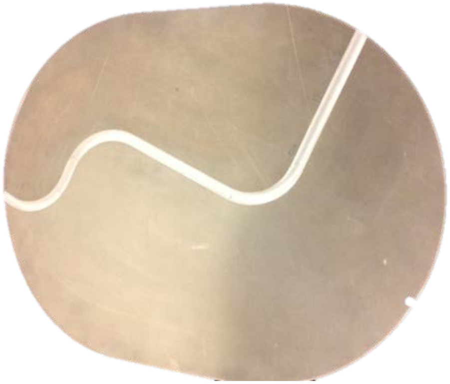
	Dome Heights (mm)	
	Step	Taper
Limit Strain	19.21	19.28
FLD	22.24	22.30



Technical Accomplishments: Curvilinear weld panels (2016 go-no-go)

- Curvilinear panel developed at TWB
  - 2 mm to 1 mm thicknesses
  - 1 corner with 50 mm radius
  - 2 corners with 60 mm radius
- Successful demonstration of translating linear high speed friction stir welding to a fully curvilinear geometry
  - Successfully completed FY16 Go-No-Go ahead of schedule





Responses to Previous Year Comments

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- Reviewer: *"it would be an improvement to see a table of success metrics, values, and milestones and when they will be accomplished."*
  - Gantt chart with milestones were added for clarification
- Reviewer: *"praised the collaboration with the material supplier, Alcoa, the process user, TWB, and the end customer, GM, as excellent, offering that they help drive the project forward, and also identify the acceptability of the results and the desirability of certain processing conditions to help the research team identify problems that need to be overcome." Barlat coefficients given as example*
  - The team whole-heartedly agrees that overall success is very much dependent on the unique goals of each team member being met.
- Reviewer: *"emphasized that the four-phase technical approach will address the critical issues with this enabling technology."*
  - Agreed, this approach is designed to overcome challenges with a deficit in material information of the dissimilar welded materials, develop stable and effective welding parameters for the dissimilar alloy blanks, provide essential scalability information, and develop an enduring predictive modeling capability for evaluating post-weld formability of the dissimilar alloy TWBs.

Collaboration and Coordination

- University Collaborators
  - Washington State University
    - Characterization of TWB joint and analysis of joint properties on process parameters
- Private Collaborations (complete automotive supply chain)
  - General Motors
    - Determine Barlat coefficients for weld material, product specific formability modeling, and market relevance, component stamping
    - High speed thermal evaluation
  - TWB Company, LLC.
    - High speed linear and curvilinear blank production, repeatability evaluations, tool durability during high volume production
  - Alcoa
    - Material provider, high temperature material properties, Barlat, formability

Remaining Challenges and Barriers

- Determining properties of dissimilar alloy weld metal
  - Task 1.5 – characterizing joint properties & material flow of dissimilar alloys
  - Task 2.3 - combining 7xxx with other precipitation strengthened alloys
    - Task 2.4 high-speed curvilinear deployment needs to be fully developed
- Production Readiness and Deployability of dissimilar alloy blanks
  - Task 3: addressing repeatability at the suppliers facilities
    - Task 3.1 & 3.2 Repeatability of the process in both linear and curvilinear geometries
    - Task 3.3 Tool durability study designed to simulate an entire shift of work
- Predictive engineering tools need to accommodate a combination of dissimilar alloys and dissimilar thicknesses
  - Addressed specifically in Task 4 – combined effort from PNNL, GM & Alcoa
    - Task 4.1 Introducing Barlat coefficients for welded material
    - Task 4.3 Demonstrate formability model for dissimilar alloy combinations
    - Task 4.4 Validate final model, and demonstrate predictive nature across other combinations

Proposed Future Work (planned)

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- Fall 2016: Disseminate in archival publication information on thermal effects of high speed FSW in various alloys (FY15 milestones)
  - Information now released for public use
- Fall 2016: Linear and curvilinear weld development of 7xxx to 6xxx alloys (FY17 milestone)
  - Develop weld parameters to support joining 5xxx and 6xxx alloys using high-speed FSW
  - Demonstrate weld quality with acceptable surface roughness, strength and post-weld formability
- Spring 2017: Demonstrate process repeatability and tool robustness across production mock-up equivalent to an entire shift at full-speed
- Summer 2017: Complete predictive modeling tools for dissimilar alloy TWBs using Barlat coefficients developed for the base material, weld material, etc. (FY17 milestone)
- Fall 2017: Validate the predictive model with additional material sets

FY16 Project Summary

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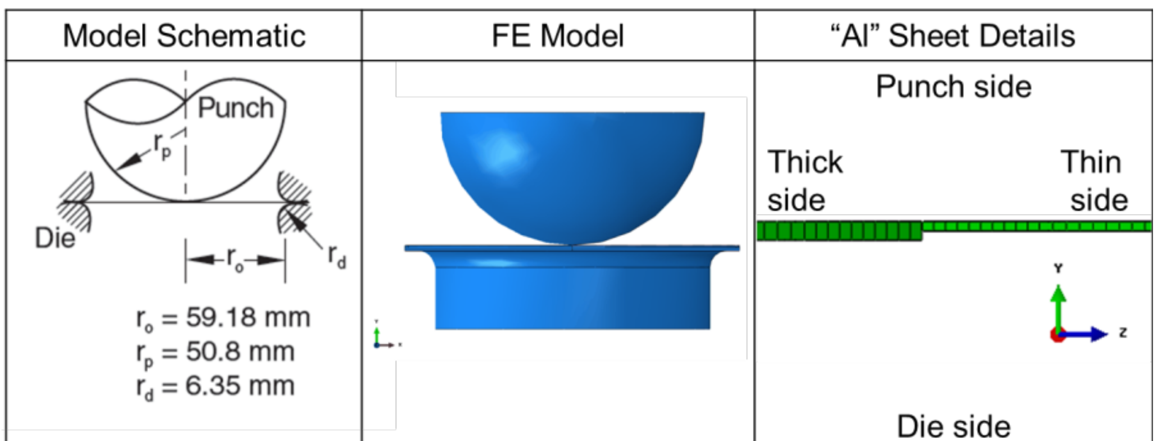
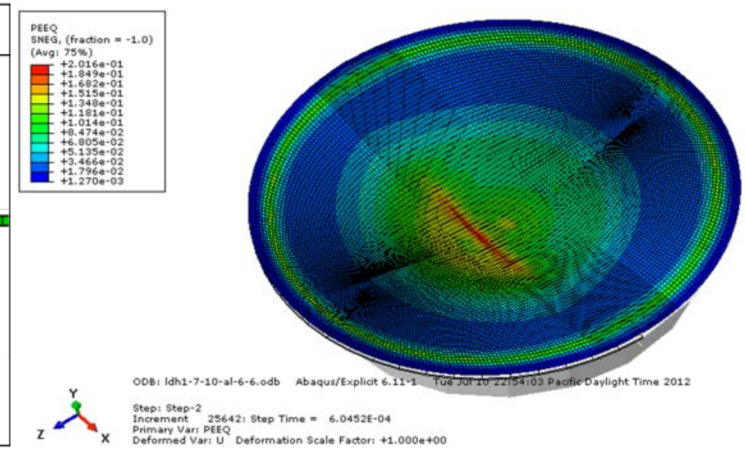
- Integrated high temperature flow stress information from material supplier with thermal telemetry to predict ideal thermal windows for joining dissimilar alloy combinations
- Developed high speed FSW parameters for welding dissimilar alloy blanks of AA5182 joined to both AA6022 and AA7075
  - Utilizing the data from the previous year's work on thermal effects and thermal telemetry as a function of welding speed.
- Demonstrated similar and dissimilar alloy, dissimilar thickness curvilinear capability between work hardenable and precipitation strengthened alloys
- Upgraded predictive modeling tools using Barlat 2000 coefficients demonstrating more accurate fit than with stress-strain behavior alone.
  - Validated the precipitation strengthened alloy AA6022-T4

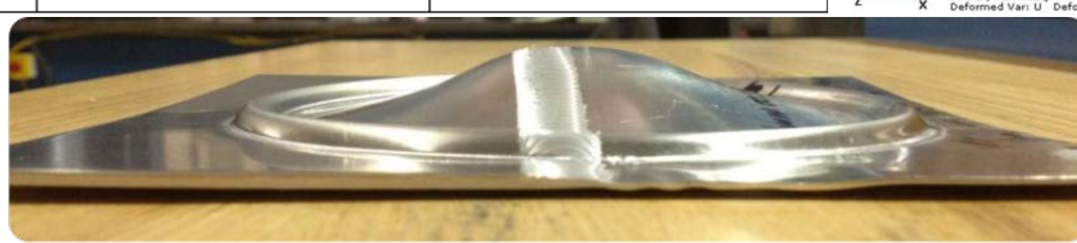
Technical Back-Up Slides

Formability Modeling – LDH Foundation

- 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







Numerically Predicted Post-Weld Formability

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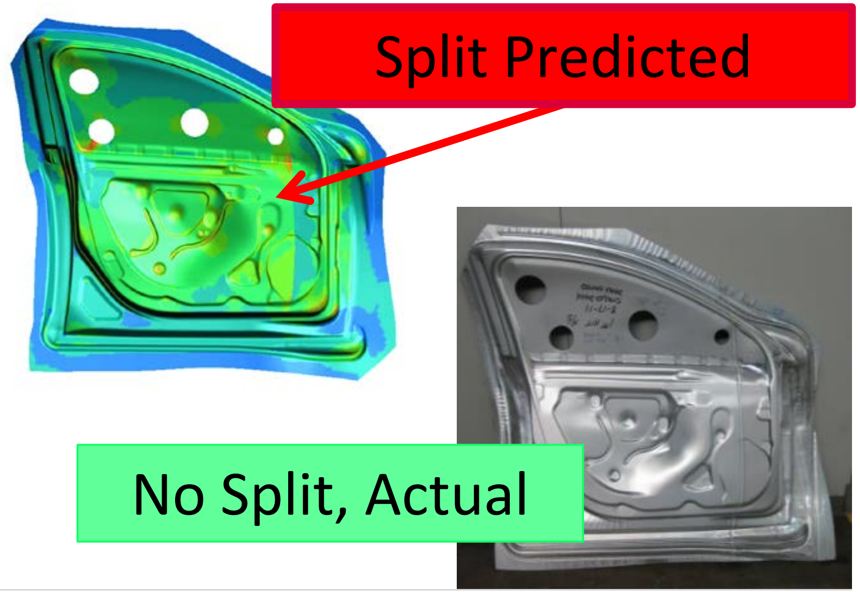
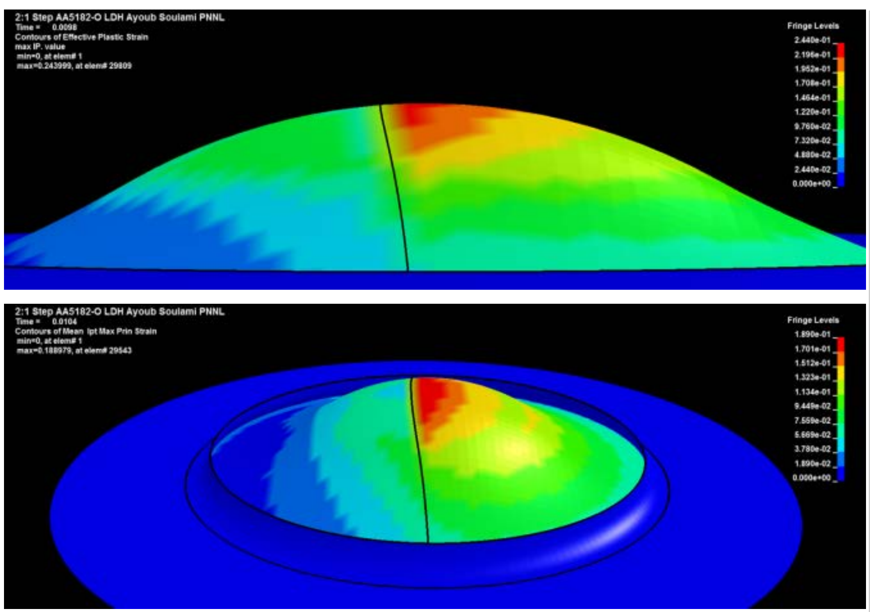
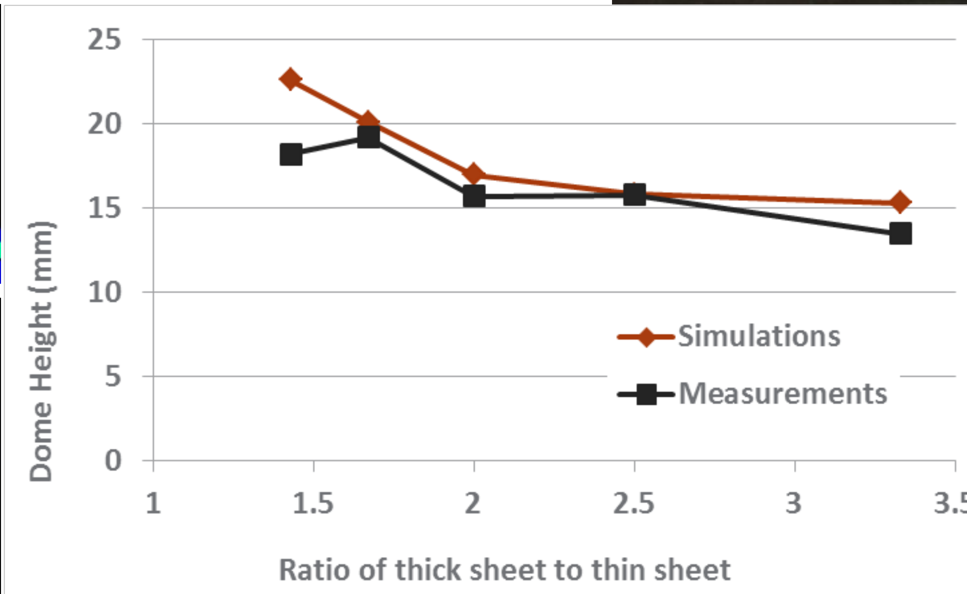
- Simulation capability being expanded to correct current numerical analysis
- LDH predictions show capability of trending across various sheet thickness ratios
- Modeling dome heights account for dissimilar thicknesses, but needs to be expanded for alloys and detailed part geometries







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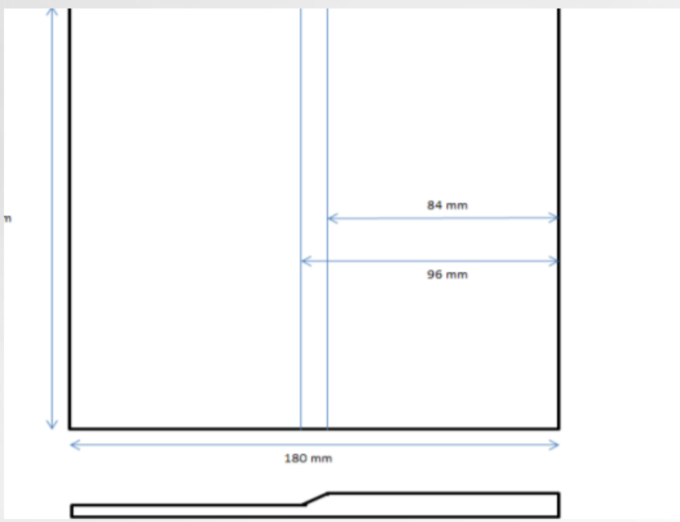
Simulations Schedule

- 2:1 thickness ratio with step and taper
  - Isotropic case with only base material (Al 5182-O)
  - Barlat 2000 Constitutive model
  - Limiting Strain set to 18%
- Five different thickness ratios with taper



Case	Thick Side (mm)	Thin Side (mm)	Ratio
a	2.0	0.6	3.33:1
b	2.0	0.8	2.5:1
c	2.0	1	2:1
d	2.0	1.2	1.67:1
e	2.0	1.4	1.43:1