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Engineered Fastening

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2015 DOE Vehicle Technologies Office Annual Merit Review

Self-Pierce Riveting (SPR) Process Simulation, Analyses, and Development for Magnesium Joints

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Stanley Engineered Fastening

June 12, 2015

PROJECT ID # LM074

U.S. DEPARTMENT OF ENERGY

Overview

Timeline

CRADA start date: December 2012

CRADA end date: June 2015

90% Complete

Barriers

- The rate and efficiency of SPR joining of Mg sheet needs to be improved.
- Non-destructive evaluation of SPR joints needs to be developed.
- Currently a limited supply base exists for the joining of Mg sheet.
- Predictive tools do not exist.

Budget

Total project funding:

- DOE - $560 K CRADA ($800 K total)
- Cost Share – 26%

Funding Year 1: $350 K
Funding Year 2: $450 K

Partner

Industrial CRADA Participant:

Stanley Engineered Fastening
- Dr. Siva Ramasamy
- Brendan Kenyon
- Ryan Belknap

Relevance – Project Motivation

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- Wider application of magnesium components offers a vehicle weight reduction of approximately 50 percent
  - Addresses key goals of the Lightweight Materials Program to significantly reduce the weight of passenger vehicles and enable development and commercial availability of low cost magnesium and its alloys by 2015

This is also an important project for Stanley's global development into magnesium SPR joining. *Currently Stanley Engineered Fastening does not offer a solution for high-rate mechanical joining of magnesium sheet products.*

- SPR is a viable method for joining similar and dissimilar metals involving Mg
- Project will enable the SPR joining technology to be used widespread in attaching magnesium intensive components and structures to similar and dissimilar metals

Relevance – Goals and Objectives

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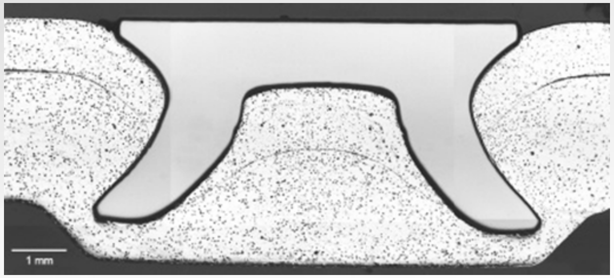
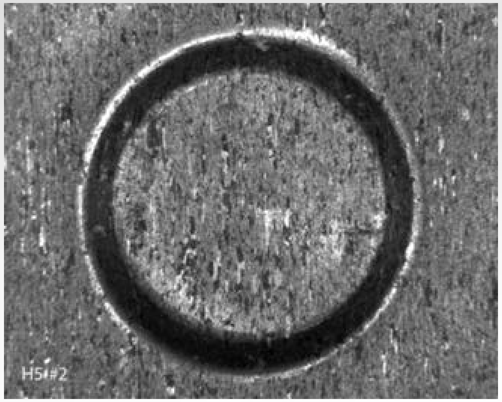
- Develop and enable the SPR process for joining magnesium components to reduce vehicle weight
  - Provide a reliable mechanical joining technology, incorporating localized heating into the SPR process for magnesium joint applications
  - Enable the success of mechanical fastening of Mg by assisting the Mg SPR process development and cycle time through rivet simulation and experiments
  - Enhance existing SPR technology through joint optimization when joining Mg similar/dissimilar joints



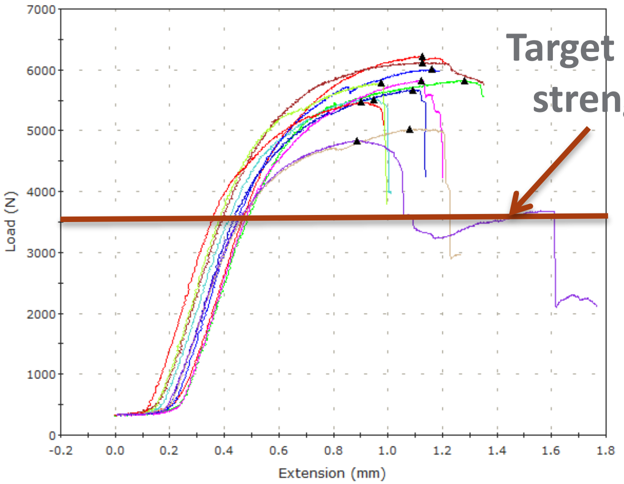
Desirable Mg SPR cross section created via induction heating (top) and representative image of tailside cracking in AZ31 SPR joint created at room temperature (bottom).

Relevance – Technology Assessment

- Target: Create Mg SPR joints with no tail side cracking - **Achieved**
  - Gap: Mg alloys have low ductility at room temperature and when conventional SPR processing is used with magnesium, rivet tail end cracking occurs
- Target: Produce Mg SPR joints with a minimum target joint strength of 1.5 kN * t (substrate thickness in mm) - **Achieved**
  - Gap: Cracks in the SPR joint are detrimental to the joint performance in terms of static and fatigue strength, as well as corrosion performance



Tailside of AZ31 Mg SPR joint with no tailside cracking.



Strength of AZ31 Mg SPR joints created at elevated temperatures with induction heating.

Relevance - Milestones

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	MILESTONE OR GO/NO GO DECISION	Status
Milestone June 2014	**Journal Article** Submit journal article to Journal of Materials Processing Technology on the numerical tool used to predict SPR joint performance of magnesium materials	**Complete**
Milestone Sep 2014 postponed to Mar 2015	**Joint Performance Characterization** Characterize SPR joint performance in terms of fatigue	**Complete**
Milestone Dec 2014 postponed to June 2015	**Design Guideline Development** Provide design guideline recommendations for effective SPR joining of magnesium	**On Track**

Approach - Solution to Successful Use of SPR with Magnesium

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- **Technology Development** - integrated solution to barriers through a combined modeling/experimental approach
  - Develop numerical tool to perform parametric study on process parameters (geometries, temperature, rivet material)
  - Validate through experimental/simulation to show localized heating of the piercing area is required
  - Identify the optimum set of parameters for a successful Mg SPR joint
  - Demonstrate successful Mg and Mg/Al joints can be produced utilizing localized heating
- **Technology Deployment**
  - Technology transfer via collaboration between PNNL and Stanley including transfer of modeling tool, development of processing parameters, and processing equipment necessary to achieve successful Mg SPR joint

Technical Accomplishments

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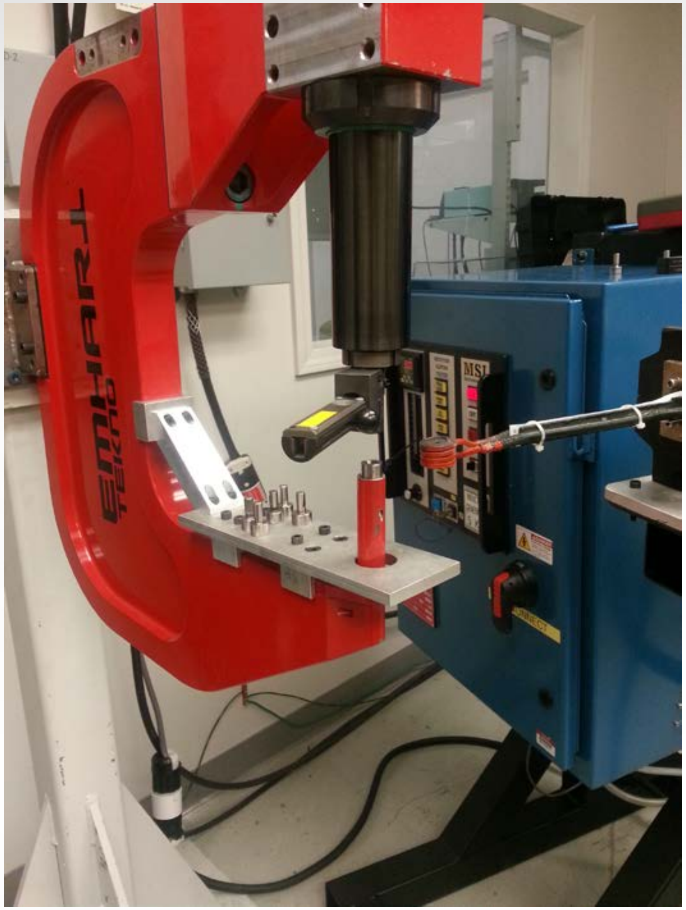
- PNNL and Stanley Engineered Fastening (Stanley) have developed and integrated a custom induction heater into a full-scale SPR system at Stanley
- Successfully made induction-heated Mg-Mg SPR joints within target cycle time = 3 s
  - Dissimilar joints of Al7075 to Mg AZ31 also achieved
- PNNL validated modeling results experimentally
  - Assessed interlock of various rivet/joint combinations through a variety of characterization techniques
- *Demonstrated for the first time a numerical modeling tool to integrate material properties of both the rivet and joined sheets, together with the rivet and die designs, to predict and optimize the SPR process*



FEM Modeling Tool

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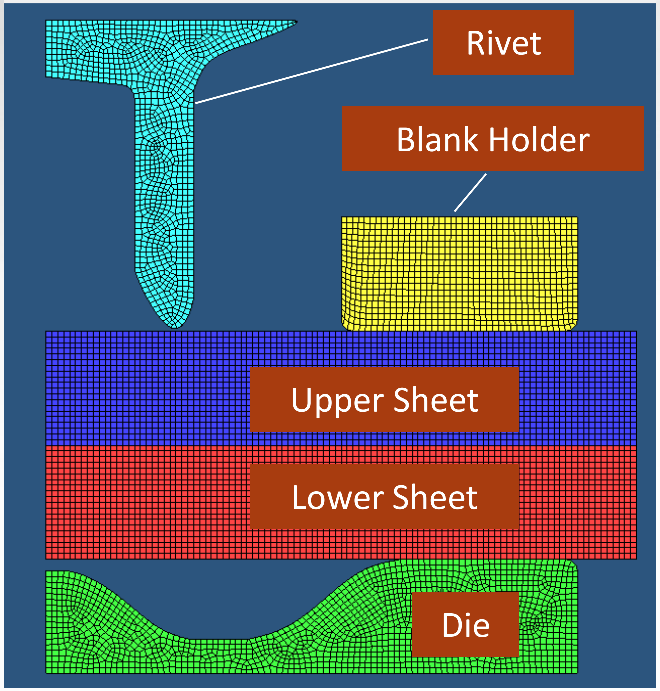
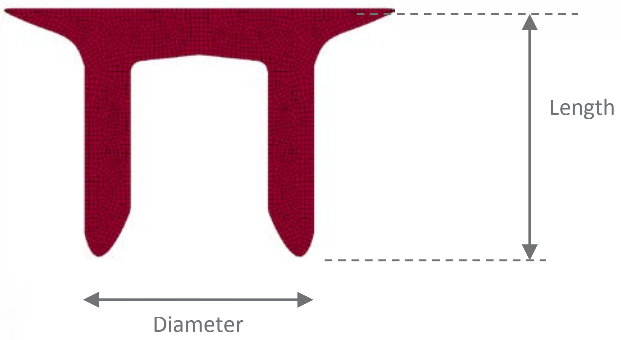
- Key to understanding role of heating mechanism, rivet material and geometry, and die geometry to achieve successful joints

- Model's Characteristics
  - Explicit Analysis - LS-Dyna
  - Axi-symmetric models
  - Rigid tools: Die, blank-holder, punch
  - Deformable materials: Carbon steel for the rivet and AZ31B and Al 7075 alloys for the sheets
  - Constitutive behavior: Elastic-Plastic-Thermal model
  - Thermo-Mechanical properties of AZ31 and Al 7075 obtained from tensile tests at various temperatures and strain rates
  - Coefficient of friction ranging from 0.1 to 0.35

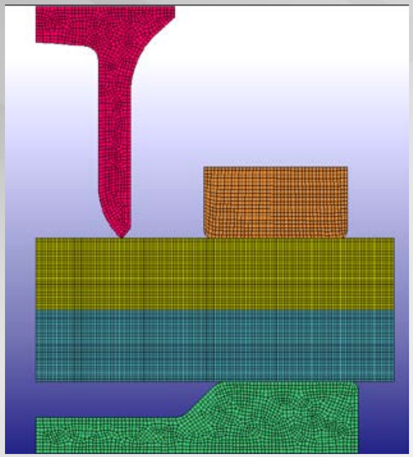


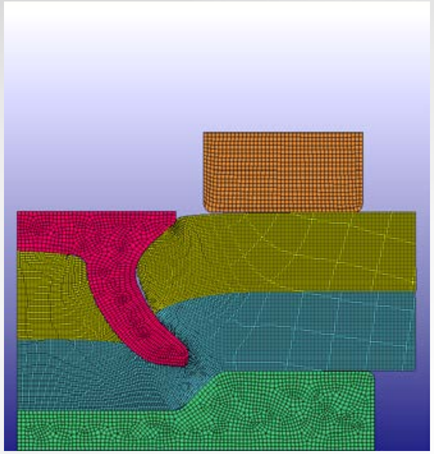


SPR FEM Model

T = 200° C, 2 mm to 2 mm AZ31

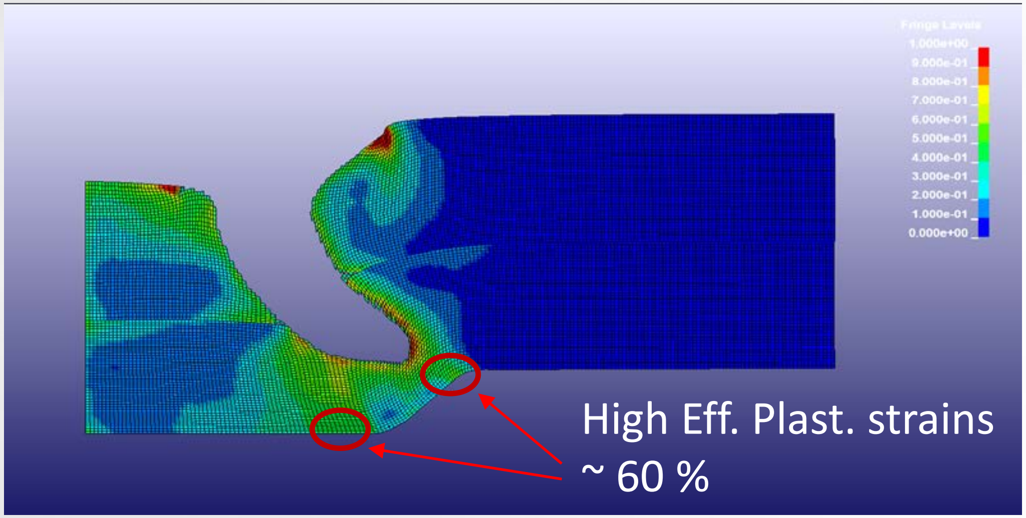
Axi-symmetric Die and Rivet





Good mechanical interlock of the joint and filling of the die observed at elevated temperature

Effective Plastic Strain Contours



- High strains observed at rivet tail and near bottom of sheet, consistent with experimental observations
- Increasing temperature (~50° C) will reduce strains and likelihood of failure

Model Validation: Load-Displacement

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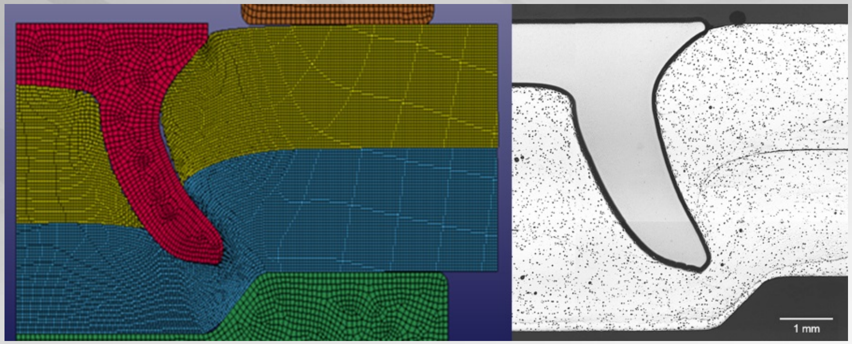
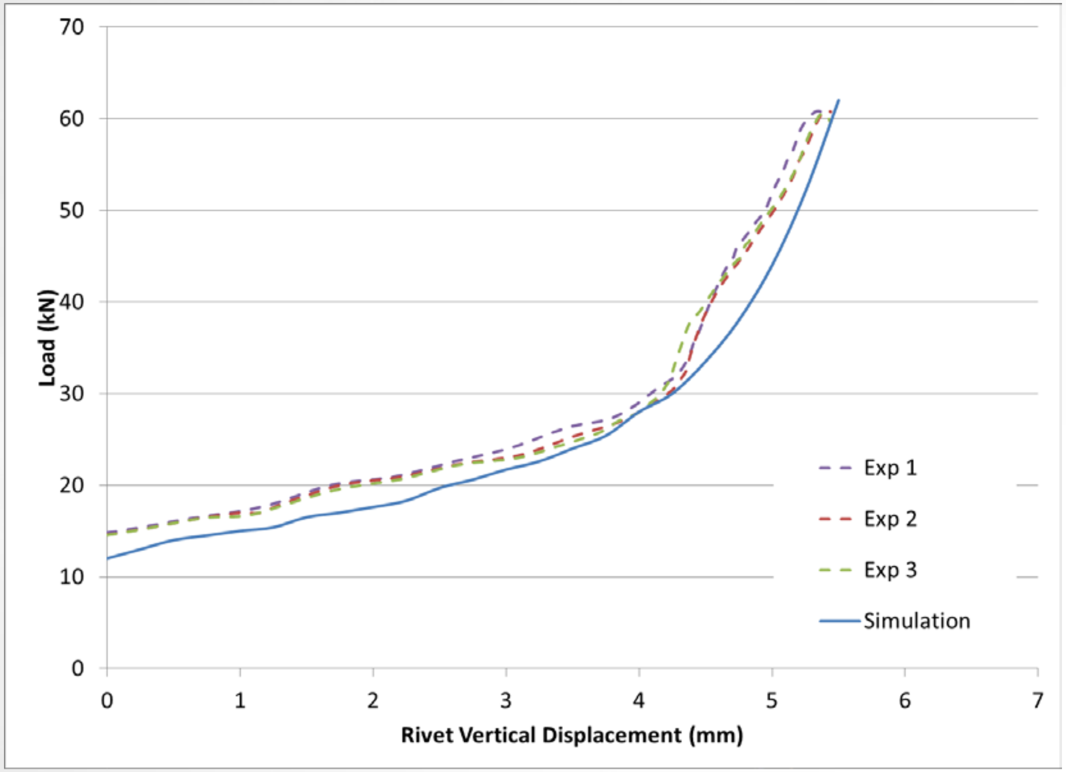
T = 200º C, 2 mm to 2 mm AZ31



- Load – Displacement data were measured experimentally and compared to the model predictions
- Model is slightly under predicting the loads, but the overall comparison for the Mg-to-Mg joints are good.



Evaluation of Mg SPR Joints

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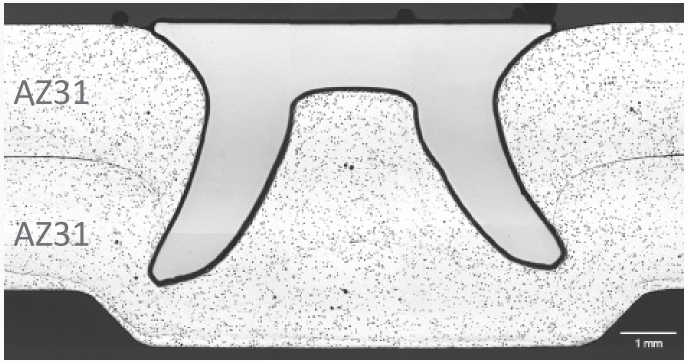
Target Criteria: Mg SPR joints with no tail side cracking

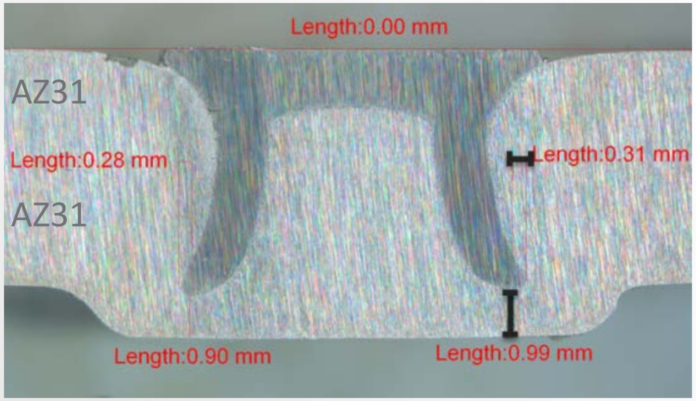
- Accomplished via induction heating
- Investigated varying combinations of Mg materials (AZ31 and Z-100), sheet thickness, rivets, and dies
  - By the end of project - 8 rivet and 9 die geometries for 5 different successful joint combinations
  - Elevated temperatures ranging from 100º to 300º C to assess joint formation
  - Final population created at ~250º C
- No cracks observed in cross-section of specimens created at ~180º to 300º C

100º C

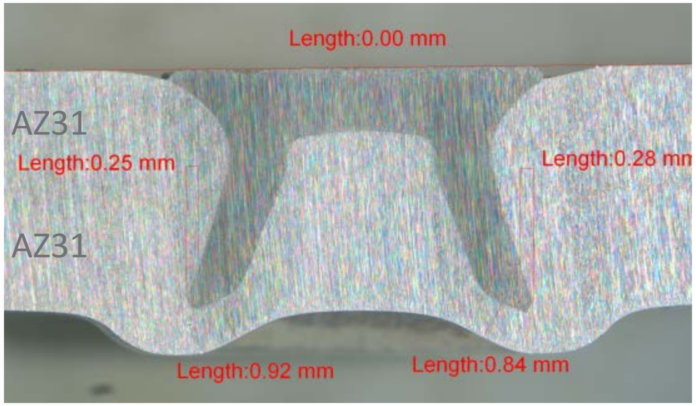
180º C



300º C



300º C

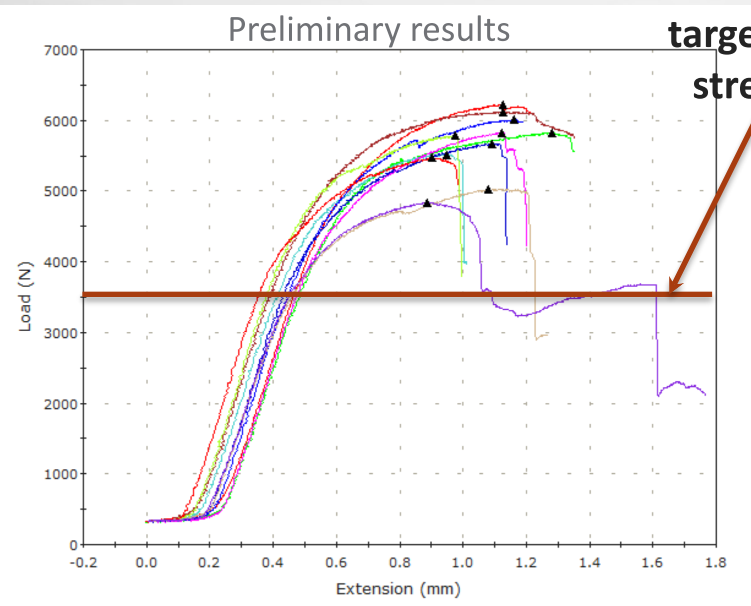


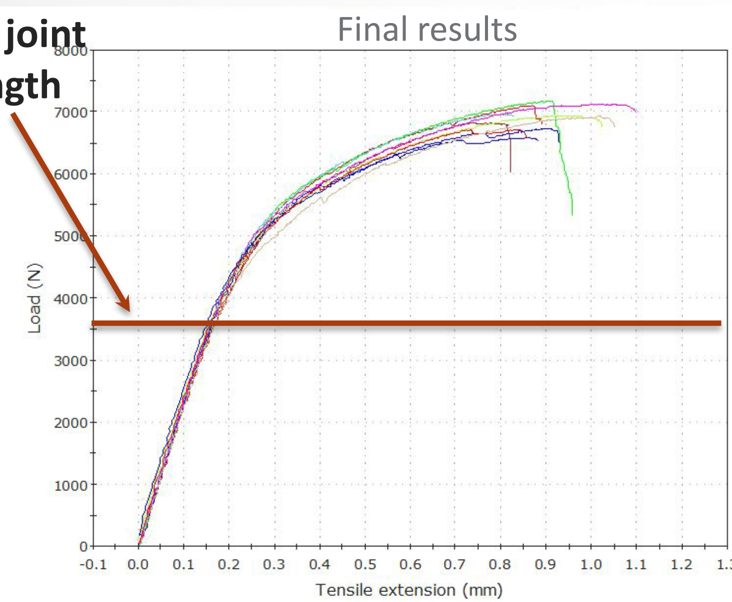
Joint Strength Evaluations under Lap Shear Loading

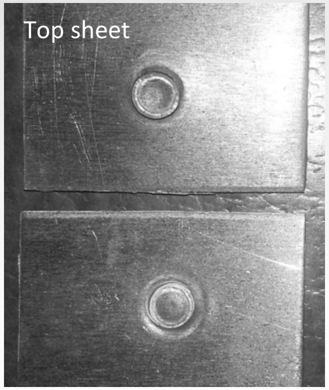
Target Criteria: Produce Mg SPR joints with a minimum target joint strength of 1.5 kN * t (substrate thickness)

- Joints created at elevated temperatures ranging from ~250º to 300º C
  - Final joint strengths achieved:
    - 2 mm to 2 mm AZ31 - 6.9 kN avg.
    - 1 mm to 2 mm AZ31 – 2.9 kN avg.

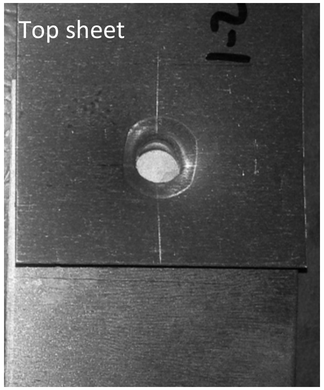
2mm-to-2mm target joint strength







2 mm to 2 mm joints tail pull-out observed



1 mm to 2 mm joints shear-out observed

NOTE: Optimization of rivet design and heating process led to more repeatable results with improved strengths

Fatigue Evaluations under Lap Shear

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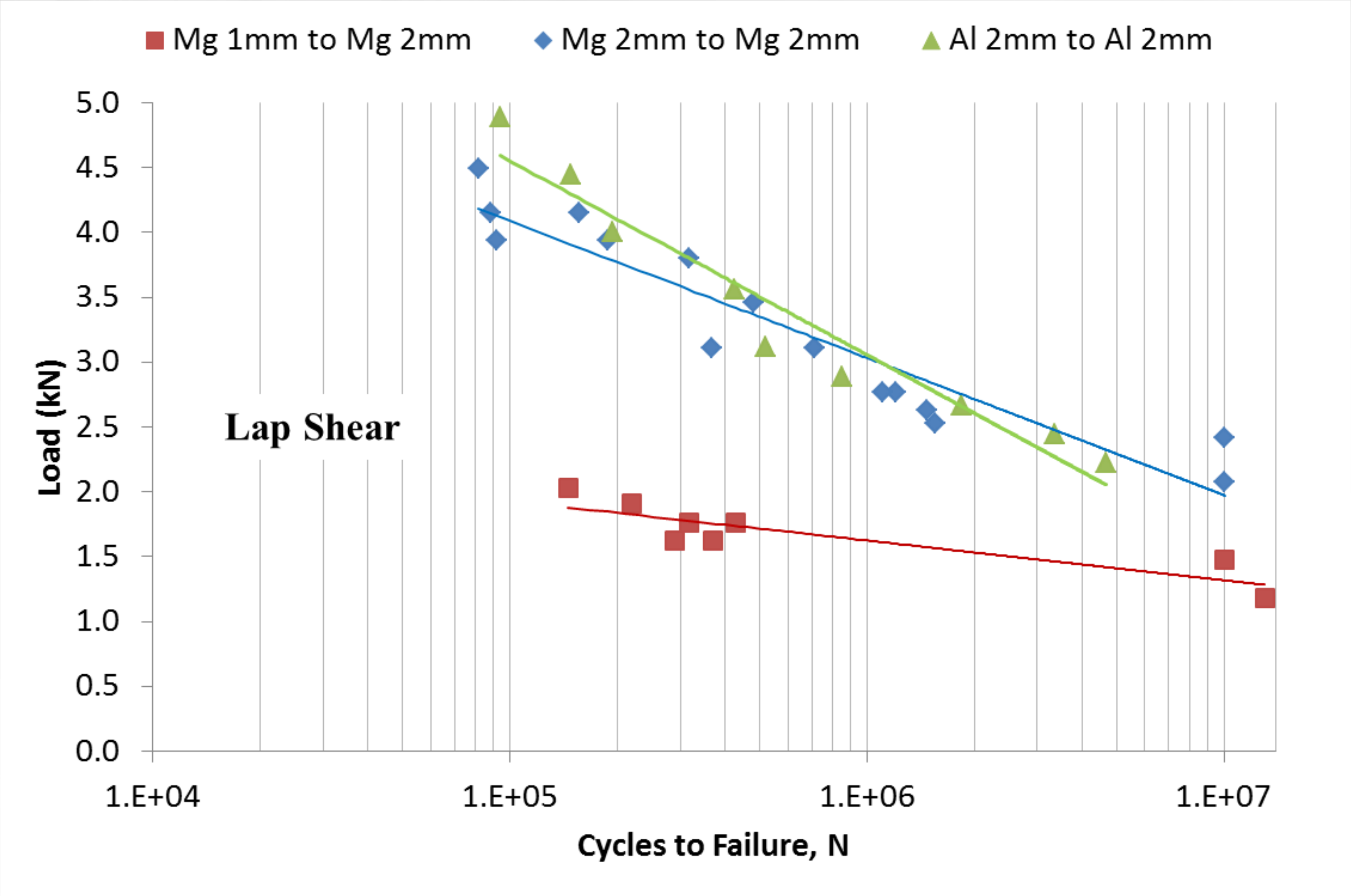
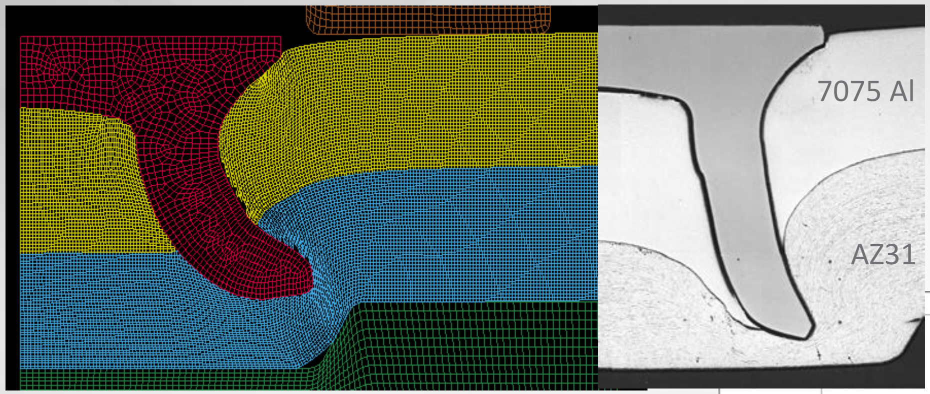


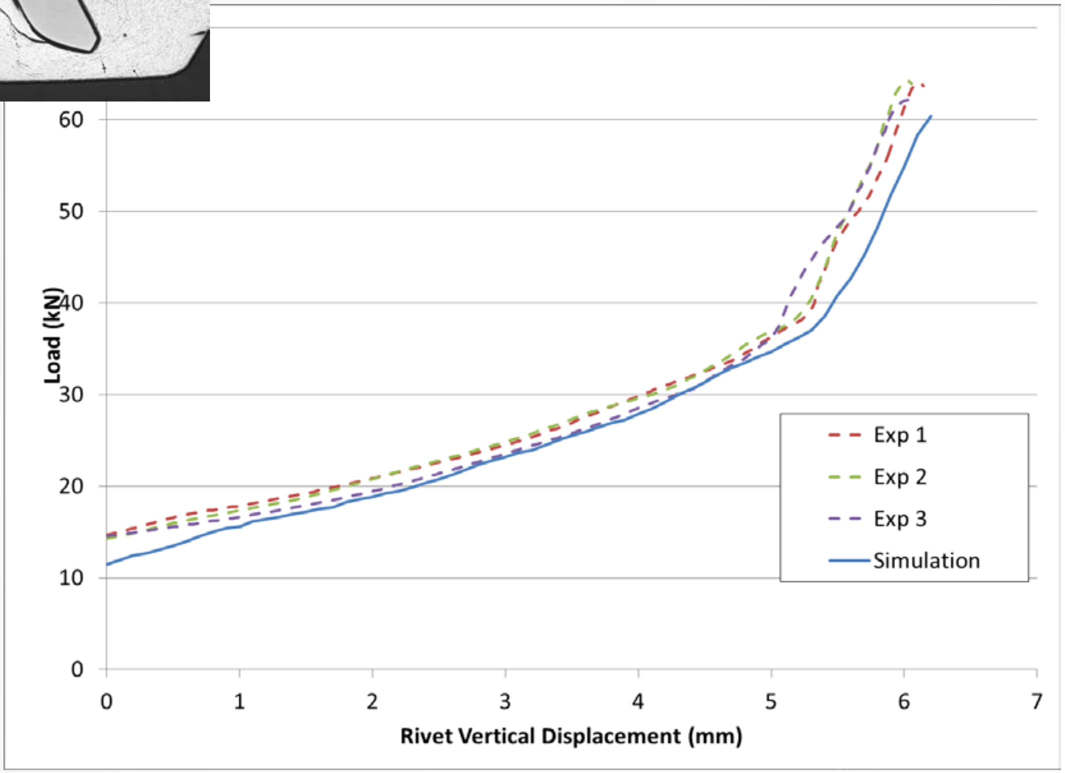
- As expected, superior fatigue performance was observed for 2 mm to 2 mm joints as compared to 1mm-to-2mm joints for Mg sheets
- For comparative purposes, at the higher load amplitudes, the Al 5182-O joined sheets had slightly better fatigue performance than the Mg joints. Overall behavior is quite similar. Mg outperforms Al at higher cycles.

Exploration of Dissimilar Material Joints

T = 250 C, 2 mm Al 7075 to 2 mm AZ31



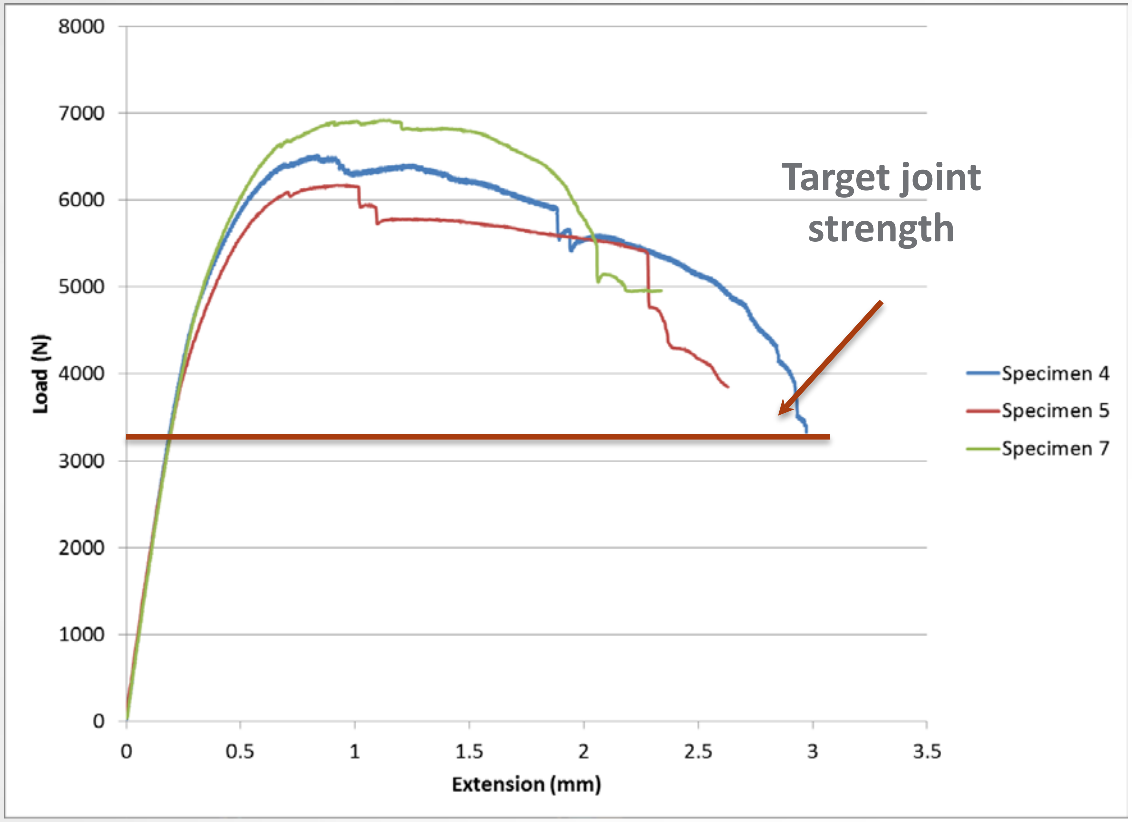
- Modeling tool was used to explore Al 7075 joined to Mg AZ31
  - Preliminary joints created
  - No tail-side cracking observed
- Validation of tool performed with dissimilar joint combination



Exploration of Dissimilar Material Joints

- Preliminary joint strength results show target strengths are achievable.
- Due to thermal instability of the Al 7075 alloy, slight variation in heat input was attributed to inconsistent joint strength behavior.

T = 250 C, 2 mm Al 7075 to 2 mm AZ31



Development of FEM Model

Lap Shear – Rivet Material Study

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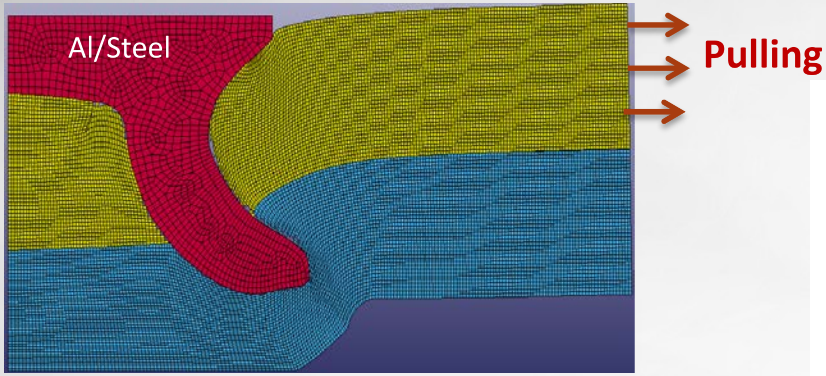
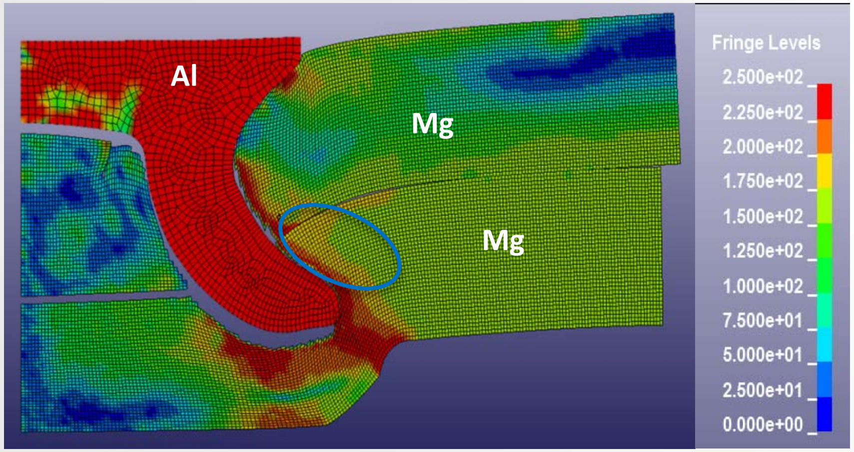
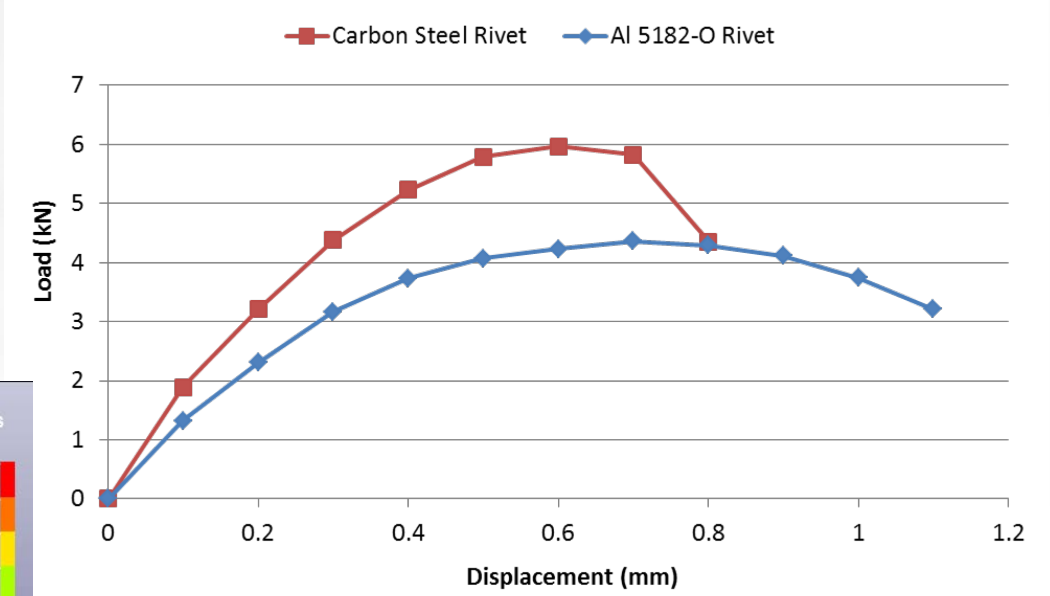
- Lap shear simulations were performed on Mg-to-Mg SPR joints using Carbon Steel and Aluminum Rivets
- After simulating the SPR joining, die and sheet holder were removed and adequate boundary conditions applied on the remaining parts to simulate Lap Shear
- Predicted joint strength is higher for Steel rivets as compared to Aluminum 5182-O rivets



Von Mises Stress Contours





Responses to Previous Year Comments

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Approach:

- Accuracy/speed of the temperature measurements was improved by utilizing fine-wire thermocouples with fast response times (accurate thermal data).

Technical Accomplishments:

- Predictive modeling of crimping, as an extension to the SPR process modeling was not evaluated due to prioritization and time constraints.
- Application of Mg sheet joining by heated SPR has yet to be demonstrated commercially, by Bollhoff, or any other company.

Collaboration:

- A pathway to commercialization is under discussion with Stanley. Their interest in the technology (modeling and heating process) has been expressed explicitly to the PNNL team.

Future Research:

- With continued industrial interest from Stanley and automotive OEMs into lightweight, dissimilar metal joining, there are several key aspects the team will propose for follow-on funding, including advanced rivet materials and extension of the numerical model .

Collaborations

- Stanley Engineered Fastening Cooperative Research and Development Agreement (CRADA) Partner
  - Key contributions included:
    - Design development of induction heat system (PNNL & Stanley)
    - Integrated induction heat system into SPR system
    - Heat joining trials (PNNL & Stanley)
      - Created room temperature and elevated temperature Mg SPR joints
      - Created elevated temperature dissimilar Al/Mg joints
      - Assessed interlock of joints created
    - Produced and implemented new die designs (Stanley)

Next Steps

- PNNL and Stanley are developing the design guidelines and recommendations for successful Mg SPR joining
  - Technical paper submitted to *Journal of Materials Processing Technology*
- Technology deployment of modeling tool to Stanley
- Due to success of the heated SPR process, Stanley is interested in exploring automation of the induction heating system
- Stanley is also interested in furthering the research using Mg castings, dissimilar metals and alternate rivet materials
- Present results at international conference "*Mg 2015 – Magnesium Alloys and Their Applications*", October 2015, Korea.

Conclusions

- Mg SPR joints were made using conventional rivets and dies
- Heating mechanism is necessary to produce mechanically sound magnesium joints
- Optimization of rivet design and processing lead to more repeatable and improved strengths
- Modeling tool was key to understanding the roles of rivet and die geometry on joint integrity
  - ***Industry partner recognized value of the numerical modeling tool to integrate sheet material properties and physical measurements with the rivet and die designs to optimize the SPR development process***