Stanley Engineered Fastening

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2014 DOE Vehicle Technologies Annual Merit Review

SPR Process Simulation, Analyses, and Development for Magnesium Joints

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Stanley Engineered Fastening

June 18, 2014

PROJECT ID # LM074

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

CRADA start date: December 2012

CRADA end date: December 2014

70% Complete

Barriers

- Tail side cracking of Mg sheet/casting due to lack of ductility at room temperature
- Lack of desired joint properties
- Lack of acceptable processing parameters

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 vehicle application of magnesium components offers a potential 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.

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

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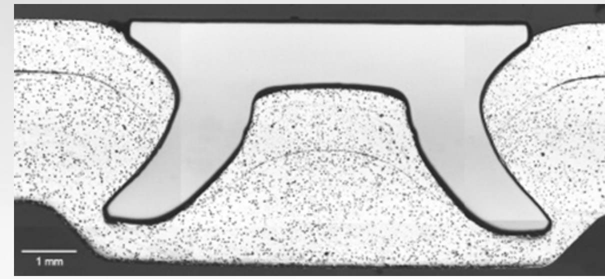
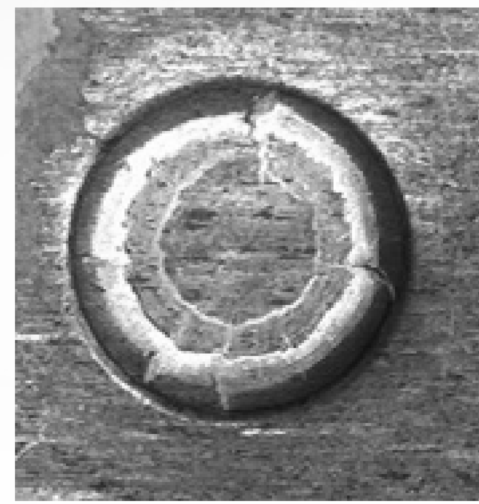
Relevance – Goals and Objectives

- Develop and enable the SPR process for joining magnesium components to reduce vehicle weight
  - Provide a reliable mechanical joining technology 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

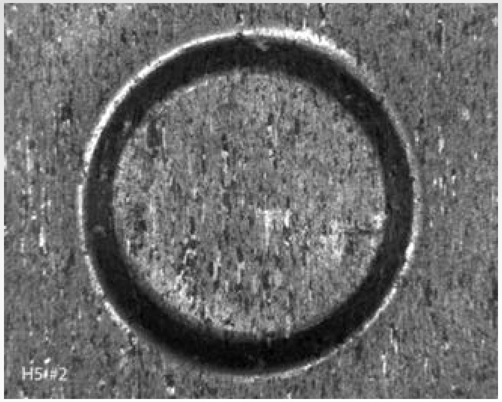




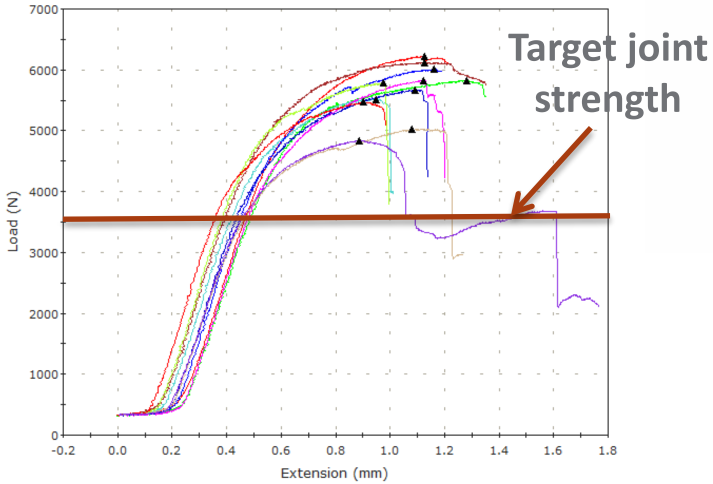
Mg SPR cross section (top) and representative image of tailside cracking in AZ31 SPR joint (bottom).

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 can be 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.



Preliminary strength results of AZ31 Mg SPR joints created at elevated temperatures with induction heat system.

Relevance - Milestones

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	MILESTONE OR GO/NO GO DECISION
Milestone Mar 2013	**Numerical Tool** Demonstrate localized heating will achieve the necessary predicted values to create Mg SPR joints
Decision Gate Sep 2013	**Create Mg SPR joints without tail-side cracking** Produce joint combinations with implemented localized heating mechanism where no visible cracks can be present in the substrate
Milestone Dec 2013	**Joint Strength** Produce Mg SPR joints with a minimum target joint strength of 1.5 kN * t (substrate thickness)
Milestone June 2014	**Journal Article** Submit journal article to Journal of Materials Processing Technology regarding development of numerical tool for SPR joining of magnesium materials
Milestone Sep 2014	**Joint Performance Characterization** Characterize SPR joint performance in terms of fatigue and corrosion
Milestone Dec 2014	**Design Guideline Development** Provide design guideline recommendations for effective SPR joining of magnesium

Schedule

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	FY2013			FY2014				FY2015
Quarter	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Phase 1: SPR Modeling								
1.1 Rivet Process Simulations								
1.2 Temperature Ranges Predictions								
1.3 Temperature Profiling of Local Heating Mechanisms								
Decision Gate								
Phase 2: Process Development and Analyses								
2.1 Heating System Development and Integration								
2.2 Process Development								
Decision Gate								
2.3 Joint Performance Characterization								
Phase 3: Mg Joint Optimization and Characterization								
3.1 Parametric Study on Rivet Material, Rivet Geometry, and Die Design								
3.2 Alternate Rivet Materials Characterization								
3.3 Design Guideline Development								

Approach - Solution to Successful SPR and Magnesium

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- **Technology Development** - integrated solution to overcome barriers by developing 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 development of processing parameters and processing equipment necessary to achieve successful Mg SPR joint

Technical Accomplishments

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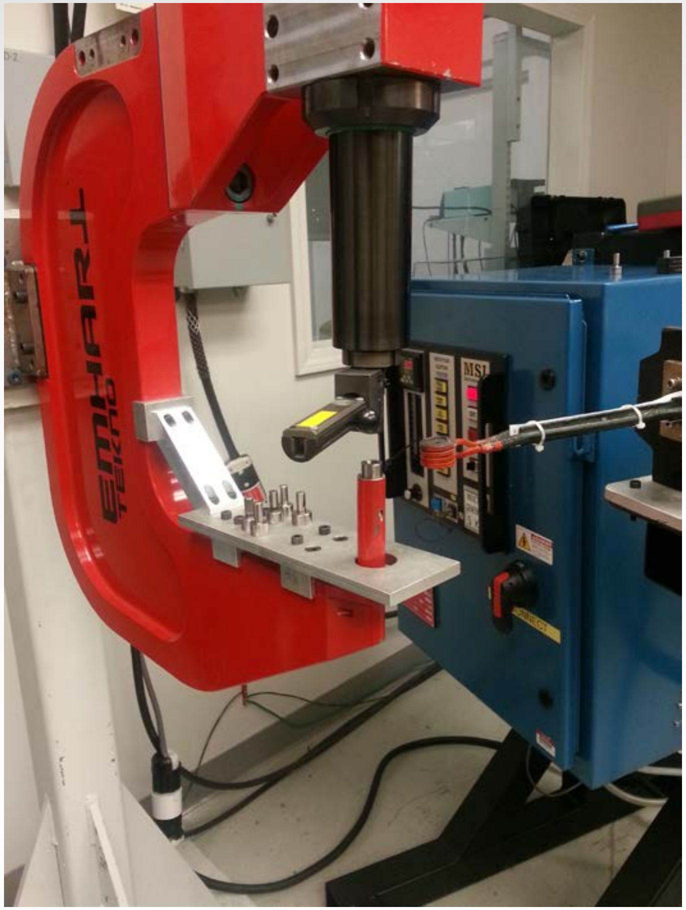
- PNNL and Stanley have developed and integrated a custom induction heater into a full-scale SPR system at Stanley Engineered Fastening
- Heated Mg-Mg SPR joints successfully made
- PNNL has validated the FY13 modeling results experimentally by forming joints at both room temperature and elevated temperature using induction heating
- Preliminary strength results under lap shear loading exceed the 1.5 kN x t goal



Implementation of Induction Heating System

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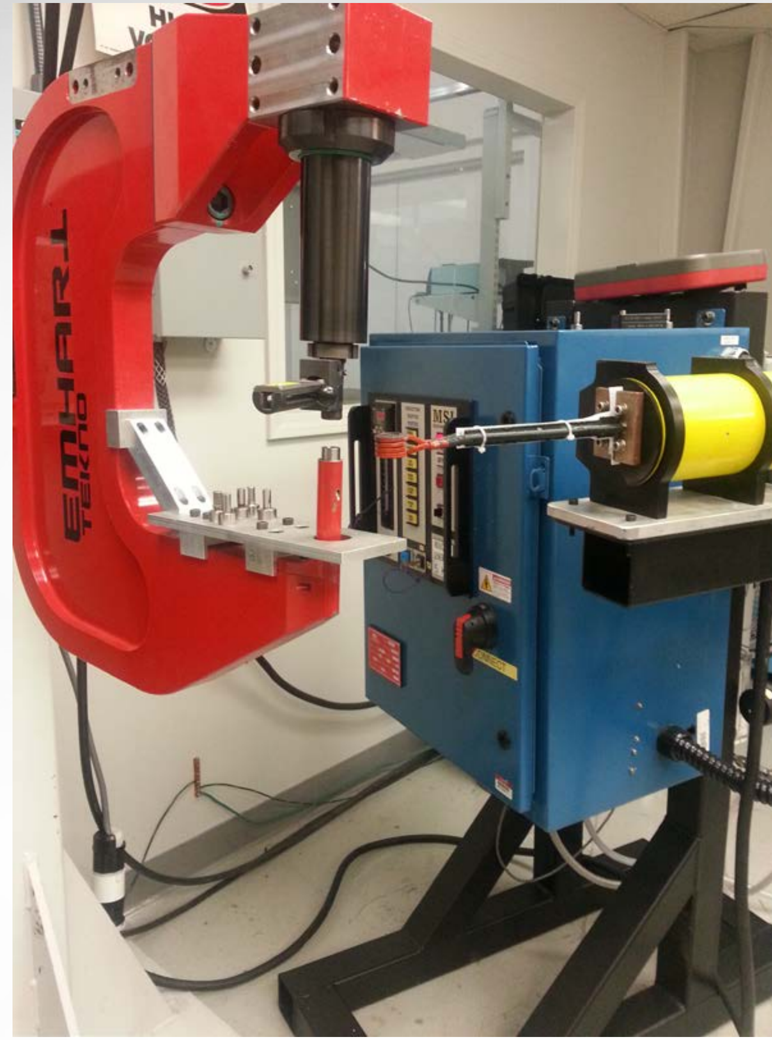
- Custom designed induction heater built by MSI Automation integrated into Stanley SPR joining system at Stanley's R&D facility located in Chesterfield, MI
- Performed preliminary heating and joining trials
- Reached target temperatures (~300 C) in 1 to 3 s with overall cycle times of 3 to 5 s
  - Target cycle time = 3 seconds



Induction heat station integrated to SPR unit.

Evaluation of Mg SPR Joints

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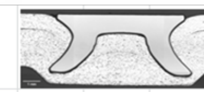
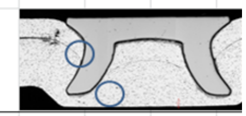
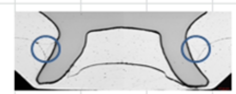
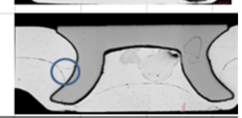
- Investigated varying combinations of materials (AZ31 and Z-100), sheet thickness, rivets, and dies
  - **Target Criteria: Create Mg SPR joints with no tail side cracking**
    - 7 rivet and 8 die geometries for 4 different joint combinations
    - Elevated temperatures ranging from 100 to 300 C to assess joint formation

1	Top Layer	Top Layer Thickness (mm)	Bottom Layer	Bottom Layer Thickness (mm)	Sample #	Rivet	Head Penetration Setting (mm)	Setting Force (kN)	Measured Head Height (mm)	Notes
14	AZ31	1.00	AZ31	2.00	7	R1	0.05	49.93	-0.04	slight cracking on button
15	AZ31	1.00	AZ31	2.00	6	R1	0.05	43.51	-0.02	severe cracking on button
16	Z-100	1.50	Z-100	1.50	6	R1	0.05	49.35	0.00	cracking around button
17	Z-100	1.50	Z-100	1.50	10	R1	0.00	44.00	0.08	severe cracking around button
18	Z-100	1.50	AZ31	2.00	6	R1	0.05	41.66	0.04	severe cracking around button
19	Z-100	1.50	AZ31	2.00	1	R1	0.00	59.31	0.02	cracking on bottom of button
20	AZ31	2.00	AZ31	2.00	7	R2	0.00	56.14	-0.02	Cracks material
21	AZ31	2.00	AZ31	2.00	12	R3	0.00	59.90		severe cracking on backside
22										

Row	Top Layer	Top Layer Thickness (mm)	Bottom Layer	Bottom Layer Thickness (mm)	Sample #	Rivet	Head Penetration Setting (mm)	Setting Force (kN)	Measured Head Height (mm)	Notes	Label	Cross-section
2	AZ31	1.00	AZ31	2.00	1	R2	0.00	57.72	-0.11	No cracking on button, 200C; no cracks observed in x-section	H2-1	
3	AZ31	1.00	AZ31	2.00	2	R2	0.00	61.48	-0.07	No cracking on button, 150C	-	
4	AZ31	1.00	AZ31	2.00	3	R2	0.00	63.58	-0.07	No cracking on button, 104C; cracks observed in x-section, upper sheet & lower sheet near rivet tail end	H2	
5	Z-100	1.50	Z-100	1.50	1	R3	0.00	52.13	-0.06	No cracking on button, 188C	-	
6	Z-100	1.50	Z-100	1.50	2	R2	0.00	57.63	-0.08	No cracking on button, 190C; cracks observed in x-section, upper sheet	H3	
7	Z-100	1.50	Z-100	1.50	1	R2	0.00	61.92	-0.02	No cracking, 150C Heated die only, 1 sec clamp time; cracks observed in x-section, upper sheet & lower sheet	H1	
8	Z-100	1.50	AZ31	2.00	2	R3	0.00	?	-0.03	No cracking on button, 150C	-	
9	Z-100	1.50	AZ31	2.00	1	R3	0.00	53.42	-0.04	No cracking on button, 200C	-	
10	Z-100	1.50	AZ31	2.00	3	R3	0.00	59.73	-0.03	Slight cracking on button, 102C; cracks observed in x-section, upper sheet & lower sheet rivet tail-end & bottom	H4	
11	AZ31	2.00	AZ31	2.00	1	R2	0.00	53.01	-0.02	No cracking on button, 181C; no cracks observed in x-section	H5	

Joint Strength Evaluations under Lap Shear Loading

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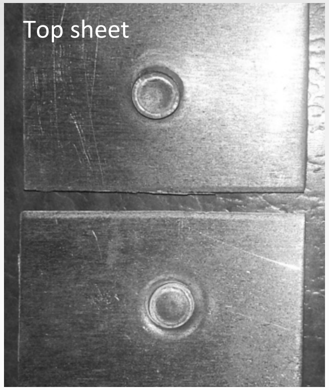
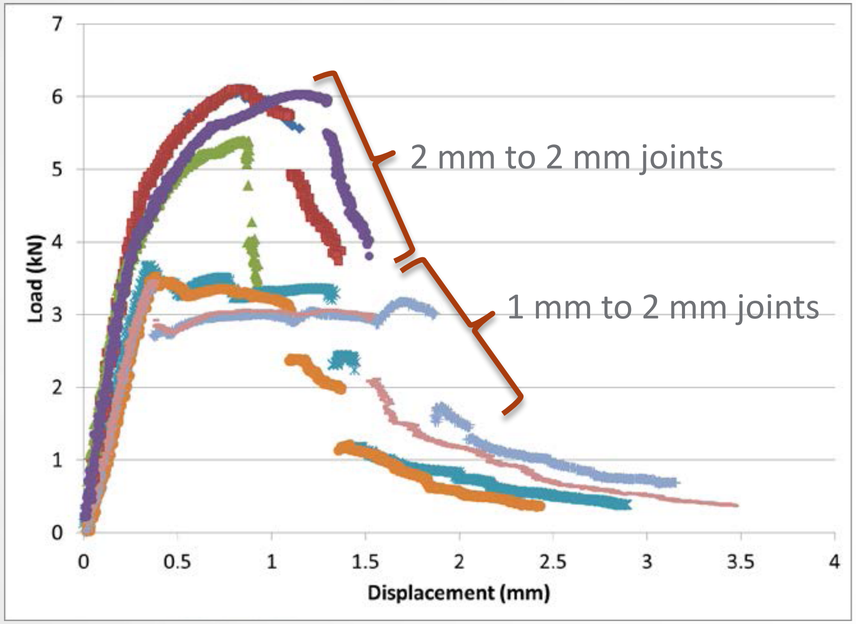
- Preliminary results of joints created at elevated temperatures ranging from ~250 to 300 C
  - **Target Criteria: Produce Mg SPR joints with a minimum target joint strength of 1.5 kN * t (substrate thickness)**
  - 2 mm to 2 mm AZ31
    - 5.9 kN ave. joint strength, 4.2 J ave. energy absorption
  - 1 mm to 2 mm AZ31
    - 3.5 kN ave. joint strength, 0.7 J ave. energy absorption



2 mm to 2 mm joints tail pull-out observed

1 mm to 2 mm joints shear-out observed



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Evaluation of Mg SPR Joints

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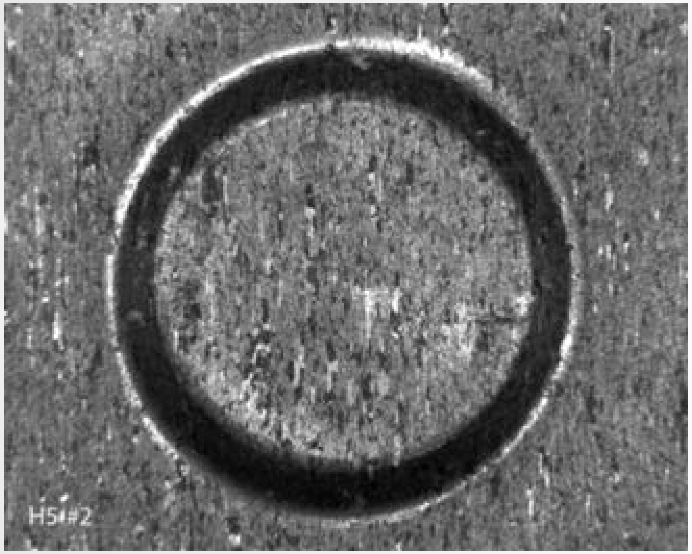
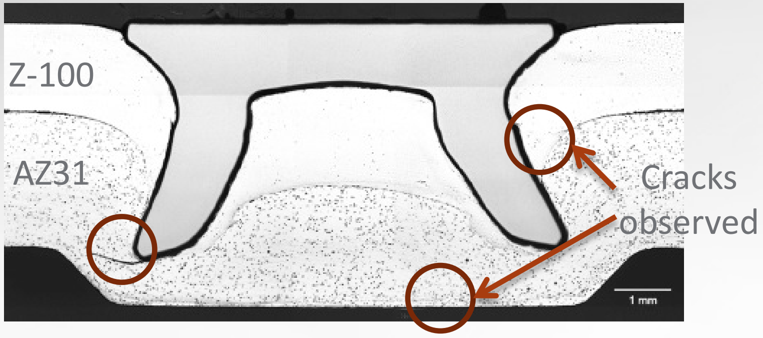
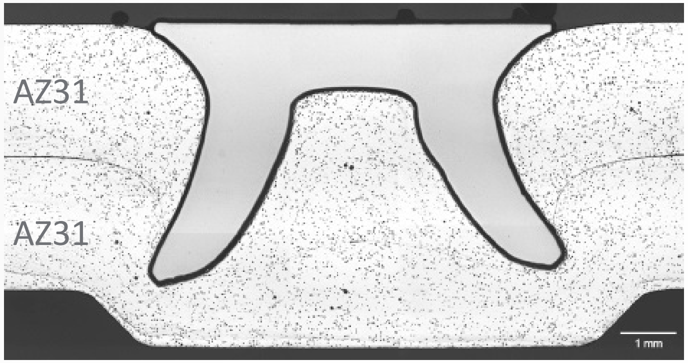
- Overall, good mechanical interlock/ joint formation observed for Mg specimens created at elevated temperatures ranging from 100 to 300 C
- No cracks observed in cross-section of specimens created at ~181 to 300 C



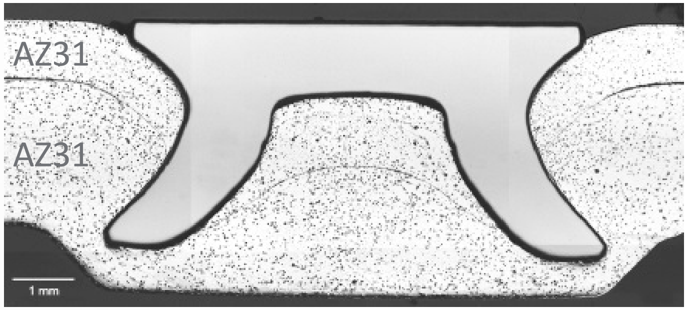
102 C



181 C

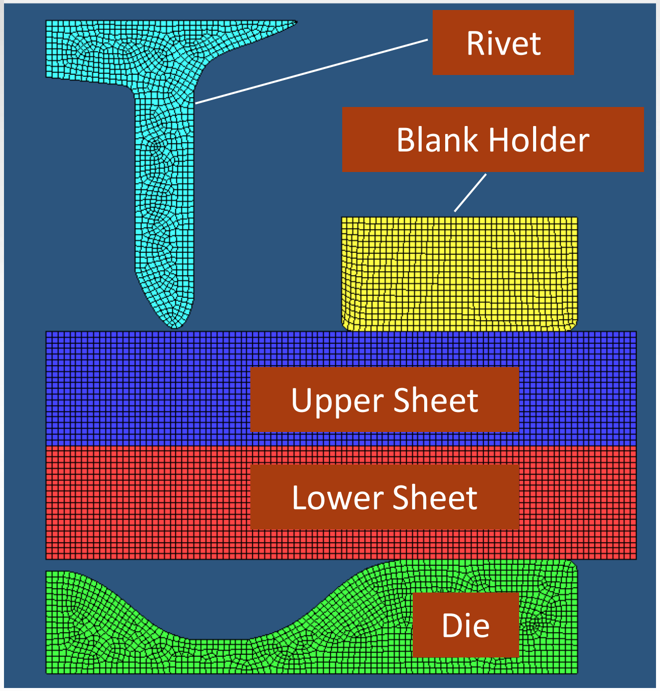


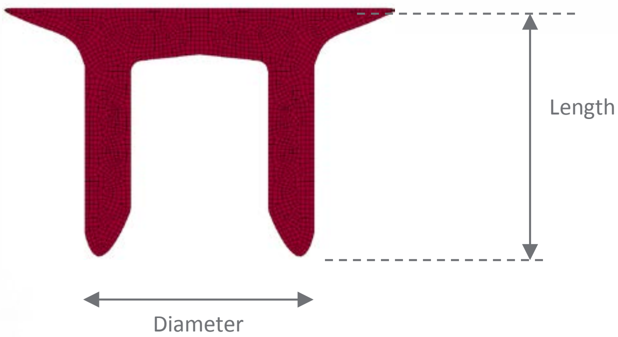
200 C



Development of FEM Model

- 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-O alloy for the Mg sheets
  - Constitutive behavior: Elastic-Plastic-Thermal model
  - Thermo-Mechanical properties of AZ31-O obtained from tensile tests at various temperatures and strain rates
  - Coefficient of friction ranging from 0.25 to 0.35





SPR FEM Model – New Die and Rivet Geometry

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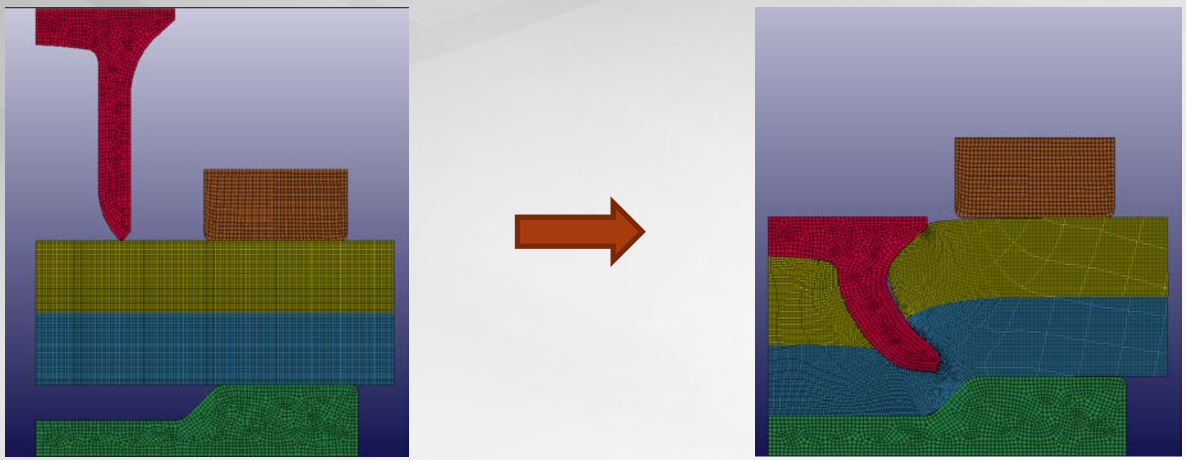
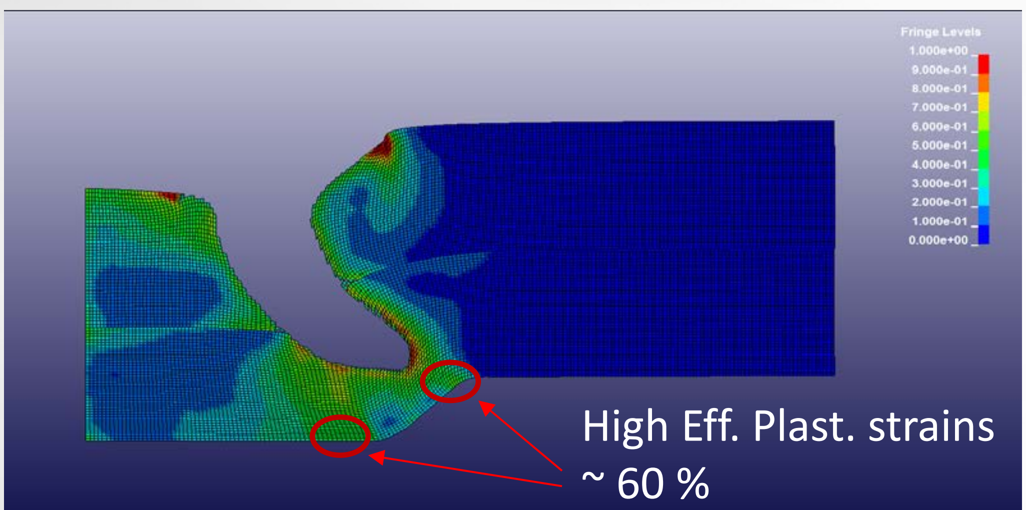
Axi-symmetric Die and Rivet



Good mechanical interlock of the joint and filling of the die observed

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

SPR FEM Model – Video of the Joining Stages

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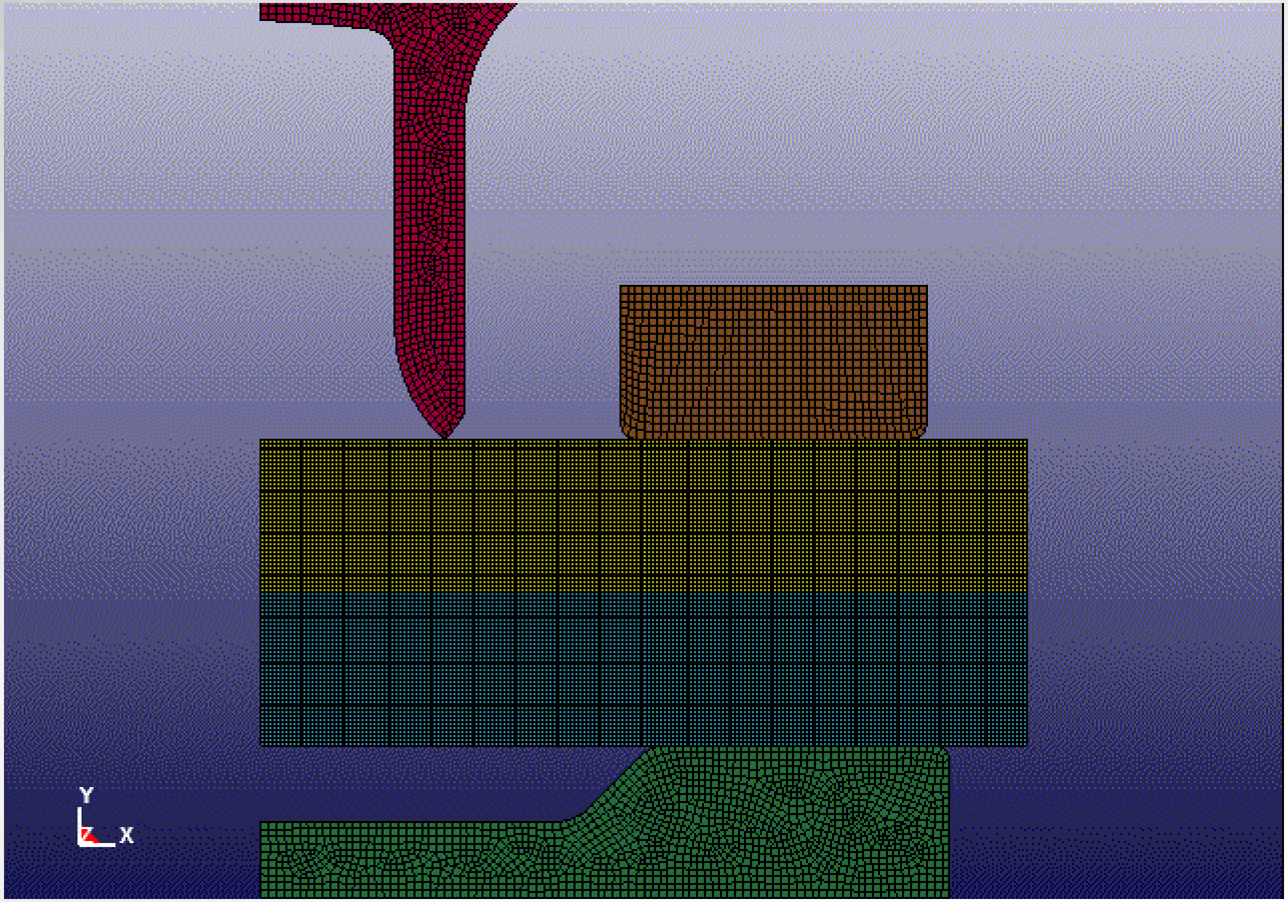
T = 200 C, 2 mm to 2 mm AZ31



SPR FEM Model – Simulation vs. Experiment

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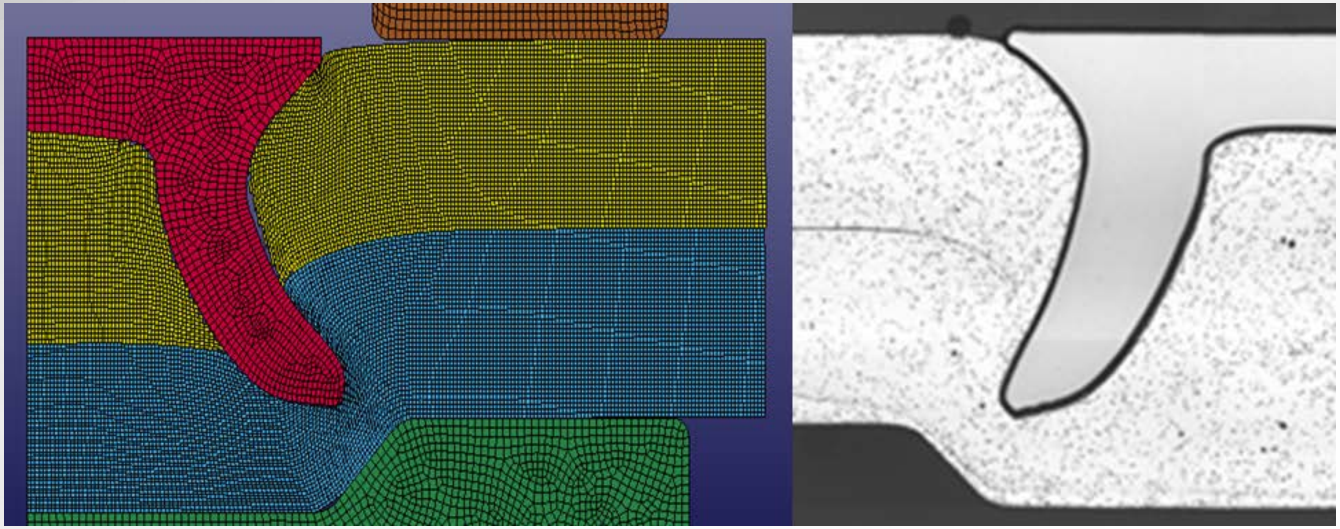
T = 200 C, 2 mm to 2 mm AZ31



- Similar joint shape observed between model and experiments

Responses to Previous Year Comments

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- Question 2: Technical accomplishments and progress toward overall project and DOE goals
  - *"Minimal accomplishments"*
    - **RESPONSE**: Although the first year of this project primarily involved PNNL's predictive model development, interaction with Stanley Engineered Fastening has been significant over the last 12 months
      - Custom induction heater designed, constructed, tested and delivered
      - Target milestones have been met and exceeded (heated joint produced)
      - Current testing scheduled to meet future milestone timeline (fatigue and corrosion testing)
- Question 3: Collaboration and coordination with other institutions
  - *"Weak industry collaboration"*
    - **RESPONSE**: Industry partner fully engaged in development of magnesium SPR
      - Integration of induction heating system into the Stanley SPR system
      - Production of heated test samples making successful SPR joints at Stanley
      - Stanley recognizing this project in their international, corporate R&D meeting, as key to future dissimilar metal joining portfolio
- Question 4: Proposed future research
  - ***"Future direction unclear"***
    - **RESPONSE:** Joint performance characterization including fatigue and corrosion evaluations clearly defined along with project milestones

Collaborations

- Stanley Engineered Fastening Cooperative Research and Development Agreement (CRADA) Partner
  - In the last 12 months, 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
    - Assessed interlock of joints created
    - Produced and implemented new die designs

Next Steps

- Stanley Engineered Fastening will complete a full matrix of induction heated SPR joints (AZ31-AZ31 and AZ31-7xxx Al) with newly implemented heating system
  - Target date – end of May
- PNNL will complete the joint characterization and performance in terms of shear strength, fatigue and corrosion
- Stanley and PNNL will jointly explore alternate rivet materials and/or interlayers
  - Initially, via the modeling tool, with potential experimental validation
  - Address joint corrosion issues (coatings)
- Together, PNNL and Stanley will develop the design guidelines and recommendations for successful Mg SPR joining

Summary and Conclusions

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Summary

- An integrated induction heating system has been incorporated into Stanley's SPR system.
  - Production and evaluations continue but preliminary results indicate heated SPR joints are crack-fee and exceed project goals.
  - Full matrix of heated joint combinations produced 3rd quarter of FY14.
- Joint strengths ranging from ~5.4 to 6.1 kN (> 1.5 t) observed under lap shear loading conditions for 2 mm to 2 mm AZ31 Mg joints created at elevated temperatures
- PNNL modified the modeling tool for SPR based on new die and rivet geometry
  - The constitutive behavior of the model was implemented using our data
- Experimental validation of SPR model
  - Modeled and experimentally confirmed 'bad' joints at room temperature
  - Good AZ31 SPR joints of 2 mm x 2 mm sheets were predicted and experimentally demonstrated at 200 C and above

Conclusions

- Mg SPR joints can be made using conventional rivets and dies
- Heating mechanism is necessary to produce mechanically sound magnesium joints