Project ID: LM030

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Friction Stir and Ultrasonic Solid State Joining of Magnesium to Steel

Yuri Hovanski
Pacific Northwest National Laboratory

Michael Santella & Tsung-Yu Pan
Oak Ridge National Laboratory

Project Overview

Project Timeline

- Start: FY2008
- Finish: FY2012
- 99% complete

Technology Gaps/Barriers

- Capacity of solid state joining techniques to bond dissimilar metal joints
- Process and geometric constraints of each process when used to join dissimilar metals
- Corrosion boundary layers that can be utilized with solid state welding techniques

Budget

- Total project funding
  - DOE – $1.5M
  - 50/50 Split with ORNL/PNNL
- FY08 Funding - $200k
- FY09 Funding - $500k
- FY10 Funding - $500k
- FY11 Funding - $300k

Partners

- USCAR Joining team
  - GM & Chrysler
- Material sheet suppliers
  - US-Steel & MENA & castings with MFERD
- Universities
  - WSU and U. of Michigan
- Coatings
  - PPG Inc.

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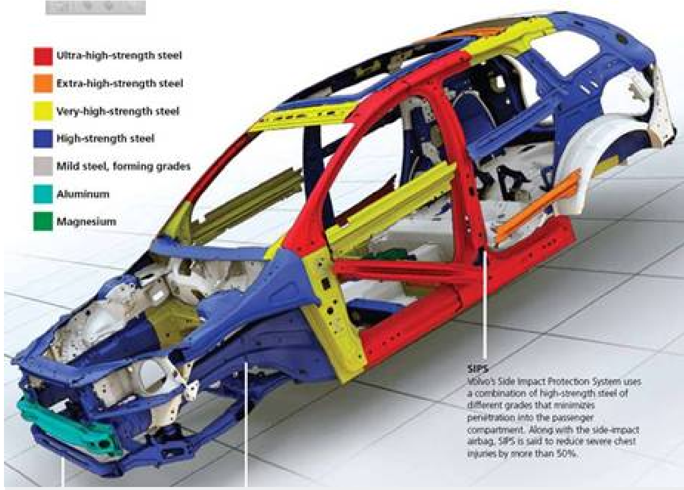
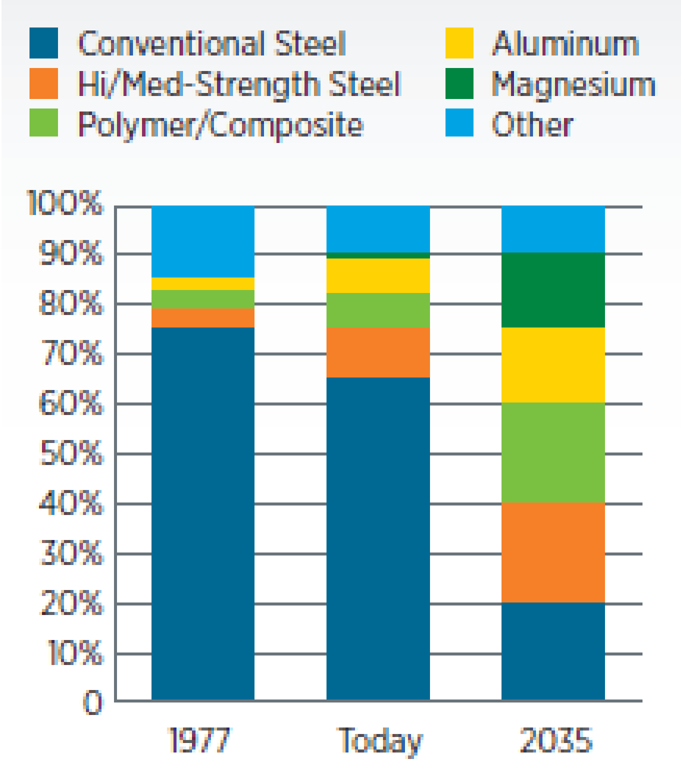
Relevance: Project Motivation

- 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
    - Solid state joining of magnesium to steel project was initiated to address critical gaps in this area
    - Goal to enable broader application of Mg alloys in automotive structures requiring integration with steel components





Typical composition of past and present cars versus a future lightweight vehicle.

Relevance: Goals and Objectives

1. Develop two specific solid state technologies (FSW & USW) for joining magnesium to steel to enable broader deployment of magnesium alloys in automotive structures that require integration with steel components.

2. Develop the applied understanding of both processes:
   a) The localized metal "forming" and potential metallurgical bonding that develops during FSW and USW processes
   b) How the process parameters influence the joint strength and performance of the joints and assemblies produced
   c) How both processes interact with existing corrosion protection methods (coatings) and how they affect the overall corrosion performance of a hybrid Mg/Steel structure

- Mg sheet, extrusions and castings need bonding mechanism to steel passenger compartment
- Solid state methods may be low cost alternatives to mechanical fastening or SPR

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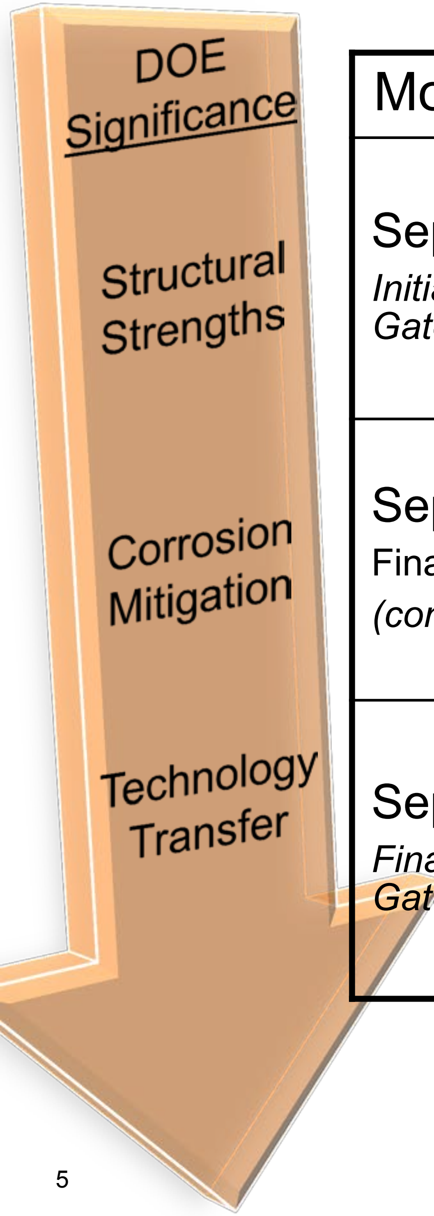
Relevance: Project Milestones



Month/Year	Milestone or Go/No-Go Decision
Sept. 2010 *Initial Decision Gate (complete)*	**Structural Joint Strengths** Demonstrate the ability to create linear FSWs with greater than 60% joint efficiency and USWs with spot strengths in excess of 1.5 x thickness for spot configurations
Sept. 2011 Final Milestone *(complete)*	**Corrosion Performance of Mg/Steel Joint** Evaluate the performance of solid state joints between magnesium and steel to determine the practical ability to retain joint strength in corrosive environments.
Sept 2011 *Final Decision Gate (passed)*	**Feasibility of joining magnesium to steel** Can joints strengths be maintained with greater than twice the baseline magnesium/steel joint after corrosion testing?

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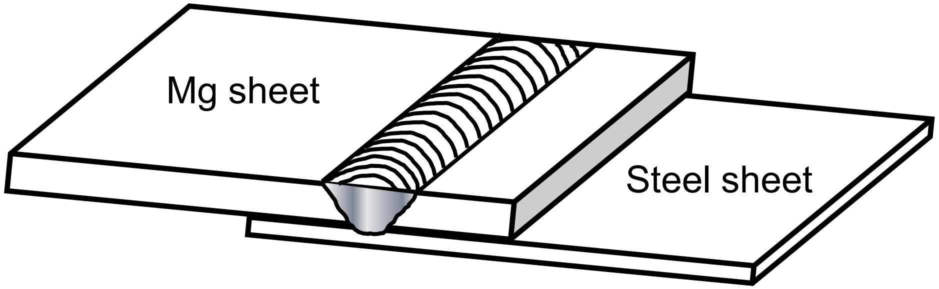
Technical Approach

- Task 1: FSW and USW process development
  - Select relevant industrial alloys
    - Alloys aligned with initial MFERD needs
    - Sheet selections made based on commercial viability
      - OEM & material manufacturer input for cost and availability
  - Initial strength gate
- Task 2: Joint Characterization
  - High strength joint development
    - Demonstrate the relationships between tooling and process parameters on joint strength
    - Intermediate strength milestone



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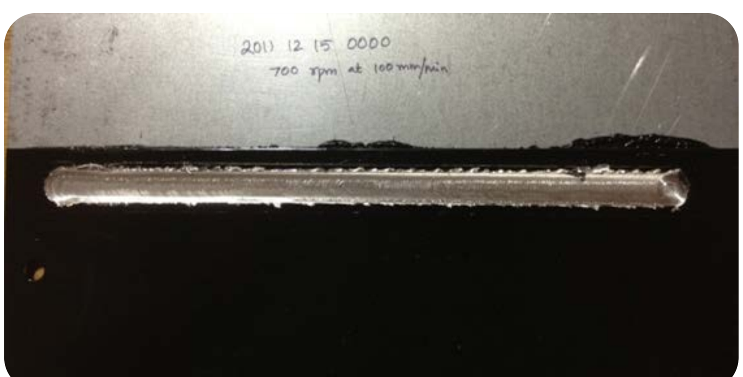
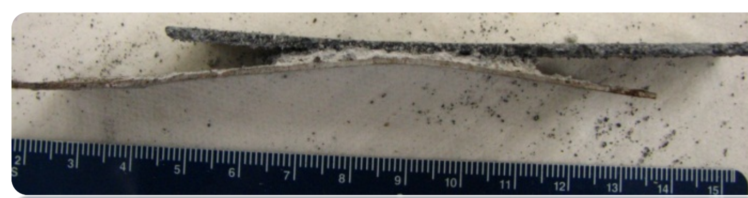
Technical Approach

- Task 2 Continued: Joint Characterization
  - Characterize the joint interface for each process
    - Determine the role of surface oxides, contamination, sheet thicknesses, alloys, process parameters, material orientation, and tooling
  - Final Strength Gate: Structural Joint?
- Task 3: Corrosion Performance and Mitigation
  - Evaluation degradation of joint strength with exposure
  - Determine the ability to utilize interlayers and coatings with each process
  - Characterize the effect of available mitigation strategies in comparison the baseline joint performance



E-coated FSW with Betamate Adhesive


Bare Mg/Steel USW

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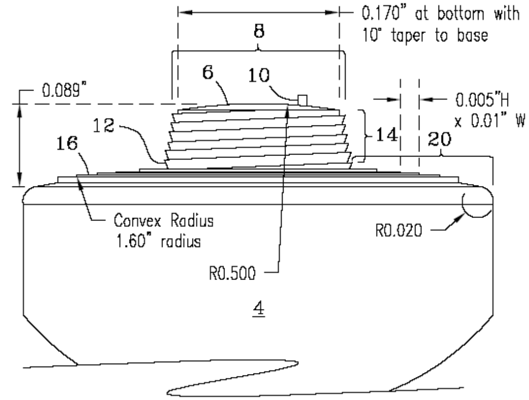
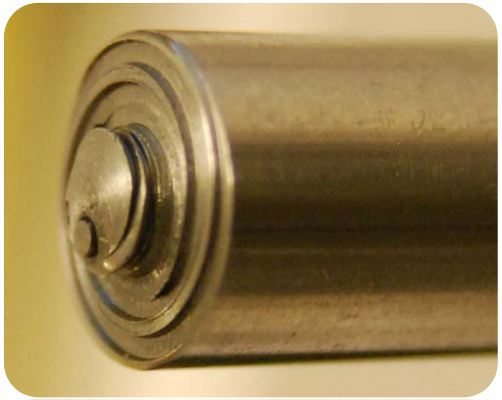
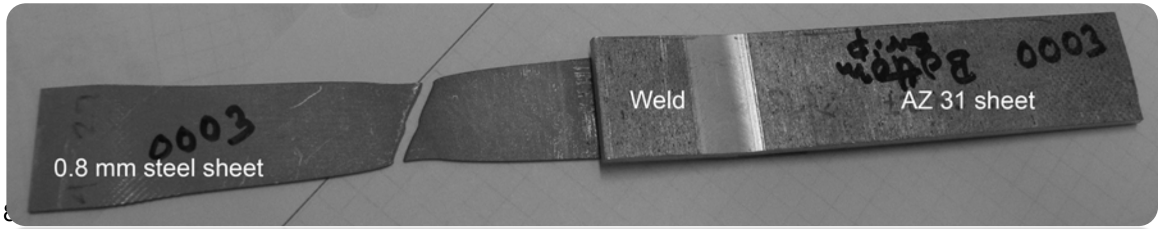
FY2011 Accomplishment: Structural Joint Strengths in Solid State Mg/Steel Welds

- Innovative tooling developed for FSW of dissimilar materials (“Scribe” technology)
  - Developed at PNNL to overcome the challenge of joining dissimilar metals with vastly differing melting temperatures
  - Combines two well understood technologies into a single process:
    - FSW tool and a milling cutter are combined into a single tool
  - Allows the cutter to contact the steel without overheating the magnesium
  - Creates a geometrically beneficial shape in the steel that increases bond strength







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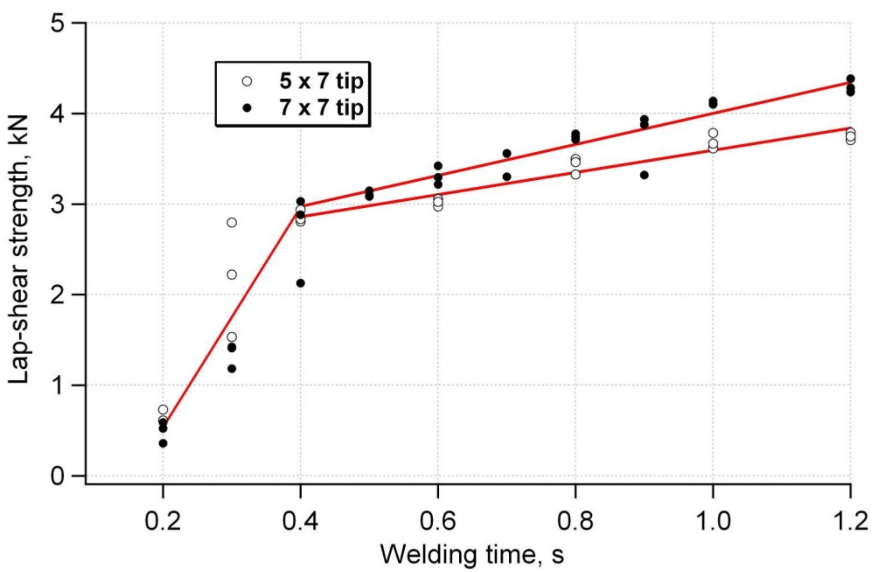
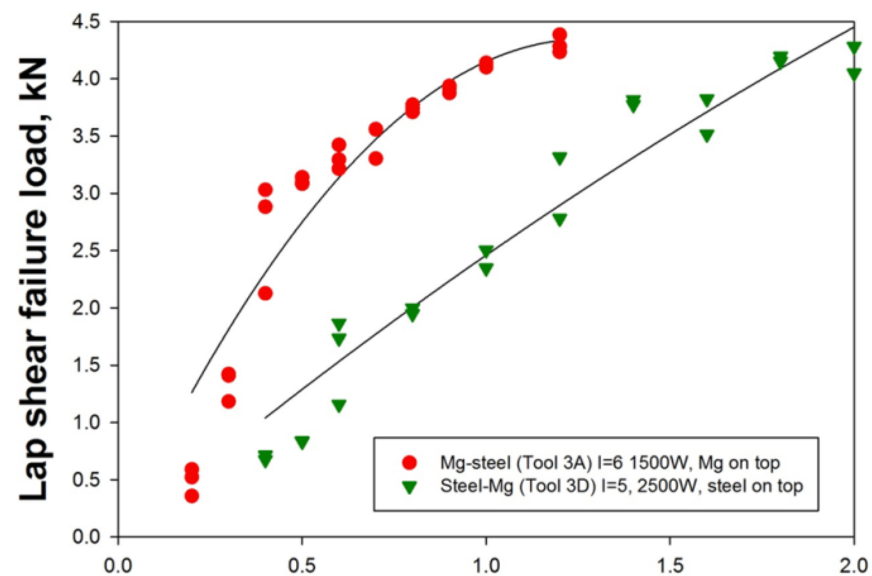
FY2011 Accomplishment: Characterize Parameter Relationships on Structural Joints

- Relationships between tooling, weld parameters, and material orientation characterized
  - Time penalty based on material orientation with USW
  - Fixed orientation with FSW (Mg in contact with tool)





RSW comparison

AZ31b to AZ31b RSWs

5 x 7 → 0.26-inch-dia; RSW strength = 3.7 kN max.

7 x 7 → 0.31-inch-dia; RSW strength ≈ 4.0 kN

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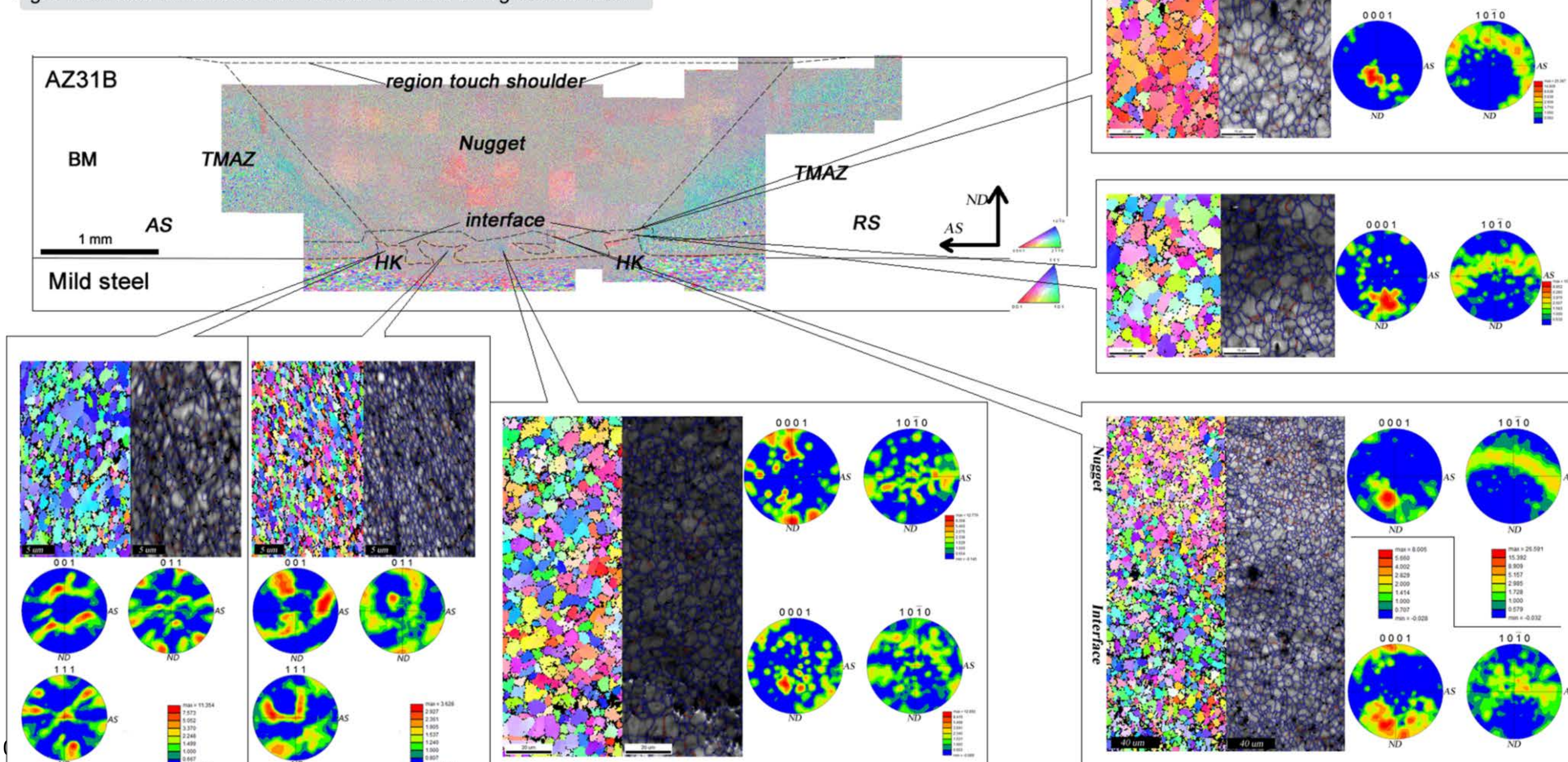
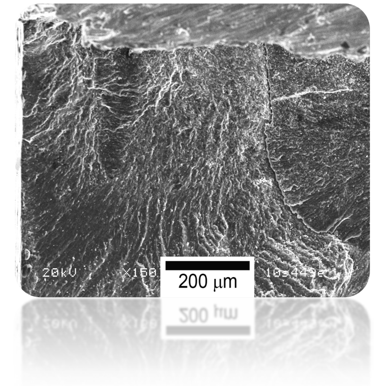
FY2011 Accomplishment: Characterize the Joint Interface

- Leveraged NSF funds for WSU to develop techniques to allow for dissimilar metal joint analysis
  - Previously lacked methods for sample preparation of Mg/Steel

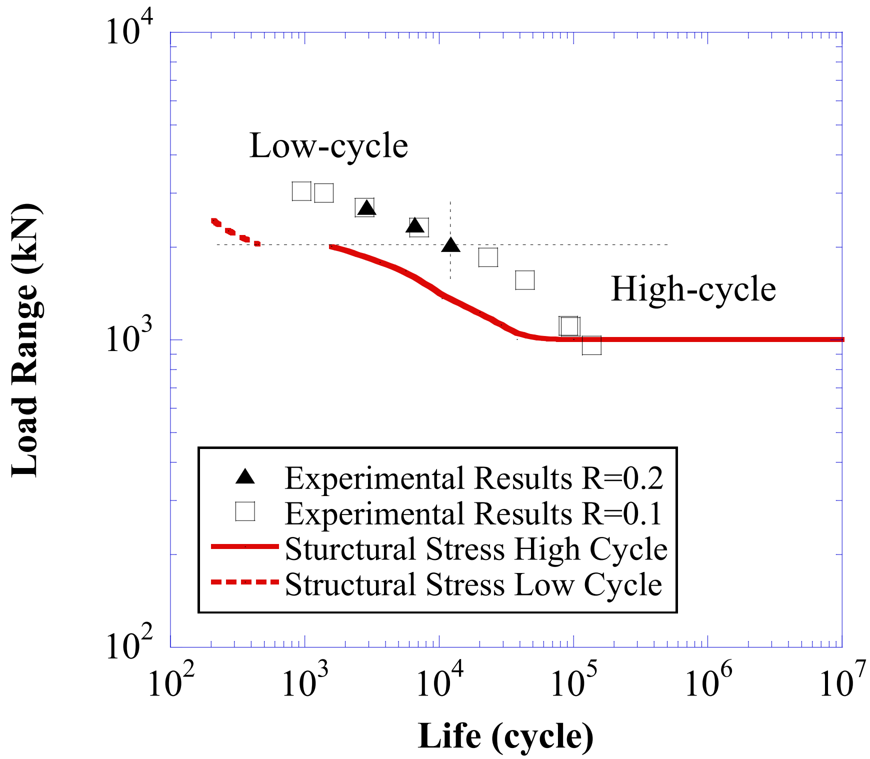
Fig.1 Overview of whole cross-section of FSW of Mg to mild steel

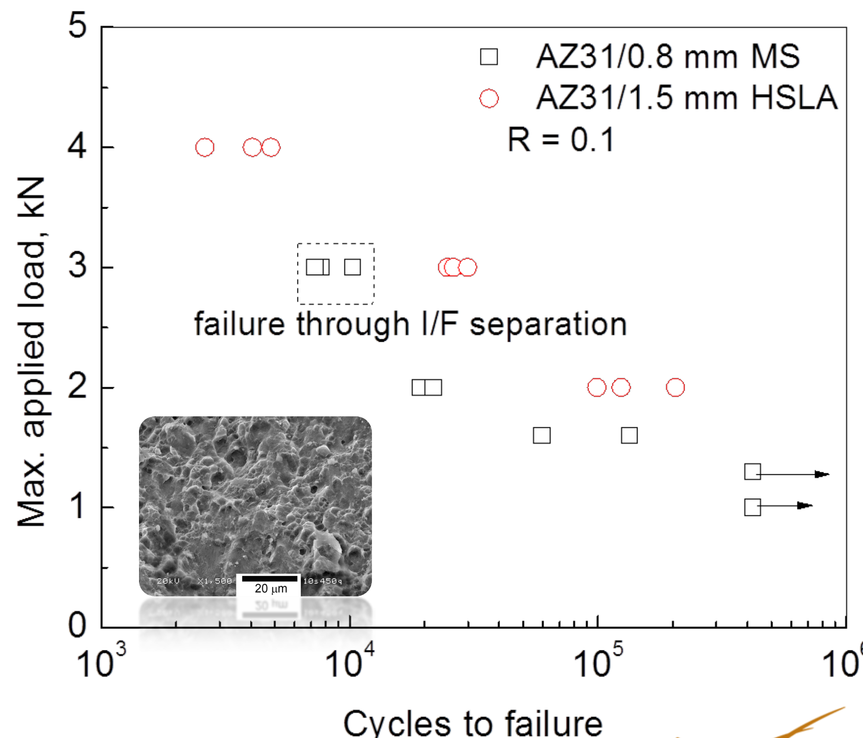


FY2011 Accomplishment: Dynamic Characterization of Solid State Joints

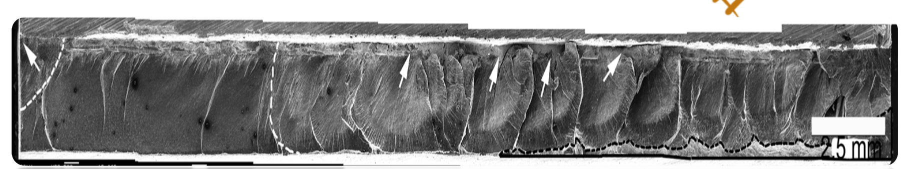


- Life prediction based on model is lower than experimental values





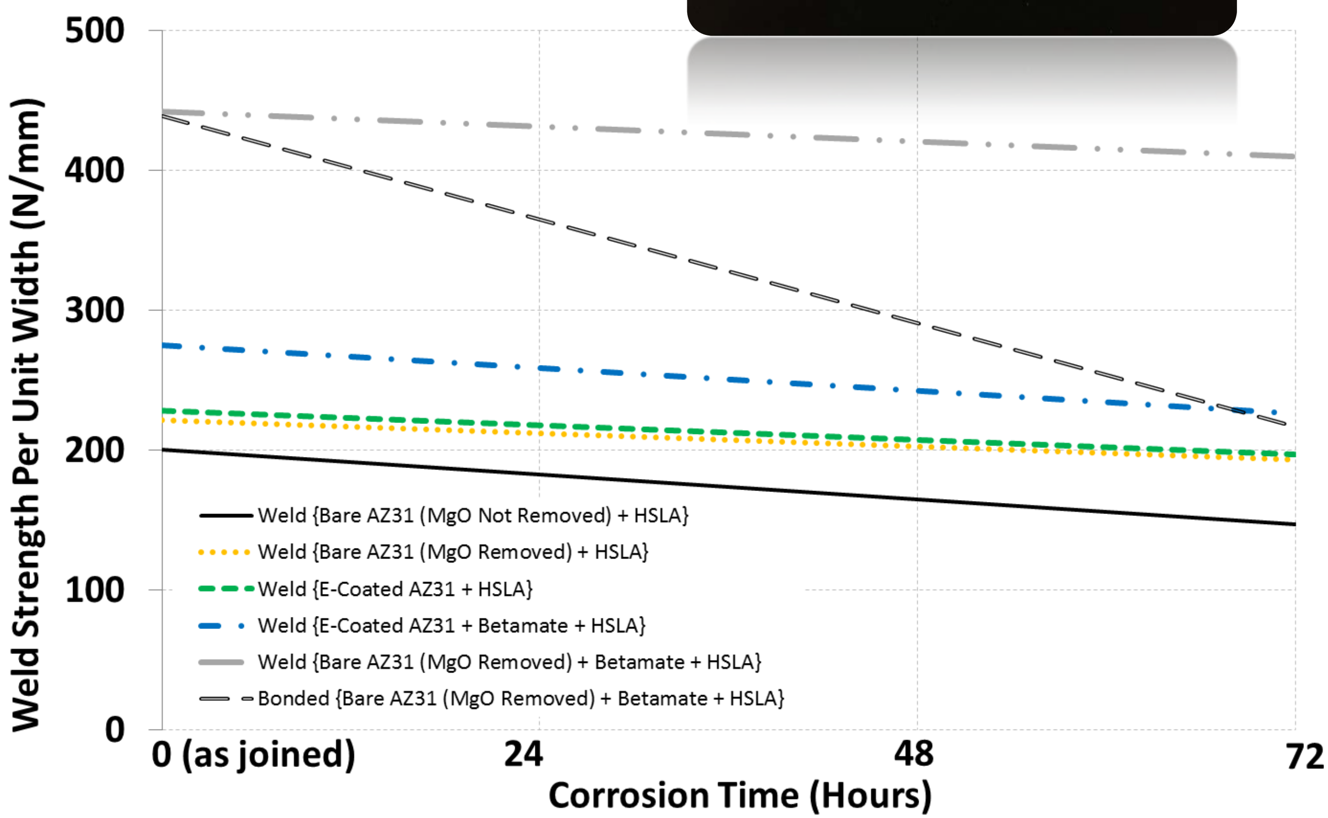
$$\sigma_{\text{total}} = \frac{-3F}{8btXY}\left[2b^2X + 4Y(a^4b^4 + b^8)\right] + \frac{3F}{2\pi at} + \frac{F}{2\pi at} + \frac{F}{4bt}\left[\frac{1}{1+v} - \frac{2}{v-3}\right]$$



FY2011 Accomplishment: Corrosion Performance and Mitigation

- Weld Strengths were not greatly altered after 72 hours of exposure to NaCl solution
- FSW was amenable to weld bond
  - Join through adhesive and e-coat

No pitting in FSW region of AZ31b NaCl exposure



Collaborations

- DOE and University Collaborators
  - Joint project 50/50 split between ORNL & PNNL
  - U. of Michigan: Fatigue studies and modeling
  - Washington State University: Microstructural characterization
- Private Collaborations
  - GM, Ford and Chrysler participated in an advisory role
  - US Steel provided all Fe based materials
  - PPG Inc.

Proposed Future Work

- With remaining project funds (this fiscal year)
  - Complete the evaluation of the corrosion mitigation of USWs
  - Determine the thickness of coatings that may be utilized with this process

- Future Projects
  - Evaluate the potential for friction stir welding and processing to enhance the corrosion performance of bare magnesium
  - Investigate Mg to Mg FSW, which is still the limitation of the Mg/steel joint
  - Investigate the viability of USW and FSW for Al/steel dissimilar joints
  - Determine the influence of clamping on the USW of structures with numerous welds required on each component

Summary and Status

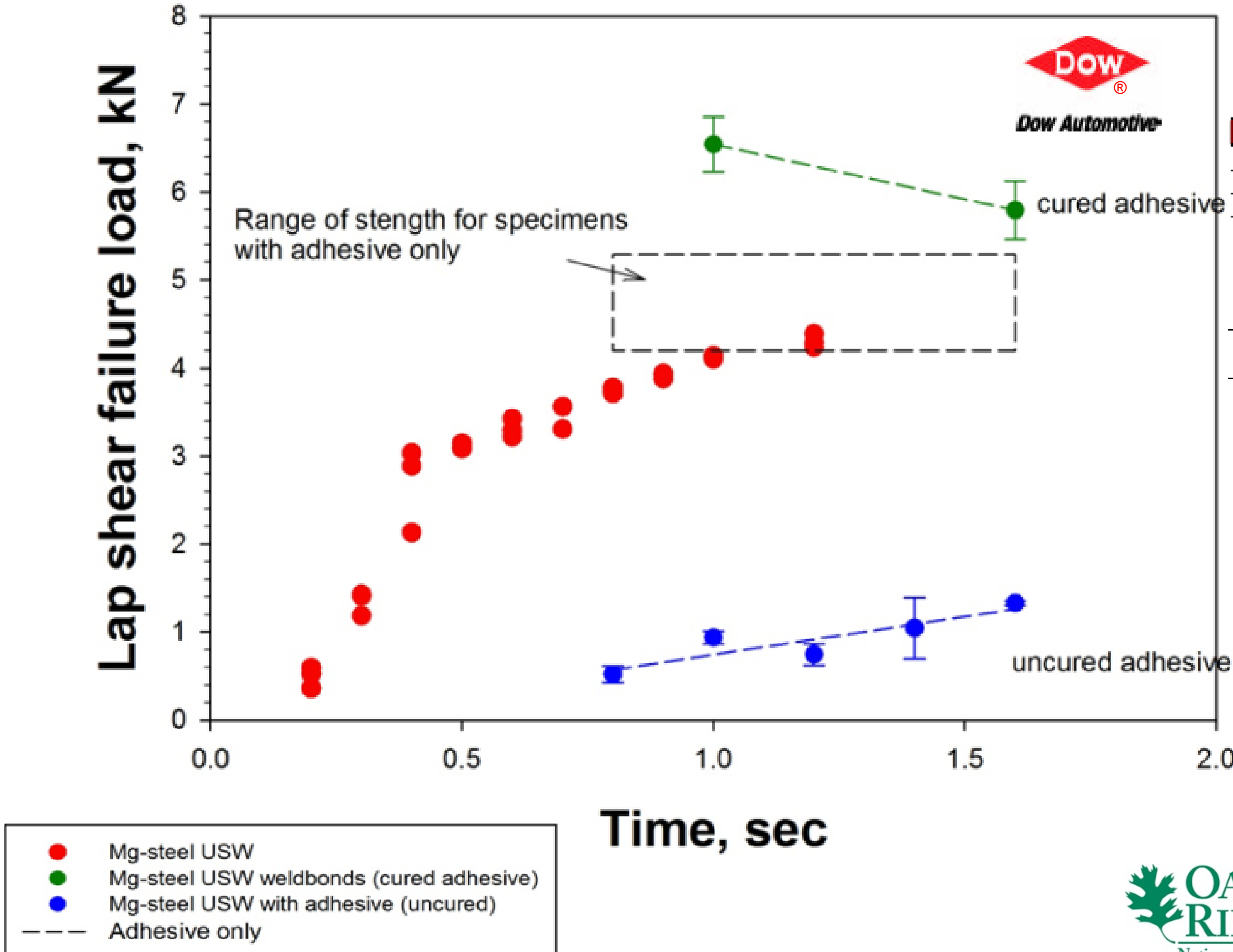
- High strength solid state welds are possible using both ultrasonic and friction stir welding processes
  - Lap shear strengths of USWs comparable with Mg-Mg RSWs
  - Joint efficiencies of FSWs greater than 90% are possible
- USW techniques were successful regardless of material orientation (magnesium or steel next to sonotrode)
  - Amenable to C-clamp fixtures
- Scribe technology enabled dissimilar material FSW
  - Avoided overheat associated with different melting temperatures
  - Enhanced the joint strength by creating beneficial geometry
- Performance of adhesive bonds were improved using either solid-state technique to form a weld bond.
  - Corrosion performance was enhanced for friction stir weld bonds
  - Strengths were improved for ultra-sonic weld bonds

Author Contact Information:
yuri.hovanski@pnl.gov
Richland, Washington
509-375-3940

Technical Backup Slides

Weld Bonding with Betamate Adhesive

- Uncured adhesive significantly decreased lap-shear
- Weld bonds achieved highest joint strength



BETAMATE™ 73305

Structural Adhesive

Performance Properties		
Test Substrate	Oily cold rolled steel	
Bondline Thickness	0.005" (0.127mm)	
Overlap	½" (12.7mm)	
Test Temperature	Lap Shear -psi (Mpa)	Side Impact -in-lbs (N-m)
75°F (23°C)	2378 (17)	>60 (6.8) -No Failure
-22°F (-31°C)	2727 (19)	>60 (6.8) -No Failure
180°F (82°C)	2219 (15)	>60 (6.8) -No Failure
Peel Strength @ RT, pli (N/m)		27 (4750)
Nominal Cure (Metal Temperature)		20 minutes @ 350°F (177°C)

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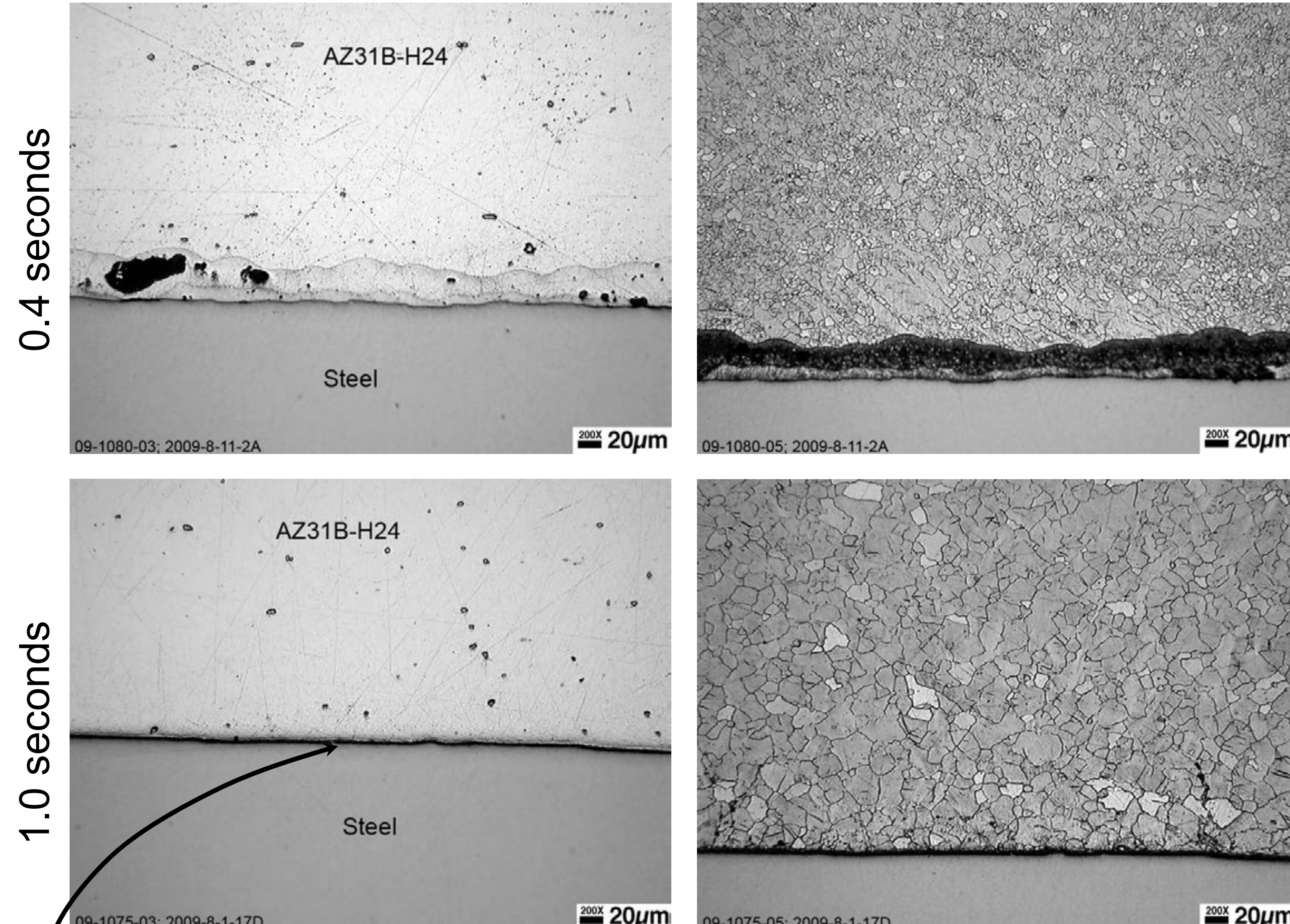
Time Based Evolution of USWs

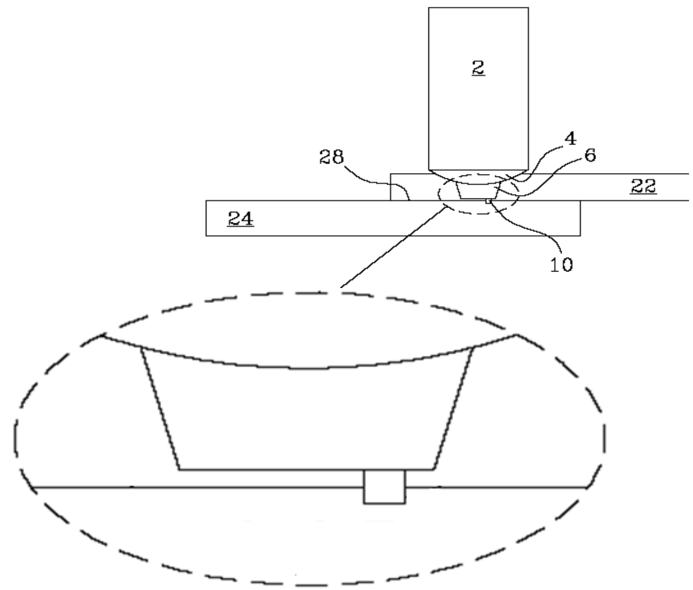


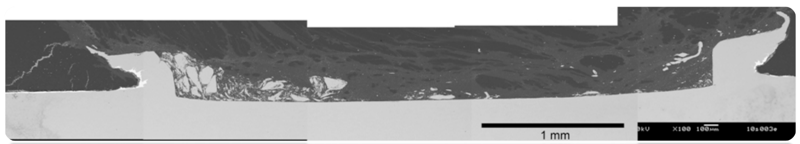
- At 0.4 seconds the microstructure remains unchanged
- After one second the microstructure of the AZ31 has recrystallized

Transport of the Zn/Mg reaction layer complete

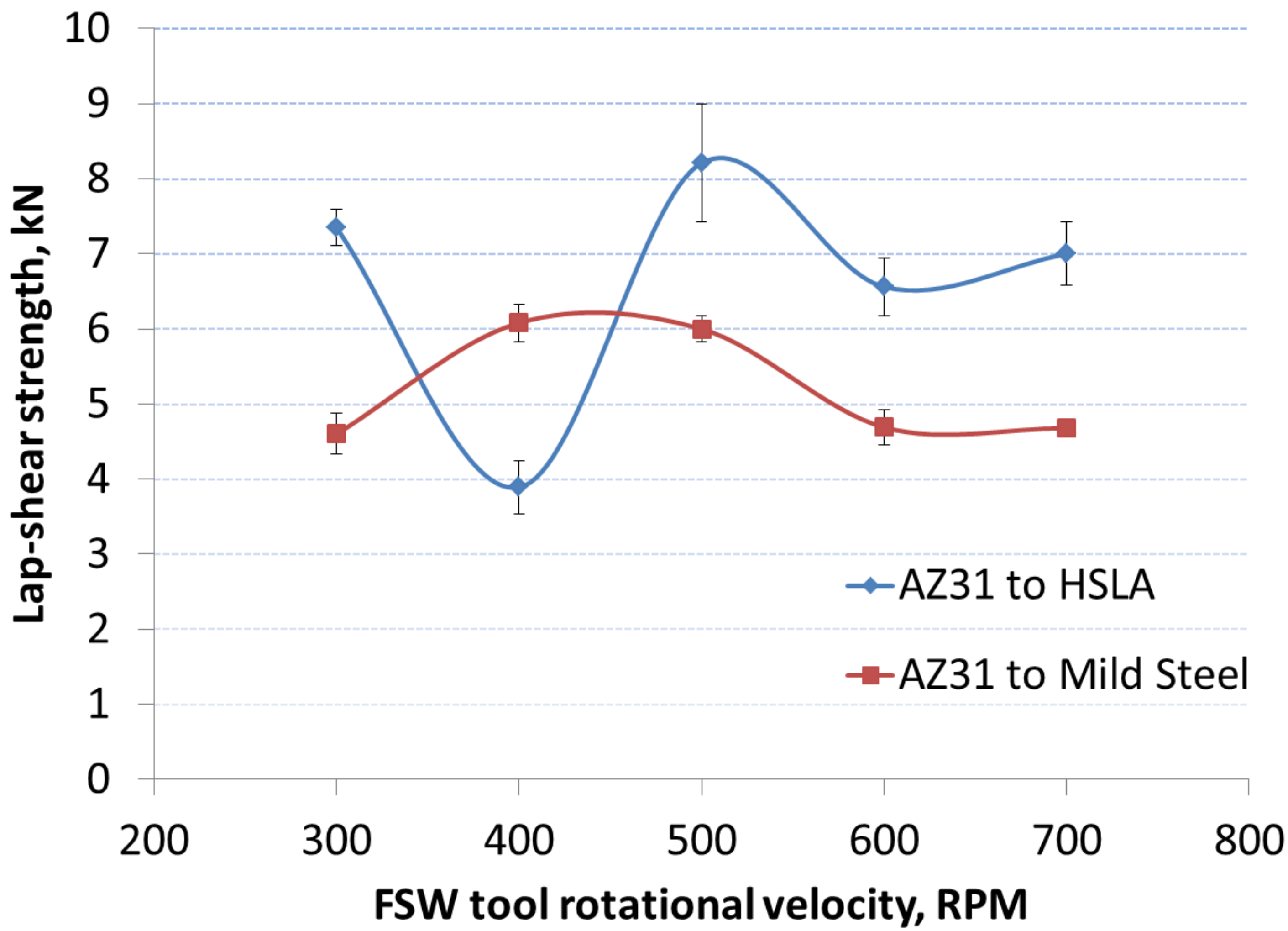
FSW Scribe Technology

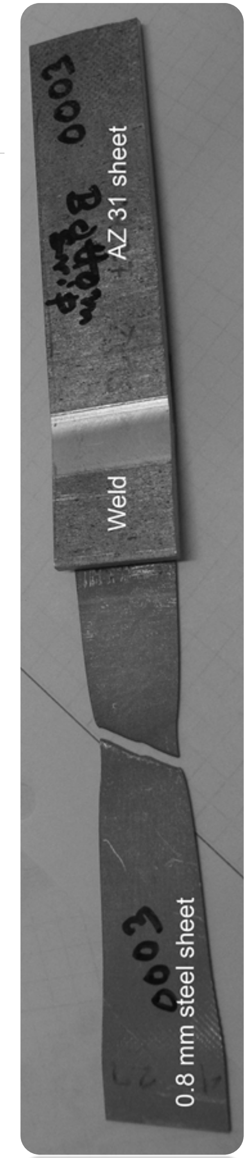
- Weld parameters designed for Mg
  - Carbide cutter speed optimized for position and linear feed rates
- Significant heat reduction at the weld interface
  - Temperatures continue to melt Zn coatings on the steel sheets, but no post-solidification Mg present
  - Indicative of the change in tool wear
    - Without scribe technology significant wear was present





Lap-shear Strength of FSWs





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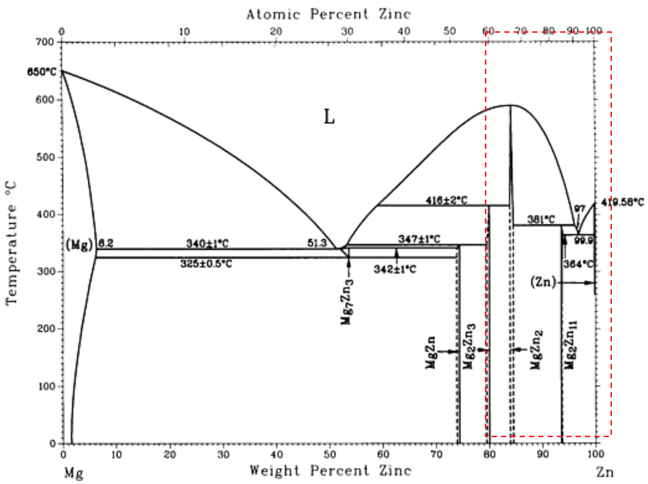
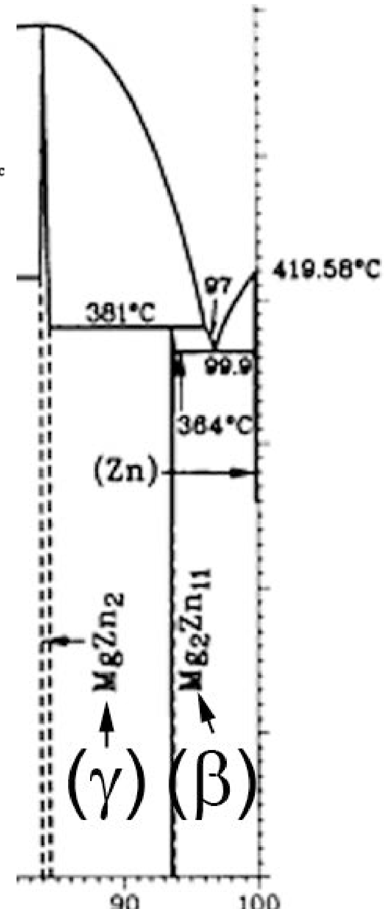
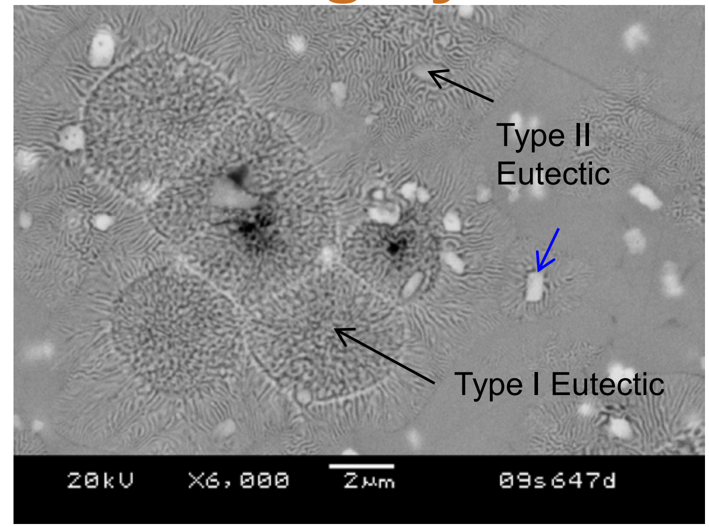
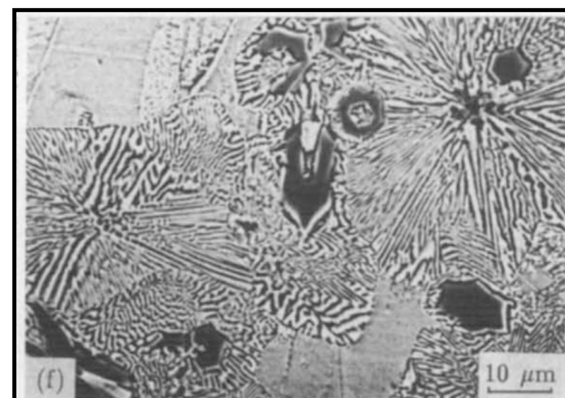
Solidification Microstructures in Zn-Mg system





Zn-Mg system is known to exhibit competitive growth between two eutectic systems, α-Zn-β–$Zn_{11}Mg_2$ (at 3.05 wt% Mg and 364° C) and α-Zn-γ-Zn_2Mg (at same Mg conc. & lower temp.) Eutectic reaction involving γ does not occur under eqlb. conditions. α–γ eutectic is spiral shaped, whereas α–β eutectic is lamellar. Further, primary γ is hexagonal and primary β is cube shaped. *(Liu and Jones, Acta. metall. mater. 40, 1992, 229-239.)*





Examples of Zn-Mg solidification microstructure; (e) Zn-5wt%Mg and (f) Zn-3.4wt%Mg *(Liu and Jones, Acta metall. Mater., 40, 1992, 229-239.)*

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