Magnesium-Intensive Front End Sub-Structure Development

2015 DOE Merit Review Presentation

Presenter and Co-PI :

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United States Automotive Materials Partnership

June 11, 2015

Project ID "LM077"

Overview - (DE-EE0005660)
Magnesium-Intensive Front End Sub-Structure Development

Timeline

- Start: June 1, 2012
- End: Nov. 30, 2015
- ~90% complete

Budget

- Total project funding
  - DOE: $3,000,000
  - Contractor share: $3,000,000
- Funding received in FY14
  $1,229,316
- Funding for FY15
  - DOE: $1,024,779
  - Contractor share: $1,024,779

Barriers and Targets

- Manufacturability - joining & assembly of Mg in multi-material systems:
  - *Demonstration of a Mg-intensive "demo" structure in automotive body application*
- Predictive modeling & performance:
  - *Performance validation of "demo" structure in corrosion, fatigue, and durability*

Partners

- OEMs: FCA, Ford, GM
- U.S. suppliers and universities
- International collaborators from China and Canada

Objectives - Relevance

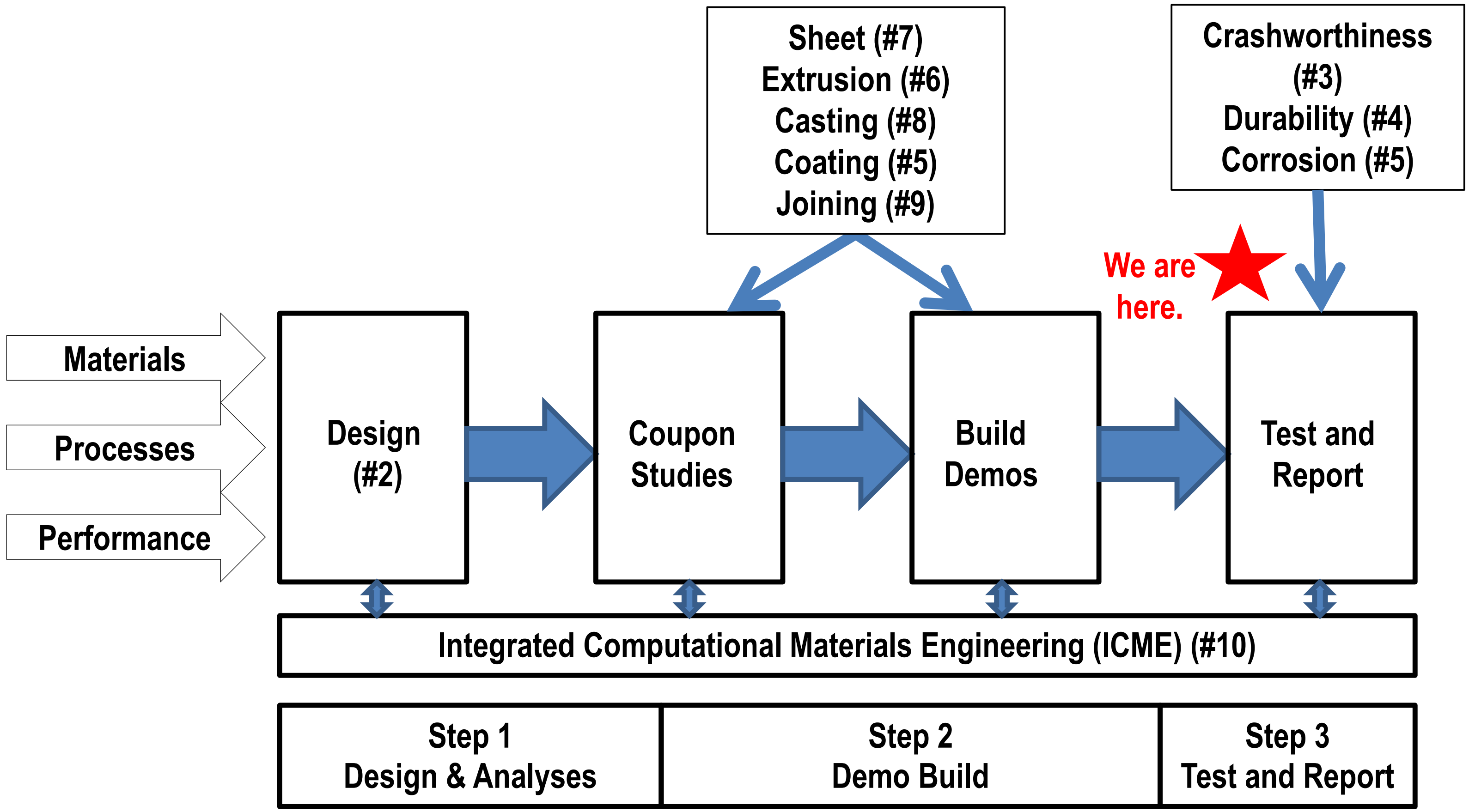
- ***Barrier: Manufacturability.*** *Methods for the cost-competitive production of automotive assemblies from advanced lightweight materials*
  - **Design, build and test a Mg-intensive, automotive front-end "demo" structure – leading to lightweight multi-material applications**
  - **Mass reduction of Mg-intensive body structures: up to 45% less than steel comparator; 20% less than aluminum comparator structure**
- **Barrier: *Performance.*** *Low cost materials needed to achieve the performance objectives (strong, durable, easily formed and joined into assemblies and components, sufficiently well-characterized) for demanding applications*
  - **Develop enabling technologies in new Mg alloys, joining (including dissimilar metals), corrosion, and materials performance and predictive capability (including fatigue and high strain rate deformation) for lightweight automotive structures**
- **Barrier: *Predictive modeling tools.*** *Adequate predictive tools that will enable the low cost manufacturing of lightweight structures*
  - **Contribute to integrated computational materials engineering (ICME) efforts specifically focused on magnesium alloy metallurgy and processing**

2014 Objectives - Relevance

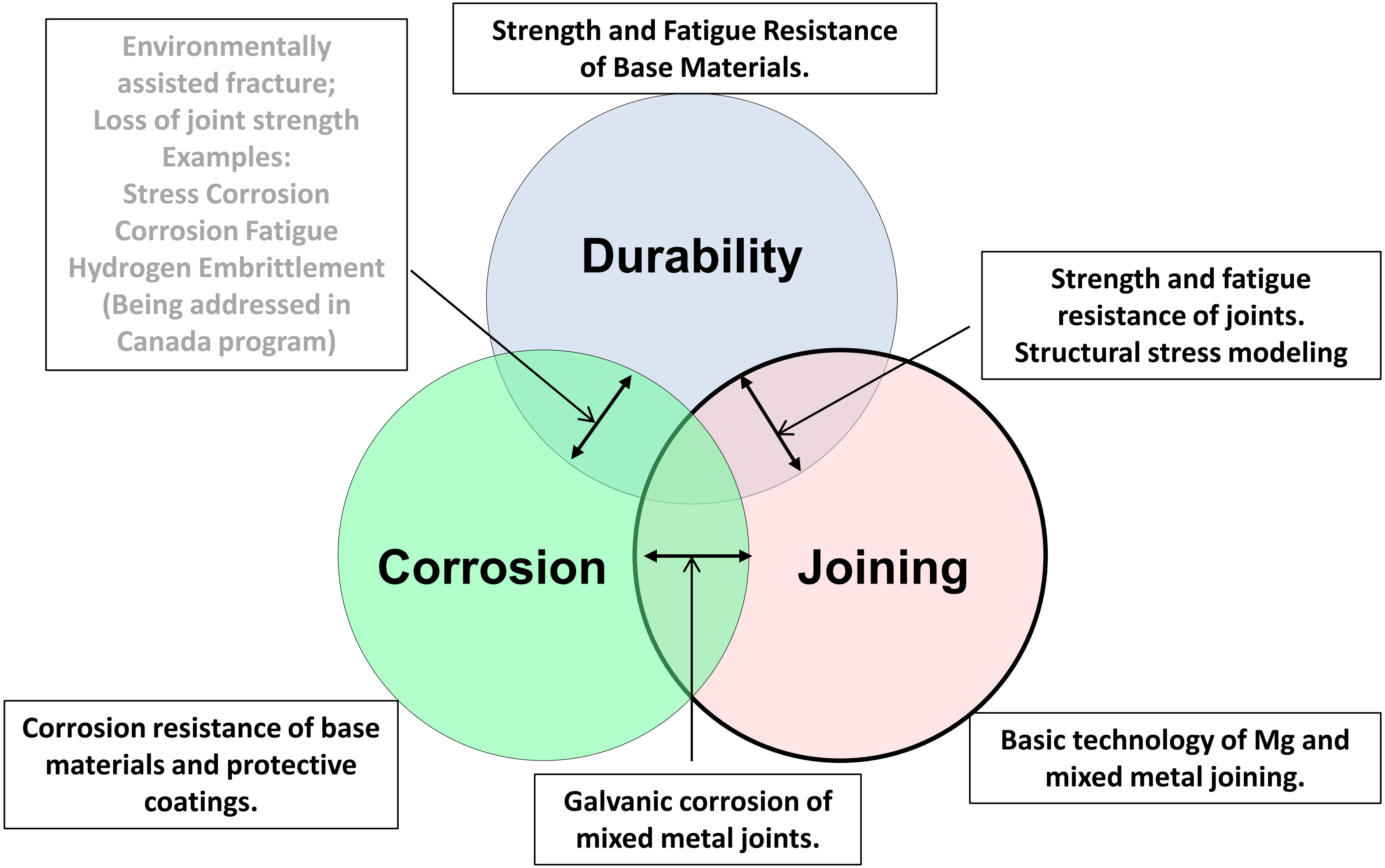
- ✓ Continue joining, corrosion protection and durability (fatigue) validation of selected dissimilar material couples.
- ✓ Continue evaluation, development, and validation of improved crashworthiness simulation capabilities for AM60 die cast and ZE20 Mg extrusion alloys.
- ✓ Continue dissimilar metal joining evaluation and development.
- ✓ Finalize production of "demo" structure component parts (upper rails and shock towers) from selected materials, and assemble "demo" structures.
- ✓ Continue development of more deformable grades of magnesium extrusion (ZE20) including acquisition of billet stock and trial runs with Mag Specialties.
- ✓ Complete ICME "fatigue" studies of MFERD Phase II "demo" structures and investigate the ICME of ZE20 magnesium.
- ❑ Conduct validation testing on "demo" structures, especially durability and corrosion evaluation.

Approach - Milestones

- Collaborate with domestic and international researchers and suppliers to leverage research and to strengthen the supply base in magnesium automotive applications
- Use a “demo” structure to validate key enabling technologies, knowledge base and ICME tools

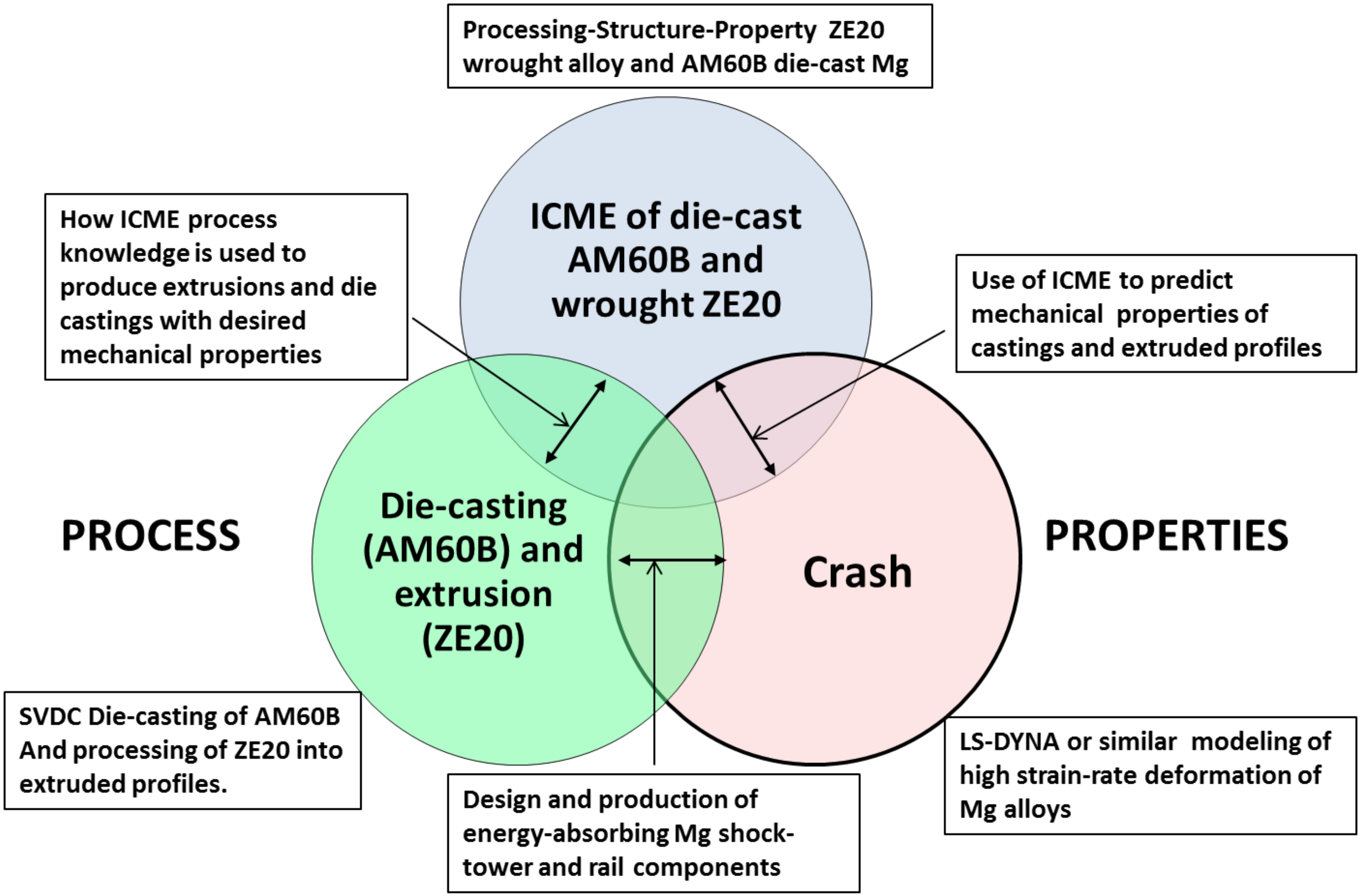


Approach


Strength and Fatigue Resistance of Base Materials.
Environmentally assisted fracture; Loss of joint strength Examples: Stress Corrosion Corrosion Fatigue Hydrogen Embrittlement (Being addressed in Canada program)
Durability
Strength and fatigue resistance of joints. Structural stress modeling
Corrosion
Joining
Corrosion resistance of base materials and protective coatings.
Galvanic corrosion of mixed metal joints.
Basic technology of Mg and mixed metal joining.

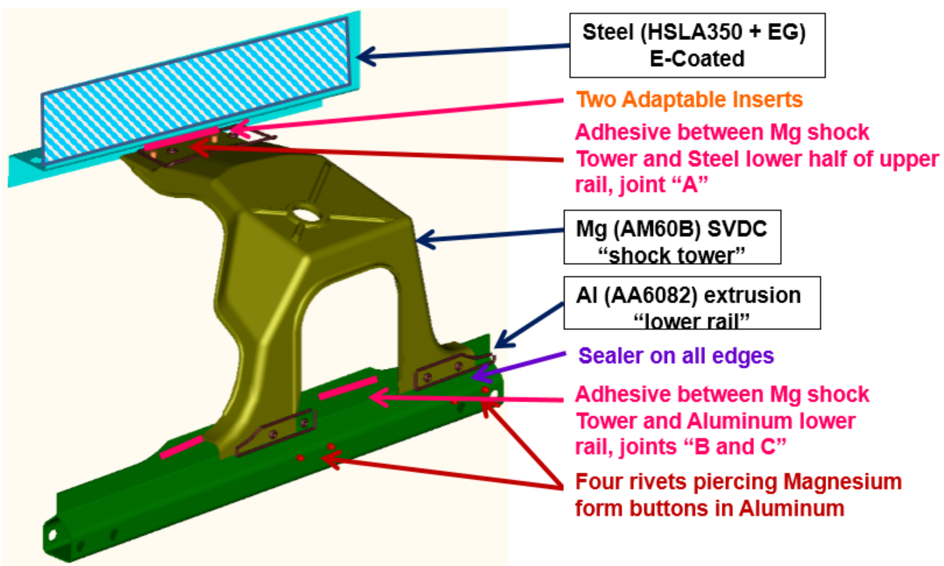
Magnesium-Intensive Front End Sub-Structure Development

Approach



FY2014 Accomplishments - Task 2 Demo Design, Analysis, Build & Testing

- Defined the Mg-intensive multi-material demonstration structure builds:
  Mg shock tower (AM60B SVDC) + Al extrusion rail (AA6082 T4) +
  Steel (HSLA350 + EG) OR Al alloy (AA6022 T4E40) sheet rail
- Developed CAD Models for "demo" structures with initial joining assumptions and fixturing guides/features.
- Managing timeline for ten variations of upper rail materials, adhesives, surface treatments and joint sealers.



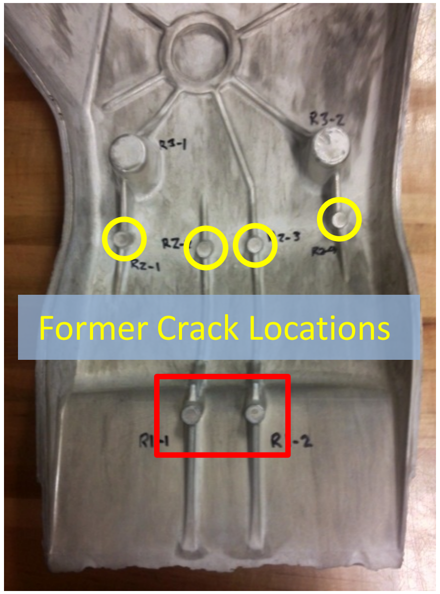
Example of Steel-Mg-Al Corrosion Demo Structure

Demo Structure Build and Test Timing

KEY TASKS		Date
Shock Tower Magnesium AM60B SVDC Castings available		received May 2014
Lower Rail Aluminum 6082 T4 Extrusions available		received January 2014
Upper Aluminum 1.5 mm 6022 T4E40 Press Brake Bending		received June 2013
Steel 1.0 mm HSLA 350 70G/70G Press Brake Bending		received June 2013
Begin Assembly of Demonstration Structures		8 September 2014
All Steel-Mg-Al parts & sub-assemblies arrive at Vehma		17 December 2014
All Al-Mg-Al parts & sub-assemblies arrive at Vehma		7 April 2015
Complete Assembly of Steel-Mg-Al Durability Structures		11 February 2015
Complete Assembly of Steel-Mg-Al Corrosion Structures		10 April 2015
Complete Assembly of Al-Mg-Al Durability Structures		1 May 2015
Complete Assembly of Al-Mg-Al Corrosion Structures		5 June 2015
Complete CAE Predictions of Durability Testing		15 December 2014
Durability Testing of Demonstration Structures	Start:	2 March 2015 (steel)
Corrosion Testing of Demonstration Structures at OEMs	Start:	22 April 2015 (steel)

FY2014 Accomplishments – Task 8 High Integrity Casting

- Canmet delivered Top hats and Shock Towers by the end of April 2014.
- Issues with shock tower cracks were satisfactorily resolved in conjunction with Canmet by making minor die modifications.
- 247 castings were delivered in May, 2014, machined to specification, and distributed to the task teams for assembly or testing. Task completed.



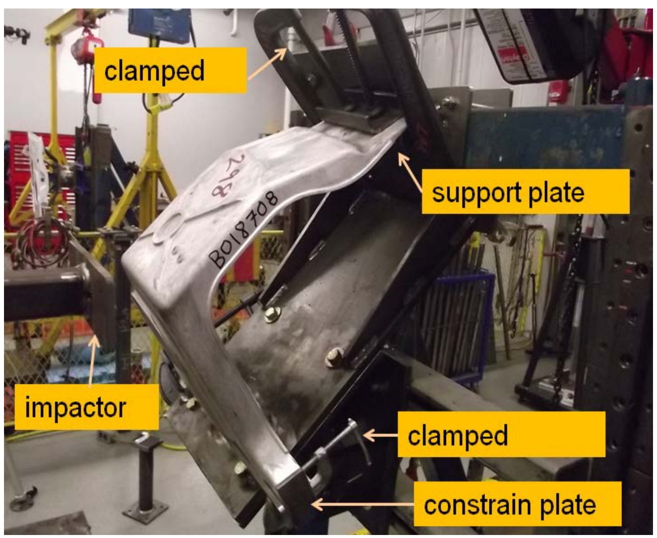
Shown in 2014 AMR Report

Final Shock Tower Casting

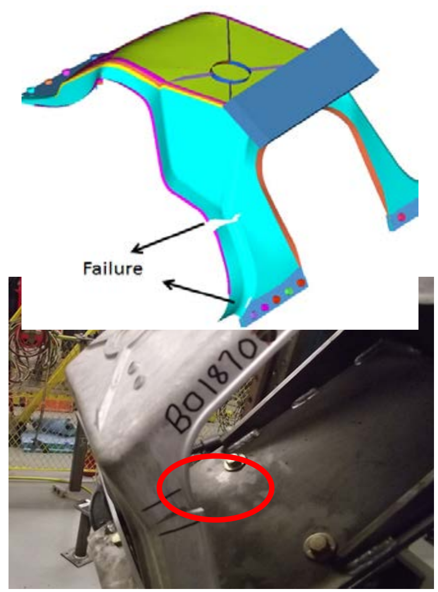
FY2014 Accomplishments - Task 3 Crashworthiness

- Delivered MAT 233 Mg for solid to simulate super-vacuum die casting (SVDC) AM60B alloy
- Conducted one quasi static and two impact tests and CAE predictions on AM60B cast shock tower using MAT 233 Mg Shell models, CAE predicted well on failure locations
- Completed tension and compression tests under different strain rates for ZE20
- Completed shear coupon tests for ZE20 with satisfactory results

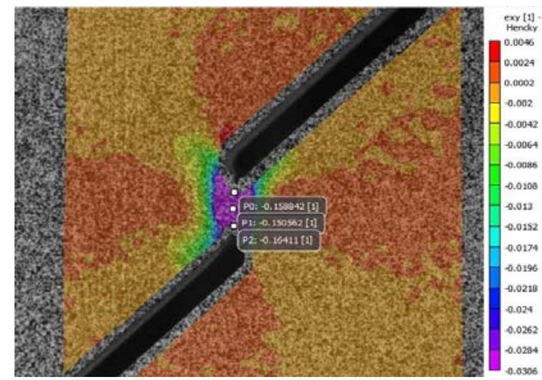
Test setup for edge impact

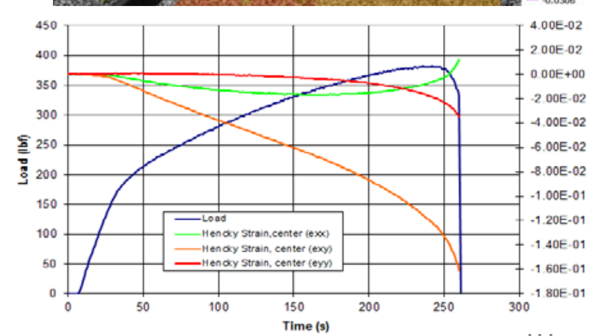


Test vs. CAE prediction failure location



Shear samples test on ZE20



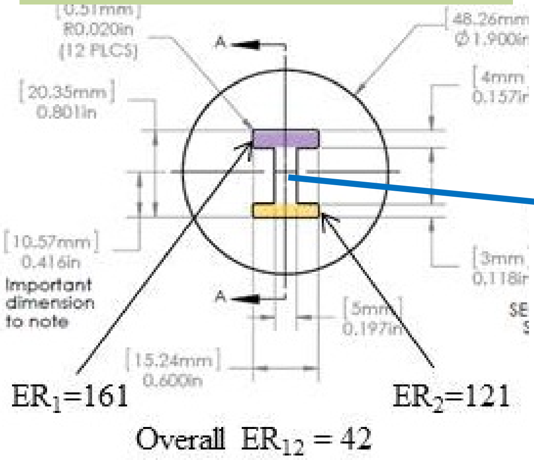


Accomplishments - Task 6 & 10 Extrusion/ICME

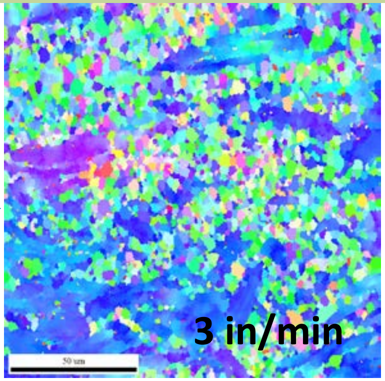
- PNNL produced two extrusion dies and delivered 4 small-scale extrusions produced under 4 different conditions to the Extrusion Team for analysis
- Ohio State University (OSU) delivered a complete matrix of Gleeble® testing results for AM30 and ZE20 for use in material model calculations for DEFORM extrusion modeling and recrystallization model development and validation.
- Lehigh completed material model for ZE20 using both Johnson Cook and Zerilli-Armstong equations and compared to OSU compression results. Also supported PNNL with small-scale extrusion design and simulated process using DEFORM code.
- Mississippi State University (MSU) characterized and compared the texture and grain size in PNNL small-scale ZE20 extrusions extruded at 2 different speeds and studied the effect of homogenization on extrusion microstructure.
- University of Michigan (UM) characterized and compared the texture in demo structure extrusion rails made of ZE20 and AM30 and showed that ZE20 rail texture is of lower intensity and is more uniform than that of AM30.
- UM developed EBSD-GOS (Grain Orientation Spread) technique to characterize and quantify the recrystallization kinetics of ZE20, incorporated DRX model in a Ford/UM crystal plasticity model and validated this model using the Gleeble ® samples and results from OSU.

Magnesium-Intensive Front End Sub-Structure Development

I-Beam Extrusion (PNNL)

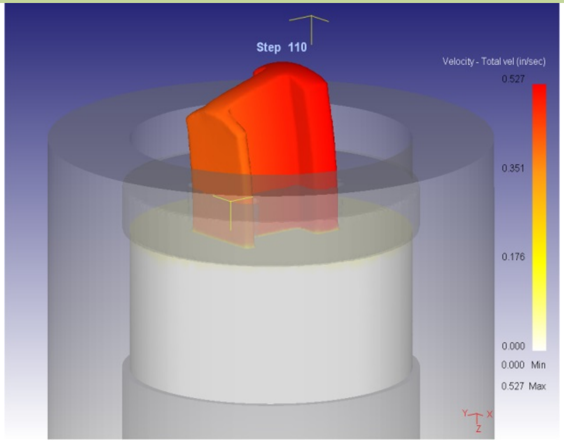


EBSD (MSSU)

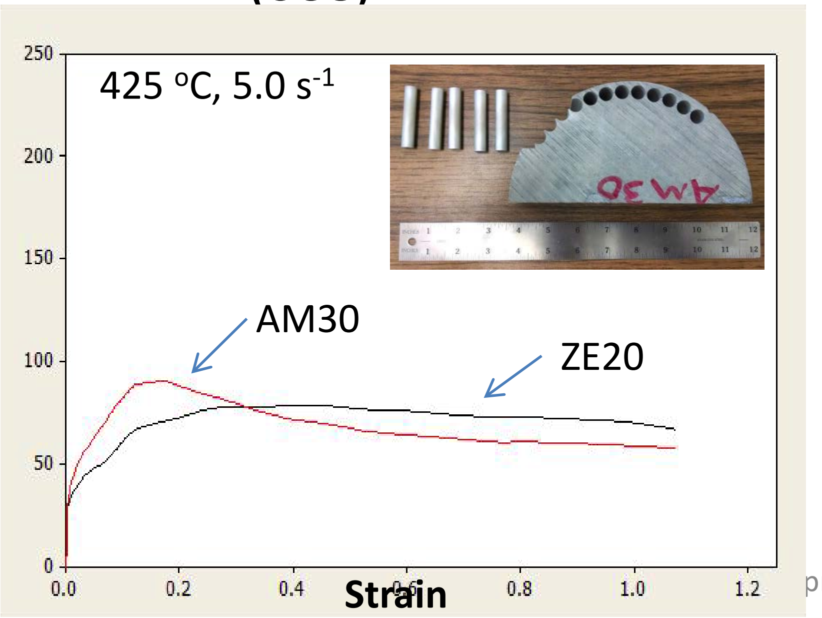


Grain Size = 7µm

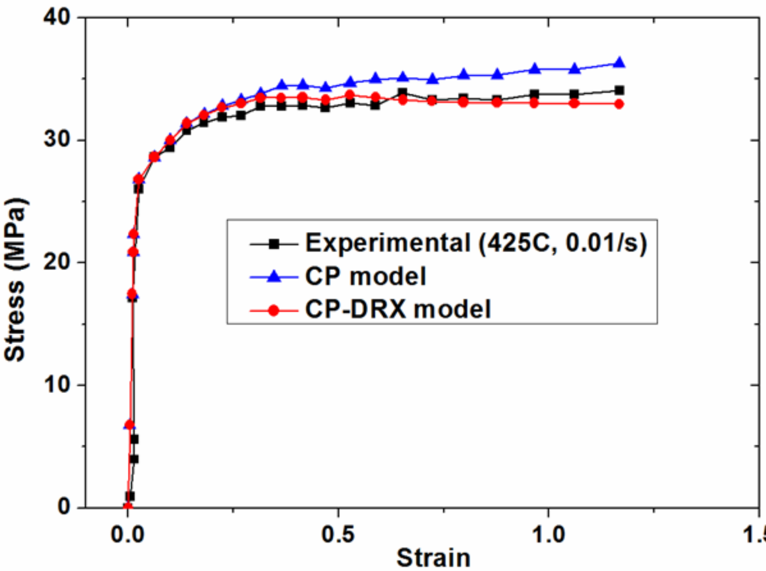
Extrusion Process Simulation w/ New Materials Model (Lehigh)



Gleeble® Testing (OSU)



Modeled Recrystallization behavior of and its effect on constitutive response (UM)

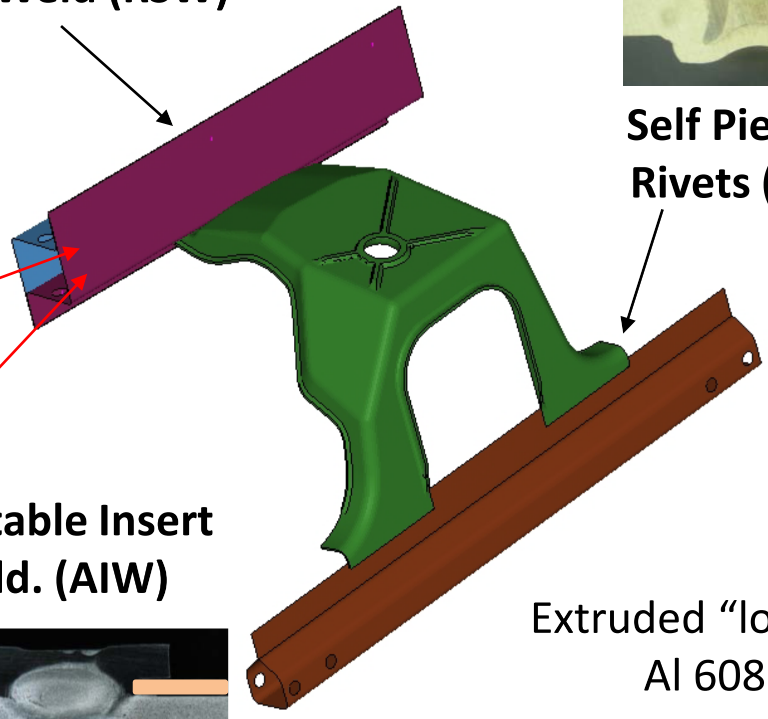


FY 2014 Accomplishments – Task 9 Joining

Developed and used Joining Technologies for Assembly of Demo Structures

Rail to Rail - **Resistance Spot Weld (RSW)**

Sheet formed "upper rail"
Al 6022 T4E40 1.5 mm
or
Steel HSLA 350EG 1.0 mm



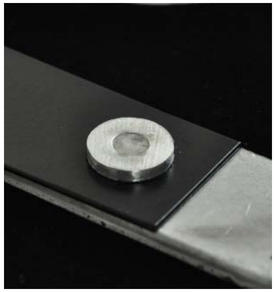
Self Piercing Rivets (SPR)

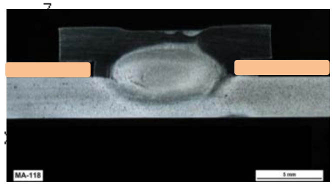
Extruded "lower rail"
Al 6082 T4

Friction Stir Linear Weld (FSLW)

Al Sheet – Mg Cast

Adaptable Insert Weld. (AIW)





Steel Sheet – Mg Cast

FY 2014 Accomplishments – Task 9 Joining

Friction Stir Welding (FSW)

- Established feasibility of friction stir welding (linear and spot) to obtain strong joints of Mg to Al and Al to Mg, with and without adhesive
- Optimized process for 3.1-mm AM60B to 1.5-mm AA6022-T4, fabricated and tested ~200 samples; selected FSLW with Al on Top; lap-shear load = 3.3 kN
- Assembled 86 demo structures for evaluation by Corrosion and Durability Teams

Adaptable Insert Welding (AIW)

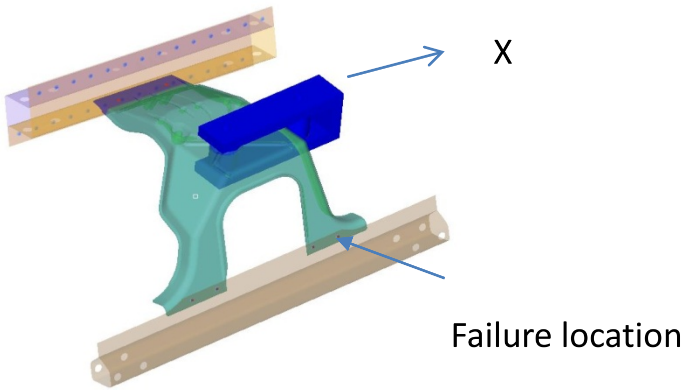
- Demonstrated capabilities for "Adaptable Insert Welding" as a novel means of joining steel to Mg, with and without adhesive
- Developed process parameters and optimized electrode design through fabrication and test of over 400 AIW joints including six unique coating/adhesive configurations
- Evaluated strength, durability (fatigue) and corrosion performance.
- Assembled 106 demo structures for durability, corrosion test.

Self Piercing Rivets (SPR)

- Successfully joined Mg casting to Al extrusion in 192 demo structure assemblies at room temperature using conventional SPR rivets, tools and processes.

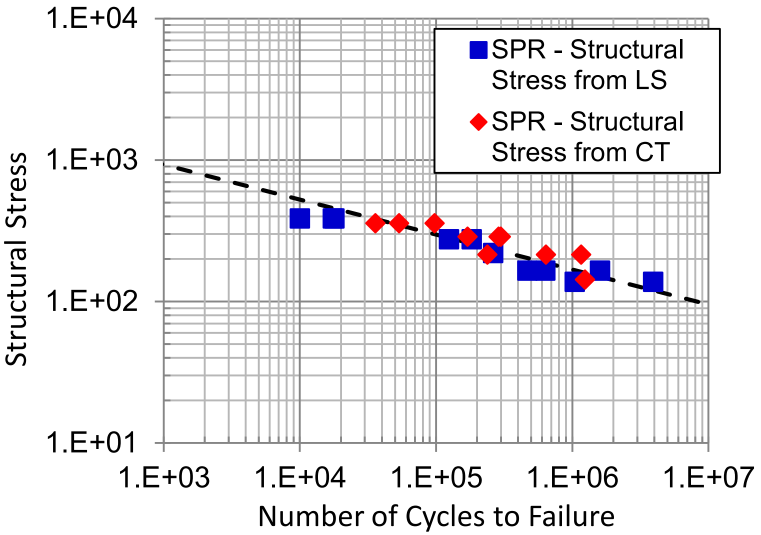
FY2014 Accomplishments - Task 4 Fatigue and Durability

- Developed/Executed Fatigue of Joint models/tests for Magnesium Intensive Structures
  - FSLW, SPR, Adaptable Inserts (UMD, UA, AET)
- Developed/Executed Material Fatigue Models for Component Design with Magnesium Alloys
- Performed Fatigue Analysis of the Demo Structures and Identified the Critical Locations for X, Y and Z loading conditions



No of Cycles	Load (N)
50,000	6,000
100,000	5,000
300,000	4,100

Predicted failure location and life for X loading

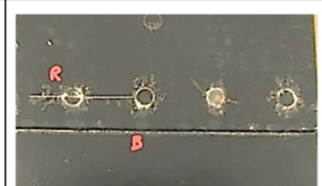
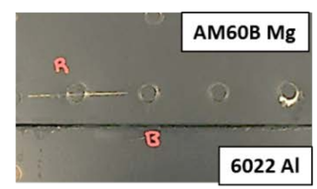
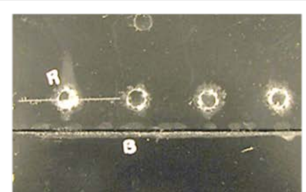
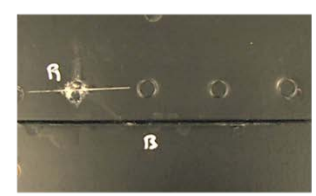


Life Prediction Models Using Structural Stress: SPR

FY2014 Accomplishments - Task 5 Corrosion and Surface Treatment

- Completed corrosion testing by SAE J2334 (Henkel Corp.) and ASTM B-117 (PPG) on an extensive multiple-join technique, multi-metal (Mg, Al steel) coupon assembly array to assess paint-shop feasibility for such assemblies of mixed materials.
- Conducted electrochemical tests (North Dakota State) of the galvanic couple between variously-coated steel self-piercing rivets and surrounding magnesium.
- Determined that selective corrosion at coated self-piercing rivets had only limited effects on lap-shear strength of Mg-Al joints (Ohio State).
- Prepared a corrosion test array of selected pretreatments and topcoats applied to ZE20 and ZEK100 wrought magnesium alloys for corrosion testing by Atotech, Inc.
- Determined likely influence of polymer thinning on cosmetic corrosion around rivet head and designed experiment to confirm such effect. (Missouri S & T)
- Identified limitations on aluminizing as a candidate rivet coating approach.

Comparison of coated rivet appearance after 60 cycles SAE J-2334 for same metal pretreatment with different rivet coatings and polymer topcoats.

Rivet Coating	E-coat	Powder Coat
Zn-Sn Baseline		
IVD Aluminum		

FY2014 Accomplishments* - Task 7 Low-Cost Sheet and Forming

- Maintained awareness of the Canadian Team's (Prof. Worswick's group) work on the mechanical behavior of magnesium alloy ZEK100 rolled sheet.

Srihari Kurkuri, Michael J. Worswicki, Alexander Bardelcik, Raja K. Mishra and Jon T. Carter, "Constitutive behavior of commercial grade ZAEK100 magnesium alloy sheet over a wide range of strain rates", *Metallurgical and Materials Transactions A, Volume 45 (8), Pages 3321-3337, 2014.*

Srihari Kurkuri, Michael J. Worswicki, Raja Mishra and Jon T. Carter, "Effects of Temperature and Strain Rate on Mechanical Response of ZEKK100 Mg Alloy Sheet.", *TMS 2014 143rd Annual Meeting and Exhibition, San Diego, CA, USA*.

- * Note - last year: Provided steel and aluminum test coupons for joining and corrosion studies, and press-brake-formed upper-rail half sections in steel and aluminum for use in magnesium-intensive demo structures

Collaboration and Coordination

- Broad participation of domestic OEMs, suppliers and universities (over 30 in total)
- Project executed at task level (9 task teams) and coordinated by a USAMP core team
- The first-of-its-kind US-Canada-China collaboration, leveraging significant international resources on coordinated pre-competitive research

U.S. Partner Organizations

USAMP Core Team

FCA (Fiat Chrysler Automobiles)
Steve Logan
Mostafa Rashidy
Dajun Zhou

Ford
Xiaoming Chen
Joy Forsmark
Bita Ghaffari
Mei Li
Xuming Su
David Wagner
Jacob Zindel

GM
Jon Carter
Richard Osborne
Jim Quinn

Bob McCune, Technical Project Administrator

Collaboration and Coordination

U.S. Partner Organizations

Industry Partners (23)

ACT Test Panels
AET Integration
Almond Products
AlumiPlate
Atotech
Cana-Datum
Duggan Mfg.
Element Technologies
Exova
Forming Simulation Technologies
Henkel Corp.
Henrob Corp.
Hitachi America
Kaiser Aluminum
Mag Specialties
Metro Technologies
PNNL
PPG Industries
Titanium Finishing
UDRI
Universal LINC
U.S. Magnesium
Vehma Int'l.

Universities (8)

Lehigh University
Mississippi State University
Missouri Science and Technology
North Dakota State University
The Ohio State University
The University of Alabama
The University of Michigan
The University of Michigan Dearborn

International Partner Organizations

China Partners (13)

China Magnesium Center	Ministry of Science and Technology	Shenyang University of Technology
Chongqing University	Northeastern University	Tsinghua University (Beijing)
Institute of Metals Research (Shenyang)	Shanghai Jiao Tong University	Xi'an University of Technology
Central South University	Shanxi Yinguang Huasheng Magnesium Co. Ltd.	Dong Guan ECONTEC
Institute of Advanced Materials- Shandong		

Canada Partners (9)

CANMET	University of Waterloo
Magna	University of Western Ontario
Meridian Light Metals	McMaster University
3M Canada	
Huys Corp.	Auto Partnership Canada

Remaining Challenges and Barriers

- ❑ Solutions remain to be validated on Demo Structures
- ❑ Ability to schedule and complete corrosion testing
  - ❑ Corrosion tests are very long duration.

Future Work

- ❑ Complete Crashworthiness Durability and Corrosion testing
- ❑ Validation of prediction of durability performance of dissimilar metal joints on complex assemblies.
- ❑ Complete Project Final Report

- ❑ This project will be completed at the end of 2015.
  - ❑ Although much work has been done to identify new and improved coating and joining processes to minimize the risk of galvanic corrosion, successful corrosion performance especially is expected to continue to be a significant challenge.

Summary

- Relevance
  - The project is clearly relevant to DOE goals of reducing vehicle weight through increased integration of magnesium into multi-material vehicle structures.
- Approach
  - The approach of leveraging a large international collaboration effort to conduct research and enabling technology development followed by the build of multi-material "demo" structures to validate processes and technologies should help to achieve DOE goals
- Technical Accomplishments
  - Made significant accomplishments in all project technology areas. E.g. (Not exhaustive list)
    - Developed and demonstrated Adaptable Insert Welding joining technique
    - Fabricated 192 Demo Structures for assessment using new / advanced joining techniques developed and demonstrated in this project
    - Corrosion & Coatings – completed comprehensive corrosion testing of extensive array of coupons multi-metals and coatings to assess paint shop compatibility
    - Extrusion and ICME – Modeled & produced trial extrusions; Integrated information from multiple universities to evaluate ZE20 and compare its performance to AM30.
- Collaborations
  - The international collaboration including three U.S. automotive OEMs, 30 U.S. industrial partners and universities, and over 20 Canadian and Chinese organizations is valuable in meeting DOE goals.
- Future Work
  - Complete Project and requisite documentation.

Response to 2014 Merit Review Comments and Questions
Magnesium Front End Development – lm077

General Observation: The 2014 reviewer comments were generally very favorable and complimentary. The following address a few of the remarks.

1. **Comment:** Regarding Collaboration and coordination – One reviewer noted "that it looks like a monumental task to keep all the involved agencies and supplier partners working to the same objective." Another noted "close collaboration between everyone is not necessary, cost effective, nor manageable."

Response: The ongoing success of this project demonstrates the team's ability to deal with the challenges of managing such a large and complex project, and the value of that effort. The U.S. Team emphasizes ongoing communication, with a weekly meeting/ conference call of leaders of each Task Team to share information and progress, identify best practices and identify and resolve potential problems before they become unmanageable.

While each country sets and manages their own project direction, we meet periodically to share information, to provide technical feedback and to prevent needless redundancies.

Response to 2014 Merit Review Comments and Questions
Magnesium Front End Development – lm077

2. **Comment:** "… reviewer is concerned with the remaining technical barriers that have not been successfully resolved (corrosion, joining, high performance casting). Specifically, this reviewer would have preferred to see a plan on how these technical barriers would be addressed with a potential risk assessment and abatement plan for the rest of the project over the future work that was presented. The future work was generic and not focused on the technical barriers.

Response: The project is aimed at determining production viable techniques to mitigate the challenges that are inherent in extending the implementation of magnesium in high volume production vehicles. Our work in developing accurate simulation and modeling tools and techniques, assessing various surface treatments, joining processes (and the influence of each on performance in corrosion, static and fatigue performance) does address the most immediate needs.

Due to the complexity of the materials involved, it is true that we will not be able to eliminate all barriers. However we feel our approach provides significant value to the industry and to DOE in the effort to lightweight vehicles ASAP.

Response to 2014 Merit Review Comments and Questions
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3. **Comment:** "reviewer commented that it may be difficult to get all the work completed by the mid-2015 target completion date "

Response: Regrettably the reviewer was correct. Due to the cracks discovered in shock tower castings as noted last year, the project was delayed sufficiently for us to assess the best way to eliminate those cracks and to determine through simulation whether or not the cracks would be expected to have a detrimental effect on our fatigue tests. That delay led to a six month no-cost extension to the project. We are confident that we will now be able to complete all of the required testing by the new , Nov. 30, 2015 end date.

Acknowledgement

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Technical Back-Up Slides

Workflow - Task 6 & 10 Extrusion/ICME

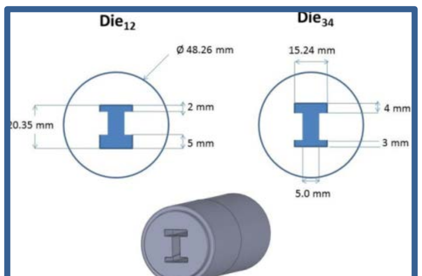
Processing → **Microstructure** → **Property** - - → **Performance**

Extrusion process simulation of ZE20
- Lehigh (DEFORM)
- MSSU (HyperExtrude)
- UM (Abaqus)

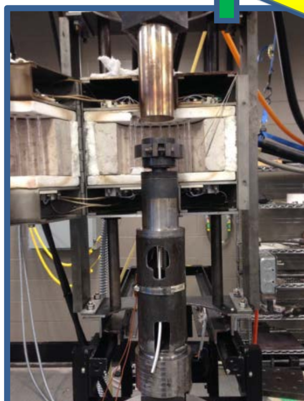
Microstructure Modeling & Characterization
- UM (CP-DRX model & microscopy)
- Lehigh (Microscopy)
- MSSU (Microscopy)

Local property
- Stress-strain curves during extrusion (UM & MSST)
- Tensile and Fatigue property (UM)

Gleeble® Testing (Ohio State U.)



I-Beam Extrusion (PNNL)



Indirecct Extrusion (MSSU)

Model Validation
Extruded ZE20 rails

- DRX kinetics, grain size and texture prediction (UM)
- Texture, grain size characterization (UM, Lehigh, MSSU & OSU)

LS-DYNA® Prediction of extrusion component performance

Magnesium-Intensive Front End Sub-Structure Development

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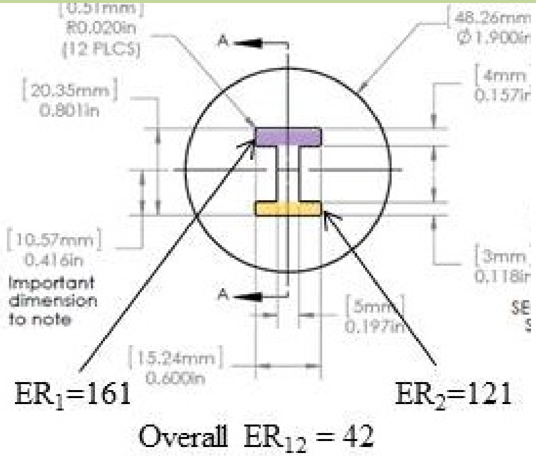
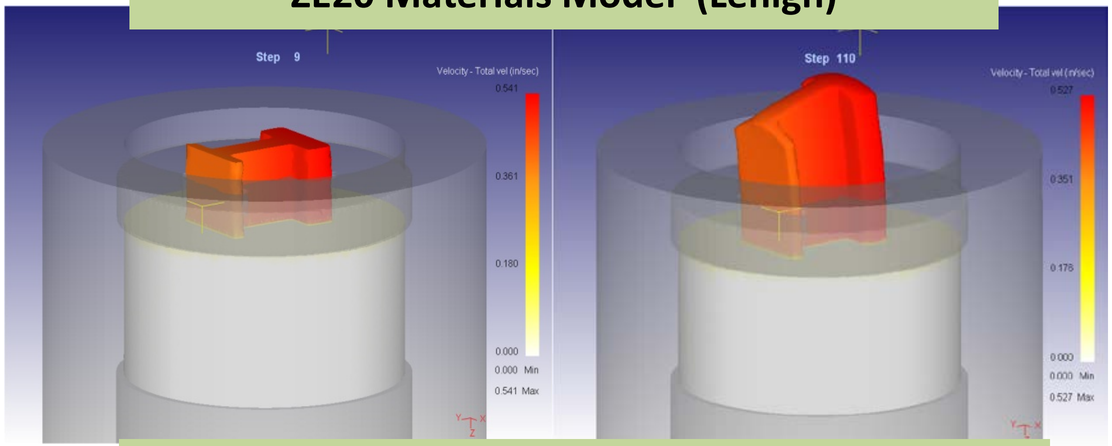
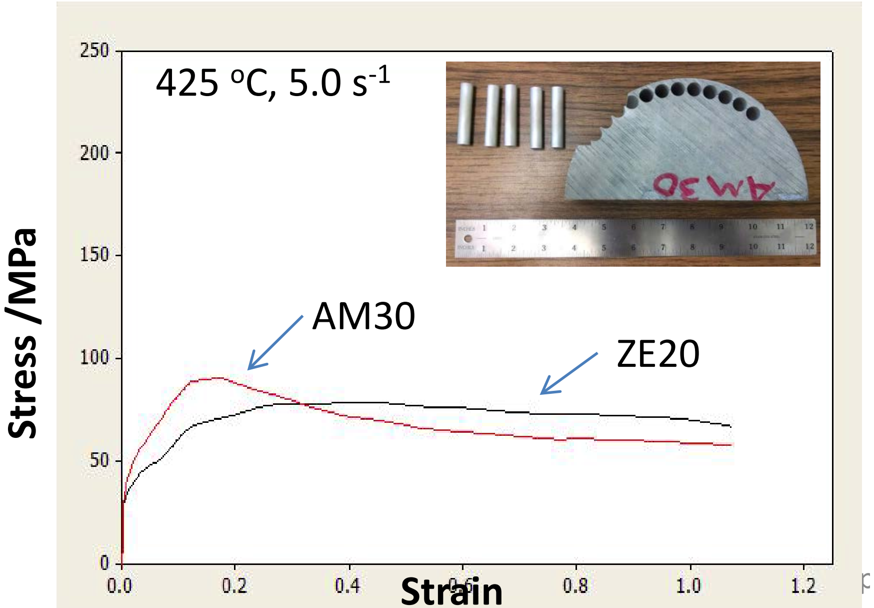


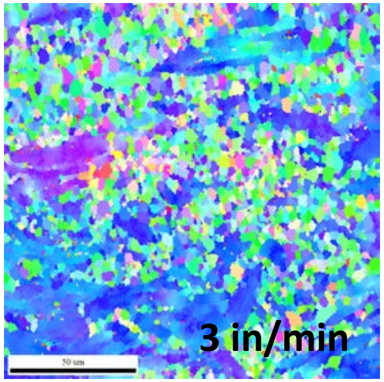
DEFORM Extrusion Process Simulation w/ New ZE20 Materials Model (Lehigh)

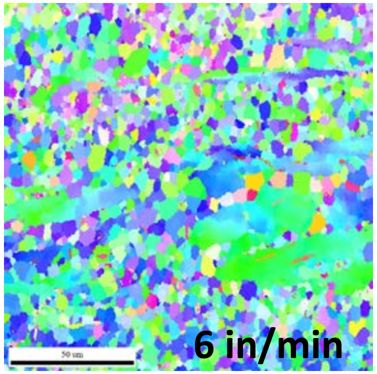


Gleeble Testing (OSU)

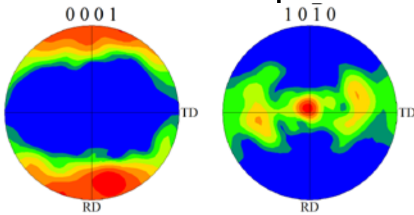


EBSD Comparison of ZE20 Extruded I-Beam at 3 and 6 in/min(MSSU)

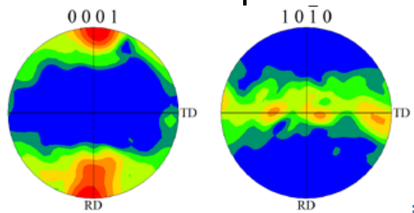




Grain Size = 7µm

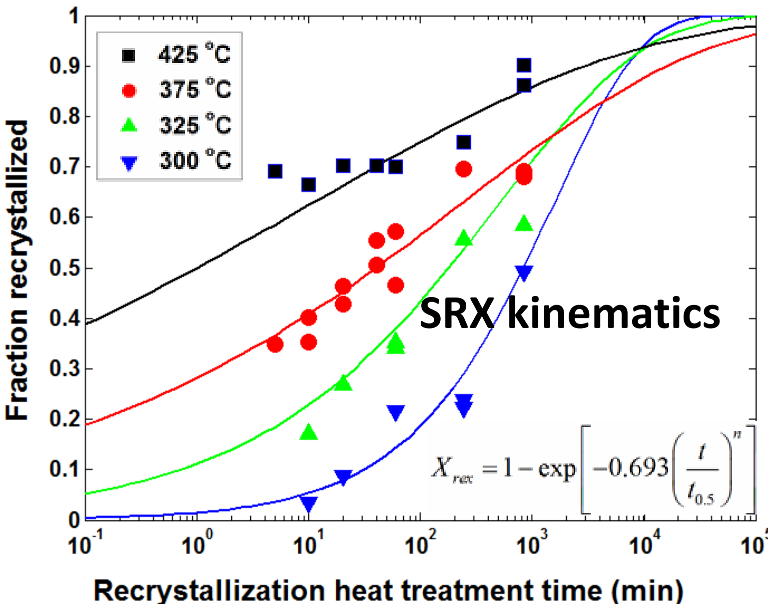


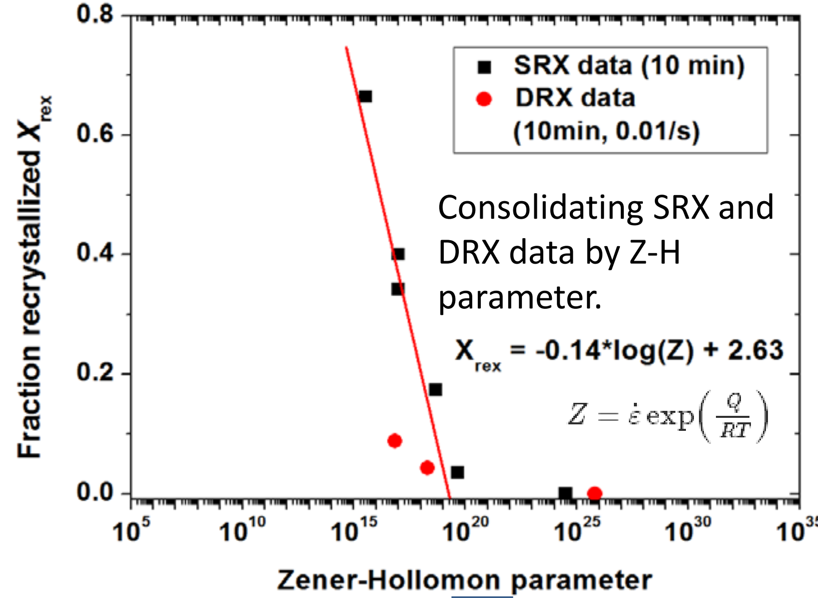
Grain Size = 10µm

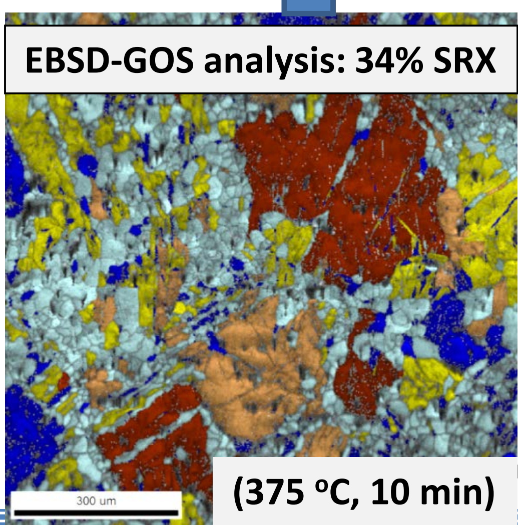


Magnesium-Intensive Front End Sub-Structure Development

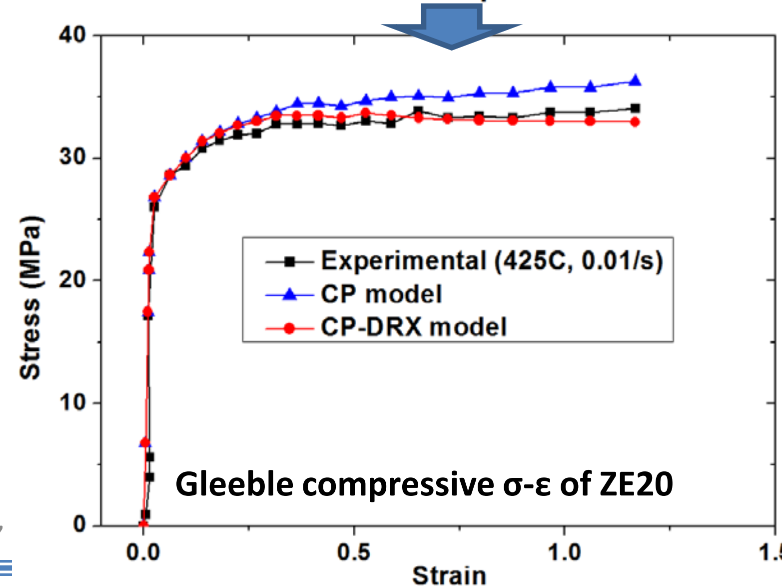
Developed and Modeled recrystallization behavior of ZE20 alloy and its effect on constitutive response (UM)



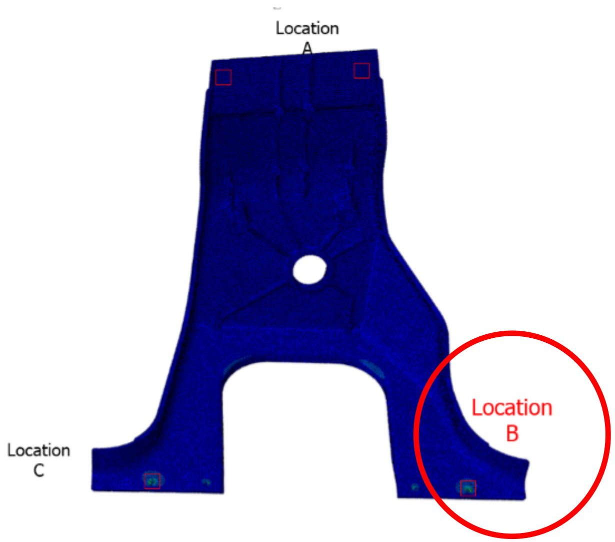




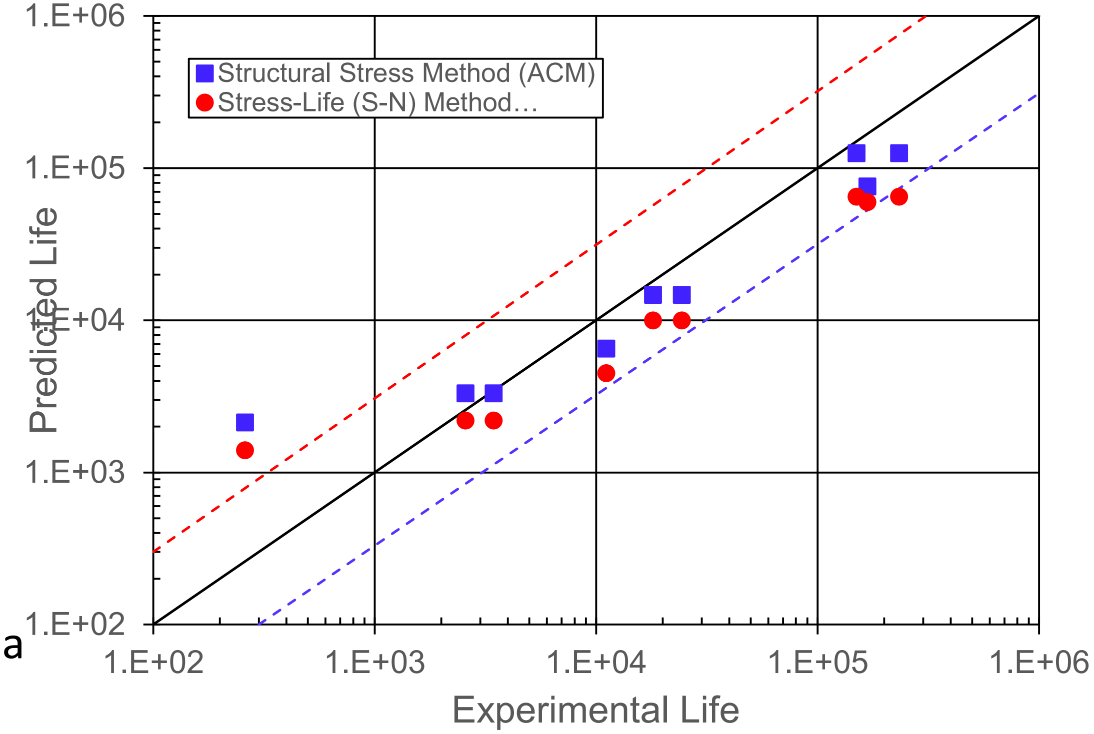
	Min	Max	Total Fraction
(light cyan)	0	1	0.342
(blue)	1	2	0.090
(yellow)	2	3	0.134
(orange)	3	4	0.084
(dark red)	4	5	0.145
(red)	5	100	0.000



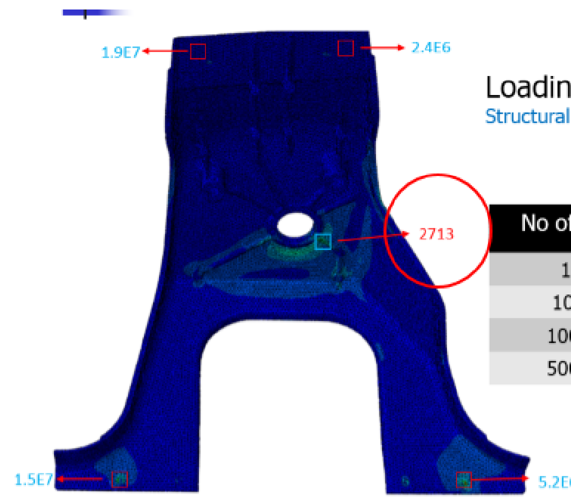
X-Direction



Location B is the critical Area



Magnesium-Intensive Front End Sub-Structure Development

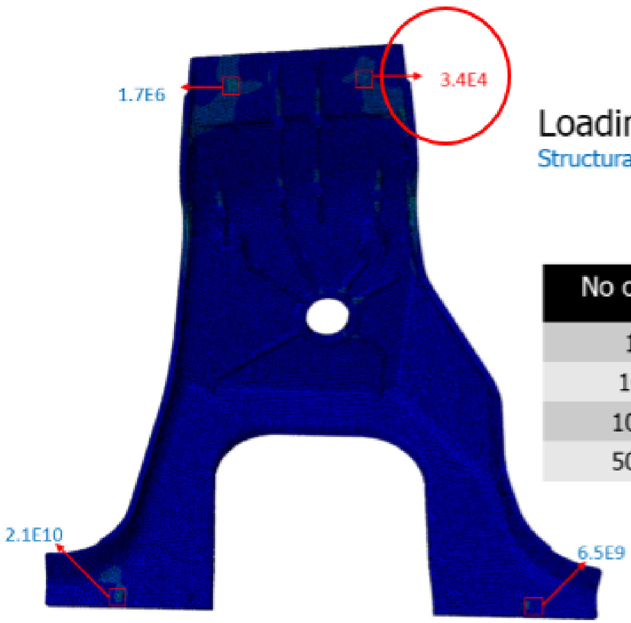


SS-N approach
EN approach

Loading: **Z**-direction
Structural S-N Curve: AIW (LS and CT), SPR (LS and CT)

No of Cycles	Load (N)
1000	10500
10,000	4800
100,000	3200
500,000	2800

** Using E-N approach in N-code we found that base material is failing at this location on the top side of the shock tower.



SS-N approach

Loading: **Y**-direction
Structural S-N Curve: AIW (LS and CT), SPR (LS and CT)

No of Cycles	Load (N)
1,000	9500
10,000	5000
100,000	3000
500,000	2000

Project Structure and Timing (MFERD Phase I, II and III)

FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15

MFEDD Phase I. Front End Design and Feasibility

USAMP PROJECT (AMD603) : Magnesium Front End Design & Development (MFEDD)

CANADA-CHINA-USA COLLABORATIVE PROJECT: Magnesium Front End Research & Development (MFERD)

Phase I. Enabling Technology Development (AMD604)
- Crashworthiness research
- NVH research
- Fatigue and durability research
- Corrosion and coatings
- Low-cost extrusion & forming
- Low-cost sheet and forming
- High-integrity body casting
- Welding and joining
- Integrated computational materials engineering

Phase II. Demo Structure (AMD904)
Magnesium only

Phase III. Mg-Intensive Front End (AMP800)
- Demo design, build and testing
- Crashworthiness research
- Fatigue and durability research
- Corrosion and coatings
- Extrusion
- Sheet and forming
- High-integrity body casting
- Welding and joining
- Integrated computational materials engineering