USAMP Low-Cost Magnesium Sheet Component Development and Demonstration Project

2021 DOE Merit Review Presentation

Presenter and PI :

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FCA US LLC

United States Automotive Materials Partnership

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Project ID #mat127

Overview

Timeline

- **Start:** October 1, 2016
- **End:** February 28, 2021
- **Percent complete:** 100% complete

Budget

Total project funding

- DOE (70%): $5,651,258
- Contractor (30%): $2,421,968

Funding received in FY20

- DOE Share: $2,081,496
- Contractor share: $1,114,937

Partners

Primary recipient – United States Automotive Materials Partnership LLC (USAMP)..

Industry subrecipients

- AET Integration, Inc.
- Fuchs Lubricants
- Henkel Corporation
- PPG Industries
- Quaker Houghton Chemical Corporation
- Vehma International of America
- Xtalic Corporation

University subrecipients

- The Ohio State University (OSU)
- University of Florida (UF)
- University of Michigan (UM)
- University of Illinios at Urbana-Champaign (UIUC)
- University of Pennsylvania (UPenn)

LightMAT national laboratory participants

- Oak Ridge National Laboratory (ORNL)
- Pacific Northwest National Laboratory (PNNL)

Vendors with substantial technical involvement

- Camanoe Associates
- Edison Welding Institute (EWI)
- FADI-AMT
- Inaltech, Inc.
- POSCO

Barriers

- High cost of Mg sheet material, and challenges in producing automotive components with it, prevents widespread use in automotive applications.
- Lack of adequate predictive tools to enable the low cost manufacturing of lightweight Mg sheet components

Targets

- Overall – 25% vehicle glider mass reduction @ less then $5/lb saved (FOA specific – Mg sheet components at no more than $2.50/lb saved) based on 2017 U.S. DRIVE MTT Roadmap Report

Relevance

Overall objective

- Demonstrate the feasibility of producing Mg sheet components to achieve a component cost increase over conventional steel stamped components of no more than $2.50/lb saved.

Objectives (March 2020 to March 2021)

- Validate Integrated Computational Materials Engineering (ICME) predictions for formability and mechanical properties
- Optimize effective, low cost pretreatments/coatings and lubricants
- Quantify suitable joining processes
- Develop and validate material cards for forming analysis
- Complete medium and large scale forming evaluation of selected alloy

Impact on Barrier(s)

- Mg sheet has the potential to reduce mass of automotive components by up to 65% compared to steel (55% targeted for this project) and this project is specifically aimed to address cost and manufacturing challenges preventing widespread use of Mg sheet.
- Demonstrating the feasibility of producing Mg sheet components at the target cost should enable increased usage in automotive applications
- Improved modeling capabilities of Mg alloys from raw ingot through fully formed and painted automotive components will be developed

Approach / Milestones

All milestones achieved ✓

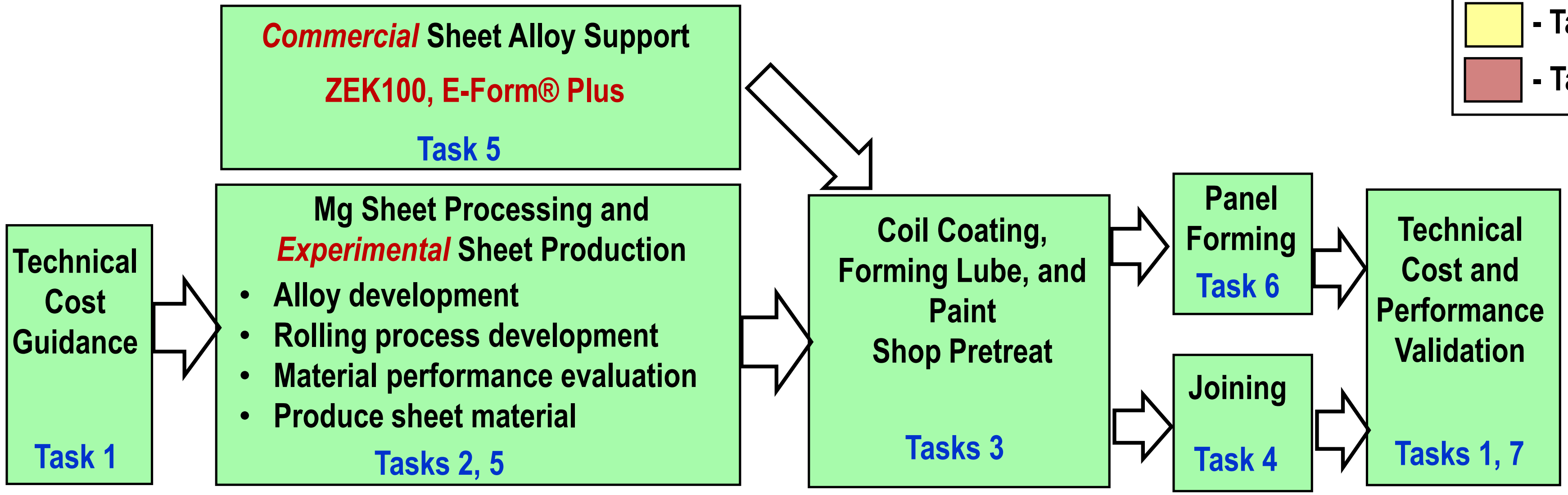
BP	Milestone Number	Milestone Type	Task	Description	Status
1	1	Go/No Go	**Task 0:** Project Management/Contracting	100% of POs issued to subs.	Complete
	2	Technical	**Task 1:** Technical Cost Guidance	Baseline cost model for Mg sheet complete.	Complete
	3	Technical	**Task 2:** Alloy and Sheet Processing Development	New Mg alloy sheet composition(s) identified.	Complete
2	4	Technical	**Task 2:** Alloy and Sheet Processing Development	Constitutive model for textured Mg-alloy completed and ideal texture suggested.	Complete*
	5	Technical	**Task 2:** Alloy and Sheet Processing Development	Forming analysis completed on medium sheet.	Complete*
	6	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Forming lubricant composition identified.	Complete
	7	Go/No Go	**Task 5:** Mg-alloy Sheet Production	Manufacture and deliver experimental medium-width sheets.	Complete
3	8	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Evaluation of corrosion protection coating completed.	Complete
	9	Technical	**Task 5:** Mg-alloy Sheet Production	Delivery of wide sheet.	Complete
	10	Technical	**Task 6:** Mg-alloy Large Body Component Production	Mg-alloy panels formed to specifications.	Complete
	11	Technical	**Task 7:** Component(s) Demonstration	Final delivery and performance evaluation completed.	Complete

Note: * = Milestone was achieved in BP3 which concluded on 2/28/2021.

Approach

Task 1	Establish a technical cost model to identify Mg cost drivers and verify proposed Mg door components achieve targets.
Task 2	Leverage ICME methods to develop at least one new, low cost Mg alloy suitable for forming large, challenging automotive panels.
Task 3	Develop effective, low cost pretreatments/coatings, forming lubricants and paint shop coatings.
Task 4	Evaluate suitable joining processes.
Task 5	Produce material test samples (both experimental and commercial) to validate ICME predictions for formability and mechanical properties compared to baseline ZEK100 material.
Tasks 6, 7	Produce and evaluate large automotive components.

- Task(s) complete or substantially under way
- Task(s) under way
- Task(s) not started or no substantial progress

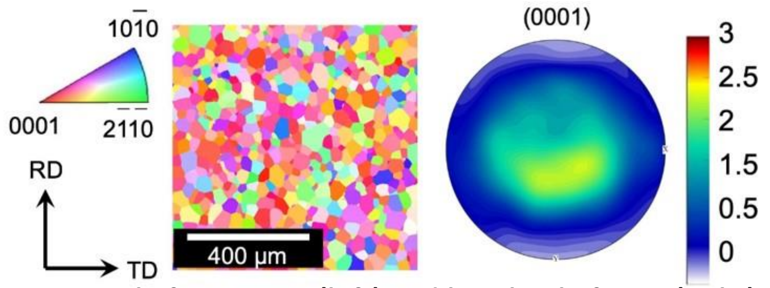


Technical Accomplishments

Previous Accomplishments

Modeling:

- Developed and validated solute strengthening models using DFT
- Quantified slip-system-dependent parameters using HEXRD
- Identified desirable texture features
- Validated polycrystal model for E-Form Plus



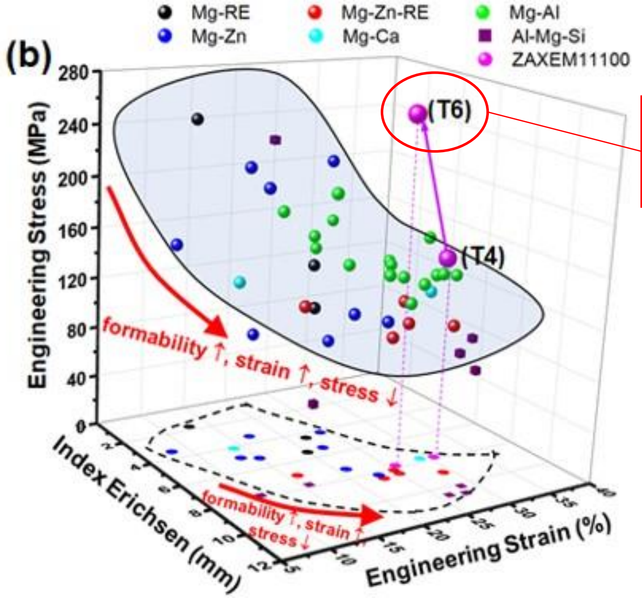
EBSD inverse pole figure map (left) and basal pole figure (right) of Mg-3Zn-0.1Ca alloy in a specimen subjected to thermomechanical processing that promoted a weak basal texture

Coating and Lubricants:

- Developed two lubricants for warm forming E-Form Plus up to 300C
- Developed two coil applied pretreatments to prevent oxidation

Alloy Development:

- Designed Experimental Alloy 2 Plus (ZAXEM11100) with highest combination of strength and elongation
- Determined alloy 3 microstructure (Mg-Ca-Zn)
- Characterized E-Form Plus



26% Elongation
270 MPa yield Strength

Outstanding formability, ductility and strength of Alloy 2 Plus compared with other Mg alloys

Technical Accomplishments

Technical Cost Model

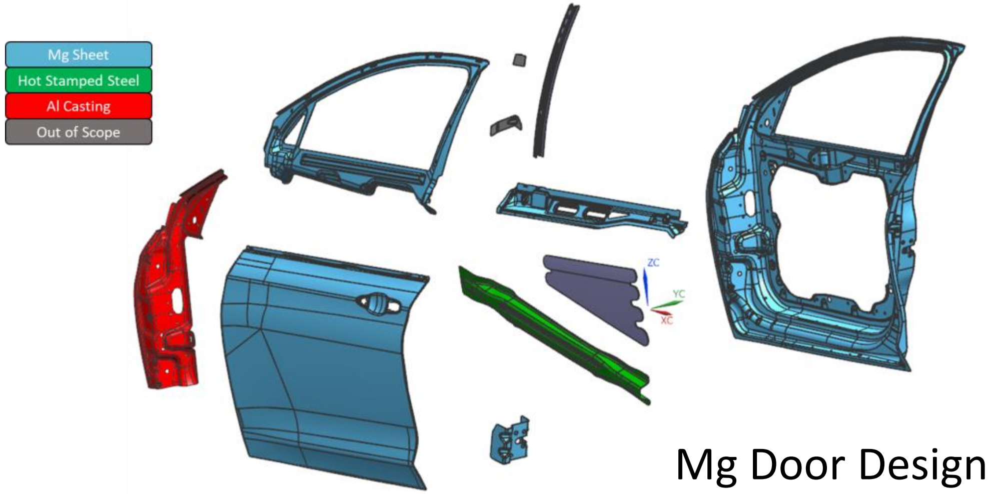
Approach

- Conduct a technical cost analysis of manufacturing a conventional steel automobile door and a lightweight magnesium door
- Compare cost difference and weight difference of two designs

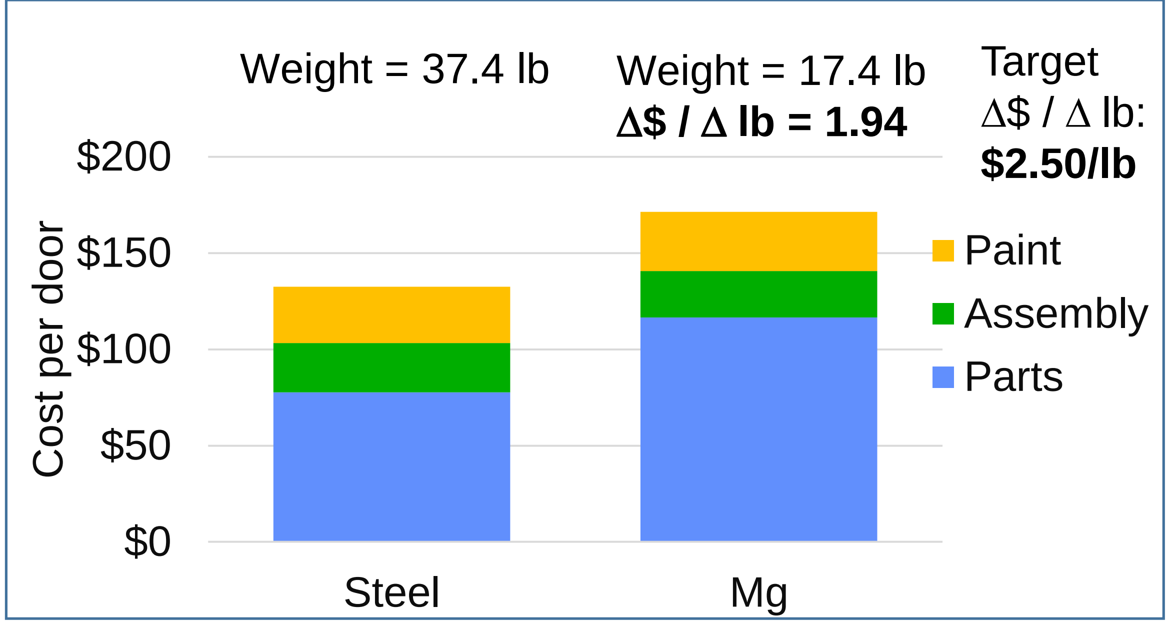
Key Accomplishments

- Mg door lightweighting cost is under cost target for scenario where Mg is produced using Chinese Pidgeon process
- Door made with US electrolytic Mg can achieve cost target with 10% material cost reduction

Magnesium doors can meet lightweighting cost target



Mg Door Design



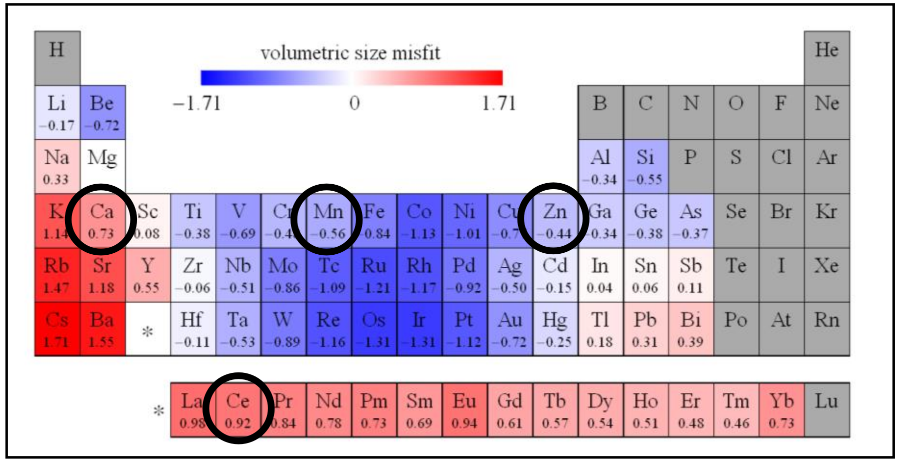
Cost and weight comparison of a steel door verses a magnesium door design shows the magnesium door can meet the cost target

Technical Accomplishments

ICME Development – Atomistics

Atomistics/Density Functional Theory (DFT) (UIUC):

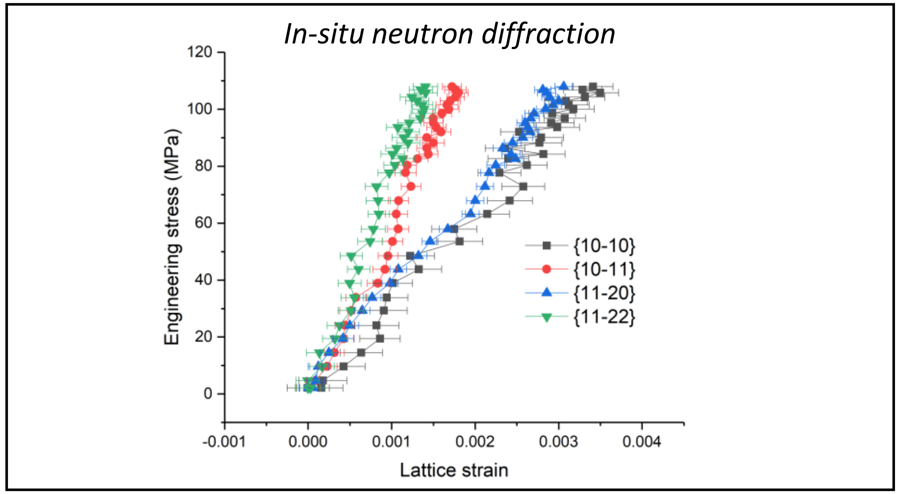
- Calculate solute energy landscapes for non-basal deformation modes to activate more slip systems to improve plasticity
- Development of predictive models of solute chemistry on deformation in magnesium
- Suggested routes for alloy chemistry of magnesium alloys with improved formability



Solute size misfits and solute-induced changes in critical resolved shear stress (CRSS) for 63 substitutional solute species

Inputs for modeling (PNNL):

- The room- temperature tensile testing was performed using *in-situ* synchrotron XRD and neutron diffraction.
- Lattice strain and peak intensity change was analyzed, providing experimental input for modeling.
- Microstructure and texture was investigated using EBSD, which indicated basal slips and $\{10\bar{1}2\}\langle\bar{1}011\rangle$ extension twinning activated during room-temperature tensile deformation.



Stress strain curves for Mg-0.2Ca generated using In-situ neutron diffraction shows stress partitioning based on grain orientation

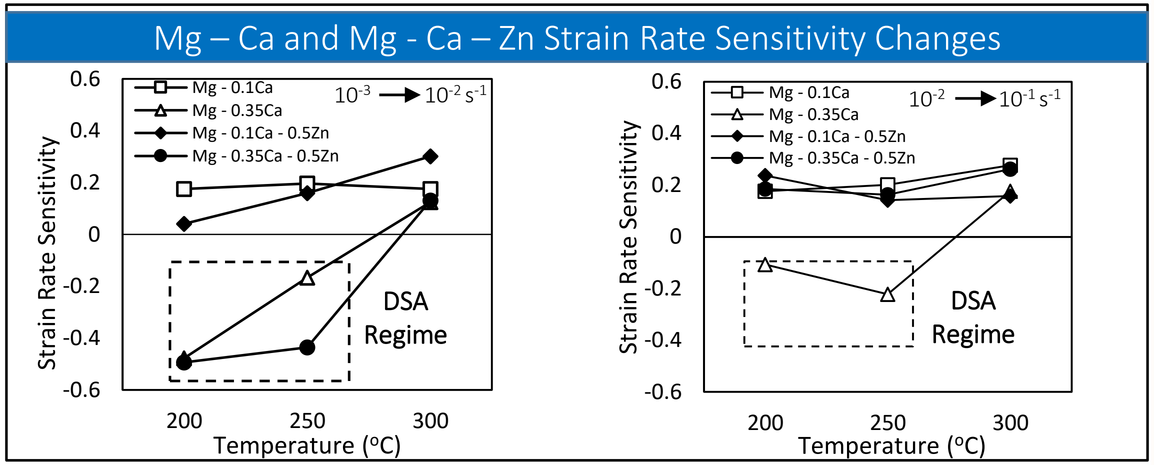
Technical Accomplishments

ICME Development – Texture Development

Solute Effects and Texture Development (UF):

- Determined DSA processing window for dilute Mg – Ca and Mg – Ca – Zn alloys as function of temperature and strain rate.
- Quantified and evaluated texture changes after static recrystallization of Mg – Ca and Mg – Ca – Zn alloys compressed under DSA and non – DSA conditions.

Verified addition of Ca and Zn solutes to the α-Mg matrix resulted in weaker textured grains after static recrystallization processing under DSA and non-DSA conditions

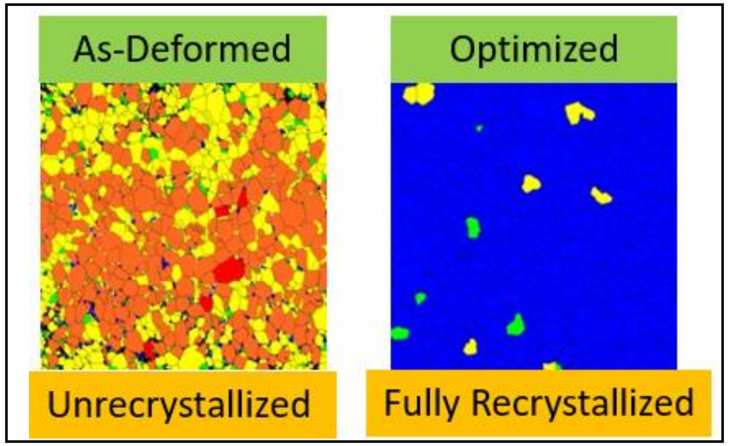


Identification of strain rate and temperature regime where texture weakening is suspected to occur for 4 alloys

Alloy Effects on Texture Evolution (UM):

- Confirmed that both Ca and Zn are required
- Found that annealing after deformation is critical to producing a weak spread (desirable) texture
- Established optimum rolling and heat treatment processing routes for Mg-Zn-Ca alloys

Identified that RX Plays an Essential Role in Producing More Formable Texture in Mg-Zn-Ca Alloys



EBSD recrystallization characteristics at different processing conditions for Mg-3Zn-0.1Ca Alloy

Technical Accomplishments

Forming Simulation

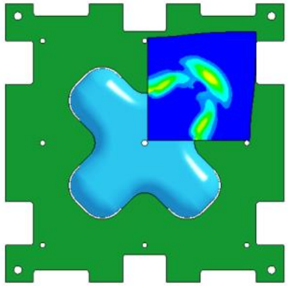
Approach

- Simulate cross-form stamping and correlate with experimental stamping
- Compare MAT233 and MAT233+ to measure improvement
- Simulate Door inner and outer panels

Key Accomplishments

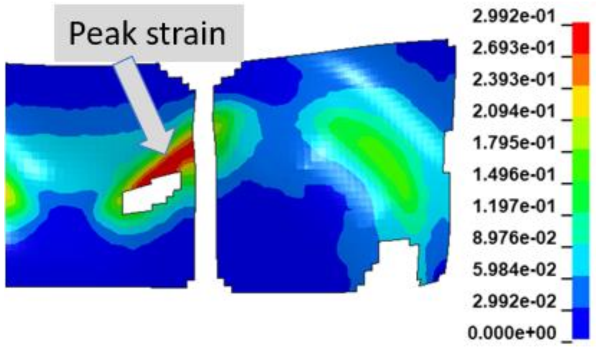
- Developed MAT233 with strain rate and temperature.
- Developed MAT233+ (rotating symmetry axis)
- Developed Forming Limit Diagram
- Verified simulation improvement of MAT233+

Cross Form



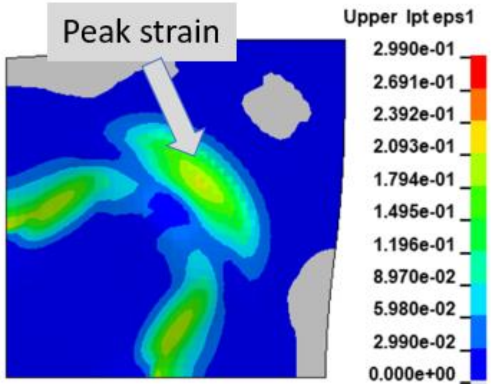
Cross-Form stamping highlighting area of compared strain

Experimental Part



Measured strain map

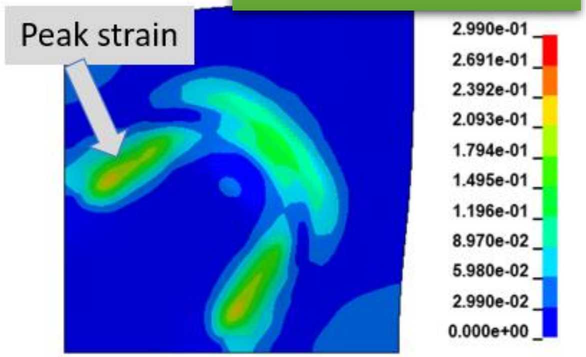
MAT233 Simulation



Peak stains slightly off location

MAT233+ Simulation

Major Improvement



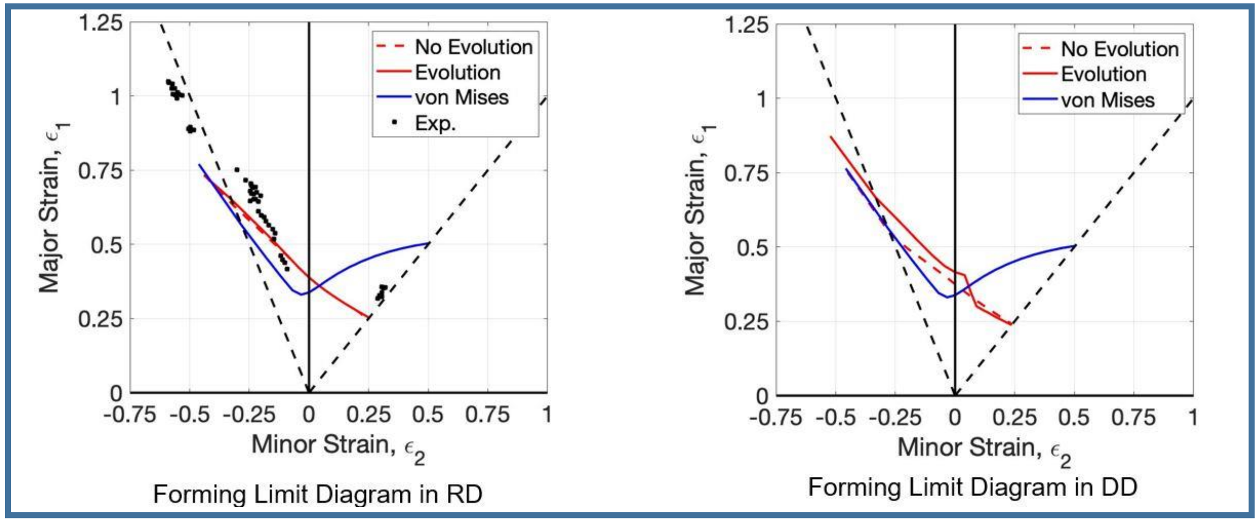
Matches experimental part

Strain maps of the cross-form stamping show the simulation using MAT233+ (right) results in a peak strain matching the location with the experimental part (left), while the simulation using MAT233 does not

Simulation with MAT233+ shows excellent correlation of strain locations compared to the experimental part

Technical Accomplishments

Forming Large Automotive Panels with E-Form Plus



Forming limit diagrams of E Form Plus in the rolling direction (left) and the diagonal direction (right) compare limits with and without texture evolution

Small Scale

Erichsen Cup

- Validated forming Temp

Erichsen cups fully formed using E-Form Plus

Medium Scale

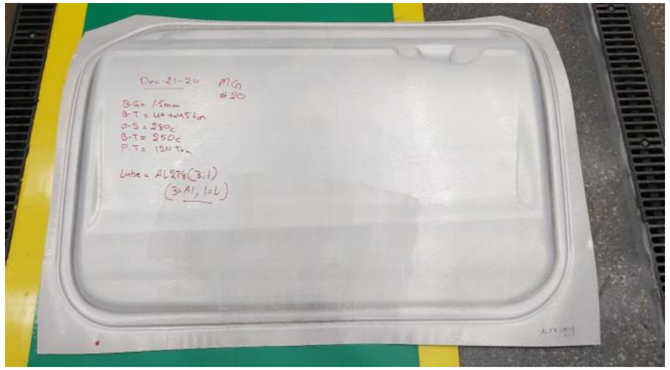
Cross-Form Stamping

- Correlated Simulation

Cross-Form part stamped using E-Form Plus

Large Scale

Door Outer Panel



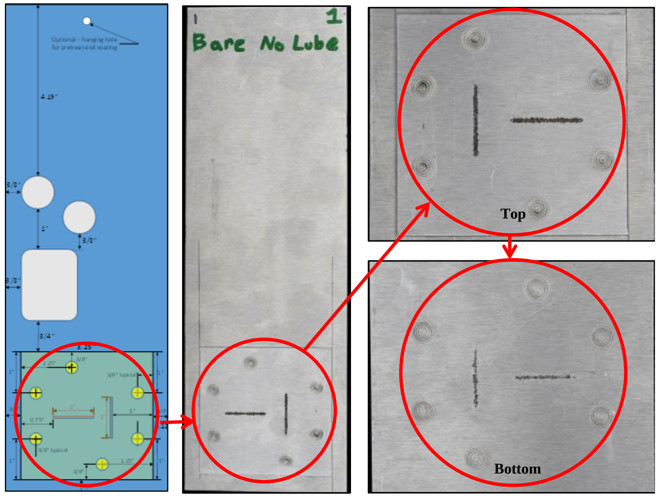
Door Inner Panel

A door outer panel (top) and a door inner panel (lower) fully formed at 250°C using E-Form Plus

✓ **Successful door panels formed at 250C**

Technical Accomplishments

Joining and Paint Shop Coating

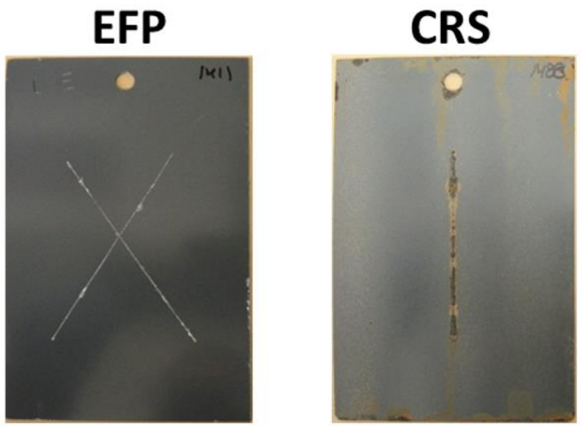


Mini-door assembly weld demonstration with RSW and laser welds

Joining Development – AET

- Identified suitable commercially available RSW weld electrodes, and process parameters to produce good welds in desired coating/forming lube combinations.
- Optimized single spot laser weld parameters to achieve good welds in all desired coating/forming lube combinations.

Suitable Commercial High Volume Production Weld Processes Developed and Demonstrated



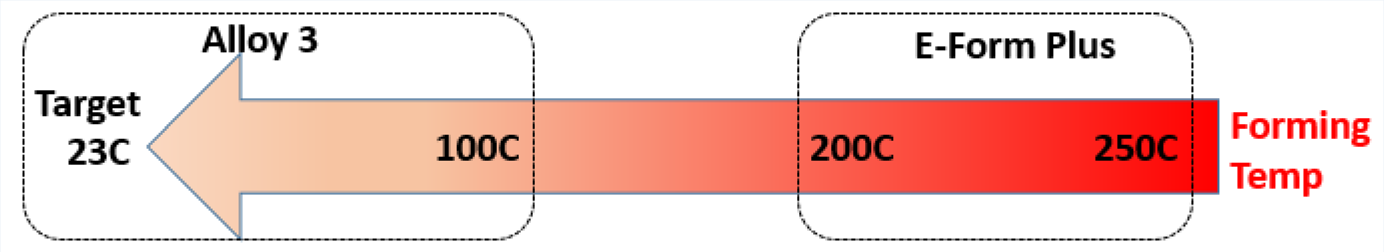
Scribe creep results for the optimized compact pretreatment process shows acceptable corrosion performance for E-Form Plus (left) and cold rolled steel (right)

Paint Shop Applied Coating Development - PPG

- Optimized several novel pretreatment solutions for E Form Plus
- Developed compact system
- Compatible with desired coatings/forming lube combinations
- Effective for Mg and cold rolled steel

Developed Suitable Paint Shop Coating Effective For Mixed Metal Automotive Bodies

Responses to Previous Years Reviewers' Comments

Comments from the 2020 Annual Merit Review	Response
It is not clear how the crystal-plasticity (CP) model is being used to correlate the microstructure to formability of the alloy.	It is a mechanism based model that captures the effects of (i) deformation modes, such as crystallographic slip and deformation twinning, and (ii) texture and grain morphologies on the formability.
The reviewer questioned the need for all the alloy development if the project teams already have an alloy (E-Form Plus) that works.	Alloy 3 is significant because it is the foundation to obtain room temperature formability in low cost, non-rare earth Mg Alloy. This was achieved through a fundamental, systematic, physics-based study of dilute Mg-Ca and Mg-Ca-Zn alloys that characterized the effect of Ca and Ca+Zn additions on texture weakening in recrystallized alloys, revealing the mechanism(s) that lead(s) to texture weakening in these alloys. 
It would be helpful to update the cost model to illustrate the cost of the demonstrator door part	The cost models has been updated with the magnesium door design and includes the following project developments: • Corrosion coatings • Lubricants • Joining

Collaboration and Coordination

- Broad participation of domestic OEMs, suppliers and universities and vendors (over 20 in total)
- Project executed at task level (7 task teams) and coordinated by a USAMP leadership team

USAMP Leadership Team

FCA US LLC

Randy Gerken, *Principal Investigator*
Leland Decker
Aslam Adam
Dajun Zhou
Jugraj Singh

Ford

Bita Ghaffari
Mei Li

General Motors

Anil Sachdev
Lou Hector
Arianna Morales

M-Tech International LLC

Manish Mehta, Technical Project Manager
John Carter

Collaboration and Coordination

Organization	Responsibility
Industry subrecipients (7)	
AET Integration, Inc.	- Joining process evaluation
Fuchs Lubricants Co.	- Development of forming lubricants for temperatures up to 250°C
Henkel Corporation	- Development of coil applied anti-corrosion treatments
PPG Industries	- Development of paint shop applied anti-corrosion coating for magnesium components
Quaker Houghton Chemical Corporation	- Development of forming lubricant for temperatures up to 250°C
Vehma International of America	- Production (stamping) of large Mg components
Xtalic Corporation	- Develop coil applied aluminum plating for Mg corrosion protection
University subrecipients (5)	
The Ohio State University	- Mg alloy design, evaluation, and validation
University of Florida	- Provide Mg thermodynamic and kinetic data for alloy development
University of Illinois at Urbana-Champaign	- Atomistic modeling for Mg crystal plasticity model development
University of Michigan	- Precipitate evolution and dynamic recrystallization characterization and modeling
University of Pennsylvania	- Develop constitutive model for textured Mg-alloy sheets, FE material user subroutine, drawing and formability simulations, and determine forming limits
LightMAT National laboratory subrecipients (2)	
Oak Ridge National Laboratories	- Development of optimized Mg sheet rolling process parameters and production of Mg strips
Pacific Northwest National Laboratories	- Mg forming model development, data management, and mechanical properties characterization
Vendors (4)	
Camanoe Associates	- Technical cost analysis and guidance
POSCO	- Production of large and medium width Mg sheet
Edison Welding Institute	- Conduct Erichsen Cup Draw Testing and Cross-Form stamping trials for validation of material cards
FADI-AMT	- Mechanical properties characterization of Mg sheet
Inaltech, Inc.	- Develop crystal plasticity model, material cards and forming limit diagram for simulation of Mg sheet

Remaining Challenges and Barriers

Project is 100% complete. No remaining challenges for this project

Remaining barriers to productionize magnesium sheet

- Corrosion
  - Corrosion performance at weld zone locations is marginal
  - Requires OEM commitment to modify paint shop for new process
- Joining
  - Hemming required for closure assemblies
  - RSW electrode life limited to 200 welds
- Sheet Production
  - No current North American production source for E Form Plus
- Simulation
  - LS-Dyna MAT233+ limited to small components
- Alloy Development
  - Magnesium sheet forming temperature limited to 250C° until Alloy 3 is further developed
  - Alloy 2 Plus potential not yet realized

Proposed Future Research

Project is 100% Complete. No future work proposed for this project.

Proposed Future Development to Productionize Magnesium Sheet

- Develop improved corrosion performance around welds
- Develop hemming to enable assembly of closure panels
- Improve RSW electrode life or develop dressing schedules
- Expand LS-Dyna MAT233+ capability to work with large panels
- Continue development of Alloy 3 composition into a room temperature formable alloy
- Study Alloy 2 plus further for other processes including forging and extrusion

USAMP

Summary

Project leveraged broad industry and academic participation:

- 22 participants doing substantial technical work, including 3 U.S. Auto OEMS, 7 industry subrecipients, 5 vendors, 5 universities, and 2 national laboratories (via LightMAT)

The holistic approach, with the exception of raw ingot production, included every major step of the process from:

- Alloy chemistry and sheet rolling process development
- New coil applied coatings and warm forming lubricants
- Warm forming and joining process development
- Paint shop pretreatment process developed to work with Mg, Al, and steel
- Final cost, weight, and performance evaluation at end of project

Significant technical accomplishments over this period include:

- Developed compact paint shop coatings effective for mixed metal automotive bodies
- Developed and demonstrated suitable commercial high volume production weld processes
- Updated the technical cost model and verified Magnesium doors can meet the lightweight cost target
- Increased computationally efficient routes to map out the solute energy landscape for other alloy systems
- Demonstrated that additions of both Ca and Zn solutes and proper recrystallization are essential in producing a formable texture in Mg-Zn-Ca alloys
- Developed a phenomenological model (Material Card MAT233+) and verified the improvement to forming simulation
- Successfully formed door panels at 250°C with E-Form Plus

Acknowledgement

Acknowledgment: "This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE0007756."

Technical Back-Up Slides

![USAMP logo]

Technical Back Up

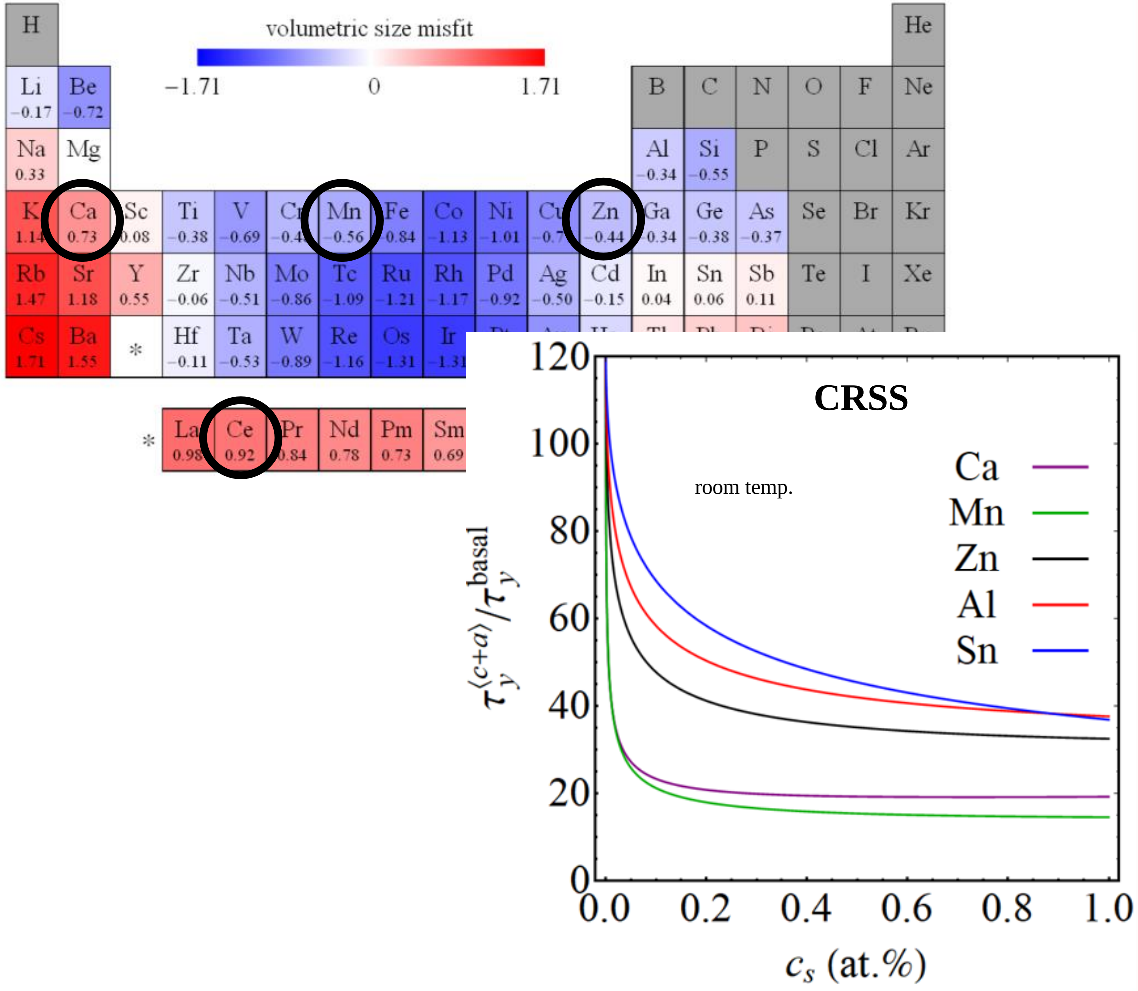
Density Functional Theory Calculations Identify Alloying Elements to Improve Formability

Approach

- Calculate solute energy landscapes for non-basal deformation modes to activate more slip systems (reduce anisotropy) to improve plasticity

Key Accomplishments

- Development of predictive models of solute chemistry on deformation in magnesium
- Suggested routes for alloy chemistry of magnesium alloys with improved formability
- Increased computationally efficient routes to map out the solute energy landscape for other alloy systems.



Technical Back Up

***In-situ* experiments for microstructure-based ductility and formability predictions**

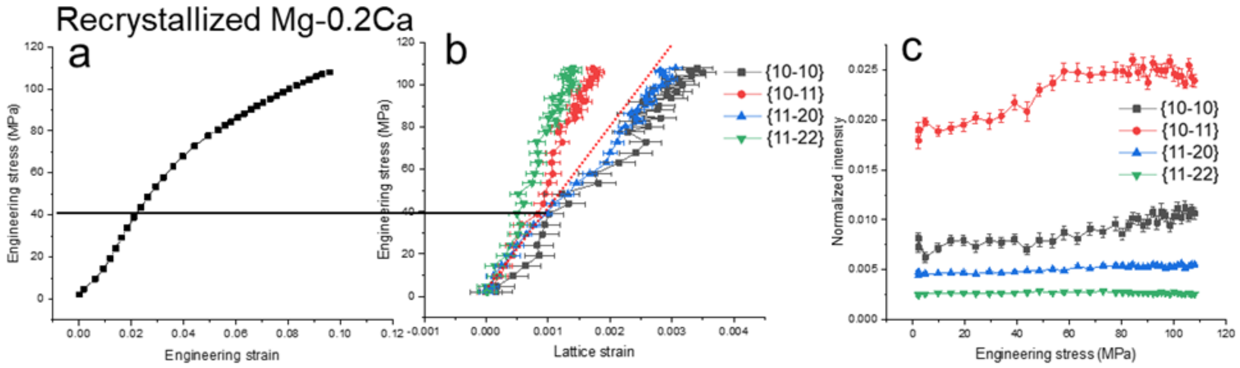
Approach

- Using Integrated *in-situ* synchrotron XRD and neutron experiments and Crystal Plasticity Modeling to help the alloys and process development of low-cost Mg alloys.

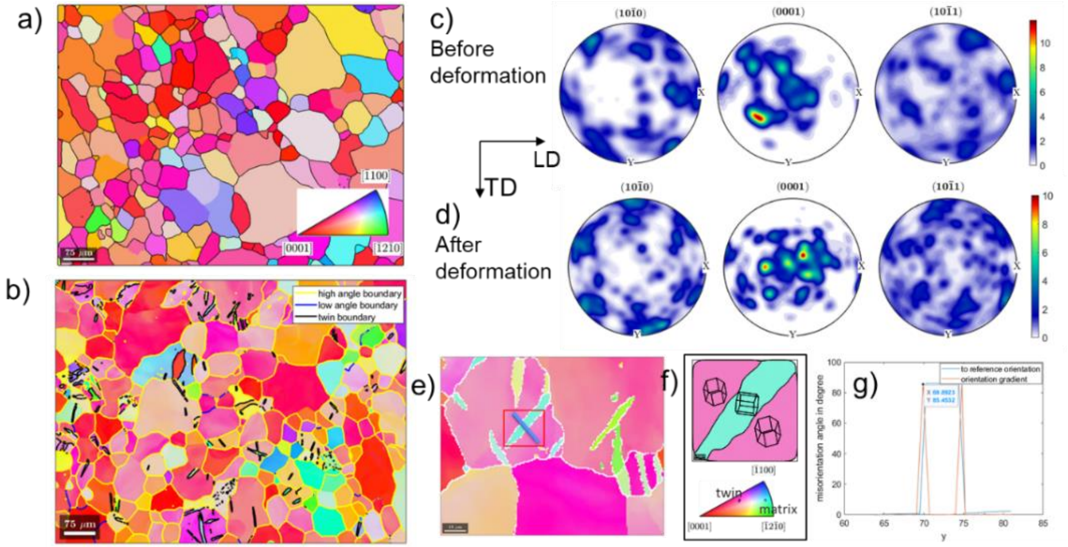
Key Accomplishments

- The room- temperature tensile testing was performed using *in-situ* synchrotron XRD and neutron diffraction.
- Lattice strain and peak intensity change was analyzed, providing experimental input for modeling.
- Microstructure and texture was investigated using EBSD, which indicated basal slips and $\{10\bar{1}2\}\langle\bar{1}011\rangle$ extension twinning activated during room-temperature tensile deformation.

In-situ neutron diffraction



EBSD analysis of the microstructure and texture



Technical Back Up

Connecting Dynamic Strain Aging to Deformation Processing and Texture Evolution in Mg-Ca-based Alloys

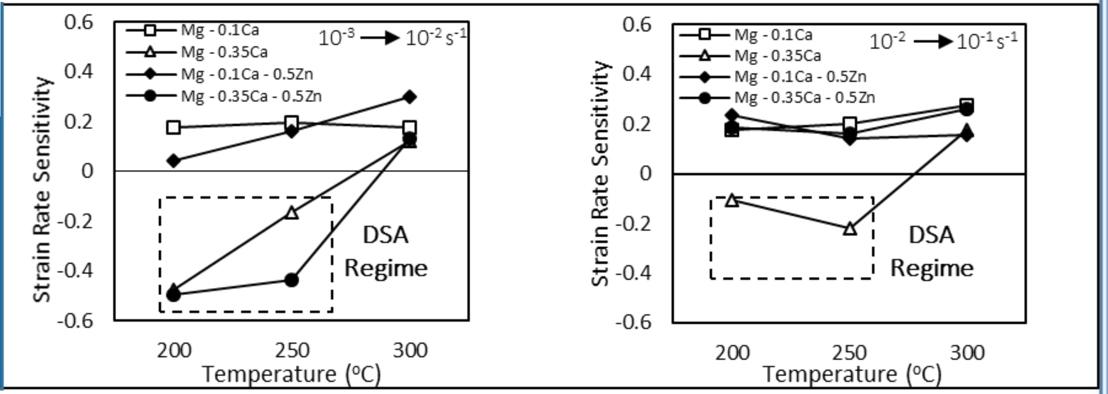
Approach

Characterize the effect of Ca and Zn solute additions in dilute Mg – Ca and Mg – Ca – Zn alloys on texture modification through observations of dynamic strain aging (DSA) as function of temperature and strain rate. It has been observed that the production of Mg alloys with weaker texture strength, i.e. improved formability at room temperature, can be enhanced by thermomechanical processing under conditions where DSA is taking place [1].

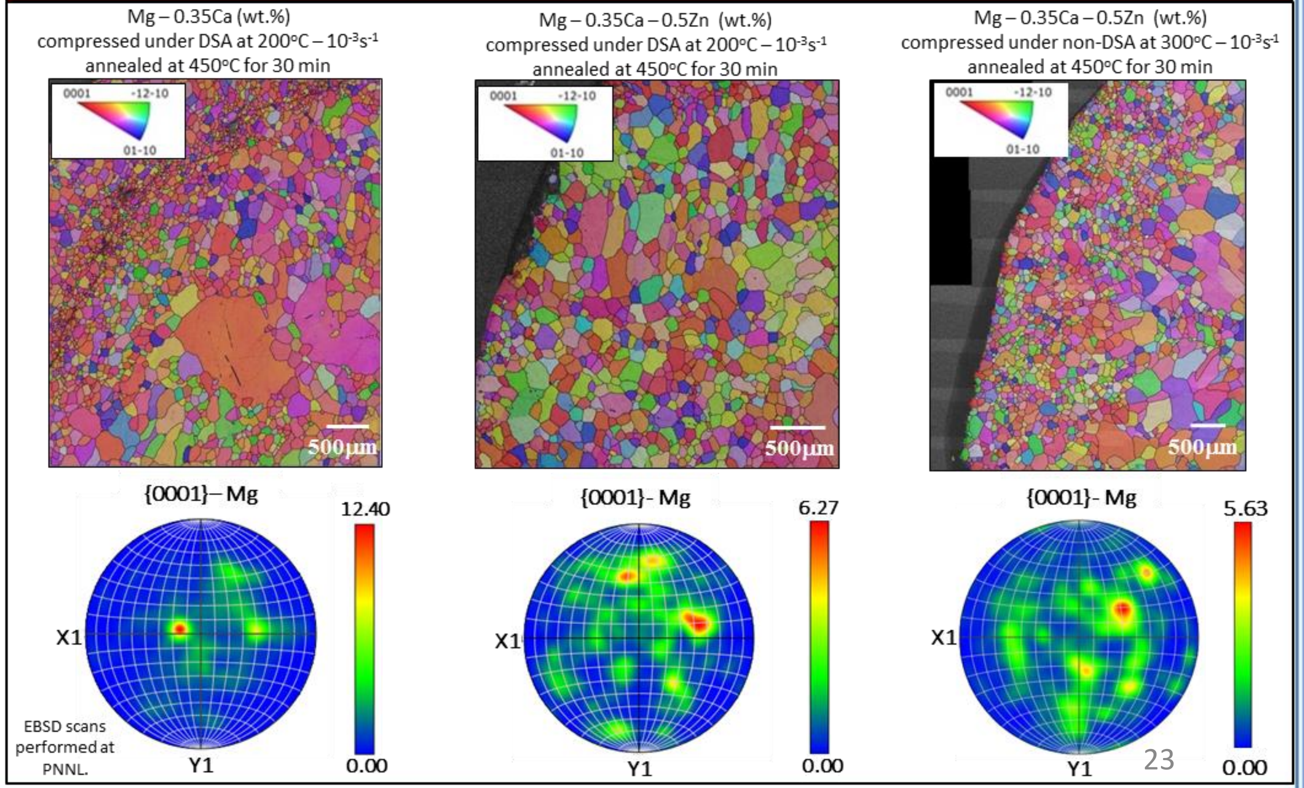
Key Accomplishments

- Determined DSA processing window for dilute Mg – Ca and Mg – Ca – Zn alloys as function of temperature and strain rate.
- Quantified and evaluated texture changes after static recrystallization of Mg – Ca and Mg – Ca – Zn alloys compressed under DSA and non – DSA conditions.
- Additions of Ca and Zn solutes to the α-Mg matrix resulted in weaker textured grains after static recrystallization processing under DSA and non-DSA conditions.

I. Mg – Ca and Mg - Ca – Zn Strain Rate Sensitivity Changes



II. Texture of Mg – Ca and Mg – Ca - Zn compressed under DSA and non-DSA conditions and annealed



Reference: 1. Jiang, L., et al., *Mat. Sci. Eng. A*, 528, (2011) 6596.

Technical Back Up

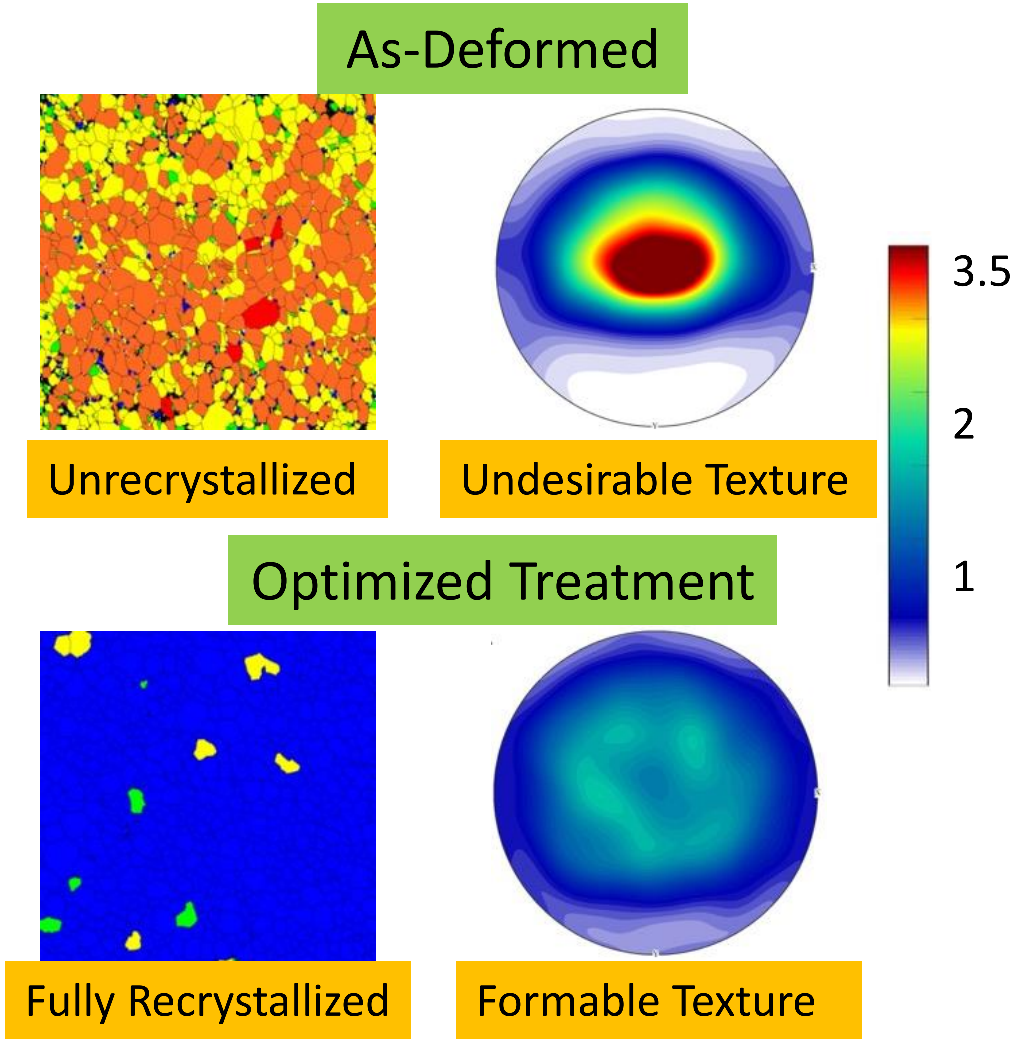
Identified that RX Plays an Essential Role in Producing More Formable Texture in Mg-Zn-Ca Alloys

Approach

- Combined Gleeble thermo-mechanical rolling process simulations with Electron Backscatter Diffraction (EBSD) characterization of microstructure and texture evolution during processing of Mg-Ca and Mg-Zn-Ca alloys

Key Accomplishments

- Confirmed that both Ca and Zn are required
- Identified Mg-Zn-Ca alloys that have a wide processing window with desirable texture
- Found that annealing after deformation is critical to producing a weak spread (desirable) texture
- Established optimum rolling and heat treatment processing routes for Mg-Zn-Ca alloys including limiting static recrystallization and grain growth during the thermal reheat between rolling passes



EBSD recrystallization and texture characteristics at different processing conditions for Mg-3Zn-0.1Ca Alloy

Technical Back Up

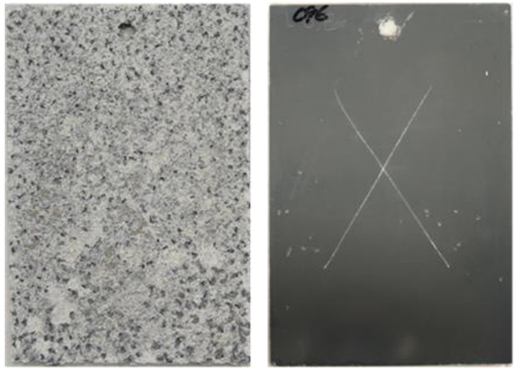
Paint Shop Applied Coating Development - PPG

PPG has formulated and optimized several novel pretreatment solutions for Eform Plus

- These cleaning and pretreatment processes show compatibility with the Task 3 coil treatments (either Henkel or Xtalic) and lubricants (either Quaker or Fuchs)
- We evaluated compact pretreatment chemistries to work with multi-metal systems with excellent corrosion performance on Eform Plus (EFP) and Cold Rolled Steel (CRS)
  - Previously established Cleaner 2 as an important pretreatment step for protection of EFP
  - Cleaner 2 was developed into Cleaner 2.21 to be used for multi-metal systems

Top performing pretreatment on Eform Plus

C1 | **C1 → C2.4**

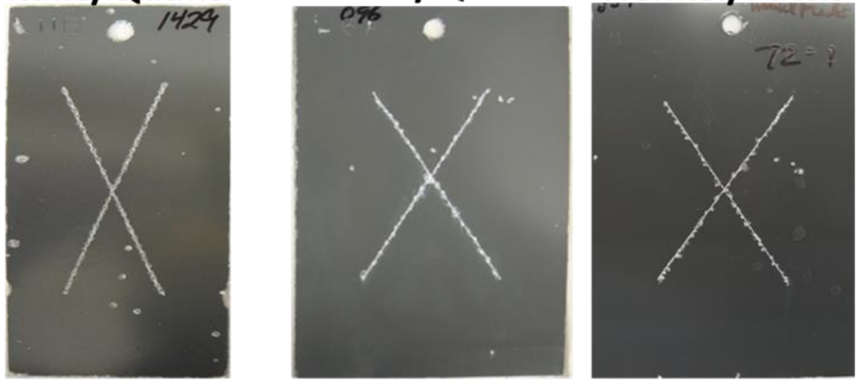


ASTM G-85 A2 testing

Top performing pretreatments for Task 3

C1 → C2.4 → PT1 | C1 → C2.4

Xtalic/Quaker | **Henkel/Quaker** | **Henkel/Fuchs**

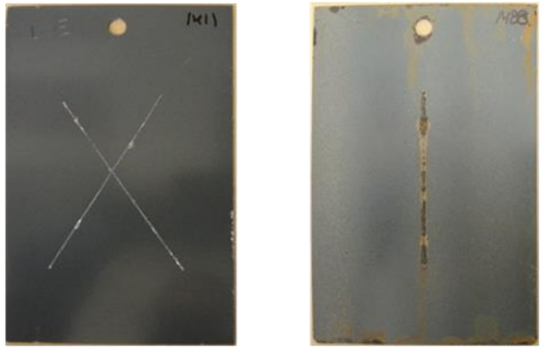


G-85 A2 3 weeks

Top performing compact pretreatment for EFP and CRS

C1 → C2.21 180 s

EFP | **CRS**



G-85 A2 6 weeks | GMW14872 30 days