Low-Cost Magnesium Sheet Production using the Twin Roll Casting Process and Asymmetric Rolling

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Project ID # LM058

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Overview

Timeline

- Project start (Phase I): September 2011
- Project end (Phase 1): September 2012
- Percent complete: 50%

Budget

- Total project funding
    - DOE $400K
    - MENA: $25K
- Funding Received in FY11: $400k
- Funding for FY12: $250k*

*Proposed

Barriers

- **Cost**: High cost of finished goods limits viability
- **Manufacturability**: Advanced materials are difficult to manufacture
- **Lack of Predictive Modeling**: Predictive tools are not available to guide manufacturing

Partners

- Lead: ORNL

Collaborators/Interactions

- Magnesium Elektron North America (MENA)
- University of Virginia, Charlottesville
- CANMET (as part of the Clean Energy Dialogue)

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Relevance and Objectives

- **"Prohibitively high cost of finished materials** is the greatest single barrier to the market viability of advanced lightweight materials such as magnesium alloys for automotive and commercial vehicle applications" – ***Vehicle Technologies Multi-year program Plan***
  - **Higher cost of sheet** produced from DC cast ingots and **lower formability** are primary reasons for higher cost associated with use of rare-earth free magnesium alloys
- "Advanced materials, by virtue of their unique or different physical and mechanical properties, are often **difficult to manufacture with current technology" – *Vehicle Technologies Multi-year program Plan***
  - Magnesium alloy sheets fabricated from DC slab cast ingots have a **predominantly basal texture** which limits their low temperature formability and increases fabrication cost
- Twin roll casting combined with shear rolling has the potential to decrease cost of magnesium alloy sheets
  - Twin roll casting reduces materials losses and number of fabrication steps to achieve thicknesses for automotive use
  - Literature shows that asymmetric (shear) rolling can reduce the basal texture and improve formability

The primary objective of the project is to evaluate the feasibility of producing lower cost magnesium alloy sheets with improved formability by asymmetric rolling of twin roll cast sheet

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Milestones

FY 2012

- Complete initial shear rolling of twin roll-cast sheet and characterize texture evolution and provide input to computational model (July 31, 2012)- On Track
- Complete development of a microstructural model for dynamic recrystallization by coupling deformation and recrystallization processes (September 31, 2012)-On Track

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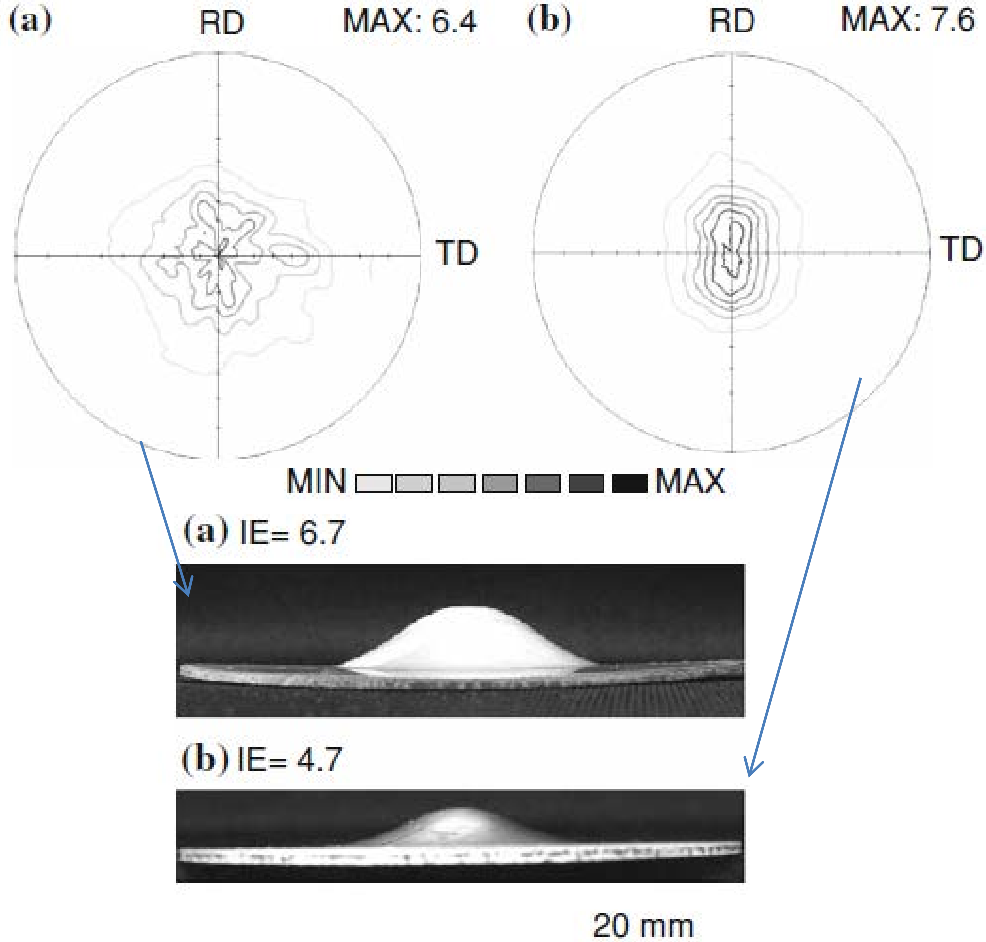
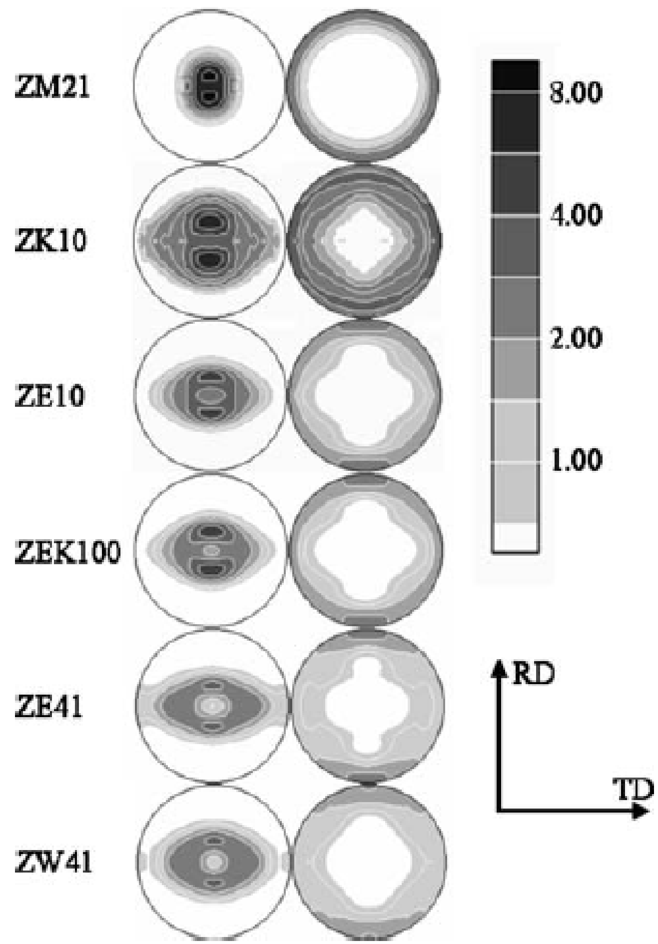
Approach: Randomizing the Texture of Wrought Mg alloys Improves Their Stretch Formability



Chino, et al. MSE A 494 (2008) 343–349



Bohlen, et al. Acta Mater. 55 (2007) 2101-2112.

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Shear Rolling Has Been Shown to Tilt the Basal Texture Towards RD

Several examples in literature show evidence for beneficial effects of shear rolling

- Basal texture is shifted to being away from ND, towards the rolling direction
- Formability has been reported to increase with shear rolling

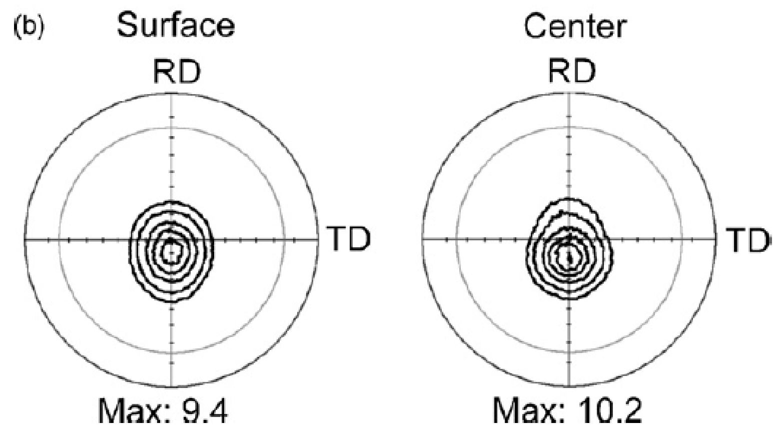

Fig. 3. (0 0 0 2) pole figures of (a) the normal rolled sheet and (b) the DSR processed sheet measured at the surface (left part) and the center (right part). Intensity levels: 1, 2, 4, 6, 8. . .

Microstructure and texture of Mg–Al–Zn alloy processed by differential speed rolling, Xinsheng Huang∗, Kazutaka Suzuki, Akira Watazu, Ichinori Shigematsu, Naobumi Saito, Journal of alloys and compounds, 457(2008), 408-412.

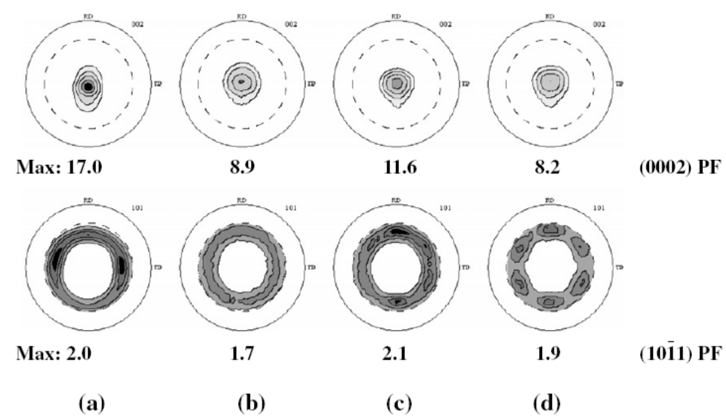

Figure 5. The (0 0 0 2) and (1 0 $\bar{1}$ 1) pole figures of the AZ31 sheets: (a) symmetrically rolled with a 30% thickness reduction at 473 K, (b) asymmetrically rolled with a 30% thickness reduction at 473 K, (c) asymmetrically rolled with a 70% thickness reduction at 433 K and (d) annealed at 473 K for 1 h after (c) treatment.

Microstructure and mechanical properties of Mg-Al-Zn alloy sheets severely deformed by asymmetrical rolling, W. J. Kim et al., Scripta Materialia 56 (2007) 309-312

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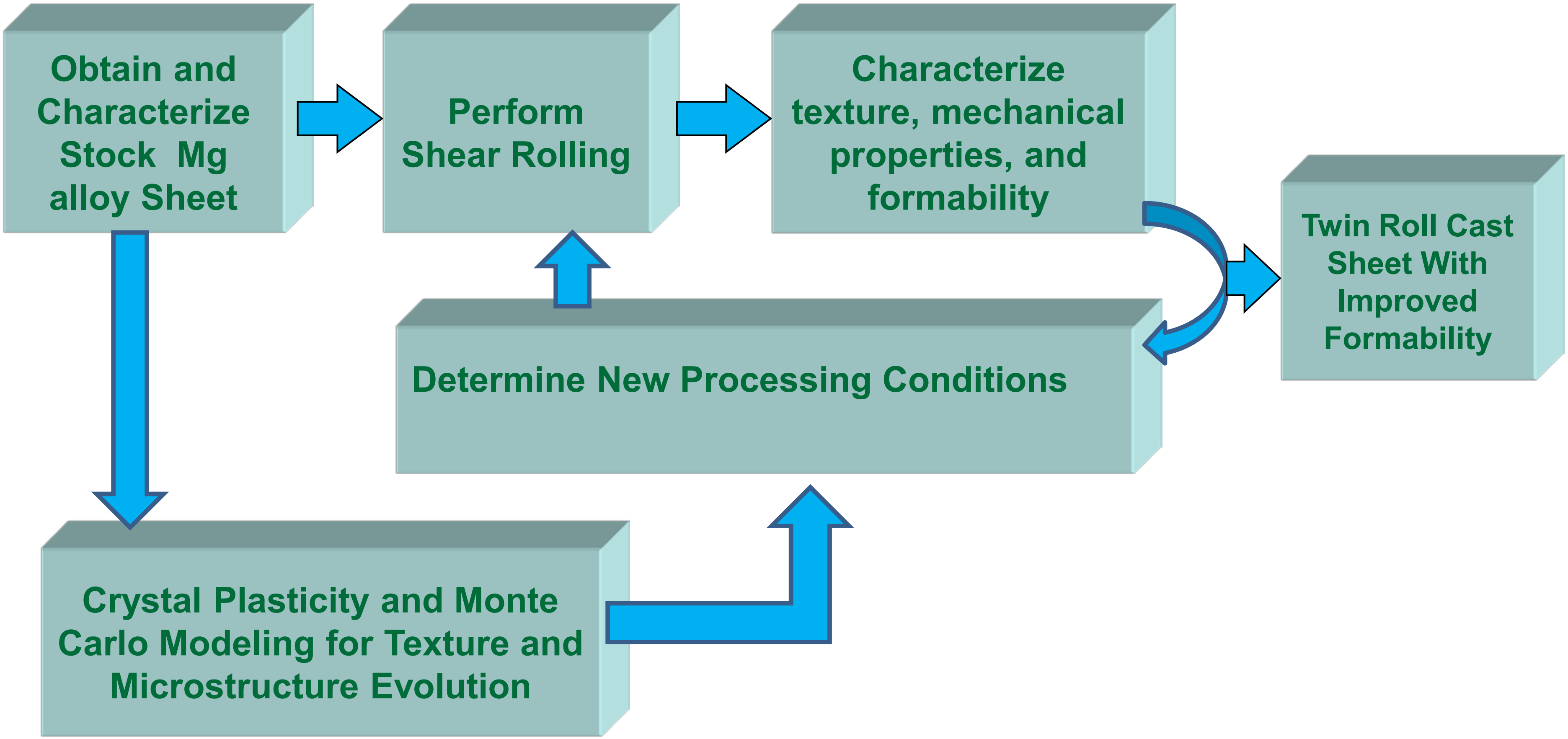
Approach: A Combined Experimental and Computational Modeling Approach is Used for Processing Path Development



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Approach: Polycrystal Deformation Model Has Been Combined with Monte Carlo Modeling to Predict Grain Texture Evolution

Initial microstructure obtained by mapping from EBSD data and texture analysis

Deformation model carried out using the neighbor compliance model and includes compression and superpose shear

- A scheme to distribute the strain in the grain structure when subjected to an external strain
- Deformation modes include basal, prism and pyramidal slip as well as tension and compression twinning

Deformation substructure contains information about grain orientation and misorientation distribution and stored energy distribution

A Monte Carlo approach coupled with a substructure recovery model was used to simulate texture and kinetics evolution during annealing by mapping deformation substructure to a three dimensional Monte Carlo grid

The texture and kinetics was simulated by systematically varying the amount of recovery

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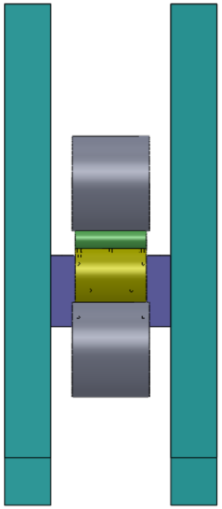
Approach: Shear Rolled AZ31B Sheet Was Characterized To Understand Material Behavior

Two types of shear rolled AZ31B were used for initial studies

- **Shear rolled using four high mill with 3:1 sized work rolls**
  - **Sheet preheated to temperature and then rolled using cold rolls**
- **Shear rolled using two high mill with 1:1 sized warm rolls, but capable of differential speeds**
  - **RP6 (Normal rolled,1:1, 200°C, 25% reduction)**
  - **RP9 (Shear rolled, 1:1.35, 200°C, 25% reduction)**
  - **RP12 (Shear rolled, 1:3, 200°C, 40% reduction)**



Four high mill with 3:1 sized work rolls

New shear roll mill

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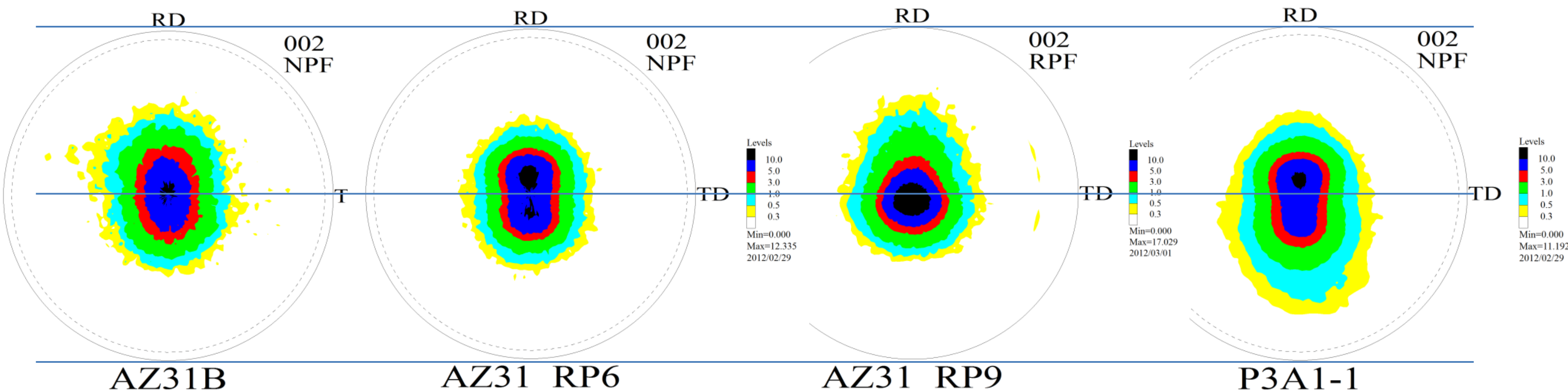
Accomplishments: Shear Rolling Clearly Demonstrates the Ability to Alter Basal Texture



As-Received (symmetric-rolled). Centerline

Symmetric - Rolled at 200°C. Centerline

Shear - Rolled at 200°C. Centerline

Shear-rolled using pre-heated sheet and cold rolls. Centerline

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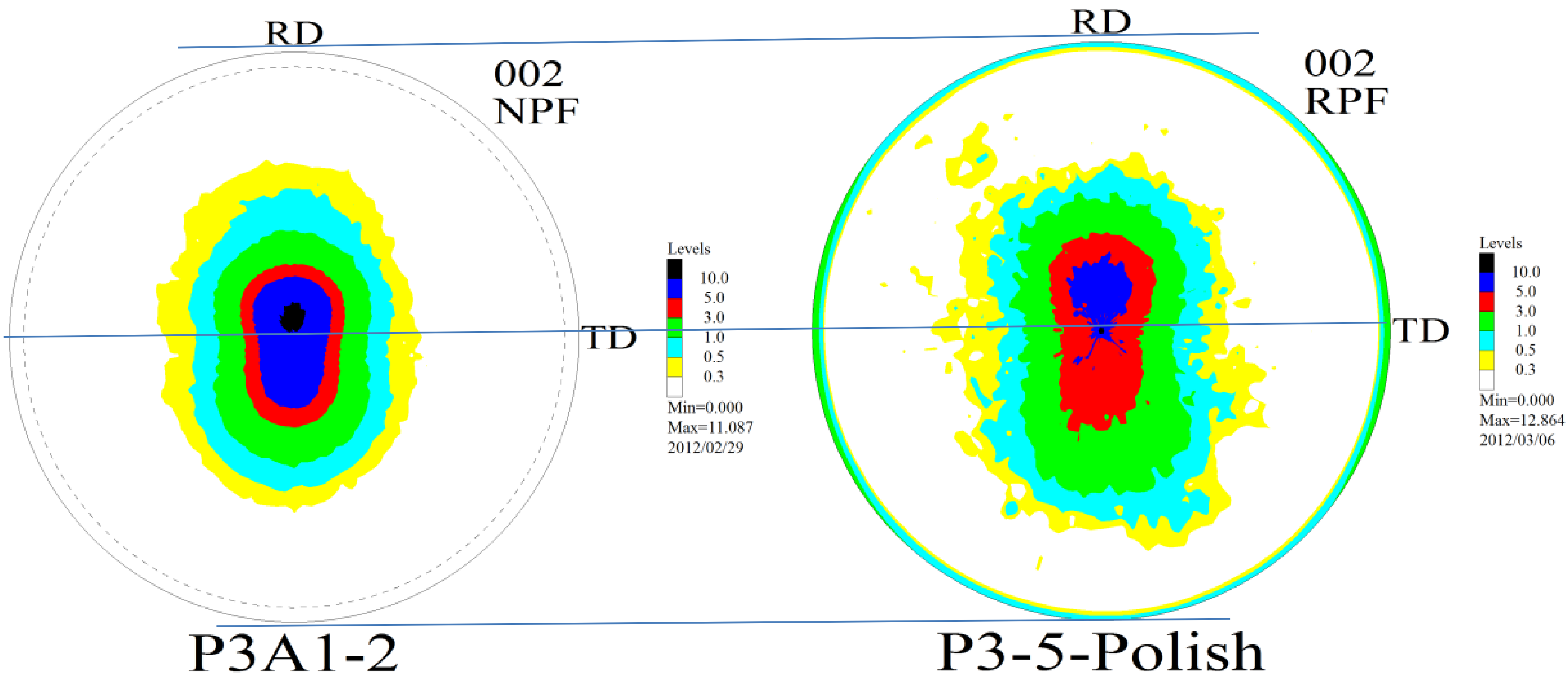
Accomplishments: Annealing Maintains Spread in Basal Poles and Decreases Intensity of Basal Texture



As-rolled

Annealed

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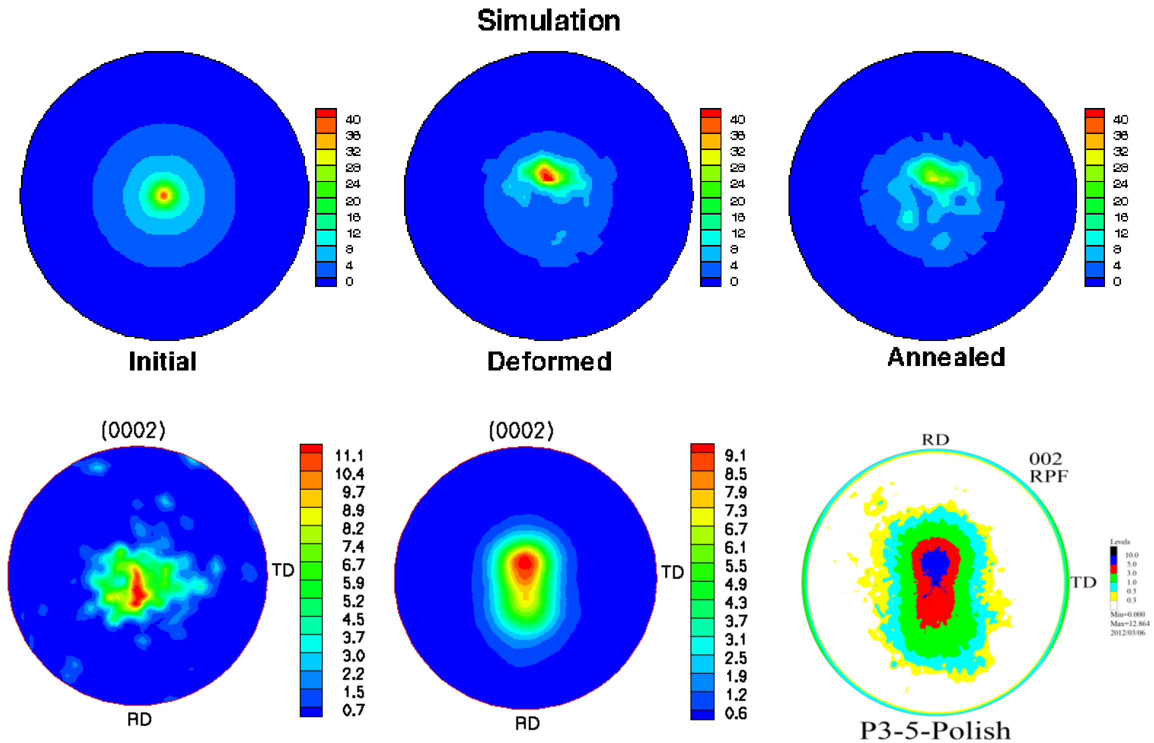
Accomplishments: Simulations are able to Qualitatively Predict Deformation and Annealing Textures in Shear Deformed AZ31



Spreading of the basal texture to off-basal orientations

Weakening of texture during annealing

Differences between and simulation and experiments largely due to uncertainty in friction coefficient and through-thickness variation

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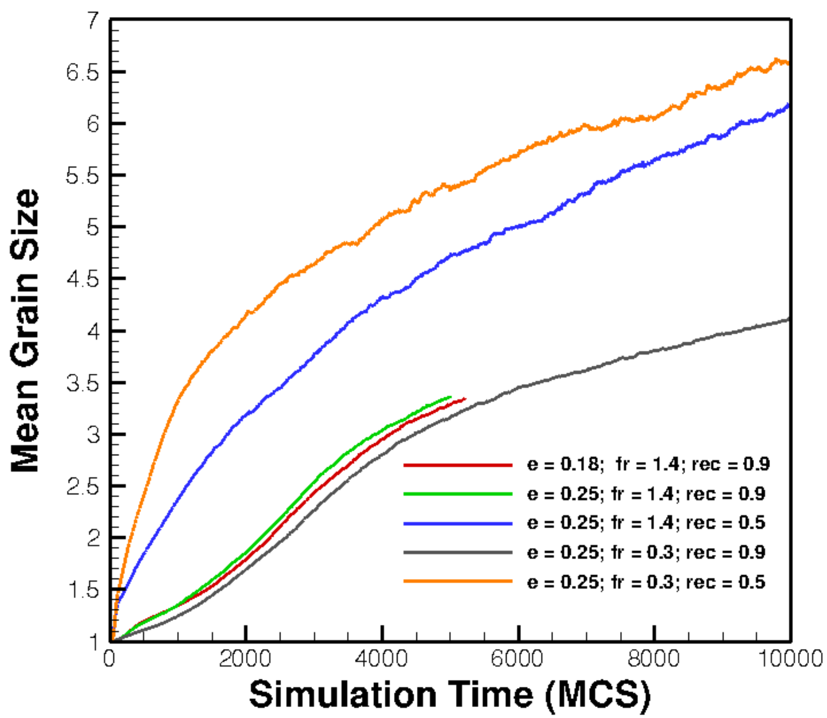
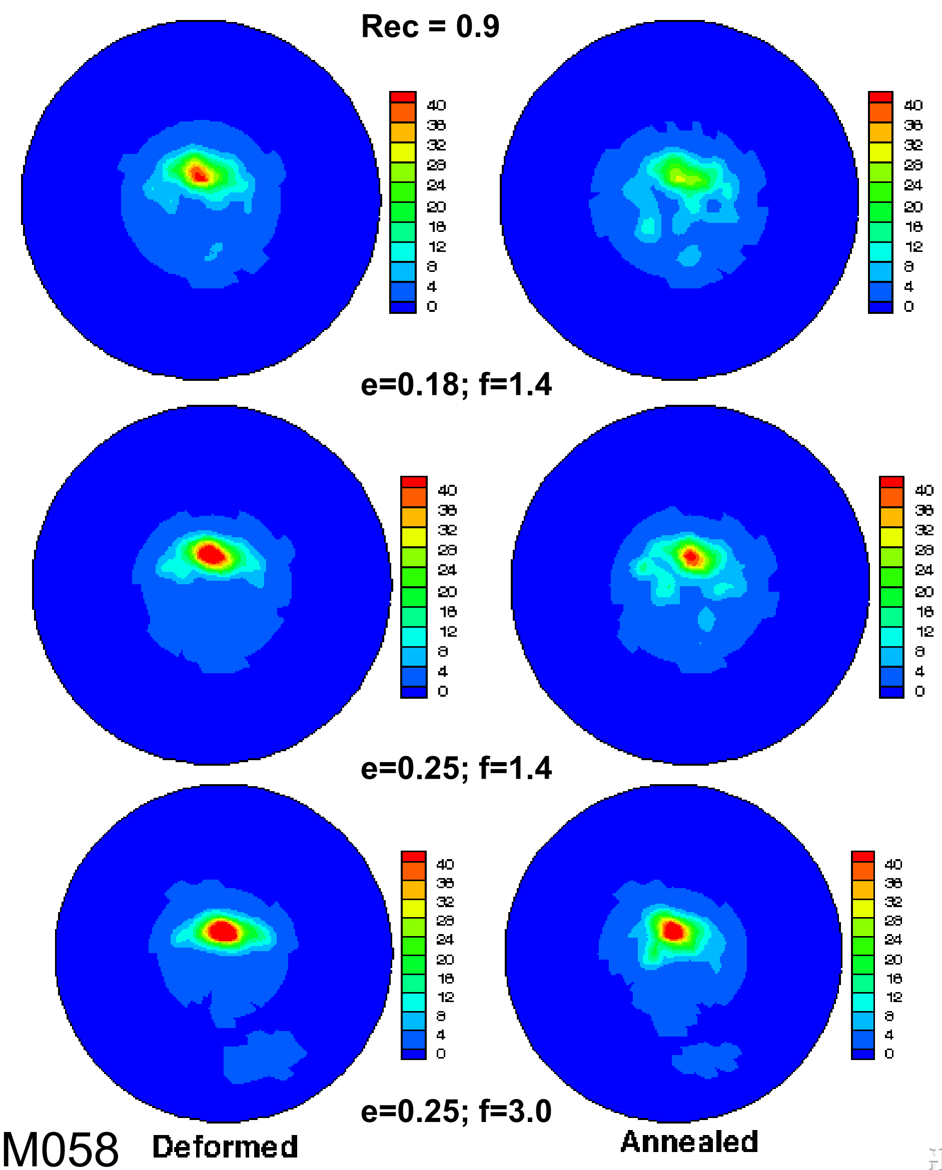
Accomplishments: Modeling Can Now Predict Effect of Recovery on Recrystallization Texture and Kinetics





Rec= Recovery/Recrystallization
e= Plastic True Strain
f= Shear Stain/Compression Strain

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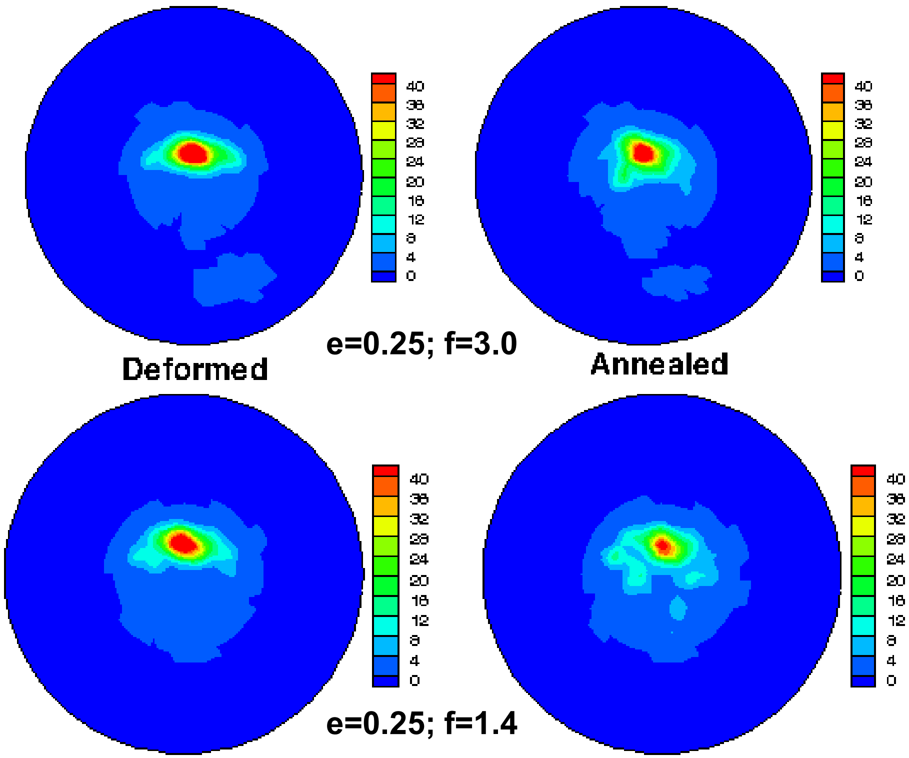
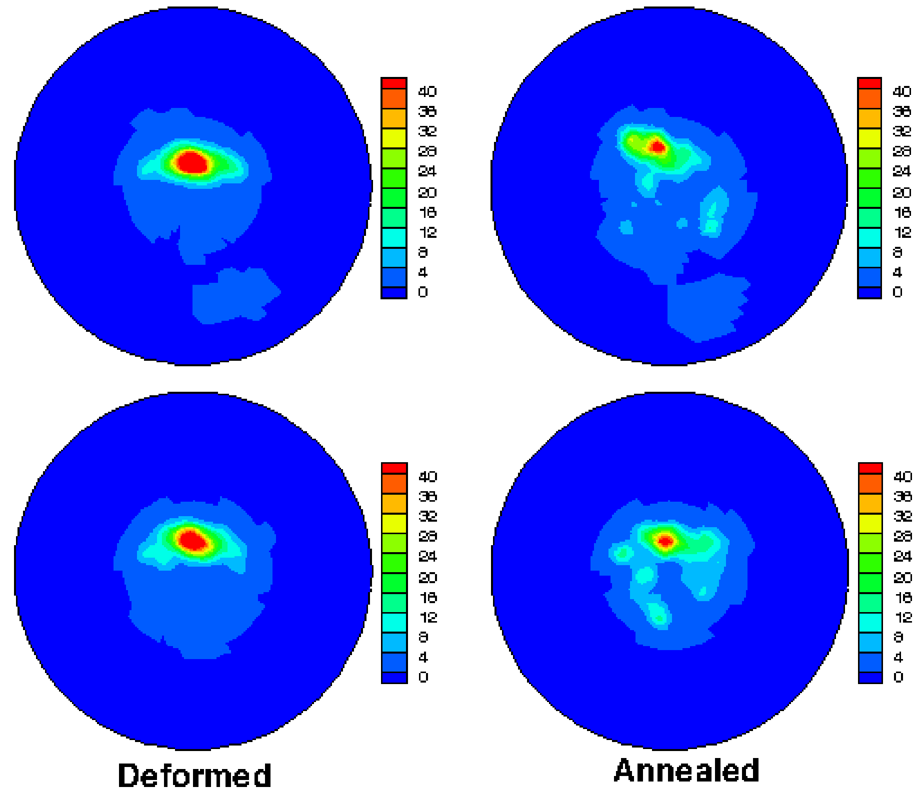
Accomplishments: Modeling Predicts Reduced Recovery Causes Strengthening of Off-Basal Components Recrystallization After Greater Deformation



Rec = 0.9

Higher Recovery



Rec = 0.5

Lower Recovery

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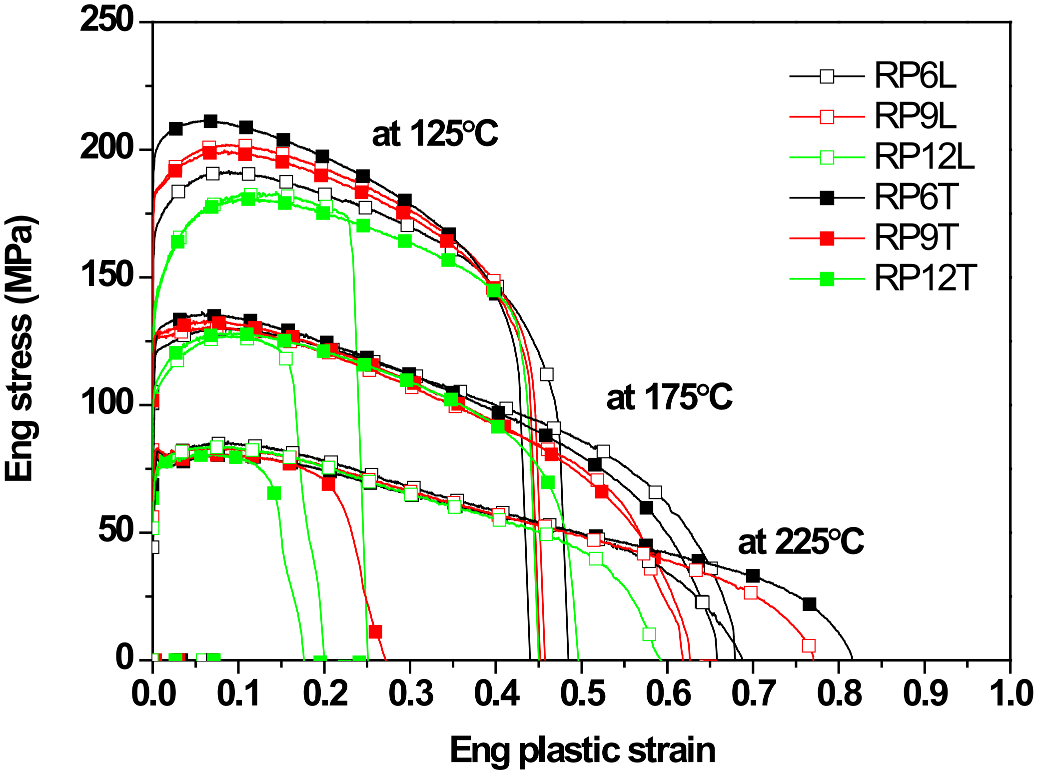
Accomplishments: Tensile Tests Have Been Completed at Different Temperatures at Constant True Strain rate ($5x10^{-3}$ s^{-1}) in the As-Rolled Condition



Yield Strength of RP12 is lowest at 125°C and 175°C but has lower ductility in the as-rolled condition

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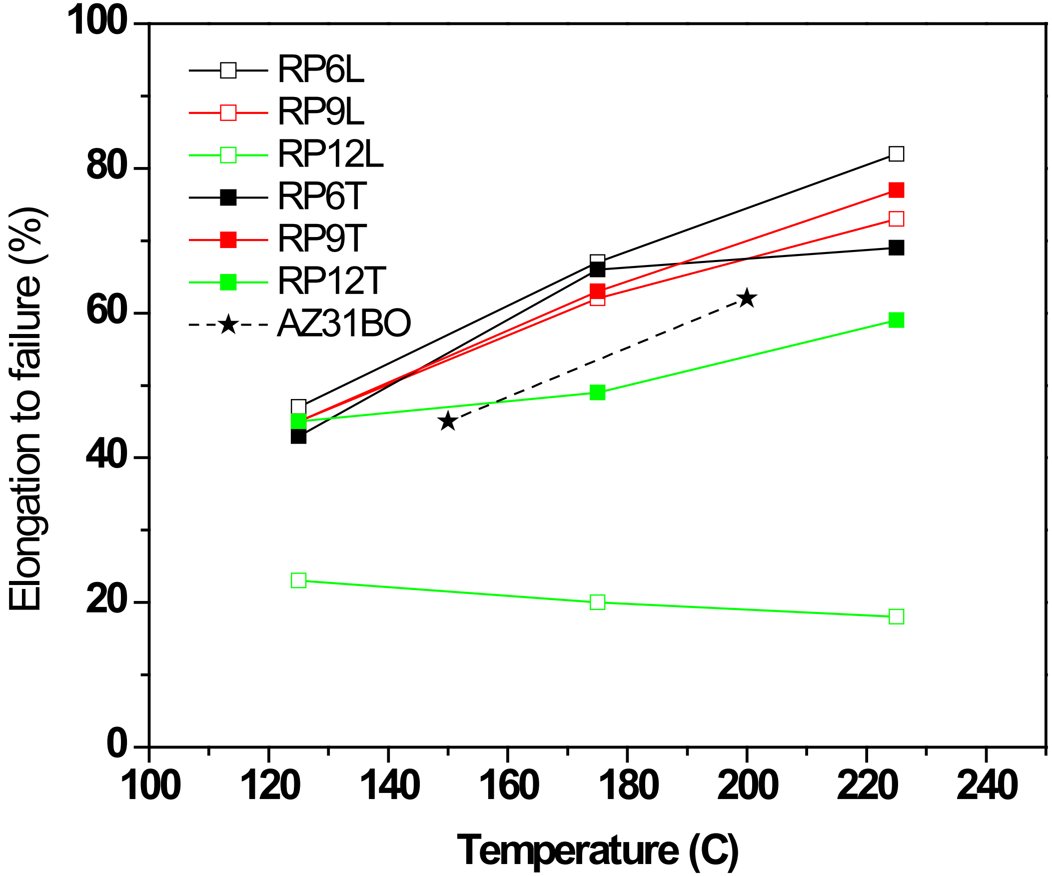
Accomplishments: Higher Speed Differential and Larger Reduction (RP12) Results in Decreased Ductility in the As-Rolled Condition



RP6 and RP9 show slightly better ductility compared to 1 mm thick AZ31B-O sheet tested in prior work

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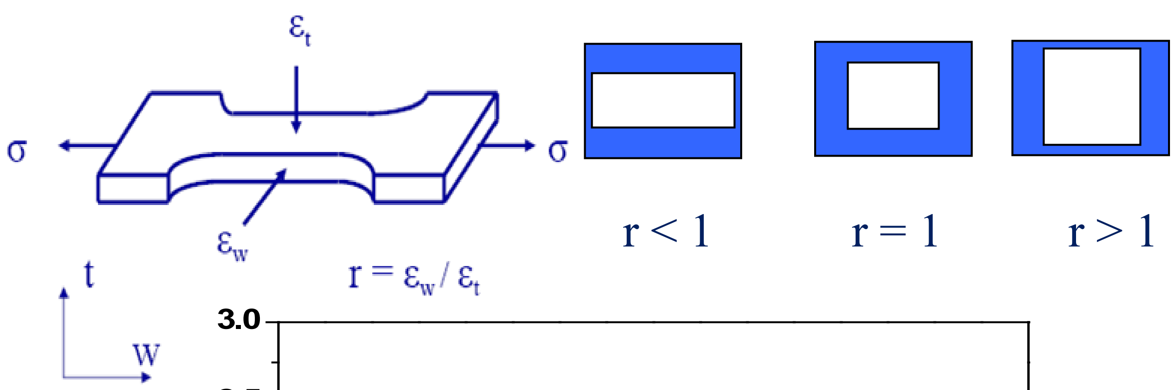
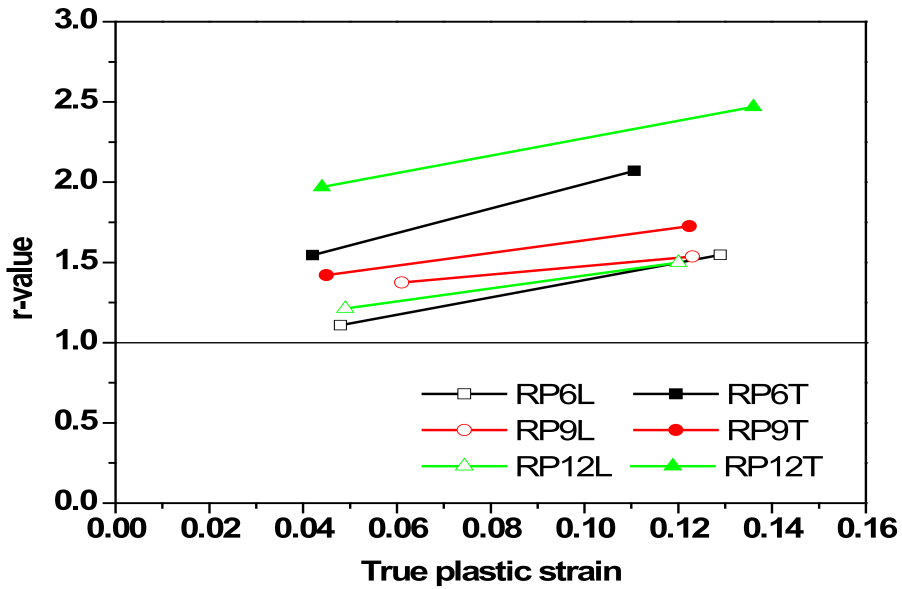
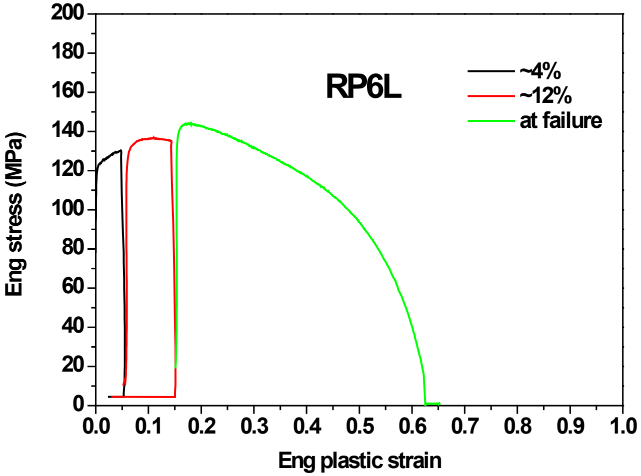
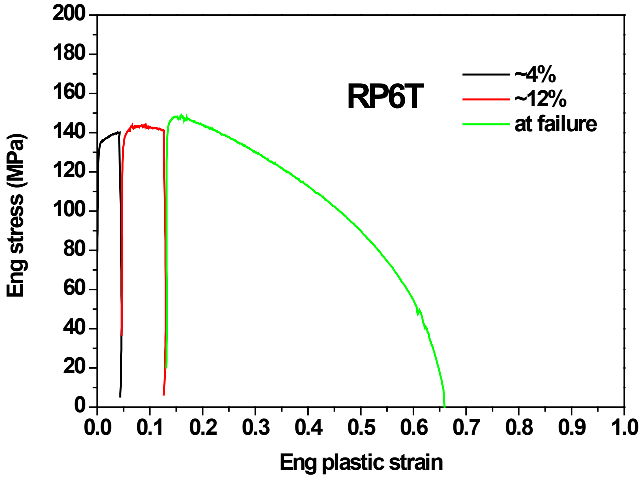
Accomplishments: RP9 Shows the Least In-Plane Strain Anisotropy at 175°C in Interrupted Tests









Higher speed differential and larger reduction (RP12) results in higher anisotropy in r-values

Future Work: Path Forward Will Leverage Lessons Learned from Experiments and Modeling

- Complete mechanical tests and formability tests in the annealed condition (as suggested by texture changes on annealing and results from modeling)
- Several additional avenues for randomizing the texture of twin roll cast AZ31-B sheets will be explored
  - Shear rolling at higher and lower temperatures using new shear roll mill
  - Vary the differential speeds (shear component) to identify the optimum value (as suggested by modeling)
- Other mechanical means to modify deformation characteristics will also be explored

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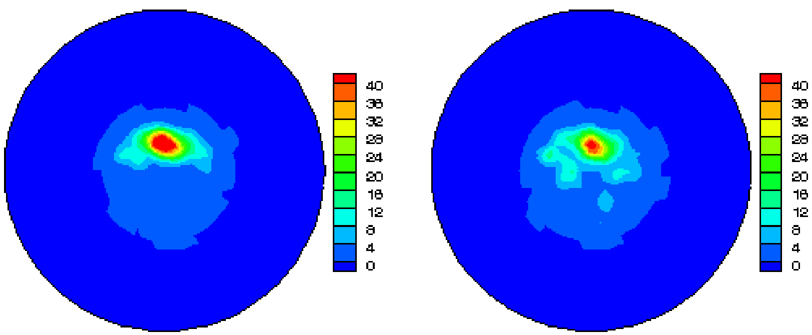
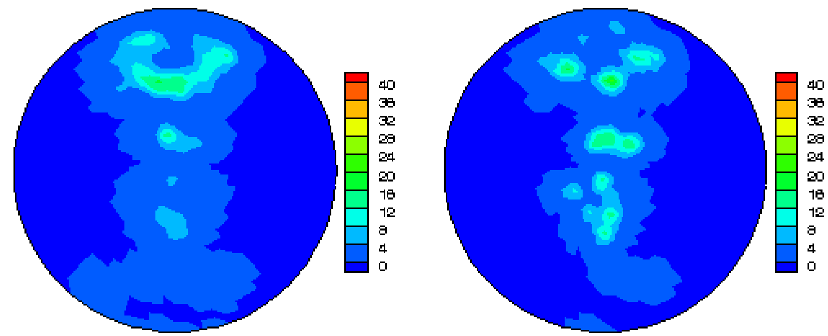
Future Work: Modeling will Incorporate More Complex Material Deformation To Enable Better Texture Prediction



Deformed Annealed

No *twinning*



Deformed Annealed

With compression twinning

Compression twinning during deformation reduced peak intensity in deformation texture

Effect of relative activity on slip and twin systems on deformation texture – correlate with experimental textures

Modeling of dynamic recrystallization by coupling recovery/recrystallization model with deformation model at each time step

Calibrate model in real time-space-temperature coordinates

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Collaborations and Coordination with Other Institutions

- Collaborations are on-going with Prof. Sean Agnew and his graduate student at the University of Virginia, Charlottesville
  - Tensile testing of shear rolled sheets have been performed at multiple temperatures in the as-rolled condition
- Collaborations are also on-going with Dr. Dave Randman and Dr. Bruce Davis from Magnesium Elektron North America
  - Magnesium Elektron North America has supplied an initial batch of twin roll cast sheet of AZ31B
- Collaborations with CANMET-MTL are on-going as part of the Clean Energy Dialogue with Canada will be supplying twin-roll cast sheet for shear rolling

Summary

- Twin roll casting combined with shear rolling has the potential to decrease the cost of fabrication of magnesium components
- Shear rolling has the potential to improve formability but existing experimental data and computational models cannot predict optimum processing conditions
- Texture measurements on shear rolled material shows that texture modification can be achieved through shear rolling but optimum path for improved formability has not yet been achieved
- Computational models using a combination of crystal plasticity and Monte Carlo techniques have been successfully developed for qualitative prediction of texture after deformation and following annealing
- Several promising paths to improve shear rolled texture have been identified using preliminary experimental data and computational modeling

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Technical Back-Up Slides

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Polycrystal Deformation Model based on Neighborhood Compliance

- **A model to partition the applied deformation rate among the individual grains of a polycrystalline aggregate**
- **A local neighborhood is defined for each grain to compute the its deformation rate**
  - **Stress among all grains within the local neighborhood is assumed to be the same**
  - **Average deformation rate is over the local neighborhood is assumed to equal the applied deformation rate**
  - **Initial estimate of crystal compliance is obtained using crystal deviatoric stress based on a Taylor model**

$$D_c = S_c \langle S_c \rangle^{-1} D$$

$$S_c = \sum_{\alpha} \frac{\dot{\gamma}_0}{\tau_0^{\alpha}} \left| \frac{\sigma'_c \cdot \mathbf{P}^{\alpha}}{\tau_0^{\alpha}} \right|^{\frac{1}{m}-1} \mathbf{P}^{\alpha} \otimes \mathbf{P}^{\alpha}$$

D is the macroscopic deformation rate assumed to be equal to the cluster deformation rate $\boldsymbol{D_c}$

$\boldsymbol{S_c}$ is the crystal compliance, is the average compliance of the neighborhood

“Predominant Twin Reorientation” model was used to incorporate twinning in the neighborhood compliance polycrystal model

- Follows Choi et. al. (2010) and Tome et. al. (1991)
- In each grain, twin volume fraction of each twin system is computed
- Accumulated twin fraction is obtained by adding contributions of all twin systems
- If accumulated twin fraction exceeds threshold, grain is reoriented based on twin system with highest volume fraction
- Reorientation is given by 180° rotation about twin plane normal

Overview of Monte Carlo Modeling of annealing

- Substructure from the deformation model mapped to a simple cubic grid
- Each grid point is assigned a crystallographic orientation derived from the deformation model
- Stored energy at each grid point is obtained from the deformation model using the effective stress
- A hybrid model (Rollett and Raabe, 2001) was integrated with the deformation code to model recrystallization and grain growth
- Recovery of substructure was included as one of the Monte Carlo moves
- Recovery model assumes that the fraction of geometrically necessary dislocations (GNDs) at any site is proportional to the misorientation of the site with respect to its neighbors
- Fractional annealing of stored energy is proportional to the stored energy and the misorientation

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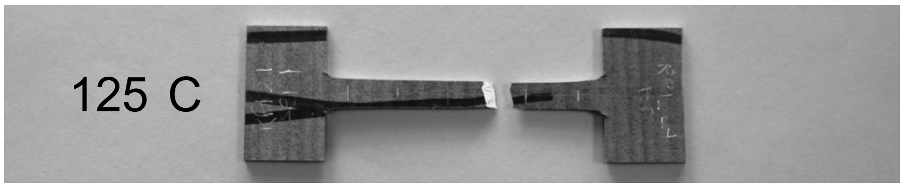
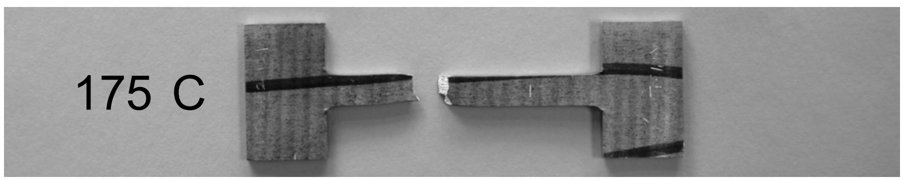
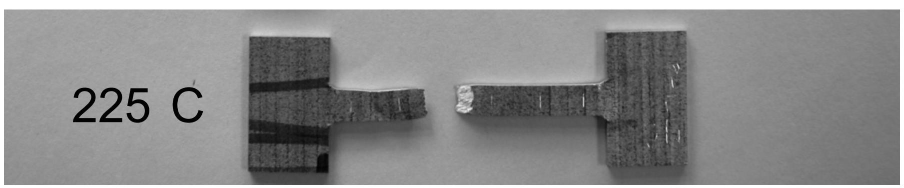
Accomplishments: Anisotropy is Observed in the Failure Modes Consistent with Texture Measurements

RP12 L







Shear Failure

RP12 T

Necking