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

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5/16/2013

Project ID # LM058

This presentation does not contain any proprietary or confidential information

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 2013
- Percent complete: 90%

Budget

- Total project funding
  - DOE $400K
  - MENA: $25K
- Funding Received in FY12: $0k
- Funding for FY13: $0k

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)
- FATA Hunter
- University of Virginia, Charlottesville

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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)- Completed

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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

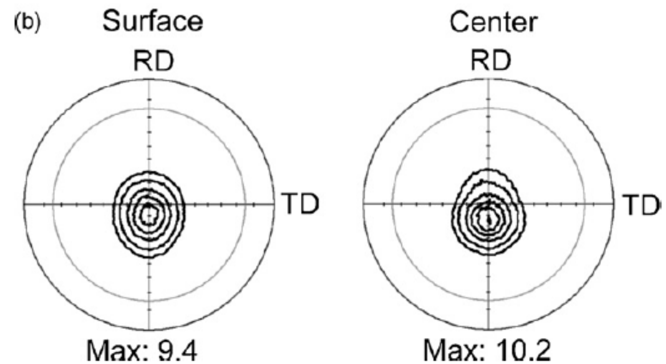

Fig. 3. (0 0 0 2) pole figures of (a) the normal rolled sheet and (b) the DSR processed sheet measured at the surface (left part) and the center (right part). Intensity levels: 1, 2, 4, 6, 8. . .

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.

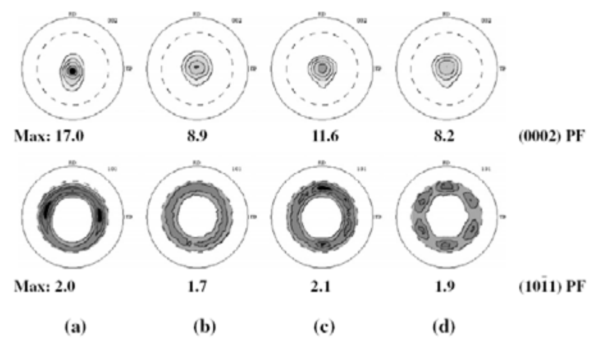

Figure 5. The (0002) and (10$\bar{1}$1) pole figures of the AZ31 sheets: (a) symmetrically rolled with a 30% thickness reduction at 473 K, (b) asymmetrically rolled with a 30% thickness reduction at 473 K, (c) asymmetrically rolled with a 70% thickness reduction at 433 K and (d) annealed at 473 K for 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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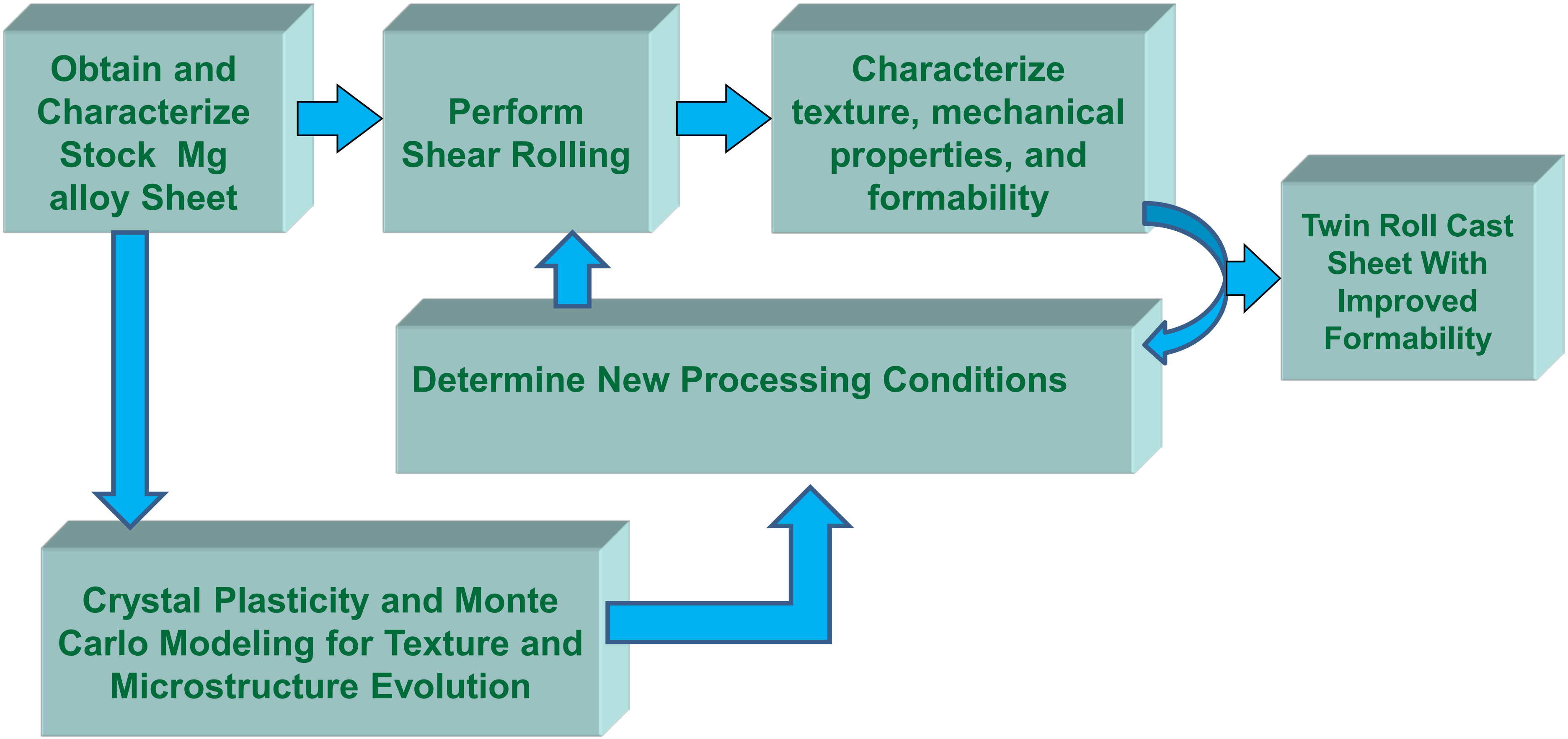
Approach: A Combined Experimental and Computational Modeling Approach is Used for Processing Path Development



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Approach: Novel Processing Routes Were Enabled by First of a Kind Rolling Mill

- New, unique asymmetric rolling mill equipped with warm rolls for isothermal rolling was installed
- Commercial scale mill designed for high throughput manufacture of asymmetrically rolled Mg-sheet based upon this mill (including roll-to-roll operation) by industrial partner (FATA Hunter) won a significant product (R & D 100 award)
- 8” wide sheet has been rolled using the newly installed mill

2012 R&D 100 50th ANNIVERSARY

FATA HUNTER
a Finmeccanica Company

Summary of Accomplishments

- AZ31B sheets (traditionally processed and twin roll cast sheets) have been asymmetrically rolled using several new processing conditions
- Sheet deformation has been characterized using embedded pins
- Sheet centerline textures have been characterized
- Effect of texture on formability has been modeled using crystal plasticity
- Dome tests procedures have been improved for warm formability testing and room temperature testing
  - Tests show that asymmetric rolling improves formability over AZ31B-O at ~175ºC and at room temperature

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Accomplishments: AZ31B Sheet Was Shear Rolled using Multiple Process Parameters and Characterized To Understand Material Behavior

- Shear rolled using two high mill with 1:1 sized warm rolls, but capable of differential speeds (8” wide sheets)
- Shear rolling was performed at temperatures of 100^{o}C, 135^{o}C, 175^{o}C, and 200^{o}C (sheet preheat and roll temperatures were kept approximately the same in most cases) (single pass only)
- Velocity ratios of 1:1, 1:1.33, 1:2, and 1:3 were used for rolling
- Centerline texture measurements were characterized using X-ray analysis
- Formability was characterized using dome testing at a temperature of ~175^{o}C, and at room temperature

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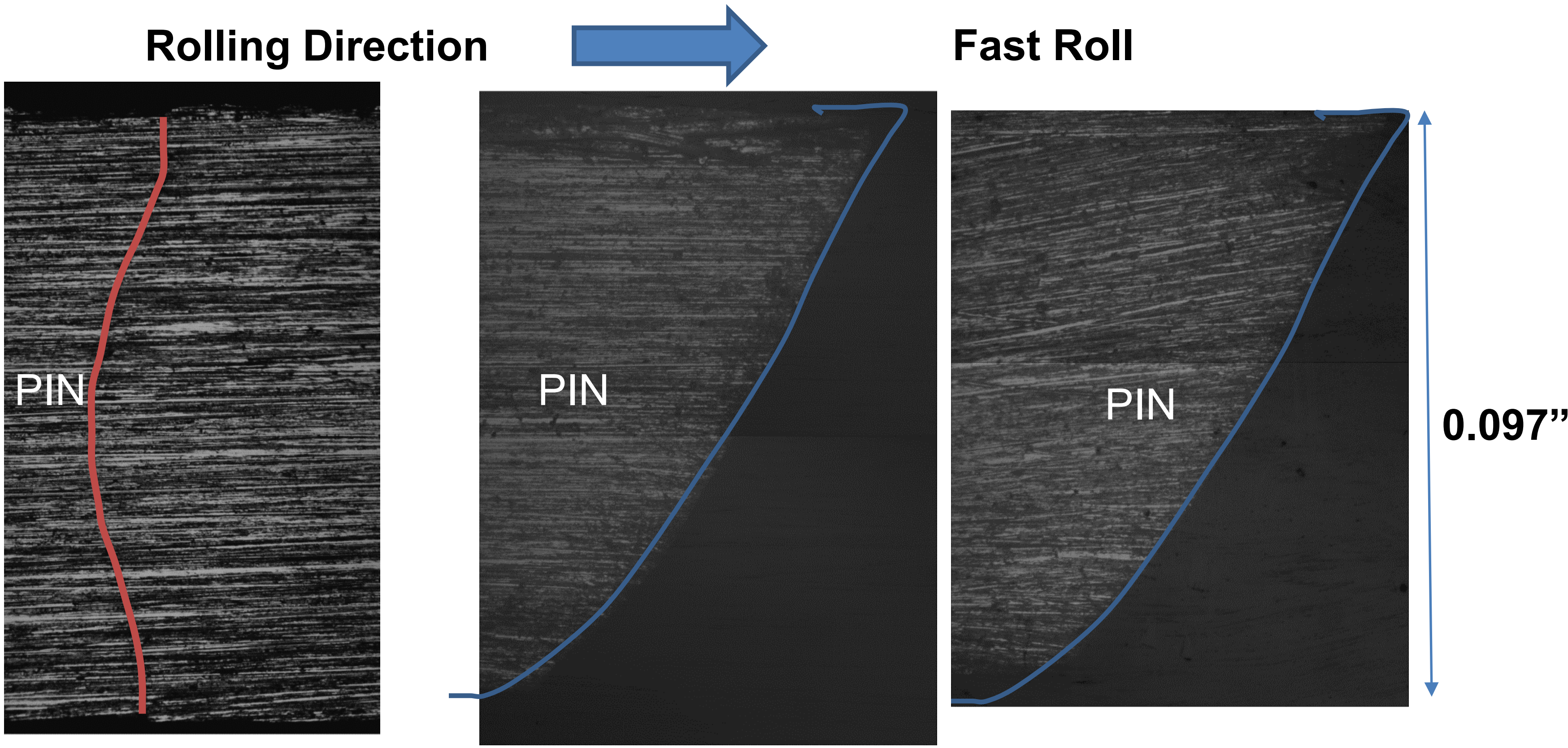
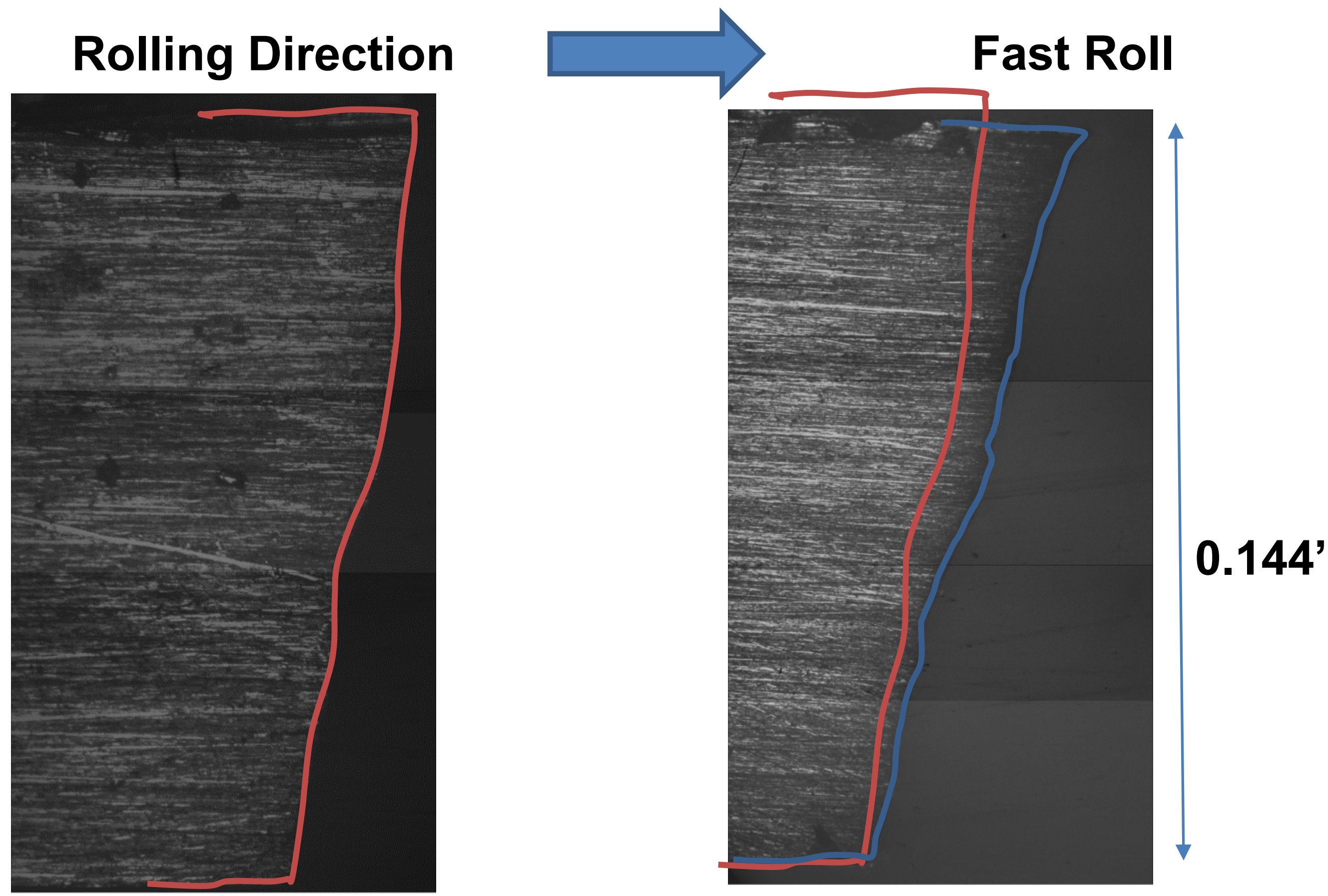
Effect of Asymmetric Rolling on Sheet Deformation Was Characterized Using Embedded Pins of AZ31B



Velocity ratio: 1:1 Velocity ratio: 1:2 Velocity ratio: 1:3

The effect of shear may saturate as a function of temperature, friction conditions, sheet thickness, and % thickness reduction

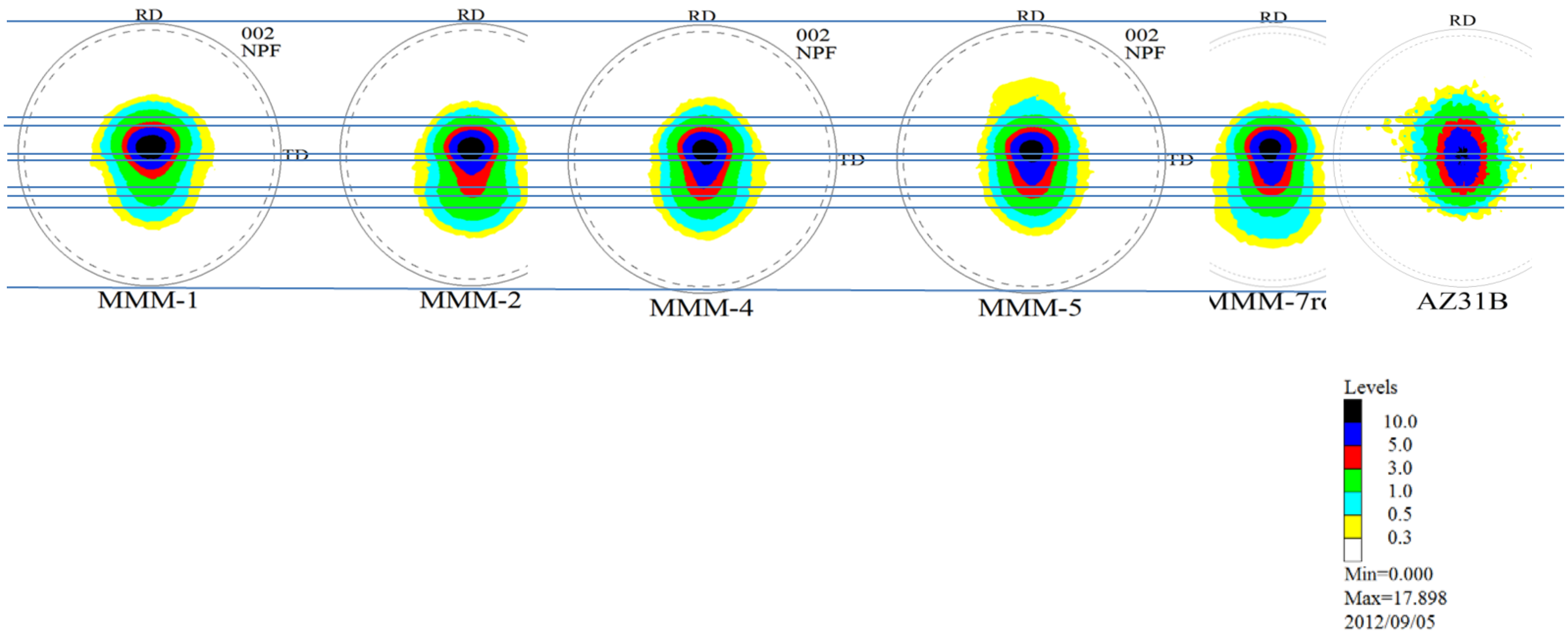
Effect of Asymmetric Rolling on Twin Roll Cast Sheet Deformation Was Characterized Using Embedded Pins of AZ31B



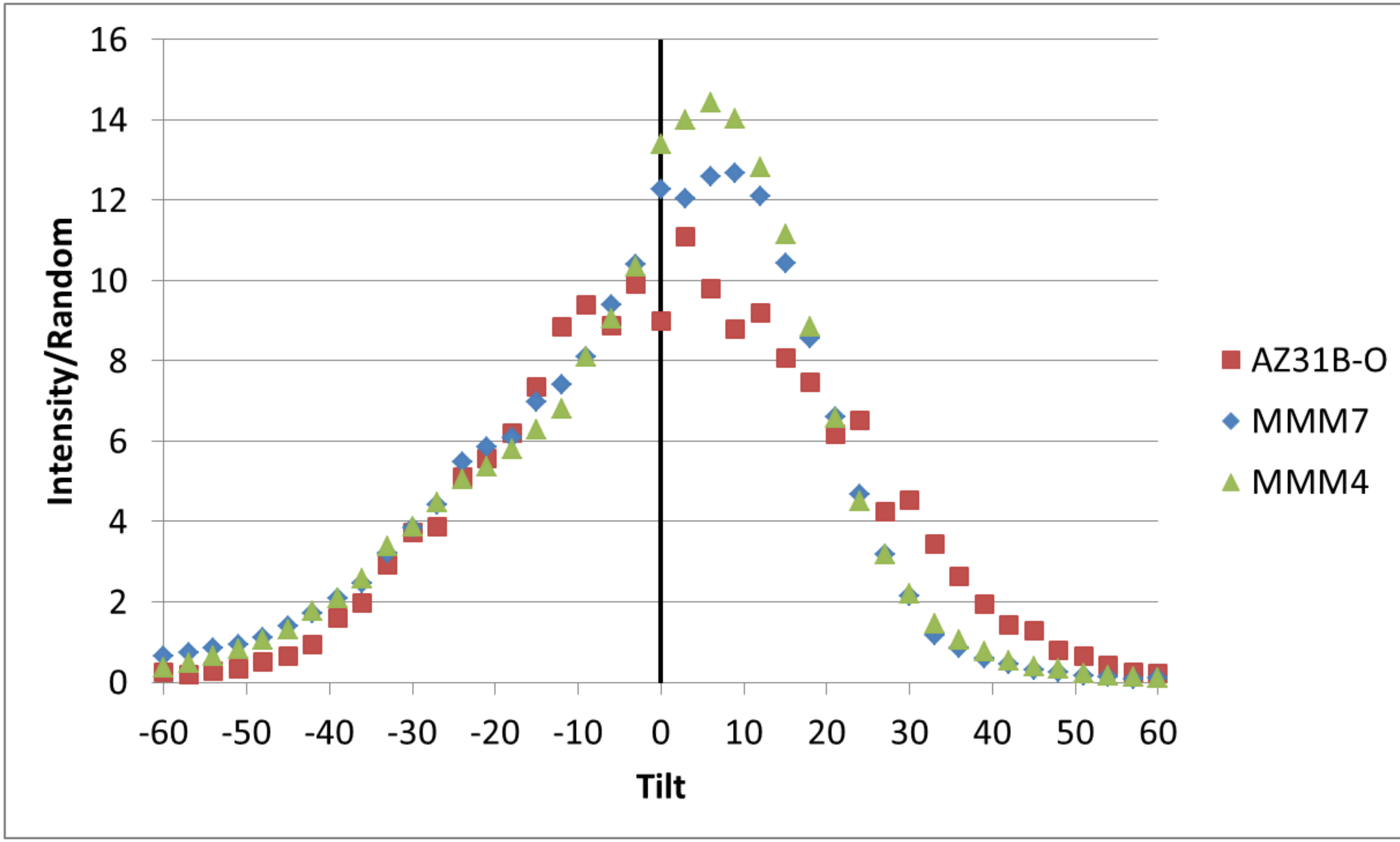
Velocity ratio: 1:1.33

Velocity ratio: 1:3

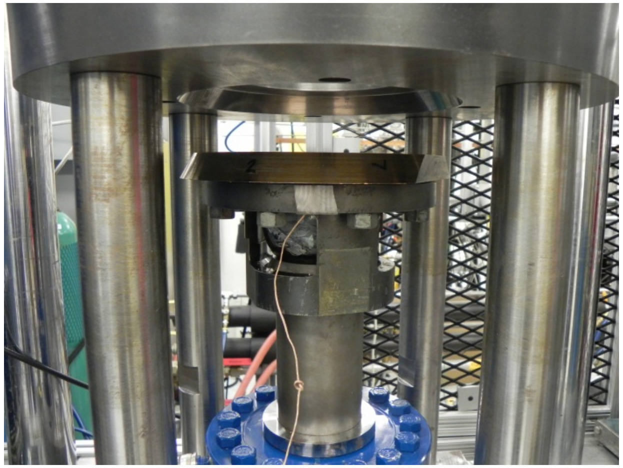
Accomplishments: Centerline Basal Texture Measurements Show Favorable Tilt in Multiple Warm Asymmetric Rolling Process Conditions

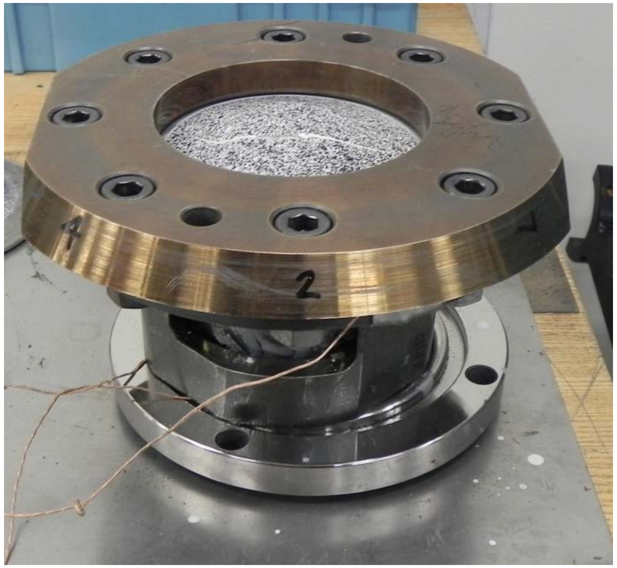


Accomplishments: Shear Rolling Demonstrates the Ability to Tilt and Modify the Intensity of Basal Texture



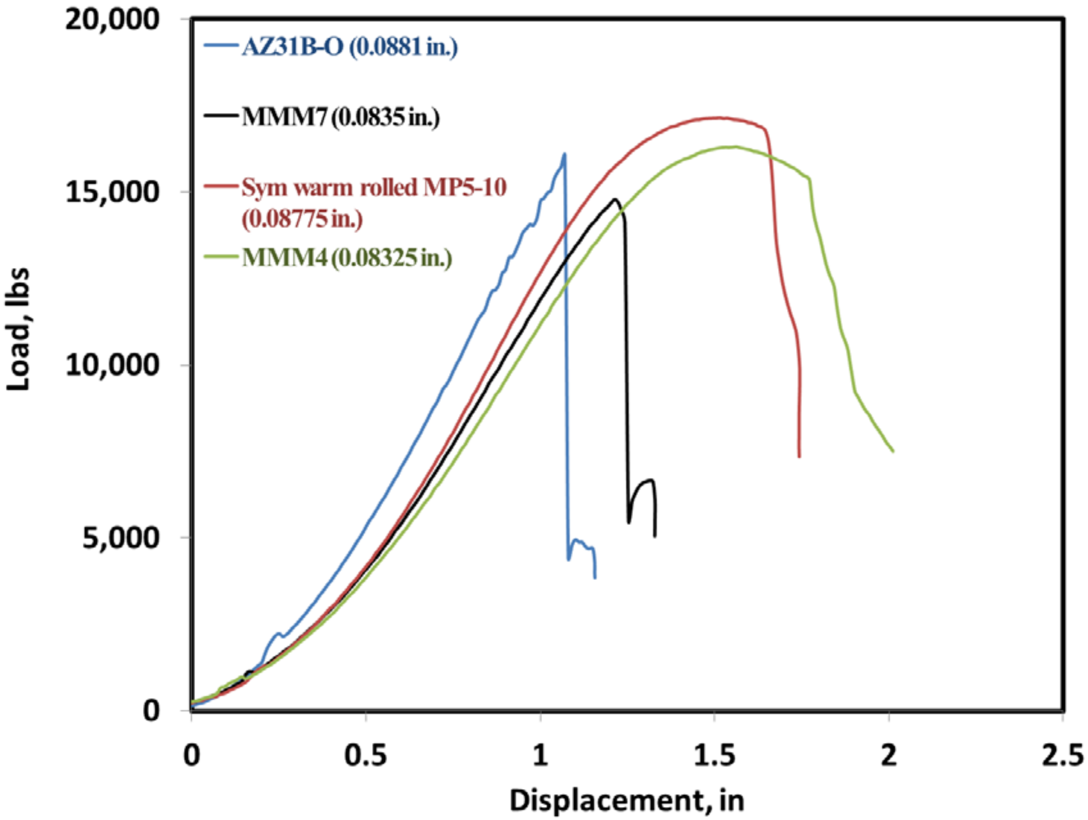
Formability (Dome Test) System at ORNL Enables Warm Formability Testing

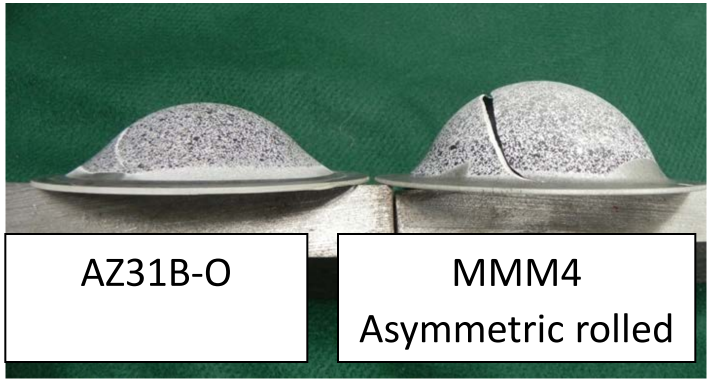




Ball dia: 100 mm
Disk dia: 138.4 mm

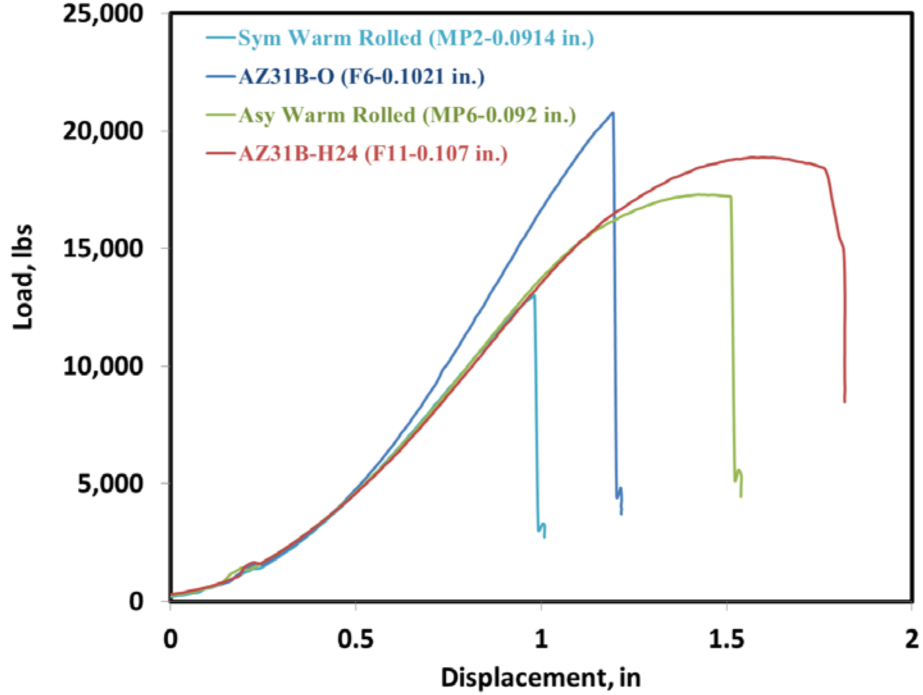
Asymmetrically Rolled Specimens Show Improved Formability Over AZ31B-O at 175ºC





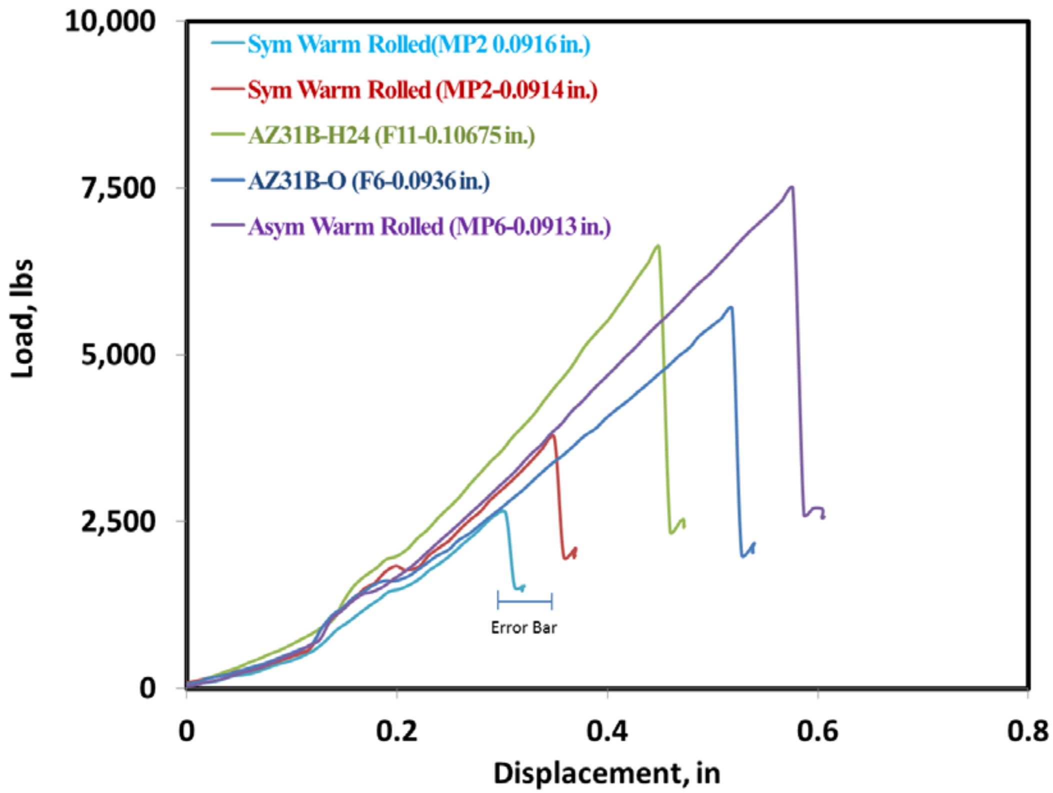
- **Favorable texture and residual deformation** is required for good formability of asymmetrically rolled sheet
- **Prior deformation** (symmetric warm rolling) also improves formability

Dome Testing at 175°C Shows Potential Role of Recovery Processes



- **For similar small deformation (~7 %), asymmetrically rolled sheet shows better formability than symmetrically rolled sheet**
- **AZ31B-H24 has good formability, close to that of asymmetric warm rolled MMM4**
  - **Recovery processes and not initial texture may dominate beyond certain levels of deformation**

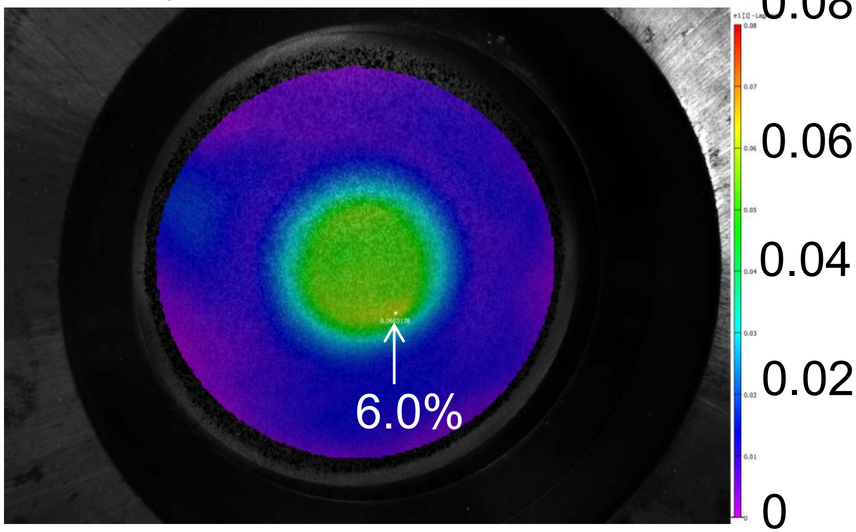
Room Temperature Formability Tests Show Asymmetric Rolling Can Improve Formability



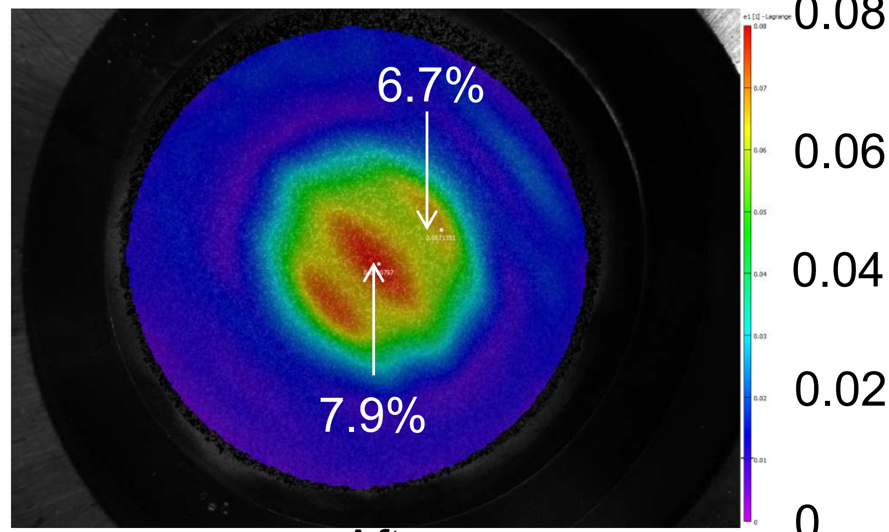
- Prior symmetric deformation reduces room temperature formability
- Asymmetric warm rolled sheets rolled under certain process conditions show better formability than AZ31B-O and H-24 of the same thickness

DIC Results Confirm Larger Strain Prior to Failure in Asymmetrically Rolled Sheet

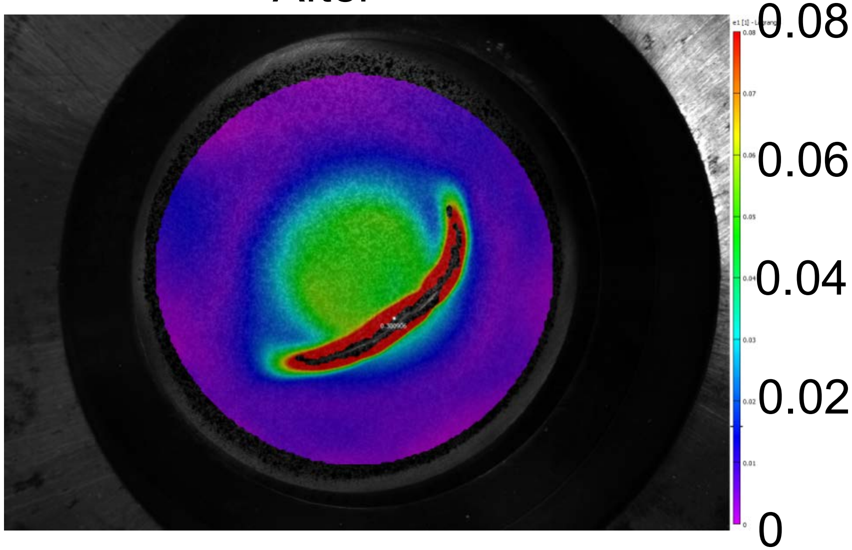
Symmetric/Before



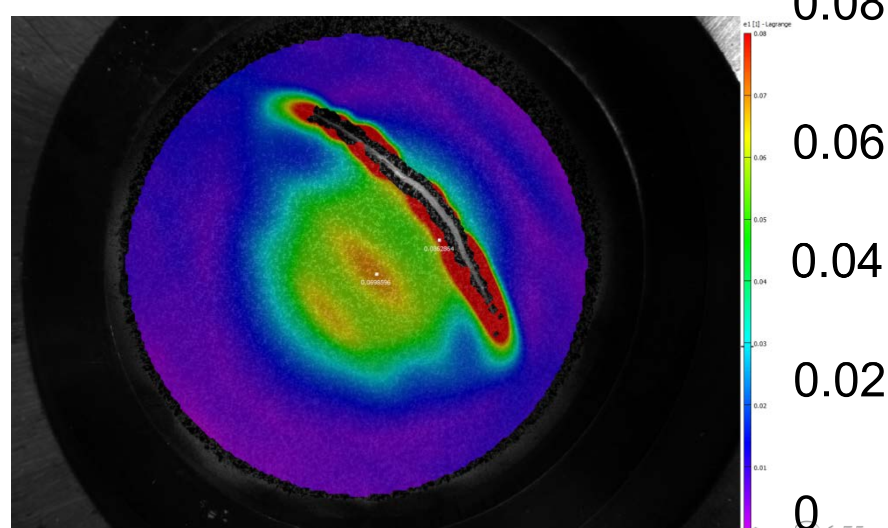
Asymmetric/Before



After



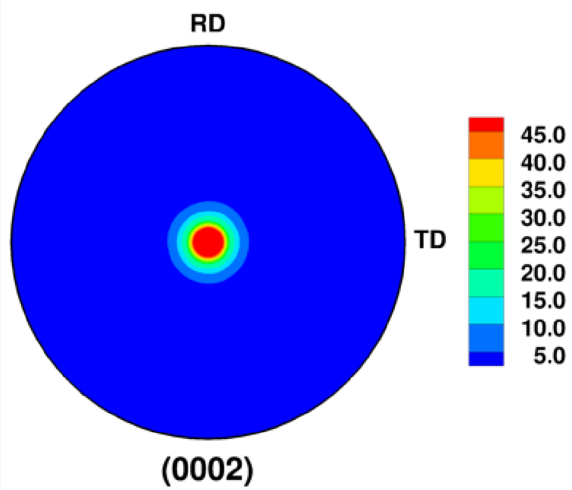
After



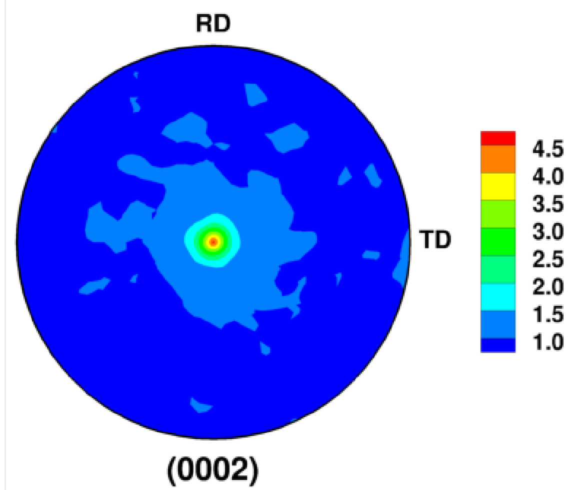
Computational Modeling: Computational Modeling was Initiated to Help Understand Role of Texture Tilt and Weakening on Formability

- Different initial textures were generated using numerical reconstruction
- Generate a strong basal texture with 80 x 80 x 80 single point grains
- Rotate texture about TD by given rotation angle
- Mix with different amounts of random texture to obtain textures with different peak intensities
- Simulated textures are similar to those obtained using asymmetric rolling
- A strong basal texture was used to represent the texture after conventional rolling

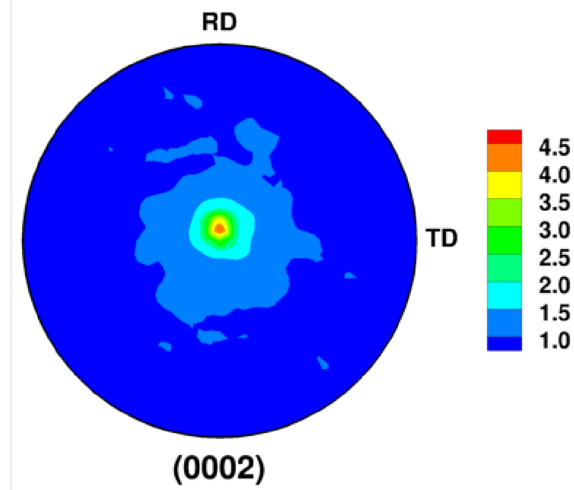
Initial Textures Obtained by Numerical Reconstruction



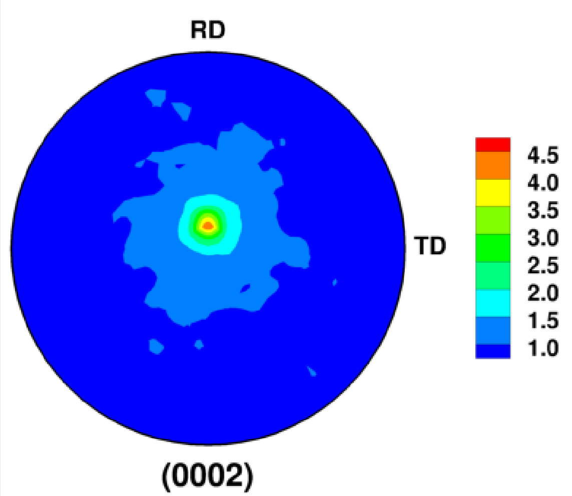
Strong Basal



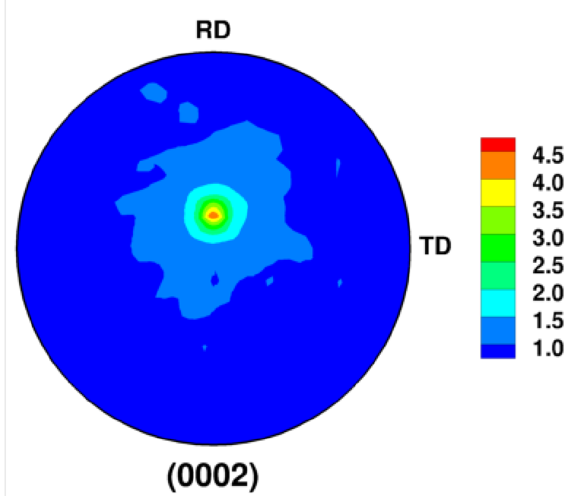
Weak Basal



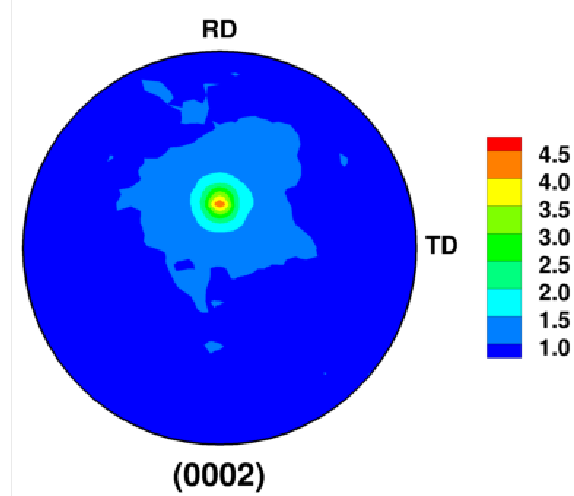
Weak Basal + 5 rotation



Weak Basal + 10 rotation



Weak Basal + 15 rotation



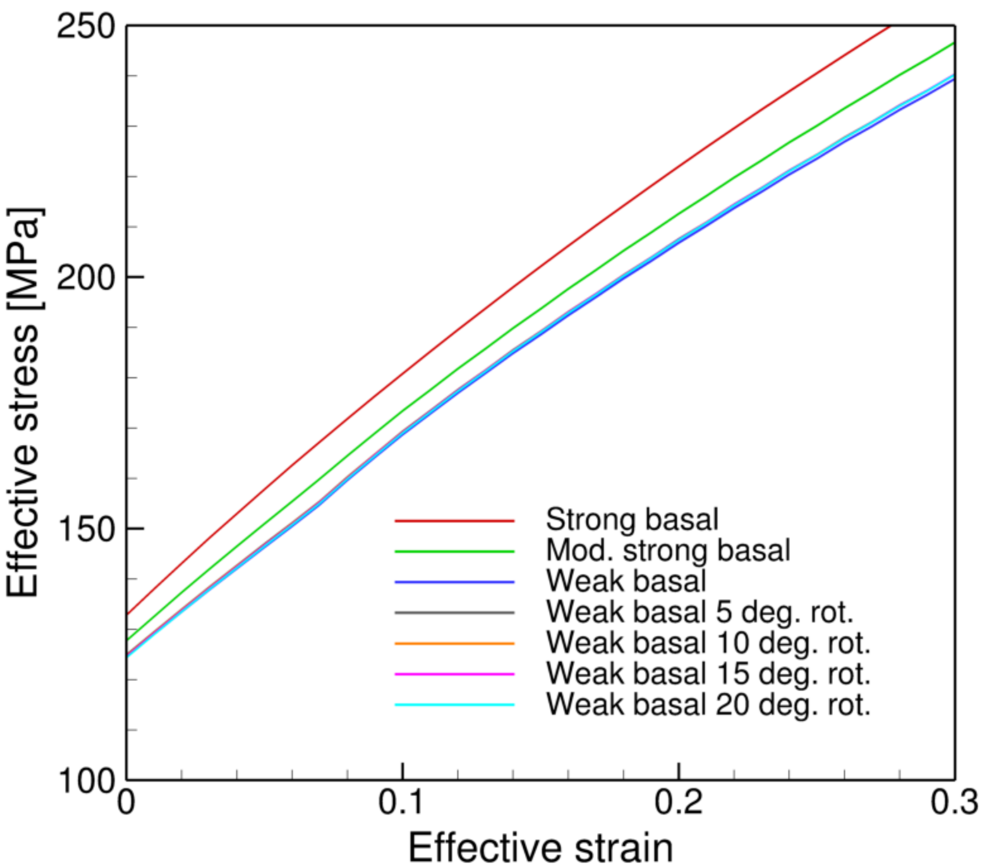
Weak Basal + 20 rotation

Crystal Plasticity Approach was used to Model the Microstructural Deformation During Biaxial Straining

- Room temperature deformation was simulated by considering both slip and twinning
- Deformation under biaxial strain conditions was simulated using different starting textures
- Critical resolved stress for twinning and slip were obtained from literature data for AZ31
- Both the stress-strain behavior and the texture evolution during deformation were calculated

Deforming at higher temperatures will reduce twinning activity and also promote dynamic recovery which will lead to increased formability; however this is not modeled

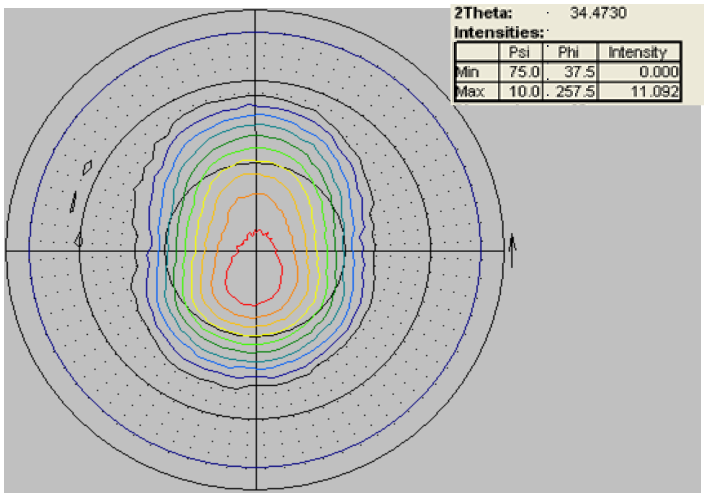
Initial Texture Has A Significant Effect on the Stress-Strain Response under Biaxial Tension



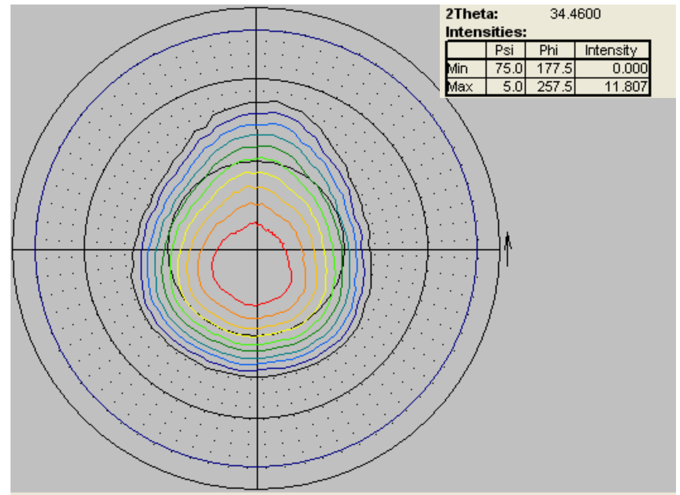
- For a given strain, strong basal texture requires the highest stress
- All weak basal textures with or without TD rotation required the least stress for a given strain
- Based on a critical stress to failure criterion, weak textures will result in greater strain to failure than strong textures
- Effect of texture weakening is more significant than texture rotation
- Significant texture change observed after deformation; deformation textures do not show significant twin activity

Intermediate Temperature Annealing Results in a Slight Decrease in Texture Strength for RP 6 & 12

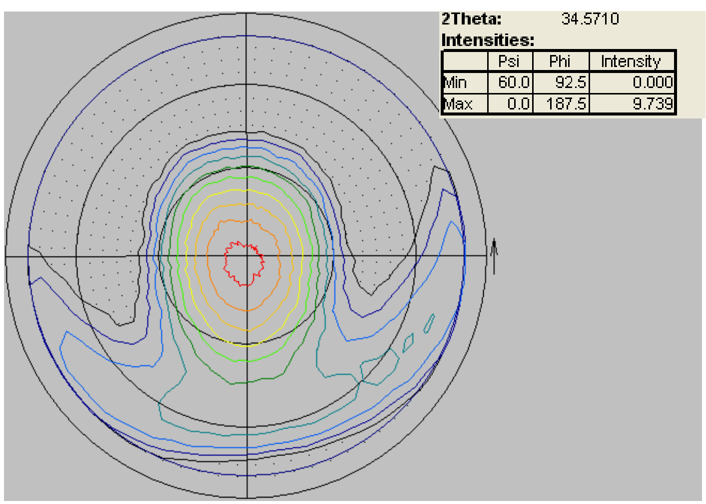
RP 6 As-rolled



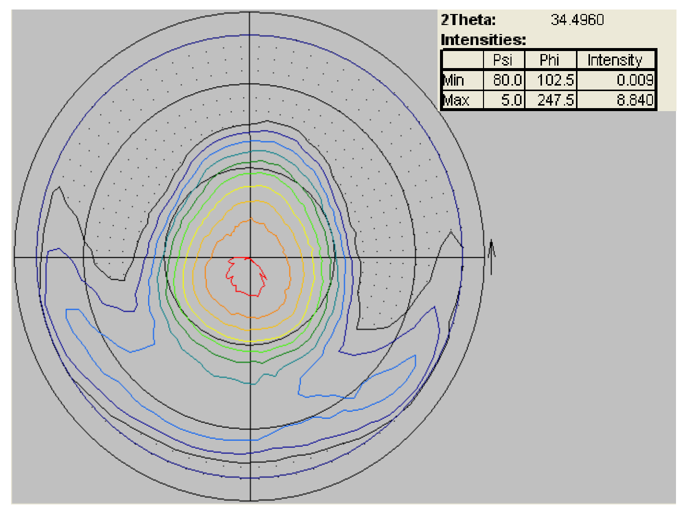
RP 12 As-rolled



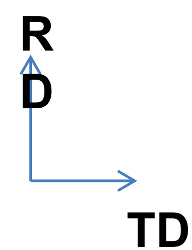
RP 6 340 C°500 min



RP 12 340 C°500 min



	Intensity	Color
1	0.353	
3	0.707	
5	1.414	
7	2.830	
10	8.000	



Note the shear components become more prominent after intermediate T anneals

Future Work: Need to Understand Factors Affecting Texture Evolution and Formability

- **Further pin deformation experiments are needed to map out relationships between deformation profile, and variables such as temperature, ratio of roll velocities, sheet thickness, thickness reduction, and friction conditions at the rolls**
- **Relationship between deformation profile and through-thickness texture evolution has to be better understood**
- **Effect of multiple passes and temperatures on deformation texture and dynamic recrystallization has to be understood**
- Effect of static recrystallization on texture weakening and formability has to be studied
- **Role of texture and recovery processes on dome testing has to be better enunciated**

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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 , and with FATA Hunter
  - Magnesium Elektron North America supplied a batch of twin roll cast sheet of AZ31B, and AZ31B in -O and –H24 temper conditions.
- A presentation on formability testing of Mg-alloy sheets was made to the USAMP Magnesium Front End, Sheet forming group
  - Comments have helped define some experiments whose results are presented here, and are gratefully acknowledged

Summary

- AZ31B sheets have been asymmetrically rolled using single passes between 100ºC and 200ºC and at several roll velocity ratios between 1:1 to 1:3.
- Tilt in the texture and modification of peak intensities have been observed to result from asymmetric rolling
- Dome tests show that asymmetric rolling improves formability over AZ31B-O at ~175ºC and at room temperature
- Multipass asymmetric rolling combined with annealing has the potential to further improve formability by a combining tilting and weakening of the texture

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Technical Back-Up Slides

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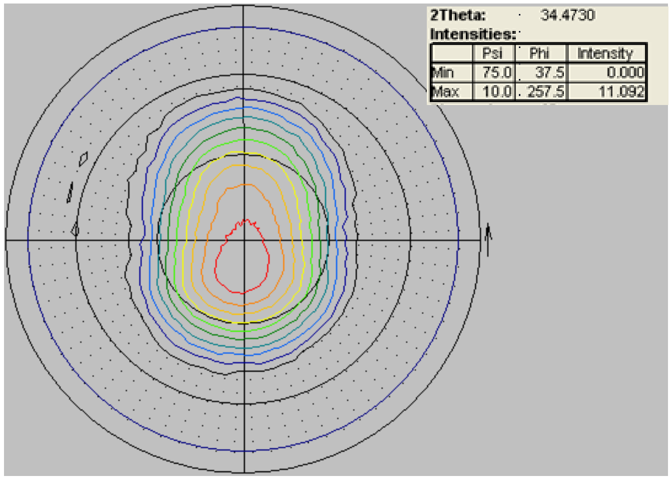
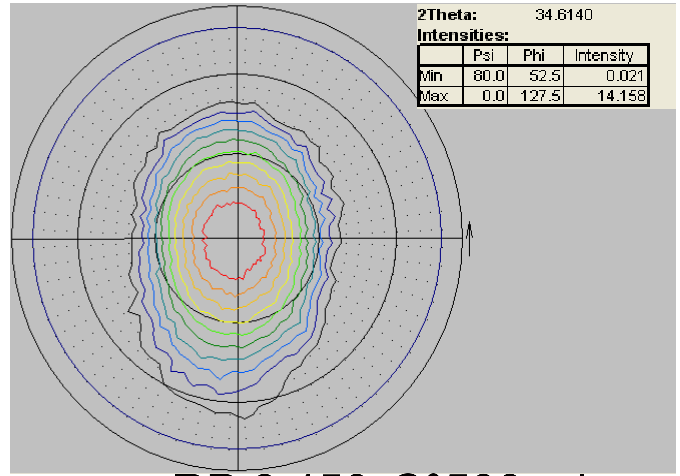
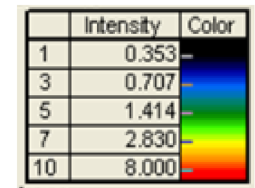
Texture Strengthening is Observed During High temperature annealing of RP 6 (symmetric rolled)

RP 6 As-rolled

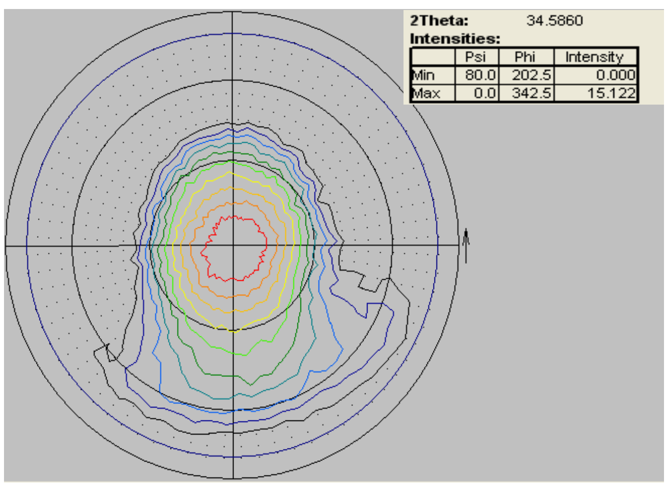


RP 6 450 C°30 min

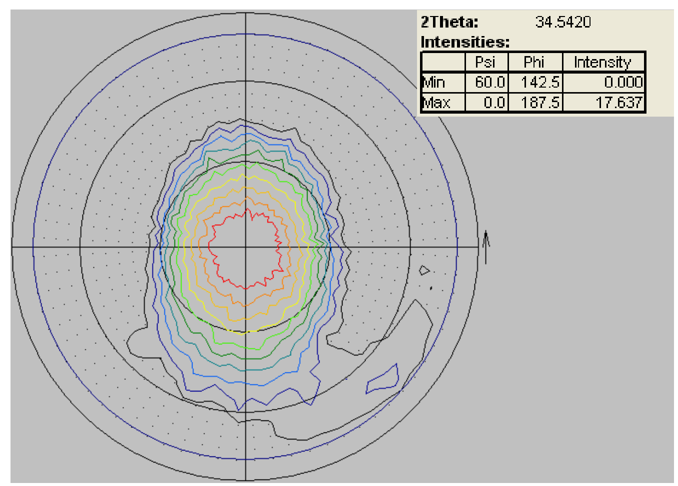


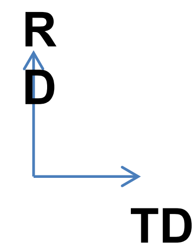


RP 6 450 C°60 min



RP 6 450 C°500 min



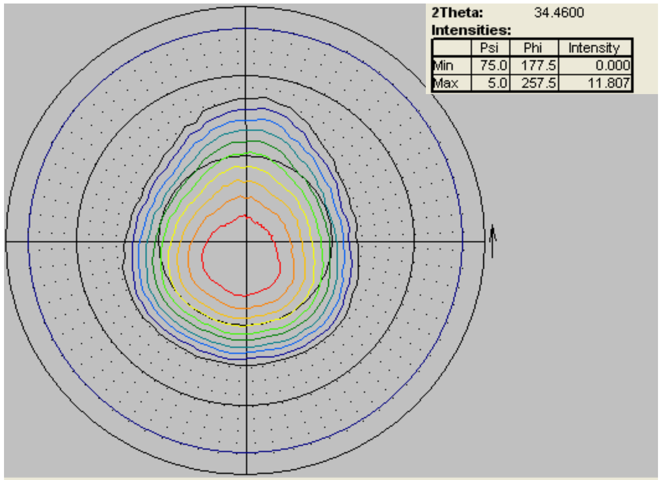


Texture strength of RP 6 increases with annealing time at high temperature

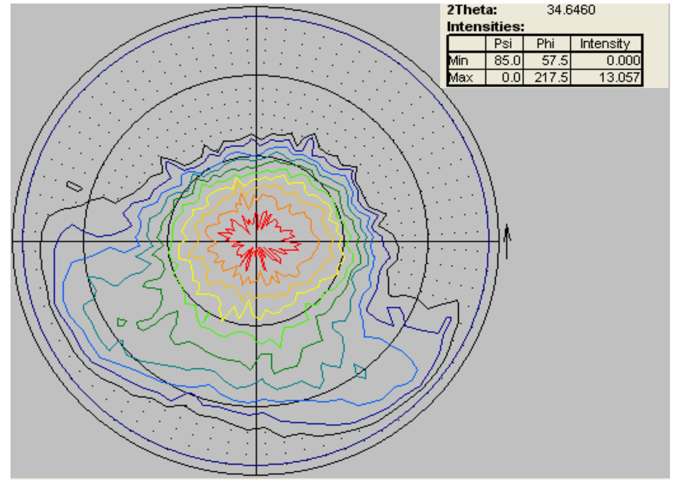
Texture becomes more axisymmetric after annealing, though intermediate intensity components typical of shear persist.

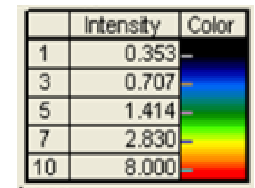
Texture Strengthening is Observed During High temperature annealing of RP 12 (Asymmetric rolled)

RP 12 As-rolled

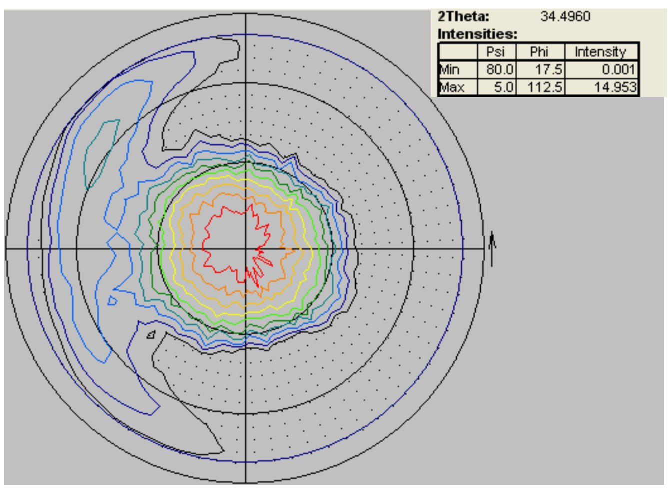


RP 12 450 C°30 min

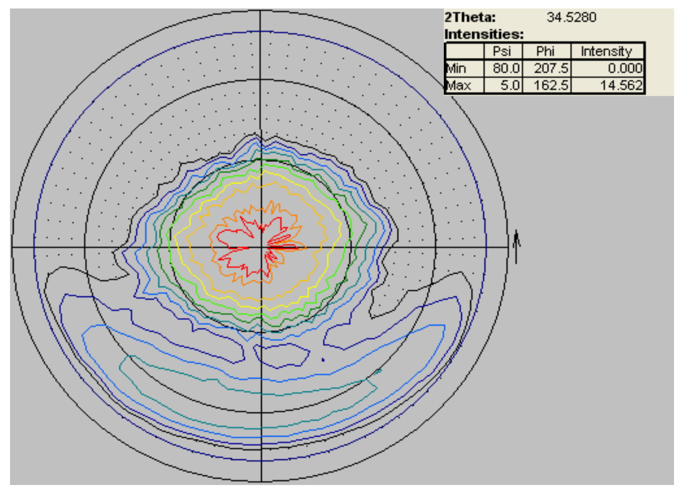


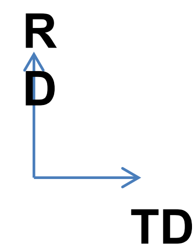


RP 12 450 C°60 min



RP 12 450 C°500 min

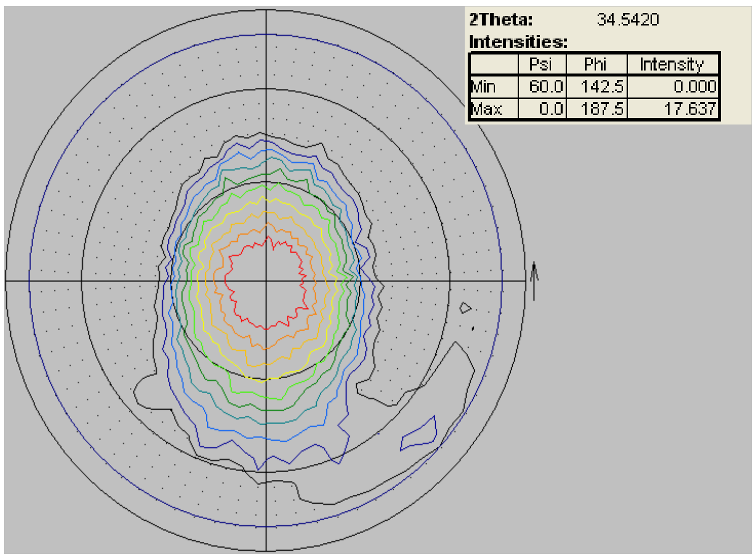




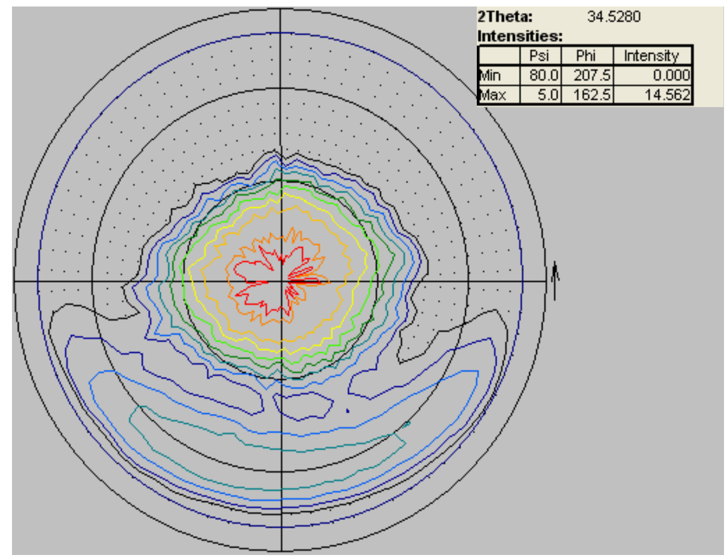
Texture strength of RP 12 also increases with annealing time at high temperature
High intensity region changes shape (again more axisymmetric), and intermediate intensity components typical of shear more obvious in RP 12 than RP 6.

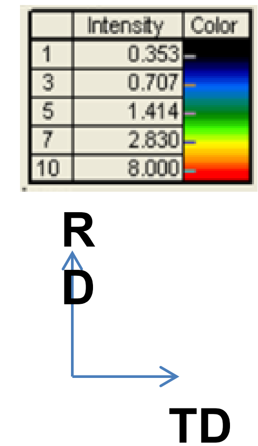
Comparison of high temperature annealed samples RP 6 and RP 12 reveals wider spread of shear components in shear rolled (12)

RP 6 450 C°500 min



RP 12 450 C°500 min





This increased texture "spread" is responsible for the slightly lower texture strength after annealing of RP 12 vs. RP 6.

Nevertheless, the intensity of the texture is high in both cases.