Project No. 60184, Agreement No. 22422

Ultra-Fine Grain Foils and Sheets by Large-Strain Extrusion Machining

Project ID: LM034

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Project Overview

Project Timeline

- Start: 10/1/2009
- Finish: 12/1/2011

Barriers

- Cost of **Magnesium** and Aluminum Sheet
  - Wrought sheet vs. direct sheet forming from cast feedstocks
- Limited Formability of **Mg** and Al sheet
  - Formability and post-formed properties
  - Sheet suitable for alternate forming methods is expensive

Budget

- Total project funding
  - DOE – $685K
- FY10 Funding - $325K
- FY11 Funding - $360K (received $83K to date)

Partners

- Purdue University (Chandrasekar/Trumble)
- ORNL (cost model)
- Material Suppliers (Alcoa, Mg Supplier)

Purdue University

Pacific Northwest National Laboratory

Objectives

- Establish deformation and process conditions for production of Mg AZ31B foil/sheet of up to 2 mm thickness
- Evaluate process scale-up, economics and capacity limits
- Demonstrate ability to make fine grain sheet from cast feedstocks
- Characterize microstructure, mechanical properties and formability of foil/sheet
- Establish scale-up equipment for producing 2 mm thick sheet with up to 250 mm width

Milestones – FY2011

Month/Year	Milestone or Go/No-Go Decision
Sept. 2010	**Decision Gate:** Demonstrate scale-up of LSEM process to produce 2 mm thickness strip, with 10 mm width. Completed
Dec. 2010	Demonstrate processing of cast ingot feedstock into strip at sheet thickness. Rescheduling to April 2011
Sept. 2011	Complete design and feasibility studies for LSEM process and equipment capable of 2 mm thick sheet up to 250 mm width.
Dec. 2011	Project complete.

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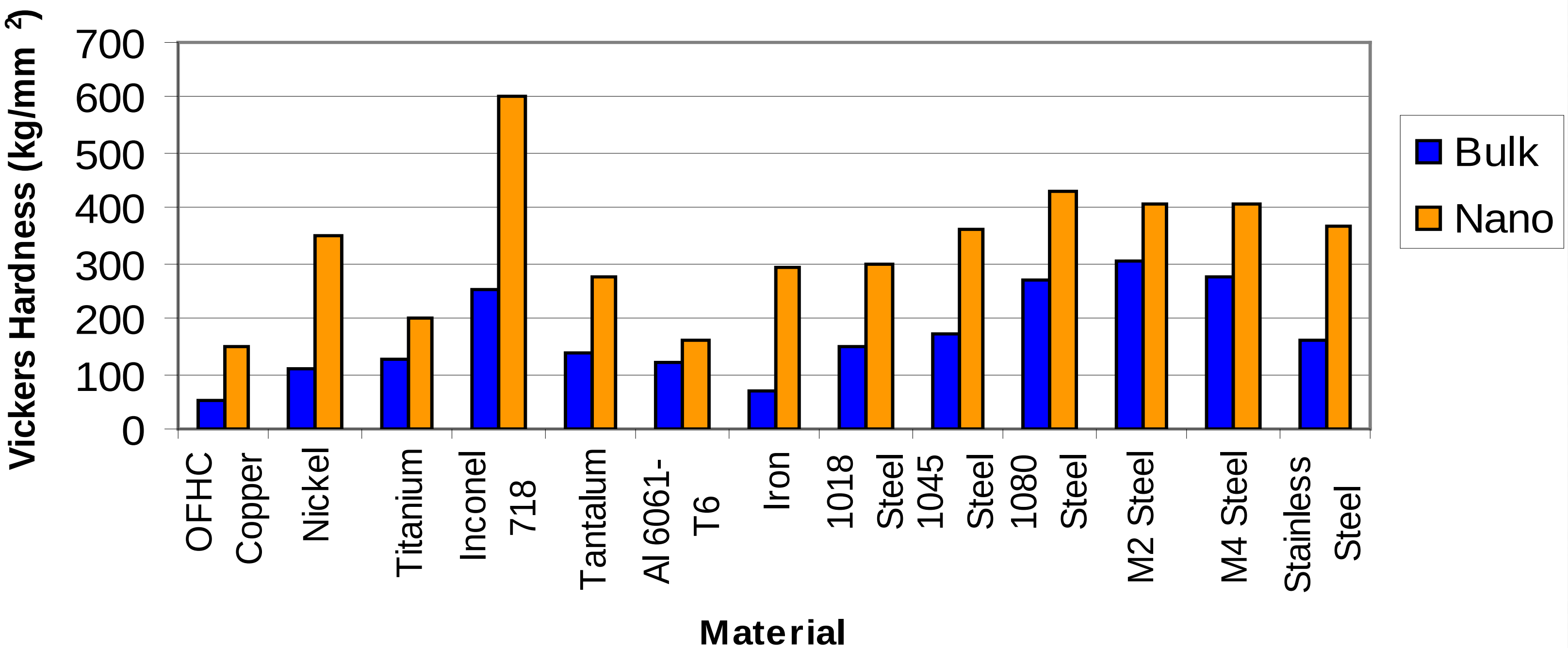
Milestones

Programmatic Issues:

•This agreement work plan is based on funding of a subcontract to Purdue University for development and demonstration of the scale-up on the LSEM equipment and process. Continuing Resolution required placement of incremental subcontracts.

•Demonstration of LSEM processing with cast feedstock delayed due to subcontract funding and PNNL equipment issues. (centrifugal casting machine)

Motivation for Fine-Grain Microstructure
(Increased Strength)



Purdue's Machining-Based Deformation Processed

- Hardness (strength) increases up to ~5-fold

Brown et al., J. Mater. Res., 17, 2484 (2002)

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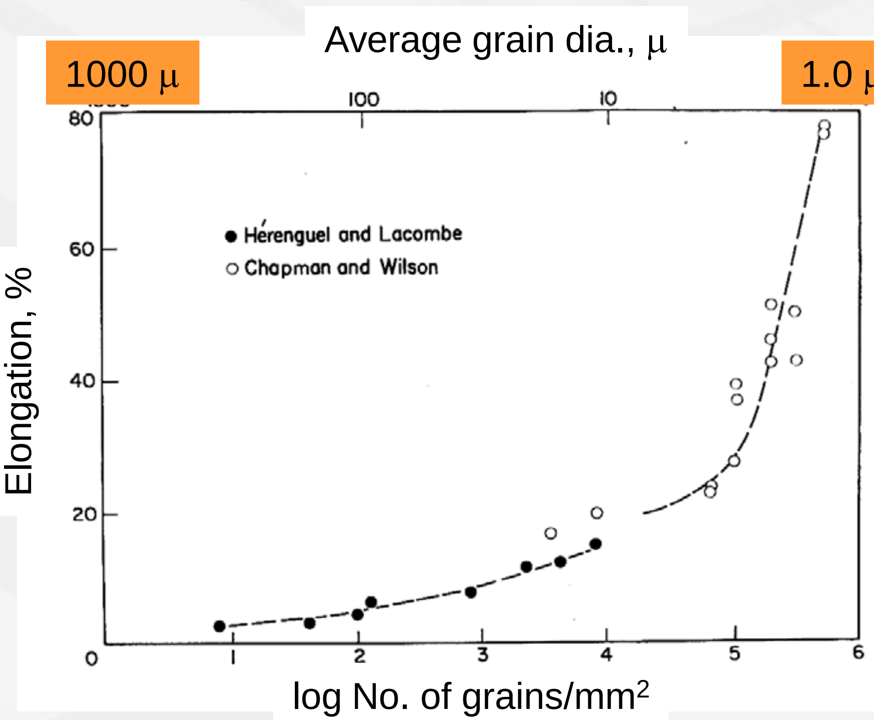
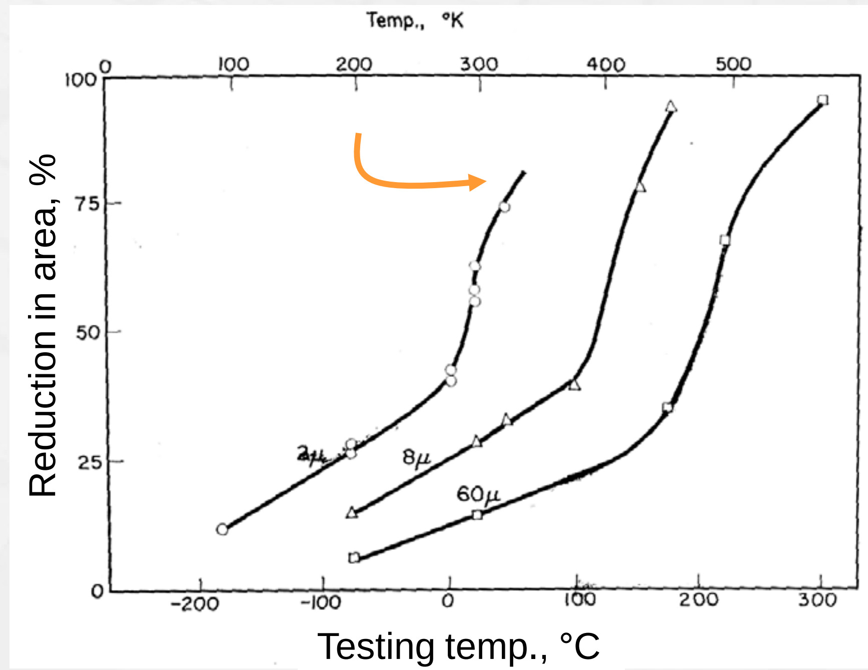
Motivation for Fine-Grain Microstructure
(Increased Ductility)

(E.F. Emley, Principles of Magnesium Technology, 1966.)





~80% Elongation at RT for ~1μm!

Improved ductility at low T

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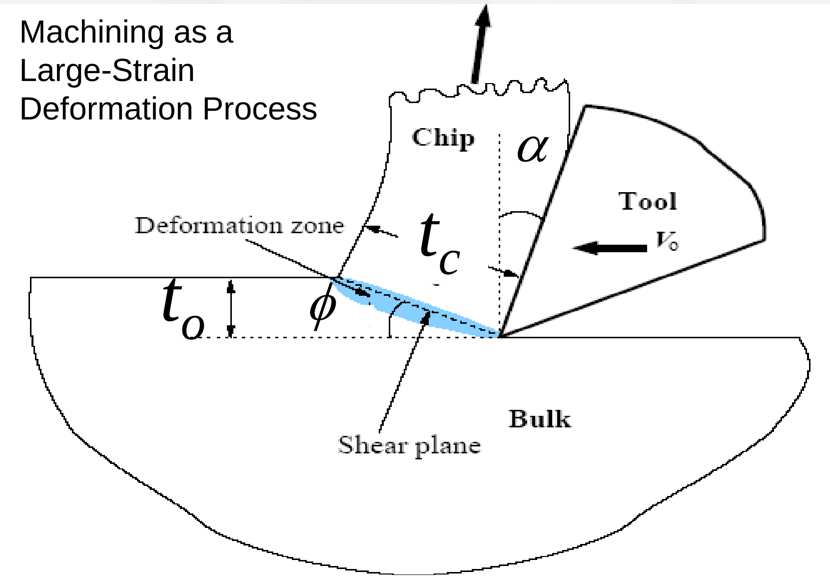
Goal

<u>Reduce processing costs</u> for automotive sheet products by replacing conventional wrought processed Mg and Al sheet with ultra-fine grain sheet produced by <u>large strain extrusion machining (LSEM)</u>.



$\lambda = t_c / t_o$

Shear strain:

$$\gamma = \frac{\lambda}{\cos\alpha} + \frac{1}{\lambda\cos\alpha} - 2\tan\alpha$$

Well-characterized deformation:

- γ = 1 to 20 in a single pass
- $\dot{\varepsilon}$ up to ~10^5 s^{-1}

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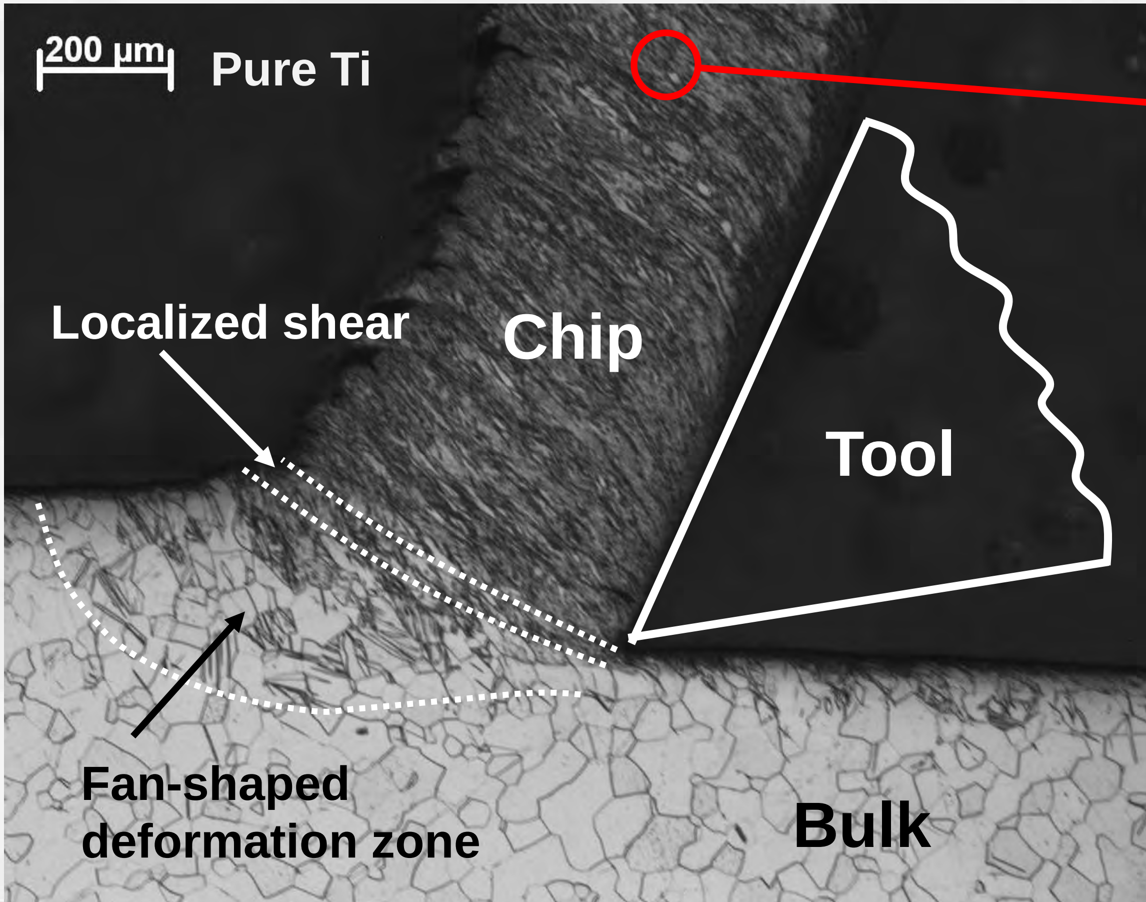
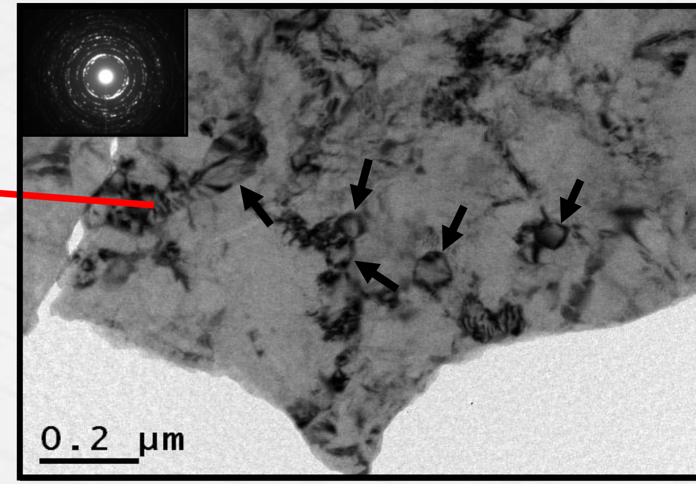
Grain Refinement
(As in Other Severe Plastic Deformation (SPD) Process)

Shear strain, $\gamma = 3$

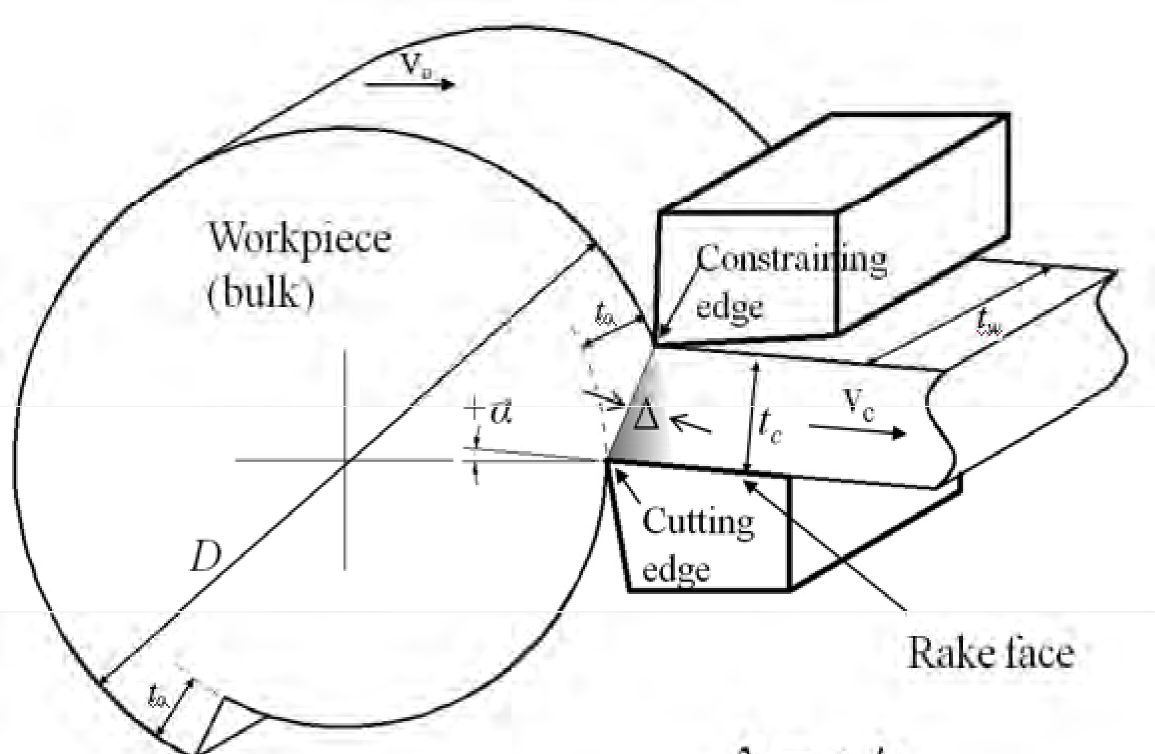




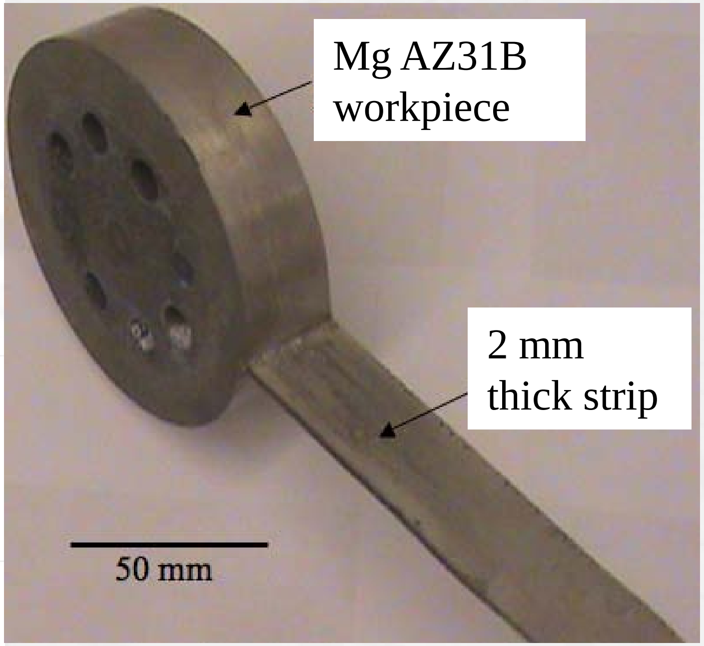
Grain size ~ 90 nm

Shankar et al., Acta Mater. 54 (2006) 3691-3700

Large Strain Extrusion Machining



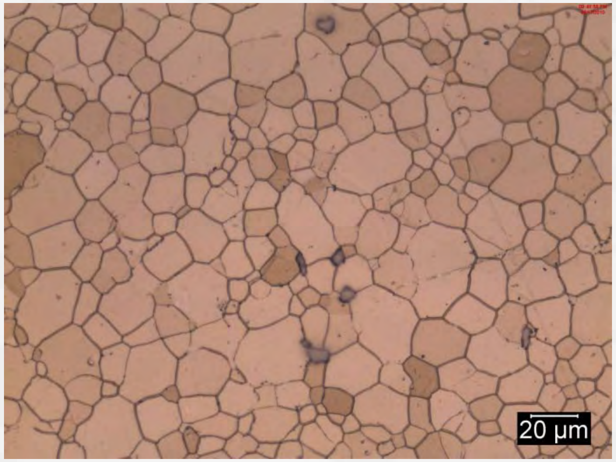
$$\lambda = t_c/t_o$$



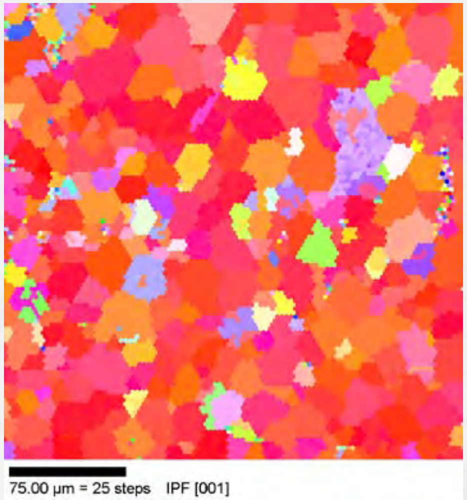
Shear strain, $\gamma = \dfrac{\lambda}{\cos(\alpha)} + \dfrac{1}{\lambda\cos(\alpha)} - 2\tan(\alpha)$

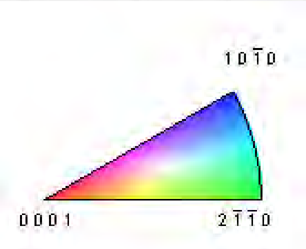
Starting Material: Bulk Mg AZ31B
(Wrought tooling plate from ThyssenKrupp, NA Inc.)

Optical micrograph



EBSD IPF map





Normal direction (ND)
Strong basal texture

Measured

<u>Grain size:</u>

16 ± 2 µm

<u>Hardness:</u>

58 ± 3 kg/mm^2

Reference Properties

Typical tensile properties of AZ31B sheet

Condition	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Parallel to rolling direction			
Annealed	255	150	21
Hard rolled	290	220	15
Perpendicular to rolling direction			
Annealed	270	170	19
Hard rolled	295	235	19

Source: Metals Handbook, 9th edition

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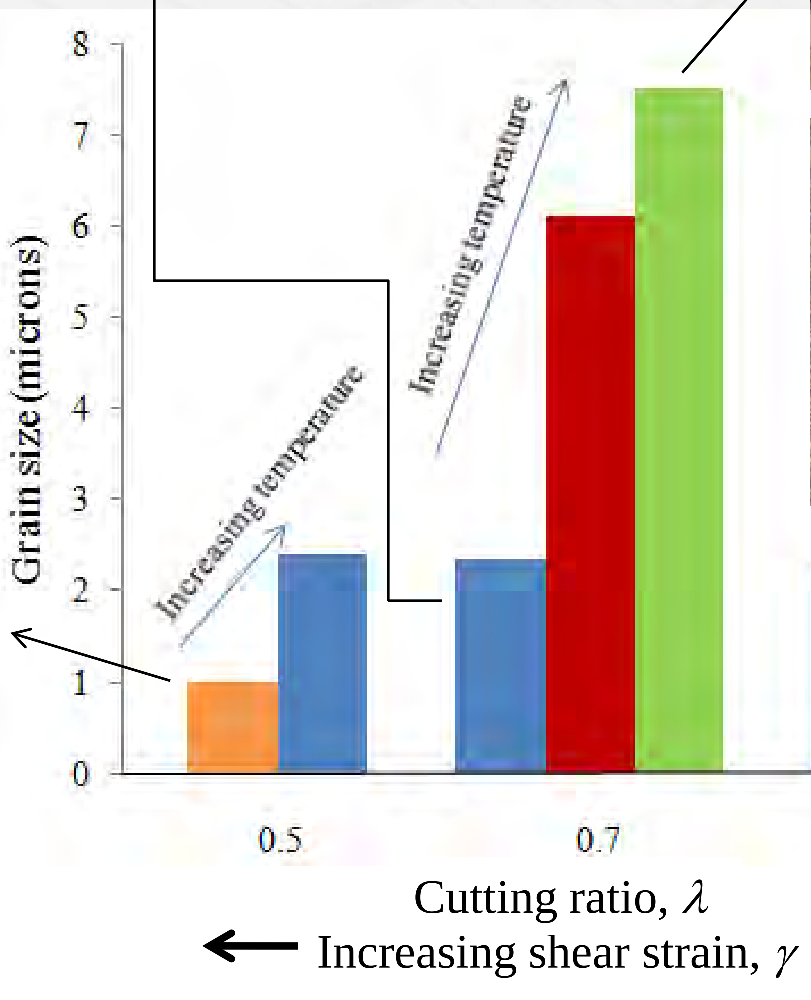
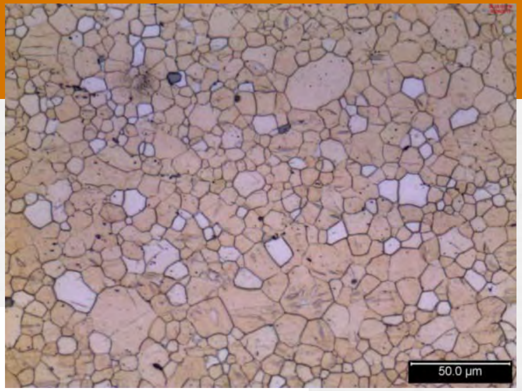
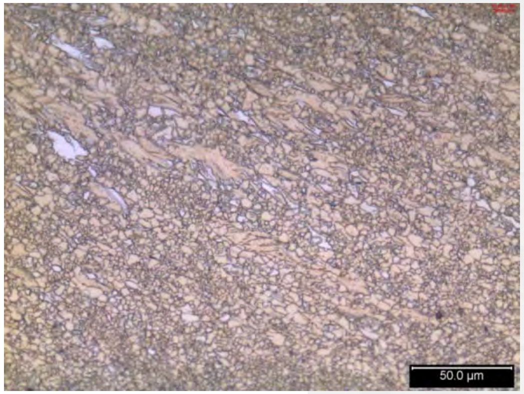
Grain Size of LSEM AZ31B
(Effect of Temperature & Cutting Ratio)

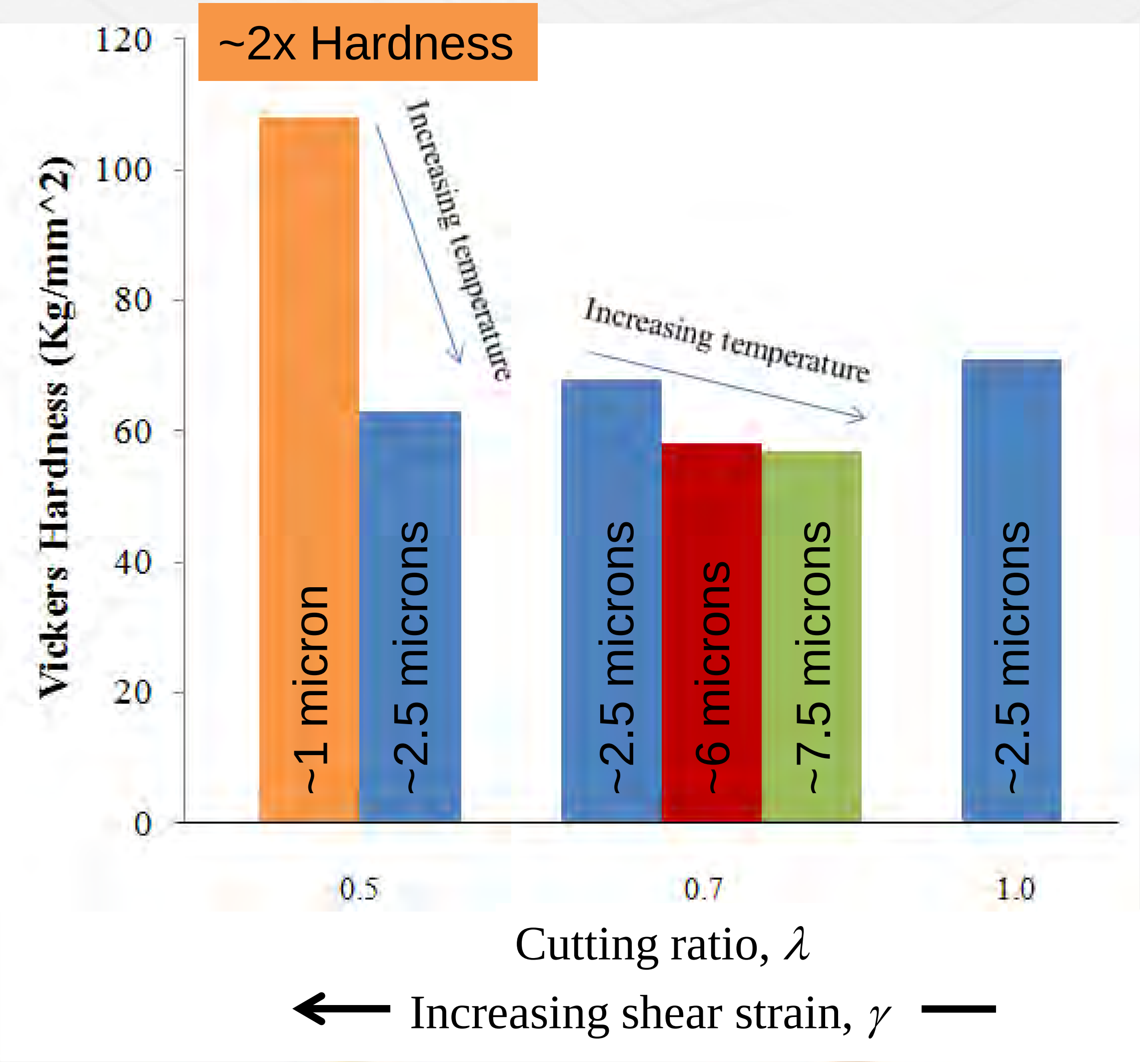
Unresolved grain structure through optical microscopy. EBSD in progress.







Hardness of LSEM AZ31B
(Effect of Temperature and Cutting Ratio)



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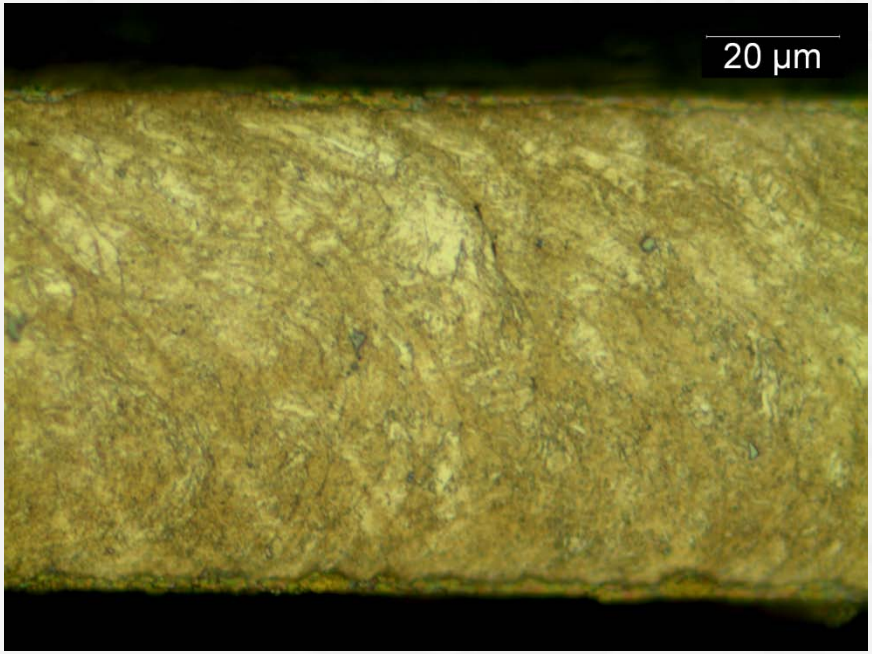
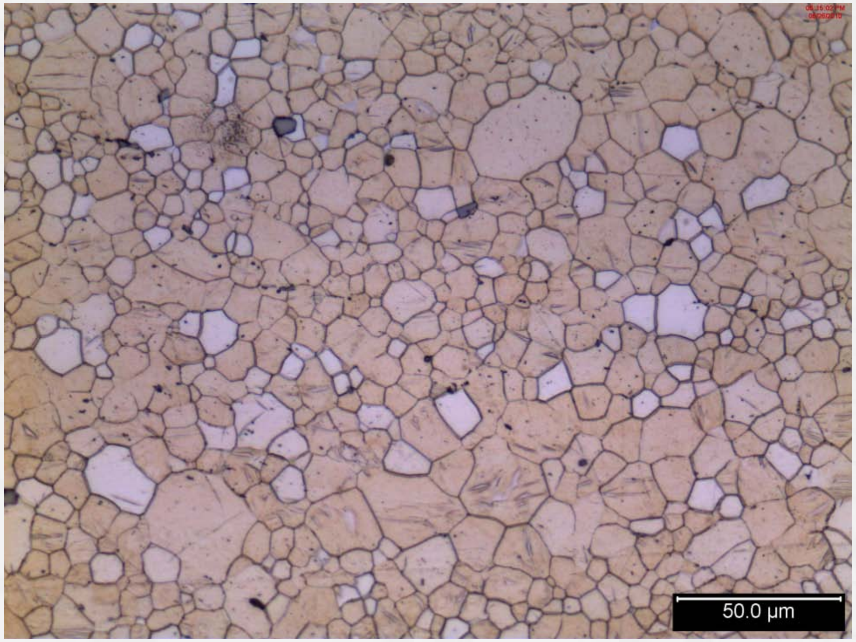
Grain Size and Strip Thickness



Thin strip (100 µm) with microstructural features unresolvable in optical microscopy. Grain size likely submicrometer.



Thick strip (1.4 mm) with recrystallized microstructure, grain size of 7.5 µm.

GOAL: Produce thick strips with sub-micrometer grains

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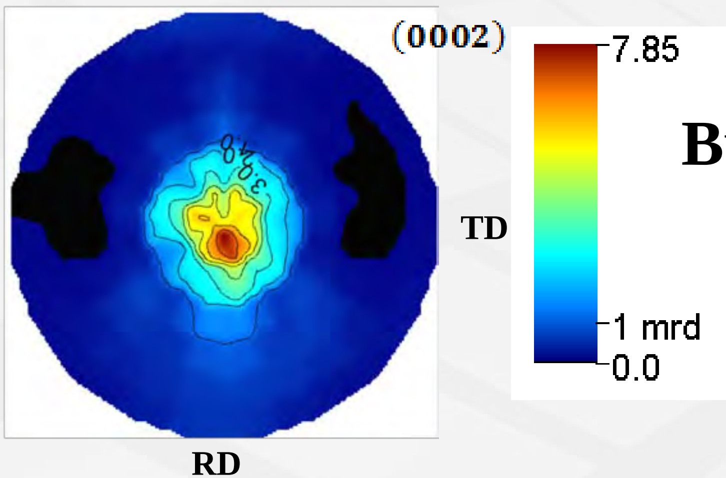
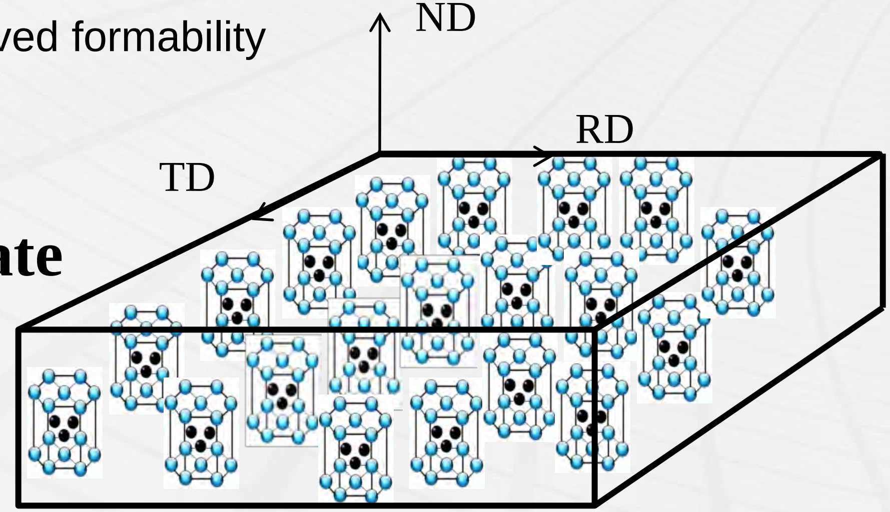
Texture Development

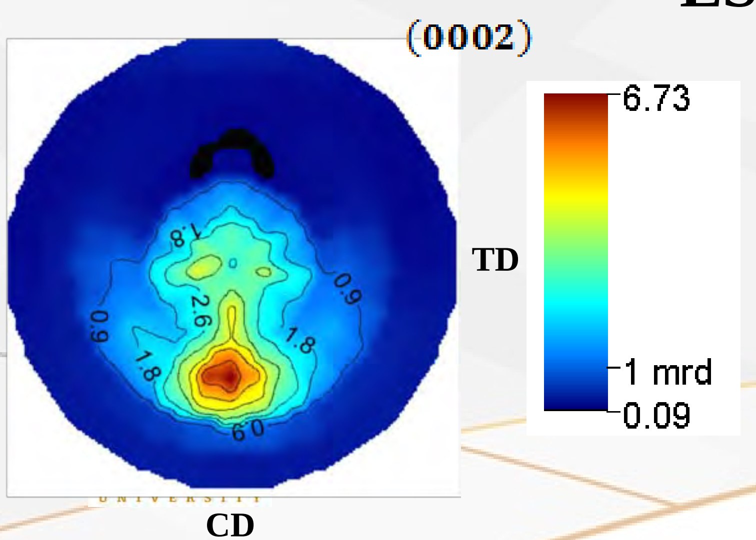
✓Substantially different textures → Improved formability

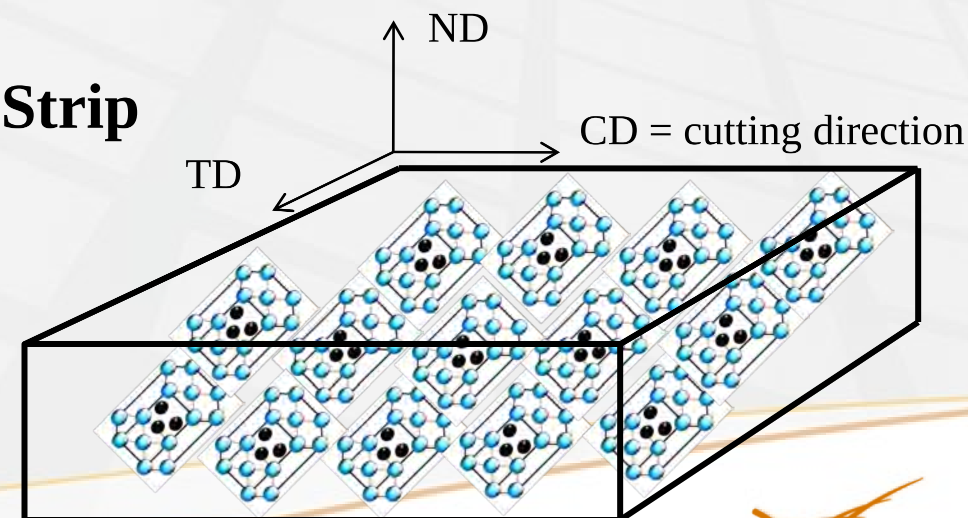


Bulk Plate



LSEM Strip





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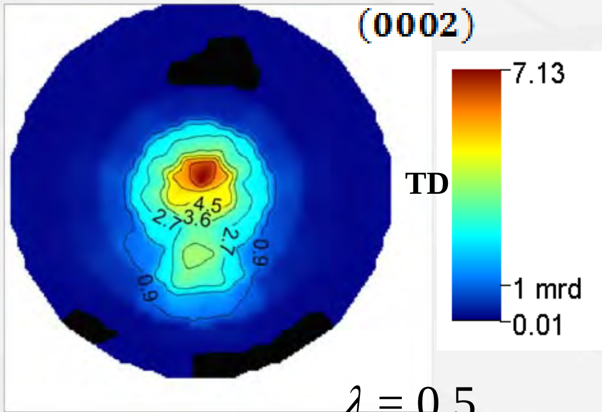
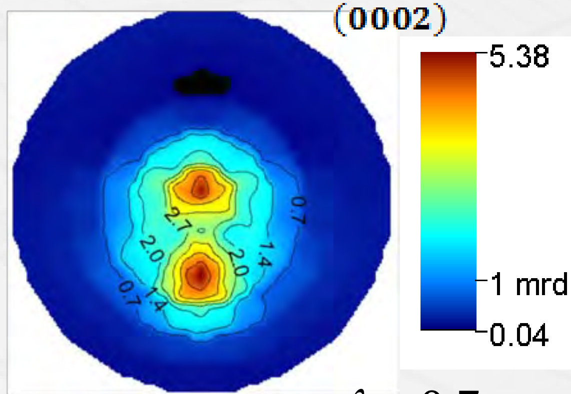
Texture Development
Effect of LSEM Process Parameters

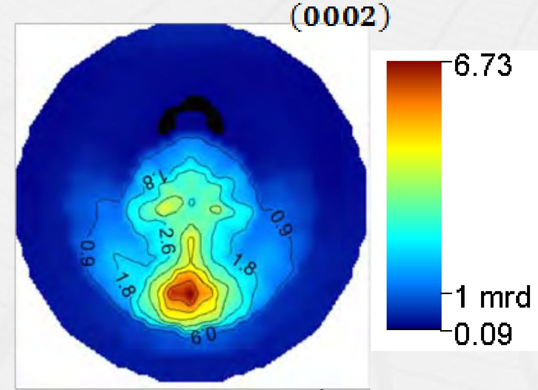
<u>Low deformation temperature LSEM strip textures</u>



$\lambda = 0.5$

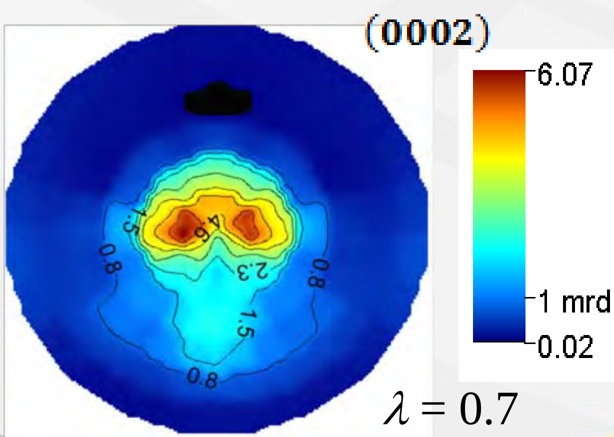


$\lambda = 0.7$

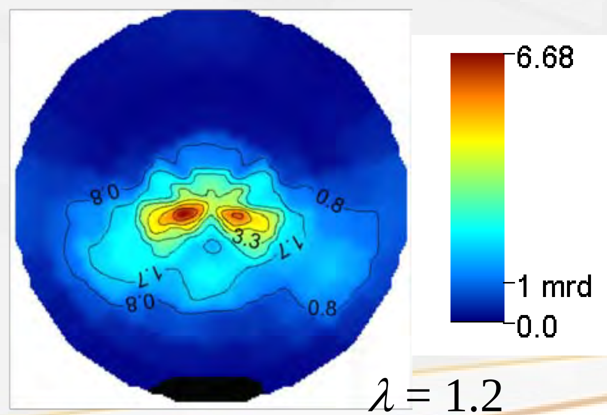


$\lambda = 1.0$

<u>High deformation temperature LSEM strip textures</u>



$\lambda = 0.7$



$\lambda = 1.2$

Texture → Formability

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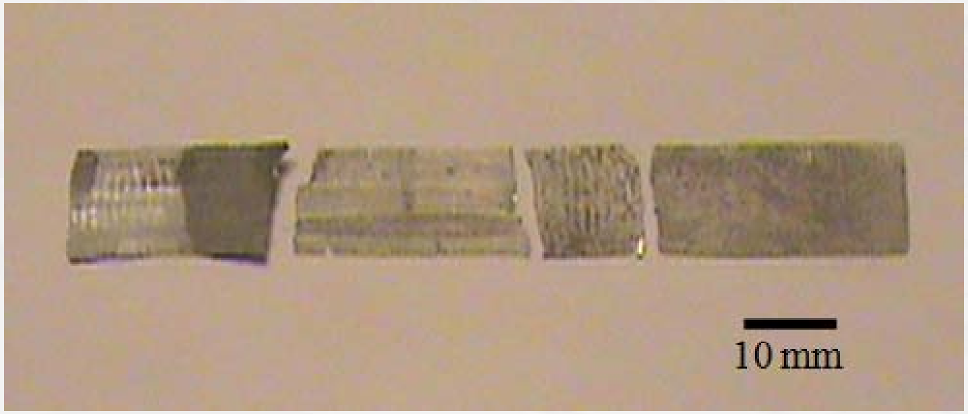
AZ31B Tensile Properties
(LSEM Strip vs. Conventional Wrought Products)

Material	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
LSEM AZ31B Strip (2.5 mm) (Miniature Tensile)	140	264	24
AZ31B Sheet Annealed*	150	255	22
AZ31B Extrusion*	200	255	12

**Typical AZ31B wrought property values from ASM Handbook, Volume 2*

Preliminary "Formability" Assessment by Cold Rolling



Bulk plate, annealed at 250°C/1 h:

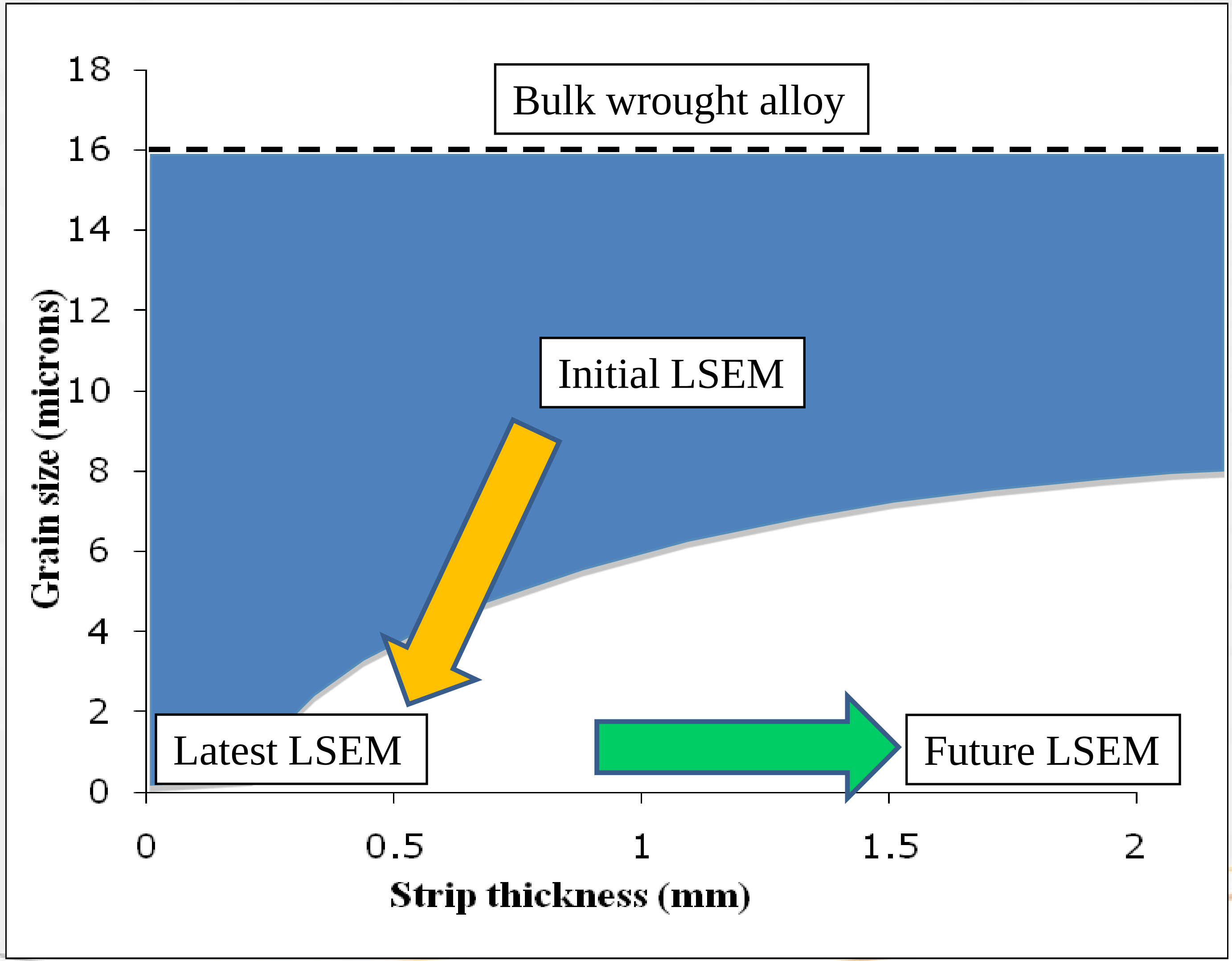
Cracking after only 25% rolling reduction.

LSEM strip, as cut:

No cracking to 65% reduction.

Enhancement of formability through LSEM process

Purdue's AZ31B LSEM
Progress and Direction



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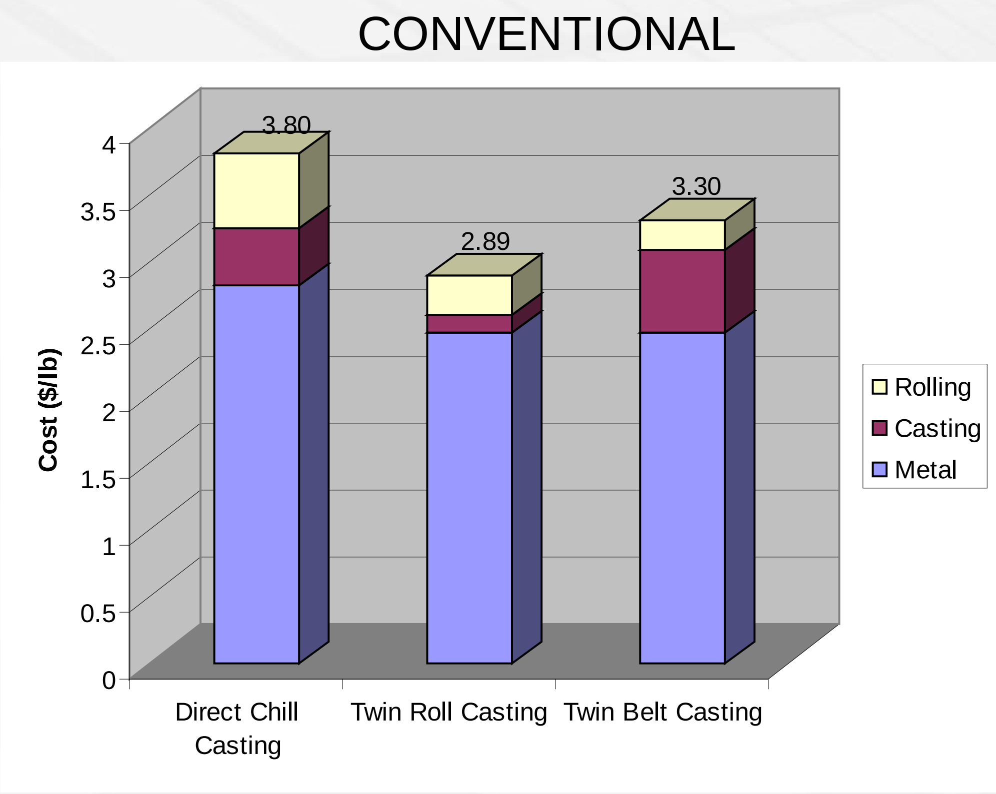
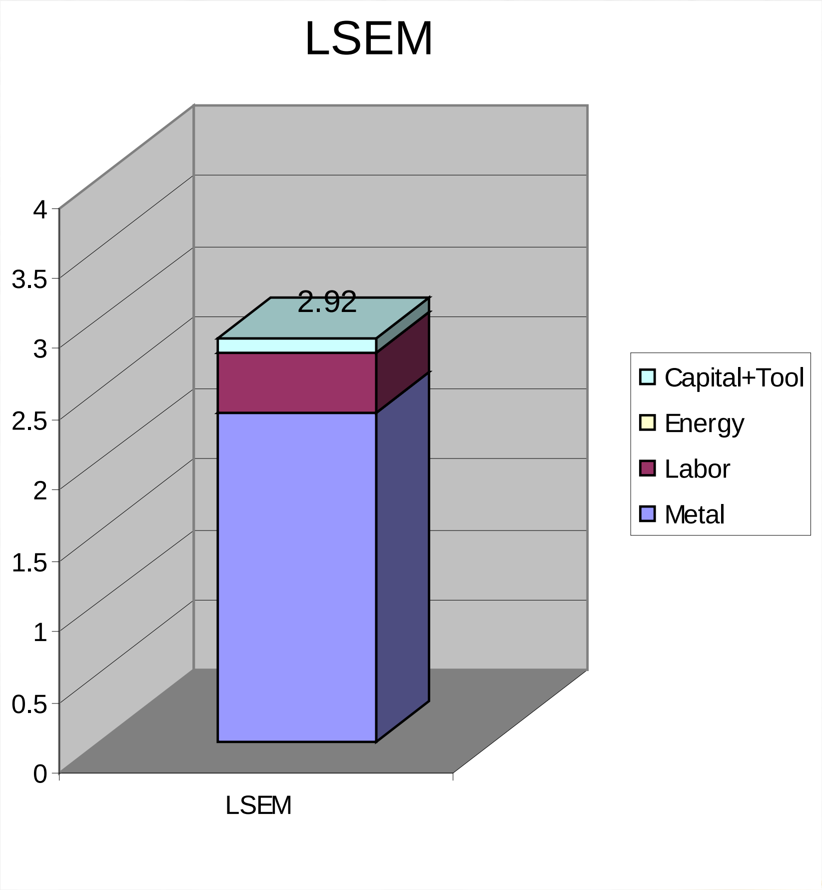
Comparative Mg Sheet Cost Estimates





Cost Modeling
by Dr. Sujit Das
(Oak Ridge National Laboratory)

Purdue University

Pacific Northwest National Laboratory

Summary

- Grain sizes down to sub-micrometer level and two-fold increase in hardness over the bulk material in thinner strips (~ 100 μm).
- At least 50% reduction in grain size compared to the bulk material in thicker strips (~ 2 mm).
- Enhanced formability of LSEM strips over the bulk material may be due to the non-basal textures (controllable textures)
- Preliminary tensile testing suggests thicker LSEM strips comparable with conventionally rolled AZ31B.
- Cost models show LSEM-type processing has potential cost advantage over conventional and continuous cast magnesium sheet
- Viability to produce Mg AZ31B strips through LSEM up to 2 mm thickness using a small capacity (10 HP) lathe.

Future Work

- Produce strips directly from cast material.

  PNNL to produce high integrity castings.

- Establish power requirements for thicker strip.

  Force measurements in progress.

- Achieve smaller grain sizes in the thicker strips.

  Linear slide apparatus under construction.

- Small-scale formability testing on LSEM strips

  Available methods under investigation.

- Evaluate LSEM product quality (surface, edge)

Patents, Publications and Presentations

PATENT

- Direct, Large-Scale Production of Bulk Forms of Metal Alloys by Machining-Based Processes:
  U.S. Provisional Patent Application Serial No. 61/430,284, Filing Date January 6, 2011.
  Inventor(s): S.Chandrasekar; K. Trumble; W. Moscoso; M. Efe; D. Sagapuram; C.J. Saldana; J.B. Mann; & W.D. Compton.

PUBLICATIONS

- C. Saldana, S. Swaminathan, T.L. Brown, W. Moscoso, J.B. Mann, W.D. Compton, and S. Chandrasekar, "Unusual applications of machining: controlled nanostructuring of materials and surfaces," ASME Journal of Manufacturing Science and Engineering, 132-3, 030908 (12 pages) doi:10.1115/1.4001665, 2010.
- J.B. Mann, C. Saldana, S. Swaminathan, W. Moscoso, T.G. Murthy, W.D. Compton, K.P. Trumble and S. Chandrasekar, Severe plastic deformation by machining and production of nanostructured alloys, Book chapter in: Nanostructured metals and alloys: Processing, Microstructure, Mechanical Properties and Applications, S.H. Whang (ed.), Woodhead Publishing, 2011, in press.
- W. Moscoso, M. Efe, K.P. Trumble, S. Chandrasekar, "Direct production of MgAZ31B sheet by large-strain extrusion machining," to be submitted to Acta Materialia. Anticipated submission March 2011.
- D. Sagapuram, K.P. Trumble and S. Chandrasekar, "Texture development in MgAZ31B foil produced by large-strain extrusion machining," under preparation for submission to Metallurgical and Materials Transactions. Anticipated submission May 2011.

PRESENTATIONS

- M. Efe, Wilfredo Moscoso, S. Chandrasekar and K. P. Trumble, "Production of magnesium AZ31B foils by machining-based processes," Materials Science and Technology (MS&T) 2009 Conference (ACerS, ASM, AIST and TMS), Pittsburgh, PA, 25-29 October 2009. (Presentation)
- W. Moscoso, M. Efe, W. D. Compton, K. P. Trumble and S. Chandrasekar, "Direct production of sheet from alloys of limited workability using machining-based processes", TMS Symposium on Functional and Structural Nanomaterials: Fabrication, Properties, Applications and Implications, San Diego, Feb 27 – March 3, 2011. (Presentation)
- D. Sagapuram, K. P. Trumble and S. Chandrasekar, "Texture Evolution in Large-Strain Extrusion Machining", TMS Annual Meeting, San Diego, CA, 27 Feb-3 March 2011. (Poster)

TECHNICAL BACKUP SLIDES

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Outline

- Project Overview
- Goal and Objectives
- Milestones
- Technical Approach
- Results and Accomplishments
- Future Work
- Summary
- Publications/Presentations

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Experimental Procedure

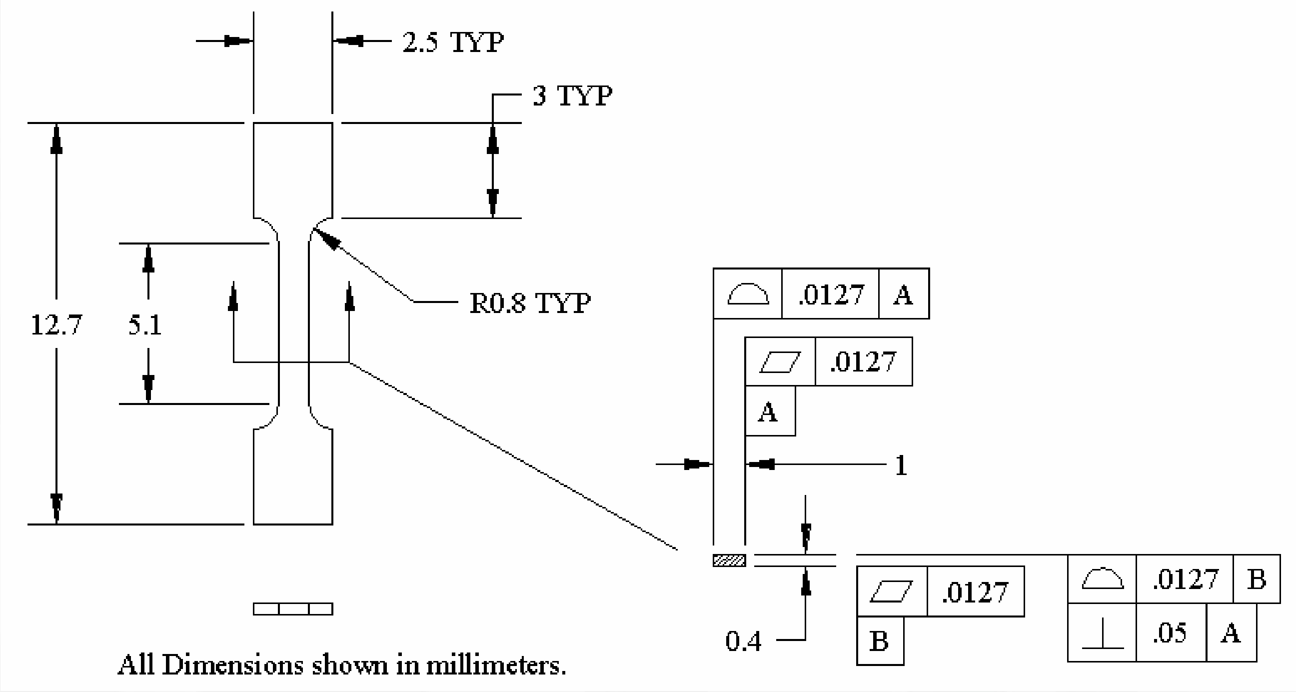
LSEM process

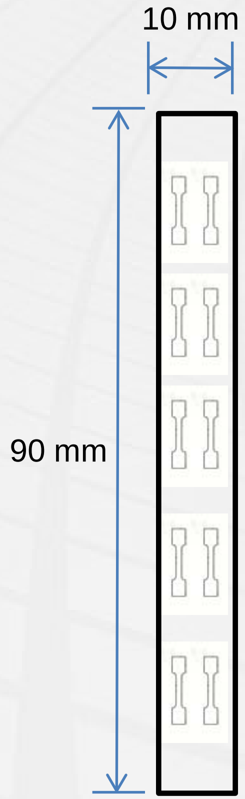
- Discs (6 to 25 mm thick and 100 mm diameter) for LSEM processing were cut from the as-received Mg AZ31B tooling plate
- Workpiece was either at ambient temperature or preheated to 200^oC for LSEM processing, λ = 0.5, 0.7, and 1.0.
- Production speeds were varied from 10 to 75 m/min

Characterization techniques

- Optical microscopy and electron backscatter diffraction (EBSD) to study microstructures
- Crystallographic textures were analyzed by X-ray diffraction using Area Detector diffractometer and Rietveld refinement
- Miniature tensile specimens for tensile strength and elongation (PNNL)
- Vickers indentation and tensile testing were used to study mechanical behavior

Miniature Tensile Specimen Geometry





Schematic of specimen removal location

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LSEM Cost Assumptions

- Strip: 2” (W) x 0.06” (T)
- Alloy Cost: AZ31B @ $2.10/lb
- Process Efficiency: 90%
- Cutting Speed: 50 m/min
- Feed per rev.: 1.5 mm/rev
- Workpiece : 4”(D) x 4”(L)
- Tool Life: 30 min
- Tool Cost: $500/pce
- Capital Cost: $150K
- Production Capacity: 356 MT/year

Cost Modeling
by Dr. Sujit Das
(Oak Ridge National Laboratory)

Cost estimation methodology based on basic economic principles of metal-cutting operations (detailed consideration of machining rate)

Magnesium LSEM Economics
Preliminary Observations

- LSEM technology demonstrated for a small sheet size of 2” wide x 0.06” thick is the most cost-effective with other competing yet-to-be commercialized magnesium sheet technologies
- With the most economical twin roll casting technology, it has a slight disadvantage due to higher labor cost from non-automated operation assumed for smaller width sheet
- Economics of larger width sheet (technology development planned during FY 11) yet to be evaluated appears to be favorable
  - Design issue for a wider sheet extension compared to technology issue for maintaining required thickness
  - Contribution of tooling cost may not change significantly with economies of scale
  - Rotary Lathe vs. Linear Planing option needs to be explored (economies of scale will reduce the higher capital cost effect)
  - With the potential of manufacturing process automation – the effect of higher labor cost seen here will be substantially reduced

Cost Modeling
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(Oak Ridge National Laboratory)

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