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)
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

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

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

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
Goal

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

Shear strain:
\[ \gamma = \frac{\lambda}{\cos \alpha} + \frac{1}{\lambda \cos \alpha} - 2 \tan \alpha \]

Well-characterized deformation:
- \( \gamma = 1 \) to 20 in a single pass
- \( \dot{\varepsilon} \) up to ~10^5 s\(^{-1}\)
Grain Refinement
(As in Other Severe Plastic Deformation (SPD) Process)

Shear strain, $\gamma = 3$

Grain size $\sim 90$ nm

Shankar et al., Acta Mater. 54 (2006) 3691-3700
Large Strain Extrusion Machining

Shear strain, \[ \gamma = \frac{\lambda}{\cos (\alpha)} + \frac{1}{\lambda \cos (\alpha)} - 2 \tan (\alpha) \]
Starting Material: Bulk Mg AZ31B (Wrought tooling plate from ThyssenKrupp, NA Inc.)

- Optical micrograph
- EBSD IPF map

Measured

Grain size:
16 ±2 μm

Hardness:
58 ±3 kg/mm²

Reference Properties

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel to rolling direction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed</td>
<td>255</td>
<td>150</td>
<td>21</td>
</tr>
<tr>
<td>Hard rolled</td>
<td>290</td>
<td>220</td>
<td>15</td>
</tr>
<tr>
<td>Perpendicular to rolling direction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed</td>
<td>270</td>
<td>170</td>
<td>19</td>
</tr>
<tr>
<td>Hard rolled</td>
<td>295</td>
<td>235</td>
<td>19</td>
</tr>
</tbody>
</table>

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

Unresolved grain structure through optical microscopy. EBSD in progress.

Cutting ratio, $\lambda$

Increasing shear strain, $\gamma$
Hardness of LSEM AZ31B
(Effect of Temperature and Cutting Ratio)

Cutting ratio, $\lambda$

Increasing shear strain, $\gamma$

~2x Hardness
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
Texture Development

✓ Substantially different textures → Improved formability

Bulk Plate

LSEM Strip

CD = cutting direction
Texture Development
Effect of LSEM Process Parameters

Low deformation temperature LSEM strip textures

- \( \lambda = 0.5 \)
- \( \lambda = 0.7 \)
- \( \lambda = 1.0 \)

High deformation temperature LSEM strip textures

- \( \lambda = 0.7 \)
- \( \lambda = 1.2 \)
### AZ31B Tensile Properties (LSEM Strip vs. Conventional Wrought Products)

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2% Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSEM AZ31B Strip (2.5 mm) (Miniature Tensile)</td>
<td>140</td>
<td>264</td>
<td>24</td>
</tr>
<tr>
<td>AZ31B Sheet Annealed*</td>
<td>150</td>
<td>255</td>
<td>22</td>
</tr>
<tr>
<td>AZ31B Extrusion*</td>
<td>200</td>
<td>255</td>
<td>12</td>
</tr>
</tbody>
</table>

*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

![Diagram showing grain size (microns) vs strip thickness (mm) for Bulk wrought alloy, Initial LSEM, Latest LSEM, and Future LSEM.](image-url)
Comparative Mg Sheet Cost Estimates

CONVENTIONAL

<table>
<thead>
<tr>
<th>Method</th>
<th>Capital+Tool</th>
<th>Energy</th>
<th>Labor</th>
<th>Metal</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Chill Casting</td>
<td>3.80</td>
<td>0.50</td>
<td>2.30</td>
<td>3.30</td>
<td>3.80</td>
</tr>
<tr>
<td>Twin Roll Casting</td>
<td>2.89</td>
<td>0.50</td>
<td>2.00</td>
<td>2.89</td>
<td>2.89</td>
</tr>
<tr>
<td>Twin Belt Casting</td>
<td>3.30</td>
<td>0.50</td>
<td>2.00</td>
<td>3.30</td>
<td>3.30</td>
</tr>
</tbody>
</table>

LSEM

<table>
<thead>
<tr>
<th>Method</th>
<th>Capital+Tool</th>
<th>Energy</th>
<th>Labor</th>
<th>Metal</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSEM</td>
<td>2.92</td>
<td>0.50</td>
<td>2.00</td>
<td>2.92</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Cost Modeling
by Dr. Sujit Das
(Oak Ridge 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:
Inventor(s): S. Chandrasekar; K. Trumble; W. Moscoso; M. Efe; D. Sagapuram; C.J. Saldana; J.B. Mann; & W.D. Compton.

PUBLICATIONS


PRESENTATIONS

Outline

- Project Overview
- Goal and Objectives
- Milestones
- Technical Approach
- Results and Accomplishments
- Future Work
- Summary
- Publications/Presentations
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°C for LSEM processing, \( \lambda = 0.5, 0.7, \) 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

All Dimensions shown in millimeters.

Schematic of specimen removal location
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 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)