The Deformation Behavior of Rare-earth Containing Mg Alloys

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This work was supported by the NSF Division of Material Research “Materials World Network” (Grant No. DMR1107117).

Our Lab and Equipment

Website:
http://www.egr.msu.edu/~boehlert/GROUP/

Scanning Electron Microscope
- Backscatter Electron detector.
- EDS detector.
- EBSD detector.

Metallography lab

In-situ stage
- Screw driven.
- Tension/compression.
- Heater (~800°C).
- Cooling system.
Magnesium

*The size of the circle corresponds to the density of the material

https://www.wikipedia.org/
http://www.cvmminerals.com/images/table.jpg
Advantages

- Mg is the lightest structural metal (1.7 g/cc).
  - 35% lighter than Al (2.7 g/cc).
  - Over four times lighter than steel (7.9 g/cc).

- High specific strength and stiffness compared to other engineering materials.

- Mg is plentiful.
  - Eight most common element on earth; third most abundant metal. (each cubic meter of sea water contains ~1.3 kg Mg).
  - The ores are found in most countries.

History

1940s: Northrop XP-56
(First airplane nearly completely designed with Mg)

1960s: Titan I rocket
(~1100 lbs Mg sheet)

1950s: B-36 Bomber
(Contained ~19000 lbs of Mg)

1930s: VW Beetle
(~20 kg of Mg; Mg crankcase and transmission housing)

Applications

- **Automotive industry** (powertrain, body parts, chassis, etc.)
- **Electronic devices** (laptop cases, etc.)
- **Sporting goods** (bicycle frame, etc.)
- **Aerospace** (transmission, etc.)
- **Hand-held working tools**
- **Biomedical applications**

Why Light-weighting?

The White House
Office of the Press Secretary
For Immediate Release
August 28, 2012

Obama Administration Finalizes Historic 54.5 MPG Fuel Efficiency Standards

WASHINGTON, DC — The Obama Administration today finalized fuel economy standards for cars and light trucks that will save American consumers comparable to losing a week’s salary, cut oil consumption by 12 billion barrels, and reduce greenhouse gas emissions by a billion metric tons.

These fuel standards represent the single most important step we can take to reduce our dependence on foreign oil, said President Obama. This historic agreement will save families money at the pump and cut our oil consumption nearly 25 miles per gallon, almost double what they would have been if we had simply maintained our current course.

The historic standards issued today by the U.S. Department of Transportation and the Environmental Protection Agency (EPA) build on the success of the standards that were put in place a few years ago. Those standards, which are already saving families money at the pump, will increase fuel efficiency nearly 10 miles per gallon by 2016.

EPA issues new fuel-efficiency standard; Autos must average 54.5 mpg by 2025
By Juliet Eilperin, Published: August 28, 2012 E-mail the writer

The Obama administration announced strict new vehicle fuel-efficiency standards Tuesday, requiring that the U.S. auto fleet average 54.5 miles per gallon by 2025, an uncontroversial move that, unlike other administration energy policies, was endorsed by industry and environmentalists alike.

LaHood and Environmental Protection Agency Administrator Lisa Jackson said the standards establish a new reality for American drivers. "The times they are a-changing," Jackson said.

The standards, which will take effect in 2017, are expected to save millions of barrels of oil and billions of dollars to American drivers over the years. They will significantly improve fuel economy of cars and light trucks, reducing fuel consumption by an estimated 13 percent compared to 2012 levels.

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Why Light-weighting?

- For every 10% of weight reduction, the fuel economy improves by 6.6-8%.
  - Weight reduction of 100 kg represents a fuel saving of about 0.5 l / 100 km for a vehicle.

- Every kg of weight reduced in a vehicle, results in ~20 kg of CO₂ reduction.

Why Mg is Attractive to Auto Industry?

22% to 70% weight reduction is possible for automotive components by using Mg alloys instead of alternative materials.

Life cycle inventory study on Mg alloy substitution suggests decrease in total energy consumption and CO$_2$ emissions.

Physical Properties of Mg

- Mg has hexagonal close-packed (HCP) structure at RT and atmospheric pressure.
  - Typical lattice parameters: \( a = 0.32 \text{ nm} \) & \( c = 0.52 \text{ nm} \)
    - \( c/a \) ratio = 1.624
  - The non-symmetric HCP structure partly complicates the mechanical and physical properties of Mg and its alloys (unlike steel or Al which has highly symmetric cubic structure).

Common Deformation Modes

**Slip**
- Basal <a> slip \{0001\}<1-210>
- 1st order prismatic <a> slip \{-1100\}<11-20>
- 2nd order pyramidal <c+a> slip \{-12-12\}<1-213>
- Extension twin \{01-12\}<0-111> 86° @ <11-20>
- Contraction twin \{01-11\}<01-1-2> 56° @ <11-20>

**Twin**

Schmid Factor & Critical Resolved Shear Stress (CRSS)

Shear stress is required to move dislocations.

Component of force in slip direction: \( F \cos \lambda \)

Area of slip surface: \( \frac{A}{\cos \Phi} \)

Resolves shear stress on the slip plane in the slip direction:

\[
\tau = \frac{F \cos \Phi \cos \lambda}{A} = \sigma \cos \Phi \cos \lambda
\]

\( \cos \Phi \cos \lambda = \text{Schmid factor.} \)

Schmid law: slip happens when resolved shear stress is greater than a critical value. So, systems with high Schmid factor are more likely to be active.

E. Schmid and W. Boas, Kristalplas (Plasticity of Crystals) (Berlin and London: Springer and Hughes, 1950)
Challenges for Mg Use

• Anisotropic material properties.

• Low elevated temperature strength.

• Limited cold formability:
  – Extension twinning and basal slip (provides only 2 independent deformation modes) are easily activated at RT.
  – According to Von Mises criterion at least 5 independent modes are required for homogeneous deformation of polycrystals.
  – Normally processed at 300-450°C to activate more deformation modes.

CRSS Vs. Temperature for different deformation modes.

Challenges – Texture Formation

- Conventional alloys: strong texture formation during wrought processing (Eg: Mg-9Al-1Zn (wt%)).

Schematic representation of texture formation in conventional alloys.

- The strong texture formation can be inhibited by dilute RE additions (Eg: Ce, Y, Gd, Nd).

Nd was shown to be a stronger texture modifier compared to other RE elements (Ce, Y) in Mg-Mn alloys.

0001 pole figure showing strong basal texture in rolled Mg-3Al-1Zn (wt%).

0001 pole figure showing weak random texture in extruded Mg-1Mn-1Nd (wt%).

Goals

• To understand why Nd additions inhibit Texture Formation in Mg alloys.
• Understand the effect of Nd on the deformation behavior, mechanical properties and microstructural evolution.
• Optimize the Nd content and microstructure for Structural Applications.

• The following alloys are part of my study (*All compositions are in wt%):
  – Extruded Mg-1Mn-1Nd (two extrusions)
  – Extruded Mg-1Mn-0.3Nd
  – Extruded Mg-1Mn
  – Cast Mg-1Mn-1Nd
  – Cast Mg-1Mn-0.3Nd
**In-Situ** Characterization Technique

**In-situ** uniaxial testing using a screw driven stage inside a SEM + EBSD analysis

A specially-designed specimen was used along with an Ernest Fullam Tensile Stage to perform *in-situ* tensile and compression experiments. SE SEM images were acquired *during* the deformation. EBSD orientation maps were acquired before and after the tensile tests.
Slip Trace Analysis

-secondary electron (SE) SEM images

-Loading direction

<table>
<thead>
<tr>
<th>Schmid Factor</th>
<th>Slip System</th>
<th>Plane/direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>3</td>
<td>(0001)[-1-120]</td>
</tr>
<tr>
<td>0.41</td>
<td>7</td>
<td>(11-2-2)[-1-123]</td>
</tr>
<tr>
<td>0.40</td>
<td>8</td>
<td>(-12-12)[1-213]</td>
</tr>
<tr>
<td>0.40</td>
<td>12</td>
<td>(2-1-12)[-2113]</td>
</tr>
<tr>
<td>0.22</td>
<td>2</td>
<td>(0001)[-12-10]</td>
</tr>
<tr>
<td>0.21</td>
<td>1</td>
<td>(0001)[-2110]</td>
</tr>
<tr>
<td>0.21</td>
<td>9</td>
<td>(-2112)[-1-13]</td>
</tr>
<tr>
<td>0.20</td>
<td>11</td>
<td>(1-212)[-12-13]</td>
</tr>
<tr>
<td>0.11</td>
<td>5</td>
<td>(10-10)[1-210]</td>
</tr>
<tr>
<td>0.11</td>
<td>4</td>
<td>(01-10)[-2-1-10]</td>
</tr>
<tr>
<td>0.02</td>
<td>10</td>
<td>(-1-122)[11-23]</td>
</tr>
<tr>
<td>0.00</td>
<td>6</td>
<td>(-1100)[11-20]</td>
</tr>
</tbody>
</table>

-Euler angle: 199.271 66.071 168.56

-Generated slip traces

-3 – Basal slip (0001)[-1-120] Schmid factor 0.44
Twin Trace Analysis

Secondary electron (SE) SEM images

Undeformed  2.7% strain  6% strain

EBSD map

- Unit cell rotation

Loading direction

Euler angle:
59.207  59.304  287.98

5 – extension twin
(0 -1 1 2)<0 1 -1 1>
Schmid factor 0.33
Rotation across
twin boundary:
83.1° about [-2 1 1 0]
The load drops indicate the stress relaxation that occurred when the experiment was paused and SE SEM photomicrographs were acquired. The strength values decreased with increasing temperature. Mg-1Mn-0.3Nd (wt%) exhibited greater strength than Mg-1Mn-1Nd (wt%) at RT.
Deformation Mode Distribution @ 50°C

**Mg-1Mn-1Nd (wt%)**

Number of observations: 42
- Extension twin: 13 nos
- Pyramidal <c+a>: 6 nos
- Prismatic <a>: 2 nos
- Basal <a>: 21 nos

**Mg-1Mn-0.3Nd (wt%)**

Number of observations: 9
- Extension twin: 8 nos
- Contraction twin: 1 nos

![Schmid Factor distribution](image)
Deformation Mode Distribution @ 150°C

**Mg-1Mn-1Nd (wt%)**

Number of observations: 49
- Extension twin: 3 nos
- Pyramidal <c+a>: 3 nos
- Prismatic <a>: 14 nos
- Basal <a>: 29 nos

**Mg-1Mn-0.3Nd (wt%)**

Number of observations: 7
- Extension twin: 1 nos
- Contraction twin: 1 nos
- Basal <a>: 5 nos

![Graph showing Schmid Factor distribution for Mg-1Mn-1Nd](image1)

![Graph showing Schmid Factor distribution for Mg-1Mn-0.3Nd](image2)
Deformation Mode Distribution @ 250°C

Mg-1Mn-1Nd (wt%)

Number of observations: 119
Pyramidal <c+a> 10 nos
Prismatic <a> 4 nos
Basal <a> 105 nos

Mg-1Mn-0.3Nd (wt%)

Number of observations: 33
Pyramidal <c+a> 1 nos
Prismatic <a> 4 nos
Basal <a> 28 nos

Schmid Factor distribution

Number of Slip Traces or Twins Observed in all of the Grains Analyzed

0.05-0.1 0.15-0.2 0.25-0.3 0.35-0.4 0.45-0.5
pyramidal <c+a> 9%
prismatic <a> 3%
basal <a> 88%
CRSS Ratio Estimation Methodology

Initial microstructure

Experimentally observed distribution

### Estimated CRSS Ratios

For Mg-1Mn-1Nd (wt%) extrusions at 50°C:

<table>
<thead>
<tr>
<th>Material/Testing condition</th>
<th>Prismatic &lt;a&gt; Basal &lt;a&gt;</th>
<th>Pyramidal &lt;c+a&gt; Basal &lt;a&gt;</th>
<th>Extension twinning Basal &lt;a&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion 1*</td>
<td>12.6 (3.1, 30.4)</td>
<td>12.2 (0.6, 40.0)</td>
<td>0.6 (0.2, 1.4)</td>
</tr>
<tr>
<td>Extrusion 2*</td>
<td>11.0 (3.4, 18.7)</td>
<td>875.9 (29.8, 4033.5)</td>
<td>0.8 (0.3, 1.5)</td>
</tr>
</tbody>
</table>

The mean CRSS ratios and the corresponding 90% confidence intervals (listed in parenthesis) for prismatic <a> slip, pyramidal <c+a> slip and extension twinning estimated using the deformation results at 50°C.

*Extrusion 1 was extruded at 300°C and extrusion 2 at 275°C.
What we have learned thus far...

- Higher Nd content results in better high temperature strength retention in Mg-1Mn (wt%).
- More than 0.3 wt% Nd is needed to inhibit the conventional extrusion texture which causes anisotropic behavior.
- The estimated CRSS ratios suggest that Nd addition to Mg-1Mn (wt%) results in an increase of the CRSS for basal slip.
- Overall, Nd-containing Mg alloys show promise for automobile applications.
- Mg alloys have a bright future and are here to stay!
Thank you for your attention!