Crashworthiness Evaluation of Empty and Foam-Filled AZ31B Magnesium Beams under Three-Point Bending

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Presenter:
Mr. Marc Hampel
Outline

- Introduction
- Motivation
- Material testing and characterization
- Three-point bending: experiment
- Three-point bending: simulation
- Conclusion and future work
DLR overview

- DLR’s mission
  - exploration of the Earth and the solar system
  - research aimed at protecting the environment
  - development of environmentally-friendly technologies to promote mobility, communication and security.

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- **Institute director:** Prof. Dr.-Ing. Horst E. Friedrich

- Orientation and research fields:
  - Road vehicle concepts
  - Rail vehicle concepts
  - Alternative power train
  - Lightweight vehicle construction

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Introduction

Magnesium Alloys:

- At room temperature Magnesium has only 2.5 active slip systems but to satisfy Taylor criterion 5 is needed.
- Twinning offers another independent deformation system under compression load, which has a limited strain accommodation capability and leads to tension-compression asymmetry.

Basic material properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.78 g/cm³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>45 GPa</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>17 Gpa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.35</td>
</tr>
</tbody>
</table>

(Twinnning (Source: Dariush Ghaffari Tari))
Introduction

**AZ31B: Magnesium-Aluminium-Zinc Alloy**

<table>
<thead>
<tr>
<th></th>
<th>Mg</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Ca</th>
<th>Cu</th>
<th>Fe</th>
<th>Ni</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norminal Composition wt.%</td>
<td>Bal.</td>
<td>2.5-3.5</td>
<td>0.6-1.4</td>
<td>0.2-1.0</td>
<td>&lt;0.04</td>
<td>&lt;0.05</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

- Strong orientation **anisotropy** is formed during rolling and extrusion processes
- Strong **tension-compression asymmetry**
- **Poor ductility** at room temperature
Automotive application for magnesium

- Main application are casting parts
- Not used as main energy absorbing structures
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- Three-point bending: simulation
- Conclusion and future work
Motivation

POLE IMPACT
left-hand drive vehicles
veicoli con guida a sinistra

Source: www.euroncap.com

Rocker rails

Source: Master thesis from M. Wongwatanyou

Simplified

Basic profile

Foam 0.4 g/cm³, 6.0 m/s
Motivation

- Stabilization of cross section
- Energy absorption through material elongation

Bar chart showing specific energy absorption (SEA) and energy absorption for different beams:
- Empty steel beam: SEA 146 J/kg, Energy absorption 1.8 kJ
- Foam-filled steel beam: SEA 507 J/kg, Energy absorption 10.78 kJ
- Empty Mg beam
- Foam-filled Mg beam

(a) Schematic view of testing setup
(b) Testing system
Outline

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- Three-point bending: experiment
- Three-point bending: simulation
- Conclusion and future work
Material testing and characterization

- Q-S uniaxial tensile and compressive tests of Mg AZ31B
Material testing and characterization

- Q-S uniaxial tensile and compressive tests of Mg AZ31B

Results and discussion

- AZ31B extrusion exhibits higher anisotropy of yield strength (≈120 MPa strength difference in tension) and total elongation (≈4% elongation difference in tension).
- AZ31B sheet exhibits lower anisotropy of yield strength in both tension and compression.
- Pronounced tension-compression asymmetry.
- Very high strain hardening rate under compression load.
- AZ31B sheet is stronger but similarly ductile in both tension and compression.
Material testing and characterization

- High speed uniaxial tensile tests

![Graph showing stress-strain relationship with markers for approximately 50 MPa and 80 MPa stress levels.](image)
Outline

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- Three-point bending: simulation
- Conclusion and future work
Three-point bending: experiment

- Testing facility

DLR-FK quasi-static component crush platform

DLR-FK dynamic component crash platform
Three-point bending: experiment

- **Design of experiment**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Shell material</th>
<th>Foam</th>
<th>Mass (kg)</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SES</td>
<td>Steel DC04, T2.0</td>
<td>Empty</td>
<td>12.35</td>
<td>0.06</td>
</tr>
<tr>
<td>S20S</td>
<td>Steel DC04, T2.0</td>
<td>0.20 g/cm³</td>
<td>16.92</td>
<td>0.06</td>
</tr>
<tr>
<td>S40S</td>
<td>Steel DC04, T2.0</td>
<td>0.40 g/cm³</td>
<td>21.15</td>
<td>0.06</td>
</tr>
<tr>
<td>S40D</td>
<td>Steel DC04, T2.0</td>
<td>0.40 g/cm³</td>
<td>21.15</td>
<td>6.0</td>
</tr>
<tr>
<td>XES</td>
<td>Mg AZ31B-F, T3.0</td>
<td>Empty</td>
<td>4.32</td>
<td>0.06</td>
</tr>
<tr>
<td>XED</td>
<td>Mg AZ31B-F, T3.0</td>
<td>Empty</td>
<td>4.32</td>
<td>2.0</td>
</tr>
<tr>
<td>X30S</td>
<td>Mg AZ31B-F, T3.0</td>
<td>0.30 g/cm³</td>
<td>11.35</td>
<td>0.06</td>
</tr>
<tr>
<td>X30D</td>
<td>Mg AZ31B-F, T3.0</td>
<td>0.30 g/cm³</td>
<td>11.35</td>
<td>4.5</td>
</tr>
<tr>
<td>MED</td>
<td>Mg AZ31B-O, T1.8</td>
<td>Empty</td>
<td>2.73</td>
<td>2.0</td>
</tr>
<tr>
<td>M05D</td>
<td>Mg AZ31B-O, T1.8</td>
<td>0.05 g/cm³</td>
<td>3.75</td>
<td>2.0</td>
</tr>
<tr>
<td>M20D</td>
<td>Mg AZ31B-O, T1.8</td>
<td>0.20 g/cm³</td>
<td>7.70</td>
<td>3.5</td>
</tr>
<tr>
<td>M30D</td>
<td>Mg AZ31B-O, T1.8</td>
<td>0.30 g/cm³</td>
<td>9.58</td>
<td>3.5</td>
</tr>
</tbody>
</table>

- **Empty and foam-filled steel beams**
- **Empty and foam-filled magnesium extruded beams**
- **Empty and foam-filled magnesium sheet beams**

- Hollow profile
- Fully foam-filled profile

Polyurethane foam filling
Three-point bending: experiment

- Deformation modes of steel beams

- Empty, 60 mm/s
- Foam 0.2 g/cm³, 60 mm/s
- Foam 0.4 g/cm³, 60 mm/s
- Foam 0.4 g/cm³, 6.0 m/s
Three-point bending: experiment

- Deformation modes of Mg AZ31B extruded beams

<table>
<thead>
<tr>
<th>Condition</th>
<th>Images</th>
</tr>
</thead>
</table>
| Empty, 60 mm/s        | ![Image 1](image1.jpg)  
  Empty, 2.0 m/s       | ![Image 2](image2.jpg)  
| Foam 0.3 g/cm³, 60 mm/s | ![Image 3](image3.jpg)  
  Foam 0.3 g/cm³, 4.5 m/s | ![Image 4](image4.jpg)  

*Note: Images show different deformation modes under varying conditions.*
Three-point bending: experiment

- Deformation modes of Mg AZ31B extruded beams
Three-point bending: experiment

- Deformation modes of Mg AZ31B sheet beams

Empty, 2.0 m/s

Foam 0.05 g/cm³, 2.0 m/s

Foam 0.2 g/cm³, 3.5 m/s

Foam 0.3 g/cm³, 3.5 m/s
Three-point bending: experiment

- Deformation modes of Mg AZ31B sheet beams
Three-point bending: experiment

- Force-deflection curves

- Bending force of the beams was significantly increased through foam-filling. Higher foam density, higher bending force.
- Higher bending force under dynamic loads, but not significant for the foam-filled Mg AZ31B extruded beams (i.e. X30S vs X30D).
- Mg beams tended to fracture earlier compared with the steel beams due to the low ductility of magnesium alloys. Higher foam density, earlier fracture.
### Three-point bending: experiment

#### Specific energy absorption capacity

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Spec. Energy Absorption [J/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SES</td>
<td>146</td>
</tr>
<tr>
<td>S20S</td>
<td>314</td>
</tr>
<tr>
<td>S40S</td>
<td>507</td>
</tr>
<tr>
<td>S40D</td>
<td>543</td>
</tr>
<tr>
<td>XES</td>
<td>315</td>
</tr>
<tr>
<td>XED</td>
<td>351</td>
</tr>
<tr>
<td>X30S</td>
<td>589</td>
</tr>
<tr>
<td>X30D</td>
<td>606</td>
</tr>
<tr>
<td>MED</td>
<td>321</td>
</tr>
<tr>
<td>M05D</td>
<td>329</td>
</tr>
<tr>
<td>M20D</td>
<td>612</td>
</tr>
<tr>
<td>M30D</td>
<td>333</td>
</tr>
</tbody>
</table>

**Steel Sheet Beam**

**Mg Extruded Beam**

**Mg Sheet Beam**

- The SEA of these beams except M05D and M30D was significantly improved through PUR foam filling.
- Mg AZ31B outperforms steel DC04 in terms of SEA for empty thin-walled beams under bending loads.
- The outperformance of Mg AZ31B is limited due to the premature fracturing.

- M20D vs S20S: M20D achieved nearly 2.9 times higher SEA than S20S, although M20D was 54% lighter than S20S and even 38% lighter than SES.
- Mg AZ31B may significantly outperform steel DC04 for foam-filled thin-walled beams for limited deformation.
Three-point bending: simulation

- Principle material properties of Mg AZ31B

Three-point bending: simulation

- Material models for metals in LS-DYNA

<table>
<thead>
<tr>
<th>Model</th>
<th>Function</th>
<th>Plastic anisotropy</th>
<th>Hardening rule</th>
<th>Tension-compression asymmetry</th>
<th>Strain rate sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT_024</td>
<td>von Mises</td>
<td></td>
<td>Isotropic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT_124</td>
<td>von Mises</td>
<td></td>
<td>Isotropic</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MAT_103</td>
<td>Hill1948</td>
<td>✓</td>
<td>Isotropic + Kinematic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT_242</td>
<td>Barlat-8P</td>
<td>✓</td>
<td>Isotropic + Kinematic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT_233</td>
<td>Cazacu-Plunkett-Barlat (CPB2006)</td>
<td>✓</td>
<td>Isotropic</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>MAT_107</td>
<td>Johnson-Cook</td>
<td></td>
<td>Isotropic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT_120</td>
<td>Gurson</td>
<td></td>
<td>Isotropic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- MAT_124 was adopted because tension-compression asymmetry is the predominant feature for magnesium alloy AZ31B.
- To consider fracture, we used the keyword *MAT_EROSION and failure criterion based on the max. principle strain.
- For the PUR foams, *MAT_MODIFIED_CRUSHABLE_FOAM was adopted.
Three-point bending: simulation

- FE simulation of empty beams using LS-DYNA

Very good correlation

Very good correlation

General good correlation
Three-point bending: simulation

- FE simulation of foam-filled beams using LS-DYNA

Very good correlation

Very good correlation

Very good correlation
Three-point bending: simulation

- Energy absorption capacity: Test vs Simulation

Max. correlation error is less than 14%
Conclusion

• Mg AZ31B extrusion and sheet exhibit significant anisotropy, strain rate sensitivity, tension-compression asymmetry and low ductility at room temperature

• Mg AZ31B outperforms steel DC04 in terms of SEA for empty thin-walled beams under bending loads

• But this outperformance of Mg AZ31B is limited due to the premature fracturing

• Mg AZ31B may significantly outperform steel DC04 for foam-filled thin-walled beams in the applications where only limited deformation is required

• Material model MAT_124 with calibrated material parameters may yield good simulation results (deformation patterns, force-deflection curves and energy absorption) for the magnesium beams subjected to bending loads
Thank you for your attention!