Magnesium Makes High-speed Train Lightweight

Ruichun LI, Gaofeng QUAN
Vice-Chief Engineer/Professor Senior Engineer, R & D Center, Changchun Railway Vehicles Co., Ltd, China
12 July 2012, Session: Rolling Stock 1 - Design & Manufacturing 1
Content

- Part 1: Requirements of Weight Reduction in Rolling Stocks
- Part 2: Comparison on performance of Mg- and Al-alloys
- Part 3: Perspective Light-weight Car body Structure from Mg Alloys
- Part 4: Effectiveness of Weight Reduction by Application of Mg-alloys
- Part 5: Strategy aspects of development
- Part 6: Ordinary inner decoration made of Mg alloys - examples
Requirements of Weight Reduction in Rolling Stocks

- **Developing Trend of High Speed Railway**
  - Smart High speed rail net and system
    - Smart cars and marshalling: light-weight cars make easy to management
  - Efficient and energy saving
    - Improving electric & driving efficient of the power system
    - Reduction in weight of rolling stocks

- **Weight Reduction Strategy**
  - Improve design and fabricating technology
    - Hollow profiles + Advanced welding (FSW)
  - New materials for car body
    - Magnesium alloys, New polymers
Comparison of Performance of Mg- and Al-alloys-1

- **General advantages and disadvantages**
  - Density: $d_{\text{Mg}}=1.8$ | $d_{\text{Al}}=2.8$ ⇒ Specific Strength: $\alpha_{\text{Mg}}=\sim 200$ | $\alpha_{\text{Al}}=\sim 160$
  - Elastic Modulus: $E_{\text{Mg}}=45$ | $E_{\text{Al}}=70$ ⇒ Specific rigidity: $\beta_{\text{Mg}}=25$ | $\beta_{\text{Al}}=25$

- **Utility property**
  - Forming and processing
    - Mg: best castability; good forgebility, good weldability
  - Durability and use security
    - Safe applied in aircrafts and automobile over 60 years

### Table: Performance Comparison of Mg- and Al-alloys

<table>
<thead>
<tr>
<th>Mark</th>
<th>Heat treatment</th>
<th>Rp$_{0.2}$/MPa</th>
<th>Rm/MPa</th>
<th>A/%</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg-alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ31B</td>
<td>H112</td>
<td>160-200</td>
<td>280-320</td>
<td>14-21</td>
<td>Sheet</td>
</tr>
<tr>
<td>AZ80</td>
<td>T6</td>
<td>180-250</td>
<td>250-320</td>
<td>6-12</td>
<td>Sheet</td>
</tr>
<tr>
<td>ZK60</td>
<td>T6</td>
<td>305-350</td>
<td>365-410</td>
<td>11-15</td>
<td>Sheet</td>
</tr>
<tr>
<td>5083</td>
<td>O, H111</td>
<td>125-200</td>
<td>275-350</td>
<td>12-15</td>
<td>Sheet</td>
</tr>
<tr>
<td>6005A</td>
<td>T6</td>
<td>200-225</td>
<td>250-270</td>
<td>6-8</td>
<td>Section</td>
</tr>
<tr>
<td>7005</td>
<td>T6</td>
<td>270-290</td>
<td>340-350</td>
<td>8</td>
<td>Section</td>
</tr>
<tr>
<td>Al-alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5083</td>
<td>H111</td>
<td>125-200</td>
<td>275-350</td>
<td>12-15</td>
<td>Sheet</td>
</tr>
<tr>
<td>6005A</td>
<td>T6</td>
<td>200-225</td>
<td>250-270</td>
<td>6-8</td>
<td>Section</td>
</tr>
<tr>
<td>6082</td>
<td>T6</td>
<td>250-260</td>
<td>290-310</td>
<td>6-8</td>
<td>Section</td>
</tr>
<tr>
<td>7005</td>
<td>T6</td>
<td>270-290</td>
<td>340-350</td>
<td>8</td>
<td>Section</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mark</th>
<th>Temper</th>
<th>Rp$_{0.2}$/MPa</th>
<th>Rm/MPa</th>
<th>$\alpha_{\text{W/B Mg}}$</th>
<th>$\alpha_{\text{W/B TIG}}$</th>
<th>$\alpha_{\text{W/B FSW}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg-alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ31B</td>
<td>H112</td>
<td>160-200</td>
<td>280-320</td>
<td>94</td>
<td>95-97</td>
<td>92</td>
</tr>
<tr>
<td>AZ80</td>
<td>T5</td>
<td>267</td>
<td>350</td>
<td>72</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>ZK60</td>
<td>T6</td>
<td>305-350</td>
<td>365-410</td>
<td>11-15</td>
<td>72</td>
<td>94</td>
</tr>
<tr>
<td>5083</td>
<td>H111</td>
<td>125-200</td>
<td>275-350</td>
<td>12-15</td>
<td>90</td>
<td>93</td>
</tr>
<tr>
<td>6005A</td>
<td>T6</td>
<td>200-225</td>
<td>250-270</td>
<td>6-8</td>
<td>75</td>
<td>93</td>
</tr>
<tr>
<td>6082</td>
<td>T6</td>
<td>250-260</td>
<td>290-310</td>
<td>6-8</td>
<td>67</td>
<td>83</td>
</tr>
<tr>
<td>7005</td>
<td>T6</td>
<td>270-290</td>
<td>340-350</td>
<td>8</td>
<td>71</td>
<td>78</td>
</tr>
<tr>
<td>7020</td>
<td>T6</td>
<td>348</td>
<td>395</td>
<td>77</td>
<td>78</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of Performance of Mg- and Al-alloys-2

Fuel saving effects

Up: price per mass
Down: per volume
(Based on data from 2009)
Perspective Light-weight Car body Structure from Mg Alloys:

1. highest level aim: car body structure

- **Technological aspect**
  - Stiffness & Strength design - Numerical method + Physical model
  - Procedure design - Key structure → infrastructure → module purchase ordering system
  - Materials and fabrication
    - Car body profiles from High strength Mg alloys, e.g. AZ80RE
    - FSW-a certificated solid weld technique, at least longitudinal weldment
    - Surface protection

- **Assessments**
  - Mechanical feature - Fatigue, vibration, crash
  - Durability, economy

- **Progress status**
  - China patent, Mg Alloy track car body and fabrication, ZL20101002323.6, 2011
Perspective Light-weight Car body Structure from Mg Alloys

2. Design criterion: Iso-Stiffness

- Under an “so-stiffness“ criterion [1]:

- Thickness of wall ratio: 
  \[ \frac{t_{Mg}}{t_{Al}} = \frac{3}{\sqrt{\frac{E_{Al}}{E_{Mg}}}} \]

- According to \( t_{Mg} / t_{Al} \), the mass ratio:
  \[ \frac{m_{Mg}}{m_{Al}} = (\frac{d_{Mg}}{d_{Al}})^{\frac{3}{2}} \sqrt{\frac{E_{Al}}{E_{Mg}}} \]

- t-wall thickness; E-elastic modulus; m-mass of the structure; d-density

- Thus, \( t_{Mg} / t_{Al} = 1.16 \) and \( m_{Mg} / m_{Al} = 0.772 \)

- Again the car body structure of Mg is 32.8% lighter than one of Al

- CRH3: Mg car body and others remain unchanged: the general weight reduction: 9%


Effectiveness of Weight Reduction by Application of Mg-alloys-1

- **Starting & Running resistance**
  - Start and stop aspect – electricity consumption: 
    
    \[ Q = n \times \frac{1}{2} M \times v^2 / (3.6^3 \times 1000) \]
    
    \( M \) - train mass (t), \( n \) - start and stop times, \( v \) - interval maximum speed (km/h)
  
  - Running aspect - Electricity consumption: 
    
    \[ Q = M \times \omega \times S \times 9.8 / 3600 \]
    
    \( \omega \) - is the train resistance, \( S \) is the running distance (km):

    \[ \omega = 11.4M + (0.025M + 17.86d)v + (0.17 + 0.0428N)dv^2 \]
    
    \( d \) - the air density (kg/m³), \( N \) - is the number of middle vehicles

<table>
<thead>
<tr>
<th>Speed Km/h</th>
<th>Train resistance kN</th>
<th>Energy consumption of single start and stop</th>
<th>Energy consumption of run aspect (Unit distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al alloy train</td>
<td>Mg alloy train</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>159.308</td>
<td>158.687</td>
<td>9.38%</td>
</tr>
<tr>
<td>380</td>
<td>97.097</td>
<td>96.554</td>
<td>9.38%</td>
</tr>
<tr>
<td>350</td>
<td>83.962</td>
<td>83.501</td>
<td>9.38%</td>
</tr>
<tr>
<td>300</td>
<td>64.440</td>
<td>63.949</td>
<td>9.38%</td>
</tr>
<tr>
<td>250</td>
<td>47.610</td>
<td>47.152</td>
<td>9.38%</td>
</tr>
<tr>
<td>200</td>
<td>33.536</td>
<td>33.110</td>
<td>9.38%</td>
</tr>
<tr>
<td>160</td>
<td>24.580</td>
<td>23.860</td>
<td>9.38%</td>
</tr>
<tr>
<td>120</td>
<td>16.747</td>
<td>16.373</td>
<td>9.38%</td>
</tr>
<tr>
<td>80</td>
<td>10.997</td>
<td>10.649</td>
<td>9.38%</td>
</tr>
</tbody>
</table>

The EMUs with Mg body in Beijing-Shanghai Passenger-Line would save 280 million kWh, reduce carbon emission 250 kt
Strategy aspects of development

- **highest level aim – long term struggle**
  - Car body by Mg alloys
  - Largest Light-weight Effectiveness

- **Secondary level aim – In effort**
  - Secondary force bearing structures as Skirtboard, sleeper-room unit structure and doors, etc.
  - With ca. 8544 kg weight reduction for an EMU train

- **Ordinary inner decoration made of Mg alloys – practical aim**
  - Sleeper framework and bed plank
  - Ventilating window
  - Honeycomb panel and honeycomb module for shock absorber
  - Floor of Honeycomb panel and frame with Mg profiles
Ordinary inner decoration made of Mg alloys - examples

Mg Berth, China patent ZL200710127585.3

Mg ventilating window-China Patent ZL201010100394.X, 2012.2.2

Mg Honeycomb structure and honeycomb panel, China patent ZL 200810011370.X, 2010.12.8

Mg honeycomb panel - sound insulation

AZ80 Mg-Vibration attenuation
Summary

- Mg alloys are the best candidate materials for lighter rolling stocks
- The highest level is Mg car body structure, that result in a car body weight reduction about 32%, and an electricity saving of 6.8%
- The second level is for secondary force bearing structures of car, that lead to a 8544 kg weight reduction
- The practical Mg use is inner parts and systems
...Thank you for your kind attention