Development of Aluminium Alloys for High Temperature Applications in Diesel Engines

- Overview of selected research activities -

CANMET Materials Technology Laboratory, Ottawa, Canada
(Program: Advanced Structural Materials for Next Generation Vehicles)

W. Kasprzak, M. Sahoo, D. Emadi

MDEC Conference 2009, Sheraton Parkway, Toronto North, Richmond Hill, October 4 - 9, 2009

Presentation Overview

- Introduction
  - Emissions in automotive sector
  - Strategies for emission reduction
    - Vehicle weight reduction
    - Innovations in manufacturing processes
  - Existing Al alloys for diesel engine components and requirements
    - Alloy survey
    - Performance challenges
  - Al Alloy development activities at CANMET-MTL
  - Energy efficient heat treatment strategies
  - New trends for engine casting’s performance improvement
**CO₂ Emissions Per Sector**

**Introduction**

- Passenger vehicles + light trucks: ~55% of transportation emissions

- Transportation sector: Heaviest contributor to GHG emissions

Source: NRCAN, Canada’s Energy Outlook: 1996 - 2020

**CO₂ Emissions for Various Vehicle Concepts and Car Makers**

**CO₂ Emissions per Different Car Concept**

Source: RHEINFELDEN Company, 2008

**CO₂ Emissions per Region**

Source: RHEINFELDEN Company, 2008

Auto manufacturers
Vehicle Weight Reduction for Improved Fuel Efficiency and CO₂ Reduction

Introduction

- Mileage of cars and light trucks sold in US must rise from current 25 to 35.5 mpg by 2016.
- Will be not enough to bring US in line with vehicles sold now in Japan and Europe.

Source: U.S Environmental Protection Agency (http://epa.gov)

Approx. 10% drop in weight
6-8% better fuel economy

Activities with Major Impact on Weight Reduction and CO₂ Emissions

Major Activities:
- Application of light weight alloys,
- Innovations in manufacturing process,
- Component design.

Reducing the weight of vehicle by 100kg results in:
- Reduces fuel consumption by 0.3 to 0.5l/100km,
- Extends the cruising range by 7.5%,
- Allows to reach 100km/h six (6) meters sooner,
- 8 to 11 less grams of hydrocarbon emission every kilometre,
- Active and passive safety improvement:
  - Quicker reaction to driver’s inputs,
  - Brings less energy to a crash.
Activities with Major Impact on Weight Reduction and CO₂ Emissions - cont.

1. Application of light weight alloys

**Chassis and body**

- **BMW Group**
  - **Technical Features**
  - **Intelligent Light Weight Construction**
    - Aluminum Hood
    - Magnesium Center for Instrument Panel
    - Cast Aluminum Front Side Tower
  - Intelligent use of Ultra High Strength Steel

100kg weight reduction
2-3% better fuel economy
3.5g/km CO₂ reduction

**Steel baseline design**
- 79 Parts & 84.3 kg

**Magnesium design**
- 35 Parts & 46.1 kg

38.2 kg mass reduction (45%)
44 part reduction (55%)

Source: US-Canada-China Collaborative R&D Project (MFERD), CANMET-MTL, 2009

**Powertrain**

- **3.0L V6 Engine Block (Al-6%Si-3%Cu alloy)**
  - Heat resistant Al Cylinder Head (Al-6%Si-3%Cu alloy)
  - Cast-in Iron Cylinder Liners
  - Liner-less Cylinder

- **Forged Al Piston (Al-11%Si-3%Cu-0.5%Mg alloy)**

30% Engine downsizing
10-15% less engine weight
10-20% less CO₂ emissions

Source: Natural Resources Canada, 2009
Activities with Major Impact on Weight Reduction and CO₂ Emissions - cont.


<table>
<thead>
<tr>
<th>Process</th>
<th>Duration, min</th>
<th>Improvement, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum HPDC</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Heat treatment (T6)</td>
<td>480</td>
<td>175</td>
</tr>
<tr>
<td>Machining Engine block</td>
<td>15.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Cylinder bore (honing)</td>
<td>15.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>


Introduction

Upcoming Diesel Cars in 2009/2010

Honda Accord Tourner Concept
- 2.2 liter i-DTEC diesel
- The i-DTEC technology is aimed at meeting Europe’s tougher Euro 6NOx regulations in 2014

BMW 335d
- Twin-turbo 3.0 liter in-line engine
- 23 mpg in the city and 33 mpg on the highway

Acura TSX Diesel
- New 2.2 liter i-DTEC four-cylinder clean diesel engine

Volkswagen Jetta TDI
- 2.0 liter four-cylinder turbo-diesel engine

Good evidence for alloy development activities

The aluminum alloys claimed to be used for gasoline and diesel engine cylinder heads:

**Category 1:**
- Al-Si-Mg alloys (ex: A356, A357)
  - (good ductility, lack of strength >250°C)

**Category 2:**
- Al-Si-Mg-Cu alloys (ex: A356 + 0.5% Cu)
  - (good ductility, retaining strength between 200-250°C)

**Category 3:**
- Al-Si-Mg-Cu alloys with Mn, Zr, V, Ti and Cr
  - (ex: A356+1%Cu+0.15%Zr+0.15%Cr and A319+0.15%Mn+0.25%V+0.15%Zr)
  - (lower ductility, higher YS and creep at 250°C)

**Limitations:**
Elevated operating temperature and internal pressure disqualify existing Al alloys for small, turbocharged, energy efficient automotive engines.

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**Alloy Castings for Engine Applications in Passenger Vehicles**

<table>
<thead>
<tr>
<th>Components</th>
<th>Engine Block</th>
<th>Cylinder Head</th>
<th>Piston</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy System</td>
<td>Al-Si-Mg-(?)</td>
<td>Al-Si-Mg-(?)</td>
<td>Al-Si-Cu-Ni-(?)</td>
</tr>
<tr>
<td>Operating Temp. (°C)</td>
<td>135</td>
<td>250</td>
<td>400</td>
</tr>
<tr>
<td>Operating Pressure (bar)</td>
<td>-</td>
<td>&gt;180</td>
<td>-</td>
</tr>
<tr>
<td>HCF (MPa)</td>
<td>180</td>
<td>140</td>
<td>&gt;200</td>
</tr>
<tr>
<td>Creep</td>
<td>-</td>
<td>44</td>
<td>-</td>
</tr>
<tr>
<td>SDAS (μm)</td>
<td>20</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Process</td>
<td>LPSP, HPDC</td>
<td>SPM</td>
<td>SPM, Forging</td>
</tr>
</tbody>
</table>

LPSP - Low Pressure Sand Package
SPM - Semi-Permanent Mold
HPDC - High Pressure Die Casting

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**Alloy Chemistries used for High Temperature Powertrain Applications (Passenger Vehicles)**

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R.Passo, M.S. Moreira, Fatigue Cracks in Aluminium Cylinder Heads for Diesel Engines, AFS 2009, 09-117
Alloy Chemistry Survey for Diesel Cylinder Heads (Passenger Vehicles)

### Existing Alloys

<table>
<thead>
<tr>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Europe 1998 Model)</td>
</tr>
<tr>
<td>(Europe 2003 Model)</td>
</tr>
<tr>
<td>(Asia 2005 Model)</td>
</tr>
</tbody>
</table>

#### Alloying Elements, %

<table>
<thead>
<tr>
<th>Element</th>
<th>Product A</th>
<th>Product B</th>
<th>Product C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>6.4</td>
<td>5.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Cu</td>
<td>3.2</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Mg</td>
<td>0.22</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>Zn</td>
<td>0.52</td>
<td>0.29</td>
<td>0.27</td>
</tr>
<tr>
<td>Fe</td>
<td>0.15</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>Ti</td>
<td>0.40</td>
<td>0.34</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>0.032</td>
<td>0.017</td>
<td>-</td>
</tr>
<tr>
<td>Ni</td>
<td>0.028</td>
<td>0.010</td>
<td>-</td>
</tr>
<tr>
<td>Cr</td>
<td>0.007</td>
<td>0.005</td>
<td>-</td>
</tr>
<tr>
<td>Sn</td>
<td>0.074</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Pb</td>
<td>0.40</td>
<td>0.34</td>
<td>-</td>
</tr>
<tr>
<td>Sr</td>
<td>0.40</td>
<td>0.29</td>
<td>-</td>
</tr>
<tr>
<td>V</td>
<td>0.01</td>
<td>0.04</td>
<td>-</td>
</tr>
<tr>
<td>Zr</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Strong popularity of conventional alloys (Al-Si-Cu-Mg)**

Development of the Al Alloy Chemical Compositions

R&D Activities

<table>
<thead>
<tr>
<th>Al Alloy chemistries under evaluation based on 356, 319, 390 grades with various addition levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>7 – 20</td>
</tr>
</tbody>
</table>

**Only compromise will lead to optimum alloy chemistry**
- Proper development of alloy chemical composition has a significant effect on mechanical properties at room and elevated temperatures.

- Increased Cu has a predominant effect on elevated mechanical properties up to 250ºC.
- Effect of Zr, V, Ti overlaps with Cu, Mg additions.
High Temperature Performance Assessment (Creep)

Stress levels for 0.1% elongation after 100hrs exposure for 356 based alloys tested in T7 condition

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Hardness (HR15T) Before Creep</th>
<th>Hardness (HR15T) After Creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>58</td>
<td>61</td>
</tr>
<tr>
<td>B</td>
<td>56</td>
<td>57</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>71</td>
</tr>
</tbody>
</table>

Additions of Zr, V, Ti improves creep performance due to formation of dispersoid phase

Microstructure Evaluation in the As-Cast Condition

The effect of Cu, Mg additions on incipient melting temperature

0% Mg - higher solution & better homogenization
**Alloy Phase Identification - Neutron Diffraction during Solidification Process**

**NRU Atomic Reactor**

NRU Reactor (Chalk River, Canada): Thermal neutron source (120MWh), Medium flux (~3 x 10^14/cm^2/s)

**Thermal-neutron spectrometers**

**Solidification Cell**

Neutron diffraction spectrum for Al-18%Si alloy obtained during solidification with ~1°C/s

**Improved signal resolution for more detailed solidification analysis**

W. Kasprzak, D. Sediako et al., Characterization of Hypereutectic Al-Si Alloys using In-Situ Neutron Diffraction and Thermal Analysis Techniques, TMS 2010

**Effect of Alloy Chemistry on Casting Dimensional Stability**

**Thermo-physical Properties**

<table>
<thead>
<tr>
<th>Alloying Element</th>
<th>Thermal Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu, Mg, Sc, Cr</td>
<td>⇑</td>
</tr>
<tr>
<td>Zr, V, Ti</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Length change between 100-500°C for various alloy chemistries

Heat treatment needs to be optimized to control stress development

Minimized residual stress for improved fatigue performance

**Zr** 2.06 (Å)

**Sc** 1.85

**Ti** 1.76

**V** 1.33

**Cr** 1.66

**Cu** 1.45

**Mg** 1.45

**Al** 1.18

**Si** 1.11
Effect of Alloy Chemistry on High Temperature Performance

Alloy: 356 base + Cu, Zr, V, Ti, Sc

Heat Treatment simulation using Quench Dilatometer

Over-aging temperature varies between 210-360°C depending from alloy chemistry

Effect of individual alloying elements on over-aging temperature - TBD
Energy Efficient Heat Treatment for Diesel Cylinder Head

Alloy: 319 (Al-7Si-3Cu-0.5Mg)

- Potential for improved fatigue performance:
  - Two-step solution treatment
  - Interrupted quenching
  - Mild quench rate (°C/s 525-200)

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Time, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA: 220°C/2hrs</td>
<td>ST: 495°C/8hrs</td>
</tr>
<tr>
<td>ST: 495°C/8hrs</td>
<td>AA: 220°C/2hrs</td>
</tr>
</tbody>
</table>

UTS, MPa

Fatigue strength, MPa

LOM micrographs (100x) of the 319 alloy heat treated test sample (T6M)

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Thank you!