Fatigue Behavior of Al-Si-Cu-Mg Casting Alloys

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Advanced Materials
GM - Powertrain
Background

• Application of Al-Si-Cu-Mg Casting Alloys
  – Complex engine components because of reasonable castability, good high temperature mechanical properties, and low cost compared with other primary alloys
  – Concerns of fatigue resistance

• Objectives
  – To study the influence of Sr, grain refinement with “TiBloy”, and low pressure filling on fatigue;
  – To determine weak links that controls fatigue, and
  – To develop microstructure tolerant design (MTD) method based on statistics and fracture mechanics.
Experimental

- Alloy (319)

<table>
<thead>
<tr>
<th>Chemistry (wt%)</th>
<th>SPECIFIC GRAVITY (g/cc)</th>
<th>Si</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Mg</th>
<th>Ti</th>
<th>Sr</th>
<th>Mn:Fe Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>2.68</td>
<td>6.86</td>
<td>3.26</td>
<td>0.17</td>
<td>0.059</td>
<td>0.31</td>
<td>0.091</td>
<td>0.0005</td>
<td>0.42</td>
</tr>
<tr>
<td>Base +TiB2</td>
<td>2.67</td>
<td>6.96</td>
<td>3.27</td>
<td>0.21</td>
<td>0.086</td>
<td>0.31</td>
<td>0.100</td>
<td>0.0008</td>
<td>0.55</td>
</tr>
<tr>
<td>Sr</td>
<td>2.67</td>
<td>7.01</td>
<td>3.20</td>
<td>0.19</td>
<td>0.068</td>
<td>0.29</td>
<td>0.091</td>
<td>0.0151</td>
<td>0.49</td>
</tr>
<tr>
<td>Sr+TiB2</td>
<td>2.68</td>
<td>7.03</td>
<td>3.30</td>
<td>0.20</td>
<td>0.079</td>
<td>0.30</td>
<td>0.101</td>
<td>0.0194</td>
<td>0.54</td>
</tr>
<tr>
<td>LP Base</td>
<td>2.68</td>
<td>6.66</td>
<td>3.26</td>
<td>0.20</td>
<td>0.048</td>
<td>0.31</td>
<td>0.102</td>
<td>0.0002</td>
<td>0.24</td>
</tr>
</tbody>
</table>

- Test castings of cylinder heads were lost foam cast using both gravity pouring and low pressure fill.

- T7 heat treatment including solution treatment for 12 hr at 493°C, Quenching into agitated warm water (70°C), and artificial aging for 8 hr at 249°C.

- Both tensile and fatigue specimens were prepared and tested at room temperature at WMT&R per ASTM E466.
Experimental

• Metallography
  – Porosity: vol%, maximum Feret diameter, area
  – Dendrite cell size (DCS): a circle grid (5 circles) used

• Fractography
  – Fatigue crack origin;
  – Initial crack (pore/oxide) size; and
  – Weak links controlling crack propagation
Microstructure

One interconnected pore
Microstructure (Grain Structure)

319 Base

319 TiB$_2$

319 Sr

319Sr TiB$_2$
Microstructure Characterization

**Dendrite Cell Size (DCS) vs. Alloys**

**Porosity vs. Alloys**
Microstructure Characterization

Maximum Pore Size vs. Alloys

3/03/03

TMS 2003, San Diego
Fatigue Crack Initiation and Propagation

Shrinkage porosity initiated fatigue crack in a HCF specimen (LP 319 Base) which failed after 1,666,452 cycles at 60MPa

3/03/03

TMS 2003, San Diego
Fatigue Crack Initiation and Propagation

SEM fractograph

Shrinkage porosity initiated fatigue crack in a LCF specimen (319 Base) which failed after 6,869 cycles at 145.5MPa

BEI fractograph

Origin at Shrink
Secondary Origin at Gas Pore

3/03/03 TMS 2003, San Diego
Fatigue Crack Initiation and Propagation

Shrinkage porosity initiated fatigue crack in a LCF specimen (319 TiB$_2$) which failed after 3,156 cycles at 144MPa
Fatigue Crack Initiation and Propagation

SEM fractograph BEI fractograph

Shrinkage porosity initiated fatigue crack in a LCF specimen (319 Sr) which failed after 3,609 cycles at 138MPa

3/03/03

TMS 2003, San Diego
Fatigue Crack Initiation and Propagation

SEM fractograph

Shrinkage porosity initiated fatigue crack in a LCF specimen (319Sr+TiB₂) which failed after 7,369 cycles at 150MPa

BEI fractograph

Origin at Gas Pore
Secondary Origin at Shrink
Gas Pore

3/03/03

TMS 2003, San Diego
No clear relationship between fatigue properties and micros

No strong relationship between fatigue and tensile ductility for T7
Comparison of Pore Sizes

Maximum sizes of pores initiated cracks, $a_{\text{max}}$ (µm)

$$f(a_{\text{max}}) = 1 - \exp \left( \frac{a_{\text{max}}}{a_{\text{max,0}}} \right)^{-b}$$

<table>
<thead>
<tr>
<th>alloys</th>
<th>b</th>
<th>$a_{\text{max,0}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP base</td>
<td>3.3</td>
<td>1756</td>
</tr>
<tr>
<td>Base</td>
<td>3.1</td>
<td>1085</td>
</tr>
<tr>
<td>TiB$_2$</td>
<td>4.0</td>
<td>1220</td>
</tr>
<tr>
<td>Sr</td>
<td>2.7</td>
<td>2790</td>
</tr>
<tr>
<td>Sr + TiB$_2$</td>
<td>4.0</td>
<td>2237</td>
</tr>
</tbody>
</table>

319-T7 alloys
Pores initiated fatigue cracks
Weak Links and Fatigue Properties

Good correlation between fatigue life and maximum pore size

Strong correlation between fatigue strength and area% of porosity and intermetallics on fracture surface
Microstructure Tolerant Design (MTD)

For applications

$N_f > 10^7$ cycles

Initial effective stress intensity factor range

$$\Delta K_{eff,i} = C \cdot \left( \frac{N_p}{a_i} \right)^{-\frac{1}{m}}$$

$3/03/03$  

$TMS \ 2003, \ San\ Diego$
Microstructure Tolerant Design (MTD)

For applications $N_f < 10^7$ cycles

$\sigma_a = 786(N_f a_{max})^{0.51}$

$N_f = \frac{1}{a_{min}} \left( \frac{782.1}{\sigma_a} \right)^{0.09}$

$\sigma_a = \frac{\sigma_{max}}{\sqrt{1-R^2}}$

$\sigma_a = \text{alternating stress amplitude}(\sigma_{max})$

Long crack model

$N_p = \frac{1}{a_i} \cdot \left( \frac{C}{\sigma_a} \right)^n$

319 alloys, T7
R = -1, LCF & HCF
500µm < $a_{max}$ < 6000µm

LP Base
Base
TiB$_2$
Sr
Sr + TiB$_2$

Gravity and low pressure
R = -1, LCF & HCF

319 - T7 alloys
Gravity and low pressure
R = -1, LCF & HCF

LP Base
Base
TiB$_2$
Sr
Sr + TiB$_2$

319 alloys, T7
R = -1, LCF & HCF

319 - T7 alloys
Gravity and low pressure
R = -1, LCF & HCF

LP Base
Base
TiB$_2$
Sr
Sr + TiB$_2$

R-squared = 0.956129

Calculated propagation life, $N_p$ (Cycles)

S-N data
$N_f*a_{max}$ data

S-Nmax.grf

319 alloys, T7
R = -1, LCF & HCF
500µm < $a_{max}$ < 6000µm

LP Base
Base
TiB$_2$
Sr
Sr + TiB$_2$

Gravity and low pressure
R = -1, LCF & HCF

lp-base, Nf data
Nf data

S-Nmax.grf

319 - T7 alloys
Gravity and low pressure
R = -1, LCF & HCF

LP Base
Base
TiB$_2$
Sr
Sr + TiB$_2$

R-squared = 0.956129
Microstructure Tolerant Design (MTD)

For applications
$$N_f < 10^7 \text{ cycles}$$

Short crack models

$$N_p = C \cdot \left( \frac{\sigma_{ys}}{\sigma_a} \right)^n \cdot \ln \left( \frac{a_f}{a_i} \right)$$

$$N_p = C' \cdot \left( \frac{\sigma_{ys}}{\varepsilon_{max} \cdot \sigma_a} \right)^n \cdot \ln \left( \frac{a_f}{a_i} \right)$$

(M.J. Caton et al., Met. Trans. 1999)
Comparison of Microporosity as Observed Metallurgically and in a SEM

Gas Porosity

Shrinkage Porosity
Comparison of Microporosity as Observed Metallurgically and in a SEM

Gas Porosity

Shrinkage Porosity

(J.M. Boileau, 2000)
Extreme Value Statistics (EVS)

\[ F(x) = \exp \left( -\exp \left( -\frac{x - \lambda}{\delta} \right) \right) \]

- \( x \) - pore size, \( \lambda, \delta \) - EVS scale parameters

\[ T = \frac{V}{V_0} \quad T_b = T \times 1000 \]

(Murakami, et al., 1994, 97)

\[ T = \frac{V}{V_0} = \frac{3.7 \times 10^6}{100} = 3.7 \times 10^4 \]

\[ T_b = 3.7 \times 10^4 \times 1000 = 3.7 \times 10^7 \]


<table>
<thead>
<tr>
<th>Alloys</th>
<th>Maximum defect size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As-polished</td>
</tr>
<tr>
<td></td>
<td>(mean ± 3σ)</td>
</tr>
<tr>
<td>LP Base</td>
<td>167 ± 316</td>
</tr>
<tr>
<td>Base</td>
<td>445 ± 477</td>
</tr>
<tr>
<td>TiB₂</td>
<td>368 ± 402</td>
</tr>
<tr>
<td>Sr</td>
<td>391 ± 400</td>
</tr>
<tr>
<td>Sr + TiB₂</td>
<td>415 ± 467</td>
</tr>
</tbody>
</table>

Maximum pore size on as-polished planes (µm)

\[ F(a) = \exp \left( -\exp \left( -\frac{\frac{a}{\lambda}}{\delta} \right) \right) \]
Application of Fracture Mechanics and EVS

Number of cycles to failure, $N_f$ (cycles)

Stress amplitude, $\sigma_a$ (MPa)

Long crack model with EVS

$\sigma_a = 782 \left( \frac{a_{\text{EV}}}{N_p} \right)^{\frac{1}{1.13}}$

Short crack model with EVS

$\sigma_a = \sqrt{\frac{E}{\sigma_{rs}} \left( \frac{1}{1.46 \times 10^8} \right)^{\frac{1}{41}} \left[ \ln \left( \frac{a_t}{a_{\text{EV}}} \right) \cdot N_p^{-1} \right]^{\frac{1}{41}}}$

319-T7, $R = -1$

$500 \mu m < a_{\text{max}} < 6000 \mu m$

- LP Base
- LP TiB$_2$
- Base
- TiB$_2$
- Sr
- Sr + TiB$_2$
Summary and Conclusions

• Porosity plays the most important role in determining fatigue resistance. Compared with porosity, eutectic structure and intermetallic phases play a minor role in crack initiation. However, they can influence crack propagation rates late in life.

• Strontium modification of eutectic Si leads to macrosegregation of Cu-rich and Fe-rich intermetallic phases, and increases microshrinkage porosity.

• Compared with conventional gravity pouring, low pressure filling appears beneficial. It significantly reduced the volume fraction of porosity and increased tensile and fatigue strengths.
Summary and Conclusions

• The effect of grain refinement using “TiBloy” additions on microstructure and mechanical properties is marginal. It showed no significant benefit in unmodified (Sr-free) alloys. In Sr-modified alloys, TiBloy additions slightly reduce the volume fraction and size of porosity as well as the degree of intermetallic phase segregation, leading to a slight improvement in fatigue performance compared to Sr-modified material. The gains do not completely restore the strength of Sr-modified material to that of the base alloy.

• Fatigue cracks initially propagate mainly through the dendrites, leading to fewer eutectic (intermetallic) particles in the fatigue crack propagation region compared with tensile overload area.
Summary and Conclusions

- For the studied alloys with lives of $\sim 10^6 – 10^7$ cycles, the effective threshold stress intensity factor ($\Delta K_{eff, th}$) is about $1\text{MPa}\sqrt{\text{m}}$. For stress and defect combinations exceeding a stress intensity factor of $1\text{MPa}\sqrt{\text{m}}$, the fatigue crack would initiate from the largest pores located at the free surface of the materials.

- Fatigue life can then be predicted using both long crack (LEFM – linear elastic fracture mechanics) and short crack (CTOD – crack-tip opening displacement) models together with inherent material characteristics.

- The largest defect (pore) size in a cast component can be estimated using extreme-value statistics (EVS) applied to metallographic measurements of pore size. Maximum pore size prediction by EVS agrees quite well with measurements of the initiation pore sizes from the fracture surface.