Effect of Shot Peening Treatments on Corrosion Fatigue of Cast or Wrought Al-base Alloys

K. Timmermann, W. Zinn, B. Scholtes

Institute of Materials Engineering, Department of Mechanical Engineering
University of Kassel, Mönchebergstr. 3, 34109 Kassel, Germany

Abstract
The consequences of near surface materials properties due to distinct manufacturing operations on damage evolution during corrosion fatigue of the Al-base alloy AA359.0 (German grade G-AlSi9Cu3) and AA6060 (German grade AlMgSi0,5) were systematically investigated. Specimens with distinct shot peening treatments were investigated in comparison with turned or shot peened states. Surface topography as well as near surface work hardening states and residual stress distributions were taken into account. Rotating bending fatigue tests under salt spray test conditions were carried out and crack formation as well as crack propagation was studied in comparison with fatigue tests in laboratory air. It could be shown, that mechanical surface treatments, which have beneficial effects in dry air are also advantageous under corrosion fatigue conditions. Characteristic results are presented and discussed taking the stability of near surface materials properties during fatigue into account.

Keywords
Corrosion fatigue, aluminium alloys, shot peening, salt spray test, residual stress.

Introduction
The beneficial effects of mechanical surface treatments on the fatigue behavior of components are well known and documented in literature [1, 2]. The aim of this work was to investigate in how far these effects are also active in the case of corrosion fatigue. To clarify this question, rotating bending fatigue tests in a corrosive environment were carried out at specimens made of AA359.0 (cast alloy) and AA6060 (wrought alloy). Specimens were loaded in salt spray fog, produced of water with 5% NaCl similar to sea water. As a reference, additional tests were carried out under laboratory air conditions. Experimental results give evidence about the different effectiveness of shot peening treatment and of consequences of environment on fatigue lifetime and strength, depending on the microstructure of the material under investigation.

Experimental Methods
Rotating bending fatigue specimens with the geometry shown in Figure 1 of aluminium base alloys AA359.0 (German grade G-AlSi9Cu3) and AA6060 (German grade AlMgSi0,5) were manufactured by turning (feed rate of 0.05 mm at a rotation speed of 4500 rpm, cutting speed of 45 m/min, cutting depth of 0.2 mm). The cast alloy was produced by a sand casting technique. Wrought alloy specimens were manufactured from cylindrical bars with a diameter of 12 mm. Table 1 shows the chemical compositions of the alloys, measured by light spectroscopic analysis. All specimens were heat treated after manufacturing. The solution annealing of the cast alloy starts at 520 °C for 60 min. Then, after quenching in water of room temperature, a one stage precipitation hardening process took place with 20 h at 150 °C. The wrought alloy was annealed to solution at 530 °C for 30 min. After quenching in water, a heat treatment was carried out at 160 °C for 8 h. Figure 2 shows the microstructures of both alloys. AA359.0 has a typical dendritic structure and many blow holes due to the sand casting process.
Table 1. Chemical composition in wt.-% 

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast alloy AA359.0</td>
<td>8.530</td>
<td>2.836</td>
<td>0.191</td>
<td>0.395</td>
<td>0.207</td>
<td>0.755</td>
</tr>
<tr>
<td>Wrought alloy AA6060</td>
<td>0.648</td>
<td>0.01</td>
<td>0.568</td>
<td>0.224</td>
<td>0.022</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Table 2. Characteristic material properties

<table>
<thead>
<tr>
<th></th>
<th>Yield stress ( R_{p0.2} ) in MPa</th>
<th>UTS in MPa</th>
<th>Young’s modulus in GPa</th>
<th>Fracture strain in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast alloy AA359.0</td>
<td>---</td>
<td>222</td>
<td>76.76</td>
<td>0.1</td>
</tr>
<tr>
<td>Wrought alloy AA6060</td>
<td>182</td>
<td>232</td>
<td>64.54</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Figure 1. Specimen geometry for rotating bending fatigue tests (Unit: mm)

Figure 2. Microstructure of cast alloy (left) and wrought alloy (right)
The mechanical properties, determined in tensile tests, are listed in Table 2. The low values of
the cast specimens should be noted, which result from the consequence of the blow holes.
This leads also to a more brittle behaviour of the cast alloy compared with the wrought one. Shot
peening with coverage of 200% and an Almen intensity of 0.2 mA was carried out using
ceramic shots ( Ø 0.6 mm) in order to avoid contact corrosion damage. Fatigue tests were
performed on a rotating bending testing machine at a frequency of 50 Hz under both laboratory
air and salt spray fog environments. The corrosive environment was produced using a specially
designed experimental set-up [3, 4].
A salt spray fog was produced from saturated steam of a 5% NaCl-solution. Woehler-curves
both under corrosive conditions and under laboratory air were produced at five different stress
amplitudes with five specimens on each load level. The diagrams always show failure
probabilities of 50%, which were calculated using the arcsin√F- method. Surface topographies
of the specimens were analysed using a white light interferometer. The topography was scanned
in an area of 1.2 x 0.88 mm². Residual stresses were determined by X-ray diffraction technique,
using the interference of CuKα-radiation at the {333} and {511} lattice planes (2θ = 162.487°). For
stress evaluation, the sin²ψ-method was applied and the elastic constant s2 = 1.865 * 10⁻⁵
mm²/N was used. Residual stress profiles were determined without correction of stress relief by
successive electrochemical materials removal. To estimate micro residual stresses, caused by
work hardening, integral width (IW) values of X-ray interference lines were determined.

Experimental Results
Table 3 lists the measured Ra and Rz values before and after shot peening for two material
types. As expected, the shot peened specimens show increased roughness values. Compared
with the wrought alloy specimens, roughness values on the cast alloy specimens are higher in
both conditions.
Residual stress states at the surface of the specimens were statistically evaluated. Results are
shown in Figure 3 and Table 4. It is easy to see two classes of residual stress states and the
dispersion of the stress amounts for both alloys. Shot peened specimens, as expected, show
high surface compressive residual stresses whereas turned ones have only negligible residual
stresses at the surface. Figure 4 shows depth distributions of residual stresses and integral
widths. Due to the coarse microstructure of the cast alloy, residual stress evaluation with the
sin²ψ-method was performed only very close to the surface. In addition, crystallographic texture
of the wrought alloy hindered X-ray measurements, but nevertheless typical depth distributions
of compressive residual stresses up to a distance of approximately 0.2 mm from the surface
were found. It is remarkable to see that a value of -250 MPa is produced at the surface and
values between -200 MPa and -340 MPa were produced below the surface of the cast alloy,
which are much higher than the respective values of the wrought alloy. In addition, the
corresponding IW-depth distributions are shown in Figure 4, which present also higher values on
the surface for the cast alloy than for the wrought alloy.

<table>
<thead>
<tr>
<th>Table 3. Comparison of roughness values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Condition</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Turned finish</td>
</tr>
<tr>
<td>Shot peened</td>
</tr>
</tbody>
</table>
Table 4. Mean values and ranges of the stress at the surface of cast alloy and wrought alloy

<table>
<thead>
<tr>
<th></th>
<th>Mean value in MPa</th>
<th>Range in MPa</th>
<th>Quantity of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA359.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turned finish</td>
<td>-60</td>
<td>± 24</td>
<td>51</td>
</tr>
<tr>
<td>Shot peened</td>
<td>-230</td>
<td>± 32</td>
<td>54</td>
</tr>
<tr>
<td>AA6060</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turned finish</td>
<td>-44</td>
<td>± 61</td>
<td>44</td>
</tr>
<tr>
<td>Shot peened</td>
<td>-116</td>
<td>± 22</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 3. Gaussian distribution of residual stresses of cast alloy (left) and wrought alloy (right)

Figure 4. Residual stress depth distributions (left) and depth distributions of integral widths (right)

Figure 5 shows S-N curves for two materials in laboratory air (left) and in corrosive conditions (right), respectively. In order to assess the influence of the environment on fatigue life, Figure 6 presents the S-N curves under two environmental conditions for the cast alloy (left) and the wrought alloy (right), respectively. Different aspects should be taken into account for the explanation of these experimental observations. One important point is that in the case of the cast alloy, blow holes or coarse dendritic structures (see Figure 2) at the near surface act as sharp notches and cracks start preferentially. Therefore, the fatigue lives and fatigue strengths of the wrought alloy are always higher than those of the cast alloy. For experimental results both under laboratory air and under salt spray conditions, shot peening greatly increases fatigue
strengths and fatigue lives. An exception are experiments with the cast alloy at higher numbers of cycles, where S-N curves of the two surface states and the two environmental conditions have an intersection. For both materials, salt spray fog reduces fatigue strength and fatigue life compared to experiments under ambient conditions, while in a different way.

In general, the detrimental effect of salt spray fog is more expressed for the wrought alloy than for the cast one. In the case of the cast alloy, shot peened specimens in salt fog almost reach the same strengths and lives of specimens tested in the laboratory air condition. In addition, it is remarkably that for the cast alloy, the finite life fatigue strength of the shot peened component under salt spray fog conditions is larger than that for turned states under ambient condition.

![Figure 5](image1.png) **Figure 5.** Fatigue endurance limit under ambient conditions (left) and under salt spray conditions (right)

![Figure 6](image2.png) **Figure 6.** Comparison of cast alloy (left) and wrought alloy (right) with turned finish and shot peened specimen under different conditions

However, this is not the case for the wrought alloy. In case of alloy AA6060, the detrimental effects of salt spray fog on fatigue strength are obvious. This observation is valid for both turned and shot peened surface states. A typical example of a fracture surface is shown in Fig. 7 (left) compared with the cracked surface of AA6060 (right). Obviously, for high cycle fatigue, these defects are the determining factors for fatigue failure even in case of shot peened surfaces, which explain the intersections in the S-N curves. This leads to the remarkable observation that, the fatigue strength (failure larger than approximately $5 \times 10^6$) of AA359.0 is really independent of the surface treatment and the environmental condition. Obviously, the positive effects of shot
peening, such as compressive residual stress and strain hardening, are not able to compensate the detrimental effects of the microstructural defects, in particular large blow holes or coarse dendritic structures as mentioned above. Due to corrosion pits, salt spray reduces fatigue strength and fatigue life of the wrought alloy AA6060 in both surface treatment conditions. Shot peening of the turned state cannot fully compensate the detrimental effect of corrosion during fatigue. Under salt spray as well as under ambient conditions, there exists a tendency that shot peening is more effective when the loading stress amplitude is lower. This can be attributed to more stable compressive residual stresses as well as strain hardening effects that suppress crack formation and decrease the crack propagation rates [4].

![Fracture surface with dendritic structure of cast alloy](image1) ![Effect of work hardened surface layer of wrought alloy](image2)

**Figure 7.** Fracture surface with dendritic structure of cast alloy (left; experiment with turned specimen in laboratory air, $\sigma_a = 200$ MPa) and effect of work hardened surface layer of wrought alloy (right; experiment with shot peened specimen in laboratory air, $\sigma_a = 210$ MPa)

**Discussion and Conclusions**

Shot peening is beneficial both under laboratory atmosphere and under salt spray fog conditions. However, a clear influence of the materials microstructure can be stated. Failure of the cast alloy AA359.0 is controlled by large microstructural defects, which limits the positive effect of shot peening and the detrimental effect of salt spray fog at lower stress amplitudes. On the contrary, for the wrought alloy AA6060, the beneficial effect of shot peening is most pronounced at lower stress amplitudes. In addition, compared to laboratory air, the detrimental effect of salt spray is very evident.

**References**

[1] V. Schulze; Modern Mechanical Surface Treatment; WILEY-VCH, Weinheim; (2006)

[2] R. Herzog; Auswirkungen bearbeitungsbedingter Randschichteigenschaften auf das Schwingungsrisskorrosionsverhalten von Ck45 und X35CrMo17; Dr.-Ing.-thesis, University of Braunschweig; Shaker Verlag; Aachen; (1998)
