Tensile and fatigue behaviour of wrought magnesium alloys AZ31 and AZ61

A. N. CHAMOS¹, Sp. G. PANTELAKIS¹, G. N. HAIDEMENOPoulos² and E. KAMOUTSI²
¹Laboratory of Technology and Strength of Materials, Department of Mechanical Engineering and Aeronautics, University of Patras, Rion, Greece,
²Laboratory of Materials, Department of Mechanical and Industrial Engineering, University of Thessaly, Volos, Greece

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ABSTRACT The mechanical behaviour of two hot rolled magnesium alloys, namely the AZ31 and AZ61, has been evaluated experimentally under both monotonic and cyclic loading. Both longitudinal (L) and long transverse (LT) directions were evaluated. The tensile behaviour of the L and LT directions is similar and differs only in the offset 0.2% yield strength for both materials. This difference is attributed to the angular spread of basal poles toward the rolling direction and is more pronounced for the case of AZ31. A distinct hardening response is obvious in both directions. Twinning formation was observed; it is more pronounced in the longitudinal direction while the fracture mode is intergranular and equiaxed facets are present in the fracture surfaces of the specimens. The S–N curves exhibit a smooth transition from the low to high cycle fatigue regime. AZ61 exhibits an overall better fatigue behaviour compared to AZ31. A transgranular crack initiation mode is observed in all tested specimens while the propagation of the cracks is characterized as intergranular.

Keywords fatigue; fracture mode; tension; texture; twinning.

NOMENCLATURES

$A_f$ = elongation to failure (%)
$f$ = frequency (Hz)
$HV$ = hardness vickers (MPa)
$K(t)$ = stress concentration factor ($-$)
$N_f$ = cycles to failure ($-$)
$P_1, P_2, P_3, P_4$ = regression analysis coefficients
$R$ = stress ratio ($-$)
$R_m$ = ultimate tensile strength (MPa)
$R_{p0.2}$ = offset yield strength (MPa)
$W$ = strain energy density (MJ/m³)
$\sigma_f$ = fatigue limit (MPa)
$\sigma_{max}$ = maximum applied stress (MPa)

INTRODUCTION

Magnesium is the lightest structural engineering metal, and therefore, particularly attractive for structural applications where weight saving is of major importance. Improvements in mechanical properties, corrosion resistance¹² and the development of advanced manufacturing processes have led to increased interest in magnesium alloys and several works are in progress to develop wrought magnesium alloys for automotive and aerospace applications.³⁻⁵ Amongst them, AZ31 and AZ61 represent two of the most popular wrought alloys of the AZ family for light-weight structures; diverse uses include satellite components, military applications, door inner automotive components, computer cases, cameras,⁶ etc. The major problems limiting the use of wrought magnesium alloys in aircraft structure applications are the high corrosion susceptibility and the poor damage tolerance behaviour. Although the corrosion problem can be presently faced by means of proper coating technologies,⁷ the fatigue issue
The scientific literature concerning the fatigue behaviour of wrought magnesium alloys is rather limited. Ogarrevic et al.\textsuperscript{17} reviewed the fatigue data of Mg alloys published between 1923 and 1990 and indicated that a significant amount of fatigue strength data existed, but most of it was not recent and fatigue crack growth data were mostly obtained in USSR. Recent studies performed on the AZ31 alloy\textsuperscript{18–20} revealed some of the fatigue characteristics of the material. In all cases, the characteristic smooth transition of the S–N curve from low to high cycle fatigue regime was observed. Furthermore, cracks initiated at a very early stage of the fatigue process, independent of the applied stress level. It has been proved that these fatigue cracks initiated mainly at the interface between the Mg matrix and the existing intermetallic phase. Finally, it was indicated that the present alloy had the worst fatigue crack growth resistance for large cracks when compared with two types of aluminium alloys and pure titanium.

The present work aims to contribute to the investigation of the mechanical behaviour of two alloys from the AZ family, namely the AZ31 and AZ61 alloys, under both monotonic and cyclic loading by accounting for the underlying physics determining it. To accomplish the above objective an extensive experimental investigation was performed. First, the microstructure of the alloys was characterized by means of grain size measurements, micro-hardness measurements and texture analysis. Then, tensile tests and constant amplitude fatigue tests were performed for both longitudinal (L) and long transverse (LT) direction of the material. Finally, the derived results were supported by extensive metallographic and fractographic investigation.

**MATERIAL AND EXPERIMENTAL PROCEDURE**

Two hot rolled magnesium alloys, namely the AZ31 and AZ61, in the form of thin plates with a nominal thickness of 2.0 mm were used for the present study. Their chemical composition is listed in Table 1. The materials are characterized as high-purity (hp), as the concentration of the contaminants (Fe, Ni and Cu) was held under certain limits. After the rolling procedure the materials were subjected to annealing (O-temper). The AZ31 was treated for 30 min at 300 °C while the AZ61 was treated for 1 h at 250 °C.

Test specimens were machined for both longitudinal (L) and long transverse (LT) direction of the material according to the ASTM standards. For the case of tensile testing, a specimen with 50 mm gauge length and 12.5 mm gauge width was used. For the case of fatigue testing, a dog-bone specimen with continuous radius of 145 and 12 mm width at the reduced section was used.
Table 1 Chemical composition of the AZ alloys

<table>
<thead>
<tr>
<th>AZ alloys</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Cu</th>
<th>Si</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31</td>
<td>3.06</td>
<td>0.80</td>
<td>0.25</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>–</td>
<td>Balance</td>
</tr>
<tr>
<td>AZ61</td>
<td>6</td>
<td>0.72</td>
<td>0.33</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>Balance</td>
</tr>
</tbody>
</table>

having a stress concentration factor of 1.0 ($K_t = 1.0$, un-notched). Prior to testing, fatigue specimens were ground with SiC papers up to 1200 grit followed by polishing with diamond paste up to 1 μm.

Two servo-hydraulic MTS machines with a capacity of 100 and 250 KN, respectively, were used for the testing procedure. Tensile tests were performed using a displacement rate of 2 mm/min which was kept constant during the test. Strain measurements were taken by adjusting an extensionmeter on the gauge length of the specimens. A total number of four tests were performed for each direction. Properties evaluated included the 0.2% offset yield strength $R_{p0.2}$, ultimate tensile strength $R_m$, elongation to failure $A_f$ and strain energy density $W$. Fatigue strength data were obtained under constant amplitude tests at a stress ratio, $R$, of 0.1. The frequency employed for these tests was 25 Hz.

After the experiments, optical metallographic observations and fracture surface analysis of both tensile and fatigue specimens has been performed. Standard metallographic preparation has been employed. The etching solution for the AZ alloys acetic picral consisted of 5 ml acetic acid, 6 g picric acid, 10 ml H$_2$O and 100 ml ethanol.

**RESULTS AND DISCUSSION**

**Microstructure and texture analysis**

Hardness and grain size measurements were performed in the three planes of the plate, as designated in Fig. 1. Typical images of the microstructure of the alloys are shown in Fig. 2. Both alloys show equiaxed structures with an almost identical average grain size of 14.5 μm. It should be mentioned that the microstructure of the AZ61 alloy is not so homogeneous as for the case of the AZ31. Furthermore, while in AZ31 there is no observable precipitation at the grain boundaries, in AZ61 there is a precipitate at the grain boundaries, most probably the β-phase Mg$_{17}$Al$_{12}$. The measured average hardness and grain size values are summarized in Table 2.

The initial texture of the materials under investigation is shown in Fig. 3. A near-basal fibre texture with cylindrical symmetry has been found, i.e., the basal {0001} plane is parallel to the rolling plane, while the $c$-axis is perpendicular to the rolling plane. The count of {0001} plane intensity comprises 70% for AZ31 and 80% for AZ61 alloy, of total measured counts from the other crystallographic planes. The {0001} pole figure shows an angular spread of basal poles toward the rolling direction of the material. This spread is more pronounced for the AZ31 alloy.

**Tensile behaviour**

**Mechanical response**

Representative engineering stress–strain curves obtained for the L and LT directions of the materials are given in Fig. 4. The material’s average tensile properties are summarized in Table 3. Higher strength values were obtained for the AZ61 alloy, which could be attributed to the higher aluminium content, while the ductility properties are comparable. Recall that both, AZ31 and AZ61 alloys are considered as candidates for aircraft applications. The derived tensile strength properties are lower as compared to the competitive structural aluminium alloys, e.g., the 2024 alloy. Yet, by considering the density advantage of magnesium alloys, the specific properties become comparable, especially for the case of AZ61 as it can be seen in Table 4. As it can be seen in the above figure, the mechanical response of the alloys is quite similar in both directions, with the exception of the 0.2% offset yield strength which indicates a clear increase for the LT direction. This increase is more pronounced for the case of the AZ31 alloy. The distinct strain hardening response is also evident.

**Deformation mechanisms under tensile loading**

As it may be concluded by the texture analysis, the higher yield strength in the LT direction especially for the AZ31 alloy is attributed to the angular spread of basal poles.
toward the rolling direction. This angular spread causes yielding by activation of basal slip in the L direction. Yielding in the LT direction requires the activation of prismatic slip, which possesses a higher CRSS. Furthermore, the tilt of the c-axis toward the L direction generates a tensile stress component along the c-axis which activates twinning. On the other hand, twinning in the LT direction requires a higher stress. Similar differences in strength, linked to texture effects, have also been observed by other workers in Mg alloys.\textsuperscript{8–10}

Displayed in Fig. 5 are the microstructures of the AZ31 tensile specimen in the uniform section (Fig. 5a) and also in the neck section (Fig. 5b) for the case of the L direction. As it may be seen, there is a clear variation in twinning density across the specimen length. A higher twinning density in the neck area relative to the uniform elongation area has been observed, meaning that there is a higher contribution of twinning deformation in the total deformation in the neck of the tensile specimen. Triaxility in the neck section may favour twinning relative to the uniform section of the tensile specimen. It is also apparent that two main twin habits form, which correspond to the two conjugate twinning planes in Mg alloys.\textsuperscript{21,22}

A similar behaviour has also been observed for the case of the LT direction (Fig. 6); yet the density of the twins was lower when compared with the L direction. This might indicate an increased resistance to twinning deformation for the LT direction relative to the L direction. It is confirmed that twinning can provide the missing, by the Von Mises criterion, independent deformation mechanism in hexagonal close-packed structures.

A similar behaviour has also been observed for the case of the AZ61 alloy. Furthermore, the coordination of twins between grains observed in the neck section (e.g., Fig. 5b) could lead to shear localization before fracture. This could explain the 45° inclination of the fracture surface of the tensile specimens.

It should be noted that although twinning may help the material to satisfy the Von Mises criterion, it is a polar mechanism which allows simple shear in only one direction relative to both forward and backward directions of dislocation slip. The overall contribution of twinning in the total plastic strain is relatively small and is directly proportional to the volume fraction of twins. In principle the twinning shear in Mg is 0.129 and the maximum tensile strain accommodated by this shear is only 6.5%.\textsuperscript{8} The

<table>
<thead>
<tr>
<th>AZ alloys</th>
<th>Hardness (HV)</th>
<th>Grain size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LT</td>
<td>LS</td>
</tr>
<tr>
<td>AZ31</td>
<td>48.2</td>
<td>57.8</td>
</tr>
<tr>
<td>AZ61</td>
<td>63.3</td>
<td>67</td>
</tr>
</tbody>
</table>

Fig. 2 Microstructure of (a) AZ31 and (b) AZ61 alloy in LT, LS and ST planes.
Fig. 3 Pole figures for the (0001) plane: (a) AZ31 and (b) AZ61.

The major contribution of twinning shear is the re-orientation of the lattice to favour deformation by dislocation slip. Other main effects of twinning are grain subdivision, i.e., an effective reduction of grain size since the twin boundaries act as obstacles to dislocation slip and stress concentrations at grain boundaries, where twins are terminated.

Fractographic analysis of tensile specimens

The fracture surfaces for both L and LT direction are shown in Fig. 7 for the AZ31 and AZ61 alloy, respectively. The above figures are characterized by equiaxed facets. At the same time no dimples are observed. It can be concluded that the dominant fracture mode is intergranular fracture. The equiaxed facets correlate with the average grain size (~14.5 μm). The intergranular mode of fracture is promoted by the following factors: stress concentrations at grain boundaries due to twin termination and plastic strain incompatibilities between neighbouring grains due to difficulties to satisfy the Von Mises criterion during deformation before fracture.

Fatigue behaviour

S–N curves

The fatigue data obtained from the fatigue tests performed were used to construct the S–N curves and also to obtain the fatigue strength data of both AZ31 and AZ61 magnesium alloys in the rolling direction. Data was plotted by means of maximum stress (linear scale) versus cycles to failure (logarithmic scale) and they were fitted by a nonlinear analysis (Weibull function) as it can be seen in Fig. 8.

The four point Weibull equation is defined as

$$\sigma_{\text{max}} = P_1 + \frac{P_2 - P_1}{\exp \left( \frac{\log N}{P_4} \right) ^ P_3}$$

where $P_1$ and $P_2$ stand for fatigue endurance limit and ultimate tensile strength and $P_3$ and $P_4$ are regression anal-
Table 4 Specific strength properties of AZ31, AZ61 and 2024 alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (ρ) (kg/m³)</th>
<th>Specific yield strength (Rp/ρ) (KJ/kg)</th>
<th>Specific tensile strength (Rm/ρ) (KJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31-O</td>
<td>1.74</td>
<td>95</td>
<td>151</td>
</tr>
<tr>
<td>AZ61-O</td>
<td>1.74</td>
<td>119</td>
<td>182</td>
</tr>
<tr>
<td>2024-T351</td>
<td>2.74</td>
<td>137</td>
<td>178</td>
</tr>
</tbody>
</table>

Fig. 5 Microstructure of the tensile specimen in (a) uniform section and (b) neck section (L-direction) for the AZ31 alloy.

Fig. 6 Microstructure of the tensile specimen in (a) uniform section and (b) neck section (LT-direction) for the AZ31 alloy.

ysis coefficients. The coefficients derived by the nonlinear analysis of the fatigue strength data for both materials are summarized in Table 5.

As it can be seen from the above figure, the S–N curves of the alloy exhibit a smooth transition from the low to high cycle fatigue regime, which is a typical behaviour for Mg alloys. The apparent stress sensitivity is a disadvantage for applications where fatigue life is of major importance. Remarkable is the large scatter observed for the case of the AZ61, especially at the lower applied stresses. This could be an indication for further optimization of the material in terms of achieving a more homogeneous initial microstructure. The fatigue limits, considered at 10⁷ cycles, were 130 and 160 MPa for the AZ31 and AZ61 material.
Fig. 7 Fracture surfaces in L and LT direction for (a) AZ31 and (b) AZ61 alloy.

respectively. The higher fatigue limit observed for the AZ61 seems to be reasonable since the yield strength is about 30 MPa higher relative to the AZ31 alloy. Similar fatigue behaviour has also been observed for the case of the LT direction. Furthermore, the fatigue ratio, defined as the ratio of the fatigue limit to the ultimate tensile strength (σ_F/σ_m), was 0.49 and 0.51 for the AZ31 and AZ61, respectively. The value obtained for the AZ31 is in the range defined by Ogarevic and Stephens\textsuperscript{17} for wrought magnesium alloys while the value for the AZ61 is slightly higher.

Fractographic analysis of fatigue specimens

In order to evaluate the fracture characteristics under cyclic loading of the alloys under investigation, the fracture surfaces of the fatigue specimens have been examined, using scanning electron microscopy. Displayed in Fig. 9 is a set of four images for the case of the AZ31 alloy.

Table 5 Regression coefficients derived by the nonlinear Weibull analysis

<table>
<thead>
<tr>
<th>AZ alloys</th>
<th>P\textsubscript{1}</th>
<th>P\textsubscript{2}</th>
<th>P\textsubscript{3}</th>
<th>P\textsubscript{4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31</td>
<td>154</td>
<td>263</td>
<td>2.9</td>
<td>2.48</td>
</tr>
<tr>
<td>AZ61</td>
<td>161</td>
<td>313</td>
<td>3.61</td>
<td>2.74</td>
</tr>
</tbody>
</table>

Fig. 8 S–N curves of the alloys AZ31 and AZ61 at R = 0.1.
selected images show fracture characteristics referring to different stages of the fatigue life of the specimen. The above mentioned specimen failed at 28828 fatigue cycles under 160 MPa maximum applied stress. The fatigue initiation site is at the specimen’s surface. As it may be seen in Fig. 9a there is an arc-shaped region of flat transgranular fracture with linear marks which could be striations. However, some marks appear in pairs and could be traces of twin boundaries (Fig. 9b). The size of the transgranular section at the direction normal to the applied load is of the order of 100 μm. The role of twinning in fatigue crack initiation is not yet clear and more work is needed to clarify this point. The fatigue crack propagation area (Fig. 9c) is characterized by a fracture surface with flake-like appearance. The flake boundaries are clearly grain boundaries, therefore the fracture surface is intergranular. The surface of the flakes shows cleavage character. Crack branching (Fig. 9d) can be observed in the fatigue crack propagation area.

Similar fracture characteristics have also been observed for the case of the AZ61 alloy. That is a flat transgranular fracture in the initiation area (Fig. 10a) where the traces of twin boundaries are more evident compared to the AZ31 alloy and a flake-like appearance of the surface in the propagation area (Fig. 10b and c). The set of the four images displayed in Fig. 10 correspond to a fatigue specimen failed at 140550 cycles under 165 MPa maximum applied stress. In both alloys, the fast fracture area was clearly intergranular (e.g., Figs 9c and 10d), similar to the fracture surface of the tensile specimen.

The intergranular mode of fatigue crack propagation can be attributed to the difficulties in satisfying the von Mises criterion. Thus, the crack propagates along strain incompatibility points (i.e., grain boundaries). In AZ61, the presence of β-phase on the grain boundaries may also have contributed in the intergranular propagation mode of fracture.

CONCLUSIONS

The experimental results presented in the previous sections, led to the following conclusions:

- For the non-stressed material, both alloys show equiaxed structures with an almost identical average grain size. No
annealing twins were observed. In AZ61 alloy there is a precipitate at the grain boundaries, most probably the β-phase Mg17Al12.

- A near-basal fibre texture with cylindrical symmetry has been observed for both alloys. The basal \{0001\} plane is parallel to the rolling plane, while the c-axis is perpendicular to the rolling plane. The (0001) pole figure shows an angular spread of basal poles toward the rolling direction of the material. This spread is more pronounced for AZ31 material.

- The mechanical response of the alloys under tensile loading is quite similar in both directions, with the exception of a clear difference in the 0.2% offset yield strength. The higher yield strength observed for both materials in the LT direction is attributed to the angular spread of basal poles toward the rolling direction. This angular spread causes yielding by activation of basal slip in the L direction. The lower anisotropy observed for the AZ61 alloy can be explained by the limited spread of basal poles toward the rolling direction when compared to the AZ31 alloy.

- Twinning was observed during tensile testing. A higher twinning density in the neck area relative to the uniform elongation area has been found for both directions. Twinning density was more pronounced in the L direction.

- The dominant fracture mode under monotonic loading is intergranular fracture. Fracture surfaces of the tensile specimens are characterized by equiaxed facets with a size equal to the average grain size. The intergranular mode of tensile monotonic fracture is promoted by stress concentrations at grain boundaries due to twin termination, and plastic strain incompatibilities between neighbouring planes due to difficulties to satisfy the von Mises criterion.

- The S–N curves of the alloy exhibit a smooth transition from the low to high cycle fatigue regime, which is a typical behaviour for Mg alloys. The fatigue limits, considered at 10^7 cycles, were 130 and 160 MPa for the AZ31 and AZ61 alloy, respectively.

- A transgranular mode of crack initiation and an intergranular mode of crack propagation have been observed in all specimens. The intergranular mode of crack propagation can be attributed to strain incompatibilities built up at the grain boundaries due to difficulties in satisfying the von Mises criterion. In AZ61 alloy the β-phase grain boundary network might also have contributed to the intergranular crack propagation.

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Fig. 10 Fracture characteristics of an AZ61 fatigue specimen (σ\text{max} = 165 MPa; N_f = 140 550 cycles): (a) crack initiation, (b) crack propagation, (c) intergranular flake-like surface and (d) intergranular fast fracture area.
Acknowledgements

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REFERENCES