Mechanical behaviour of AZ31B Magnesium alloy subjected to in-plane biaxial fatigue

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ABSTRACT

The present work was carried out in order to better understand and characterize the mechanical behaviour of the magnesium alloy AZ31B, subjected to multiaxial fatigue. The study was conducted by performing experimental tests on cruciform specimens with a geometry specially optimized for use in these tests, obtained from 3.25 mm thick sheet, subjected to in-plane biaxial loading. The testing apparatus used was a biaxial testing machine developed in-house and built with four iron-core linear motors and with a non-conventional guiding device which allows for precise and efficient experimental testing of engineering materials. The tests were performed with sinewave loadings for both in-phase and out-of-phase cases, with constant load ratio and mean stress equal to zero. With crack initiation and propagation being monitored recurring to a USB microscope that took snapshots on periodic intervals defined by the number of cycles. The critical plane results were reasonably accurate for models that defined the critical plane based only on normal stresses and/or strains. For crack propagation, the estimations obtained from finite element analyses provided reasonable results except for the case of the fully reversed loading path when related with the experimental data regarding crack propagation. Throughout all tests, crack initiation and propagation showed a trend to occur in directions approximately normal to the rolling direction.

KEYWORDS: Biaxial fatigue, Magnesium alloy, experimental tests, cruciform specimens.

1. INTRODUCTION

Fatigue failure of mechanical components, structures and systems has been observed since the 19th century, and has become a well-documented phenomenon to the present day. Simply put, fatigue is a phenomenon due to the accumulation of damage, caused by cyclic loads.

Although no official figure is available, many sources suggest that 50 to 90 percent of all mechanical failures are caused by fatigue, and most of these failures are unforeseen. The considerably large percentage of failures due to fatigue, takes into account a wide range of applications, from household items, such as door springs or tooth brushes, to much more complex structures and systems, like ground vehicles, aircrafts or ships to name a few, [1].

Since failure by fatigue impacts such a wide range of applications, it is engineering’s duty to avoid this kind of failure, as it may carry dire consequences. Fatigue failures have claimed human lives in some cases and generally carry a significant economic impact. Due to all of this, it is of the utmost importance to study and understand fatigue in order to avoid the catastrophic failure of structures.

Magnesium alloys have become more and more desirable in recent times, mainly due to some of its properties, such as its density for instance. The fact that magnesium alloys are the lightest alloys available makes them a strong candidate to be used in several industries, mainly automotive and aerospace, as well as in many other industries, such as medical, electronic and sports. In the automotive and aerospace industries, the use of magnesium alloys tracks back to the late 1930’s and its use by automobile manufacturer Volkswagen, or Sikorsky helicopters in the 1950’s, and extends to the present day, with magnesium alloys being used in high-end applications like Formula 1 and current aircraft models from Boeing. While the usage of magnesium in medical, electronic and sports applications might be more recent, it still holds high importance in improving said applications.

Magnesium is the lightest structural metal available, with a density lower than aluminium’s by about a third, and close to that of fibre reinforced plastics. Another characteristic of interest lies on the fact that magnesium possesses a hexagonal close-packed crystal structure, which makes
magnesium less deformable at room temperature.

The aim of the present research work is to understand the behaviour of the AZ31B magnesium alloy subjected to in-plane biaxial fatigue, due to two main reasons: the need to be aware and understand the behaviour of the material for fatigue loading; and the appeal of the material as the lightest structural metal available.

2. MATERIAL EQUIPMENT AND EXPERIMENTAL METHODS

2.1. Material

The magnesium alloy presented and studied in this work, is designated as AZ31B-H24, which corresponds to an alloy whose main alloying elements are Aluminium and Zinc, with around 3 and 1% respectively.

The chemical composition of the alloy is presented in Table 2.1. The letter B, in the designation indicates it is an alloy that differs slightly in composition.

The properties of interest for the magnesium alloy AZ31B-H24 are summarized in Table 2.2.

Table 2.1 – Percentage range of the alloying elements in the AZ31B-H24 alloy, [2].

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight % Min</th>
<th>Weight % Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Ca</td>
<td>-</td>
<td>0.04</td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Fe</td>
<td>-</td>
<td>0.005</td>
</tr>
<tr>
<td>Mg</td>
<td>-</td>
<td>97</td>
</tr>
<tr>
<td>Mn</td>
<td>-</td>
<td>0.20</td>
</tr>
<tr>
<td>Ni</td>
<td>-</td>
<td>0.005</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>Zn</td>
<td>0.60</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Table 2.2 – AZ31B-H24 properties, [2].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, [g cm$^{-3}$]</td>
<td>1.77</td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>73</td>
</tr>
<tr>
<td>Ultimate Tensile Strength, [MPa]</td>
<td>290</td>
</tr>
<tr>
<td>Yield Tensile Strength, [MPa]</td>
<td>220</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>15 %</td>
</tr>
<tr>
<td>Modulus of Elasticity, [GPa]</td>
<td>45</td>
</tr>
<tr>
<td>Compressive Yield Strength, [MPa]</td>
<td>180</td>
</tr>
<tr>
<td>Ultimate Bearing Strength, [MPa]</td>
<td>495</td>
</tr>
<tr>
<td>Bearing Yield Strength, [MPa]</td>
<td>325</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.35</td>
</tr>
<tr>
<td>Shear Modulus, [GPa]</td>
<td>17</td>
</tr>
<tr>
<td>Shear Strength, [MPa]</td>
<td>160</td>
</tr>
<tr>
<td>Melting Point, [°C]</td>
<td>605 to 630</td>
</tr>
</tbody>
</table>

2.2. Specimen

The specimens used to conduct this study were cruciform-shaped, as this general geometry is adequate for in-plane biaxial fatigue testing, [3]. The specific geometry of the specimens used has been optimized in a previous study conducted by Baptista et al. [4], and this optimization study allowed obtaining a set of design variables which are all Pareto fronts, which provide stress uniformity at the centre of the specimen as well as maximum stress in that same region, to favour crack initiation. The specimen geometry can be observed in Figure 2.1 and the dimensions are presented in Table 2.3. The specimen arms were numbered counter clockwise with arms 1 and 3 lying along the rolling direction of the sheet, and arms 2 and 4 perpendicular to the rolling direction.
The specimens were manufactured in two separate stages: first a general shape was obtained from the raw sheet by abrasive waterjet and in the second stage, the final geometry was machined in a CNC milling machine.

2.3. Testing apparatus

The testing apparatus used to perform the experimental tests of the present work was a Biaxial Testing Machine (BTM), developed by Instituto Superior Técnico (IST) in collaboration with Instituto Politécnico de Setúbal (IPS). This machine (Figure 2.2) was purposefully designed and built aiming to test small samples of engineering materials in a very efficient manner and provide a low cost alternative to the similar options available commercially. The cruciform arrangement ensures symmetry, and is essential to at least minimise movement of the specimen’s centre during testing.

2.4. USB Microscope

In order to capture images of the centre of the specimen during the experimental tests, a Veho VMS-001 200X USB microscope was employed. This device, worked in tandem with the interface software of the BTM taking a picture on pre-defined intervals defined by the user. The microscope proved to be a crucial element due to the fact that it allowed gathering important information regarding crack propagation.

2.5. Experimental Tests

The experimental tests with the apparatus and specimens previously described, were conducted at room temperature, under load control, with constant load amplitude, equal loads on both directions, stress ratio $R=-1$, and a frequency of 20 Hz, which provided stable behaviour of the apparatus. A brief description of the parameters that differed between tests is presented in Table 2.4. All tests took place until fracture of the specimen was attained.
Table 2.4 – Test parameters for each specimen.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Load amplitude, [kN]</th>
<th>Phase shift, [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTM2022-003</td>
<td>2.7</td>
<td>0</td>
</tr>
<tr>
<td>BTM2022-004</td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td>BTM2022-005</td>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>BTM2022-008</td>
<td>1.7</td>
<td>45</td>
</tr>
<tr>
<td>BTM2022-009</td>
<td>1.2</td>
<td>90</td>
</tr>
<tr>
<td>BTM2022-010</td>
<td>0.65</td>
<td>180</td>
</tr>
</tbody>
</table>

Taking the previous table into account, the loading waveforms were defined as sine waves of the following form:

\[ F_1 = F_a \sin(\omega t) \]  \hspace{1cm} (2.1)
\[ F_2 = F_a \sin(\omega t + \delta) \]  \hspace{1cm} (2.2)

Where \( F_a \) is the load amplitude, \( F_1 \) and \( F_2 \) are the loads in directions 1 and 2 respectively, \( \omega \) is the frequency, \( t \) is the time and \( \delta \) is the phase. As a consequence of using loadings with phase shifts, the loading paths lose the linear behaviour, for a more complex one. Figure 2.3 to Figure 2.6 show the load paths applied during the experimental tests according to Table 2.4.

3. THEORETICAL ANALYSIS

The theoretical approach undertaken, aimed to predict the direction of crack initiation through the following critical plane models

3.1. Findley

This model considers the normal stress on a shear plane has a linear influence on the alternating shear stress and determines the critical plane in the following way:
\[ \max_\theta (\tau_n + k\sigma_{n,max}) \]  
(3.1)

Where \( \tau_n \) is the alternating shear stress on plane \( \theta \), \( k \) is a material constant and \( \sigma_{n,max} \) is the normal stress on plane \( \theta \).

### 3.2. Brown and Miller

The Brown and Miller model considers cyclic shear and normal strains in the plane of maximum shear based on the principle that cyclic shear strains help crack nucleation, while normal strains contribute to crack growth. It is given by the following equation:

\[ \max_\theta \left( \frac{\Delta \gamma_{\text{max}}}{2} + S\Delta \varepsilon_n \right) \]  
(3.2)

Where \( \Delta \gamma_{\text{max}} \) is the maximum shear strain range, \( S \) is a material parameter and \( \Delta \varepsilon_n \) is the normal strain range on the plane subjected to maximum shear strain range.

### 3.3. Fatemi and Socie

This model is built on the same grounds as the Brown and Miller, however, this model proposes that normal strain terms should be replaced by normal stress. It is given in the following way:

\[ \max_\theta \left( \frac{\alpha \gamma}{2} \left( 1 + \frac{\sigma_{n,max}}{\sigma_y} \right) \right) \]  
(3.3)

Where \( \Delta \gamma \) is the shear strain range, \( \sigma_y \) is the material’s tensile yield stress, \( \sigma_{n,max} \) is the maximum normal stress on the plane of maximum shear strain and \( k \) is a material constant.

### 3.4. Smith, Watson and Topper

The SWT model is a critical plane model based on principal strain range and maximum stress on the corresponding plane, and can be found through equation (3.4).

\[ \max_\theta \left( \sigma_{n,max} \frac{\Delta \varepsilon_i}{2} \right) \]  
(3.4)

Where \( \sigma_{n,max} \) is the maximum stress and \( \Delta \varepsilon_i \) is the principal strain range.

### 3.5. Liu I and Liu II

Liu’s model is based on virtual strain energy (VSE) and is composed by one term related to mode I loading and a second one related to mode II loading. Liu I parameter corresponds to the term related to mode I and can be computed in the following way:

\[ \Delta W_I = (\Delta \sigma_n \Delta \varepsilon_n)_{\text{max}} + (\Delta \tau \Delta \gamma) \]  
(3.5)

Analogously, Liu II, can be computed in the following way:

\[ \Delta W_{II} = (\Delta \sigma_n \Delta \varepsilon_n) + (\Delta \tau \Delta \gamma)_{\text{max}} \]  
(3.6)

### 3.6. Chu, Conle and Bonnen

This model is based on the same principal as Liu’s models, although it considers maximum stresses instead of stress ranges and strain amplitudes instead of strain ranges as given in equation .

\[ \Delta W^* = \left( \frac{\tau_{n,max} \Delta \gamma}{2} + \frac{\sigma_{n,max} \Delta \varepsilon_i}{2} \right)_{\text{max}} \]  
(3.7)

### 4. NUMERICAL ANALYSIS

The numeric study was based on a finite element analysis (FEA) recurring to commercial FEA code ABAQUS®, which took into account the existence of a crack and allowed computing the SIF for the different crack sizes obtained at different instants from the monitoring of crack growth during the experimental tests. Half thickness was modelled in order to simplify the specimen.

In order to simulate the ideal crack behaviour, the crack tip was modelled with small circles around its end, partitioned into quarters as shown in Figure 4.1. Partitioning the circles is a step of elevated importance to emulate the singularity at the crack tip. Due to the fact that ABAQUS only recognizes one crack tip, a second crack tip was modelled, following the same modus operandi.

![Crack tip model detail](image)

Figure 4.1 – Crack tip model detail

At the crack tip the mesh was generated with wedge elements (C3D15) and the rest of the mesh was created with brick elements (C3D20R). All elements were 3D solids of quadratic geometric order. The resulting mesh was constituted by 32856 elements and 154172 nodes. Figure 4.2 shows the detail at
The crack tip, where the presence of the wedge elements is noticeable, and a representative sample of the rest of the mesh, showing the regularity of the mesh.

![Specimen mesh detail](image)

*Figure 4.2 – Specimen mesh (a) crack tip detail; (b) Rest of the mesh.*

The boundary conditions were applied in an adequate manner in order to replicate the experimental tests. The face at the specimen’s arms extremities were constrained in the respective normal direction, and in order to properly constrain the specimen a symmetry condition was applied at the midplane of the specimen, since only half thickness was modelled. The loads were applied in the faces opposing the constrained ones. The loads were discretized in increments of 0.05 to simulate a complete loading cycle, and the intensity of the load was computed with equations (2.1) and (2.2).

In order to correlate the data from the experimental tests with the numerical analysis, the stress intensity factor obtained from the finite element analysis for mode I and II was used in order to compute an equivalent stress intensity factor according to the one presented in [6], which can be computed in the following way.

$$K_{eq} = \frac{K_I}{2} + \frac{1}{2}\sqrt{K_I^2 + 4(1.155K_{II})^2} \quad (4.1)$$

Where $K_I$ and $K_{II}$ are the stress intensity factors for loading modes I and II respectively. The equivalent SIF range was computed through equation (4.2).

$$\Delta K_{eq} = K_{eq,max} - K_{eq,min} \quad (4.2)$$

Where $\Delta K_{eq}$ is the SIF range, $K_{eq,max}$ is the maximum value of the equivalent SIF for a complete load cycle and $K_{eq,min}$ is the minimum value of the equivalent SIF for a complete load cycle.

As the SIF is dependent on crack geometry, stress range, crack dimension for instance, the analysis conducted in this numeric study were based on the results of the experimental tests, i.e. crack length and the angle of the crack were used in the finite element modelling.

5. RESULTS AND DISCUSSION

5.1. Critical plane and crack initiation

The critical plane models do not provide an estimate of the crack initiation angle for the in-phase loading cases, due to the fact that no shear stresses are applied. For that reason, only the experimental measurement of the crack initiation angle is presented in Table 5.1. The measurement of specimen 003 was not possible due to the inadequate time interval for image capture during the test.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Crack initiation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTM2022-004</td>
<td>6°</td>
</tr>
<tr>
<td>BTM2022-005</td>
<td>6°</td>
</tr>
</tbody>
</table>

Table 5.2 shows the experimental and theoretical results regarding crack initiation angles.

<table>
<thead>
<tr>
<th>Model</th>
<th>Specimen</th>
<th>Crack initiation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Findley</td>
<td>008</td>
<td>±45°</td>
</tr>
<tr>
<td>BM</td>
<td>±72°/±18°</td>
<td>±45°/±16°</td>
</tr>
<tr>
<td>FS</td>
<td>±45°</td>
<td>±45°</td>
</tr>
<tr>
<td>SWT</td>
<td>±90°/0°</td>
<td>±90°/0°</td>
</tr>
<tr>
<td>Liu I</td>
<td>±90°/0°</td>
<td>±90°/0°</td>
</tr>
<tr>
<td>Liu II</td>
<td>±45°</td>
<td>±45°</td>
</tr>
<tr>
<td>Chu</td>
<td>±45°</td>
<td>±45°</td>
</tr>
<tr>
<td>Experimental</td>
<td>1°</td>
<td>0°</td>
</tr>
</tbody>
</table>

It is possible to verify that SWT and Liu I are the models that are closer to the experimental results. These models define the critical plane based only on normal...
strain/stress. When cracks initiate with a near zero angle a situation of Mode I loading might arise, and control crack propagation due to the fact that mode I is the most dangerous. Regarding specimens 004 and 005, The crack initiation angle is seen to be 6°, however it must be clarified that the rolling direction of this specimen was not parallel with arms 1-3 (and consequently not perpendicular to arms 2-4), instead the rolling direction showed an angle of approximately 15°. Even in this latter case, it can be considered that mode I controls crack propagation.

5.2. Crack propagation

Following the crack initiation results, this subsection presents the experimental data of crack length vs number of cycles as well as some of the images captured for all specimens. The relation between crack length and the corresponding number of cycles at which it was verified for the tests of specimens 004 and 005 are presented in Figure 5.1 and Figure 5.2 respectively.

![Figure 5.1 – Crack length vs number of cycles for specimen 004.](image1.png)

![Figure 5.2 – Crack length vs number of cycles for specimen 005.](image2.png)

For both these specimens, the direction of rolling of the sheet was of approximately 15° relative to the vertical direction of the images. Although the applied loads were quite different and the influence of that on specimen life is very significant, both specimens presented the same behaviour regarding crack propagation, which in this case translates as the crack propagation occurring nearly transverse to the direction of rolling of the sheet.

The relation between crack length and the corresponding number of cycles at which it was verified for the out-of-phase tests is presented from Figure 5.3 to Figure 5.5.

![Figure 5.3 – Crack length vs number of cycles for specimen 008.](image3.png)

![Figure 5.4 – Crack length vs number of cycles for specimen 009.](image4.png)

![Figure 5.5 – Crack length vs number of cycles for specimen 010.](image5.png)

Figure 5.6 To Figure 5.10 show the final fracture of the specimens 004 to 010, respectively.
For the out-of-phase tests (specimens 008 to 010), the rolling direction of the sheet was aligned with the directions of the specimens. It was verified that cracks propagated along the same direction as they initiated. In all out-of-phase loadings crack branching occurred, with the branches forming generally in a normal direction to the main crack.

5.3. Correlation of experimental and numeric data

The result of the numeric study, yielded an equivalent stress intensity factor range for every test and crack size measured. The correlation was attained establishing a relation between the crack propagation rate and the stress intensity factor range according to Paris Law:

$$\frac{da}{dN} = C \Delta K^m$$

(5.1)

Where $da/dN$ is the crack propagation rate, $\Delta K$ is the stress intensity factor range, and $C$ and $m$ are material constants.

For specimen 005, this relation is shown in Figure 5.11.
the following values: \( C = 1 \times 10^{-11} \text{ (mm/cycle)/(MPa√m)} \) and \( m = 5.82 \) and with a goodness of fit of \( R^2 = 0.8634 \). The constants found with this trend line show some agreement with the results found in literature, namely references [7] and [8], even though other magnesium alloys were the object of study.

For specimen 008, the relation is shown in Figure 5.12.

Figure 5.12 – da/dN vs ΔKeq.

The power trend line obtained in this case yielded the following constants: \( C = 6 \times 10^{-9} \text{ (mm/cycle)/(MPa√m)} \) and \( m = 3.93 \) with a goodness of fit \( R^2 = 0.8247 \). The constants obtained are along the same order of magnitude as the constants given in references [9] and [10].

For specimen 009, the relation is shown in Figure 5.13.

Figure 5.13 – da/dN vs ΔKeq.

The power trend line obtained in this case yielded the following constants: \( C = 2 \times 10^{-9} \text{ (mm/cycle)/(MPa√m)} \) and \( m = 4.45 \) with a goodness of fit \( R^2 = 0.7172 \). The constants obtained are along the same order of magnitude as the constants given in references [7] and [10].

For specimen 010, the relation is shown in Figure 5.14. For this particular case the data obtained showed larger scatter, with a lower goodness of fit than in previous cases (\( R^2 = 0.6637 \)). The constants obtained with the power trend line added to the data set were the following: \( C = 4 \times 10^{-12} \text{ (mm/cycle)/(MPa√m)} \) and \( m = 7.4 \). No correspondence to the constants obtained was found in the literature, particularly for the value of \( m \).

Figure 5.14 – da/dN vs ΔKeq.

5.4. Fracture surface analysis

In Figure 5.15 it is possible to observe indicators of crack propagation like the smoother surface in Figure 5.15a followed by a region with a rougher surface, which indicate that the crack propagated due to cyclic loading rather than overload, up to the point where material strength decreased enough, leading to final fracture. Another indication is present in Figure 5.15b where it is possible to observe radial marks fanning out from the crack initiation site suggesting rapid crack growth took place, which is coherent with the numeric/experimental data correlations, in the way that the exponents found for the crack propagation power laws consisted of considerably large values.

Figure 5.15 – Fracture surfaces of specimen 003.

Another interesting characteristic in Figure 5.15 is the apparent buckling (near the bottom of the figure) which may have
happened due to the reduction in strength caused by the cracks.

The fracture surfaces of specimen 008, subjected to a 45° out-of-phase loading, are shown in Figure 5.16. It is possible to observe the radial marks fanning out of the crack initiation site, and it is also possible to observe the growing surface roughness of the surface on Figure 5.16b.

Figure 5.16 – Fracture surfaces of specimen 008.

6. CONCLUSIONS

This research allowed drawing the following conclusions:

Most critical plane models did not provide reasonable estimations for the crack initiation angles, and no estimation in the cases of in-phase loading, due to the fact that no shear stresses are explicitly applied;

Critical plane models of SWT and Liu I provided good estimations for crack initiation, due to the fact that these models define the critical plane based on normal strains or stresses;

Crack initiation and propagation nearly perpendicular to one of the loading directions suggests heavier influence of mode I loading, the same way it was verified with the numeric study;

Although the in-phase tests were performed with specimens that were not aligned with the rolling direction, the general trend of crack initiation and propagation normal to the rolling direction was achieved;

Crack branching leading to significant secondary cracks normal to the initial crack took place for every out-of-phase case, which generated two mode I and mode II loadings due to the geometry of the specimen and loading conditions;

The correlation of experimental and numerical data provided acceptable results, namely the crack propagation power law constants, except for the fully reversed loading cycle;

Further tests should be carried out in order to verify and consolidate the obtained results.

REFERENCES