Multiaxial Fatigue Behaviour (HCF and LCF) of AZ31 Magnesium Alloy.

V. Anes, L. Reis, B. Li and M. Freitas

ICEMS, Instituto Superior Técnico, UTL, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.

ABSTRACT. *Nowadays in the automotive and aerospace industry, the improvement on fuel consumption and inherent vehicle performance has been an economical approach and a driving force from the customer side; moreover the fuel consumption reduction is also motivated by legislative rules to reduce primary energy consumption and environmental impact. In this context, magnesium alloys have been used to replace heavier structural materials such as steel and aluminium alloys; however exists a lack of information on the mechanical behaviour on magnesium alloys, in particular under multiaxial fatigue conditions. In this paper investigations were carried out to characterize the wrought magnesium alloy AZ31B-F behaviour in high and low cycle fatigue. Monotonic and cyclic mechanical properties were determined by tests on cylindrical specimens, moreover the multiaxial fatigue tests were performed with hourglass shape specimens. All specimens were machined from extruded rods. Four loading paths were considered; proportional, 90º out-of-phase and two uniaxial cases with R=-1 in tension and torsion. For each loading path a SN curve was determined. Under tension-compression tests, was found that the AZ31 magnesium alloy has a different mechanical behavior. Two different cyclic yield stress, one for tension, other for compression were determined. Furthermore, in high cycle fatigue regime it was observed that for the same equivalent stress the loading path type has a significant influence in the AZ31B-F fatigue strength.*

INTRODUCTION

In the 50´s a US bomber B-36 had about 8.6 tons of magnesium on structural and non-structural components, at that time consumption has reached 10000 tons per year in the US. However at 70´s and 80´s due to corrosion problems and the aluminium low cost alternative, conducted to set aside the magnesium alloys until the 90´s where the automotive industry has reached solutions to avoid the corrosion problem [1].

Nowadays, in the automotive and aerospace industries, fuel consumption plays an important role on strategic and economic decisions. In that context engineers are concerned about selecting lighter materials with improved mechanical properties to design structures in a synergetic contribution to energetic efficient systems.

However, the selecting options on structural materials with low weight and high specific strength are very few.

Lately magnesium alloys have been reconsidered as a good alternative to the aluminium alloys due to their improved combination of high strength at room temperature, good hot rolling, improved corrosion resistance and an 1/3 weight reduction comparatively to the aluminium alloys [2].
Nevertheless, the advantage on the magnesium alloys, the reduced cold formability and corrosion has been a problem on the industrial applications and a fatigue strength reducer factor. A new generation of magnesium alloys with high purity coupled with newer surface treatment techniques was developed to replace steel and aluminium alloys even in a harsh environment such as gearbox or pressure vessels. The actual research goal remains to achieve improved and lighter structural magnesium alloys with the capability to resist to physical phenomenon's such as creep or fatigue as the same time that magnesium is expanding into more critical applications [3].
Die casting magnesium alloys are common in the automotive industry being relatively well known their cyclic behaviour, however for the extruded magnesium only a limited work has been reported in literature. The AZ31B cyclic behaviour shows a accentuated anisotropy on plastic deformation and different yield strengths at tensile and compression loadings, the fatigue strength on magnesium alloys can be improved by mechanical mechanisms such as residual stress, micro plasticity or surface treatments such as shot peening or deep rolling being necessary to know the monotonic and cyclic behaviour to optimize the results from such techniques [4].
The objective of this work is to determine the extruded magnesium alloy AZ31-BF cyclic properties such as: cyclic strain hardening exponent, cyclic strength coefficient, fatigue strength coefficient, fatigue strength exponent, fatigue ductility coefficient, and fatigue ductility exponent. Also is studied the AZ31B-F behaviour subjected to a typical multiaxial fatigue loadings as well as two uniaxial fatigue loadings, pure tensile and pure shear in order to evaluate the material fatigue strength in LCF and HCF.

MATERIALS AND METHODS

Material

The material used in this study was the AZ31B-F magnesium alloy. This alloy was acquired in rod shape with 26 mm of diameter and 1000 mm of length. The rods were extruded in a temperature range of 360 to 382 ºC with an extrusion speed of 50.8 mm/s. The applied extrusion ratio was about six; after extrusion the alloy was air quenched. Test specimens were machined in the extrusion/longitudinal direction and polished with decrease levels of sandpaper. Two kind of specimen geometries were used; one to perform low cycle fatigue tests under strain control and other to perform multiaxial and uniaxial fatigue tests under stress control.
The axial low cycle fatigue tests were performed under strain control with R=-1 and a sinusoidal strain wave. Several total strain amplitudes were considered and obtained at same strain rate. The strain rate considered in this study was 0,003 [1/s].

The specimen geometry and dimensions for strain and stress control are presented in Figs. 1 and 2 respectively. The chemical composition of the magnesium alloy studied is presented in Table 1.

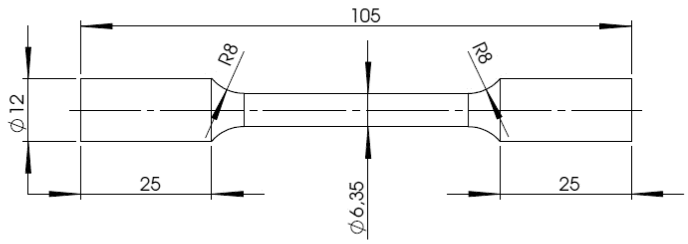

Figure 1. Specimen test geometry and dimensions for LCF tests.

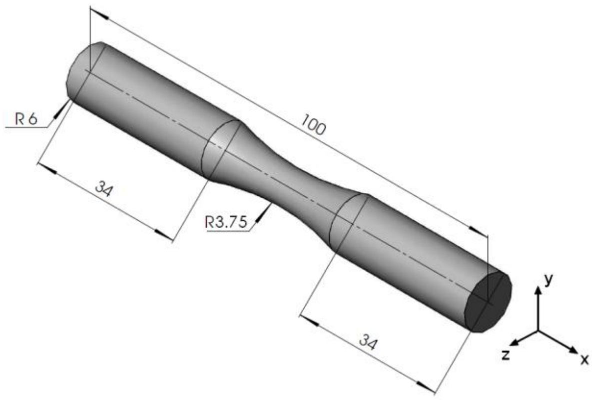

Figure 2. Specimen test geometry and dimensions for HCF tests.

Table 1: AZ31 magnesium alloy chemical composition.

Element	Al	Zn	Mn	Fe	Ni	Cu	Mg	Ca	Si
Weight[%]	3,1	1,05	0,54	0,0035	0,0007	0,0008	97	0,04	0,1

Tests were carried out in a Instron servo-hydraulic machine and considering 4 types of loading paths, shown in Figure 3.

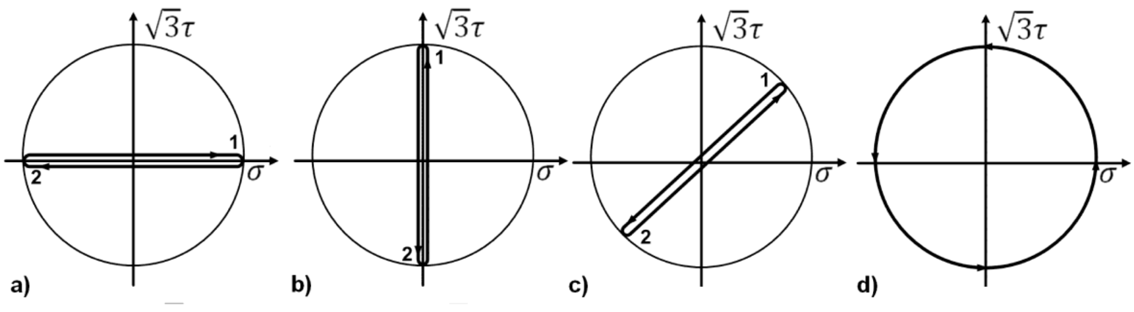

Figure 3. Uniaxial and multiaxial loading paths.

On Figure 3 a) and b) are shown the selected uniaxial loading paths, the pure tensile (PT) and pure shear (PS) loading cases; on c) and d) are shown the multiaxial loading cases considered on this study, proportional (PP) and out-of-phase (OP), respectively.

Theoretical Analysis

Cyclic material properties

From uniaxial strain control fatigue results can be obtained the material cyclic properties' by considering an appropriated correlation between stresses, strains and fatigue lives. Considering that the total strain amplitude can be expressed by the summation of elastic and plastic amplitudes as shown in Eq. (1).

$$\left(\frac{\Delta\varepsilon_t}{2}\right)=\left(\frac{\Delta\varepsilon_e}{2}\right)+\left(\frac{\Delta\varepsilon_p}{2}\right) \quad 1$$

Then the two right terms from Eq. (1) can be replaced by the Basquin and Coffin-Mason stress strain relation present in Eq. (2) and Eq. (3) leading to Eq. (4) which can be used to estimate fatigue lives when coupled to a damage parameter [5].

$$\frac{\Delta\varepsilon_e}{2}=\frac{\sigma_f^{'}}{E}\left(2N_f\right)^b \quad 2$$

$$\frac{\Delta\varepsilon_p}{2}=\varepsilon_f^{'}\left(2N_f\right)^c \quad 3$$

$$\frac{\Delta\varepsilon_t}{2}=\frac{\sigma_f^{'}}{E}\left(2N_f\right)^b+\varepsilon_f^{'}\left(2N_f\right)^c \quad 4$$

From experimental results a power law regression can be used to correlate the fatigue life with the correspondent strains, elastic and plastic, in order to obtain the material cycle parameters introduced on Eq. (4).

von Mises approach

The ASME Boiler and Pressure Vessel code Procedure [6] is based on the von Mises hypothesis, but employs the stress difference $\Delta\sigma_i$ between to two arbitrary instants t1 and t2:

$$\Delta\sigma_{eq}=\frac{1}{2\sqrt{2}}\sqrt{\left(\Delta\sigma_x-\Delta\sigma_y\right)^2+\left(\Delta\sigma_y-\Delta\sigma_z\right)^2+\left(\Delta\sigma_z-\Delta\sigma_x\right)^2+6\left(\Delta\tau_{xy}{}^2+\Delta\tau_{yz}{}^2+\Delta\tau_{xz}{}^2\right)} \quad 5$$

where the equivalent stress range $\Delta\sigma_{eq}$ is maximized with respect to time.

Eq. (5) produces a lower equivalent stress range, for some conditions, as is the case of out-of-phase, leading to an increase on the fatigue life, which is in contradiction with experimental results. However, this equivalent stress has been used to represent biaxial loading paths, see Figure 3.

MCE approach

The minimum circumscribed ellipse (MCE) approach [7, 8] was proposed to compute the effective shear stress amplitude taking into account the non-proportional loading effects. The MCE concept is based on a minimum circumscribed ellipse construction around the loading path trajectory represented on the deviatoric stress space. The MCE shear stress amplitude is given by:

$$\sqrt{J_{2,a}} = \sqrt{R_a^2 + R_b^2} \qquad 6$$

where Ra and Rb are the lengths of the major and minor semi-axis of the minimum circumscribed ellipse, respectively.

RESULTS AND DISCUSSION

Material Cycle parameters

On Table 2 is shown the cyclic fatigue parameters determined for the AZ31B-F alloy. The cyclic strain exponent achieved is near the average values for metals which are around 0.15.

Table 2. AZ31 monotonic and cyclic mechanical properties.

Tensile strength, MPa	290
Yield strength, MPa	203
Elongation, %	14
Young´s modulus, GPa	45
Strain hardening exponent	0,13
Cyclic Strain Hardening exponent, n´	0,17
Cyclic Strength coefficient, K´, MPa	576
Fatigue strength coefficient, σ´f, MPa	450
Fatigue strength exponent, b	-0.12
Fatigue ductility coefficient, ϵ´f	0,26
Fatigue ductility exponent, c	-0,71

Also the fatigue strength exponent and fatigue ductility exponent are under the expected results for metals alloys. In steels the fatigue strength coefficient is close to the true fracture strength and the fatigue ductility coefficient is close to the true fracture

ductility, in the case of reasonable values achieved. Also the cyclic strain hardening exponent is greater that the monotonic one which was expected, however the difference between values is smaller than the ones verified in literature [9].
On Figure 4 a) is represented the hysteresis loops for several strain amplitudes, starting on 0,5% and ended at 1,2% of total strain. From these results can be concluded that the cyclic yield stress at tension and compression are different; for the maximum strain amplitude the stress yield difference is about 70 MPa.
Despite this unsymmetric hysteresis behavior, under plastic deformation the material yield stress difference at compression and tension remains constant; which indicates a Bauschinger effect presence on the material plastic response.
Magnesium alloys tend to have a tensile cyclic hardening behavior being highly depend on the grain refinement, purity, lattice intrinsic behavior like twinning or foundry transformation processes [10].
On Figure 4 b) are shown the AZ31 monotonic and cyclic curves, there can be seen that Mg alloy has a cyclic hardening behavior in tensile with a slight softening behavior in compression. The yield stress difference between monotonic and cyclic values is about 50 MPa, moreover at compression this difference is about 20 MPa.

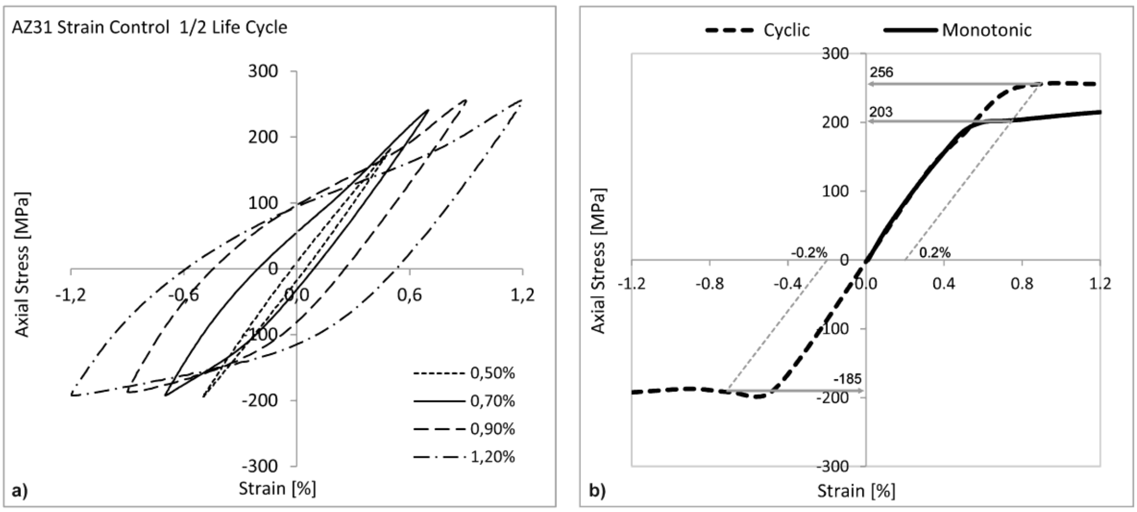

Figure 4. a) Half fatigue live hysteresis loops and b) AZ31 monotonic and cyclic behavior

SN fatigue life results

From Figure 5 a) can be seen that for the proportional and uniaxial loading cases the von Mises equivalent stress correlates well the AZ31 fatigue life behavior, moreover the selected non-proportional loading case, case OP, has a strong impact on the fatigue life strength under von Mises approach.
Using the MCE approach as an equivalent stress, it was verified an improvement on the scatter reduction around the uniaxial fatigue life reference, case PT; see Figure 5 b).

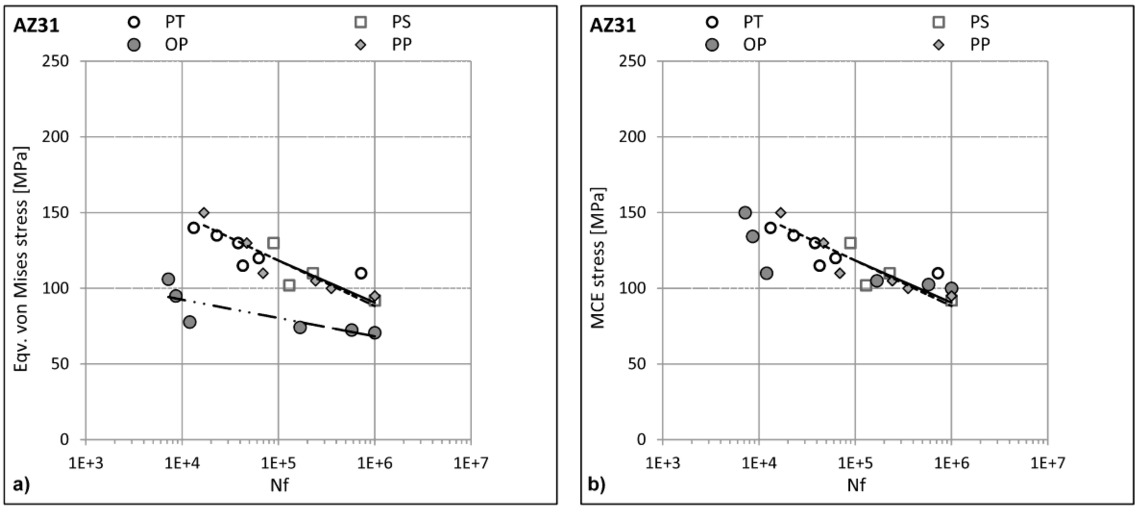

Figure 5. a) Az31 SN results for von Mises and b) Az31 SN results for MCE approaches

Using the Coffin-Manson equation with the AZ31B-F material parameters presented on Table 2, and using the von Mises and MCE equivalent stress as damage parameters it was estimated the AZ31 fatigue life; on Figure 6 is shown the fatigue life correlation with a life factor of 3 for the von Mises and MCE criteria.

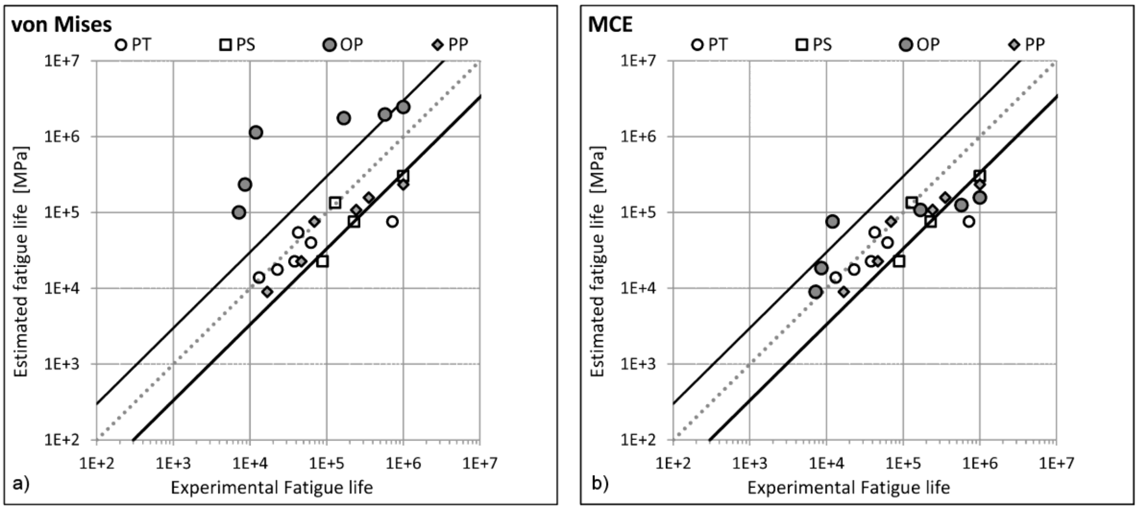

Figure 6. Theoretical/experimental fatigue life correlation a) von Mises approach, b) MCE approach

The scatter reduction around the pure tensile SN trend line resulted from the MCE approach verified on the Figure 5 b) leads to an improvement on the fatigue life estimations; see Figure 6 b). The MCE fatigue life correlation indicates that the MCE approach estimates non-proportional loading cases conservatively in contrast with the von Mises approach.

CONCLUSIONS

Strain controlled low cycle fatigue tests were carried out on an extruded AZ31B-F magnesium alloy. Cyclic deformation characteristics and fatigue parameters were evaluated and determined; also uniaxial and multiaxial fatigue tests were performed. A theoretical/experimental fatigue life correlation was made using the von Mises equivalent stress and the MCE approach. The AZ31 magnesium alloy shows different behaviors under tensile and compression regime, at tension was verified a cyclic hardening and at compression was observed a slight softening behavior. Under the von Mises approach, the computed AZ 31 fatigue strength under the selected non-proportional loading path gives non-conservative fatigue life estimations. However, that shortcoming was overcomed by using the MCE approach with acceptable correlations in the non-proportional and proportional loading cases.

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