

Cyclic Stress-Strain Behaviour of AM60B and AE44 Cast Magnesium Alloys and Its Impact on LCF Characterisation and Fatigue Analysis

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ABSTRACT

Light weight alloys are widely used in the automotive industry in order to meet environmental requirements. Cast magnesium alloys are candidate materials due to their high strength to weight ratio, high stiffness and excellent castability. However, some previously reported anomalous cyclic stress-strain behaviours of magnesium alloys have not been fully investigated especially in LCF characterisation. The main objective of this work was to investigate the cyclic loading-unloading behaviour of high pressure die cast (HPDC) AM60B and AE44 magnesium alloys under uniaxial tension or/and compression and its effect on LCF behaviour. It was found that classical linear stress-strain behaviour, for both AM60B and AE44 alloys, applied only to a very small range of stress beyond which significant pseudo-elastic behaviour was discovered. This affected LCF characterisation and subsequent fatigue analysis processes. It is revealed that the traditional Manson-Coffin and Ramberg-Osgood equations could not be used for magnesium alloys without considering the pseudo-elastic behaviour. It was also found that the 0.2% proof stress could be under-estimated significantly if the pseudo-elastic effect was neglected. The ISO 12106 (2003) standard for LCF data analysis breaks down when describing the LCF behaviour. A secant elastic modulus was introduced to describe the pseudo-elastic behaviour. The secant modulus decreased linearly with increasing applied stress amplitude. New parameters and equations for LCF characterisation and a new method for LCF analysis, including mean stress correction, are introduced for magnesium alloys.

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INTRODUCTION

Increasingly, light weight alloys are re-used in the automotive industry to reduce both vehicle weight and fuel consumption to meet environmental requirements. Cast magnesium alloys are of interest due to their low density, high strength to weight ratio, high stiffness and excellent castability. In modern durability (fatigue) design/analysis in the automotive industry, one of the most widely used methods is the strain-life approach (LCF), especially in the body and chassis areas. This method has been used predominantly to model steels and aluminium alloys which exhibit linear elastic behaviour under cyclic loading. Magnesium alloys, however, exhibit pseudo-elastic behaviour has been identified in cast AZ91 [1] and in cast Mg and Mg-Zn alloys [2]. Generally, any non-linearity in the unloading curve, in tension or compression after being plastically deformed, can be referred to as pseudo-elasticity. Upon reloading, the non-linearity creates a hysteresis loop. The development of a large pseudo-elastic strain when the material is plastically deformed results in a problem in any design/analysis where a constant value of the elastic modulus is assumed. If the pseudo-elastic effect is significant, conventional formulae relating stress and strain may become invalid. This is particularly important for low cycle fatigue (LCF)

characterisation. Numbers of papers have been published within the last decade regarding the LCF behaviour of a range of cast and extruded magnesium alloys [3,4,5,6,7,8,9,10]. The general view is that the LCF behaviour of magnesium alloys can be described by the Manson-Coffin and Basquin equations. However, any detailed consideration of the effects of pseudo-elasticity on LCF data analysis is absent. The main objective of this work was to investigate the cyclic loading-unloading behaviour of a high pressure die cast (HPDC) AE44 and AM60B magnesium alloys and its effect on their LCF behaviour.

MATERIALS AND EXPERIMENTAL PROCEDURES

Commercial alloys, AE44 (Mg-Al-rare earth alloy) and AM60B (Mg-Al alloy), produced by the high pressure die casting (HPDC) process were used in the work. The specimens for both materials were cut from vehicle components; from flat areas with effective thickness of 4~5 mm. The specimen geometry is presented in Figure 1. The chemical composition is listed in Table 1 and the monotonic stress-strain parameters are summarised in Table 2.

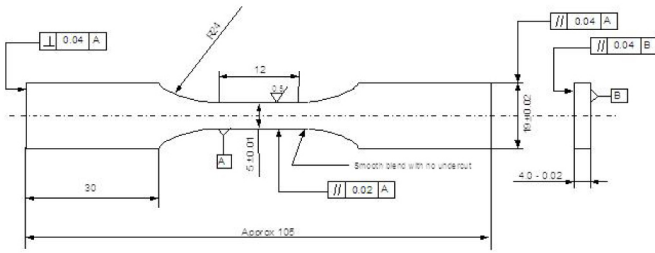


Figure 1. Specimen geometry.

Table 1. Chemical composition (wt%).

	Al	Mn	Cu	Fe	Zn	Si	Mg
AE44	4.1	0.21	<0.01	0.002	0.02	0.02	Rem
AM60B	6.0	0.28	<0.002	0.003	0.08	0.02	Rem

Table 2. Monotonic behavior.

	R_m [MPa]	$R_{p0.2}$ [MPa]	E [MPa]
AE44	251	119	43900
AM60B	220	122	42400

Both loading-unloading and LCF tests were performed on an MTS 810 servo-hydraulic test machine at room temperature using a 10 mm gauge length extensometer. The loading-unloading tests were run under load control. The LCF tests were carried out under fully-reversed ($R_\epsilon = -1$), constant strain amplitude at a frequency of 0.5-1Hz with 10% drop in the maximum stress defined as the crack initiation life.

RESULTS AND DISCUSSIONS

Loading-Unloading Test

The loading-unloading results for AE44 are shown in Figure 2. Generally, symmetrical hysteresis loops were evident in both tension and compression. The loop widths increased with the amount of total or plastic pre-strain. Similar result was observed for AM60B.

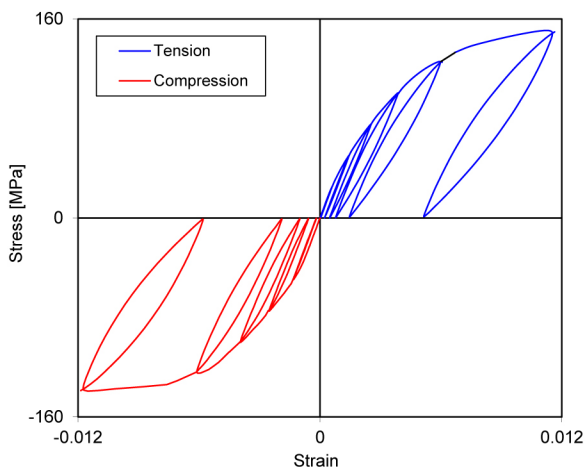


Figure 2. Loading-unloading result for AE44.

More detailed analysis is illustrated in Figures 3 and 4. It is clear that linear elastic behaviour applies only up to about 25MPa for AE44 and 50MPa for AM60B where the Young's modulus, E , is measured. With further loading, plastic deformation occurs. On unloading after some applied plastic strain (as low as 0.025%) a quantity of anelastic strain ϵ_{ae} (defined in Figures 3 and 4) is introduced. The total strain, ϵ_t , can therefore be separated into three parts: linear elastic strain ϵ_{le} , anelastic strain ϵ_{ae} and plastic strain ϵ_p ; i.e:

$$\epsilon_t = \epsilon_{le} + \epsilon_{ae} + \epsilon_p \quad (1)$$

On reloading, a closed loop is formed. The closed loop means that some energy, in addition to the plastic strain energy, has been introduced into the material (closed loop area) when the external force has been removed. This is believed to be the stacking fault energy due to twinning during deformation. Cáceres et al [1] identified that twinning rather than dislocation plasticity was responsible for the anelastic hysteresis. Twinning behaviour during tensile loading-unloading and LCF tests on magnesium alloys has also identified by a number of researchers [1-2, 11-12] in a range of magnesium alloys.

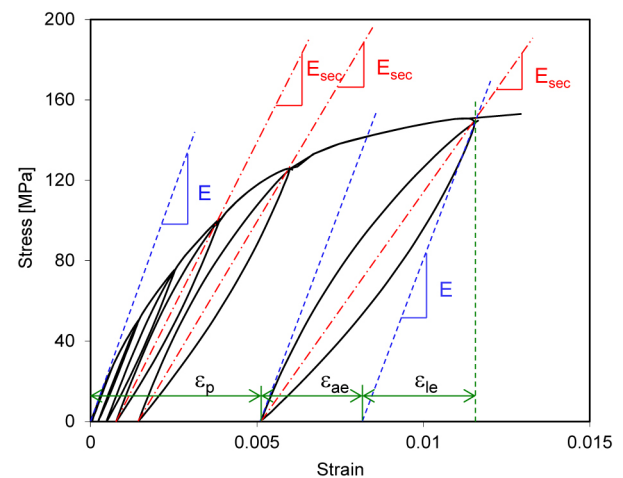


Figure 3. Hysteresis loop analysis for AE44.

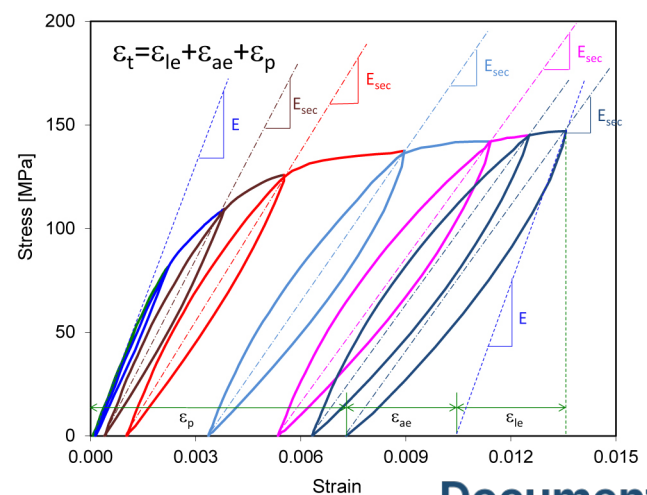


Figure 4. Hysteresis loop analysis for AM60B.

Based on the hysteresis (anelastic) strain, a series of secant moduli, E_{sec} , can be defined. With increasing plastic pre-strain (or applied stress amplitudes up to 150MPa), the loop width increases and the E_{sec} decreases to around 60% of the Young's modulus. Figures 5 and 6 demonstrate the relationship between the applied stress σ , E_{sec} and normalised E_{sec} (E_{sec}/E) for both alloys respectively. Little change was found for E_{sec} and E_{sec}/E within -50MPa to 50MPa range, and that a linear relationship applies beyond this range as shown in Figure 7:

$$\frac{E_{sec}}{E} = \alpha\sigma + \beta \quad (2)$$

where α and β are material constants which can be obtained from curve fitting (Figure 7).

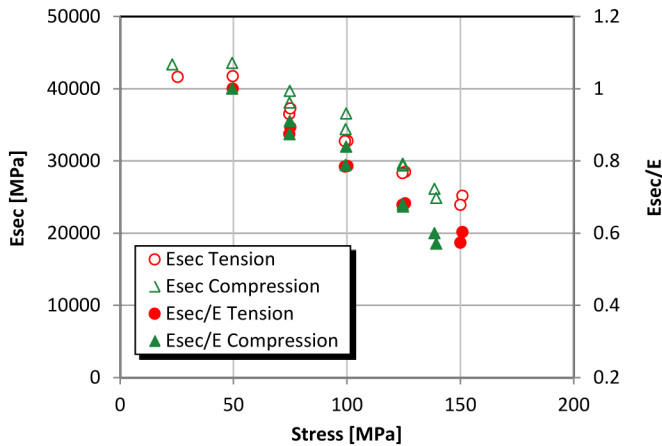


Figure 5. Relationship between stress, E_{sec} and normalised E_{sec} for AE44

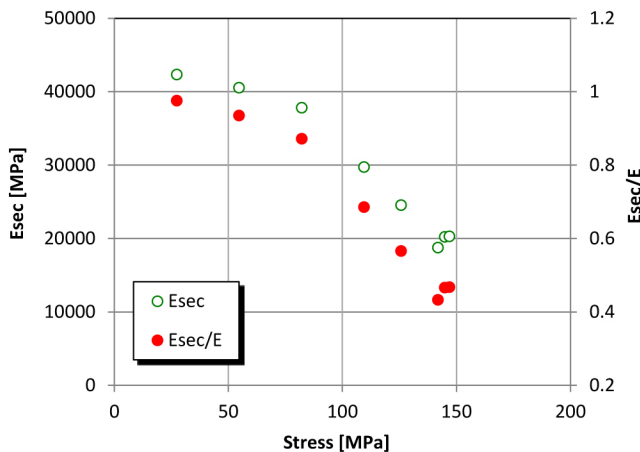


Figure 6. Relationship between stress, E_{sec} and normalised E_{sec} for AM60B.

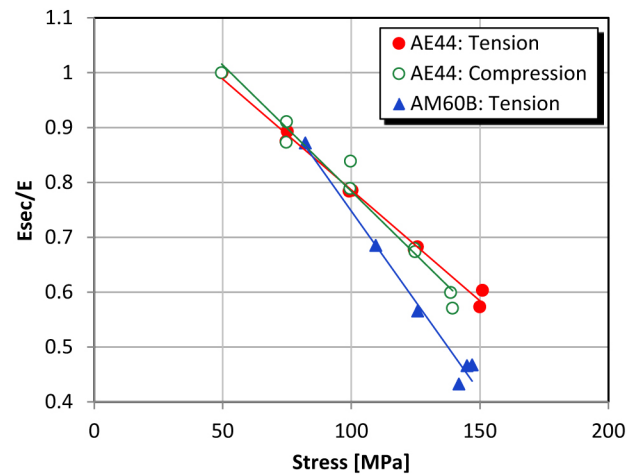


Figure 7. Relationship between stress and normalised secant modulus.

LCF Characterisation

LCF (Low Cycle Fatigue or Strain-Life approach) behavior is often defined by seven parameters through Manson-Coffin (5) and Ramberg-Osgood (6) relationship:

$$\frac{\Delta \epsilon_e}{2} = \frac{\sigma'_f}{E} (2N_f)^b \quad (3)$$

$$\frac{\Delta \epsilon_p}{2} = \epsilon'_f (2N_f)^c \quad (4)$$

$$\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \epsilon'_f (2N_f)^c \quad (5)$$

$$\epsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}} \quad (6)$$

E: Elastic Modulus

σ'_f : Fatigue strength coefficient

b: Fatigue strength exponent

ϵ'_f : Fatigue ductility coefficient

c: Fatigue ductility exponent

K': Strain hardening coefficient

n': Strain hardening exponent

Equations (3) and (4) represent the elastic and the plastic components respectively. The parameters are worked out through curve fitting based on a series of elastic and plastic strain components separated from the total strain amplitude from hysteresis loops obtained in strain controlled tests. Therefore the procedure used to define the elastic and the