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Influence of an overload applied within compressive base-line loading on crack propagation retardation in AM60B magnesium alloy

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ABSTRACT

Application of a tensile overload within an otherwise constant amplitude cyclic loading scenario is known to retard the resulting crack propagation in metals, thus resulting in longer fatigue life. The magnitude of retardation and crack length increment that would be affected by such an overload would depend on the overload ratio and the nature of baseline loading. However, the influence of an overload within a baseline loading with negative stress ratio on crack propagation has not been extensively investigated. Consequently, the influence of overload (with various overload ratios), applied within various baseline loadings consist of both positive and negative stress ratios, is considered in our experimental investigation. It is shown that the retardation response of AM60B magnesium alloy varies when the stress ratio of the baseline loading changes. Wheeler model's parameters are evaluated separately for positive and negative stress ratios. For positive stress ratio, the affected zone was modified based on the baseline loading's stress ratios.

The experimental results reveals that retardation trend in crack propagation would be affected significantly by negative stress ratios; therefore, Wheeler's model would have to be modified to account for this important issue. Moreover, the influence of loading sequence (i.e., when the overload is followed by a compressive underload) on retardation of crack propagation is also investigated.

Finally, surface roughness of the fractured specimens is carefully examined by a profilometer and its variation with respect to stress ratio is reported in this paper.

1. Introduction

In order to increase the application of high pressure die casting (HPDC) AM60B magnesium alloys in auto industry, more knowledge about alloys mechanical properties is required. Some investigators [1–5] have reported the monotonic and cyclic response, crack initiation and propagation mechanisms, influence of porosities and casting defects on fatigue response of the alloy. The influence of cold and elevated temperature on fatigue response of the alloy was also investigated by Nur Hossain and Taheri [6,7]. Nevertheless, due to the increase in alloy's application in auto industry, and considering the fact that cyclic loading is a dominant loading type in those applications, more investigation on characterization of fatigue and fracture responses of the alloy are required.

In general, any cyclic loading could be characterized by the stress range ($\Delta\sigma$) and stress ratio (R) as defined by the following equation.

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{1}$$

In the case of negative stress ratios, a portion of each cycle would be compressive. Ironically however, some standards [8,9] and investigators have either recommended the complete dismissal of the compressive loading cycles' amplitudes, or partial consideration of the compressive amplitudes when estimating fatigue life of metallic materials. For instance, Kujawski [10,11] proposed the positive stress intensity range (ΔK^+) and maximum stress intensity (K_{max}) in a cyclic loading as driving forces for crack propagation under such loading scenarios. It has however been shown that cracks could propagate even under fully compressive cyclic loading due to tensile residual stress around the crack tip and progressively decreases to be arrested [12–14]. It should also be noted that dismissal of the compressive portion of a cyclic loading in fatigue life estimation has been based on the hypothesis that the crack faces would be closed under a compressive loading cycle, and that the crack would not propagate under the compressive loading.

The importance of the compressive stress cycles (CSC) within a constant amplitude loading scenario has been thoroughly investigated in last decade. It has been proven that a crack would indeed propagate faster when subject to a negative stress ratio. In some of the recent works [15–17], the finite element analysis has been employed to show that the maximum stress intensity

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Nomenclature

R	stress ratio
σ_{min}	minimum stress
σ_{max}	maximum stress
da/dN	fatigue crack growth rate (FCGR)
$(da/dN)_{CAL}$	FCGR under constant amplitude baseline loading
Φ_R	reduction factor
$r_{p,i}$	current plastic zone radius
$r_{p,OL}$	overload plastic zone radius
a_i	current crack length
a_{OL}	crack length at which overload applied
m	shaping factor
Φ_D	delay parameter
Φ_R'	modified reduction factor
β	sensitivity parameter
a_d	crack length at which the propagation rate reaches to its minimum
α	plastic zone coefficient
K_{max}	maximum stress intensity factor
σ_y	material's yield strength
t	thickness
ρ	plastic zone dimension over the thickness of the plate
$r_{p,c}$	cyclic plastic radius
ΔK	stress intensity range
$\Phi_{R,\ min}'$	minimum reduction factor
a_{acc}	crack length at which the maximum acceleration occurs
Φ_{acc}	initial acceleration factor
$\Phi_{acc,\ max}$	maximum acceleration factor
R_a	surface roughness parameter
z	height of the asperity

factor (K_{max}) and the maximum compressive stress ($\sigma_{c,max}$) govern the crack propagation rate when the stress ratio is negative. Huang and Moan [18] proposed a modification parameter to the Paris model [19] in order to predict the crack propagation resulting due to both positive and negative stress ratios. Some modification of Walker's model [20] has also been suggested by the authors [21] in order to increase the predictive accuracy of Walker's equation for estimating crack propagation in AM60B magnesium alloy under a wide range of stress ratios. Silva [22] showed experimentally that the influence of compressive cycles would vary from one material to the other. He performed experimental studies on materials considering three different aspects; that is: cyclic hardening, cyclic softening and cyclic neutral. Due to the varied responses of those materials to the presence of compressive stress portion within a cyclic loading, he suggested that the intrinsic properties of the material should be considered within crack propagation models.

In most Industrial applications, however, structural components are rarely subjected to constant amplitude cyclic loading (CAL) and are usually subject to a random amplitude loading (RAL). In order to study the material response under real fatigue loading conditions, some simplified scenarios, such as the inclusion of an overload or underload within an otherwise CAL have been investigated.

The application of an overload has also been known to produce retardation in crack propagation and several models have been proposed to predict the crack propagation in such a circumstance. Among them, Wheeler [23] characterized the retardation by the affected zone, and suggested the use of the following equation for evaluating the magnitude of the crack propagation retardation.

$$\frac{da}{dN}=\Phi_R\left(\frac{da}{dN}\right)_{CAL},\ \Phi_R=\begin{cases}\left[\frac{r_{p,i}}{a_{OL}+r_{p,OL}-a_i}\right]^m & \text{when } a_i+r_{p,i}\langle\ a_{OL}+r_{p,OL}\\ 1 & \text{when } a_i+r_{p,i}\rangle\ a_{OL}+r_{p,OL}\end{cases} \tag{2}$$

where Φ_R' (da/dN) and $(da/dN)_{CAL}$ are the reduction factor, the retarded and steady state crack propagation rates, respectively. The reduction factor is a function of the current and overload plastic zone radii (i.e., $r_{p,i}$ and $r_{p,OL}$, respectively), and the shaping factor (m). It has been shown however that the affected zone in some materials would be larger or smaller than what was originally stated by Wheeler [21]. Therefore Wheler's model was modified by adding a sensitivity parameter.

The crack closure concept was originally introduced by Elber [24] and has been used by other researchers to predict the crack propagation rate. Elber observed that the crack faces may stay closed during a cyclic loading, even under the application of some levels of tensile stress. He proposed the "effective stress intensity range" as a driving force for crack propagation. Nevertheless, Silva [25] has shown that the crack closure is not adequate to predict the crack propagation at negative stress ratios. He also reported that under some specific negative stress ratios, the crack opening stress level could be compressive.

It has been observed that investigations considering the influence of overload on crack propagation rate in baseline loadings with negative stress ratio have been quite scarce. The lack of such

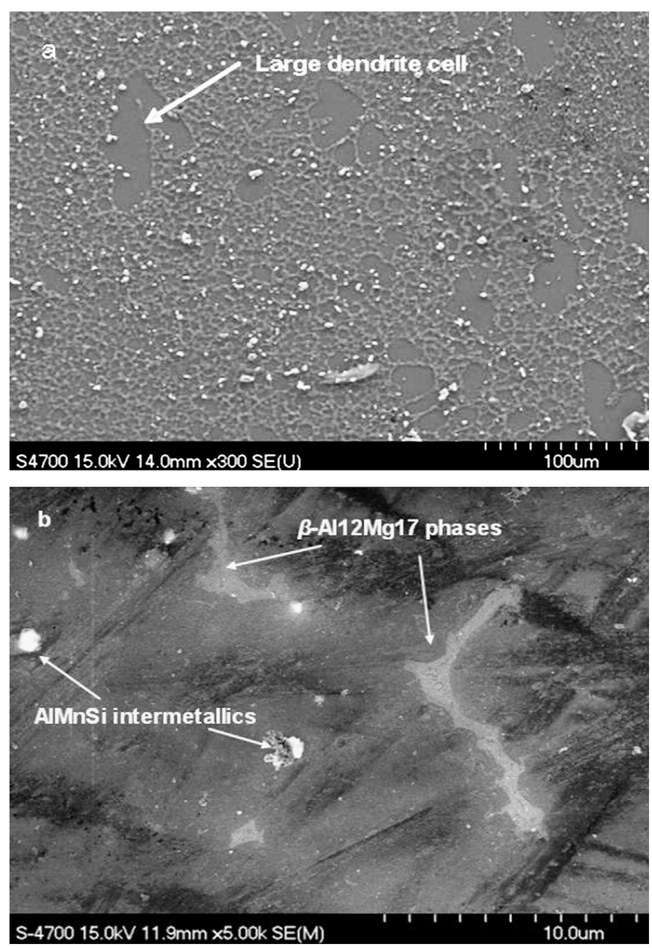

Fig. 1. (a) SEM observation of the microstructure of the alloy and (b) magnified SEM [1].