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A material sensitive modified wheeler model for predicting the retardation in fatigue response of AM60B due to an overload

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ABSTRACT

Application of an overload within an otherwise constant-amplitude loading scenario causes retardation in crack propagation. Several models have been proposed for predicting retardation in crack propagation due to an overload cycle. Among them, the widely used Wheeler model, assumes the ''affected zone dimension'' to be a function of the current and overloaded plastic zone radii. When one considers the actual shape of the plastic zone, however, one realizes that the affected zone dimension does not agree with that assumed by Wheeler.

In this paper, the influence of a single overload (but by considering three different overload ratios) on the fatigue crack growth retardation of center-cracked AM60B magnesium alloy plates is experimentally investigated. The retardation effect on crack growth due to an applied overload within a random-amplitude loading scenario, using various ''clipping levels'', is also investigated. The sensitivity of this material to overload is compared with the response of some other materials.

The actual radius of the plastic zone is evaluated for various stress intensity factors, using the finite element method. The results indicate that depending on the material, the affected zone would be sometimes larger or smaller than that produced by Wheeler's model. Subsequently, a new parameter, hereafter referred to as the ''sensitivity parameter'' (β), is introduced that enables one to evaluate the affected zone dimension more accurately. It is shown that the proposed modified model is more effective than the original one in predicting the retardation response of the alloy. The integrity of the modified model is also investigated by evaluating the retardation in some other materials.

1. Introduction

High-pressure die-cast (HPDC) magnesium alloys are increasingly being used in automobile and light-truck industries, mainly due to their lower density, higher specific strength and excellent castability and machinability. A few investigations have been carried out to study the monotonic and cyclic mechanical response of the alloy at room, elevated and sub-zero temperatures [1,2]. Due to the wide application of these alloys in auto industry however, cyclic loading is considered as one of the more dominant loading conditions. Therefore investigation of fatigue and fracture behavior of these alloys is of importance.

Application of overload in a cyclic loading is known to produce retardation in crack propagation [3,4]. Kumar et al. [3] studied the fatigue crack growth retardation in IS-1020 steel plate due to application of a single overload (with various overload ratios) applied within a constant-amplitude cyclic loading. They also attempted to formulate the number of delayed cycles as a function of overload ratio. The same experimental studies have been carried out on 6082-T6 aluminum alloy by Borrego et al. [4], in which the crack closure concept was applied to analyze the crack propagation retardation. The crack closure concept was initially introduced by Elber [5]; this procedure however requires a large body of experimental data in order to establish the stress intensity factor at the onset of crack opening. Shuter and Geary [6] showed that the degree of retardation would depend on specimen's thickness, stress intensity level and stress ratios. Tur and Vardar [7] studied the influence of a periodic tensile overload on crack growth retardation. They claimed that the maximum interaction was observed when the overload spacing was approximately half of the delayed cycles. Sander and Richard [8] showed that the amount of retardation would depend on the overload ratio, baseline stress intensity range and stress ratio, number of overload and fraction of mixed mode. Crack arresting, due to the application of overload with ratios greater than two, was also observed in their research.

Several models have been proposed for predicting the retardation of crack propagation due to application of an overload. Some modeling efforts [9,10] led to the introduction of various equivalency parameters into the constant-amplitude loading fatigue crack growth (FCG) models for predicting the crack propagation rate under variable-amplitude loading. For instance; Barsom

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[9] applied the root-mean-square technique to define the equivalent stress intensity factor, and Hudson [10] defined the equivalent minimum and maximum stress, using the same technique. These equivalent parameters were applied along with a Paris-like model [11] to determine the crack propagation rate. In one of our previous works [12], it was demonstrated that these models could not accurately predict the crack propagation rate in AM60B plates under variable amplitude loading. Some other models [13,14] have also been developed with focus on the plastic zone radius developed ahead of the crack tip. At this juncture it should be acknowledged that the shape of the plastic zone is not a perfect circular shape; therefore, the word "radius" used throughout this paper refers to the distance from the track tip to the boundary of the zone ahead of the crack.

Wheeler [13] assumed that as soon as an overload is applied, a larger plastic zone (than that developed in the previous loading cycle) would develop ahead of the crack tip. This larger plastic zone becomes active in suppressing (or retarding) the crack growth; as a result, the crack tip would grow in a slower rate during the subsequent cycles. Wheeler then assumed that the retardation in FCG would continue until the boundary of the current plastic zone reaches to the boundary of the large plastic zone developed as a result of the overload. He developed the following equation for the evaluation of the FCG rate:

$$\frac{da}{dN} = \Phi_R \left(\frac{da}{dN}\right)_{\mathrm{CAL}} \tag{1}$$

$$\text{where}: \Phi_R = \begin{cases} \left[\frac{r_{\mathrm{p,i}}}{a_{\mathrm{OL}}+r_{\mathrm{p,OL}}-a_i}\right]^m & \text{when} \quad a_i + r_{\mathrm{p,i}} < a_{\mathrm{OL}} + r_{\mathrm{p,OL}} \\ 1 & \text{when} \quad a_i + r_{\mathrm{p,i}} > a_{\mathrm{OL}} + r_{\mathrm{p,OL}} \end{cases} \tag{2}$$

In the above equations Φ_R is the retardation factor, which is a function of the current plastic radius, $r_{\mathrm{p,i}}$, the overload plastic radius, $r_{\mathrm{p,OL}}$, the current crack length, a_i, and the crack length at which the overload is applied, a_{OL}, and m is a shaping exponent obtained through curve-fitting, which controls the magnitude of retardation. This model has been used widely due to its simplicity. Using this approach, Taheri et al. [15] attempted to estimate the fatigue life of a 350WT steel plate subjected to some overloads applied within a constant amplitude loading scenario. They used the plane strain assumption to model the plastic zone region and reported a good agreement with the experimental results. It should also be noted that fundamentally, the development of the Wheeler model is based on the plastic zone developed under monotonic loading, not due to cyclic loading.

Khan et al. [16] used both the Wheeler and Elber models to predict the fatigue life of specimens subjected to variable amplitude loading. They obtained better prediction when the Wheeler model was incorporated in comparison to Elber's model. Rushton and Taheri [17] modified the Wheeler model in order to better predict the crack propagation rate when a compressive underload was applied following a tensile overload. For this purpose, they introduced an effective plastic zone radius and modified the shaping exponent. Kim and Shim [18] studied the crack retardation and variability of the results on a 7075-T6 aluminum alloy. Their model, similar to the wheeler model, is characterized by a retardation coefficient, the affected zone and one extra parameter, which tracks the retardation in crack-growth. They have also shown that the affected zone is a function of the overload plastic zone radius.

In this paper, the influence of a single overload (having various overload ratios), on the crack propagation rate of AM60B magnesium alloy plates hosting a centre-crack is studied. A modified Wheeler model is developed to improve the original model's accuracy in assessing the retardation in FCG due the applied overload.

2. Experimental investigation (constant-amplitude loading baseline)

The material used in our investigation was AM60B magnesium alloy that was provided by Meridian Technologies Inc. (Strathroy, Ontario). The specimens, with the as received thickness of 3 mm, were configured according to ASTM E647-08 recommendations [19]. As shown in Fig. 1, a 6 mm long center notch was incorporated using a jeweler's saw (having thickness of 0.25 mm). Specimens were drilled at both ends so they could be attached to the fixtures. The alloy manifests a bilinear elastic–plastic behavior; its mechanical properties are summarized in Table 1.

Cyclic loading was applied using the Instron servo-hydraulic universal test machine, with a capacity of ±100 kN under dynamic, or 200 kN under static loading conditions, controlled with 8501 digital electronics. In order to generate sharp crack tips, a constant amplitude cyclic loading with the maximum stress of 45 MPa and stress ratio of $R = 0.1$ was applied to grow the notch tips to sharp cracks in the specimens. This pre-cracking procedure continued to increase the crack length to $2a = 8$ mm (where "a" is half of the crack length). Then, the loading scenarios were applied and the crack length, measured from the sharp pre-crack tips, was recorded against the number of cycles. Our fixtures were designed such that any unwanted planer bending (potentially generated as a result of misalignment) could be cancelled out, thus enabling to crack tips to grow in equal lengths.

Specimens' surfaces were polished as per ASTM 1245 [20] recommendations, using various grits of fine abrasive papers and finalized with a rotary pad and a suspension of 3-μm aluminum oxide. A 92× magnifying power digital microscope, mounted on a travelling micrometer, was used to measure the crack length accurately. The microscope was equipped with 8 LEDs to illuminate the crack surface. The test setup is shown in Fig. 2.

A single overload with different overload ratios (i.e., OLR = 1.5, 1.75 and 2) was applied within an otherwise constant amplitude loading scenarios. The baseline loading consisted of a cyclic loading with the maximum stress of 45 MPa and stress ratio of $R = 0.1$. All baseline loadings were applied at 10 Hz frequency, while the overload was applied very slowly. Each overload was applied at crack length of $2a = 11.5$ mm. Fig. 3 shows the crack tip after the application of the largest overload (i.e., OLR = 2). The dark area surrounding the crack tip represents the bean shape plastic zone.

Two specimens were tested at each overload ratio and the crack propagation versus the number of cycles was recorded and shown in Fig. 4. As can be seen, the application of overload ratio of OLR = 2 significantly increased the fatigue life of the specimens. Attempts were made to apply smaller OLR (for instance, OLR = 1.25), but no substantive increase in fatigue life was observed as a result; therefore, the results are not reported.

In order to measure the crack propagation length, the loading was interrupted for a few seconds after the application of a certain number of CAL cycles. Then, at the desired interval of loading cycles, the overload was applied, but at a slower rate (when compared to the base CAL loading cycles), so that the exact response

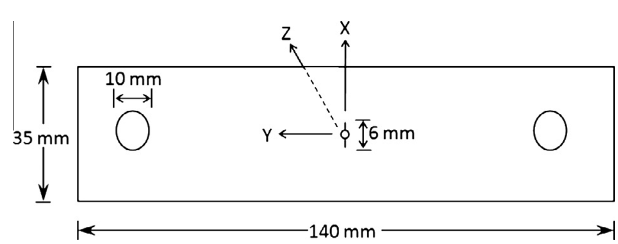

Fig. 1. Specimen geometry.