Engineering Fracture Mechanics 114 (2013) 42–54

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Loading history effect on fatigue crack growth of extruded AZ31B magnesium alloy

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ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 22 September 2013
Accepted 8 October 2013

Keywords:
Extruded AZ31B magnesium alloy
Fatigue crack growth
Specimen orientation
Overload
Sequence loading

ABSTRACT

An experimental investigation was conducted on the fatigue crack growth (FCG) behavior of an extruded AZ31B magnesium (Mg) alloy in ambient air. Compact tension (CT) specimens oriented in three different directions with respect to the extrusion direction were employed in the study. The influences of overloading and two-step high-low sequence loading on FCG were investigated in detail. Single tensile overloads with three overload ratios (1.5, 1.75, and 2.0) were applied during otherwise constant amplitude loading. A single overload retarded the crack growth rate in all the three specimen orientations. The crack growth rate decreased immediately to a minimum value right after the application of a tensile overload and increased quickly to a stable value expected at constant amplitude loading. No visible torn fracture was observed at the crack tip right after overloading but the crack tip was clearly blunted. Results from the two-step high-low sequence loading reveal that FCG retardation occurred at the beginning of the lower amplitude step when the maximum load was lowered in the second loading step, which is similar to the case of a single overload. Walker's model can correlate well the crack growth experiments with different *R*-ratios. Wheeler's model can reasonably predict the influence of overload and high-low loading sequence on the FCG in the AZ31B Mg alloy.

1. Introduction

Magnesium (Mg) alloys are the lightest structural metal and are environment-friendly. Due to their exceptional physical properties such as high specific strength, good machinability, and excellent recyclability, they are being adopted as structural components in transportation vehicles, electronic apparatus, and aircraft industry [1–3]. Structural components are inevitably subjected to cyclic loading, and fatigue fracture is the most frequent form of material failure. In the last decade, extensive studies have been carried out to study the fatigue behavior of Mg alloys.

Cast Mg alloys usually show low fatigue strength under cyclic loading, which is caused by casting pores and inclusions left from the casting process [4–8]. Wrought Mg alloys exhibiting superior fatigue properties are typically free of casting defects. Consequently, wrought Mg alloys are more appropriate for the study of the intrinsic fatigue mechanisms [9–33]. The strain-life curve of a Mg alloy often exhibits a detectable transition from the low-cycle fatigue regime to the high-cycle fatigue regime and two Manson-Coffin equations can be used to fit these two parts [24,26–30]. The fatigue properties of Mg alloys are significantly affected by factors such as heat treatment [34,35], environments [36], and loading condition [30,37]. Additionally, the fatigue properties of wrought Mg alloys are anisotropic due to initial texture and microstructure [37–40].

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http://dx.doi.org/10.1016/j.engfracmech.2013.10.012

Nomenclature

a_h	crack length at the end of the first loading step
a_o	initial crack length measured from the line of action of the applied load
a_f	crack length at termination of experiment
a_{OL}	crack length at overload applied
C	material constant
da/dN	crack growth rate
FCG	fatigue crack growth
$K_{\max}$	maximum stress intensity factor in a loading cycle
K_{OL}	stress intensity factor caused by overload
$\overline{K}$	effective stress intensity factor
L	extrusion direction
n	material constant
$P_{\max}$	maximum load in constant amplitude experiment
P_{OL}	overload
R	radial direction
$R_{1\text{-ratio}}$	load ratio of higher load amplitude
$R_{2\text{-ratio}}$	load ratio of lower load amplitude
$RROL$	ratio of the FCG rate right after the application of the overload to the FCG rate right before the application of the overload
T	direction perpendicular to the L–R plane
W	specimen width measured from the line of action of the applied load to the edge of the specimen
α	material constant
Δa_{oizs}	overload influencing zone size which is the crack length measured from the moment of overloading to the moment when the FCG rate returns to that of the stable FCG expected under constant amplitude loading
ΔK_f	stress intensity factor range at termination of experiment
ΔK_{op}	stress intensity factor range before overload
ΔK^+	positive part of the stress intensity factor range
$\Delta P_1/2$	load amplitude in first loading step
$\Delta P_2/2$	load amplitude in second loading step
ΔK_H	stress intensity factor range of last loading cycle in the first step
ΔK	stress intensity factor range in a loading cycle
k	effective stress intensity factor

The fatigue life of most structures and materials are composed of two stages: crack initiation and crack propagation. Fatigue crack growth (FCG) under constant amplitude loading is often described by the crack growth rate (da/dN) as a function of the stress intensity factor range (ΔK) in a log–log scale. Similar to other metallic materials, the FCG curve of a Mg alloy consists of three stages: slow crack propagation (threshold), stable crack growth, and unstable crack growth. The FCG rate is largely influenced by the microstructure of Mg alloys. Fine grains and precipitates in Mg alloys can increase the tensile strength and the FCG resistance [41–44]. Inhomogeneous microstructure leads to a low FCG rate in wrought Mg alloy [37,41–45]. In addition, extensive investigations reveal that the FCG rate of a Mg alloy increases with decreasing loading frequency [44,46] and increasing load ratio [47–49]. It is also found that wet atmosphere and distilled water can accelerate the FCG rate while oxidation will retardate crack propagation [50,51].

In engineering applications, a structural component is often subjected to variable loading rather than constant loading. In order to evaluate the fatigue property of structural components under realistic loading spectrum, FCG experiments have been conducted for aluminum (Al) alloys [52–55], carbon steels [56–59], stainless steels [60–63], and Mg alloys [64–66] under variable amplitude loading. A tensile overload usually results in retardation in FCG and the FCG behavior after overloading is material-dependent. For an aluminum alloy [55], the FCG rate decreases immediately to a minimum value right after the application of the overload and increases as the crack extends. For some steels, the FCG rate decreases gradually to a minimum value before increasing to reach the stable growth rate [56,58,60]. Crack growth acceleration is observed to occur immediately after the application of a tensile overload in some other materials [54,57,59,61,63]. On the other hand, acceleration in FCG rate are usually observed by application of a compressive underloading [62,67,68].

The influence of overloading and sequence loading on FCG is commonly interpreted by crack closure, crack blunting, and compressive residual stresses ahead of the crack tip induced by the application of overload [52–65]. Based on the crack closure concept, Elber [69] proposed an effective stress intensity factor range to evaluate the retardation effect caused by overloading. Considering of crack closure and residual plastic zone size, Matsuoka [70] developed a model to explain the retardation induced by single and multiple overloading. Wheeler's model [71] introduces a retardation factor in the Paris law by taking into account the enlarged yield zone in front of the crack tip induced by overloading. Based on experiments on mild steel specimens, Lu and Li [72] proposed a semi-empirical model for the consideration of overload effect on FCG.