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Effect of notch acuity on the fracture behavior of AZ31 Mg alloy

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ABSTRACT

In this work, the effect of notch acuity on fracture behavior of rolled AZ31 Mg alloy is investigated by conducting mode-I fracture experiments using four point bend specimens with different notch root radii. Digital Image Correlation (DIC) technique is employed to determine the angle of rotation of the specimen and the fracture toughness is obtained from moment versus rotation curves. It is found that the fracture toughness J_c increases linearly with notch root radius beyond a threshold value and is almost constant below this limit. This trend is rationalized from fractographic observations near the crack initiation region which show predominantly quasi-brittle features for fatigue pre-cracked specimen and dimples of increasing size in notched specimens with enhancement in notch root radius. Significant tensile twinning is noticed in the ligament for all specimens, especially near their far edge. This is found to impart substantial toughening even in the fatigue pre-cracked specimen which fails by a locally quasi-brittle mechanism. Finally, the strong increase in J_c with notch root radius beyond a threshold is interpreted using two ductile fracture initiation models.

1. Introduction

In recent years, weight reduction of automobile vehicles is being achieved by using components made of light metals like magnesium in the form of cast or wrought products [1,2]. Magnesium possess low density, high specific strength, good damping capacity, machinability and castability. However, the widespread usage of magnesium and its alloys for structural applications is impeded by their poor corrosion resistance, low ductility and fracture toughness at room temperature.

Magnesium has a hexagonal close-packed (HCP) crystal structure and plastic deformation occurs by activation of various slip (basal, prismatic, pyramidal) and twin systems [3–5]. Among the twin systems, $\{10\bar{1}2\}$- and $\{10\bar{1}1\}$-types, referred to as tension twins (or TTs) and contraction twins (or CTs), operate to accommodate extension/ contraction along the c-axis of the HCP crystal [3,6]. TTs possess low critical resolved shear stress or CRSS, are lenticular in shape, can widen rapidly to engulf entire grains [7] and play a crucial role in imparting hardening [8]. There have been numerous studies which have addressed the role of various slip and twin systems in causing plastic deformation during uniaxial tension/compression loading of Mg alloys [7,9–15]. An inherent characteristic about the deformation response of these alloys is their highly anisotropic nature owing to the HCP structure. By contrast, only a few studies have been carried out on the fracture behaviour of Mg alloys.

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Nomenclature

P, Δ	load and load point displacement
M, θ	moment and rotation
J	energy release rate
J_c	energy release rate at crack initiation
P_c,	load at crack initiation
M_c, θ_c	moment and rotation at crack initiation
ρ	initial notch root radius
$\bar{\rho}$	current notch root radius
L, W	half-span and width of four point bend specimen
a	crack length
B	specimen thickness
d	offset distance between support and loading rollers
η	shape factor in J calculation
K_{IC}	fracture initiation toughness
σ_m, τ_o	hydrostatic stress and initial shear yield strength
σ_c	mean nucleation stress
L_o	initial distance between notch tip and center of the nearby nucleated void
$\bar{L}$	current distance between notch tip and center of the void
ε_c	critical value of plastic strain at crack initiation
δ_{tc}	notch opening displacement at crack initiation
J_c^{nt}	near-tip value of J, at crack initiation
J_{co}	contribution to J_c from dissipation in background plastic zone
R_o	initial radius of spherical void located ahead of the notch tip in Rice and Johnson model
R_1, R_2	current longitudinal and traverse void radii
D, E, F, G	material parameters in the Rice and Tracey void growth equations
U	horizontal component of displacement field
J_e, J_p	elastic and plastic parts of J-integral
A_{tot}	total area under M-θ curve
A_e, A_p	elastic and plastic parts of A_{tot}

Somekawa and Mukai [16–18] and Somekawa et al. [19–21] conducted K_{IC} tests using fatigue pre-cracked three point bend (TPB) specimens cut from rolled plate/extruded rods of Mg alloy. In these experiments, the fracture toughness was determined by using stretch zone (SZ) analysis and was reported in the range 15–29 MPa $m^{1/2}$ based on different orientations, grain sizes and alloy composition. Somekawa et al. [20] observed crack propagation along the boundary between TTs and the matrix without much crack blunting. They also found that the fracture surface showed twin induced quasi-brittle cracks. Sharma et al. [22] examined the mode I/III behavior of Mg alloys with different Al content. Kaushik et al. [23] conducted mode-I fracture experiments using notched TPB magnesium single crystal specimens with three lattice orientations. They noted that while crack propagation occurs along TT boundaries, the evolution of TT volume fraction in the specimen for different orientations correlates well with the energy release rate history. Thus, they concluded that tensile twinning is an important dissipation mechanism that can impart toughness. This view was further reinforced from the mode-I fracture experiments using compact tension (CT) specimens of rolled AZ31 Mg alloy with notches of diameter about 90 μm by Prasad et al. [24]. They found ductile fracture features involving micro-void growth and coalescence and a moderately high notched J_c value of around 46 N/mm (equivalent K_c of 48 MPa $m^{1/2}$). Also, they estimated that the dissipation caused by tensile twinning alone in the ligament can account for 70% of the J_c value.

The effect of stress triaxiality on plastic anisotropy, ductility and failure mechanism in AZ31B Mg alloy was investigated by Kondori and Benzerga [25]. They conducted tension tests with smooth and externally notched cylindrical specimens with different notch root radii to create a range of stress triaxiality levels. Ductility was found to be maximum at moderate triaxiality and to decrease with increase in triaxaility. They observed ductile failure with micro-void growth and coalescence in blunt notch specimens as opposed to twin induced quasi-brittle cracks in the case of acute notch specimens. Therefore, they proposed that ductile to brittle transition in failure behaviour occurs with increase in triaxiality. These findings were further supported by the finite element simulations of Selvarajou et al. [26,27] wherein notched cylindrical tensile specimens with different notch acuities were analyzed using crystal plasticity formulation. In addition, the texture was systematically varied to understand its role on the stress state and slip/twin activities. It must be mentioned that similar brittle to ductile transition with reduction in stress triaxiality has been reported for AZ91 and AM60 Mg alloys as well [28,29].

A series of experimental studies have been carried out very recently to understand ductile damage processes in commercially pure Mg and its alloys using thin sheet specimens with laser-drilled holes [30–34]. These investigations have revealed

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