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Flow and fracture study for ZK60 alloy at dynamic strain rates and different loading states

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ABSTRACT

This paper presents an on-going study of light-weight alloy ZK60 magnesium. The uniaxial tensile tests were carried out with strain rate range of (0.0001–1000)/s^{-1} and with different stress states. Elemental data was identified through an iteration process using finite element analysis. The modified Johnson-Cook (J-C) model was calibrated to describe the flow stress as a function of strain and strain rate. The modified Mohr-Coulomb (M-C) model, considering the effects of strain, stress state and strain rate, was proposed with satisfactorily determined parameters. Compared by the original J-C fracture model, the modified M-C fracture model tracks the fracture behavior more accurately. To complement the macroscale fracture information, fractography reveals the fracture and deformation mechanism in microscale. The agreements between the simulations and tests further confirmed that the modified J-C material model and the modified M-C material model can give a precise estimate of the mechanical and fractural behavior of the ZK60 alloy.

1. Introduction

As lightweight measures have direct impacts on driving agility and fuel consumption, lightweight materials and designs are becoming increasingly important in many industries. Magnesium alloy is among the lightest structural metal and exhibits good strength and stiffness at both room and elevated temperature [1–3], thus it shows high potential for weight reduction in certain applications. In automobile industry, it severs as automobile parts, such as seat frame and hub, to optimize ride comfort. Aircraft applications of magnesium alloy mainly include fins, stabilizers and jet engines. Those magnesium structures, with their higher exposure to dynamic loads at different stress states, tend to fail by plastic deformation and fracture. To meet all the needs in design stage, Finite Element Method (FEM) is taken to analyze the structure of the magnesium components and the simulation of the impact environment in the test stage. Presently, the constitutive equation development incorporating strain rates and stress states is a necessary prerequisite for numerical simulation. As simulations involve events such as plastic flow and fracture behavior, the usual methods are to develop with two different models, one representing plastic flow and the other representing fracture.

Material models are mathematical representations describing the relationship between flow stress, strain and strain rate [4]. In particular, the Johnson-Cook (J-C) model [5] is most widely embedded in commercially available computational codes [6–9], as it incorporates the strain rate effect and only requires five material constants providing for easy calibration. Nevertheless, the model is still not advanced enough to account for the complexity of the dynamic response [10–13], so there also exist several modifications of the J-C model in open literature. Modifications have been made to formulate material model considering flow softening [13] and couple effects [11,12].

Fracture models are proposed to make the damage stage mathematically tractable. Continuous efforts have been made in the development of ductile fracture models of different complexities [14,15]. Among these fracture criteria, two fracture models have been successfully utilized in literature for industrial applications. One is the Johnson-Cook (J-C) fracture model, which is a definition of fracture strain based on empirical observation and the model is commonly used in the high-velocity impact problem [16]. Another one is the modified Mohr-Coulomb (M-C) model [17]. The M-C model considers the stress triaxiality and lode angle effect and finding wide application for ductile fracture of uncracked bodies [17–20].

This paper is aiming at proposing a reliable numerical description to predict the mechanical and fracture behaviors incorporating strain rates and stress states for a magnesium alloy. The following section introduces the experimental programme of tests conducted in different

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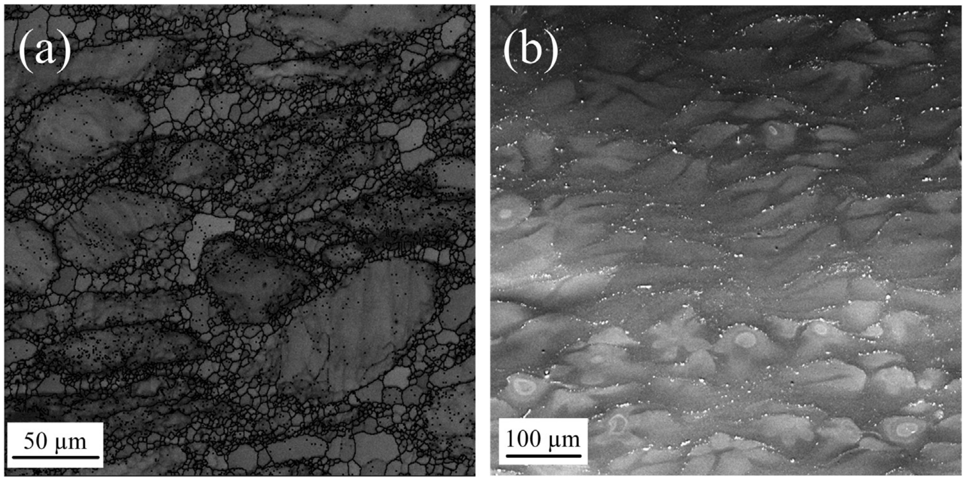

Fig. 1. Microstructure for ZK60 magnesium alloy. (a) Metallography and (b) Back Scattered Electron (BSE) image.

loading conditions and dynamic strain rates. Several experimental data are identified through an iteration process using finite element analysis. In Section 3, a modified J-C model is developed at dynamic strain rates. Experimental results are used to calibrate the J-C model and the modified J-C model for flow stress. The accuracy between the two models is compared. Section 4 establishes a modified M-C model concerning the effects of strain rate. Then numerical simulations are conducted based on the original J-C fracture model and the modified M-C model respectively. The reliability between the two models is evaluated. Then the fractography is studied to reveal the possible mechanism for failure and deformation in microscale.

2. Experimental procedures and results

This paper explores the ZK60 magnesium, which performs excellent plastic toughness during thermal process, and high strength at room temperature [2,3]. The chemical composition (mass %) of ZK60 alloy is 5.8 Zn, 0.65 Zr, 0.1 Mn, 0.003 Si, 0.003 Fe, 0.002 Cu, 0.001 Ni and a balance of Mg. The material was semi-continuous cast into ingots, peeled after homogenizing heat treatment, and formed by forging, spinning and machining. Fig. 1 presents the microstructure of the ZK60 alloy. It can be seen from Fig. 1(a) that ZK60 magnesium alloy consists both deformed grains and fine grains caused by spinning, and the average grain size is around 3.8 μm. Back Scattered Electron (BSE) image shown in Fig. 1(b) presents the precipitates, which also distributed in the grain boundaries. To calibrate the material model and fracture model, four series of tests were conducted. These series include smooth, notched, shear and dynamic tests. Smooth, notched and shear tests are conducted at quasi-static condition, and the dynamic tests are conducted at different strain rates. It is important to emphasize that the samples used in the mechanical characterization shared the same microstructural conditions.

2.1. Quasi-static tensile tests

Uniaxial tensile specimens of ZK60 alloy are performed by wire-cutting. The dimensions of these specimens are determined by the recommendation of GB/T 228.1–2010 standard. Fig. 2 shows different kinds of specimen: one flat smooth, one simple shear, two flat shear specimens at the shear angle θ of 30° and 60° and three flat notched specimens at the notch radii R of 1 mm, 5 mm and 10 mm. Simple shear test is at pure shear stress state with shear angle of 0°. The shear tests at the shear angle θ of 0°, 30° and 60° are simplified as S0, S30 and S60, and notched tests at the notch radii R of 1 mm, 5 mm and 10 mm are simplified as R1, R5 and R10 hereinafter.

Quasi-static tensile tests were conducted in ETM504C electronic universal testing machine with capacity of 5 kN/ 50 kN and the speed range of (0.001–500) mm/min. Those tests were performed at 1.8 mm/min, and the loads were measured by the load cell. As for measuring the response of the movement, the Digital Image Correlation (DIC) method [21] was chosen to measure the deformation and contour over the interesting surface, and tracked the crack propagation of the naturally occurring.

The stress-strain curves obtained from the experimental data are presented in Fig. 3. Note that those tensile tests have been repeated third times with similar results obtained, indicating the uniformity of the material and the repeatability of the tests, so these stress-strain curves are achieved by the average values of the three parallel tests. A typical smooth tensile response of ZK60 alloy is shown in Fig. 3(a), where the black line is the engineering stress-strain curve and the red line is the true stress-strain line. It should be noted that, in the red line of Fig. 3(a), the true stress is calculated from the corresponding engineering value by using plastic incompressibility condition. Notched and shear stress-strain curves are given in Fig. 3(b). For notched tests, tensile strength increases with the increasing notch radii R, while the fracture strain decreases with the increasing notch radii R. For shear tests, tensile strength and fractural strain both increase with the increasing shear angle θ.

2.2. Dynamic tensile test

Dynamic tensile tests were conducted to obtain the mechanical behaviors of ZK60 alloy at different strain rates. The dimension of the dynamic specimen is shown in Fig. 4, with a gauge length of 8 mm. Dynamic tests were conducted by using a Zwick5020 high speed testing machine, covering a broad range of strain rate spanning 1–1000/s.

Fig. 5 gives the experimental data of true stress-strain curves, obtaining from the average value of parallel tests. These curves show that the ultimate tensile stress and fractural strain both increase with the strain rate. In details, the two variables increase slowly for strain rates between 1 and 100/s, but the strain rate effect becomes noticeable at higher strain rates beyond 100/s.

2.3. Iterated FEM method

An iterated FEM [22] method is taken to obtain the elemental data including the elemental plastic strain at fracture ε_{ele}^{f}, elemental stress triaxiality σ_{ele}^{*} and elemental lode angle $\bar{\theta}_{ele}$. The three elemental variables are crucial in calibrating the fracture model. Reasons come as follow. Numerical fracture is determined by ε_{ele}^{f} which is storied in the element, rather than the overall fracture strain calculate by $\Delta l/L$, where L is the gauge length. The overall fracture strain is not identical to ε_{ele}^{f},