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Full Length Article

Experimental and numerical analyses of magnesium alloy hot workability

F. Abbassi [a,b,*], M. Srinivasan [a], C. Loganathan [c], R. Narayanasamy [d], M. Gupta [e]

[a] *Mechanical Engineering Department, College of Engineering, Dhofar University, P.O. Box 2509, 211 Salalah, Oman*
[b] *URMSSDT, Ensit, University of Tunis, 5 Avenue Taha Hussein, BP, 56, Bâb Manara 1008, Tunisia*
[c] *Department of Mechanical Engineering, Chartered Institute of Technology, Abu Road, Sirohi, Rajasthan 307 510, India*
[d] *Department of Production Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu 620 015, India*
[e] *Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117 576, Singapore*

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Abstract

Due to their hexagonal crystal structure, magnesium alloys have relatively low workability at room temperature. In this study, the hot workability behavior of cast-extruded AZ31B magnesium alloy is studied through hot compression testing, numerical modeling and microstructural analyses. Hot deformation tests are performed at temperatures of 250 °C to 400 °C under strain rates of 0.01 to 1.0 s^{-1}. Transmission electron microscopy is used to reveal the presence of dynamic recrystallization (DRX), dynamic recovery (DRY), cracks and shear bands. To predict plastic instabilities during hot compression tests of AZ31B magnesium alloy, the authors use Johnson–Cook damage model in a 3D finite element simulation. The optimal hot workability of magnesium alloy is found at a temperature (T) of 400 °C and strain rate ($\dot{\varepsilon}$) of 0.01 s^{-1}. Stability is found at a lower strain rate, and instability is found at a higher strain rate.

Keywords: AZ31B magnesium alloy; Hot workability; Damage; Plastic instability; TEM analysis; FEM

1. Introduction

Magnesium based alloys are now the best candidate materials for structural applications owing to their light weight. This property renders magnesium alloys a good candidate for use in transportation industry applications such as spur bevel gears [1] and digital camera barrels [2] (Fig. 1). The superior workability of AZ31B magnesium alloy achieved at higher temperatures relative to that achieved at ambient temperatures has attracted the interest of researchers. Hot deformation involves the plastic deformation of materials formed at elevated temperatures without plastic instability. Deformation is affected by temperature, strain and strain rates. Hot deformation is dependent on extrinsic properties namely strain (ε), strain rates ($\dot{\varepsilon}$), work piece temperature and inherent material flow characteristics [3]. Hot workability analyses of various materials such as steel, aluminum and magnesium have been carried out using constitutive models and processing maps developed by Hu et al. [4] and Suresh et al. [5]. The hot workability of magnesium AZ31B alloy was established by Srinivasan et al. [6] using processing maps. Their study revealed DRX in the stability domain at temperature and strain rates of 350 to 400 °C and 0.1 to 0.01 s^{-1}, respectively.

In the present study, Johnson–Cook (J–C) model was used to predict the behavior of AZ31B during hot deformation. This model assumes thermal softening, strain rate hardening and strain hardening. The J–C model is used in a finite elements model of compression test of cast-extruded AZ31B samples while taking account the deterioration of mechanical characteristics through the application of a damage model. Transmission electron microscopy and macroscopic observations were performed to identify the occurrence of dynamic recrystallization dynamic recovery and plastic instability (cracks and shear bands).

2. Materials and processing

The material used in the present work was AZ31B, and its chemical composition is presented in Table 1 [7]. Ingots of AZ31B magnesium alloy (MGAL) were processed by disintegrated melt deposition at an alternative casting route. Ingots

* Corresponding author. College of Engineering, Dhofar University, P.O. Box 2509, Salalah 211, Oman. Fax. +968 23237777.
E-mail addresses: fethi@du.edu.om, abbassi.fethi1@gmail.com (F. Abbassi).

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(a) (b)

Fig. 1. Photos of magnesium alloy AZ31B applications: (a) spur bevel gear [1], (b) digital camera barrel [2].

were extruded at a temperature and extrusion ratio of 350 °C and 20:1, respectively. Extruded billets were formed into pieces of 15 mm in diameter and 15 mm in height with 0.8 mm diameter hole at mid-height for thermocouple insertion. Hole was provided to insert thermocouple that came into contact with the inner core of the extruded billets for measuring adiabatic temperature increases during hot deformation. Hot workability tests were conducted through uni-axial compression tests using a universal testing machine (make: FIE; model: UTES-10 servo-controlled) with a maximum load capacity of 100 kN and equipped with an environmental chamber. Specimen and die surface lubrications were carried out by spraying dry graphite before conducting the experiments. Very little barreling was observed as a result of the friction free lubricated surfaces prepared. All of the billets were water quenched after they were deformed up to true strain level of 0.5. Hot deformation tests were conducted at temperatures and strain rates of 250–400 °C and 0.01–1.0 s^{-1}, respectively.

The deformed billets were sliced at the center parallel to the compression axis. A transmission electron microscopy (TEM) metallographic examination was carried out on the polished cut-surface of the deformed specimens. The samples were ion-milled to perforation at an ion accelerating voltage of 3 kV on mechanically ground cut disks of less than 100 μm in thickness followed dimple grinding to less than 20 μm in thickness.

Table 1
Chemical composition (wt.%) of AZ31B magnesium alloy.

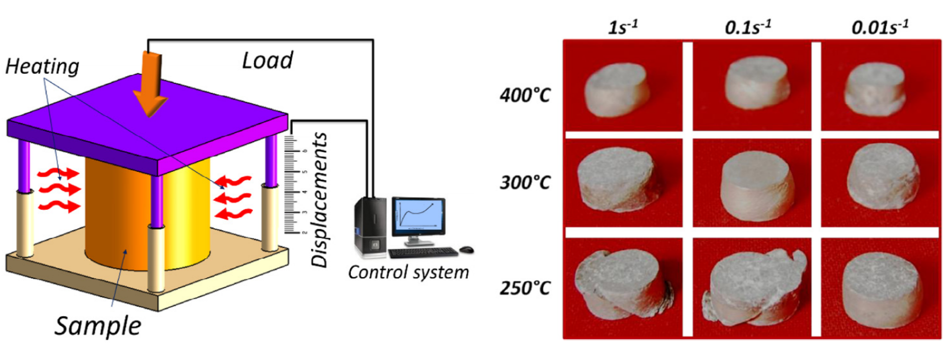
Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
2.94	0.87	0.57	0.0027	0.0112	0.0008	0.0005	Bal.

3. Experimental results and discussion

Several experimental investigations were conducted to study the fracture mechanism of magnesium alloys [8,9] and behaviors during hot forming [10,11]. Fig. 2a shows the results of the test. Fig. 2b shows the macrostructure of the compressed test samples studied at three different temperatures (250, 300, and 400 °C) and at three strain rates (0.01, 0.1 and 1 s^{-1}) of magnesium alloy AZ31B. The figure shows characteristics of metal flow during hot compression. Surface cracking was sensitive to strain rates and occurred in the flow instability region within the temperature range. It is evident that no cracking occurred after the compression test, as the deformation temperature was higher than 400 °C at each strain rate. Cracking was observed in all of the test samples when the deformation temperature was lower than 250 °C. These results also denote that the appropriate forging temperature of AZ31B alloy should exceed 400 °C.

3.1. Hot deformation behavior

The true stress–strain curves presented in Fig. 3 were converted from load–displacement curves using the constant



(a) (b)

Fig. 2. (a) Principal of compression test; (b) the specimens were deformed to a strain of about 0.5.