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An exponential material model for prediction of the flow curves of several AZ series magnesium alloys in tension and compression

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ABSTRACT

This paper is concerned with flow behaviors of several magnesium alloys, such as AZ31, AZ80 and AZ81, in tension and compression. The experiments were performed at elevated temperatures and for various strain rates. In order to eliminate the effect of inhomogeneous deformation in tensile and compression tests, the Bridgeman's and numerical correction factors were respectively employed. A two-section exponential mathematical model was also utilized for prediction of flow stresses of different magnesium alloys in tension and compression. Moreover, based on the compressive flow model proposed, the peak stress and the relevant true strain could be estimated. The true stress and strain of the necking point can also be predicted using the corresponding relations. It was found that the flow behaviors estimated by the exponential flow model were encouragingly in very good agreement with experimental findings.

1. Introduction

Nowadays, various magnesium (Mg) alloys have found many applications in several important industries such as automotive and aerospace industries [1]. For this reason, many researchers are interested in investigating the mechanical properties of these alloys. Low density, good recyclability and weldability together with high strength/weight ratio of magnesium alloys [2,3] have made these materials very suitable for mechanical and structural applications. Among different Mg alloys, the AZ series is quite the most important one and many studies have been carried out regarding the mechanical behavior of this series.

Mathis et al. [4] and Trojanova et al. [5] studied the deformation behavior of AZ91, AS21 and AE42 commercial Mg alloys in a wide range of temperature and various strain rates. The temperature varied from 20 to 300 °C, whereas the strain rates were an order of 0.0001 s^{-1}. In order to distinguish the strain hardening from strain softening, the dependency of stress on the strain hardening exponent was examined and calculated. It was shown that the work hardening coefficient decreased when the temperature and stress increased.

Sivapragash et al. [6] proposed an analytical model for deformation behavior of ZE41A Mg alloy. The model included strain, strain rate, temperature and Zener–Hollomon parameter. After studying the mechanical behavior of AZ31, Wen et al. [7] claimed that the unsymmetric yield stresses of this alloy in tension and compression could be due to twinning.

Abedi et al. [8] investigated the formability and behavior of wrought AZ31 Mg alloy in tension for temperatures between 300 and 500 °C and a strain rate of 0.001 s^{-1} and showed that how the formability of this material increased for higher temperatures. Masoudpanah et al. [9] investigated the microstructure and shear as well as tensile deformations of AZ31 alloy subjected to extrusion or Equal Channel Angular Pressing (ECAP) operations. They found that, compared with the extruded samples, the specimens subjected to ECAP exhibited lower flow stress and higher formability in tension.

Zhao et al. [10] obtained and compared the tensile flow stress and the microstructure of ZK60-Y Mg alloy produced from two different operations. The test conditions for two groups of samples were the same. The deformation behaviors of various Mg alloys in tension, bending and buckling were compared with those of steel and aluminum alloys by Easton et al. [11]. Their research illustrated that, compared with the mild steel, the magnesium alloys represented higher strength and energy absorption in bending and buckling.

Palumbo et al. [12] carried out experimental and numerical investigations on formability of AZ31 at elevated temperatures and a constant strain rate. With this regard, a relationship between the strain rate and the ram displacement of the testing machine was proposed in order to attain a constant strain rate during the test. Anbuselvan et al. [13] studied the mechanical behavior of ZE41A magnesium alloy at temperatures between 300 and 500 °C by means of the compression test. Their investigation showed that this behavior was significantly dependent on the temperature and strain rate. The strain rate sensitivities of several cast Mg alloys were also examined by Song et al. [14]. The sensitivities of

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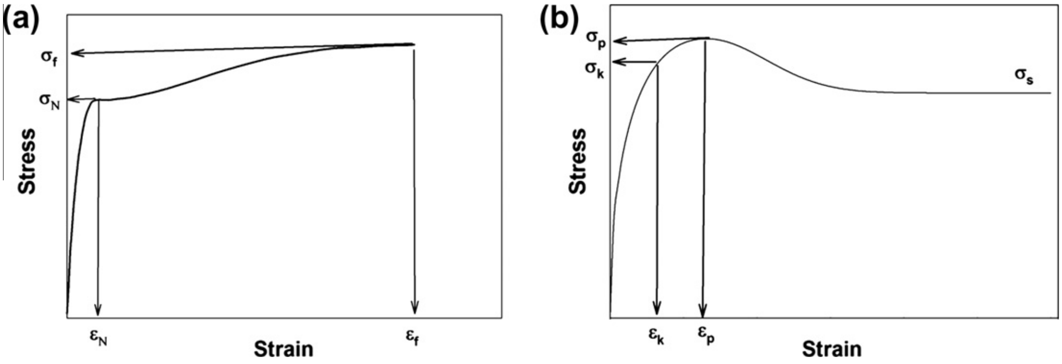

Fig. 1. Various parts of the flow curves in tension (a) and compression (b).

AM60, AM50 and AM20 alloys were obtained in a wide range of strain rate, namely 0.001–1700 s^{-1}. It was found that, for low levels of strain rate, the greater the percentage of aluminum, the smaller was the strain rate sensitivity of the Mg alloy.

Several researches were carried out to obtain appropriate stress–strain relations for magnesium alloys or materials with similar behavior, especially at elevated temperatures, and several material models were proposed in order to predict the flow stress of the material. With this regard, Sheng and Shivpuri [15] proposed a mathematical model base on the deformation mechanisms of Mg alloys. They divided the stress–strain curve into four parts and employed a function of the Zener–Hollomon parameter, which included simultaneously the effects of temperature and strain rate, for modeling each part. He et al. [16] modeled the behavior of a titanium alloy at elevated temperatures. By combining several relations, a mathematical model was suggested for prediction of the flow curve of this alloy based on its material parameters. In this model the material parameters were considered as polynomial functions of the strain. Then, the least square method was used in order to find the coefficients of these polynomial functions.

Ebrahimi et al. [17] studied the flow behavior of a steel alloy and proposed a mathematical model for estimation of the compressive flow stress of the material at elevated temperatures. The model was based on the slop of the flow curve at different strains. They divided the flow curve into two sections and employed the results of the first section for the second one. In this method the material coefficients were calculated for both regions of peak stress and steady state stress.

He et al. [18] predicted the flow stresses of AZ31B and 42CrMo steel alloys at high temperatures considering the dynamic recrystallization in their models. Raghunath et al. [19] employed the Zener–Hollomon parameter in order to model the compressive behavior of AZ91 alloy for various strain rates and temperatures. Other researches [20–22] were also conducted in order to model the flow curves of various alloys at elevated temperatures, and including different strain softening behaviors.

In this paper, the deformation behaviors of several Mg alloys, namely AZ31, AZ80 and AZ81, in tension and compression and for various strain rates and elevated temperatures are described. Because of interfacial friction, the compression samples were subjected to inhomogeneous deformation and barreling occurred. Fereshteh-Saniee and Fatehi-Sichani [23] suggested numerical correction factors, obtained from finite-element (FE) analyses, to calculate accurate flow stresses of the material. In the present investigation, appropriate correcting factors were obtained for the above – maintained alloys by means of the FE simulations. In a tensile test, also, the stress state changes from uniaxial to triaxial when the necking occurs and use of the Bridgman's correction factor is unavoidable.

Table 1
Compositions of various magnesium alloys employed in the experiments.

Material	Mg	Al	Zn	Mn	Si	Ni
AZ31	Bal.	3.02	0. 91	0.19	0.10	0.001
AZ80	Bal.	7.83	0.46	0.25	0.03	0.001
AZ81	Bal.	7.11	0.86	0.18	0.03	–

The present paper also describes mathematical models for prediction of the flow stresses of the magnesium alloys under consideration in tension and compression at elevated temperatures. In both the cases, the stress–strain curve is divided into two parts and a separate model is used for each part. Then the coefficients of each model are determined. Using the proposed model, one can specify the peak stress and the relevant strain as well as the steady state stress of the flow curve in compression. Moreover, for the tensile test, the flow stress of the necking point together with the corresponding strain and the fracture stress can be determined based on the proposed models. Suitable relationships are suggested for determination of these material parameters. Finally, some microstructural phenomena of deformation of the above Mg alloys are presented and discussed in this paper. Interesting conclusions are drawn based on these research works which are described at the end of this article.

2. Description of the material model

The material model proposed in this paper is based on the one suggested by Ebrahimi et al. [17] for modeling the behavior of a steel alloy at elevated temperatures. They proposed the mathematical model for steel in compression. However, in the present research work, after necessary modifications, the model is employed for prediction of flow stresses of different magnesium alloys in both tension and compression.

For prediction of the tensile flow stress, there are two parts for the flow curve. The first portion includes the data before onset of the necking, whereas the second part involves the continuation of the flow curve from necking to the fracture stress (Fig. 1a). In the case of the compression test, the first segment of the flow curve contains from beginning to the peak stress and the second portion includes the work softening and the steady flow stress (Fig. 1b).

2.1. Modeling the first part of the flow curve

The first sections of the true stress–strain curves for compression and tension can be modeled using the following relations, respectively [24,25]: