MATHEMATICAL MODELING OF THE STRESS–STRAIN CURVES OF AZ91 MAGNESIUM ALLOY DURING HOT COMPRESSION

[1]F. BARATI, [2]L.SHAMEKHI

[1]Assistant Professor of Mechanical Engineering, Department of Mechanics, Faculty of Engineering, Hamedan Branch, Islamic azad University, Hamedan, Iran

[2]Phd Candidate of Mechanical Engineering Department of mechanics, faculty of engineering, Bualisina university, Hamedan, Iran

E-mail: farzanbarati@yahoo.com

Abstract- In this investigation, hot compression tests were performed at 230 °C-290 °C and strain rate of 0.001-0.1 s^{-1} to study hot deformation behavior and flow stress model of AZ91 magnesium alloy. In order to eliminate the effect of inhomogeneous deformation in compression tests, the numerical correction factors were employed. The effects of the temperature and strain rate on hot deformation behavior have been expressed in terms of an exponent-type Zener–Hollomon equation. A A-section exponential mathematical model was also utilized for prediction of flow stress of this magnesium alloys in compression. The validity of the model was demonstrated by comparing the experimental data with the numerical results. The predicted stress–strain curves are in a very good agreement with those obtained experimentally, both illustrating the occurrence of dynamic recrystallization. Also, in both cases, the peak and steady-state stresses raised with decreasing temperature and increasing strain rate.

Keywords- Flow Stress; Mathematical Model ; Hot Compression; Dynamic Recrystallization; AZ91

I. INTRODUCTION

Nowadays, various magnesium (Mg) alloys have found many applications in several important industries such as automotive and aerospace industries. For this reason, many researchers are interested in investigating the mechanical properties of these alloys. Low density, good recyclability and weld ability together with high strength/weight ratio of magnesium alloys 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. Many researchers have studied different models for predicting material behaviors. It is very important to understand the flow stress behavior and changes of microstructures during hot working to achieve desired mechanical properties after deformation.

In order to employ the more advanced modeling techniques such as finite element analysis, the constitutive behavior at each point during the deformation regime must be determined the finite element analysis (FEA) has been extensively used to assist simulating the metal forming processes, with the purpose of ascertaining the optimum deformation conditions (Ref 1,2). In general, the constitutive equations, which correlate flow stress, strain rate, strain and temperature, as the key thermo-mechanical processing (TMP) parameters, are employed to describe the plastic flow properties of metals and alloys in a form that can be introduced into the FEA codes (Ref 3). The credibility of simulation results depends solely on the accuracy of the developed constitutive equations.

Dharmendra et al. (Ref 4) studied the hot deformation behavior of Mge3Sne2Ca alloy with 0.4 wt.% Al was studied in the temperature range 300-500 OC and strain rate range 0.0003-10 s-1 and the flow stress data have been analyzed by processing maps and kinetic analysis. This investigation showed that at strain rates higher than 0.1 s-1, the stress-strain curves exhibited flow softening behavior while at lower strain rates near steady-state flow has been observed.

Changizian et al. (Ref 5) analyzed the strain-compensated constitutive behavior of AZ81 magnesium alloy through performing hot compression tests in the temperature range of 250–450 ^{O}C under different strain rates of 0.003, 0.03 and 0.3 s^{-1}. In his research, the material constants (a, Q, n and ln A) displayed significant dependence on the amount of strain. The general trend was found to be an initial increasing followed by a maximum value at a certain strain, with the exception of a-value, which increased continually with the true strain.

Yin-Jiang Qin et al. (Ref 6) investigated the flow behavior of magnesium alloy ZK60 by using the hot compression tests. Based on the experimental results, a model was developed to predict the flow stress curve of magnesium alloy at hot deformation condition. The proposed model is capable of predicting the flow behavior of work hardening and DRV region as well as the softening caused by DRX. The flow stress curves of ZK60 magnesium alloy predicted by the developed model are in good agreement with experimental results, which confirms the validity of the proposed model. F. Fereshteh-Saniee et al. (Ref 7) Considered the 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. A two-section exponential material model was also employed for prediction of the tensile and compressive flow stresses of the alloys under consideration. The exponential model, employed for the first time for Mg alloys, can represent both the tensile and compressive flow behaviors of AZ series magnesium alloys under consideration very well. The predicted flow stresses were in very good agreement with those of experiments. Maximum errors in both tension and compression were around 11%.

F. Fereshteh-Saniee et al. (Ref 8) In another research, conducted practical tests on AZ80 alloy which includes tension and compression tests at high temperature and different strain rates. The traditional compression test should be conducted in zero-friction condition but such a condition is impossible to prepare. Therefore, bulge correction factor and numerical correction factor are used to eliminate the friction effect which exists between the surfaces. Their investigation showed that these results are more acceptable when numerical correction factor is used in comparison with bulge correction factor. The main reason of this difference is that the bulge correction factor does not consider parameters such as geometry, material properties and friction factor. All of these parameters can be changed by temperature variation.
H.Z. Li et al. (Ref 9) performed compression tests of Mg–10Gd–4.8Y–2Zn–0.6Zr alloy in the compression temperature range from 350 ◦C to 500 ◦C and the strain rate range from 0.001 s^{-1} to 1 s^{-1}. The critical strain (ε_c) for initiation of DRX of Mg–10Gd–4.8Y–2Zn–0.6Zr alloy deformed at the temperature of 500 ◦C and the strain rate of 0.01 s^{-1} is 0.07.

I. Ulacia et al. (Ref 10) characterized rolled AZ31B sheet over a wide range of strain rates and temperatures, serving to understand the tensile behavior of this material. It was observed that the AZ31B magnesium alloy exhibit a hardening behavior which increases with strain rate. As temperature increases the flow stress decreases with larger differences occurring at quasi-static strain rates.

A. Momeni et al. (Ref 11) analyzed the hot working behavior of VCN200 medium carbon low alloy steel by performing hot compression tests in temperature range of 850-1150 ^{O}C and at strain rates of 0.001-1 s^{-1}. Dynamic recrystallization is the major microstructural phenomenon during hot working over temperature range of 900-1150 ^{O}C and strain rates of 0.001-1 s^{-1}.

R. Ebrahimi et al. (Ref 12) developed a mathematical model to predict the stress-strain curves of a Ti-IF steel during hot deformation in the temperature range of 950-1100 ^{O}C with strain rates between 0.02 and 1 s^{-1}. The model predicts the constitutive behavior at each point during the hot deformation. The estimated stress-strain curves under different hot deformation conditions were in good agreement with experimental results.

Anbuselvan et al. (Ref 13) performed compression tests of ZE41A magnesium alloy in the compression temperature range from 300 ^{O}C to 500 ^{O}C and the strain rate 0.001 s^{-1}. Their investigation showed that the temperature and strain rate are important parameters for magnesium alloy deformation.

In this paper, the deformation behaviors of AZ91 Mg alloy, is described in compression, various strain rates and elevated temperatures. The uniaxial hot compression testing is usually employed to provide the necessary data in order to extract constitutive equations. Because of interfacial friction, the compression samples were subjected to inhomogeneous deformation and barreling occurred. bulge correction factor and numerical correction factor are used to eliminate the friction effect which exists between the surfaces. numerical correction factors, obtained from finite-element (FE) analyses, to calculate accurate flow stresses of the material.

The present paper also describes mathematical model for prediction of the flow stress of the AZ91 magnesium alloy under compression at elevated temperatures. the constitutive equations have been applied and they have been used to predict the flow stress of AZ91 magnesium alloy. 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. Finally, the predictability of the established constitutive model has been verified over the entire experimental range.

II. EXPERIMENTAL

Cylindrical hot compression specimens, 9 mm in height and 6 mm in diameter with height to diameter ratio of 1.5 (in accordance with ASTM E209 (Ref 14)), were machined from the homogenized ingots. Hot compression tests were conducted under isothermal condition at three different strain rates of 0.001, 0.01 and 0.1s^{-1} and at temperatures of 230, 260, and 290 ^{O}C. the specimens were soaked at deformation temperature for 5 min. Finally, at the end of straining the specimens were immediately quenched in water. The conventional compression test should theoretically be carried out under zero friction condition. However it is impossible to create such condition. For this reason, the compression tests were performed under dry conditions and, consequently, it was necessary to employ correction factors to eliminate the effect of interfacial friction and obtain precise effective stresses (Ref 15). in the bulge correction factor method (BCFM), various geometrical parameters of the deformed sample should be measured for each value of axial strain, each flow curve of individual alloys were gained using 8 samples, each sample for a specific value of the axial strain.

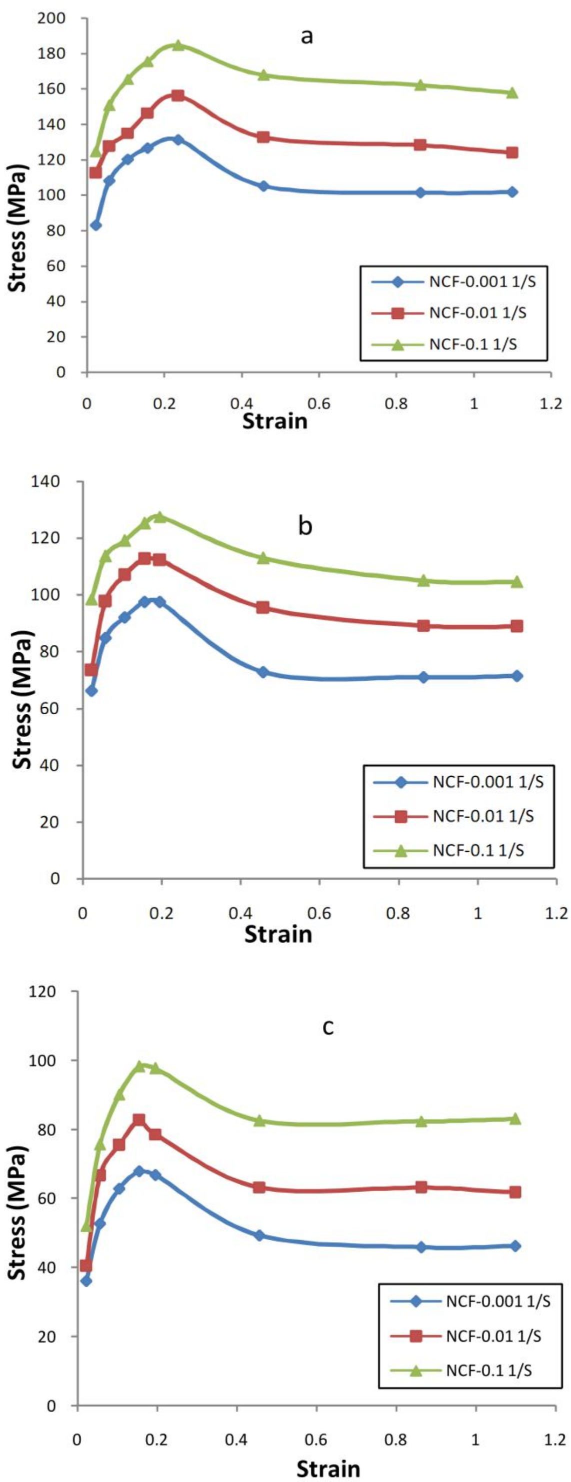


Fig. 1 experimental flow stresses of AZ91 in compression for various strain rate at temperature of 503 K (a), 533 K (b) and 563 K (c)

III. RESULTS AND DISCUSSION

True stress-true strain curves obtained from the hot compression tests of AZ91 magnesium alloy under different conditions are depicted in Fig. 1. As is seen, the flow stress level is significantly affected by temperature and strain rate at all the test conditions. The greater the strain rate and the lower the temperature, the higher the flow stress level. The formation of tangled dislocation structures, as barriers to dislocation movement, due to the higher strain rates is believed to be the main reason for the observed behavior (Ref 15).

3-1. Description of the material model

The material model proposed in this paper is based on the one suggested by Ebrahimi et al. (Ref 12) for modeling the behavior of a steel alloy at elevated temperatures.

For prediction of the compression flow stress, there are two parts for the flow curve. 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. 2).

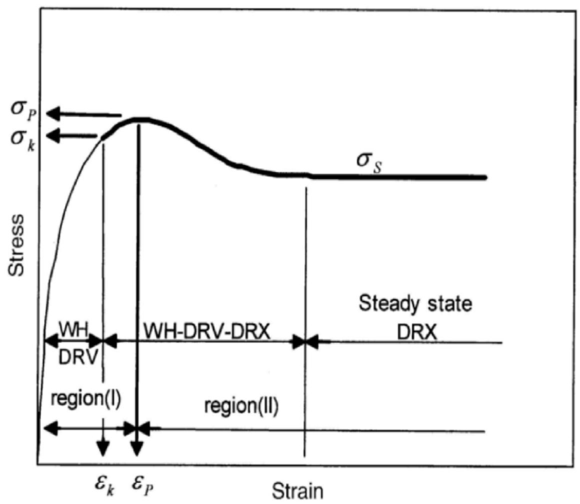


Fig. 2.Schematic diagram of the stress–strain curve for DRX.

a). Modeling the first part of the flow curve

The first sections of the true stress–strain curves for compression can be modeled using the following relation (Ref 19,20):

$$\frac{\sigma}{\sigma_p} = \left[\left(\frac{\varepsilon}{\varepsilon_p}\right)\exp\left(1-\frac{\varepsilon}{\varepsilon_p}\right)\right]^C \qquad \text{(Eq 1)}$$

where C_C hold various values for different materials. σ_p and ε_p are the peak stress and the relevant true strain, respectively. Based on Eq 1 one can derive the following relationship.

$$\mathrm{Ln}\left(\frac{\sigma}{\sigma_p}\right) = C\left[\mathrm{Ln}\left(\frac{\varepsilon}{\varepsilon_p}\right) + \left(1-\frac{\varepsilon}{\varepsilon_p}\right)\right] \qquad \text{(Eq 2)}$$

Therefore, by plotting $\mathrm{Ln}(\sigma/\sigma_p)$ against $\mathrm{Ln}(\varepsilon/\varepsilon_p) + (1-(\varepsilon/\varepsilon_p))$ for all the flow stresses before the peak stress, value of C_C, which is the slope of this curve, can be determined.

Figs. 3 illustrate the estimated stress–strain curves superimposed on the corresponding experimental data points for AZ91 alloy in compression. Observing Figs. 7, one can find out that the agreements between the flow curves, estimated by different obtained material models, and the experimental flow stresses are encouragingly very good for this Mg alloy under consideration. It is worthy to mention that each sampling point in Figs. 7 represents an individual experiment.

The requirement constants for modeling of flow stress of AZ91 in compression . are tabulated in Table 1.

Table 1. table of constants for AZ91 magnesium alloy

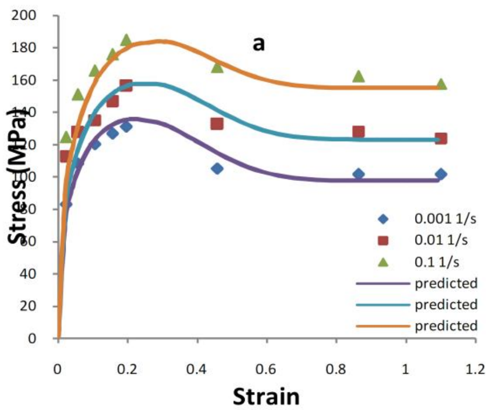
All oy	**C**	**n p**	**n_s**	**Q_p (J/**	**Q_s (J/**	**B_P**	**B_S**
A Z9	0.42	1 5.	9. 9	404 290	253 890	3243 290.8	**329 8.6**

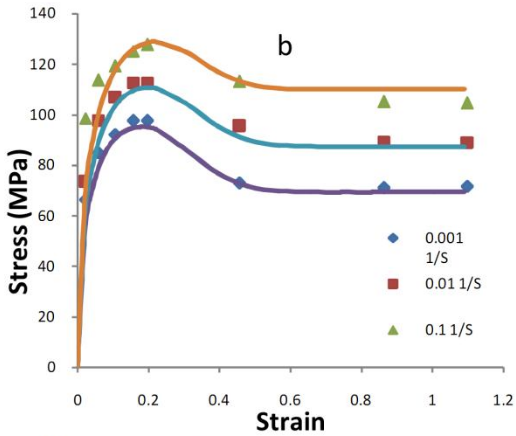
CONCLUSIONS

The flow curve of AZ91 Mg alloy in hot compression tests in the temperature range of 230-290 ^{O}C under different strain rates of 0.001, 0.01 and 0.1 s^{-1} was studied in the present research. A two-section exponential material model which is based on a phenomenological shape of true stress–strain curves during hot working has been developed. The main points of this investigation are as follows:

(1) The flow stress in the isothermal compression of the alloy is significantly sensitive to the strain rate and the deformation temperature. The flow stress increased with increasing the strain rate and decreasing the deforming temperature, which can be described by a Zener-Hollomon parameter Z.

(2) The estimated stress–strain curves under different hot deformation conditions were in good agreement with experimental results.





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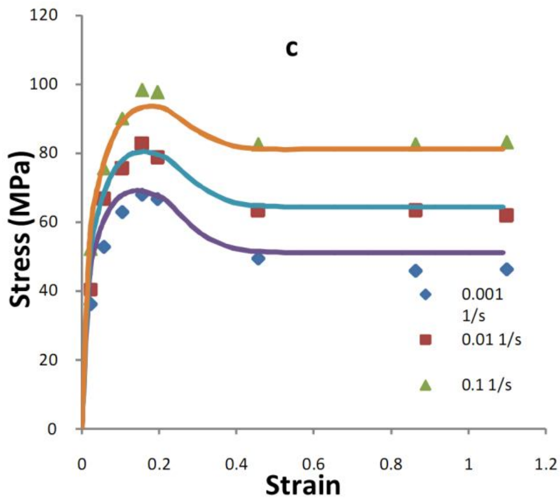

Fig3. Predicted value and experimental material model

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