Research Article

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Mathematical modeling of AZ30 magnesium alloys at high temperature using the ring compression test and genetic algorithm method

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Abstract: In the present investigation, a new method is proposed to study the AZ30 flow curve at elevated temperatures and various strain rate. Experiments were carried out with the goal of obtaining flow curve of AZ30 at three different temperature and strain rates by using the ring test method. The presented work aims to develop a model using genetic algorithm for AZ30 flow stress prediction during different test conditions. The Santam machine was implicated that was able to perform experiments by controlling both the position and load modes. At each temperature and strain rate the isothermal test was performed respectively. In the present investigation for three various temperatures and strain rates, 54 ring compression tests were carried out with different levels of reduction in height. Then each specimen was water cooled quickly to investigate the microstructure of AZ30 magnesium alloy by using optical microscope. The model used in the present study was able to predict the flow curve with an 2.3% accuracy. This model has excellent potential to be employed in various industry applications.

Keywords: AZ30 Mg alloy, compressive strength, high temperature, and genetic algorithm

1 Introduction

Because of the high ratio of strength to weight and proper heat dissipation, damping, applications of Mg and its alloys have been used extensively at several important industries. Magnesium has very low ductility property at room temperature because of its HCP structure and low stacking fault energy [1, 2, 3, 4]. Magnesium alloys are the lightest structural alloy in nature, therefore these alloys are used widely at mobile device cases. Analyzing the hot deformation behavior of these alloys needs describing the mechanical behavior changes under an exerted load at each forming condition. This important issue should be expressed in terms of a constitutive equation which can relate stress state and strain state to their related conditions. At this time, the amount of as cast magnesium products is definitely more than wrought product amounts. However, wrought magnesium alloys may have more development potential with the higher strength, improved ductility and other mechanical property advantages. Due to very bad formability and negligible ductility at room temperature, the elevated forming technology should be employed [5, 6, 7, 8, 9]. Jia Zhou *et al.* investigate the compressive behavior of at the temperature range of 573 K to 673 K and led to increase of grain size with the increasing the strain rate and decreasing of temperature. They also showed that evolution of the grain size is more influenced by the temperatures rather than the strain rate [11].

In the case of magnesium and its related alloys investigations, very little works were performed to predict the flow stress considering its forming condition. Only few research teams studied the mechanical behavior of magnesium alloys to hot deformation using constitutive equations [12].

In the present study, The hot compression ring test was employed for the as-cast AZ30 magnesium alloys, then by employing finite-element analyses numerical calibration curves and numerical sigmoid curves were obtained. By using these numerical curves flow curve of as-cast AZ30 magnesium alloy was obtained. For the AZ30 flow stress prediction, a two part model using Zener-Hollomon was in-

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roduced. This model can predict flow stress of magnesium alloys precisely.

2 Methodology

2.1 Material

The studied material was as-cast AZ30. The chemical composition used in the present work had the following (wt.%): Al = 3.02%, Zn = 0.45%, Mn = 0.15%, Si = 0.18% mg matrix.

2.2 Isothermal ring compression tests

The ring test can be used for determining the friction factor between die and the sample as well as flow behavior of the samples. The friction factor leads to increase or decrease in internal diameter based on amount of friction factor but external diameter increases for each value of friction factor. The ring test is capable of determining the flow curve as well as the friction factor at the same time. This advantages lead to low costs and time of experiments.

Figure 1: The 150 KN Santam testing machine used in this research.

Isothermal ring compression tests were carried out implicating a 15 KK Santam machine that was equipped by an electrical furnace involving a thermocouple. Ring samples were machined precisely with an initial height (h_0), inner diameter (d_i) and diameter (d_0) of 3, 4.5 and 9 mm. The experimental samples were compressed more than 55% height reduction during isothermal conditions in the three different temperatures of from 473 to 513 K and strain rate range from of 0.025 s^{-1} , 0.0025 s^{-1} to 0.00025 s^{-1} . The ring compression tests were conducted under dry interfacial

Figure 2: The calibration curve for calculating the f [13].

condition. To find out the stress curve of as-cast AZ 30 magnesium alloys, samples were compressed at 6 different amount of height level decrease. Finally, at least six different points were obtained for the stress curve at each test conditions. The 150 KN Santam machine is illustrated in the Figure 1. The analytical calibration curve as well as the numerical one should be calculated precisely. The analytical calibration curve is shown at Figure 2 [13].

To determine the flow stress, various numerical sigmoid curves should be obtained by implicating the finite-element method procedure. The numerical calibration curve should be provided for measuring the friction factor (f). The results indicate that the flow curves of as-cast AZ30 indicates DRX phenomenon that lead to increase the flow stress to a peak, and then decreases sharply to a steady state.

The initial sigmoid curves were achieved in analytical form as shown at Figure 3 and any effects of mechanical properties were not considered on the analytical sigmoid curve shapes. But material property affects on sigmoid curve, therefore numerical sigmoid curve were obtained using finite-element analysis. FE simulations were shown in Figure 3 [13]. Each specimen after deformation was water

Figure 3: Analytical sigmoid curves for measuring the compressive stress using the ring compression test [13].

quenched, then polished carefully and etched for investigation of microstructure of as-cast AZ30 magnesium alloys.

3 Results and discussions

3.1 Flow stress curve of AZ30 magnesium alloy

The AZ30 specimens with d_o , d_i , and h_o of 9mm, 4.5mm and 3mm were examined at temperature range of 473 to 493K and strain rate ranging from 0.025 s^{-1} to 0.00025 s^{-1} . Isothermal ring test were conducted for all of the samples. At each deformation condition the ring compression test carried out at all the different height reductions using hydraulic testing machine equipped with the thermocouple. During the experiments, The thermocouple is connected to the specimen at each time in order to obtain testing temperature very carefully. After using numerical calibration curves obtained from finite-element procedure according Figure 3 at each testing temperature and strain rates, friction factors were calculated. Results of friction factor showed that by decreasing the strain rates and increasing the temperature, friction factor increased. This can be resulted of increasing the local welding between die and samples. The maximum amount of friction factor from the calibration curve was 0.36 at strain rate of 0.00025 s^{-1} and temperature of 513 K and the minimum amount of that was 0.27 that was observed at the strain rate of 0.025 s^{-1} and temperature of 473 K.

Results from flow stress shows that in the initial stage of the forming process in as-cast AZ30magnesium alloy, the stress sharply reached to its maximum amount approx-

imately near strain about 0.2. This could be interpreted as the dominance of work hardening at this stage. After this stage the flow stress sharply decreases due to the dominance of DRX phenomenon. Finally, the flow stress exhibits steady-state region that could be as a result of the equilibrium between DRX and work hardening and the same results obtained by other researchers that verified the experimental results of this study [14, 15, 16].

3.2 Material model for as-cast AZ30 magnesium alloy

Manufacturing the products with proper mechanical, physical, and chemical properties can be achieved by using the implication of hot forming process. A lot of factors can affect on material flow such as strain, strain rate, temperature, and other forming conditions can affect the flow behavior of the materials. It is worthy to know that it is very difficult to understand their effects due to their very complicated interactions with each other's.

As stated before, the flow stress of magnesium alloy increases sharply to its maximum amount because the hot deformation properties for magnesium alloys. After this stage, the stress state decreases with the same rate after peak stress due to DRX phenomenon. The steady stress state is the final step. Both strain rate and temperature affect on flow stress.

There is a specific relationship among flow stress, strain rate, and temperature that was introduced by the Zener-Hollomon parameter. This parameter can successfully express the interaction between these parameters to each other.

from ring compression test result, the material constants can be properly determined. The Zener-Hollomon parameter can be expressed as bellow [17, 18].

$$Z = \dot{\epsilon} \exp \left(\frac{Q_d}{RT} \right)$$

Where Q , R , and T are the deformation activation energy, the universal gas constant, and the deformation temperature respectively, The activation energy can be calculated as below:

$$Q = RnT_p$$

T_p is known as the slope of $\ln(\sinh(\alpha\sigma))$ against $1000/T$ at the same strain and strain rate and n is known as the slope of $\ln(\sinh(\alpha\sigma))$ against $\ln(\dot{\epsilon})$ when the deformation temperature is considered to be constant. These slopes are shown at Figure 5 and Figure 6 at strain equal 0.2 and different forming condition.

Figure 4: Determining the friction factor as well as the flow curve of the presented model.

For prediction the compressive flow curve of AZ30 magnesium alloys a two part material was introduced by equation 3.

$$\sigma = k\epsilon^m \sinh^{-1} \left[(A_1 z)^n \right] \left\{ 1 + \exp \left(-A_2 \delta (\epsilon - \epsilon_p) \right) - \exp \left[-A_3 \delta (\epsilon - \epsilon_p) \right] \right\}$$

$$\delta (\epsilon - \epsilon_p) = \epsilon - \epsilon_p \quad \text{for} \quad \epsilon > \epsilon_p \quad \delta (\epsilon - \epsilon_p) = 0 \quad \text{for} \quad \epsilon < \epsilon_p$$

Where ϵ_p is the strain corresponding with the maximum amount of stress and A_1 , A_2 , A_3 and n are material constants. By using genetic algorithm method these coefficients can be determined as shown in Table 1. As shown at Figure 8–9 the output of this new model results show excellent agreements with the experimental ones. The average error is about 2% and at the worst state the maximum difference between predicted data and experimental data exceed only 5%.

Figure 5: Plotting $\text{Ln}(\sinh(\alpha\sigma))$ against $1000/T_p$ at the same strain rates and different temperatures and strain = 0.2.

Figure 6: Plotting $\text{Ln}(\sinh(\alpha\sigma))$ versus $\text{Ln}(\dot{\epsilon})$ at constant temperature and different strain rates condition at the maximum amount of strain related to stress.

3.3 Microstructure observation

The samples were water quenched quickly for microstructural study. Then samples were polished very precisely to be prepared for etching process. The etching decomposition was the combination of picric acid, ethanol, and pure water. After etching the specimens an optical microscope was implicated. As shown at Figure 10, the AZ30 magnesium with average grain size of $64.7 \mu\text{m}$ are encompassed by the grain boundary phase chain because solidification process occurs and $\text{Mg}_{17}\text{Al}_{12}$ phase is visible clearly. Figure 11 shows the AZ30 microstructure at T equals 493K with a minimum forming rate of at a strain of 0.3 and the mean

Table 1: Coefficients predicted model for as-cast AZ30 magnesium alloys obtained from genetic algorithm.

K(Mpa)	m	A_1	N	A_2	A_3	$Q_{optimum}$ (kJ/mol)
98.7	0.44	3.2×10^{-12}	0.32	2.408	2.2×10^{-1}	165

Figure 7: Predicted model and experimental data at temperature of 473 K and different forming rates.

grain size is about 14.6 μm . Observations were conducted on the cross-sections compression plane.

Figure 12 shows the microstructure of deformed AZ30 magnesium alloy at a strain of 0.3, 493 K and the maximum studied deformation rate and the mean grain size is nearly 8.7 μm . By comparing Figures 11 and 12 it is obvious that the increasing of the forming rate leads to the average grain size decreases.

4 Conclusions

The present study aimed to identify the forming rates and forming temperature effects on flow curve of AZ 30 magnesium by employing the ring compression tests. Also a new model was introduced for predicting of the flow curves. In addition, the microstructural study of AZ30 alloy were studied by implicating the optical microscope and the following interesting results were obtained:

1. Increasing the forming temperature as well as decreasing the forming rate leads to increase the amount friction factor coefficient due to the local welding between the die and the specimen.

Figure 8: Predicted and experimental data at temperature of 493 K and different forming rate conditions.

2. By increasing the temperature flow stress decreases but by increasing the strain rate the flow stress increases.
3. A two-part model presented in this research work can predict the flow stress curve very precisely. The results were validated by the experiments and very proper agreement between these results were seen. The maximum amount of error was about 5 percent but the mean average error was about 2 percent.
4. Increasing the strain rate led to increasing the average grain size.
5. After peak stress dynamic recrystallization and increasing the number of twins were observed clearly.
6. The maximum amount of stress was seen at the strain near 0.2.
7. AZ30 grains were encompassed by the grain boundary phase chain Mg₁₇Al₁₂ because of the occurrence of the solidification process

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Figure 9: Predicted and experimental data at temperature of 493 K and different strain rates.

Figure 10: Optical microscope image of as-cast AZ30 after casting at room temperature.

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Figure 11: Optical microscope image of as-cast AZ30 at strain of 0.3 and temperature of 493 K and forming rate of 0.00025 s⁻¹.

Figure 12: Optical microscope image of as-cast AZ30 magnesium alloy at strain of 0.3 and temperature of 493 K and strain rate of 0.025 s⁻¹.

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