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Full length article

A comparative study on the hot flow stress of Mg–Al–Zn magnesium alloys using a simple physically-based approach

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Abstract

A comparative study was carried out on the hot flow stress of AZ31, AZ61, and AZ91 magnesium alloys. Their hot working behaviors were studied through constitutive analysis based on a simple physically-based approach which accounts for the dependence of the Young's modulus and the self-diffusion coefficient of magnesium on temperature. Since the main difference between these alloys is the difference in their amount of aluminum, the differences in constitutive behavior were quantitatively characterized by relating the hot flow stress to amount of Al, which was not possible without the consideration of physically-based parameters. It was concluded that the used approach in the current work can be considered as a versatile tool in future hot working and alloy development studies.

Keywords: Mg–Al–Zn alloys; Hot deformation; Constitutive equations; Activation energy; Diffusion

1. Introduction

The AZ magnesium alloys are based on the Mg–Al–Zn system [1]. Since the solid solution hardening effect of Al in Mg is significant, several alloys based on Mg–Al system have gained commercial attention [2–4]. Among them, AZ31 (Mg – 3 wt% Al – 1 wt% Zn), AZ61 (Mg – 6 wt% Al – 1 wt% Zn), and AZ91 (Mg – 9 wt% Al – 1 wt% Zn) are some of the most commonly used alloys. Due to their hexagonal closed packed (HCP) crystal structure with a limited number of slip systems, the ductility of polycrystalline Mg alloys are usually poor at room temperature and hence hot deformation processing is a suitable shaping method due to the activation of additional slip systems at elevated temperatures [5,6]. The structural refinement is another important advantage of hot working [7,8].

The understanding of the hot working behavior and the constitutive relations describing material flow are two of the prerequisites for the implementation of shaping technology in the industry [9]. The modeling of hot flow stress is thus important in metal-forming processes because any feasible mathematical simulation needs accurate flow description. Moreover, since the main difference between the AZ magnesium alloys is the difference in their amount of aluminum, the difference in constitutive behaviors can be characterized by relating the hot flow stress to amount of Al.

A common constitutive equation in hot working is expressed by a hyperbolic sine relation of the form $Z = \dot{\varepsilon}\exp(Q/RT) = A[\sinh(\alpha\sigma)]^n$, where Z is the Zener–Hollomon parameter, Q is the deformation activation energy, $\dot{\varepsilon}$ is the strain rate, T is the deformation temperature and its unit is Kelvin, and finally A (the hyperbolic sine constant), n (the hyperbolic sine power), α (the stress multiplier) are the material's parameters [8]. Conventionally, A, n, α, and Q are

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considered to be apparent parameters. However, a reliable constitutive equation will be resulted by consideration of the underlying mechanisms.

Recently, it has been shown that when the deformation mechanism is controlled by the glide and climb of dislocations, a constant hyperbolic sine power of $n = 5$ and self diffusion activation energy (Q_{sd}) can be used to describe the appropriate stress [10]. This is possible by taking into account the dependences of Young's modulus (E) and self-diffusion coefficient (D) on temperature in the hyperbolic sine law. Accordingly, the unified relation can be expressed as $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$ where $D = D_0 \exp(-Q_{sd}/RT)$, in which D_0 is a pre-exponential constant. The constants α' and B are the modified stress multiplier and the hyperbolic sine constant, respectively. The consideration of physically-based constants (the hyperbolic sine power of 5 and self diffusion activation energy) reduces the number of unknown parameters and constants to 2 (α' and B). This results in a more reliable constitutive equation, simplifies the constitutive analysis, and makes it possible to conduct comparative hot working studies.

In the current work, the constitutive behaviors of AZ31, AZ61, and AZ91 alloys will be studied by consideration of physically-based material's parameters in order to propose a reliable constitutive equation for hot deformation of each material and elucidate the effect of Al on hot working behavior of Al-bearing magnesium alloys.

2. Experimental materials and procedures

2.1. Hot flow stress database for Mg–Al–Zn alloys

The flow stress data for hot compression testing of AZ31, AZ61, and AZ91 alloys were taken from the literature [11–24]. The considered flow curves exhibited typical dynamic recrystallization (DRX) behavior with a single peak stress (σ_P) followed by a gradual fall towards a steady state stress. Note that the description of flow stress by equation $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$ is incomplete, because no strain for determination of flow stress is specified. Therefore, characteristic stresses that represent the same deformation or softening mechanism for all flow curves, such as steady state or peak stress, should be used in this equation. Since the peak stress (σ_P) is the most widely accepted one in obtaining the hot working constants [25–28], its values were taken with emphasis on the consistency of stress level among different research works for each material.

Since the flow data has been taken from the literature and the details of the considered materials and experiments in each research work is different, some other factors such as the initial microstructure and grain size [29,30], the details of the precipitates [31,32], and small variations in chemical compositions can affect the level of flow stress or the hot deformation behavior. However, the consideration of these parameters is not easy and needs a huge database, which is not the case for the considered materials in the current work. Therefore, the following analysis can fairly demonstrate the averaged constitutive behavior of these materials based on the differences in the amount of Al.

2.2. Temperature dependence of E and D

In equation $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$, the values of D_0 and Q_{sd} can be taken from the Frost and Ashby tables [33]. In these tables, the dependence of the shear modulus (G) on temperature in the form of $G/G_0 = 1 + \eta(T - 300)/T_M$ is also available. Here, G_0 is the shear modulus at 300 K, T_M is the melting temperature of the material, and $\eta = (T_M/G_0)\mathrm{d}G/\mathrm{d}T$ shows the temperature dependence of the shear modulus. According to the relation of $E = 2G(1 + \nu)$, the values of E can be estimated (ν is usually taken as 0.3). Using the available data for magnesium (as shown in Table 1), the following expressions can be derived for D and E:

$$D = 1.0 \times 10^{-4} \times \exp(-135000/RT) \tag{1}$$

$$E = 43160 \times \{1 - 0.49(T - 300)/924\} \tag{2}$$

3. Results

In equation $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$, there are only two unknown parameters (B and α'). In order to find the value of α', the power ($Z = A'\sigma^{n'}$) and exponential ($Z = A'' \exp(\beta\sigma)$) laws for description of flow stress were modified as $\dot{\varepsilon}/D = B'(\sigma_P/E)^{n'}$ and $\dot{\varepsilon}/D = B'' \exp(\beta'\sigma_P/E)$, respectively. In the modified equations, B', B'', n', β' are constants. Therefore, the value of α' can be estimated by β'/n' [10]. It follows from these expressions that the slope of the plot of $\ln(\dot{\varepsilon}/D)$ against $\ln(\sigma_P/E)$ and the slope of the plot of $\ln(\dot{\varepsilon}/D)$ against σ_P/E can be used for obtaining the values of n' and β', respectively. These plots are shown in Fig. 1. The linear regression of the data resulted in the values of $\alpha' = 632$, 529, and 431 for the AZ31, AZ61, and AZ91 alloys, respectively.

According to equation $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$, the slopes of the plots of $\{\dot{\varepsilon}/D\}^{0.2}$ against $\sinh\{\alpha'\sigma_P/E\}$ by fitting straight lines with the intercept of zero ($y = ax + 0$ as shown in Fig. 2) was used for obtaining the values of $B^{0.2} = 453.3$, 531.1, and 531.6 for the AZ31, AZ61, and AZ91 alloys, respectively. The resultant constitutive equations can be expressed as:

$$\frac{\dot{\varepsilon}}{D} = \begin{cases} 453.3^5 \times \{\sinh(632 \times \sigma_P/E)\}^5 \Leftrightarrow \text{AZ31} \\ 531.1^5 \times \{\sinh(529 \times \sigma_P/E)\}^5 \Leftrightarrow \text{AZ61} \\ 531.6^5 \times \{\sinh(431 \times \sigma_P/E)\}^5 \Leftrightarrow \text{AZ91} \end{cases} \tag{3}$$

where $D = 1.0 \times 10^{-4} \times \exp(-135000/RT)$. Therefore, suitable constitutive equations for describing the hot working behaviors of these materials can be expressed as:

Table 1
Data used to obtain the temperature dependence of D and G for Mg.

D_0 (m²/s)	Q_{SD} (kJ/mol)	η	G_0 (MPa)	T_M (K)
1.0×10^{-4}	135	−0.49	16,600	924

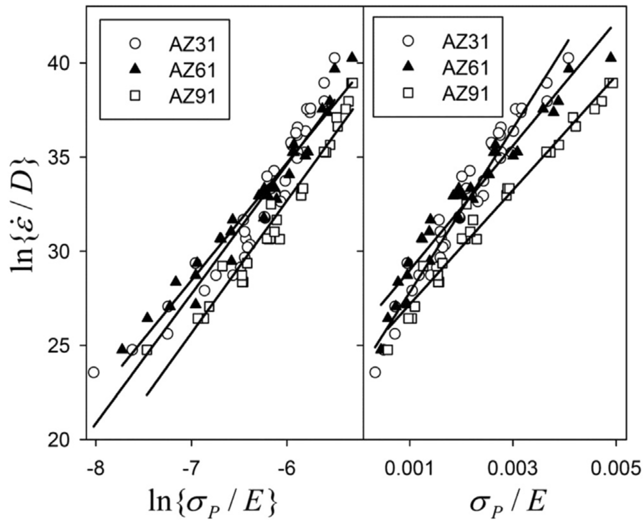

Fig. 1. Plots used to obtain the values of the modified stress multiplier α'.

$$Z = \dot{\varepsilon}\exp\left(\frac{135{,}000}{RT}\right) = \begin{cases} 71.84^5 \times \{\sinh(632 \times \sigma_P/E)\}^5 \Leftrightarrow \mathrm{AZ31} \\ 84.17^5 \times \{\sinh(529 \times \sigma_P/E)\}^5 \Leftrightarrow \mathrm{AZ61} \\ 84.25^5 \times \{\sinh(431 \times \sigma_P/E)\}^5 \Leftrightarrow \mathrm{AZ91} \end{cases} \quad (4)$$

4. Discussion

Based on Eq. (4), it seems that the consideration of hyperbolic sine power of 5 and the lattice self-diffusion activation energy of Mg as the deformation activation energy works well for the AZ31, AZ61, and AZ91 alloys. A comparison between the hot flow stresses of these alloys can be made by rewriting Eq. (4) in the following form:

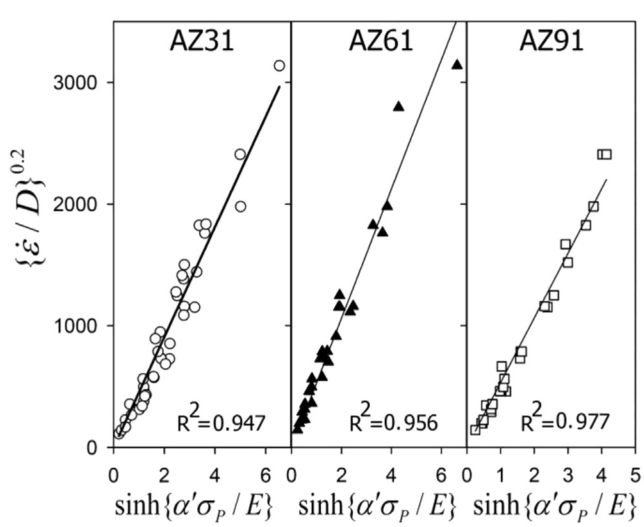

Fig. 2. Plots used to obtain the physically-based constitutive equations by using the obtained values of α'.

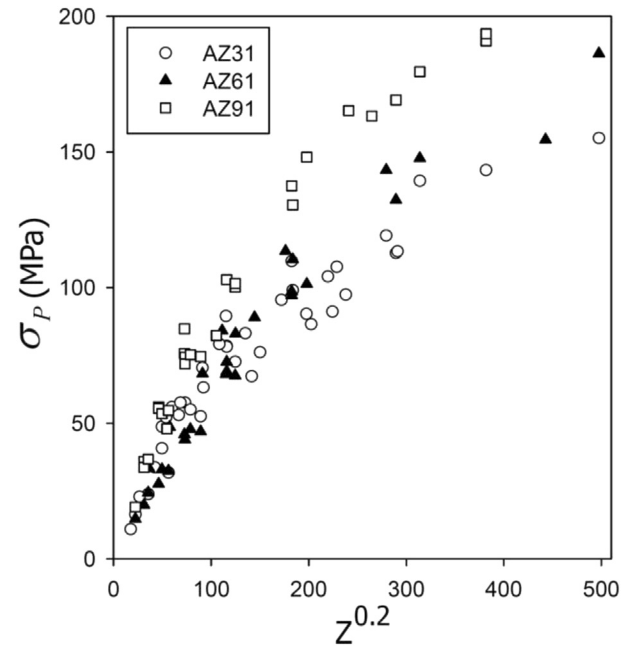

Fig. 3. Dependence of σ_P on Z for AZx_{Al}1 alloys by consideration of $Q = 135$ kJ/mol.

$$\sigma_P = \begin{cases} E \times \sinh^{-1}\{Z^{0.2}/71.84\}/632 \Leftrightarrow \mathrm{AZ31} \\ E \times \sinh^{-1}\{Z^{0.2}/84.17\}/529 \Leftrightarrow \mathrm{AZ61} \\ E \times \sinh^{-1}\{Z^{0.2}/84.25\}/431 \Leftrightarrow \mathrm{AZ91} \end{cases} \quad (5)$$

Based on Eq. (5), there is no possibility for elucidating the effect of Al on the hot flow stress due to the differences in the values of B and α'. However, the physically-based approach employed in this study makes it possible to compare the hot flow stresses of these materials based on the experimental data as shown in Fig. 3, which depicts the values of σ_P *vs.* $Z^{0.2}$.

Since the values of Z were determined based on the lattice self-diffusion activation energy of Mg as the deformation activation energy, the values of Z are the same for these alloys at a given deformation condition (deformation temperature and strain rate). As can be seen in Fig. 3, at each Z, the level of flow stress is the highest for the AZ91 alloy and is the lowest for the AZ31 alloy. This is consistent with the fact that a higher amount of alloying elements, especially Al in Mg, generally increases the flow stress of the material by solid solution hardening effects.

The value of α' for the AZ31, AZ61, and AZ91 alloys were determined as 632, 529, and 431, respectively. The average value of $\alpha' = (632 + 529 + 431)/3 \approx 530$ can be considered for further analysis, which makes it possible to compare the hot flow stress of AZ31, AZ61, and AZ91 alloys based on the values of the modified hyperbolic sine constant (B). Again, according to equation $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$, the slopes of the plots of $\{\dot{\varepsilon}/D\}^{0.2}$ against $\sinh\{\alpha'\sigma_P/E\}$ by fitting straight lines with the intercept of zero were used for obtaining the values of $B^{0.2} = 629.84$, 528.97, and 344.8 for the AZ31, AZ61, and AZ91 alloys, respectively. The corresponding plots are shown in Fig. 4, which show that the correlation coefficients of the fitted lines are relatively high. The resultant

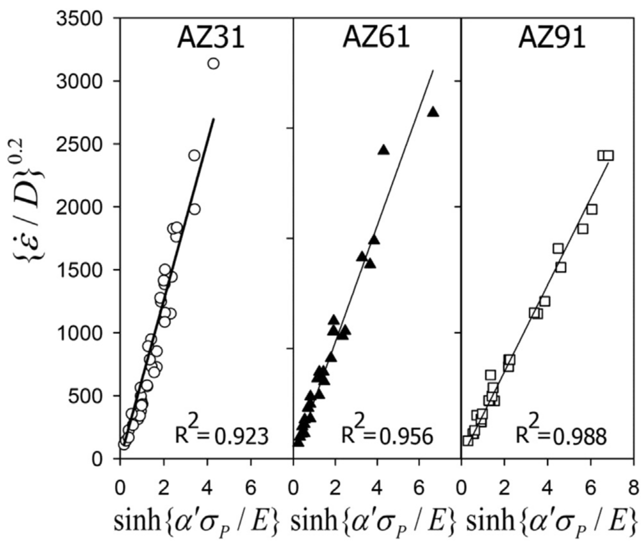

Fig. 4. Plots used to obtain the physically-based constitutive equations by using the average value of $\alpha' = 530$.

constitutive equations can be expressed in their simplified form as follows:

$$Z = \dot{\varepsilon}\exp\left(\frac{135,000}{RT}\right) = \begin{cases} 99.82^5 \times \{\sinh(530 \times \sigma_P/E)\}^5 \Leftrightarrow \text{AZ31} \\ 83.83^5 \times \{\sinh(530 \times \sigma_P/E)\}^5 \Leftrightarrow \text{AZ61} \\ 54.65^5 \times \{\sinh(530 \times \sigma_P/E)\}^5 \Leftrightarrow \text{AZ91} \end{cases} \quad (6)$$

The value of the proportionality constant of Eq. (6) is 54.65^5 for the AZ91 alloy, which is smaller than the values determined for the AZ61 and AZ31 alloys. Therefore, it can be concluded that the hot flow stress of AZ91 alloy and probably its creep resistance is higher. This also implies that the used approach in the current work can be considered as a versatile tool in future hot working studies, especially in studies dedicated to alloy development.

Since the value of $\alpha' = 530$ was used for the AZ31, AZ61, and AZ91 alloys and the main difference between these alloys is the difference in their amount of aluminum, the difference in constitutive behaviors can be deduced from the proportionality constants of Eq. (6). The required plot is shown in Fig. 5. As a result of regression analysis, the appropriate constitutive equation to characterize the hot deformation behavior of AZx_{Al}1 alloys, where x_{Al} denotes the weight percent of Al, can be expressed as follows:

$$Z = \dot{\varepsilon}\exp\left(\frac{135,000}{RT}\right) = \left(105.1 - 0.5x_{Al}^{2.1}\right)^5 \times \left\{\sinh\left(530 \times \frac{\sigma_P}{E}\right)\right\}^5 \quad (7)$$

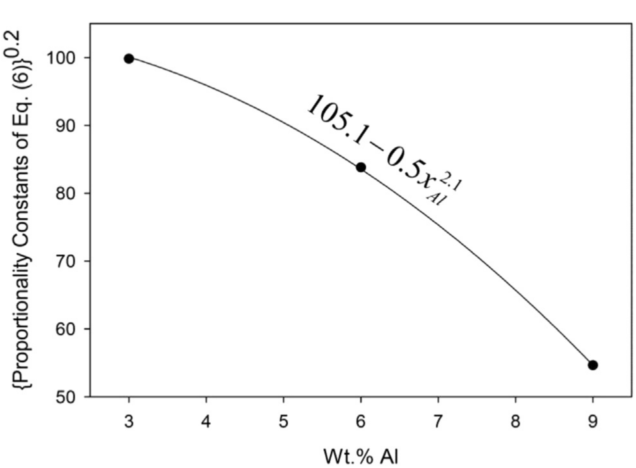

Fig. 5. Plot used to obtain the generalized constitutive equation for hot deformation of AZx_{Al}1 alloys based on the weight percent of Al.

5. Conclusions

The following conclusions can be drawn from the study on the constitutive behaviors of AZ31, AZ61, and AZ91 magnesium alloys during hot deformation:

(1) It was found that the theoretical equation of the form $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$ can be used to express the constitutive behavior of these materials. It was also shown that the lattice self-diffusion activation energy of magnesium (135 kJ/mol) can be used as the hot deformation activation energy to calculate the Zener–Hollomon parameter.
(2) Based on the used approach in the current work, the difference in constitutive behaviors of AZ31, AZ61, and AZ91 magnesium alloys can be described by only two parameters (α' and B), which makes it possible to conduct a comparative study based on the level of Al.
(3) By taking the average value of the modified stress multiplier (α'), the constitutive behaviors of AZ31, AZ61, and AZ91 magnesium alloys was characterized by relating the hot flow stress to weight percent of Al (x_{Al}) as shown by the following equation:

$$Z = \dot{\varepsilon}\exp\left(\frac{135,000}{RT}\right) = \left(105.1 - 0.5x_{Al}^{2.1}\right)^5 \times \left\{\sinh\left(530 \times \frac{\sigma_P}{E}\right)\right\}^5$$

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