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Constitutive analysis of Mg–Al–Zn magnesium alloys during hot deformation

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ABSTRACT

The constitutive behaviors of Mg–Al–Zn magnesium alloys during hot deformation were studied over a wide range of Zener–Hollomon parameters by consideration of physically-based material's parameters. It was demonstrated that the theoretical exponent of 5 and the lattice self-diffusion activation energy of magnesium (135 kJ/mol) can be used in the hyperbolic sine law to describe the flow stress of AZ31, AZ61, AZ80, and AZ91 alloys. The apparent hyperbolic sine exponents of 5.18, 5.06, 5.17, and 5.12, respectively for the AZ31, AZ61, AZ80, and AZ91 alloys by consideration of deformation activation energy of 135 kJ/mol were consistent with the considered theoretical exponent of 5. The influence of Al upon the hot flow stress of Mg–Al–Zn alloys was characterized by the proposed approach, which can be considered as a versatile tool in comparative hot working and alloy development studies. It was also shown that while the consideration of the apparent material's parameters may result in a better fit to experimental data, but the possibility of elucidating the effects of alloying elements on the hot working behavior based on the constitutive equations will be lost.

1. Introduction

Due to their hexagonal closed packed (HCP) crystal structure with a limited number of slip systems, the ductility of polycrystalline magnesium alloys are usually poor at room temperature (Al-Samman and Gottstein, 2008; Ding et al., 2010). The activation of additional slip systems at elevated temperatures normally increases the workability of Mg and its alloys (Bhattacharya et al., 2012) and hence hot deformation processing can be considered as a suitable processing route for shaping of magnesium-based products. Moreover, owing to its influence upon the structural refinement (Miura et al., 2012; Rao et al., 2012), hot working is an indispensable tool for enhancing the properties of castings.

The understanding of the hot deformation behavior of the material under consideration together with the constitutive relations describing material flow is the prerequisite for large-scale production in the industry. The modeling of hot flow stress is thus important in metal-forming processes because any feasible mathematical simulation needs accurate flow description (Cipoletti et al., 2011; Han et al., 2013; Lin and Chen, 2011; Mirzadeh et al., 2012; Mirzadeh and Najafizadeh, 2013). The most commonly used constitutive equation in hot working is expressed as $Z = \dot{\varepsilon}\exp(Q/RT) = A[\sinh(\alpha\sigma)]^n$, where Z (the Zener–Hollomon parameter) is the temperature-compensated strain rate, Q is the deformation activation energy, $\dot{\varepsilon}$ is the strain rate, T is the absolute temperature, R is the universal gas constant, and finally A (the hyperbolic sine constant), n (the hyperbolic sine power), α (the stress multiplier) are the material's parameters (Mirzadeh et al., 2011).

Conventionally, the obtained material's constants and deformation activation energy in hot deformation studies are apparent parameters resulted solely from data fitting. However, a reliable constitutive equation to characterize

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the hot deformation behavior of the material will be resulted by consideration of the underlying mechanisms. Recently, Mirzadeh et al. (2011) have proposed an easy to apply approach that considers a theoretical values of n and Q in the constitutive analysis. In the current work, the constitutive behaviors of some of the most commercially important Al-bearing Mg alloys (AZ31, AZ61, AZ80, and AZ91) with emphasis on the application of physically-based constitutive equations will be analyzed to show the capabilities of the proposed approach for future comparative hot working studies. This in turn brings about a possibility to study the effect of aluminum on constitutive behavior and hot flow stress of AZ magnesium alloys based on the obtained values of A and α.

2. Experimental materials and procedures

The flow stress data for hot compression testing of AZ31 (Mg – 3 wt% Al – 1 wt% Zn), AZ61 (Mg – 6 wt% Al – 1 wt% Zn), AZ80 (Mg – 8 wt% Al – 0.5 wt% Zn), and AZ91 (Mg – 9 wt% Al – 1 wt% Zn) alloys were taken from the literature (Cerri et al., 2007; Ding et al., 2007; Gall et al., 2013; Kawalla and Stolnikov, 2004; Liu and Ding, 2009; Luan et al., 2014; Mu et al., 2012; Niu et al., 2007; Poletti et al., 2009; Quan et al., 2011; Sanjari et al., 2012; Slooff et al., 2010; Wu et al., 2012; Xu et al., 2013; Zhong et al., 2013; Zhou et al., 2010). 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 $Z = \dot{\varepsilon}\exp(Q/RT) = A[\sinh(\alpha\sigma)]^n$ 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, peak, or critical stress for initiation of DRX, should be used in this equation. It should be noted that the nature of material's constants and equations are dependent on the characteristic stress used to derive them. In general, the peak stress is the most widely accepted one in order to find the hot working constants (Mirzadeh et al., 2010; Mirzadeh et al., 2013). Therefore, a wide range of deformation temperatures (200–500 °C) and strain rates (0.000016–100 s^{-1}) was considered for constitutive analyses and the peak stress of more than 140 flow curves were extracted with emphasis on the consistency of stress level among different research works dealing with the given alloys.

It should be noted that the initial grain size, texture, and variations in chemical compositions can affect the level of flow stress of each considered material but the consideration of these parameters needs a suitable database, which is not the case for these alloys.

3. Results

3.1. The stress multiplier (α)

The Zener–Hollomon parameter (Z) can be related to flow stress in different ways (Mirzadeh et al., 2012). The power law description of stress ($Z = A'\sigma_P^{n'}$) is preferred for relatively low stresses. Conversely, the exponential law ($Z = A''\exp(\beta\sigma_P)$) is only suitable for high stresses. However, the hyperbolic sine law ($Z = A[\sinh(\alpha\sigma_P)]^n$) can be used for a wide range of temperatures and strain rates. In these equations, A', A'', A, n', n, β and α ($\approx\beta/n'$) are constants. The stress multiplier α is an adjustable constant which brings $\alpha\sigma$ into the correct range to make constant T curves in $\ln\dot{\varepsilon}$ versus $\ln\{\sinh(\alpha\sigma_P)\}$ plots linear and parallel. Based on the power and exponential laws, the slopes of the plots of $\ln\dot{\varepsilon}$ against $\ln\sigma_P$ ($n' = [\partial\ln\dot{\varepsilon}/\partial\ln\sigma_P]_T$) and $\ln\dot{\varepsilon}$ against σ_P ($\beta = [\partial\ln\dot{\varepsilon}/\partial\sigma_P]_T$) can be used for obtaining the values of n' and β and subsequently $\alpha \approx \beta/n'$. Some representative plots are shown in Fig. 1a. The linear regression of the data resulted in the average value $\alpha \approx 0.010\ \text{MPa}^{-1}$ for the AZ31, AZ61, and AZ91 alloys and $\alpha \approx 0.017\ \text{MPa}^{-1}$ for the AZ80 alloy. It should be noted that α values of about 0.001 (Wu et al., 2012), 0.004 (Slooff et al., 2010), 0.01 (Gall et al., 2013; Liu and Ding, 2009), 0.017 (Zhou et al., 2010), 0.02 (Gall et al., 2013; Poletti et al., 2009; Spigarelli et al., 2007), 0.05 (Barnett, 2001; Mwembela et al., 1997; Sanjari et al., 2012), and 0.07 MPa^{-1} (Cerri et al., 2007) have also been reported for hot deformation of AZ magnesium alloys.

3.2. The hot deformation activation energy (Q)

Taking natural logarithm from the both sides of the hyperbolic sine equation results in

$$\ln Z = \ln\dot{\varepsilon} + (Q/R)(1/T) = \ln A + n\ln\{\sinh(\alpha\sigma_P)\} \quad (1)$$

or equivalently

$$Q = R[\partial\ln\dot{\varepsilon}/\partial\ln\{\sinh(\alpha\sigma_P)\}]_T[\partial\ln\{\sinh(\alpha\sigma_P)\}/\partial(1/T)]_{\dot{\varepsilon}} \quad (2)$$

It follows that the slopes of the plots of $\ln\dot{\varepsilon}$ against $\ln\{\sinh(\alpha\sigma)\}$ and $\ln\{\sinh(\alpha\sigma)\}$ against $1/T$ can be used for obtaining the value of Q. Some representative plots are shown in Fig. 1b and c. The linear regression of the data resulted in the values of Q = 135.94, 136.71, 134.62, and 136.27 kJ/mol for the AZ31, AZ61, AZ80, and AZ91 alloys, respectively. These values are close to the value reported for the lattice self-diffusion activation energy of magnesium, which is about 135 kJ/mol (Porter and Easterling, 1992; Frost and Ashby, 1982). It has been shown by Mirzadeh et al. (2011) and Cabrera et al. (1997) that in hot deformation studies, the self-diffusion activation energy can be used as the deformation activation energy to calculate Z. Therefore, the value of Q = 135 kJ/mol was considered for all of the investigated materials. It should be noted that Q values between 120 and 204 kJ/mol for the AZ31 alloy (Barnett, 2001; Bhattacharya et al., 2012; Fatemi-Varzaneh et al., 2007; Gall et al., 2013; Luan et al., 2014; Mwembela et al., 1997; Poletti et al., 2009; Sanjari et al., 2012; Spigarelli et al., 2007; Zhong et al., 2013), between 115 and 178 kJ/mol for the AZ61 alloy (Cerri et al., 2007; Slooff et al., 2010; Wu et al., 2012; Xu et al., 2013), about 154 kJ/mol for the AZ80 alloy (Zhou et al., 2010), and about 176 kJ/mol for the AZ91 alloy (Liu and Ding, 2009) have also been reported.