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Quantification of the strengthening effect of rare earth elements during hot deformation of Mg-Gd-Y-Zr magnesium alloy

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ABSTRACT

The flow stress of Mg-Gd-Y-Zr, Mg-Al-Zn, and Mg-Zn-Zr magnesium alloys during hot deformation were correlated to the Zener–Hollomon parameter through analyses based on the proposed physically-based and apparent approaches. It was demonstrated that the theoretical exponent of 5 and the lattice self-diffusion activation energy of magnesium (135 kJ/mol) can be set in the hyperbolic sine law to describe the peak flow stresses. As a result, the influence of rare earth elements, gadolinium (Gd) and yttrium (Y), upon the hot working behavior was readily characterized by the proposed approach, which was not possible by the conventional apparent approach. It was shown quantitatively that the rare earth addition exerts a profound effect on the hot strength and hence on the creep resistance.

1. Introduction

Magnesium (Mg) alloys containing rare earth elements are promising structural materials due to their notable creep resistance and high specific strength at both ambient and elevated temperatures. The rare earth additions can remarkably improve the heat resistance of the Mg alloys due to solid solution strengthening and precipitation hardening effects [1–6]. Hot deformation processing is a suitable shaping method for polycrystalline Mg alloys due to the activation of additional slip systems at elevated temperatures and the possibility of structural refinement [7–12]. The understanding of the hot working behavior and the constitutive relations describing material flow is one of the prerequisites for the implementation of shaping technology in the industry [13,14].

Heat resistant cast Mg alloy development includes three categories [3]: (1) alloying of Mg-Al based alloys with Ca (forming AX alloys), with Zn and Ca (forming AZX alloys), with Sr (forming AJ alloys), with Ca and Sr (forming AXJ alloys), with RE (forming AE alloys), with Si and Sb (forming ASS alloys), with Ca and RE (forming ACM alloys and MRI alloys), with Zn, Ca and RE (forming ZACE alloys), with Zn, Sn (forming ASZ alloys); (2) development of a new type of Mg-RE-Zr alloys, including Mg-Y-Nd-Zr (WE) alloys, Mg-Gd-Nd-Zr (GN), Mg-Dy-Nd-Zr (DN) and Mg-Gd-Y-Zr (GW) alloys; (3) development of Mg-RE-Zn (MEZ) alloys. Thanks to their magnificent room- and high-temperature strength, magnesium alloys containing rare

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earth elements Gd and Y have been recently developed and extensively investigated [3].

In the current work, the constitutive behavior of Mg alloyed with Gd and Y will be compared with those of the high-strength Mg alloys, namely AZ91 (Mg-9Al-1Zn) [7,12] and ZK60 (Mg-6Zn-0.6Zr) [15,16], using a proposed method that utilizes the physically-based material's parameters, which makes it possible to conduct comparative studies.

2. Experimental details

The flow stress data of Mg-Gd-Y-Zr alloys with 9–10 wt% Gd, 2.7–4.8 wt% Y and 0.4–0.6 wt% Zr, hot compressed at deformation temperatures between 350 and 500 °C under strain rates of 0.001 to 10 s^{-1}, were taken from the literature [17–21]. Since the level of the peak flow stress did not show any considerable dependence on the small variation of Gd and Y among the considered research works, the flow data were combined together to determine the constitutive behavior of the Mg-Gd-Y-Zr alloy. The flow stress data for ZK60 (with 0.61 to 0.76 wt% Zr) and AZ91 were also taken from the literature [7,15,22–29]. The considered flow curves exhibited typical dynamic recrystallization (DRX) behavior [30,31] with a single peak stress (σ_P) followed by a gradual fall toward a steady state stress.

The well-known Zener–Hollomon parameter $Z = \dot{\varepsilon}\exp(Q/RT)$ can be related to flow stress in different ways. The power law description of stress ($Z = A'\sigma^{n'}$) is preferred for relatively low stresses. Conversely, the exponential law ($Z = A''\exp(\beta\sigma)$) is suitable for high stresses. However, the hyperbolic sine law ($Z = A[\sinh(\alpha\sigma)]^n$) can be used for a wide range of temperatures and strain rates. In these equations, A', A'', A (the hyperbolic sine constant), n', n (the hyperbolic sine power), β and $\alpha \approx \beta/n'$ (the stress multiplier) are constants and Q is the hot deformation activation energy. In these equations, no strain for determination of flow stress is specified. As a result, characteristic stresses such as steady state stress, peak stress, or the critical stress for initiation of DRX may be used. Since the steady-state stress may not be precisely attained for all of the flow curves and obtaining the critical stress for initiation of DRX needs work-hardening rate analysis [31], it is usual to use the peak stress to find the values of A, n, α, and Q [32–35]. For each alloy, the selection criterion of the peak stress data from the literature was based on the consistency of stress level among the considered research works.

3. Results

Based on the power and exponential laws, the slopes of the plots of $\ln\dot{\varepsilon}$ against $\ln\sigma_P$ and $\ln\dot{\varepsilon}$ against σ_P can be used for obtaining the values of n' ($n' = [\partial\ln\dot{\varepsilon}/\partial\ln\sigma_P]_T$) and β ($\beta = [\partial\ln\dot{\varepsilon}/\partial\sigma_P]_T$), respectively. This is shown in Fig. 1a and b for the Mg-Gd-Y-Zr alloy and the subsequent linear regression of the data resulted in the average value $\alpha \approx 0.00973$ or simply $\alpha \approx 0.01\ \mathrm{MPa}^{-1}$. The same average value of $\alpha \approx 0.01\ \mathrm{MPa}^{-1}$ was also obtained for AZ91 [7] and ZK60 [15] alloys by similar type of analysis. Taking natural logarithm from the hyperbolic sine equation and subsequent partial differentiations at constant temperature and also at constant strain rate together with algebraic operations results in $Q = R[\partial\ln\dot{\varepsilon}/\partial\ln\{\sinh(\alpha\sigma_P)\}]_T[\partial\ln\{\sinh(\alpha\sigma_P)\}/\partial(1/T)]_{\dot{\varepsilon}}$. 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. The representative plots are shown in Fig. 1c and d for the Mg-Gd-Y-Zr alloy. The linear regression of the data results in the average value of Q = 199.83 kJ/mol or simply 200 kJ/mol for the Mg-Gd-Y-Zr alloy. The average values of Q for the AZ91 and ZK60 alloy were determined as 136.27 and 140.30 kJ/mol, respectively. The values of hot deformation activation energy of 136.27 and 140.30 kJ/mol are close to that reported for the lattice self-diffusion activation energy of magnesium, which is about 135 kJ/mol [7,15]. Conversely, the value of 200 kJ/mol is effectively higher than 135 kJ/mol. Therefore, while AZ91 (Mg-9Al-1Zn) and ZK60 (Mg-6Zn-0.6Zr) alloys have relatively high amount of Al or Zn as alloying elements, the self-diffusion of Mg occurs rather easily during hot deformation of these alloys. However, the rare earth addition in Mg-Gd-Y-Zr alloy is very effective in hindering the self-diffusion that is a major factor in increasing creep rate [36].

Based on the hyperbolic sine law, the slope and the intercept of the plot of ln Z against $\ln\{\sinh(\alpha\sigma_P)\}$ can be used for obtaining the values of n and A. The corresponding plots are shown in Fig. 2a for all of the considered materials using the apparent values of Q. The linear regression of the data results in the following equations:

$$\begin{cases} \text{Mg-Gd-Y-Zr} \Leftrightarrow \dot{\varepsilon}\exp(200,000/RT) = 429^5\{\sinh(0.01\times\sigma_P)\}^{4.96} \\ \text{AZ91} \Leftrightarrow \dot{\varepsilon}\exp(136,270/RT) = 98.79^5\{\sinh(0.01\times\sigma_P)\}^{5.15} \\ \text{ZK60} \Leftrightarrow \dot{\varepsilon}\exp(140,300/RT) = 160.55^5\{\sinh(0.01\times\sigma_P)\}^{5.43} \end{cases} \quad (1)$$

Note that there is no possibility for elucidating the effects of alloying elements on the hot flow stress due to the differences in the values of Q and n.

4. Discussion

Recently, Mirzadeh et al. [37] have proposed an easy to apply approach that considers theoretical values of n and Q based

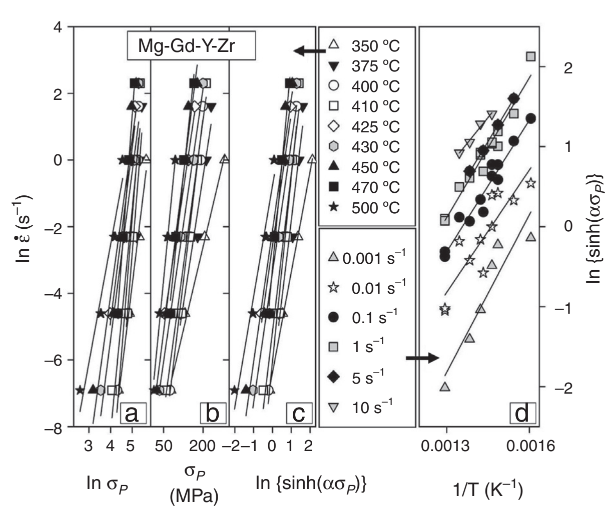

Fig. 1 – Plots used to obtain the values of the stress multiplier α and the deformation activation energy Q for the Mg-Gd-Y-Zr alloy.