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Hot deformation characteristics of AZ80 magnesium alloy: Work hardening effect and processing parameter sensitivities

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ABSTRACT

Isothermal compression experiment of AZ80 magnesium alloy was conducted by Gleeble thermo-mechanical simulator in order to quantitatively investigate the work hardening (WH), strain rate sensitivity (SRS) and temperature sensitivity (TS) during hot processing of magnesium alloys. The WH, SRS and TS were described by Zener-Hollomon parameter (Z) coupling of deformation parameters. The relationships between WH rate and true strain as well as true stress were derived from Kocks-Mecking dislocation model and validated by our measurement data. The slope defined through the linear relationship of WH rate and true stress was only related to the annihilation coefficient Ω. Obvious WH behavior could be exhibited at a higher Z condition. Furthermore, we have identified the correlation between the microstructural evolution including β-$Mg_{17}Al_{12}$ precipitation and the SRS and TS variations. Intensive dynamic recrystallization and homogeneous distribution of β-$Mg_{17}Al_{12}$ precipitates resulted in greater SRS coefficient at higher temperature. The deformation heat effect and β-$Mg_{17}Al_{12}$ precipitate content can be regarded as the major factors determining the TS behavior. At low Z condition, the SRS becomes stronger, in contrast to the variation of TS. The optimum hot processing window was validated based on the established SRS and TS values distribution maps for AZ80 magnesium alloy.

1. Introduction

Magnesium alloys, as the lightest structural metals, have drawn considerable attention from aerospace and automobile industries due to their low density, high specific stiffness and good recyclability [1,2]. Unfortunately, owing to the hexagonal close packed (HCP) crystal structure and restricted number of slip systems, conventional magnesium alloys have poor plastic deformation property at room temperature [3]. The wide application of magnesium alloys in industry is, thus, hindered despite of the outstanding advantages mentioned above. However, the workability of magnesium alloys can be enhanced dramatically through thermo-mechanical processing, such as hot extrusion and hot forging, which can increase the number of slip planes and decrease the critical shear stress of non-basal plane slips [4,5]. Therefore, the quantitative characterization of hot deformation behavior is essential for optimizing the forming process of magnesium alloys. In view that the workability can be represented by flow stress curves at some aspect, greater attention has been placed on the correlation between hot deformation behavior and the characteristics of flow curves [6,7]. Flow stress curves serve as a comprehensive and external reflection of the deformation mechanisms and microstructural evolution. The work hardening (WH), strain rate sensitivity (SRS) and temperature sensitivity (TS) are associated with the flow stress curves so become the mechanical and metallurgical topics for magnesium alloys during hot deformation.

Several works have done for relating the WH, SRS and TS behaviors with different hot deformation mechanisms for magnesium alloys [8–27]. Abundant analyses in thermodynamics have been performed based on the WH curves of θ (θ=dσ/dε) complying with the form of external power dissipation rate [8,9,13]. The inflection points on the WH curves or the minimums on the -$\partial\theta/\partial\sigma$ curves are recognized to correspond to the onset of dynamic recrystallization (DRX) softening [8]. This recognition has been extensively validated and applied during the investigation in hot deformation of various metallic materials, including magnesium alloys [9]. The WH curves of magnesium single crystals exhibited the features of stages I, II, and III which were observed in face-centered cubic (fcc) crystals [10]. For magnesium polycrystalline, however, their WH behavior is more complicate owing to their low symmetry that restricts the plastic anisotropy as well as the number of active slip systems [11,12]. Tahreen et al. [13] investigated

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the effects of strain rate and aluminum content on the compressive WH behavior of AZ31, AZ61 and AZ91D magnesium alloys and showed that the WH rate of all the three magnesium alloys exhibited the appearance of stage III hardening followed by stage IV hardening. Qin et al. [14] developed a kinetic model to predict the WH and dynamic softening (DS) behaviors basing on the analysis of true stress-true strain data for ZK60 magnesium alloy. Wang et al. [15] combined Arrhenius constitutive equation with WH behavior to study the hot deformation of AE21 magnesium alloy. The DRX, dynamic recovery (DRV), and kink bands have been observed during microstructure evolution, in accordance with the result from WH analysis. Guo et al. [16] studied the influences of grain size, basal texture intensity and twinning conditions on the WH behavior of AZ31 magnesium alloys. Xu et al. [17] characterized the WH variation $-\partial\theta/\partial\sigma$ during hot deformation for AZ61 magnesium alloy. The influences of strain rate and temperature on WH curves have been illustrated and it is revealed that the WH effect is stronger at lower temperature and higher strain rate.

Several studies have examined the strain rate sensitivity (SRS) and temperature sensitivity (TS) during plastic processing [18–26]. Korla et al. [18] used SRS measurements together with microstructure evolution identifying the phase transformations as one of the deformation mechanisms in AZ31 magnesium alloy. The dependence of the SRS coefficients on twinning has been analyzed and the results showed that twinning is associated essentially with zero SRS value. Chun et al. [19] explained the decreasing SRS trend due to the accommodation of strain within contraction twins and subsequent tension twinning within them (double twinning). Sabokpa et al. [20] studied the hot ductility and SRS behaviors of AZ81 magnesium alloy and found that lower stress level corresponds to more remarkable SRS behavior and the SRS values maintain at a continuous increase trend with reducing strain rate and elevating temperature. Guo et al. [21] employed a compressive split Hopkinson pressure bar (SHPB) apparatus to investigate the SRS behavior of Mg-8Li alloy under quasi-static strain rates. It was observed that strong strain hardening occurred in Mg-8Li alloy and the SRS values increase with increasing strain rate that is opposed to the Sabokpa's [20] results. del Valle et al. [22] pointed out that the SRS exponent increases significantly with the decreasing grain size below 15 μm for Mg-3Al-0.75Zn alloy. Xiao et al. [23] quantified the SRS and TS behaviors of magnesium nanocomposites by considering the effect of strain rate and temperature, and noted that there is no regular tendency for TS coefficient versus true strain. Other researches about the TS behavior mainly focused on titanium alloys [24–26] and showed that the TS coefficient varies significantly with strain, temperature, strain rate, and composition for titanium alloys. To our knowledge, however, similar studies have not been reported to the magnesium alloys. It is, thus, unclear how these process parameters and precipitates influence the TS behavior for magnesium alloys.

As mentioned above, the correlation between the WH behavior and microstructure evolution has been extensively characterized for hot forming process of various magnesium alloys. Feaugas et al. [27] clearly stated that grain size is not an effective structural feature to describe the WH behavior. The occurrence of heterogeneous dislocation structures could be more predominant than grain sizes during plastic deformation. However, only a few investigations have been devoted to obtain the dislocation contribution to WH behavior. Meanwhile, there is no appropriate model to demonstrate the WH variation during the plastic forming process and the dependence of WH behavior on deformation parameters has not been analyzed in detail. On the other hand, the SRS has frequently been characterized as only a phenomenological and mechanical coefficient. Its correlation with deformation mechanism has not been well examined. Accordingly the study of the effect of β-$Mg_{17}Al_{12}$ precipitates on the SRS coefficient for magnesium alloys can rarely be found. The quantitative description of SRS behavior has not been proposed yet so the influence and physics of the SRS still remain unclear. The same problem also exists for the TS behavior of magnesium alloys, thus, needs to be systematically explored. Furthermore, magnesium alloys are sensitive to strain rate and deformation temperature during hot working process. It is difficult to control the mechanical properties and the stability of the forming product quality. The investigation of intrinsic relationship between deformation behavior and strain rate as well as temperature has a great significance.

Therefore, in the present paper, we report our investigation on the WH, SRS and TS behaviors during hot working process basing on our isothermal compression experiments on AZ80 magnesium alloy. The internal relationship between process parameters and hot deformation behavior is detailed. Kocks-Mecking dislocation relation is introduced to reveal the dependence of WH rate on true strain and stress. The tendency of the WH curves and the significant influence of deformation parameters are examined and discussed. Based on the SRS and TS values distribution maps, the SRS and TS coefficients are correlated to the hot deformation mechanisms and the optimum hot processing window is identified. The influences of the DRX evolution and the morphology change of β-$Mg_{17}Al_{12}$ precipitates on the SRS behavior are analyzed, and the major factors determining SRS and TS behaviors are demonstrated. The results are meaningful and shed light on manufacturing the magnesium alloys in practical hot process.

2. Material and experimental procedures

2.1. Material preparation

The pre-extruded AZ80 magnesium alloy used in the present investigation was provided in the form of a bar with a diameter of 200 mm and a height of 150 mm. The chemical composition of this magnesium alloy is given in Table 1. Before the experiment, the cylindrical specimens, with 12 mm in height and 8 mm in diameter (in accordance with ASTM: E209 [28]), were machined with their cylinder axes parallel to the axial direction of the bar. Two end surfaces of cylindrical specimens were ground as smooth as possible in order to eliminate the effects of any surface defect on the hot deformation behavior. Fig. 1 displayed the microstructures of the as-received AZ80 magnesium alloy obtained from the typical optical microscope (OM) and scanning electron microscope (SEM). It can be seen that the initial grain size was about 30 μm, and the β-$Mg_{17}Al_{12}$ precipitates as well as particles of Al-Mn compound distributed in the grain interiors and along the grain boundaries.

2.2. Isothermal compression tests

The schematic illustration of sample extraction, isothermal compression tests, and the spot for microstructure characterization is presented in Fig. 2. The isothermal compression tests were performed on a Gleeble-1500D thermo-mechanical simulator. Five deformation temperatures (200, 250, 300, 350, 400 °C) and four strain rates (0.001, 0.01, 0.1 and 1.0 s^{-1}) were employed, and the height reduction was 60% that is associated a true strain 0.916. Graphite sheets were used as a lubricant between the specimen and anvils to minimize the influence of friction during hot compression. A thermocouple was spot-welded on the surface of the specimen at the mid height for temperature measurement and feedback control. Prior to compression, each specimen was heated up to the target temperature at a linear rate of 5 °C/s then held isothermally for 180 s to eliminate thermal gradient. Each sample was quenched in water immediately to reserve its deformed microstructure for subsequent investigations after isothermal compres-

Table 1
Chemical composition of AZ80 magnesium alloy.

Component	Al	Zn	Mn	Si	Fe	Ni	Cu	Mg
wt%	8.16	0.42	0.03	0.01	0.005	0.001	0.001	Bal.