Hot Deformation Behavior and Processing Map of As-Homogenized Mg-6Zn-1Al-0.5Mn-0.5Ca Alloy

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Abstract: The valid processing window of the Mg-Zn alloy with high strength is narrow. In order to gain the best processing parameter economically and fastly, the relationship between true strain and stress of as-homogenized Mg-6Zn-1Al-0.5Mn-0.5Ca alloy has been investigated using the GLEEBLE simulation under the temperatures ranging from 423 to 573 K, strain rate ranging from 0.01 s−1 to 10s−1. The processing map at a total strain of 0.67 has also been plotted. The results show that the best processing temperature and strain rate range are from 533 to 573 K, and not higher than 0.1s−1, respectively. The corresponding maximum coefficient of energy dissipation is 21 %. The investigated alloy has no crack, and its microstructure is fine and homogeneous. The kinetic analysis reveals that the stress exponent and activation energy of this alloy are 14.178 and 158.9 kJ/mol.

Keywords: Mg-6Zn-1Al-0.5Mn-0.5Ca; flow stress; processing map; dynamic recrystallization; activation energy.

1. Introduction

Magnesium alloys are the lightest structural metal materials, and have broad prospect in automobile, aerospace and 3C areas, etc [1-3]. Due to the HCP lattice, the cold working of magnesium alloy are so difficult that the main product of magnesium alloy are castings. However, the wrought Mg alloys are so admire due to their predominant strength and toughness. For instance, the mechanical properties of the double peak aged Mg-6Zn-1Mn-4Sn (wt.%.) alloy are an UTS of 390MPa and an elongation of 4.16%. However the toughness of alloy is poor [4].

The stacking fault energy of magnesium alloys is so low (76 mJ/m2) that dynamic recrystallization is of common occurrence during hot working. Meanwhile, the non-basal plane sliding system is also easily activated as well as the <c+a> sliding system, which could significantly improve the workability of magnesium alloys. Thus, it is important to investigate the hot deformation behaviors of magnesium alloys.

Because the plastic deformation processing window of magnesium alloy is quite narrow, many experiments are needed to acquire best processing technology by tradition method. It is time and money wasting. Recently, the processing map based on the Dynamic Material Model (DMM) proposed by Prasad has been a strong tool to optimize the hot working parameter and control the deformed microstructure [5-7]. S.Anbu Salvan et al. have investigated the hot deformation behaviors of as-cast ZE41A alloy using processing map [6]. Wang, et al and Juqiang, et al have also done similar work on the as-extruded WE43 alloys and ZK60 alloy, respectively [5, 7].

The authors have developed a new wrought Mg-6.0Zn-0.5Mn-1.0Al-0.5Ca (wt.%., ZAMX6100) with low cost, high strength and toughness. The alloy could achieve high performance (ultimate strength 358 MPa, yielding strength 317 MPa, and elongation 16.5 %) prepared by squeeze casting, hot extrusion and subsequent aging treatment. In this work, the hot deformation behaviors of as-homogenized ZAMX6100 alloy are further investigated using processing map, so as to confirm the valid working temperature and strain rate zone (dynamic recrystallization zone, DRX), as well as the unstable working zone of this alloy.

2. Materials and method

The size of as-homogenized ZAMX6100 alloy is Φ150×100 mm, and its chemical composition is listed in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Zn</th>
<th>Al</th>
<th>Mn</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>5.74</td>
<td>1.05</td>
<td>0.423</td>
<td>0.57</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 1 Chemical Composition of the ZAMX6100 Alloy (wt.%)

Figure 1 and 2 show the optical microstructure and XRD pattern of ZAMX6100 alloy. The as-casting alloy mainly consists of α-Mg and the grain boundary τ-Mg32(Al,Zn)49. The dendrite spacing of as-homogenized alloy is 200 ~ 300 μm. The sample size for hot deformation is Φ8×12 mm. The working temperatures are set as 423, 473, 523 and 573 K. The investigated strain rates are 0.01, 0.1, 1.0 and 10.0 s−1, respectively. In addition, the total strain is 0.67. The hot deformation behaviors were conducted using a Gleeble-3500 simulation.

Firstly, the sample is heated under vacuum to the scheduled temperature as a rate of 120 K/min, and hold for temperature homogenization by an additional 2 min. The true strain and stress data are collected automatically by the machine, to build processing map. After hot deformation, the samples are immediately quenched in water to conserve the microstructures. The deformed samples are polished and etched for microstructure observations. The etch solution is 5 g picric acid, 15 ml glacial acetic acid and 100 ml ethyl alcohol. The optical microstructures are observed at the sample center along the compression direction.
3. Results

3.1 Flow characteristics

Figure 3 shows the true stress vs. true strain curves of ZAMX6100 alloy under different deforming conditions. The flow stress of the investigated alloy increases with the descending temperature and the ascending strain rate. During the initial stage, the increasing strain is followed by the dislocation displacement and multiplication. Thus, the dislocations are tangled after the dislocation density increase rapidly, which retard the dislocation migration. As a result, the flow stress increases significantly, called “work hardening”. When the strain reach a critical value, the flow stress does not increase rapidly any more. It might be ascribed that some opposite sign dislocations are offset so that the dislocation density decreases as well as the total strain energy. It is called “softening stage”, where the flow stress grows slowly and then reach a peak value. Finally, it reaches a balance between the hardening and softening.
The deforming characteristics of ZAMX6100 are closely related to the strain rate and temperature. The specific strain corresponding to the maxi flow stress decreases with the increasing temperature and descending strain rate. For instance, the work hardening rate is rapid at low temperature (423 K), while the working softening is quite weak correspondingly. At this time, the dislocations accumulate around the grain boundaries and induce nucleation of microcracks. Finally, the alloy fracture, as shown in Fig.4. It could also be seen that the flow stress at 423 K decrease rapidly, as shown in Fig.3. Meanwhile, the strain to fracture decreases sharply, then increases with the strain rate increased, as shown in Fig.5. The dynamic recovery and DRX play a significant role of softening at high temperatures. By implication, the softening effect becomes strong at high temperature, and the hardening effects gets weak correspondingly. Furthermore, at low strain rate (≤1s⁻¹), the strain for maxi hardening effect decreases with the ascending temperature, while the time to open softening effect is shorten. As a result, the strain corresponding to the balance between hardening and softening also decreases. However, it could not observe any balance point at high strain rates, because the deforming time is too short to reach steady flow stress. The flowing characteristics of ZAMX6100 are similar to other magnesium alloys [6, 8-10].

Compared with the processing of ZK60 alloy[5], during the deformation of 523–573K, the maximum stress of ZAMX6100 alloy under low strain rate (\(\dot{\varepsilon} < 0.1\text{s}^{-1}\)) deformation is higher than that of ZK60 alloy. But lower much than that of ZK60 alloy during high strain rate deformation. That is to say, the process hardening effect of ZAMX6100 alloy under same condition is lower than ZK60 alloy, and is beneficial for plastic deformation processing.

Figure 4 Macroscopic features of specimens compressed to a true strain of about 0.67 at different temperatures and strain rates
3.2 Processing map

The processing map is a model integrating the effectiveness of energy dissipation and instability of deformation. In DMM model, the work piece is regarded as a body to dissipating energy. The instant total energy dissipation $P$ consists of temperature-rise induced energy dissipation $G$ and metallurgical working energy dissipation $J$. The $G: J$ ratio is effected by a sensitivity coefficient of flow stress to strain rate ($m$) [6, 11]. $M$ is a function of temperature and strain rate, which is opposite to the stress coefficient in the standard kinetic rate equation of hot deformation.

\[
J = \sigma \dot{\varepsilon} m/(m + 1) \tag{1}
\]

\[
\eta = J/J_{\text{max}} = 2m/(m + 1) \tag{2}
\]

where $\sigma$ is flow stress, $\dot{\varepsilon}$ is strain rate, and $\eta$ is energy dissipation coefficient (EDC). For the ideal linear energy dissipation body, $m=1$, and $J = J_{\text{max}} = \sigma \dot{\varepsilon}/2$. The Equation (2) implies the energy dissipation characteristics induced by microstructures evolution of work piece during deformation. Under a specific temperature and strain rate, the energy dissipation map could be plotted from the true stress vs. true strain curves of hot compression.

Based on the deformation instability criterion proposed by Prasad [11], metal flow gets instable when the deformation instability parameter $\xi(\dot{\varepsilon}) < 0$. $\xi(\dot{\varepsilon})$ is also a function of temperature and strain rate, which could be written as:

\[
\xi(\dot{\varepsilon}) = (\partial \ln(m/(m + 1))/\partial \ln \dot{\varepsilon}) + m \tag{3}
\]

A deformation instability map could be plotted based on $\xi(\dot{\varepsilon})$. Furthermore, the processing map could be drawn by overlapping these two maps (the deformation instability map and the energy dissipation map).

Fig.6 shows the processing map of ZAMX6100 under a strain of 0.67. The isoline represent the energy dissipation percentage, and the shadow part represent the deformation instability zone, where $\xi(\dot{\varepsilon}) < 0$. The shadow part possess the most area, which means the processing window of the investigated alloy is very narrow. Compared with the processing of ZK60 alloy [5], the best processing temperature of ZAMX6100 alloy is low, and strain rate is high, i.e. ZAMX6100 alloy has a better plastic processing property than ZK60 alloy.

![Figure 6 Processing map for as-homogenized ZAMX6100 alloy at a true strain of 0.67](image-url)
3.2.1 DRX zone

Figure 7 shows the DRX zones of the deformed alloy with high EDC value (Temperature zone, 533–573 K; Strain rate, <0.1 s⁻¹). The largest EDC is 21% at the temperature and strain rate of 573 K and 0.1 s⁻¹, respectively. The peak stress is very small due to the soften effects by DRX, according to Fig.3b. Meanwhile, it could not observe surface cracks on the deformed samples as the temperature/strain rate are 523 K/0.01s⁻¹, 573 K/0.01s⁻¹ and 573 K/0.1s⁻¹, respectively. Fig.7b shows the DRX zone in the deformed microstructures. The DRXed grains firstly nucleate at the dendritic grain boundaries, then gradually cover the initial coarse dendrites. Because DRX is driven by deformation, it stops when the deformation is over. It could also be seen that some dendrites are still not covered by DRXed grains, which implies that it requires larger strain to replace the initial coarse grains with fine equiaxial grains.

In general, the optimum working parameters should be selected at the high EDC zones, because DRX is easy to eliminate the nonuniform deformation and obtain stable metal flow [8]. As a result, the optimum working temperature and strain rate should be 573 K and 0.1s⁻¹ for the ZAMX6100 alloy.

3.2.2 Instable flow zone

Figure 6 shows the deformation instability zone at low temperature (T< 523 K) and low strain rate (\(\dot{\varepsilon}\) <1 s⁻¹) as well as temperature zone (from 423 to 573 K) and high strain rate (\(\dot{\varepsilon}\) >1 s⁻¹). In this zone, the EDC decreases significantly with the increasing strain rate. Fig.8 shows the microstructures corresponding to the deformation instability zone. The microstructures consist of the adiabatic shear band (45°), elongated grains and fine grains, as shown in Fig.8b. The local temperature of deformation zone rises up rapidly due to the deformation heat at high strain rate. Consequently, the flow stress also decreases. With the strain going on, microcracks nucleate and grow up at the fine grain or the shear band boundaries, due to the strong local metal flow [11]. The surface cracks are also observed, as shown in Fig. 4. Similar instable deformation behaviors occur at as-cast AZ61 alloy and ZE41A alloy [6, 12]. Thus, it should be avoid performing the process at the deformation instability zone.

4 Discussion

Plastic deformation is very sensitive to the applied stress, temperature and strain rate. The hot deformation kinetics of metals describe the rate control mechanisms in the given range [13]. Based on the flow stress at different temperatures and strain rates, Fig.9 and 10 show the relationship between \(\ln \sigma\) and \(\ln \dot{\varepsilon}\) as well as that between \(\sigma\) and \(\ln \dot{\varepsilon}\).
Figure 8 Representative microstructures obtained on specimens deformed at (a) 473 K/ 0.1 s$^{-1}$ and (b) 523 K/ 1 s$^{-1}$. The compression axis is vertical.

Figure 9 $\ln \dot{\varepsilon}$ as a function of $\ln \sigma$ at different deformation temperatures.

Figure 10 $\ln \dot{\varepsilon}$ as a function of peak stress $\sigma$ at different deformation temperatures.
Figure 11 ln $\dot{\varepsilon}$ as a function of ln[$\sinh(\alpha \sigma)$] at different deformation temperatures.

Figure 12 ln [sinh($\alpha \sigma$)] as a function of reciprocal T at different strain rates.

\[ \ln \sigma \text{ and } \sigma \text{ grow up linearly with the ln } \dot{\varepsilon} \text{, and the linear dependent coefficient is around 0.9425-0.9936. It implies that the investigated temperature and strain rate zone are controlled by kinetic rate. According to the flow stress and peak stress vs. strain rate, it can be calculated that } \alpha \text{ and } n \text{ are 0.00712 and 14.178, respectively. Thus, the ln } \dot{\varepsilon} \text{, ln}[\sinh(\alpha \sigma)] \text{ and ln}[\sinh(\alpha \sigma)] \text{ as a function of temperature could be plotted as shown in Fig. 11 and 12.}

The deformation kinetics of ZMX6100 at the strain of 0.67 could be described by the standard kinetic rate equation:

\[ \dot{\varepsilon} = A \sigma^n \exp\left[-\frac{Q}{RT}\right] \]  

where $\dot{\varepsilon}$ is strain rate, $\sigma$ is flow stress, $n$ is stress exponent, $Q$ is active energy, $R$ is gas constant (8.31 J/mol), $T$ is the absolute temperature, $K$ and $A$ are materials constant. It can be calculated that the active energy $Q$ is 158.9 kJ/mol in this work. Feng, et al have also obtained the similar $n$ (9.5) and $Q$ (177.6 kJ/mol) of the Mg-8.3Al-1.1Y-0.8Zn [10].

5. Conclusions

This work investigates the hot deformation behaviors of ZAMX6100 at the temperature zone from 423 to 573 K, strain rate from 0.01 s$^{-1}$ to 10 s$^{-1}$. The conclusions are as follows:

(1) The temperature and strain rate zone for DRX of ZAMX6100 are from 533 to 573 K, and <0.1 s$^{-1}$, respectively. Meanwhile, the optimum deformation parameter should be 573 K and 0.1 s$^{-1}$, and the corresponding energy dissipation coefficient is 21 %;

(2) With the increasing temperature and decreasing strain rate, both the peak and stable flow stress decrease, as well as the required strain. The flow stress also increases with the decreasing temperature and increasing strain rate;

(3) The stress exponent and active energy of ZAMX6100 in hot compression are 14.178 and 158.9 kJ/mol, respectively.

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