Hot Compression Deformation Behavior of Mg-Gd-Nd-Zr Heat-Resistant Magnesium Alloy

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Abstract. The hot compression deformation of Mg-12Gd-2.5Nd-0.5Zr heat-resistant magnesium alloy was carried out on Gleeble-1500D thermo-mechanical simulator with the strain rate range of 0.002-1 s⁻¹, the deformation temperature range of 623-773 K and maximum strain of 50%. The results show that true stress decreases with the increase of deformation temperature at a constant strain rate, and the true stress increases with the increase of strain rate at a same temperature. The deformation constitutive equation was established, and the hot deformation activation energy of 292.679 kJ/mol is determined.

1. Introduction
Magnesium alloys are the lightest material used in modern industry, which has the advantages of low density, high specific strength, and other advantages, and magnesium alloys are widely used in automotive industry[1]. It has been shown that the high temperature creep resistance of the alloy can be improved obviously by adding rare earth element gadolinium and other heavy rare earth elements in magnesium alloy[2].

At present, most magnesium alloy products are produced by casting. However, the defects, such as voids and inclusions in the casting process have caused great harm to the mechanical properties of the alloy. Compared with cast magnesium alloys, wrought magnesium alloy products produced by extrusion, rolling and forging have excellent properties[3].

In this work, the hot compression deformation behavior of Mg-12Gd-2.5Nd-0.5Zr magnesium alloy was performed on Gleeble-1500D thermo-mechanical simulator. The relationships between flow stress and deformation temperature as well as strain rate of the tested alloy were analyzed. Furthermore, the deformation activation energy of plastic deformation is obtained by numerical calculation, and the constitutive equation is also established, which provides theoretical and experimental basis for optimizing the hot deformation processing conditions.

2. Experimental
The nominal composition of investigated alloy is Mg-12Gd-2.5Nd-0.5Zr (wt.%). The tested alloy was prepared from high purity Mg (99.9%) and Mg-30%Gd, Mg-25%Nd, Mg-30%Zr master alloys (wt.%) by melting in a medium-frequency induction furnace with a Al₂O₃ crucible under the protection of mixture gas of SF₆ and CO₂.

The ingot was homogenized at 798 K for 8 h, and then the ingot were machined to cylindrical specimens with dimension of ø10mm×15mm. The specimens were compression deformed at the
temperature range from 623 K to 773 K and the strain rate range from 0.002 s⁻¹ to 1 s⁻¹ on the Gleeble-1500D thermo-mechanical simulator.

3. Results and analysis

3.1. Microstructure of the as-cast alloy

Figure 1(a) shows the optical microstructure of the as-cast Mg-12Gd-2.5Nd-0.5Zr alloy. The as-cast structure of the alloy is composed of the α-Mg matrix and the eutectic phase distributed at the grain boundaries. In this picture, the black non-continuous phase in the grain boundary is a eutectic structure formed by non-equilibrium solidification, which is composed of α-Mg and magnesium rare earth intermetallic compound. According to the X-ray diffraction (XRD) spectrum analysis of the as-cast alloy in figure 1(b), it is found that there are mainly α-Mg, Mg₅Gd and Mg₄Nd₅ phases in the alloy.

![Figure 1](image1.png)

**Figure 1.** (a) The optical micrograph and (b) the XRD pattern of the as-cast alloy.

3.2. Microstructure of the homogenized alloy

The microstructure of the alloy after homogenizing treatment at 798 K for 8 h is shown in figure 2. dendritic segregation has been basically eliminated, and most of the eutectic compounds distributed at grain boundaries have disappeared and dissolved into the matrix.

![Figure 2](image2.png)

**Figure 2.** The optical micrograph of the homogenized alloy

3.3. Flow stress behavior

The high temperature plastic deformation behavior of Mg-12Gd-2.5Nd-0.5Zr alloy at different deformation conditions was studied by hot compression simulation test. The true stress-true strain curves measured at different deformation temperatures and different strain rates are shown in figure 3.
Figure 3. True stress-true strain curves of the alloy during hot compression: (a) 0.002 s⁻¹, (b) 0.01 s⁻¹, (c) 0.1 s⁻¹, (d) 1 s⁻¹.

As can be seen from the figure 3. The variation trend of flow stress is that the flow stress firstly increases sharply to a maximum value and then decreases gradually to a steady state as the strain increases. This flow behavior is a work hardening accompanied by dynamic recrystallization softening behavior[4]. At the initial stage of strain, hardening rate is higher than the softening rate, thus the flow stress rises sharply; After it attains the peak stress, all stress-strain curves are almost in flat shape, this is because a balance is established between work hardening and softening. Alternatively, as shown in figure 3(d), when the specimen was deformed at 623 K and strain rate of 1 s⁻¹, the true stress-strain curves of the alloy appears obvious instability phenomenon, the specimen is early cracked at a strain of 0.45, which implies that strain hardening dominated the plastic deformation at 623 K and strain rate of 1 s⁻¹. Meanwhile, at a constant strain rate, the flow stress decreases with the increase of deformation temperature; at a same temperature, the flow stress increases with the increase of strain rate. This is because the higher the deformation temperature, the stronger the effect of the thermal activation energy, and the kinetic energy of the atoms in the alloy increases, and the critical resolved shear stress to decrease, and the dislocation is easier to move. Furthermore, with the increase of temperature, the dynamic recrystallization is easier to carry out, and the softening effect is enhanced, which result in the decrease of flow stress[5]. In the case of constant temperature, the greater strain rate, the dynamic recrystallization cannot be fully carried out, and rapid increment and accumulation of dislocations, which result in the increase of flow stress.

3.4. Constitutive equation
In order to further investigate the high-temperature plastic deformation behavior of the alloy, it is necessary to establish the constitutive equation of the alloy.

The relationship among the flow stress, the strain rate and the deformation temperature is usually expressed by the following three forms[6, 7]:

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

(1)
\[ \dot{\varepsilon} = A_2 \exp(\beta \sigma) \exp\left( -\frac{Q}{RT} \right) \]  
\[ \dot{\varepsilon} = A[\sinh(\alpha \sigma)]^n \exp\left( -\frac{Q}{RT} \right) \]

Where \( \sigma \) is the flow stress (MPa), \( \dot{\varepsilon} \) is the strain rate (s\(^{-1}\)), \( Q \) is the activation energy for deformation (kJ/mol), \( R \) is the ideal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), \( T \) is the absolute temperature (K), \( A_1, A_2, A, n_1, n, \alpha \) and \( \beta \) are the material constants, with \( \alpha = \beta / n_1 \).

For the low stress level (\( \alpha \sigma < 0.8 \)) and high stress level (\( \alpha \sigma > 1.2 \)), the relationship between flow stress and strain rate can be described by Equation (1) and Equation (2), respectively. Equation (3) is a hyperbolic sine law proposed by Sellars and Tegart[8], which can be applied to all the stress levels.

Get the natural logarithms of both sides for Equations (1) and (2). Then we have

\[ \ln \dot{\varepsilon} = \ln A_1 + n_1 \ln \sigma - \frac{Q}{RT} \]  
\[ \ln \dot{\varepsilon} = \ln A_2 + \beta \sigma - \frac{Q}{RT} \]

The values of \( n_1 \) and \( \beta \) can be determined according to Equations (4) and (5) from the slopes of the \( \ln \dot{\varepsilon} - \ln \sigma \) and \( \ln \dot{\varepsilon} - \sigma \) plots, respectively. By linear regression of the relations of \( \ln \dot{\varepsilon} - \ln \sigma \) and \( \ln \dot{\varepsilon} - \sigma \), \( \alpha \) was determined as 0.0076. The linear relationships of \( \ln \dot{\varepsilon} - \ln \sigma \) and \( \ln \dot{\varepsilon} - \sigma \) at different temperatures were fitted as shown in figure 4.

![Figure 4. Linear relationship fitting: (a) \( \ln \dot{\varepsilon} - \ln \sigma \) and (b) \( \ln \dot{\varepsilon} - \sigma \).](image)

Taking the natural logarithm of both sides of the above Equation (3), then we have

\[ \ln \dot{\varepsilon} = \ln A + n \ln[\sinh(\alpha \sigma)] - \frac{Q}{RT} \]  

The deformation activation energy \( Q \) can be determined by differentiating Equation (6):

\[ Q = R \left[ \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha \sigma)]} \right]_T \left[ \frac{\partial \ln[\sinh(\alpha \sigma)]}{\partial (1/T)} \right]_T \]

The linear relationships of \( \ln \dot{\varepsilon} - \ln[\sinh(\alpha \sigma)] \) and \( \ln[\sinh(\alpha \sigma)] - 1/T \) were fitted as Equation 5. The mean value of \( \left[ \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha \sigma)]} \right]_T \) can be obtained as 6.87434 from the slopes of \( \ln \dot{\varepsilon} - \ln[\sinh(\alpha \sigma)] \) plots (figure 5(a)), and the average of \( \left[ \frac{\partial \ln[\sinh(\alpha \sigma)]}{\partial (1/T)} \right]_{\dot{\varepsilon}} \) can be determined as 5.12094 from the slopes in plots of \( \ln[\sinh(\alpha \sigma)] - 1/T \) (figure 5(b)). Finally, The \( Q \) value of the alloy is calculated as 292.679 kJ/mol.
The effects of temperature and strain rate on the flow stress can be expressed by Zener-Hollomon parameter[9], and the hyperbolic sine function incorporated with the Z parameter at all the stress levels as follows:

\[ Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A \sinh(\alpha\sigma)^n \]  

(8)

Where \( Z \) is the temperature compensated strain rate factor; \( A \) is the structural factor; \( n \) is the stress exponent; \( \alpha \) is the stress level parameter.

Taking the natural logarithm of both sides of Equation (8) gives

\[ \ln Z = \ln A + n \ln \sinh(\alpha\sigma) \]  

(9)

Based on Equation (9), it can be concluded that \( \ln Z \) and \( \ln \sinh(\alpha\sigma) \) should exhibit linear relationship. The relationship between \( \ln Z \) and \( \ln \sinh(\alpha\sigma) \) is plotted in figure 6 through linear regression. Therefore, \( n \) and \( \ln A \) in Equation (9) are determined as 6.87434 and 47.17858, respectively. And then, the value of \( A \) can be obtained as \( 3.08601 \times 10^{20} \).

Finally, the calculated values of \( Q \), \( \alpha \), \( n \) and \( A \) were substituted into the Equation (3), and the constitutive equation for the hot compression of Mg-12Gd-2.5Nd-0.5Zr alloy was obtained as follows:

\[ \dot{\varepsilon} = 3.08601 \times 10^{20} \sinh(0.0076\sigma)^{6.87434} \exp(-292679/8.314T) \]  

(10)

4. Summary

There is a dendritic segregation in the as-cast Mg-12Gd-2.5Nd-0.5Zr alloy, and most of the precipitates are distributed at the grain boundaries. The alloy after homogenizing treatment at 798 K for 8 h, the majority of segregation structure can be eliminated.
The flow stress increases to a maximum and then decreases slowly to a steady state with the increasing of strain. Furthermore, the flow stress decreases with the increasing of deformation temperature and decreasing of strain rate.

The hot deformation activation energy of the alloy is 292.679 kJ/mol, and the constitutive equation of the alloy is 

\[ \dot{\varepsilon} = 3.08601 \times 10^{30} \left[ \sinh(0.0076 \sigma) \right]^{0.87434} \exp(-292679 / 8.314T). \]

5. References

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