Hot compression constitutive equation of Mg-5Sm-2Y alloy

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Abstract. The hot compression tests were carried out at deformation temperatures ranging from 300 to 450 °C and strain rates ranging from 0.01 to 1 s\(^{-1}\), and the hot deformation behavior and constitutive equation of Mg-5Sm-2Y magnesium alloy was investigated. The results showed that the flow stress of the alloy is affected greatly by deformation temperature and strain rate during the hot compression deformation. The flow stress of the alloy decreases with the increase of deformation temperature at the same strain rate, and decreases with the decrease of strain rate at the same deformation temperature. The constitutive equation for hot compression flow stress of the alloy is established in a hyperbolic-sine form. In the equation, the stress index \(n\) is 7, and the hot deformation activation energy \(Q\) is 212 kJ/mol.

Key words. magnesium alloy, hot compression, flow stress, constitutive equation

1. Introduction

As the lowest density metal structural materials widely used in modern industries, magnesium alloys have great application potential in aerospace, automobile industry, electronic products and other fields\textsuperscript{[1-3]}. However, because of hexagonal close-packed structure, magnesium alloys have the fewer movable slip systems at room temperature and low temperature than aluminium alloys, resulting in more difficult plastic processing of magnesium alloys, and the applications of wrought magnesium alloys are restricted\textsuperscript{[4-6]}. Similar to aluminium alloys, the deformation ability of magnesium alloys can be improved by hot working, and the constitutive equation is applied to describe the basic deformation parameters of magnesium alloys. Therefore, it is of importance to study hot deformation behavior and to establish constitutive equation of magnesium alloys\textsuperscript{[7-10]}.

It is an effective approach to strengthen the mechanical properties of magnesium alloys by adding suitable rare earth elements. Among the available rare earth elements, the combination of Y (yttrium) and Sm (samarium) has been proved to have significant effect on improving the heat resistance of magnesium alloys\textsuperscript{[11]}. Therefore, more and more research has been reported on the application of Y and Sm in heat resistance magnesium alloys. However, there are few reports on the deformation behavior of Mg-Sm-Y system heat resistant magnesium alloys. In this work, hot compression tests were carried out under different deformation conditions to study the flow stress of Mg-5Sm-2Y
magnesium alloy. The hot deformation parameters were derived from data processing, and then the constitutive equation of the alloy was established.

2. Experimental
The experimental material was as-cast magnesium alloy, and its chemical composition was Mg-5Sm-2Y (mass fraction, %). Alloy smelting was carried out in induction furnace, using corundum crucible to load raw materials. The raw materials including pure magnesium and Mg-Sm, Mg-Y master alloys were dried before smelting. After the melting of raw materials, the alloy liquid was heated up to 750 °C and held for a certain time. Then it was poured into a preheated metal mould, and the alloy ingot was obtained.

The ingot was divided into thin pieces and machined into cylindrical specimens with 10 mm in diameter and 15 mm in height. The hot compression tests were carried out on Gleeble 1500D thermal simulation machine. The deformation temperatures were 300, 350, 400 and 450 °C, namely 573, 623, 673 and 723 K. The strain rates were 0.01, 0.1 and 1 s⁻¹, respectively. The maximum strain was 0.7. After the hot compression, the data processing was carried out, and then the constitutive equation of the alloy was established.

3. Results

3.1 Flow stress
The true stress-true strain curves of Mg-5Sm-2Y magnesium alloy during hot compression deformation are shown in Figure 1. It can be seen from Figure 1 that the true stress of the alloy increases first and then decreases with the increase of true strain, which has obvious dynamic recrystallization characteristics. The true stress increases sharply with the increase of strain at the beginning of deformation. When the true strain is more than a certain value, the true stress does not change significantly with the increase of strain. That is, the alloy shows steady-state flow characteristics during hot compression deformation. In the initial plastic deformation stage, work hardening plays a dominant role, and its effect is much more than softening, which leads to the rapid increase of flow stress with the increase of strain. Subsequently, the softening effect of dynamic recrystallization is gradually enhanced with deformation, and the work hardening effect is gradually reduced. Meanwhile, the slopes of the curves decrease gradually. When the balance between dynamic recrystallization softening and work hardening is reached, the peak of flow stress appears. Thereafter, dynamic recrystallization continues to increase with the continuous deformation, and its softening effect gradually exceeds the work hardening effect, resulting in a gradual decrease in the flow stress.
When the strain rate remains unchanged, the true stress decreases with the increase of deformation temperature. For example, when the strain rate is 0.1 s\(^{-1}\) and the deformation temperature increases from 300 to 450 °C, the peak flow stress decreases from 214 to 92.6 MPa. It indicates that the deformation temperature affects the flow stress of the alloy greatly. The higher the deformation temperature, the easier the slip systems start and the lower deformation resistance of the alloy is. When the deformation temperature is constant, the true stress decreases with the decrease of strain rate. For example, when the alloy is deformed at 400 °C and the strain rate decreases from 1 to 0.01 s\(^{-1}\), the peak flow stress decreases from 153.6 to 85.2 MPa. It shows that the flow stress of the alloy is sensitive to the change of strain rate. This is due to the decreasing growth rate of dislocation density and work hardening with the decrease of strain rate. In addition, the lower the strain rate, the easier the dynamic recovery or recrystallization occurs and the easier the deformation of the alloy carries out.

### 3.2 Activation energy

Hot working deformation of materials is a very complex process accompanied by thermal activation. Usually, constitutive models of flow stress in plastic deformation of materials can be established in the forms of Arrhenius equation. In order to describe the relationship between flow stress \(\sigma\), deformation temperature \(T\) and strain rate \(\dot{\varepsilon}\), Sellars and Tegart proposed a modified Arrhenius equation in 1966, which is a hyperbolic-sine form and contains hot deformation activation energy \(Q\)\(^{[12]}\)

\[
\dot{\varepsilon} = A[\sinh(\alpha \sigma)]^n \exp[-Q/(RT)]
\]

In the equation, \(A\), \(\alpha\), \(n\) are constants independent of deformation temperature, \(A\) is the structural factor, \(\alpha\) is the stress level parameter, and \(n\) is the stress index; \(\sigma\) is the flow stress in MPa corresponding to a certain strain; \(Q\) is the hot deformation activation energy in J/mol; \(R\) is the molar gas constant, \(R = 8.31\) J/(mol·K); \(T\) is the absolute temperature in K.

Constant \(\alpha\) is the ratio of slope \(n'\) to \(\beta\) obtained by linear fitting according to the relationship of \(\ln \dot{\varepsilon} - \ln \sigma\) and \(\ln \dot{\varepsilon} - \sigma\), i.e. \(\alpha = \beta / n'\). In this experiment, from the relationship between flow stress and strain rate (see Figure 2), \(\alpha = 0.008\) is obtained by fitting analysis.
Take logarithms on both sides of equation (1) and assume that the activation energy of hot deformation is independent of deformation temperature, and the following result is obtained as:

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

(2)

According to the relationship of \( \ln \dot{\varepsilon} - \ln[\sinh(\alpha\sigma)] \) and \( \ln[\sinh(\alpha\sigma)] - 1/T \), the slopes obtained by linear fitting are recorded as \( n \) and \( b \), respectively. And the calculation expression of hot deformation activation energy can be obtained as follows:

\[ Q = R \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]} \bigg|_{\varepsilon = \dot{\varepsilon}} \ln[\sinh(\alpha\sigma)] = Rnb \]  

(3)

Based on the relationship between flow stress and strain rate, temperature (see Figure 3), the slopes are calculated respectively, i.e. \( n = 7 \), \( b = 3.64 \). By substituting the values of \( R \), \( n \) and \( b \) into equation (3), it can be obtained that the hot deformation activation energy of the alloy in this experiment is \( Q = 212 \text{ kJ/mol} \).

3.3 Constitutive equation

In order to facilitate the analysis, the effects of deformation temperature and strain rate can be combined into one parameter, Zener-Hollomon parameter, namely \( Z \) parameter, and

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

(4)

From the logarithm of equation (4), it can be obtained as follows:

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

(5)
According to the relationship between flow stress and $Z$ parameter (see Figure 4), regression analysis shows that $\ln A = 34.81$ and $A = 1.31 \times 10^{15}$.

![Figure 4. Relationship between flow stress and $Z$ parameter](image)

By substituting all the above parameters into equation (1), the constitutive equation for flow stress of the experimental alloy during hot compression is obtained as follows

$$\dot{\varepsilon} = 1.31 \times 10^{15} [\sinh(0.008\sigma)]^7 \exp[-212000/(RT)]$$

4. Conclusions

With the increase of deformation temperature from 300 to 450 °C and the decrease of strain rate from 1 to 0.01 s$^{-1}$, the flow stress of Mg-5Sm-2Y alloy decreases during hot compression deformation. Under the experimental conditions, the constitutive equation for hot compression flow stress of Mg-5Sm-2Y alloy is established in a hyperbolic-sine form. In the equation, the stress index $n$ is 7, and the hot deformation activation energy $Q$ is 212 kJ/mol.

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