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Constitutive relationship for high temperature deformation of Al−3Cu−0.5Sc alloy

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Abstract: The high temperature compressive deformation behavior of Al−3Cu−0.5Sc alloy was investigated at temperatures from 350 to 500 °C, and strain rates from 0.01 to 10 s^{-1} with the Gleeble−1500 thermo-mechanical simulator machine. The flow curves after corrections of the friction and temperature compensations were employed to develop constitutive equations. The effects of temperature and strain rate on deformation behaviors were represented by Zener-Hollomon parameter in an exponent type equation. The influence of true strain was incorporated in the constitutive equation by considering the effect of true strain on material constants. A four-order polynomial is found to be suitable to represent the influence of strain on the constitute equations.

Key words: Al−3Cu−0.5Sc alloy; constitutive relationship; high temperature deformation

1 Introduction

The research on scandium (Sc) addition in aluminum (Al) alloys has been received increasing attention over the last decade because of their interesting benefits. Most of the benefits are related to the formation of Al_3Sc particles, including Al_3Sc dispersoids and Al_3Sc precipitates [1]. The addition of Sc in pure aluminum or non-heat-treatable Al alloys has been extensively investigated [2,3]. In comparison, there are much fewer studies on the Sc addition in heat-treatable Al alloys [4]. But previous studies have shown that Sc can improve the strength of Al−3Cu alloy [5], however, as a deformed aluminum alloy, the deformation behavior is as important as the heat treatment process.

The flow stress of metals during hot deformation processes can be significantly influenced by several metallurgical phenomena such as working hardening, dynamic recovery and dynamic recrystallization. Therefore, the understanding of flow stress is of great importance in metal forming processes and the hot deformability can be improved by optimizing the process parameters [6,7]. So far, many researches have been done on the hot deformation behaviors and microstructure evolution of Al alloys [8−10]. However, many constitutive models are based on the Arrhenius type of equation, which assume that the influence of strain on high temperature deformation behavior is insignificant. In fact, the flow stress is changed with the increase of the true strain, which is important for the high temperature deformation behavior. On the other hand, the effects of the friction and the temperature raise on the stress—strain curves are usually ignored. Since a strain-dependent parameter for the sine hyperbolic constitutive equation was introduced by SLOOFF et al [11], a revised sine hyperbolic constitutive equation was adopted by the incorporation of the strain to predict the elevated temperature flow behaviors for steel [12,13], pure titanium [14] and P/M TiAl based alloy [15].

In this work, a comprehensive constitutive model for describing the relationship among the flow stress, strain rate and temperature was proposed with the compensation of the strain, and it was used to predict the high temperature flow behaviors of the Al−3Cu−0.5Sc alloy.

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2 Experimental

The composition (mass fraction) of the alloy used in the test was as follows: 3.0% Cu, 0.5% Sc and balance Al. The ingot was homogenized at 500 °C for 18 h. The specimens were cut from the ingot with dimensions of *d* 8 mm×12 mm. The specimens were compression deformed in the temperature range from 350 to 500 °C and the strain rate range from 0.01 to 10 s^{-1} on the Gleeble−1500 thermo-mechanical simulator. All specimens were deformed to the total true strain of about 0.7. The specimens were induction-heated to deformation temperatures within 1 min and held for 3 min in order to obtain a stable and uniform temperature prior to the deformation.

3 Results and discussion

3.1 Friction correction

It is well known that the interfacial friction between the specimen and dies will affect the symmetrical deformation of the specimens [16]. In this work, although lubricants were used to minimize the interfacial friction, the interfacial friction becomes more and more evident with the increase of deformation. Thus, the deformation is more and more heterogeneous, leading to the drum-like shape of specimens, as shown in Fig. 1. ROEBUCK et al [17] developed a criterion for evaluating the effect of friction by a barreling coefficient, which is expressed as

$$B=\frac{hR_{\mathrm{M}}^{2}}{h_{0}R_{0}^{2}} \tag{1}$$

where B is the barreling coefficient; h is the height of deformed specimens; R_{M} is the maximum radius of deformed specimens; h_0 and R_0 are the initial height and radius of specimens, respectively. When $1<B\le 1.1$, the difference between the measured flow stress and the true flow stress is small, the measured flow stress curves do not need to be corrected; when $B\ge 1.1$, the measured flow stress curves must be corrected.

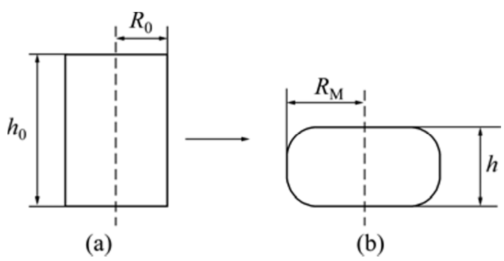

Fig. 1 Schematic plot of sample before (a) and after (b) compression

Based on the above criterion, the sizes of deformed specimens under various deformation conditions were measured, and the values of B were calculated, as shown in Table 1. From Table 1, it can be observed that all the values of B are greater than 1.1, so the measured flow stresses under all the deformation conditions must be corrected.

Table 1 Values of *B* under various deformation conditions

Strain rate/s^{-1}	Value of *B*			
	350 °C	400 °C	450 °C	500 °C
0.01	1.16628	1.15762	1.16987	1.1744
0.1	1.11878	1.15762	1.20377	1.17143
1	1.16793	1.11878	1.12	1.17904
10	1.15967	1.18348	1.13017	1.16545

Based on the upper-bound theory, a simple theoretical analysis of the compression test for the determination of the constant friction factor (m) was proposed [18]. The base equation is shown as follows:

$$\frac{p}{\sigma}=\frac{8bR}{H}\cdot\left\{\left[\frac{1}{12}+\left(\frac{H}{Rb}\right)^{2}\right]^{3/2}-\left(\frac{H}{Rb}\right)^{3}-\frac{m\mathrm{e}^{-b/2}}{24\sqrt{3}(\mathrm{e}^{-b/2}-1)}\right\} \tag{2}$$

where σ is the corrected true stress; p is the external pressure applied to specimens in compression (uncorrected stress); b is the barrel parameter; m is the constant friction factor; R and H are radius and height of samples, respectively, $R=R_0\mathrm{e}^{-\varepsilon/2}$ and $H=h_0\mathrm{e}^{-\varepsilon}$. m and b can be evaluated by the following equations:

$$m=\frac{R_{\mathrm{f}}}{h}\cdot\frac{3\sqrt{3}b}{12-2b} \tag{3}$$

$$b=4\cdot\frac{R_{\mathrm{M}}-R_{\mathrm{T}}}{R_{\mathrm{f}}}\cdot\frac{h}{h_0-h} \tag{4}$$

where R_{f} is the average radius of samples after the deformation; R_{T} is the top radius of deformed samples.

$$R_{\mathrm{f}}=R_0\sqrt{\frac{h_0}{h}} \tag{5}$$

$$R_{\mathrm{T}}=\sqrt{3\cdot\frac{h_0}{h}\cdot R_0{}^{2}-2R_{\mathrm{M}}^{2}} \tag{6}$$

Therefore, by this method, the corrected true stress can be calculated only by measuring the maximum radius and the height of samples after the deformation.

The true stress—true strain curves modified by considering the effects of interfacial friction are shown in Fig. 2. It can be easily found that the measured flow stress is greatly larger than the corrected ones. Meanwhile, the effect of the friction is obvious with the increase of the strain rate and the decrease of the deformation temperature.