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Hot deformation behavior and microstructure evolution of 1460 Al−Li alloy

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Abstract: The hot deformation behavior and microstructure evolution of 1460 Al−Li alloy were investigated by isothermal compression test conducted at various strain rates (10^{-3}−10 s^{-1}) and temperatures (573−773 K). The flow stress curves were corrected by considering the friction at the platen/specimen interface and the temperature change due to the deformation heating. The effects of strain, strain rate and temperature on the deformation behavior were characterized by the Zener−Hollomon parameter in a hyperbolic-sine equation, and the constitutive equations were established according to the peak flow stress associated with dynamic recovery, dynamic recrystallization and the dissolution of T_1 phases. In the entire strain rate and temperature range, the prediction capabilities of the developed constitutive equation are proved to be feasible and effective with a linear correlation coefficient and an average absolute relative error coefficient of 0.9909 and 6.72%, respectively.

Key words: 1460 Al−Li alloy; friction correction; temperature rise correction; constitutive equation; hot deformation behavior

1 Introduction

Al alloys containing a certain amount of Li are recognized as the most promising aeronautical materials, which offer significant improvements in aero-structural performance through density reduction, strength increase and low temperature resistance, etc [1−3]. Among these Al−Li alloys, 1460 Al−Li alloy was developed in Russia and successfully applied in Energia rocket tank. However, its deformation under as-cast condition at elevated temperature is difficult, not merely because of its low ductility but also due to its high sensitivity to hot cracking and dynamic instability. Therefore, it is important to understand its hot deformation behavior so as to design a suitable process schedule.

Although hot deformation behavior of various Al alloys have been reported in Refs. [4−6], the thermo-mechanical processing parameters associated with 1460 Al−Li alloy have not yet been identified or optimized. Among these parameters, the flow stress and the Zener−Hollomon parameter play a fundamental role to construct its constitutive equation during the deformation process. So far, numerous articles concerning the constitutive relations have been reported. LAASRAOUI and JONAS [7] put forward a model to determine the flow stress of steel, which was an evolution equation considering dislocation density and fractional softening by dynamic recrystallization. LIN and LIU [8] proposed a new material parameter (L) sensitive to the deformation heating and strain rate for developing the constitutive equation. LANGKRUIS et al [9] assessed five constitutive models with varying numbers of fitting parameters for modeling the stress−strain curves of four high-purity Al−Mg−Si alloys, and concluded that the general exponential saturation equation combining with the hyperbolic sine law was the most promising model.

Nevertheless, the friction at the platen/specimen interface and the temperature rise due to the deformation heating during the deformation process will inevitably cause the data distortion. These two factors should be taken into account when the constitutive equation is established. Hence, EBRAHIMI and NAJAFIZADEH [10] used barreling degree during the barrel compression test to calculate the constant friction factor (m). Only the physical measurement of shape change was involved in this method, which evidently simplified the evaluation of the interfacial frictional conditions and thus easily corrected the experimental stress. As for the friction

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correction, various mechanical properties of the material and the forming loads are often taken into consideration in some models [11−13]. In the case of the temperature correction, a adiabatic correction factor (η) was applied by GOETZ and SEMIATIN [14] to calculate the temperature change resulted from the deformation heating during the uniaxial compression test, which demonstrated that η was not constant with strain, but decreased with increasing the strain from an initial value of 1.0. It was noted that most studies concerning the flow stress during the hot deformation process only considered the friction correction [11−13] and temperature rise correction [15,16].

In this study, the deformation heating together with the constant friction factor was considered to correct the flow stress curves of 1460 Al−Li alloy during the uniaxial compression process. The corrected stress was then applied to establishing appropriate constitutive equations. Meanwhile, the microstructural variation during the deformation process was observed.

2 Experimental

The as-cast 1460 Al−Li alloy was used in the hot compression test. Its chemical composition is presented in Table 1. After homogenization at 803 K for 24 h, the cylindrical specimens with dimensions of 12 mm in height and 8 mm in diameter were machined out from the ingot.

Table 1 Chemical composition of 1460 Al−Li alloy (mass fraction, %)

Li	Cu	Sc	Zr	Ce	Ti	Al
2.13	3.0	0.12	0.12	0.015	0.05	Bal.

The hot compression tests were carried out with a thermo-mechanical simulator Gleeble Systems 3180 at ambient pressure. For temperature control during the tests, thermocouples were welded onto the middle of surfaces of the specimens. Between the specimen and the tungsten carbide, a punched graphite slice (thickness of 0.12 mm) with a thin film of nickel-containing paste was placed to reduce the friction. Before compression, the specimens were resistance-heated at a rate of 5 K/s and then kept at the preset temperature for 120 s. The test temperature ranged from 573 to 773 K with a step of 50 K and the strain rates ($\dot{\varepsilon}$) were 0.001, 0.01, 0.1, 1 and 10 s^{-1}, respectively. After deformation at a final strain (ε) of 0.5, the specimen was immediately water-quenched to ambient temperature. Finally, the microstructures of the deformed specimens were observed by an FEI Tecnai G^2 20 transmission electron microscope (TEM).

3 Results and discussion

3.1 Flow stress correction

During the compression process, there exist friction at the platen/specimen interface and temperature changes due to the deformation heating. The correction of the initial experimental flow stress must be conducted to accurately predict the hot deformation behavior of the alloy.

In the compression test for 1460 Al−Li alloy, the clear bulges can be seen in the middle of the final specimen (Fig. 1), though the lubricant (graphite slice) is used to minimize the interfacial friction. With higher temperature and larger deformation degree, the interface area between the specimen and dies increases. The interfacial friction becomes more and more evident as the compression proceeds, and the deformation is increasingly heterogeneous. Therefore, the consideration of interfacial friction effects should be significant in the flow stress correction. Some shape parameters of the specimens must be measured before and after deformation. According to the friction correction model proposed by EBRAHIMI and NAJAFIZADEH [10], the experimental flow stress can be corrected by the following equation:

$$\frac{P_{\mathrm{ave}}}{\sigma_0}=8b\frac{R}{H}\left[\left(\frac{1}{12}+\frac{H^2}{R^2b^2}\right)^{3/2}-\frac{H^3}{R^3b^3}-\frac{m}{24\sqrt{3}}\frac{\mathrm{e}^{-b/2}}{\mathrm{e}^{-b/2}-1}\right] \tag{1}$$

where P_{ave} is the external nominal stress imposed on the cylinder specimen, σ_0 is the stress after the friction correction, R is the nominal radius of cylinder after deformation, which equals $R_0\sqrt{H_0/h}$, H_0 and h denote the heights of the undeformed and deformed specimens, respectively, and H is the height of cylinder after deformation. The parameters of m and b represent the constant friction coefficient and the barrel parameter, respectively, which can be evaluated as follows [10]:

$$m=\frac{(R/H)b}{(4/\sqrt{3})-(2b/3\sqrt{3})} \tag{2}$$

$$b=4\frac{\Delta R}{R}\frac{H}{\Delta H} \tag{3}$$

where

$\Delta R=R_{\mathrm{M}}-R_{\mathrm{T}}$,

$R_{\mathrm{T}}=\sqrt{3\frac{H_0}{h}R_0^2-2R_{\mathrm{M}}^2}$,

$\Delta H=H_0-h$.

R_{M} and R_{T} are the maximum and top radius of the deformed specimens, respectively. R_0 stands for the initial radius of the specimens.