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Constitutive equations for high temperature flow stress prediction of 6063 Al alloy considering compensation of strain

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Abstract: In order to develop the appropriate constitutive equation which can precisely model high temperature flow stress of 6063 Al alloy, a series of isothermal hot compression tests were performed at temperatures from 573 to 773 K and strain rates from 0.5 to 50 s^{-1} on a Gleeble−1500 thermo-simulation machine. Zener–Hollomon parameter in an exponent-type equation was used to describe the combined effects of temperature and strain rate on hot deformation behaviour of 6063 Al alloy, whereas the influence of strain was incorporated in the developed constitutive equation by considering material constants (α, n, Q and A) to be 4th order polynomial functions of strain. The results show that the developed constitutive equation can accurately predict high temperature flow stress of 6063 Al alloy, which demonstrates that it can be suitable for simulating hot deformation processes such as extrusion and forging, and for properly designing the deformation parameters in engineering practice.
Key words: 6063 Al alloy; constitutive equation; flow stress; strain; hot deformation

1 Introduction

6063 Al alloy is one of the representative aluminium alloys. This alloy has an attractive combination of characteristics such as high specific strength, high corrosion resistance and easy workability, which make it an ideal choice for structural applications. It is well known that plastic deformation conditions, such as temperature, have an important influence on the deformation behavior of 6063 Al alloy [1,2]. Therefore, it is of vital importance to thoroughly study the high temperature deformation behavior of 6063 Al alloy for the purpose of the deformation parameter optimization.

Constitutive equation which describes the flow behavior of materials has been widely cited to stimulate the materials response under different plastic deformation conditions. It is an essential input for computer modeling thermomechanical process using finite element methods. The reliability of simulation results greatly depends on the accuracy of prediction of the constitutive equation. Therefore, great efforts have been made to propose various analytical, phenomenological and empirical equations which are essential to predict the flow stress in a wide range of materials [3−8]. Although these constitutive equations are relatively successful in prediction, more efforts are still needed to further enhance the accuracy of prediction. Recently, in the phenomenological approach which was proposed by SELLARS and McTEGARTA [9], a sine hyperbolic constitutive equation was revised by incorporation of strain dependent term to predict high temperature flow behaviour of alloys [10−14]. The revised sine hyperbolic constitutive equation exhibited good correlation and generalization.

The aim of this study is to find the suitable relationship among the flow stress, strain, strain rate and temperature to model high temperature flow stress of 6063 Al alloy. Based on the experimental stress–strain data of isothermal hot compression tests, a constitutive equation including the flow stress, strain rate and temperature considering compensation of strain was developed, and the performance of the developed constitutive equation was also analyzed.

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2 Experimental

Commercial 6063 Al alloy was used for the present test using the following chemical composition: 0.7% Mg, 0.423% Si, 0.043% Cu, 0.145% Fe, 0.002% Mn, 0.0127% Ti, 0.046% Cr and balance of Al (mass fraction).

Cylindrical specimens were machined with a diameter of 10 mm and a height of 15 mm. In order to decrease the effect of friction at the specimen−indenter interface during compression deformation, the flat ends of the specimen were recessed to a depth of 0.2 mm to entrap the lubricant of graphite mixed with machine oil. A series of isothermal hot compression tests were conducted on a Gleeble–1500 thermo-simulation machine. The testing temperatures ranged from 573 to 773 K at an interval of 50 K and at constant strain rates of 0.5, 5 and 50 s^{-1}. All specimens were heated up to test temperatures at a rate of 1.7 K/s by thermo-coupled feed-back-controlled AC and hold for 180 s before compression for the purpose of heat balance. The reduction in height is 50% at the end of the compression tests. The load-stroke data obtained in hot compression tests were transformed into true stress–true strain curves.

3 Results and discussion

3.1 True stress–true strain curves

A series of typical true stress–true strain curves obtained during hot compression of 6063 Al alloy at strain rate of 0.5−50 s^{-1} and deformation temperature of 573−773 K are shown in Fig. 1. It can be found that the flow stress is sensitive to the deformation temperature and strain rate. There is a general trend that the flow stress increased with increasing strain rate at a given temperature, or decreasing the deformation temperature while the strain rate remains unchanged. It can be also seen that the true stress−true strain curves exhibit peak stresses at small strains, and the flow stresses decrease monotonically until high strains. Especially, flow stress softening appears in higher temperature or/and higher strain rate regions, which suggests that dynamic softening dominates over work hardening. These characteristics can be commonly related to the nucleation and growth of dynamically recrystallized grains and dislocation annihilation during hot deformation.

3.2 Constitutive equation for flow stress

In terms of the curvilinear trend of the flow stress, the well-known Arrhenius equation can be used to establish the relationship between the flow stress, strain rate and temperature during hot deformation. Simultaneously, the combined effects of temperature and

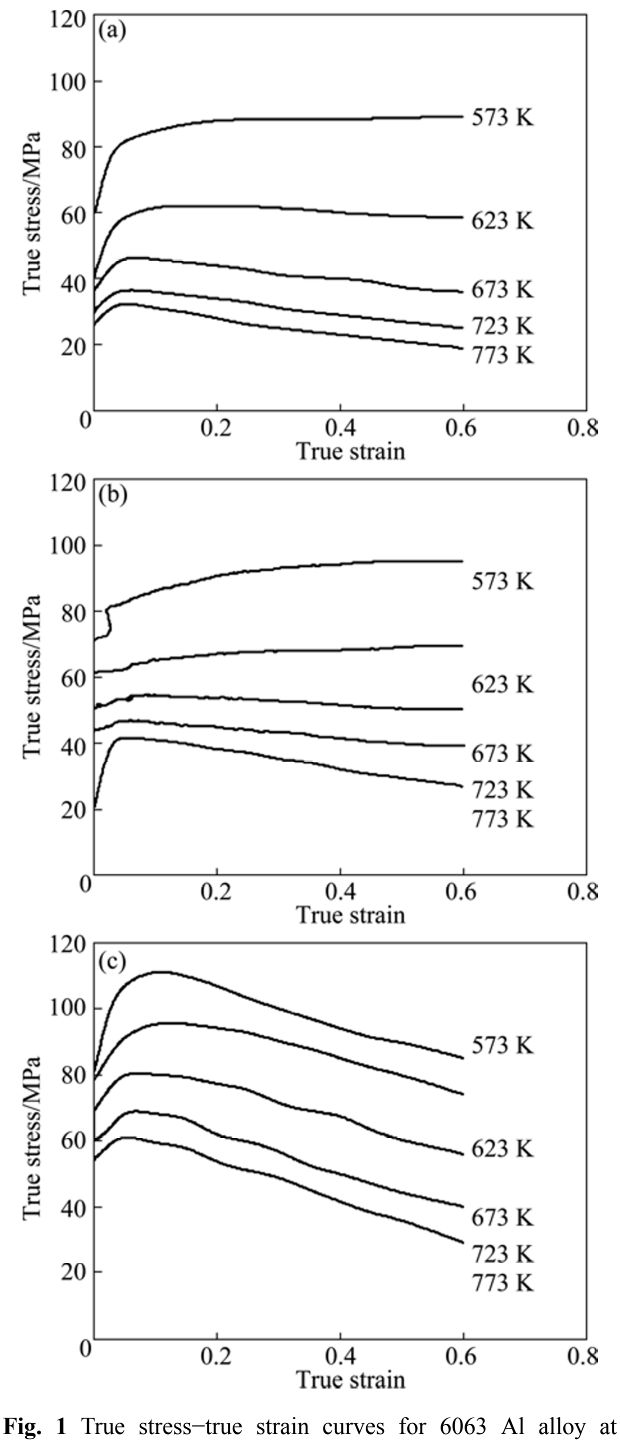

Fig. 1 True stress−true strain curves for 6063 Al alloy at various temperatures with different strain rates: (a) 0.5 s^{-1}; (b) 5 s^{-1}; (c) 50 s^{-1}

strain rate on the deformation behaviors can be also represented using Zener–Hollomon parameter, Z, in an exponent-type equation. These equations have been successfully applied to flow stress prediction [9,15]. They are often given by

$$Z=\dot{\varepsilon}\exp[Q/(R_0T)] \quad (1)$$

$$\dot{\varepsilon}=AF(\sigma)\exp[-Q/(R_0T)] \quad (2)$$

and $F(\sigma)$ can be expressed by the following equations: