

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

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Received 8 January 2014; accepted 5 March 2014

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.

Foundation item: Project (2012B090600051) supported by Al and Mg Light Alloys Platform on the Unity of Industry, Education and Research Innovation of Guangdong Province, China; Project (2012B001) supported by the PhD Start-up Fund of Guangzhou Research Institute of Non-ferrous Metals, China

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DOI: 10.1016/S1003-6326(14)63492-0

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

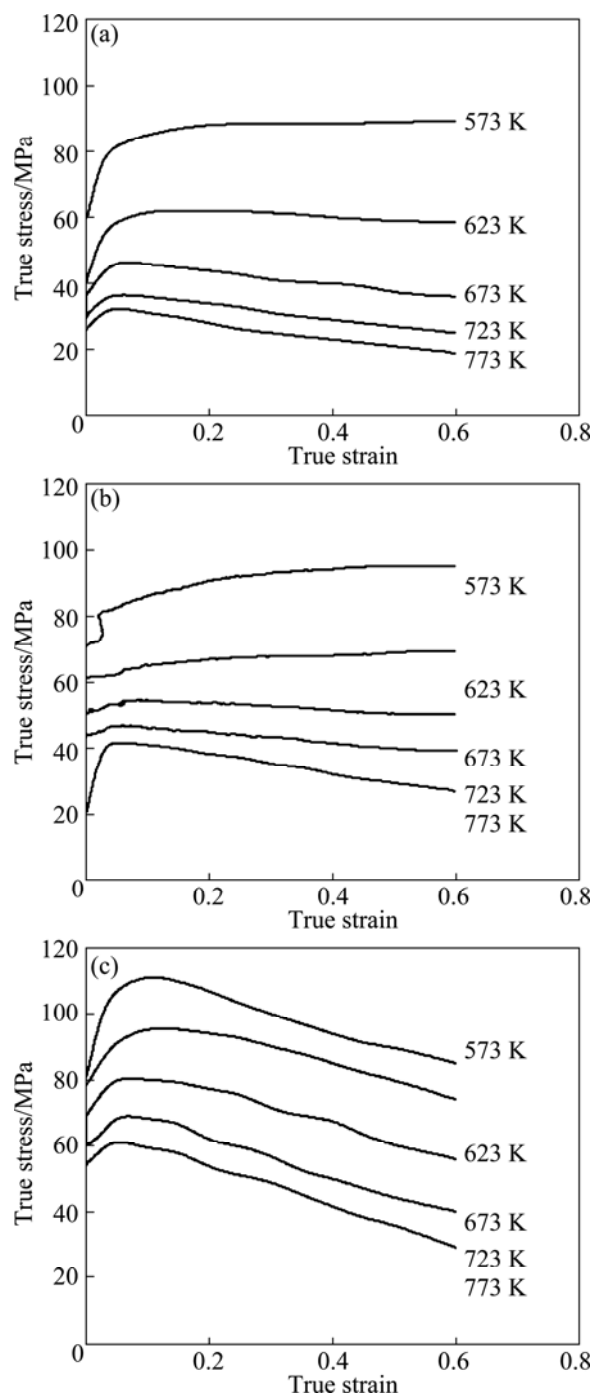


Fig. 1 True stress–true strain curves for 6063 Al alloy at various temperatures with different strain rates: (a) 0.5 s⁻¹; (b) 5 s⁻¹; (c) 50 s⁻¹

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

$$Z = \dot{\epsilon} \exp[Q/(R_0 T)] \quad (1)$$

$$\dot{\epsilon} = AF(\sigma) \exp[-Q/(R_0 T)] \quad (2)$$

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

$$\begin{cases} F(\sigma) = \sigma^n, & \alpha\sigma < 0.8 \\ F(\sigma) = \exp(\beta\sigma), & \alpha\sigma > 1.2 \\ F(\sigma) = [\sinh(\alpha\sigma)]^n, & \text{for all } \sigma \end{cases} \quad (3)$$

where $\dot{\epsilon}$ is strain rate; σ is the flow stress for a given true strain; Q is the deformation activation energy; R_0 is the universal gas constant; T is the temperature; A , α , n and β are the material constants, $\alpha = \beta/n$.

3.3 Mathematical analysis for constitutive equation

For the purpose of determining the materials constants of the above constitutive equations, the experimental true stress–true strain data obtained from the compression tests under various deformation conditions were used to analyze the constitutive equation. As an example, the true strain of 0.1 is first taken to present the solution procedures of the material constants.

For low stress levels ($\alpha\sigma < 0.8$) and high stress levels ($\alpha\sigma > 1.2$), $F(\sigma)$ is substituted into Eq. (2), respectively, Eq. (2) can be expressed as the power law and the exponential law as follows:

$$\dot{\epsilon} = B\sigma^n \quad (4)$$

$$\dot{\epsilon} = B'\exp(\beta\sigma) \quad (5)$$

where B and B' are the material constants. By taking logarithms of both sides of Eq. (4) and Eq. (5), the equations can be obtained as follows:

$$\ln \sigma = \frac{1}{n} \ln \dot{\epsilon} - \frac{1}{n} \ln B \quad (6)$$

$$\sigma = \frac{1}{\beta} \ln \dot{\epsilon} - \frac{1}{\beta} \ln B' \quad (7)$$

By substituting the values of different strain rates and flow stresses at different deformation temperatures into Eq. (6) and Eq. (7), the relationships of $\ln \sigma - \ln \dot{\epsilon}$ and $\sigma - \ln \dot{\epsilon}$ can be effortlessly obtained, as shown in Fig. 2. As a result, the mean values of n and β can be determined from the slope of the lines in $\ln \sigma - \ln \dot{\epsilon}$ and $\sigma - \ln \dot{\epsilon}$ plot, respectively, for the range of temperatures studied. Moreover, it can be also observed from Fig. 2 that the lines are almost parallel. The results show that there is a very small variation in the slope of the lines. The slight variation of the slope of the lines which is considered to be due to scattering in the experimental data points should be neglected in this study. Thus, the mean values of n and β are calculated as 9.0439 and 0.1486 MPa^{-1} , respectively. By using the relationship of $\alpha = \beta/n$, α was determined as 0.0164 MPa^{-1} .

For all stress levels, Eq. (2) can be also represented as the hyperbolic sine law:

$$\dot{\epsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{R_0T}\right) \quad (8)$$

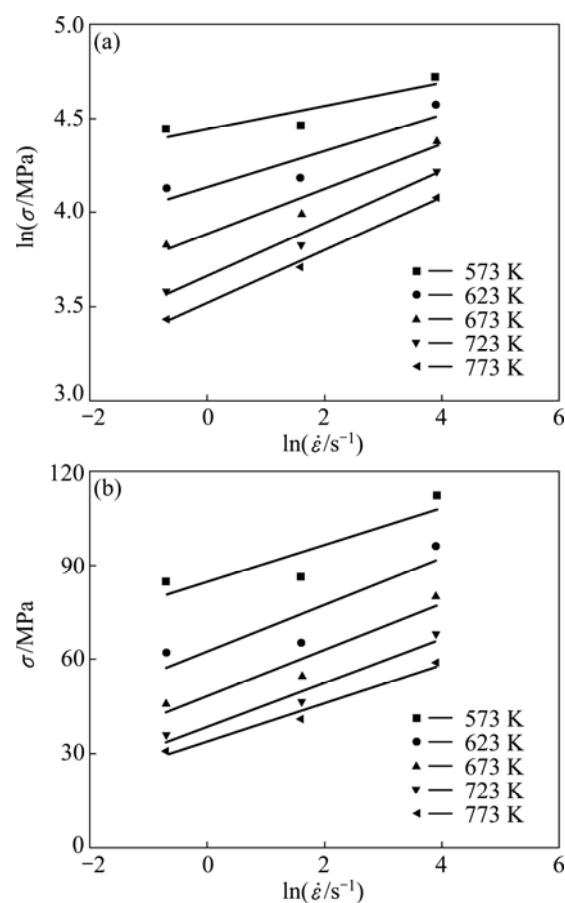


Fig. 2 Evaluating value of n by fitting $\ln \sigma - \ln \dot{\epsilon}$ (a) and β by fitting $\sigma - \ln \dot{\epsilon}$ (b)

For a particular strain rate, differentiating Eq. (8), the deformation activation energy, Q , can be expressed as follows:

$$Q = R_0 n \frac{d \ln[\sinh(\alpha\sigma)]}{dT^{-1}} \quad (9)$$

In order to determine the relationship in the plot of $\ln[\sinh(\alpha\sigma)]$ vs T^{-1} , the values of the tested temperature and flow stress for all the strain rates were substituted into Eq. (9) and the slopes of the lines were obtained, as shown in Fig. 3. Thus, the mean value of Q can be obtained under different strain rates. At the true strain of 0.1, the Q -value was found to be 181.8906 kJ/mol .

The logarithm of both sides of Eq. (8) was taken and the value of A was obtained by using the following equation:

$$\ln[\sinh(\alpha\sigma)] = \frac{1}{n} \ln \dot{\epsilon} + \frac{Q}{nR_0T} - \frac{1}{n} \ln A \quad (10)$$

It was clear from Eq. (10) that the values of A for all the tested temperatures can be derived from the intercept of Fig. 3. The mean value of A (at the strain of 0.1) was found to be $1.4506 \times 10^{14} \text{ s}^{-1}$.

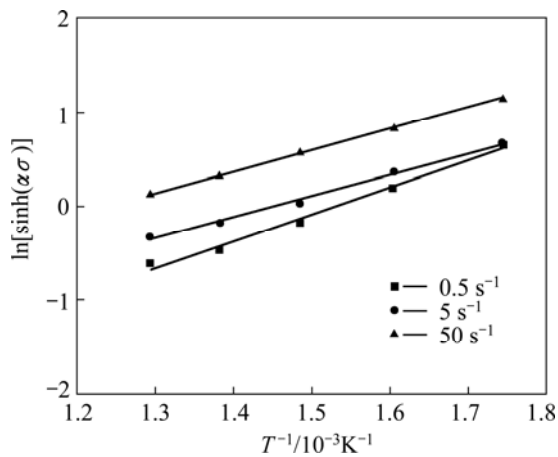


Fig. 3 Evaluating value of Q by plotting $\ln[\sinh(\alpha\sigma)]$ versus T^{-1}

3.4 Material constants as functions of strain

In the above equations, it is apparent that the flow stress is related to both the deformation temperature and strain rate. However, the effect of strain should be also taken into account. It can be evidently found from the true stress–true strain curves of Fig. 2 that the influence of strain on the flow stress is important. Therefore, in the present work, the compensation of strain incorporated into material constants (α , n , Q and A) was adopted to further increase prediction accuracy. The material constants (α , n , Q and A) were assumed to be the polynomial function of strain [16].

In order to know the relationships between material constants and true strain for 6063 Al alloy, the above-mentioned solution procedures were employed to calculate the values of material constants of the constitutive equations under different true strains within the range of 0.05–0.6 and the interval of 0.05. Furthermore, the values of α , n , Q and $\ln A$ of 6063 Al alloy can be polynomial fitted by a 4th order as follows:

$$\begin{aligned}\alpha &= a_0 + a_1\varepsilon + a_2\varepsilon^2 + a_3\varepsilon^3 + a_4\varepsilon^4 \\ n &= n_0 + n_1\varepsilon + n_2\varepsilon^2 + n_3\varepsilon^3 + n_4\varepsilon^4 \\ Q &= Q_0 + Q_1\varepsilon + Q_2\varepsilon^2 + Q_3\varepsilon^3 + Q_4\varepsilon^4 \\ \ln A &= A_0 + A_1\varepsilon + A_2\varepsilon^2 + A_3\varepsilon^3 + A_4\varepsilon^4\end{aligned}\quad (11)$$

where α_0 – α_4 , n_0 – n_4 , Q_0 – Q_4 and A_0 – A_4 are the coefficients of the polynomial and ε is the true strain. The coefficients of the polynomial fitting are listed in Table 1.

Thus, the developed constitutive equation that relates the flow stress to Zener–Holloman parameter can be expressed as

$$\sigma = \frac{1}{\alpha} \ln \left\{ \left(\frac{Z}{A} \right)^{1/n} + \left[\left(\frac{Z}{A} \right)^{2/n} + 1 \right]^{1/2} \right\} \quad (12)$$

Table 1 Coefficients of polynomial for α , n , Q and $\ln A$

α coefficient	n coefficient	Q coefficient	$\ln A$ coefficient
$\alpha_4=0.25703$	$n_4=76.17119$	$Q_4=1431.27744$	$A_4=79.81129$
$\alpha_3=-0.33273$	$n_3=-88.01757$	$Q_3=-3.68094$	$A_3=189.56696$
$\alpha_2=0.1652$	$n_2=54.5226$	$Q_2=119.98787$	$A_2=-60.44259$
$\alpha_1=-0.01797$	$n_1=-7.91864$	$Q_1=324.6309$	$A_1=66.16806$
$\alpha_0=0.01686$	$n_0=9.35697$	$Q_0=144.79785$	$A_0=25.95781$

It is also known from the above analyses that this developed constitutive equation involves material constants (α , n , Q and A) which vary with true strain. Once the polynomial coefficients of all material constants are determined, the flow stress considering the effects of temperature, strain rate and strain can be predicted by the use of Eq. (12).

3.5 Developed constitutive equation performance

The developed constitutive equation (considering the effect of strain) can be used to model the flow stress of 6063 Al alloy during hot deformation. As shown in Fig. 4, the actual prediction values are in good accordance with the experimental data.

It can be also found that different measures of prediction error such as average absolute relative error (AARE) can be used to further evaluate the performance of the developed constitutive equation. The expression of AARE (E_r) can be written as follows:

$$E_r = \frac{\sum_{i=1}^k \left| \frac{\sigma_{\text{pre}}^i - \sigma_{\text{exp}}^i}{\sigma_{\text{exp}}^i} \right|}{k} \times 100\% \quad (13)$$

where k is the total number of data; σ_{pre} is the value predicted by the constitutive equation; σ_{exp} is the value of the experimental data.

In the present study, the value of mean percentage error (AARE) is found to be only 4.65%. As shown in Fig. 5, a good correlation (the correlation coefficient, $R=0.97953$) between experimental and predicted data is also obtained. From Figs. 4 and 5, it can be concluded that good correlation between experimental and predicted data is obtained other than some deviation due to the scatter in the experimental data. In spite of this divergence, R and E_r are found to be 0.97953 and 4.65%, respectively, which reflects the good prediction capabilities of the developed strain compensated constitutive equation. The results indicate that the developed constitutive equation can effectively estimate the high temperature flow stress of 6063 Al alloy and can be used to numerically analyze the hot deformation process of this material.

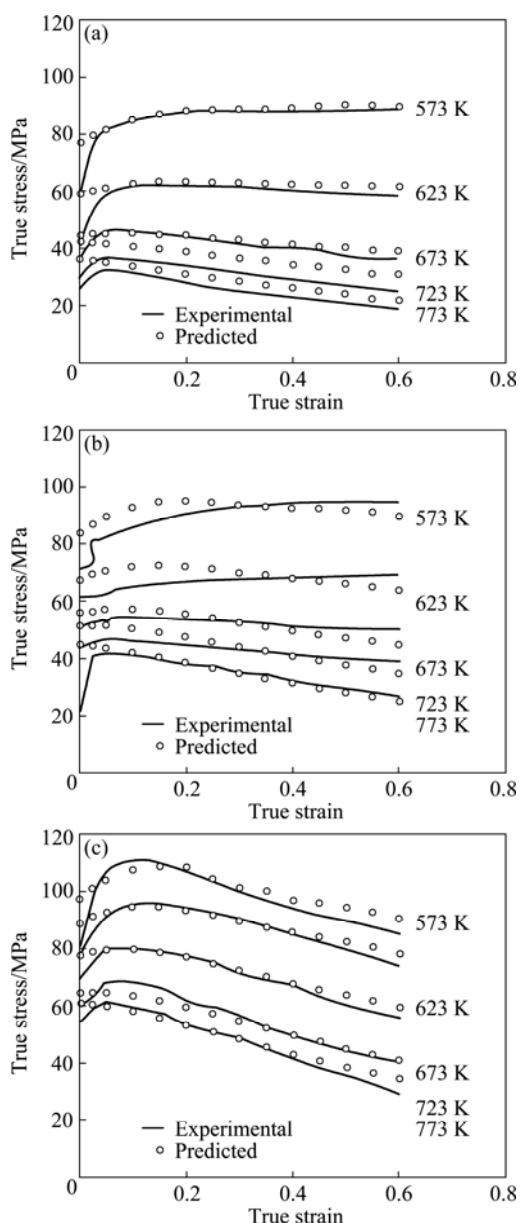


Fig. 4 Comparison between predicted and measured true stress–true strain curves for specimens deformed at different strain rates: (a) 0.5 s^{-1} ; (b) 5 s^{-1} ; (c) 50 s^{-1}

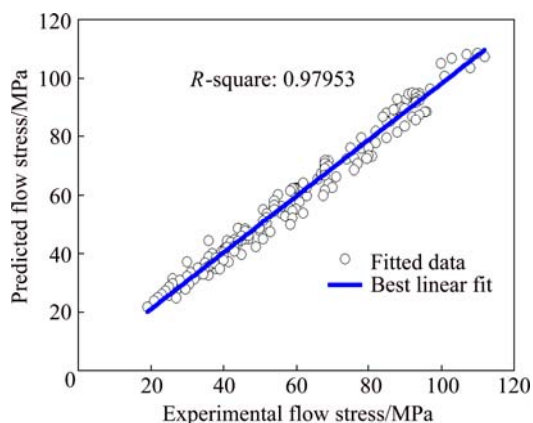


Fig. 5 Comparison between experimental and predicted flow stresses of 6063 Al alloy using developed constitutive equation

4 Conclusions

1) Based on the experimental true stress–true strain data, a strain compensated constitutive equation incorporating the effects of temperature and strain rate was proposed to describe high temperature flow stress of 6063 Al alloy.

2) A 4th order polynomial was found to suitably describe the influence of strain on materials constants (α , n , Q and A) in the constitutive equation.

3) A comparison between the experimental and predicted results confirmed that the developed constitutive equation considering the effect of strain had the excellent prediction capabilities. The average absolute relative error (AARE) associated with the prediction over the entire domain was found to be 4.65%.

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考虑应变补缩的 6063 铝合金 高温流变应力本构方程

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摘 要: 为了建立精确模拟 6063 铝合金高温流变应力的本构方程, 在温度为 573~773 K 和应变速率为 0.5~50 s⁻¹ 的条件下, 采用 Gleeble-1500 热模拟机进行等温热压缩实验。结果表明: 可以采用参数 Z 描述温度和应变速率对 6063 铝合金热变形行为的影响, 建立的本构方程中的材料常数(α , n , Q 和 A)可以表示成应变的 4 次多项式函数。模拟结果表明: 所建立的本构方程能精确预测 6063 铝合金高温流变应力, 因此, 本构方程适合用于模拟热变形过程, 如挤压和锻造, 并且可以在工程应用中正确设计变形参数。

关键词: 6063 铝合金; 本构方程; 流变应力; 应变; 热变形

(Edited by Chao WANG)