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ARTICLE

Constitutive Analysis to Predict High-Temperature Flow Stress of 25vol% B_4Cp/2009Al Composite

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Abstract: Isothermal compression tests of 25vol% B_4Cp/2009Al composite have been carried out at temperatures ranging from 300 ℃ to 500 ℃ and strain rates ranging from 0.001 s^{-1} to 1 s^{-1}. The results show that high-temperature flow stress of the composite decreases with the increase of deformation temperature and the decrease of strain rate. The flow stress has been corrected by friction and the friction corrected stress is lower than experimental values. The influence of friction becomes more obvious with decreasing temperature and increasing strain rate. Then a constitutive equation considering the effect of strain on material constants (i.e. α, n, Q and A) is developed on the basis of Arrhenius type equation. Compared with the experimental results, the flow stress calculated by the constitutive equation possesses a high precision with the correlation coefficient of 0.992. Higher temperature and lower strain rate is beneficial to hot deformation of B_4Cp/2009Al composite.

Key words: B_4Cp/2009Al composite; hot deformation behavior; constitutive equation; flow stress prediction

Particulate reinforced aluminum matrix composites play a critical role in automotive, aerospace, military and nuclear fields due to their excellent mechanical properties, which combined metallic properties of Al or Al alloy with ceramic particles[1,2]. Among them, the B_4Cp/Al composites are developing rapidly in recent years. B_4C is known as the third hardest material after diamond and boron nitride. It possesses several advantages. Compared with other ceramic particles such as SiC, Al_2O_3, TiC and WC, B_4C has low density (2.51 g/cm^3) and high hardness, high strength, high wear resistance, low thermal expansion coefficient and good chemical stability[3]. The most important is that boron carbide can be used to absorb neutrons, so the B_4Cp/Al composites are applied widely in the nuclear industry[4].

Researchers have already studied some aspects of B_4Cp/Al composites, including the preparation, interfacial reaction[5], microstructure and mechanical properties[6,7]. However, the literature on hot workability and flow characteristics of B_4Cp/Al composites is quite limited. The presence of the reinforcement induces both direct and indirect strengthening effects on the composite. Direct strengthening effects associate with higher strength and elastic module of the reinforcement. Indirect strengthening results from the microstructure evolution of matrix metal, such as finer grains strengthening and dislocation strengthening[8]. On the deformation process of matrix metal, the particles also reorient themselves in the same way to cope with the matrix[9]. As a result, the deformation behavior of composite is quite different from bulk material and the hot workability of the composite is much worse than that of matrix[10]. The plastic deformation process of the composite also involves the distribution of particles and the particle-matrix interfacial bonding conditions[11]. Therefore, the hot deformation behavior of B_4Cp/Al composites during deformation at elevated temperature should be of great value.

Generally, the hot deformation behavior of a given material can be represented by the flow stress which is closely related with the deformation parameters including deformation temperature, strain rate and strain. The inner connections among them can be described by constitutive equation. The constitutive equation models the dynamic response of material

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under specified deformation conditions. Most of constitutive equations were based on the Arrhenius type and developed from numerous experimentally measured data [12-14].

In the previous papers, some tests have been carried out to reveal the hot deformation behavior, hot workability and the optimum processing parameters of B_4Cp/AA6061 composite[15], B_4Cp/A356 composite[4] and B_4Cp/Al composite[16]. However, no literature seems to exist on deformation behavior of 2009Al-based composite with B_4C. In this study the hot deformation behavior of B_4Cp/2009Al composite was studied by uniaxial compression tests.

1 Experiment

The B_4Cp/2009Al composite used in the present investigation containing 25vol% B_4C particles with the average particle size of 5 μm, was produced by powder metallurgy method and the mass percentage of individual elemental alloy powder of 2009Al alloy are given in Table 1.

The samples were machined to 10 mm diameter and 15 mm length for compression testing. Graphite lubricant was used to minimize the friction between the press indenters and specimens. Isothermal hot compression tests were carried out on the Gleeble-1500D thermal simulator at temperatures ranging from 300 ℃ to 500 ℃ with an interval of 50 ℃ and the strain rates ranging from 0.001 s^{-1} to 1 s^{-1}. Prior to tests, each specimen was heated to the deformation temperature at a rate of 10 ℃/s, and held for 180 s at isothermal condition before compressing. Then the specimens were compressed to 50% reduction, which corresponded to a true strain of 0.7. Finally, at the end of compression the specimens were immediately quenched in water to reserve the deformed microstructure.

2 Results and Discussion

2.1 Flow stress behavior

The solid lines in Fig.1 show the true stress-true strain curves of 25vol% B_4Cp/2009Al composite at various strain rates and temperatures. Obviously, the flow behavior of B_4Cp/2009Al composite is sensitive to temperature and strain rate. It is a general trend that flow stress decreases with the increase of temperature and the decrease of strain rate. The flow stress increases to a peak value at a very small strain and then decreases monotonically. The composite undergoes greater work hardening at lower temperature and higher strain rate because the matrix around the B_4C particles presents lots of dislocations. These high dislocation density regions restrict the plastic flow of matrix. With the increase of temperature, the strength of composite decreases and the

Table 1 Composition of 2009Al alloy (wt%)

Cu	Mg	Si	Fe	Al
3.2~4.4	1.0~1.6	0.25	0.05	Bal.

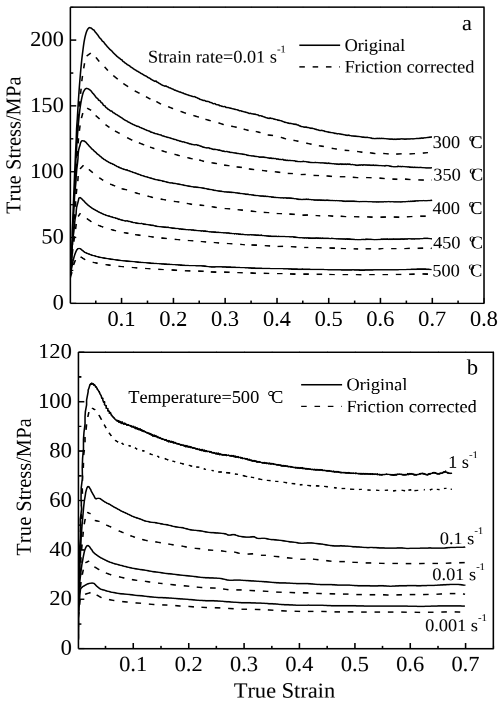

Fig.1 Flow stress curves of 25vol% B_4Cp/2009Al composite at various temperature and strain rates: (a) 0.01 s^{-1} and (b) 500 ℃

strengthening effect of B_4C particles is weakened. In addition, there is enough time for flow softening (dynamic recovery and dynamic recrystallization) with decreasing of strain rate. It should be noted that, B_4C particles have dual effects on the DRX process. On the one hand, particles hinder the movement of grain boundaries and limit the growth of recrystallized grains. On the other hand, particles in the composites act as potential sites for nucleation of recrystallization[17].

2.2 Friction correction

In practice, although lubricant can minimize the interfacial friction between the dies and specimens, the friction becomes more and more evident due to the area of interface increasing. In consequence, the deformation is heterogeneous and the experimental flow stress should be corrected with the friction.

According to the Ebrahimi and Najafizadeh[18], the measured flow stress could be transformed by the following equation:

$$\frac{P_{\mathrm{ave}}}{\sigma}=8b\frac{R}{H}\left\{\begin{array}{l}\left[\frac{1}{12}+\left(\frac{H}{R}\right)^2\frac{1}{b^2}\right]^{3/2}-\left(\frac{H}{R}\right)^3\frac{1}{b^3}- \\ \frac{m}{24\sqrt{3}}\frac{\mathrm{e}^{-b/2}}{\mathrm{e}^{-b/2-1}}\end{array}\right\} \quad (1)$$

where P_{ave} is the external pressure applied to specimens, σ is the corrected flow stress, b is the barrel parameter, m is the constant friction factor, R and H are the values of radius and height of specimens, respectively. They can be evaluated by the following equations:

$$R = R_0 \exp\left(-\varepsilon/2\right) \tag{2}$$

$$H = H_0 \exp(-\varepsilon) \tag{3}$$

$$m = \frac{R_f}{h} \cdot \frac{3\sqrt{3}b}{12-2b} \tag{4}$$

$$b = 4 \times \frac{R_M - R_T}{R_f} \cdot \frac{h}{h_0 - h} \tag{5}$$

R_M is the maximum radius of deformed samples, R_f is the average radius of specimens after the deformation, R_T is the top radius of deformed samples, where

$$R_f = R_0 \sqrt{\frac{h_0}{h}} \tag{6}$$

$$R_T = \sqrt{3\frac{h_0}{h}R_0^2 - 2R_M^2} \tag{7}$$

Fig.1 also shows the comparison between the original curves and friction corrected curves of 25vol% B_4Cp/2009Al composite under different deformation conditions. It is obvious that the friction corrected stress is smaller than the original experimental stress. With the decrease of deformation temperature and increase of strain rate, the effect of the friction becomes more remarkable.

2.3 Determination of material constants for the constitutive equation

The relationship of flow stress, deformation temperature and strain rate could be described by an Arrhenius type constitutive equation[19], which includes the Zener-Hollomon parameters[20]. These equations are mathematically represented as follows:

$$\dot{\varepsilon} = Af(\sigma)\exp\left(-Q/RT\right) \tag{8}$$

$$Z = \dot{\varepsilon}\exp\left(Q/RT\right) \tag{9}$$

where,

$$Z = \begin{cases} A_1\sigma^{n_1} = \dot{\varepsilon}\exp\left(Q/RT\right), & \alpha\sigma < 0.8 \\ A_2\exp(\beta\sigma) = \dot{\varepsilon}\exp\left(Q/RT\right), & \alpha\sigma > 1.2 \\ A\left[\sinh(\alpha\sigma)\right]^n = \dot{\varepsilon}\exp\left(Q/RT\right), & \text{for all} \end{cases} \tag{10}$$

where, Q is the activation energy (kJ·mol^{-1}); R is the gas constant (8.314 J·mol^{-1}·K^{-1}); T is the absolute temperature (K); A is the structure factor (s^{-1}); α is stress level parameter (MPa^{-1}); n is stress exponent; A_1, A_2, A, n_1, n, α and β are the material constants, and $\alpha=\beta/n_1$.

The friction corrected flow stress values at various deformation conditions were used to evaluate the material constants of the constitutive equation. Herein, a strain of 0.2 will be employed to calculate the constants as an example.

Taking the logarithm of Eq.(10), the following equations can be obtained:

$$\ln\dot{\varepsilon} = n_1\ln\sigma + \ln A_1 - Q/RT \tag{11}$$

$$\ln\dot{\varepsilon} = \beta\sigma + \ln A_2 - Q/RT \tag{12}$$

Whereafter, substituting the values of the flow stresses and corresponding strain rates at different temperatures into Eqs. (11) and (12), the relationship of $\ln\dot{\varepsilon}$-$\ln\sigma$ and $\ln\dot{\varepsilon}$-σ can be obtained using the linear regression fit method. As shown in Fig.2a and 2b, the flow stresses and strain rates can be approximated by a group of parallel and straight lines. The value of n_1 and β can be obtained from the slope of every single line in the $\ln\dot{\varepsilon}$-$\ln\sigma$ and $\ln\dot{\varepsilon}$-σ plots. The result is 5.91 and 0.087 MPa^{-1}. Then, $\alpha=\beta/n_1$=0.0147 MPa^{-1}.

For all the stress levels, Eqs. (8) and (9) can be represented as following:

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)\right]\exp\left(-Q/RT\right) \tag{13}$$

$$Z = \dot{\varepsilon}\exp\left(Q/RT\right) = A\left[\sinh(\alpha\sigma)\right]^n \tag{14}$$

Taking the logarithm of both sides of Eq. (13) and the following equation can be gained:

$$\ln\dot{\varepsilon} = \ln\sinh(\alpha\sigma) + \ln A - Q/RT \tag{15}$$

For the given strain rate, the deformation activation energy Q can be obtained by differentiating Eq. (15):

$$Q = R\left\{\frac{\partial\ln\dot{\varepsilon}}{\partial\ln\left[\sinh(\alpha\sigma)\right]}\right\}_T \left\{\frac{\partial\ln\left[\sinh(\alpha\sigma)\right]}{\partial\left(1/T\right)}\right\}_{\dot{\varepsilon}} \tag{16}$$

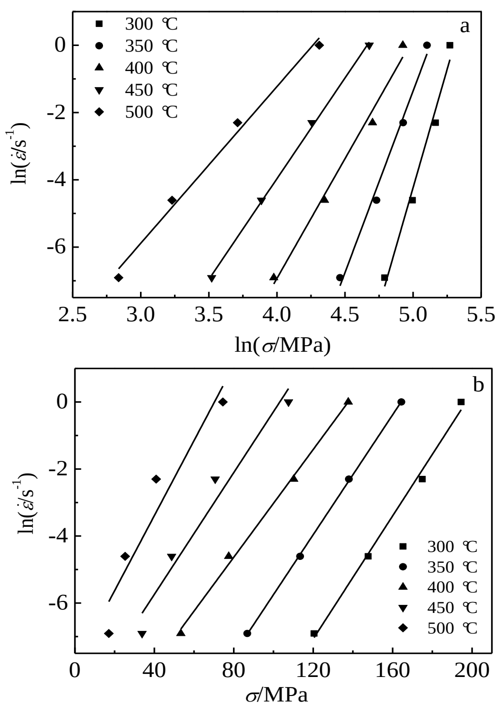

Fig.2 Relationship between strain rate and flow stress: (a) $\ln\dot{\varepsilon}$-$\ln\sigma$ and (b) $\ln\dot{\varepsilon}$-σ

The plots of ln $\dot{\varepsilon}$ -ln[sinh($\alpha\sigma$)] and ln[sinh($\alpha\sigma$)]-1/T can be obtained by substituting the values of flow stress, deformation temperature and corresponding strain rate into Eq. (16), as shown in Fig.3a and 3b. Thus the value of Q can be evaluated as 206.149 kJ·mol^{-1}.

By substituting the values of Q, $\dot{\varepsilon}$ and T into Eq. (14), the value of Z at different deformation conditions can be calculated. Then taking the logarithm of both sides of Eq. (14), ln$Z$ can be represented as follows:

$$\ln Z = \ln A + n\ln\left[\sinh\left(\alpha\sigma\right)\right] \tag{17}$$

The relationship between ln$Z$ and ln[sinh($\alpha\sigma$)] can be seen in Fig.4. Obviously, it is better fitted. The value of n and ln$A$ is the slope and the intercept of ln$Z$-ln[sinh($\alpha\sigma$)] plot.

Thus the value of A and n can be calculated as 3.13×10^{13} s^{-1} and 5.03, respectively.

2.4 Compensation of strain

The strain has a significant influence on the flow behavior at elevated temperature. It can be obviously observed in the friction corrected stress-strain curves, especially in the initial stage of the deformation process. Moreover, the influence of strain on the material constants is also remarkable. Therefore, in order to develop an accurate constitutive equation and give an exact prediction for the 25vol% B_4Cp/2009Al composite, the effects of deformation strain should be taken into consideration.

On the basis of the aforementioned method, the values of material constants (ln$A$, n, α and Q) of the constitutive equations were calculated at strains ranging from 0.05 to 0.7 with the interval of 0.025. The relationship between strain and material constants for 25vol% B_4Cp/2009Al composite can be polynomial fitted by the compensation of strain.

As shown in Fig.5, eighth order polynomial was adopted to describe the effects of the strain on material constants. It is evident that the variation of material constants with the strain is complex and irregular.

When the material constants are calculated, the flow stress at a given strain can be obtained. According to the hyperbolic law, the constitutive equations for hot deformation behavior of 25vol% B_4Cp/2009Al composite can be described as follows:

$$\begin{cases}
\sigma = \dfrac{1}{\alpha}\ln\left\{\left(Z/A\right)^{1/n} + \left[\left(Z/A\right)^{2/n}+1\right]^{1/2}\right\} \\
Z = \dot{\varepsilon}\exp\left(Q/RT\right) \\
\alpha = 0.0112 - 0.0021\varepsilon + 0.3845\varepsilon^2 - 3.1399\varepsilon^3 + 14.5182\varepsilon^4 \\
-41.7705\varepsilon^5 + 73.3538\varepsilon^6 - 70.4272\varepsilon^7 + 27.8587\varepsilon^8 \\
n = 4.0949 + 24.9526\varepsilon - 346.1744\varepsilon^2 + 2542.8519\varepsilon^3 - 10668.9696\varepsilon^4 \\
+26587.7040\varepsilon^5 - 38958.777\varepsilon^6 + 30972.107\varepsilon^7 - 10291.5971\varepsilon^8 \\
Q = 178.2279 + 961.1308\varepsilon - 13430.1947\varepsilon^2 + 95305.7967\varepsilon^3 - 379592.7294\varepsilon^4 \\
+887085.5473\varepsilon^5 - 1201160\varepsilon^6 + 871197\varepsilon^7 - 260296.0539\varepsilon^8 \\
lnA = 25.5373 + 196.4435\varepsilon - 2677.2484\varepsilon^2 + 18391.5137\varepsilon^3 - 71145.0649\varepsilon^4 \\
+1623323.4649\varepsilon^5 - 216546.2102\varepsilon^6 + 155959.2629\varepsilon^7 - 46747.1421\varepsilon^8
\end{cases}$$

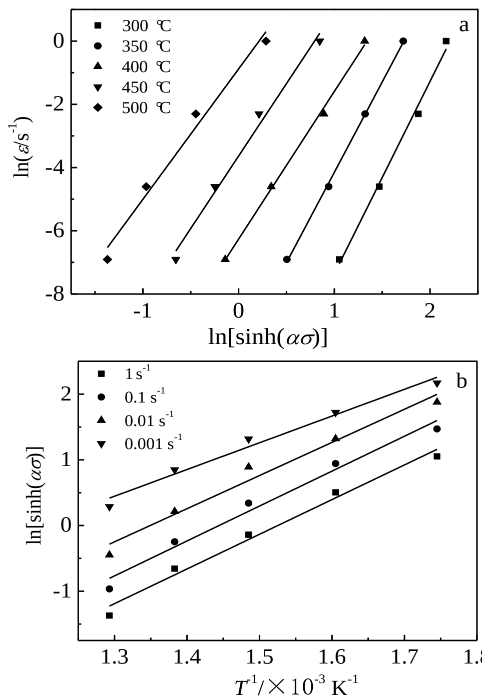

Fig.3 Relationships between flow stress with strain rate and temperature: (a) ln $\dot{\varepsilon}$ -ln[sinh($\alpha\sigma$)] and (b) ln[sinh($\alpha\sigma$)]-1/T

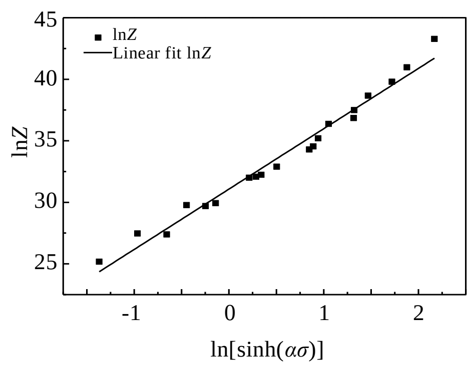

Fig.4 Relationships between flow stress and Z parameter

2.5 Verification of constitutive equation

According to the above constitutive equations, the predicted flow stress of 25vol% B_4Cp/2009Al composite can be obtained under all the experimental conditions by substituting the calculated material constants. In order to evaluate the accuracy of the constitutive equations, a comparison between the predicted values and the friction corrected flow stresses were carried out, as shown in Fig.6. Obviously, the predicted values from the constitutive equations agree well with the friction corrected flow stress values. Only at a deformation temperature of 300 ℃ and a strain rate of 1 s^{-1}, a bigger deviation can be observed (Fig.6d). According to Zhang[14], the deviation between the experimental and the predicted data of flow stress may be due to material constants fitting.

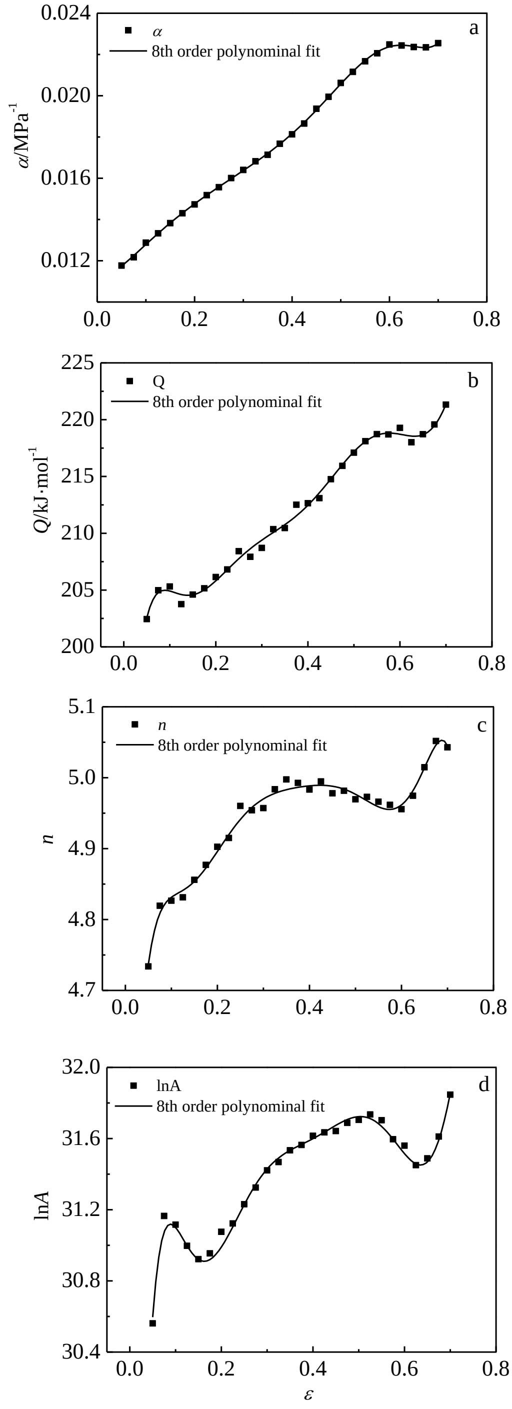

Fig.5 Variations of α (a), Q (b), n (c) and ln$A$ (d) with true strain based on the polynomial fitting for 25vol% B_4Cp/2009Al composite

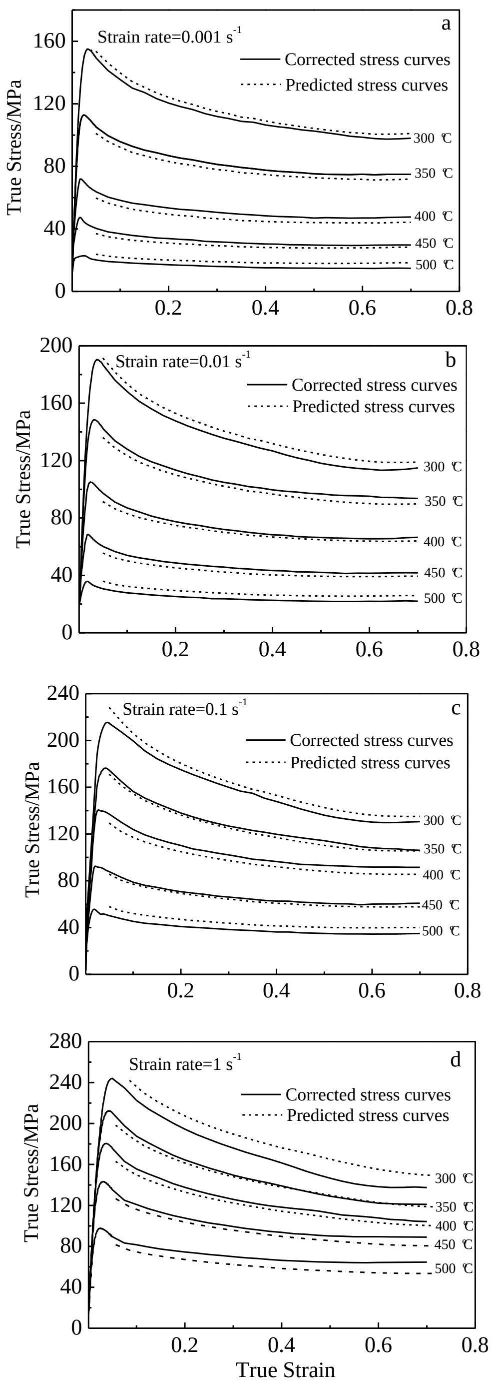

Fig.6 Comparison between the experimental and the predicted flow stress curves of B_4Cp/2009Al composite: (a) $\dot{\varepsilon}=0.001$ s^{-1}, (b) $\dot{\varepsilon}=0.01$ s^{-1}, (c) $\dot{\varepsilon}=0.1$ s^{-1} and (d) $\dot{\varepsilon}=1$ s^{-1}

In addition, standard statistical parameter correlation coefficient (R) was used to verify the precision of developed constitutive equations. Fig.7 shows the correlation between the predicted and friction corrected values. It can be observed that almost all points lie close to the regression line and the correlation coefficient (R) is 0.992, which indicates that the constitutive equations are accurate. Therefore, the developed constitution equations can be used to predict the flow behavior and analyze the problems during hot deformation process.

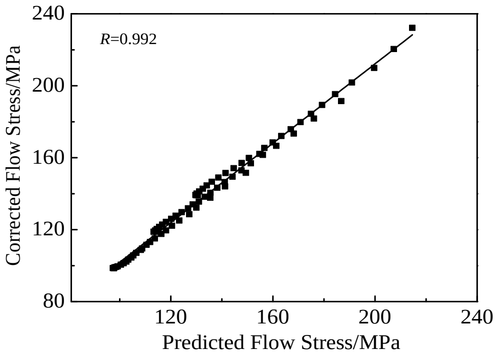

Fig.7 Correlation coefficient of the predicted and the experimental flow stress data

3 Conclusions

1) The flow stress decreases with the increase of deformation temperature and the decrease of strain rate. It increases to a peak value at a small strain and decreases with the increase of strain. The whole deformation process can be considered as a dynamic competition process of work hardening and dynamic softening.

2) The measured flow stress can be modified by the friction. Friction-corrected flow stress is lower than the experimental values and the effect of friction becomes obvious with decreasing temperature and increasing strain rate.

3) A constitutive equation considering the effect of strain on material constants (i.e. α, n, Q and A) is developed on the basis of Arrhenius type equation. Compared with the experimental values, the flow stress calculated by the constitutive equation possesses a high precision with the correlation coefficient of 0.992. Higher temperature and lower strain rate is beneficial to hot deformation of B_4Cp/2009Al composite.

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25vol%B_4Cp/2009Al 复合材料热变形本构模型

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摘　要：对 25vol% B_4Cp/2009Al 复合材料进行等温压缩实验，采用的温度范围为 300~500 ℃，应变速率范围为 0.001~1 s^{-1}。结果表明，B_4Cp/2009Al 复合材料的高温流变应力随着变形温度的升高和应变速率的减小而下降。对流变曲线进行了摩擦修正，修正后的流变应力值低于实验结果。摩擦力的影响随着温度的降低和应变速率的增大而更明显。随后构建了基于 Arrhenius 形式的本构方程，求解了不同应变量下的材料常数(α，n，Q 和 A)。与实验结果进行对比，利用构建的本构方程计算得到的流变应力值具有很高的计算精度，相关系数达到 0.992。研究发现，较高的温度和较低的应变速率有助于 B_4Cp/2009Al 复合材料的高温热变形。

关键词：B_4Cp/2009Al 复合材料；热变形行为；本构方程；流变应力预测

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