

Strain Compensation of the Constitutive Equation for High Temperature Flow Stress of a Al-Cu-Li Alloy

Ling Ou, Yufeng Nie, and Ziqiao Zheng

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In order to study the workability of a Al-Cu-Li alloy, isothermal hot compressive deformation was investigated in the temperature range of 350–500 °C at strain rates in the range of 0.01–10/s up to a true strain of 0.9 on Gleeble-1500 mechanical testing machine. The flow stress increased rapidly to a peak value. The peak stress decreased with increasing deformation temperature and decreasing strain rate. The effects of strain rate and temperature on hot deformation behavior can be represented by a Zener-Hollomon parameter including an Arrhenius term. The influence of the strain has also been incorporated in the constitutive equation and four material constants α , n , A , and the activation energy Q were calculated by compensation of strain. The proposed constitutive equation (considering the compensation of strain) gives an accurate description for the flow stress of the Al-Cu-Li alloy.

Keywords activation energy, Al-Cu-Li alloy, constitutive equation, flow stress

1. Introduction

With the development of the aerospace industry, the specific properties (property/density) of Al-Li alloys and products have been improved overtime. Al-Li alloys offer opportunities for significant improvements in aerostructural performance through density reduction, stiffness increase, as well as their other benefits (Ref 1–3). Al-Li alloys are frequently formed by hot rolling, forging, or extrusion. Deforming Al-Li alloys in the as-cast condition at elevated temperature is difficult because of its low ductility and high sensitivity to hot cracking. Therefore, the investigation of the deformation behavior and the flow behavior at elevated temperatures was necessary.

The flow stress is the most basic parameter to characterize plastic deformation properties of metals and alloys and the flow behavior is influenced by many factors such as initial microstructure of materials, the strain, strain rate, and temperature of deformation. The relationship between flow stress and deformation parameters is conveniently described by constitutive equations. The constitutive relations can be used in computer code to model material forming process. Numerical simulation can be

reliable only when a proper material flow stress relationship is built (Ref 4). Therefore, various investigators have attempted to develop constitutive equations of materials from the experimentally measured data to describe the hot deformation behavior (Ref 5–8). Laasraoui and Jonas (Ref 9) developed a model to determine the flow stress of steel based on a rate equation, consisting of a hyperbolic sine law, an evolution equation with dislocation density and fractional softening by dynamic recrystallization. These expressions can be employed in computer models for on-line gage control during hot rolling. Lin et al. (Ref 10) proposed a new material parameter L sensitive to the forming temperature and strain rate to develop a constitutive model. Langkruis (Ref 11) assessed five constitutive models with varying numbers of fitting parameters for modeling the stress-strain curves of four high-purity Al-Mg-Si alloys. It is concluded that the general exponential saturation equation proposed by Sah et al. combined with the hyperbolic sine law is the most promising one out of the five models. Samantaray et al. (Ref 12) made a comparative study on the capability of Johnson Cook (JC), modified Zerilli-Armstrong (ZA), and strain-compensated Arrhenius-type constitutive models for representing the elevated temperature flow behavior of modified 9Cr-1Mo steel. In the case of Al-Li alloys, there are no reports on the constitutive equation during hot deformation.

The objective of this study is to establish an appropriate constitutive equation to predict the flow stress of a Al-Cu-Li alloy at evaluated temperature. On the basis of hyperbolic-sine Arrhenius-type constitutive equation, the effect of strain on the constitutive parameters is unraveled. A comprehensive model describing the relationship of the flow stress, strain rate, and temperature of the alloy is proposed by compensation of strain and the validity of the developed constitutive equation is examined over the entire range of temperatures and strain rates.

2. Experiments

The chemical composition of the alloy used in this study is Al-3.7Cu-1.7Li-0.8Zn-0.55Mg-0.3Mn-0.14Zr (wt.%). The alloy

Ling Ou, School of Materials Science and Engineering, Central South University, Changsha 410083, China; School of Metallurgical Engineering, Hunan University of Technology, Zhuzhou 412000, China; and Mittal Metal Industry Research Institute, Central South University, Room 406, 932 Lushan South Road, Changsha 410083, China; **Yufeng Nie**, School of Materials Science and Engineering, Central South University, Changsha 410083, China; and School of Metallurgical Engineering, Hunan University of Technology, Zhuzhou 412000, China; **Ziqiao Zheng**, School of Materials Science and Engineering, Central South University, Changsha 410083, China. Contact e-mail: ouling24@126.com and ouling@csu.edu.cn.

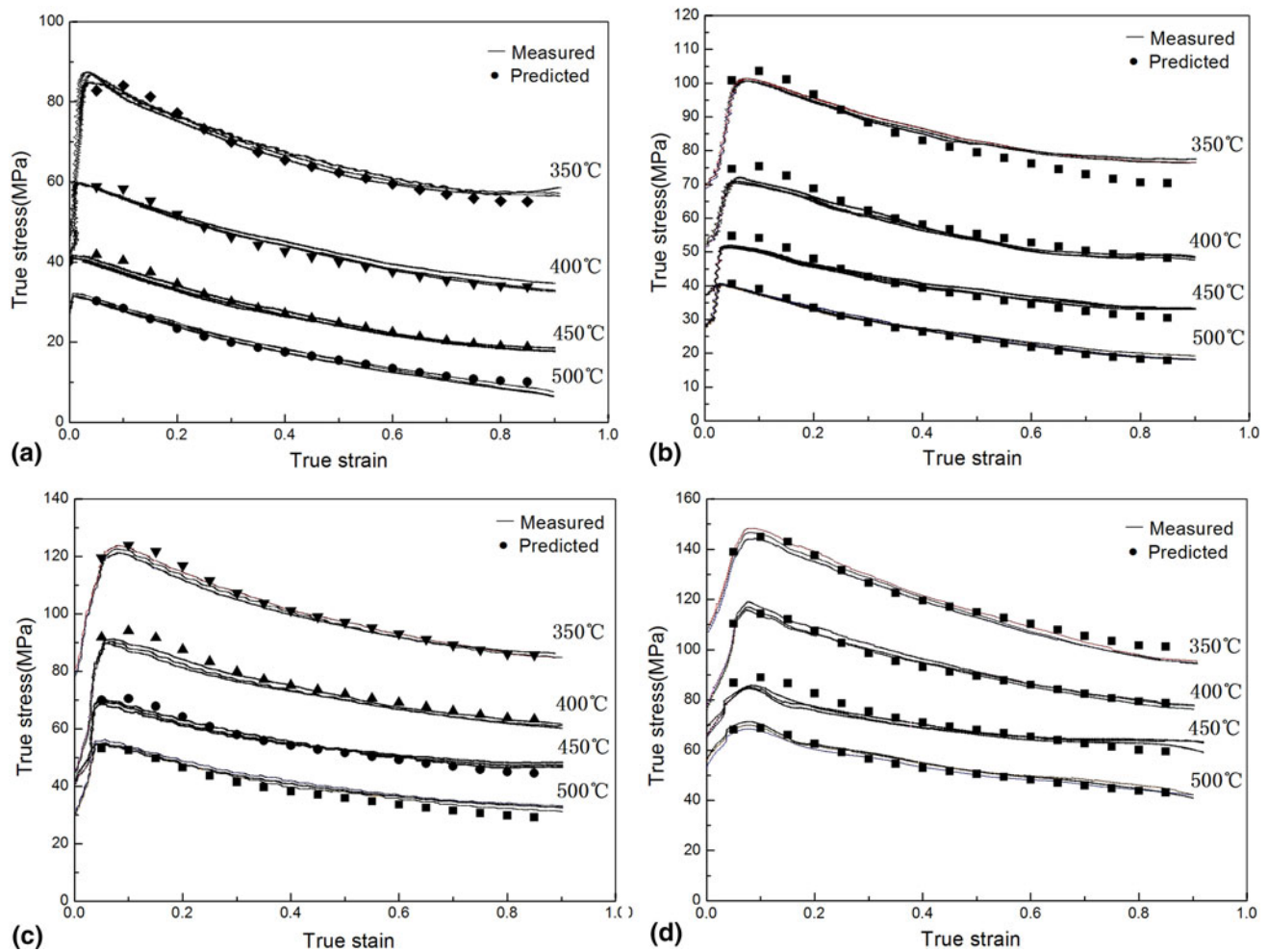


Fig. 1 Comparison between calculated and experimental flow stress values of the Al-Cu-Li alloy during hot deformation: (a) $\dot{\epsilon} = 0.01/s$ (b) $\dot{\epsilon} = 0.1/s$ (c) $\dot{\epsilon} = 1/s$ (d) $\dot{\epsilon} = 10/s$

was cast and homogenized at 500 °C for 24 h. The material in this condition was used for modeling the behavior during extrusion processing. The ingot was machined to cylindrical specimens and the diameter of the specimens was 10 mm and the height was 15 mm. Both ends of each specimen were recessed to a depth of 0.2 mm to entrap the lubricant for compression (Rastegaev-type specimen). A graphite lubricant was used to reduce the friction during compression. The compression tests were performed on a Gleeble 1500 mechanical testing machine in the temperature range of 350-500 °C and at strain rates ranging from 0.01 to 10/s. Three samples were tested for each experimental condition. Samples were heated to the test temperature at a heating rate of 200 °C/min and held for 5 min by the thermocouple feedback control prior to compression. The strain-stress curves were recorded automatically in isothermal compression.

3. Results

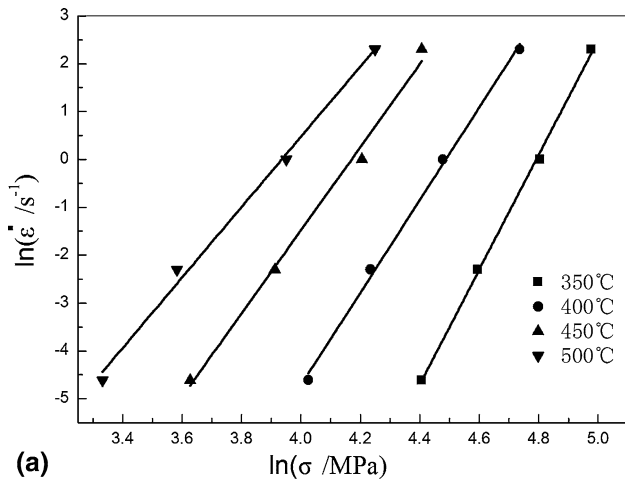
3.1 True Stress-True Strain Curves

The true stress-true strain curves of the Al-Cu-Li alloy under different deformation conditions are shown in Fig. 1. The repeatability of the data in three tests is good and the maximum

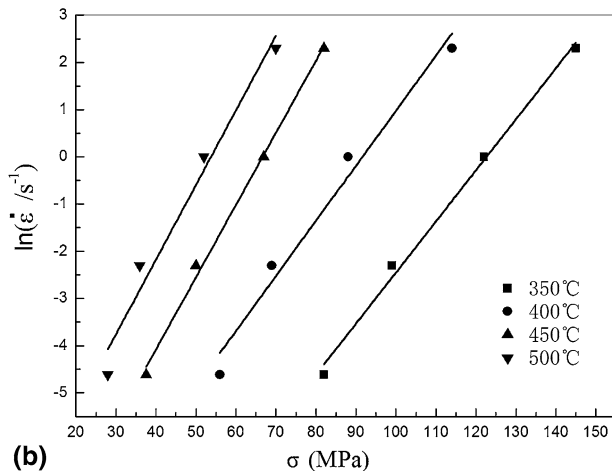
error is 2.3%. The average value of the three tests is used for calculation in later sections of the paper. The flow behavior is significantly influenced by the temperature, strain, and strain rate. At the early stage of straining, the flow stress reaches a peak value caused by excessive work hardening that dynamic softening is unable to balance. The peak stress decreases with increasing deformation temperature and decreasing strain rate. The strain at the peak stress increases as strain rate increases and temperature decreases. After reaching the peak flow stress, the flow stress curves show a continuous decline with rising strain.

3.2 Constitutive Equation

In hot working, several constitutive equations have commonly been applied for description of the deformation process. Equation 1 is based on the Arrhenius equation. The Arrhenius equation is widely used to describe the relationship of the strain rate, temperature, and flow stress, especially at high temperature (Ref 13, 14). According to Eq 1, the steady-state stress (Ref 14-16) or the peak stress (Ref 17-19) can be calculated at a given strain rate and temperature. It is required that the material constants α , n , A , and activation energy Q of the hot forming be known. Also, the effects of the strain rate and temperature on the deformation behavior can be represented by Zener-Hollomon



(a)



(b)

Fig. 2 Relationships between (a) $\ln \dot{\epsilon}$ and $\ln \sigma$; (b) $\ln \dot{\epsilon}$ and σ for $\epsilon = 0.1$

parameter in an exponent-type equation (Ref 20). For $F(\sigma)$ in Eq 1, the power law and the exponent-type equation apply to low stress ($\alpha\sigma < 0.8$) and to high stress ($\alpha\sigma > 1.2$), respectively. The hyperbolic law gives a superior approximation between the Zener-Hollomon parameter and the flow stress (Ref 20, 21).

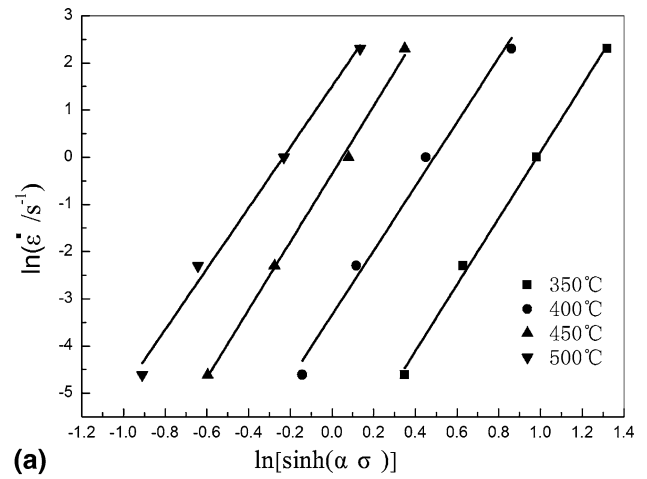
$$\dot{\epsilon} = AF(\sigma)\exp\left(-\frac{Q}{RT}\right) \quad (\text{Eq 1})$$

$$Z = \dot{\epsilon}\exp\left(\frac{Q}{RT}\right) \quad (\text{Eq 2})$$

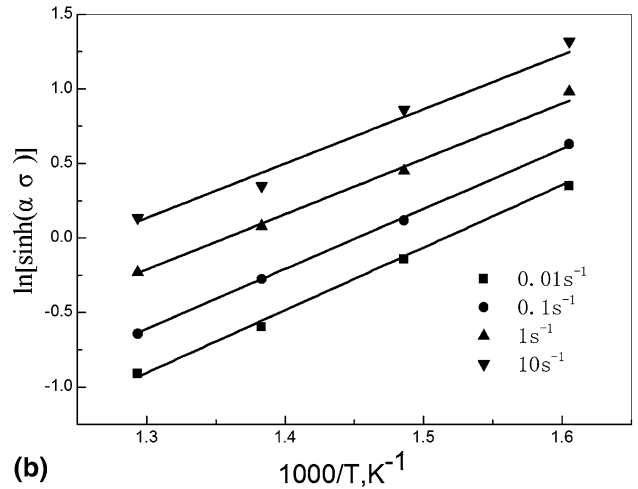
where,

$$F(\sigma) = \begin{cases} \sigma^{n_1} & \alpha\sigma < 0.8 \\ \exp(\beta\sigma) & \alpha\sigma > 1.2 \\ [\sinh(\alpha\sigma)]^n & \text{for all } \sigma \end{cases}$$

in which, A , α , β , and n are constants, R is the gas constant, σ is the flow stress, T is the absolute temperature (K), $\dot{\epsilon}$ is the strain rate (s^{-1}), and Q is the activation energy of hot forming. The constant n is the stress exponent and the stress multiplier α is an adjustable constant which brings $\alpha\sigma$ into the correct range to make constant T curves linear and parallel. For the high-stress level, mathematical analyses of the exponential law and the hyperbolic law show that: $\beta \approx \alpha n$. For the low-stress level, mathematical analyses of the power law and the hyper-



(a)



(b)

Fig. 3 Relationships between: (a) $\ln \dot{\epsilon}$ and $\ln[\sinh(\alpha\sigma)]$; (b) $\ln[\sinh(\alpha\sigma)]$ and $1000/T$ for $\epsilon = 0.1$

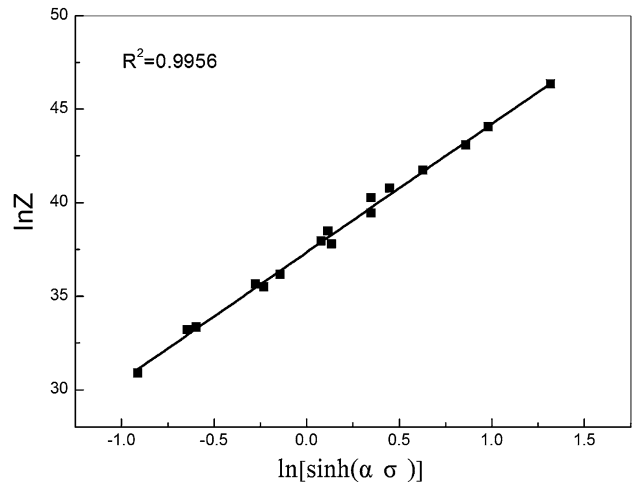


Fig. 4 Relationship between $\ln Z$ and $\ln[\sinh(\alpha\sigma)]$ for $\epsilon = 0.1$

bolic law show that: $n_1 \approx n$. So α and n can be simply determined from data for high and low stresses. This relation has satisfactorily correlated hot-working data for a number of metals and simply alloys (Ref 14, 17, 21-23).

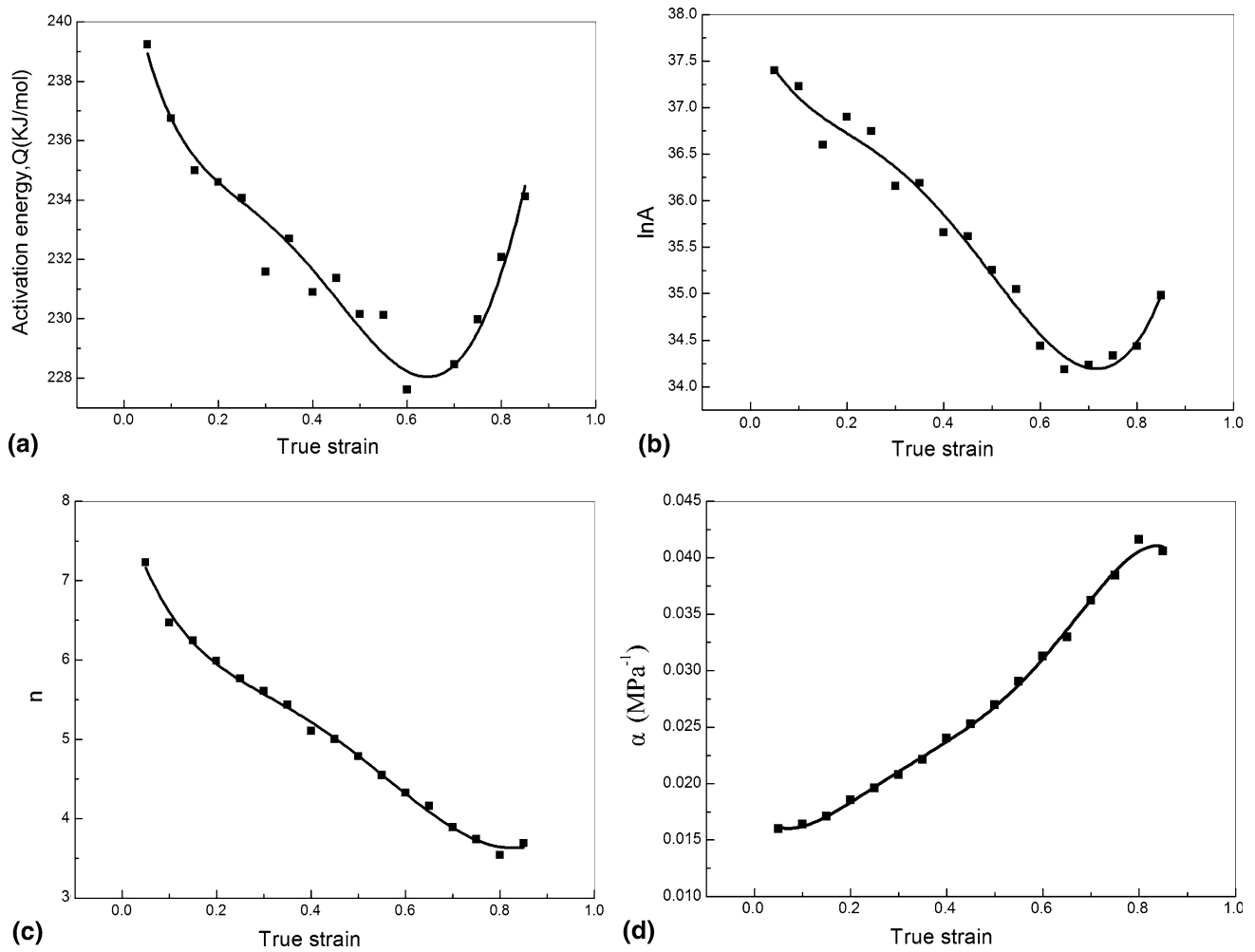


Fig. 5 Relationships between (a) Q ; (b) $\ln A$; (c) n ; (d) α and true strain by polynomial fit

3.3 Mathematical Analysis

Equation 1 combines the effects of temperature and strain rate on flow stress at the same time. However, the effect of strain on stress is not considered. In this paper, the effect of strain on the material constants α , n , A , and activation energy Q of the constitutive equation is investigated. The experimental true stress-true strain data can be used to determine the material constants of the constitutive equation as a function of strain. Taking the true strain of 0.1 as an example, the solution procedure of the material constants is demonstrated in the following.

For the low-stress range ($\alpha\sigma < 0.8$) and the high-stress range ($\alpha\sigma > 1.2$), substituting the power law and exponential law of $F(\sigma)$ into Eq 1 gives

$$\dot{\epsilon} = A_1 \sigma^{n_1} \exp\left(-\frac{Q}{RT}\right) \quad (\text{Eq 3})$$

$$\dot{\epsilon} = A_2 \exp(\beta\sigma) \exp\left(-\frac{Q}{RT}\right), \quad (\text{Eq 4})$$

where A_1 and A_2 are material constants.

By taking natural logarithms for both sides of Eq 3 and 4, these expressions can be written as:

$$\ln \dot{\epsilon} = \ln A_1 + n_1 \ln \sigma - \frac{Q}{RT} \quad (\text{Eq 5})$$

$$\ln \dot{\epsilon} = \ln A_2 + \beta\sigma - \frac{Q}{RT} \quad (\text{Eq 6})$$

A plot of the values of flow stress and corresponding strain rate at different temperatures at the true strain of 0.1 is depicted in Fig. 2 and analyzed according to Eq 5 and 6. In the temperature range of 350–450 °C, the values of the stress exponent n_1 vary from 8.7 to 12 (Fig. 2a) and are higher than the highest value of the stress exponent n_1 of 8 typically reported for the power law behavior (Ref 24). The value of $n_1 = 7.35$ at 500 °C was taken as a first approximation. In fitting to the exponential law (6), the straight lines at 350 and 400 °C are parallel (Fig. 2b) and $\beta = 0.1124/\text{MPa}$ was calculated from the average slopes of the two lines. Therefore, $\alpha = \beta/n \approx \beta/n_1 = 0.0153/\text{MPa}$.

For all stress levels, Eq 1 is given as

$$\dot{\epsilon} = A [\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{RT}\right) \quad (\text{Eq 7})$$

Differentiating Eq 7 gives,

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

Q , kJ/mol	$\ln A$	n	α , MPa ⁻¹
$B_0 = 242.48846$	$C_0 = 37.88556$	$D_0 = 7.97965$	$E_0 = 0.01745$
$B_1 = -88.89535$	$C_1 = -11.56574$	$D_1 = -19.35283$	$E_1 = -0.04583$
$B_2 = 401.62908$	$C_2 = 48.92539$	$D_2 = 68.25603$	$E_2 = 0.44801$
$B_3 = -952.98702$	$C_3 = -121.65381$	$D_3 = -131.96909$	$E_3 = -1.2929$
$B_4 = 965.1194$	$C_4 = 109.31341$	$D_4 = 110.13976$	$E_4 = 1.72424$
$B_5 = -318.18066$	$C_5 = -24.27718$	$D_5 = -30.76612$	$E_5 = -0.8277$

$$Q = R \left| \frac{\partial \ln \dot{\epsilon}}{\partial \ln[\sinh(\alpha\sigma)]} \right|_T \left| \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial (1/T)} \right|_{\dot{\epsilon}} \quad (\text{Eq 8})$$

Therefore, by substituting the values of flow stress, temperature, and corresponding strain rates into Eq 8, the relationships of $\ln \dot{\epsilon} - \ln[\sinh(\alpha\sigma)]$ and $\ln[\sinh(\alpha\sigma)] - 1000/T$ can be obtained and are shown in Fig. 3. The first approximation of Q can be derived from the slopes of $\ln \dot{\epsilon} - \ln[\sinh(\alpha\sigma)]$ and $\ln[\sinh(\alpha\sigma)] - 1000/T$ plots and is calculated as 236 kJ/mol.

By substituting the values of Q and different hot deformation conditions into Eq 1, Z values are calculated. Combining Eq. 2 and 7 gives:

$$Z = A[\sinh(\alpha\sigma)]^n \quad (\text{Eq 9})$$

Taking the natural logarithm of both sides of Eq 9, gives

$$\ln Z = \ln A + n \sinh(\alpha\sigma) \quad (\text{Eq 10})$$

A linear relationship between $\ln Z$ and $\ln[\sinh(\alpha\sigma)]$ is shown in Fig. 4. The values of $\ln A$ and n are obtained according to the intercept and slope of the straight line. The first approximations of A and n can be obtained as $6.35 \times 10^{16}/s$ and 7, respectively. Then, the value of n is iterated to obtain the optimum values of the constants α , n , Q , and A . The final value of n chosen is the one corresponding to the best correlation coefficient over full range of temperatures and strain rates.

So the material constants α , n , A , and the activation energy Q of the constitutive equation have been calculated for the fixed value of true strain equal to 0.1. The values of all material constants and the activation energy are calculated by the aforementioned method for different true strains within the range of 0.05-0.85 at a strain interval of 0.05. The results are shown in Fig. 5. The relationships of the parameters Q , $\ln A$, n , and α on true strain (Fig. 5) can be fit to a polynomial equation, thereby compensating strain, as shown in Eq 11. The coefficients of the polynomial are given in Table 1.

$$\begin{cases} Q = B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5 \\ \ln A = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5 \\ n = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5 \\ \alpha = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5 \end{cases} \quad (\text{Eq 11})$$

From Eq 9, the flow stress can be written as a function of Zener-Hollomon parameter, considering the definition of the hyperbolic law. Combining Eq 9 with Eq 2, the constitutive equation for hot deformation of the Al-Cu-Li alloy is obtained as

$$\begin{cases} \sigma = \frac{1}{\alpha} \ln \left\{ \left(\frac{Z}{A} \right)^{1/n} + \left[\left(\frac{Z}{A} \right)^{2/n} + 1 \right]^{1/2} \right\}, \\ Z = \dot{\epsilon} \exp \left(\frac{Q}{RT} \right) \end{cases} \quad (\text{Eq 12})$$

where the values of Q , $\ln A$, n , and α can be calculated by Eq 11.

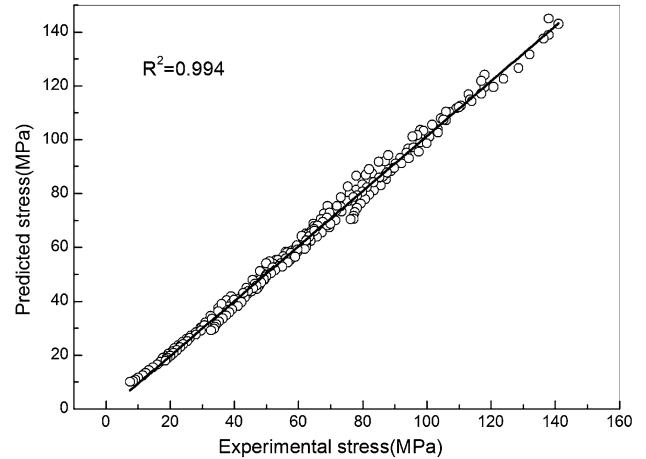


Fig. 6 Correlation between calculated and experimental flow stress values at all strain values for which the strain-dependence of the parameters was evaluated (strains within the range of 0.05-0.85 at a strain interval of 0.05)

3.4 Verification of the Developed Constitutive Equation

In order to verify the accuracy of the proposed constitutive equation for hot deformation behavior of the Al-Cu-Li alloy, comparisons between the experimental and calculated flow stress values were carried out and are shown in Fig. 1. It is evident that the calculated flow stress values show good agreement with the experimental results.

For better visualization, all calculated flow stress values are plotted against the experimental ones in Fig. 6 which show a high correlation characterized by a correlation coefficient of 0.994.

4. Discussion

As shown in Fig. 5(a), the values of Q vary from 228 to 239 kJ/mol, which are much higher than the normal value of 150 kJ/mol for climb or volume diffusion in pure aluminum (Ref 25). However, the results are consistent with some other Al-Li-based alloys. Torsion tests and compression tests on 2090 (Al-2.1Li-2.6Cu-0.4Mn) alloy were conducted and the values of activation energy were found to be 236 and 219 kJ/mol, respectively (Ref 19). Avramovic-Cingara et al. (Ref 26) calculated the value of Q to be about 282 kJ/mol for the 8090 alloy and 287 kJ/mol for 8091. Transmission electron microscopy analysis found an additional dynamic precipitation of T_2 and T_1 phases and composite $Al_3(Zr, Li)$ precipitates during deformation, which made dynamic recovery more difficult. Thus, precipitates reaction with dislocations may be responsible

for the high Q value of the Al-Cu-Li alloy. For other dispersion-strengthened aluminum alloys Al-0.65Fe and Al-0.5Fe-0.5Co, similar activation energies (270 and 260 kJ/mol) were determined as a result of changes in interaction between dislocations and particles (Ref 27).

The constant α is the stress multiplier, an adjustable parameter. The usual values of α vary from 0.01 to 0.08/MPa (Ref 17, 19). As the strain increases from 0.05 to 0.85, the values of α for the alloy used increase from 0.016 to 0.04 (Fig. 5d). The actual magnitude of α should be indicative of a material's intrinsic ability to resist deformation. The analogy of creep and hot working suggested that the more resistant a material is to deformation, the lower will be its value for α in both processes (Ref 16). The change of α with rising strain shows the opposite trend compared with the flow stress in the present study.

5. Conclusions

In the present work, hot compression tests were carried out to study the flow behavior of a Al-Cu-Li alloy. The following conclusions are drawn:

- (1) The flow stress increased rapidly to a peak value. The peak stress decreased with increasing deformation temperature and decreasing strain rate.
- (2) The effects of strain rate and temperature on hot deformation behavior were represented by a Zener-Hollomon parameter including an Arrhenius term.
- (3) A revised constitutive equation incorporating the effects of temperature, strain rate, and strain was proposed. The material constants A , n , α , and activation energy Q were calculated by compensation of strain using polynomials. The developed constitutive equation gives an accurate description for the flow stress of the Al-Cu-Li alloy.

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