# Hot Deformation Behaviors of Cu/Al Laminated Composites

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**Abstract.** In order to research the hot deformation behaviors of Cu/Al laminated composites, isothermal hot compression tests were conducted on a Gleeble-1500D thermo-mechanical simulator in the temperature range of 300 ~ 450 ℃ and strain rate range of 0.01 ~ 1 $s^{-1}$. After hot compression, the cooperative deformation behaviors between Cu and Al were discussed. The effects of deformation temperature and strain rate on the deformation behaviors were described using an Arrhenius-type constitutive equation. Furthermore, considering the effect of strain, the constitutive model was modified. The predicated flow stress values obtained from the modified constitutive equation could be well in accord with the experimental values. High correlation coefficient and low average absolute relative error demonstrate the high accuracy of the constitutive model developed in this work.

## 1. Introduction

In recent years, scientists have pay great attention on copper/aluminum (Cu/Al) laminated composites because the materials can reduce the weight of 40 ~ 50%, save the cost of 30 ~ 50 % and keep almost same electrical and thermal conductivity compared to monometallic copper or copper alloy [1]. And several fabricate methods were presented gradually [2-6]. Whereas, researches on the hot deformation behavior of Cu/Al laminated composites are still not comprehensive enough.

Arrhenius-type constitutive equation is a commonly used mathematical model to describe the metal hot deformation behavior. It can be easily constructed based on a limited number of experimental data such as deformation temperature, strain rate and stress. In this paper, the isothermal compression deformation tests were conducted in the temperature range of 300 - 450 ℃ and strain rates range of 0.01- 0.1 $s^{-1}$. Deformation activation energy, which indicates the dislocation slipping ability, was established [7, 8]. Constitutive equation, which relates the flow stress to deformation temperature and strain rate, was applied to describe the hot deformation behaviors of Cu/Al laminated composites [9]. At the same time, the effect of strain on the flow stress was compensated by developing the material parameters as functions of strain. Finally, the accuracy of the modified constitutive model was evaluated by the statistical correlation coefficient of parameters and average absolute relative error.

## 2. Material and experimental procedure

Experimental Cu/Al laminated composite plates were produced by horizontal twin-roll casting technology. The thickness of copper layer and aluminum layer are 1.5 mm and 8.5 mm, respectively. The chemical components of constituent metals are list in Table 1. The sample of as-cast composite plates was homogenized at 350 ℃ for 1 hour in an electrical resistance furnace. Then cylindrical specimens were machined from the homogenized sample with a diameter of 8 mm and a height of 10 mm. The isothermal compression experiments were conducted on a Gleeble-1500D thermo-mechanical simulator at constant temperatures of 300, 350, 400 and 450 ℃ and strain rate of 0.01, 0.1 and 1 $s^{-1}$, respectively. Prior to hot compression, graphite lubricant was used for reducing the friction between the specimen and the anvil, and the specimens were heated to the set temperature at a heating rate of 10 ℃ /s and held for 60 s to eliminate the thermal gradients without increasing the interfacial thickness. The specimens were compressed at a reduction rate of 50%, and followed by water quenching to keep the deformed microstructure. The true stress-strain data were automatically collected by Gleeble-1500D thermo-mechanical simulator.

**Table 1.** Chemical composition of Cu plate and Al alloys

| Alloys | Chemicals compositions (wt %) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cu | Fe | Zn | S | P | Si | Mg | Al |
| Cu | 99.96 | 0.0009 | 0.0008 | 0.0007 | 0.0009 | 0.0006 | - | - |
| Al | 0.04 | 0.16 | 0.04 | - | - | 0.17 | 0.04 | 99.5 |

## 3. Results and discussion

*3.1 Deformation models*

After hot compression, the typical cross sectional morphology of the compressive specimens are shown in figure 1. As we can see, Cu layer was wrapped by extruded Al matrix because of different plastic deformation ability. Meanwhile, under the normal stress in the vertical direction, the horizontal flow in different region of Al matrix is inhomogeneous. Obviously, the horizontal flow distance in bottom region of Al layer is larger than that in top region (Xb>Xt). The inhomogeneous deformation may be attributed to excellent Cu/Al bonding interface. During hot compression process, harder Cu layer make great restrict on the flow of aluminum matrix through the bonding interface so that they can deform simultaneously. However, Due to good lubrication, the constraint effect of the anvil on the flow of Al layer is relatively small.

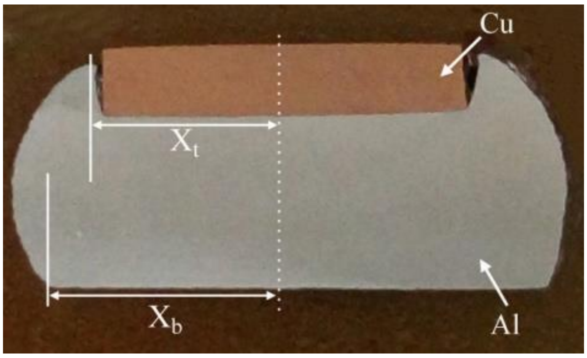


**Figure 1.** The cross-sectional morphology of specimen after hot compression

The true stress-true strain curves of Cu/Al laminated composites are shown in figure 2. As we can see, once the beginning of compression, flow stress increases sharply and reaches peak stress at an extremely small strain values. And the peak stresses increase with the increase of strain rate or the decrease of deformation temperature. After reaching up to the peak stress, dynamic softening mechanism gradually plays a dominant role, and then true stresses decrease and reach steady conditions with the continuous increase of strain.

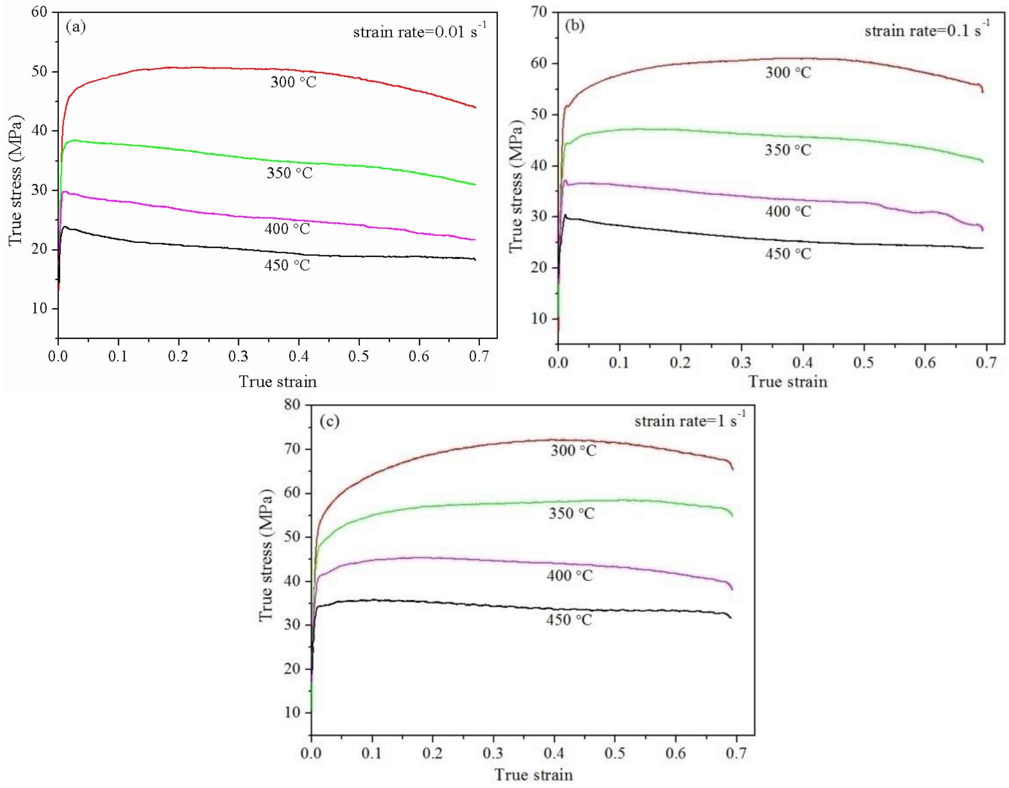


**Figure 2.** True stress–strain curves of Cu/Al clad composites under different strain rates of (a) 0.01 $s^{-1}$, (b) 0.1 $s^{-1}$ and (c) 1 $s^{-1}$

*3.2 Deformation constitutive equations*

In the hot deformation process, the Arrhenius equation, considering the relation between strain rates, deformation temperatures, stress and deformation activation energy, generally is used to describe the metal flow behavior as shown in equation (1).

$$\dot{\varepsilon} = Af(\sigma)\exp\left(-\frac{Q}{RT}\right) \tag{1}$$

Where $f(\sigma)$ is a function of flow stress:

$$f(\sigma) = \begin{cases} [\sinh(\sigma)]^n & for\ all\ \sigma \\ \sigma^{n_1} & \alpha\sigma < 0.8 \\ exp(\beta\sigma) & \alpha\sigma > 1.2 \end{cases} \tag{2}$$

here in, $A$, $n$, $n_1$, $\alpha$ and $\beta$($\alpha=\beta/n_1$) are material constants, $\dot{\varepsilon}$ is the strain rate ($s^{-1}$), $\sigma$ is the flow stress (MPa), $Q$ is the deformation activation energy (KJ/mol), $R$ is the gas constant (8.314 KJ/ (mol K)), and $T$ is the deformation temperature (K). Taking the natural logarithm of both sides of equations (1) and (2), equations (3), (4) and (5) can be obtained.

$$\ln\dot{\varepsilon} = n\ln[\sinh(\alpha\sigma)] + \ln A - \frac{Q}{RT} \tag{3}$$

$$\ln\dot{\varepsilon} = n_1\ln\sigma + \ln A_1 - \frac{Q}{RT} \tag{4}$$

$$\ln\dot{\varepsilon} = \beta\sigma + \ln A_2 - \frac{Q}{RT} \tag{5}$$

It is obvious that $\text{Ln}\,\dot{\varepsilon}$-$\ln[\sinh(\alpha\sigma)]$, $\ln\dot{\varepsilon}$-$\ln\sigma$ and $\ln\dot{\varepsilon}$-$\sigma$ all meet some linear relationship at constant deformation temperatures. Then the flow stresses and strain rates under the true strain of 0.4

are submitted to equations (3), (4) and (5). And the average slops under every deformation temperature were calculated. The value of $n$ is 6.90 and the constant $\alpha$ can be attained as $\alpha=\beta/n_1=0.0254$ MPa$^{-1}$.

The hot deformation activation $Q$, which indicates the difficulty degree of deformation in test material [10], can be calculated by taking partial differential of equation (3), as shown in equation (6).

$$Q = R\left[\frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]}\right]_T \cdot \left[\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\right]_{\dot{\varepsilon}} = RnS \tag{6}$$

The parameter $S$ represents the average slop of $\ln[\sinh(\alpha\sigma)]$-1/$T$ plots under test temperatures. By substituting the values of flow stress and deformation temperature under constant strain rate, the value of $S$ can be calculated and it is 3249.44. Additionally, the activation energy ($Q$) can be obtained to be 186.43 KJ/mol. It was higher than that of self-diffusion in commercial pure aluminum (126.45 KJ/mol) due to the obstacle effect of harder copper to the flow of softer aluminum matrix [11].

### *3.3 The compensation of strain*

The foundation of the constitutive equation is the equilibrium between the work hardening and the dynamic softening, and the flow stresses change little with the increase of strain. Obviously, the change of flow stress in this experiment shows that the constitutive equation built according to the parameters of strain 0.4 is not representative over the all strain situations. The compensation of strain should be taken into account when the material constants ($A$, $\alpha$, $n$ and $Q$) are computed so that the flow stress can be predicted more accurately [12, 13].

Using the same calculation method, the material constants are calculated again at the strain range of 0.05 - 0.65 at the interval of 0.05. Moreover, the relationship between these material constants and true strain can be polynomial fitted, as shown in figure 3. The order of polynomial was experimented from 2 to 9. And results show that 5 order polynomial fits the experimental data very well. The polynomials are shown in equation (7) and the coefficients of polynomials are list in table 2.

**Table 2.** Coefficients of polynomial for $\alpha$, $n$, $Q$ and ln $A$

| $\alpha$ coefficient | $n$ coefficient | $Q$ coefficient | ln $A$ coefficient |
|---|---|---|---|
| $B_0$ = 2.5409 | $C_0$ = 12.3182 | $D_0$ = 209.4480 | $E_0$ = 34.9790 |
| $B_1$ = -2.2942 | $C_1$ = -47.5148 | $D_1$ = -191.4209 | $E_1$ = -28.2479 |
| $B_2$ = 14.0243 | $C_2$ = 192.5064 | $D_2$ = 370.7157 | $E_2$ = 35.9870 |
| $B_3$ = -31.8606 | $C_3$ = -420.2749 | $D_3$ = 903.3894 | $E_3$ = 232.5851 |
| $B_4$ = 31.7676 | $C_4$ = 460.1838 | $D_4$ = -3544.5115 | $E_4$ = -714.7760 |
| $B_5$ = -10.2397 | $C_5$ = -199.5526 | $D_5$ = 2675.6823 | $E_5$ = 514.9587 |

$$\begin{cases} \alpha(\varepsilon) = B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5 \\ n(\varepsilon) = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5 \\ Q(\varepsilon) = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5 \\ lnA(\varepsilon) = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5 \end{cases} \tag{7}$$

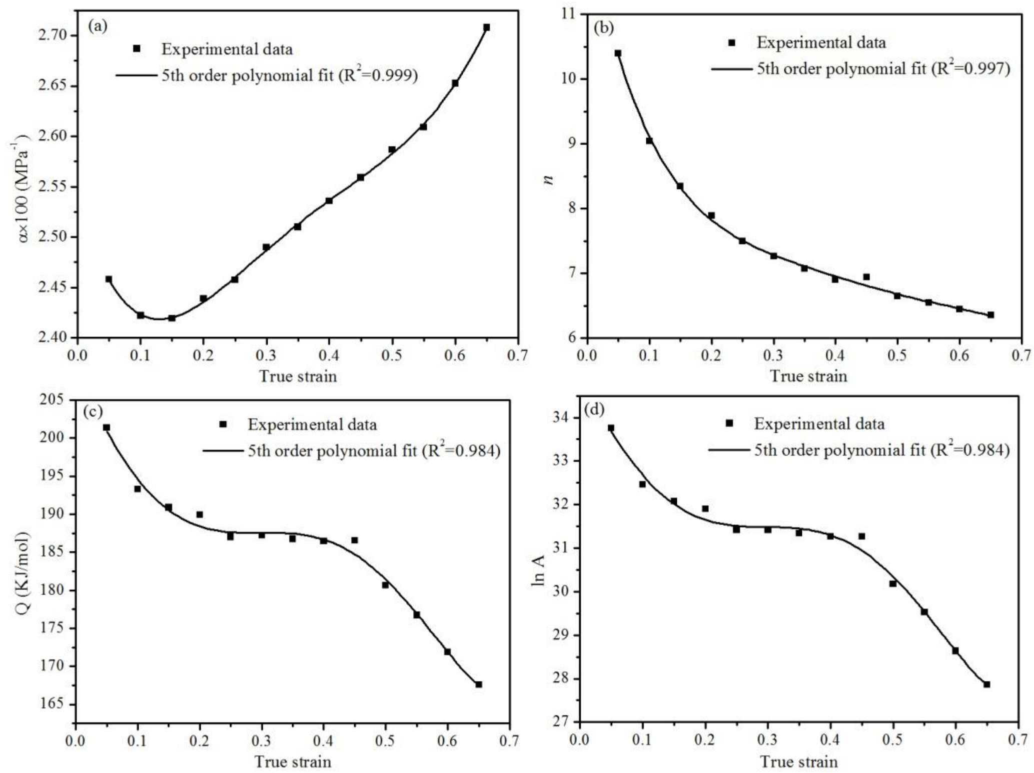


**Figure 3.** Relationship between (a) $\alpha$, (b) $n$, (c) $Q$ and (d) ln $A$ with true strain by polynomial fit

Under such a condition, strain modified constitutive equations can accurately describe the deformation behavior of Cu/Al composite plate at different strain rates, deformation temperatures and strains as shown in equation (8).

$$\dot{\varepsilon} = A(\varepsilon)[\sinh(\alpha(\varepsilon)\sigma)]^{n(\varepsilon)}\exp\left(-\frac{Q(\varepsilon)}{RT}\right) \tag{8}$$

*3.4 Verification of the constitutive model*

The calculated flow stress values were plotted against the experimental flow stresses in figure 4(a), (b) and (c), which shows they have a satisfactory match. In order to further verify the accuracy of the modified constitutive model, the correlation coefficient ($R$) and average absolute relative error (*AARE*) also are computed. They are expressed as follows:

$$R = \frac{\sum_{i=1}^{N}(E_i - \bar{E})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2 \sum_{i=1}^{\mathrm{N}}(P_i - \bar{P})^2}} \tag{9}$$

$$AARE(\%) = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{E_i - P_i}{E_i}\right| \times 100 \tag{10}$$

where $N$ is the total number of the calculated stress values over the entire experimental temperatures and strain rates, $E_i$is the measured flow stress values, $P_i$ is the calculated flow stress values, $\bar{E}$ and $\bar{P}$ are the average values of $E_i$ and $P_i$, respectively.

Figure 4d shows the correlation between the experimental and predicated flow stress values. The correlation coefficient ($R$) can be obtained as high as 0.9976. Meanwhile, average absolute relative error (*AARE*), an unbiased statistical parameter, also is calculated to be only 1.84%. The high correlation coefficient and low average absolute relative error collectively indicate the high accuracy of the modified constitutive model. Therefore, it is reasonable to believe that the developed constitutive model in this paper can accurately describe the deformation behavior of the Cu/Al composite plate at elevated temperature and strain rate.

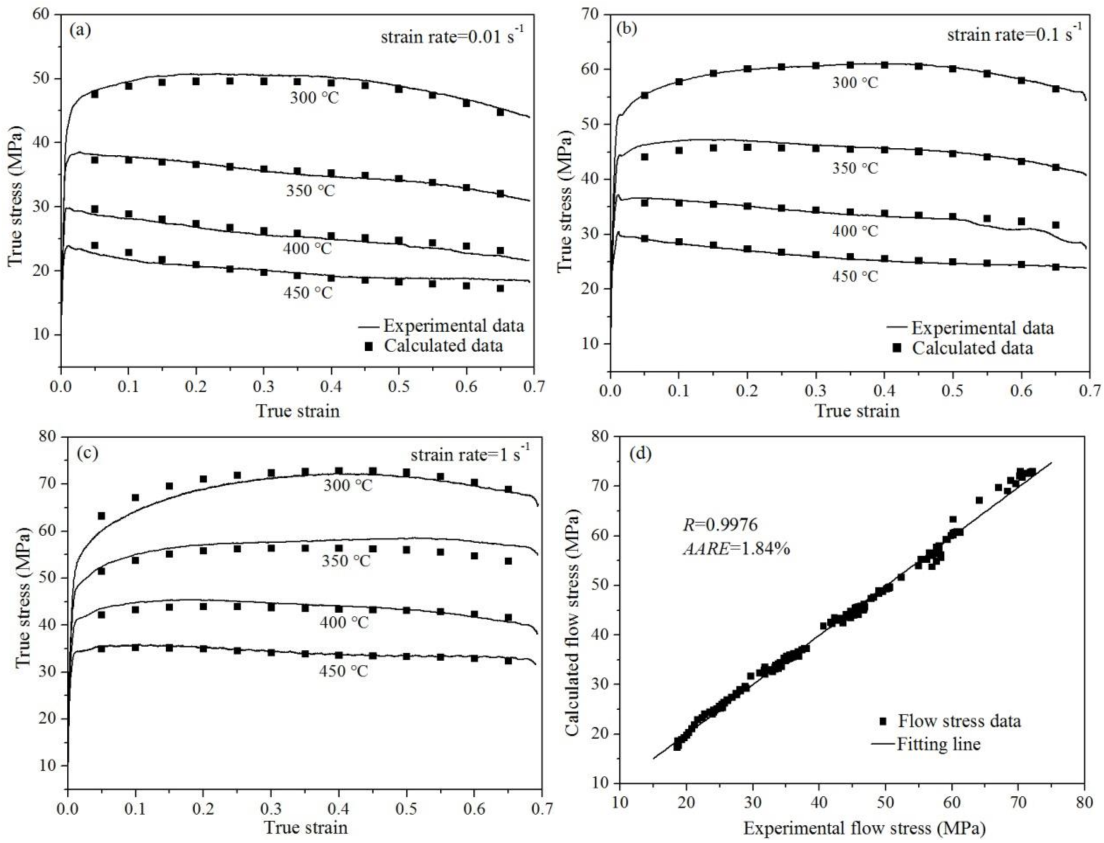


**Figure 4.** Comparisons between the measured and predicted flow stress of Cu/Al composite plate at strain rates of (a) 0.01 $s^{-1}$; (b) 0.1 $s^{-1}$; (c) 1 $s^{-1}$ and (d) the correlation between the experimental and calculated flow stress values

## 4. Conclusions

(1) During the isothermal compression, soft Al layer and hard Cu layer will coordinate each other. The flow stresses are related to deformation temperature, strain rate and composites structure, and increase with the increase of strain rate and decrease of deformation temperature.

(2) A constitutive model, comprehensively coupling flow stress with strain rate and deformation temperature, is developed based on the experimental results. Furthermore, a modified constitutive equation is proposed by incorporating the strain compensation in the equation parameters ($\alpha$, $n$, $Q$ and $A$).

(3) The calculated flow stress values, obtained from the modified constitutive equation, can match the experimental values very well. High correlation coefficient and low average absolute relative error show that the modified constitutive equation can accurately predict the deformation behavior of Cu/Al laminated composites.

## 5. **References**

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