An Investigation on Constitutive Model of Aluminum Alloy 2A12 by Isothermal Hot Compression

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Abstract. The plasticity flow behavior of 2A12 aluminum alloy under a wide range of temperatures ranging from 300°C to 450°C and strain rates ranging from 0.01s⁻¹ to 1s⁻¹ was studied by isothermal hot compression testing. The plastic behavior shows a peak stress in stress strain curve. At the beginning stage of deformation, the stress increases with strain rapidly, then flow stress decreases showing softening characteristics. The results show that the peak stress increases with the strain rate showing rate hardening, while decreases with the temperature showing heat softening. The strain flow stress curve was modeled by a novel function which consist an exponential and linear term with hardening coefficient, peak stress and softening modulus. The coupling effect of strain rate and temperature on the peak stress was studied by an Arrhenius-type equation. The effect of strain rate and temperature on hardening coefficient, peak stress and softening modulus was discussed and modeled by linear equations.

1. Introduction
The study on material plasticity behavior under hot temperature is basic knowledge for that a lot of structures are made by plastic deformation. The constitutive model is the basic relationship of stress with strain, while the relationship depends on the deformation condition such as strain rate and temperature. So, a lot of study on the plastic deformation behavior especially for metals has been made in the past decades [1]. Aluminum, copper, steel alloys are widely used in modern industry, some results have been reported in refs[2,3,4,5]. The novel researches in [2,3,5] proposed a novel type equation in which the relationship of flow stress with strain was established, which is concerned the deforming temperature and strain rates. In order to obtain the stress varying with strain, tension or compression test are widely used by Gleeble, MTS or other experimental setup. This method and model were employed to study the constitutive model of some alloys in [2,3,5]. In this paper, the flow behavior of aluminum alloy 2A12 under compression in a static temperature environment was studied by this model.

2. Experiments
2A12 aluminum alloy is widely used as structure material, which is a kind of age-hardening aluminum alloy. A series of 2A12 rolling bars with a diameter of 20 mm were bought from market. The sampled cylindrical specimen's diameter is 10 mm and the height is 15 mm. By Gleeble-3500 simulator, the compression tests was carried out in a static temperature environment by body heating and constant strain rate. The deformation conditions are temperatures $T=300, 350, 400, 450$°C and strain rates...
\[ \varepsilon = 0.01, \ 0.1, \ 1 \text{ s}^{-1}. \] The nominal strain \( \varepsilon_{\text{nom}} \) and stress \( \sigma_{\text{nom}} \) were recorded at experiments, and converted to true strain and true stress by Eq. (1, 2):

\[
\varepsilon_{\text{true}} = \ln \left( 1 + \varepsilon_{\text{nom}} \right) \\
\sigma_{\text{true}} = \sigma_{\text{nom}} \left( 1 + \varepsilon_{\text{nom}} \right)
\]

Fig. 1 shows the stress-strain results obtained by isothermal hot compression tests. The results show that the flow stress increased with strain rate to a peak stress at certain strain while decreased with temperature, showing hardening-peak-softening character.

![Stress-strain results](image)

Figure 1. The measured stress-strain curves for 2A12.

### 3. Constitutive model

According to the researches by Guo in ref\[2,3,5\], a series of equations containing peak stress, exceptional strain hardening term at early stage and following linear strain softening term were concluded below as Eq(3). Here, \( \alpha, A, n, Q, b, k_i, i = 0,1,2,3 \) are 12 material constants. In Eq(3), the study results by C. Zener and J.H. Hollomon was referenced.

\[
\sigma = \sigma_{\text{max}} \left( 1 - e^{-b \varepsilon} \right) - k \varepsilon \\
\sigma_{\text{max}} = \left( \frac{1}{\alpha} \right) \ln \left[ \left( \frac{Z}{A} \right)^{ln} + \left( \frac{Z}{A} \right)^{2ln} + 1 \right] \\
Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) \\
b = b_0 + b_i T + b_2 \ln \dot{\varepsilon} + b_i T \ln \dot{\varepsilon} \\
k = k_0 + k_i T + k_2 \ln \dot{\varepsilon} + k_i T \ln \dot{\varepsilon}
\]

\( \sigma \) is the flow stress, \( \varepsilon \) is the strain, \( \sigma_{\text{max}} \) is the peak flow stress, \( b \) is the strain hardening coefficient with respect to strain, \( k \) is the strain softening modulus with respect to strain, \( \dot{\varepsilon} \) is the strain rate, \( T \) is
the temperature, $Z$ is activation parameter, $R$ is the universal gas constant ($8.3145 \text{ J mol}^{-1}\text{K}^{-1}$), $Q$ is the activation energy ($\text{J mol}^{-1}$), $A$, $\alpha$, $n$ are the materials constants.

4. Results and discussion

4.1. Regress three parameters for testing conditions

The experimental data in Fig. 1 were used to fit three parameters as strain softening modulus $k$, strain hardening coefficient $b$ and peak flow stress $\sigma_{\text{max}}$ by nonlinear regressions. The fitted strain stress curves are illustrated in Fig. 2, comparing with the original results.

![Figure 2](image)

Figure 2. The fitted stress-strain curves for 2A12 at different temperatures and strain rates.

4.2 Effect of deformation conditions on parameters $b$ and $k$

The relation between strain hardening coefficient $b$, softening modulus $k$ with temperature $T$, strain rate $\dot{\varepsilon}$ can be plotted in Fig 3 and Fig 4, respectively. It can be seen that the effect of temperature and strain rate on $b$ and $k$ are nearly monotonous. As researches in ref[2,3,5], some basic phenomenon can be obtained. At a certain temperature, strain hardening coefficient $b$ decreased with strain rate. At a certain strain rate, strain hardening coefficient $b$ increased with temperature. While for a given temperature, softening modulus $k$ increased with strain rate. At a certain strain rate, softening modulus $k$ decreased with temperature. So that the comprehensive effect of temperature and strain rate on strain hardening coefficient $b$ and softening modulus $k$ can be treated as bi-linear. By nonlinear regression, the coefficients in Eq(3) can be obtained as $b_0 = 105$, $b_1 = 0.224$, $b_2 = 19.4$, $b_3 = -0.0365$, $k_0 = 400$, $k_1 = -0.530$, $k_2 = 9.21$, $k_3 = -0.0107$. 
Figure 3. Relationships between hardening coefficient \( b \), strain rate \( \dot{\varepsilon} \) and temperature \( T \).

Figure 4. Relationships between softening modulus \( k \), strain rate \( \dot{\varepsilon} \) and temperature \( T \).

4.3 Effect of temperature and strain rate on peak stress

As researches in ref[2,3,5], a whole calculation method calling linear regressions with multiple steps to obtain the coefficients in Eq(3) was thoroughly introduced. Here, this method is employed in this paper in order to obtain the correlation of the peak flow stress \( \sigma \) with temperature \( T \) and strain rate \( \dot{\varepsilon} \). In this paper, only the final results for these coefficients are given as \( \alpha = 0.00932 \), \( Q = 298 \text{ kJ} \cdot \text{mol}^{-1} \), \( A = 1.29 \times 10^{21} \text{ s}^{-1} \) and \( n = 7.31 \), respectively. In order to comparing the fitting results, the original flow stress and fitting flow stress are drawing in the same figure with deformation conditions such as temperature \( T \) and strain rate \( \dot{\varepsilon} \) as shown in Fig. 5. Comparisons for peak flow stress between experimental and predicted results of aluminum alloy 2A12 is shown in Fig. 6. A meaningful agreement can be find in Fig. 6.

Figure 5. Fitting results by constitutive model for peak flow stress \( \sigma_{\text{max}} \) varying with deformation conditions such as temperature \( T \) and strain rate \( \dot{\varepsilon} \).
4.4 Validation and discussions

By comparing the experimental and predicted stress strain results, the novel constitutive equations for 2A12 aluminum alloy was verified. The results are shown in Fig. 7. It can be seen that good agreement between predicted results and experimental results was achieved when deform temperatures are 300 °C, 400 °C and 450 °C, while when deform temperatures are 350 °C there are little differences. It can be concluded that novel function with 3 parameters can be used to describe the hardening-peak-softening character of 2A12 aluminum alloy.

5. Conclusion

The flow behavior of 2A12 aluminum alloy was studied by isothermal hot compression tests, in a wide range of temperatures ranging from 300 °C to 450 °C and strain rates ranging from 0.01 s\(^{-1}\) to 1 s\(^{-1}\). The conclusions are listed below.
1) The novel strain stress function with 3 parameters was used to describe the material hardening-peak-softening behavior. These 3 parameters are the strain hardening coefficient $b$, peak stress $\sigma_{\text{max}}$, and the strain softening $k$.

2) The effects of strain rate and temperature on hardening coefficient $b$ and softening modulus $k$ were analyzed empirically and regressed by multiple linear functions.

3) The effects of strain rate and temperature on peak flow stress was revealed by Arrhenius equation. By comparing the experimental results and predicted results, the novel constitutive equations was verified by and good agreement was achieved.

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