The study on plastic flow behavior and constitutive model of H96 brass alloy under compression

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Abstract. The plastic behavior of H96 brass alloy under a wide range of temperatures ranging from 20°C to 600°C and strain rates ranging from 0.01 s\(^{-1}\) to 6300 s\(^{-1}\) was studied by Gleeble-3500 simulator and split Hopkinson bar test. The results show that the flow stress increases with the strain and strain rate, while decreases with the temperature. The flow behavior is modeled by Johnson-Cook model and the parameters were obtained by regressions. The effect of strain rate and temperature on the flow stress was studied by modified JC model.

1. Introduction
The study on mechanical behavior of material is fundamental for applications. The constitutive model is the relationship of stress with strain, strain rate and temperature when material subjects loading and deforms. Therefore, a thoroughly investigation on the material deformation behavior under different temperatures and strain rates is necessary. So, great efforts have been made on the constitutive models in the past decades and reviewed in ref [1-4], especially at large deformation.

Johnson-Cook (JC) model[5] has been widely accepted constitutive models for metal or alloy under plastic deformation. The flow behavior of copper was studied and modeled in ref [6-8], while the deformation and fracture mechanism in tensile test were investigated in ref [9]. In ref [10], a research method was developed for high strength steels under median deformation rate. Since brass and their alloys are widely used in modern industrial applications due to its well plasticity and strength, but their constitutive models have rarely been reported[11]. H96 brass is widely used as projectile rotating band of large caliber gun. In this paper, the study on flow behavior and constitutive model of H96 brass under a wide range of temperature and strain rates was conducted, which is essential for manufacture and application of this material. The constants of JC models are obtained and verified, and the capability of models are discussed.

2. Experiments
H96 brass as rolled was selected. Two sizes of cylindrical specimens with a diameter of 5 mm and a height of 7.5 mm and 4 mm were sampled by electrical discharge machining, the sample with height 7.5 mm were prepared for carrying out low strain rate and the others for high strain rate test, respectively. The low strain rate tests or isothermal hot compression tests was carried out by Gleeble-3500 simulator, at temperatures T=20, 100, 200, 400, 600°C and strain rates are \(\dot{\varepsilon} = 0.01, 0.1, 1, 10\ s^{-1}\). While high strain rate tests was conducted by split Hopkinson bar tests with temperature control unit,
at temperatures \( T=20, 100, 200, 400, 600^\circ C \) and strain rates are \( \dot{\varepsilon} = 3000, 6300 \text{ s}^{-1} \). The H96 brass samples and test equipments are shown in figure 1.

![H96 brass samples and test equipments](image)

(1) Samples (2) Gleeble-3500 simulator (3) Hopkinson bar equipment

Figure 1. The H96 brass samples and test equipments.

The nominal strain \( \varepsilon_{\text{nom}} \) and stress \( \sigma_{\text{nom}} \) are record at experiments, and can be transforming to true strain and true stress by Eq. (1, 2):

\[
\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{nom}}) \tag{1}
\]

\[
\sigma_{\text{true}} = \sigma_{\text{nom}} (1 + \varepsilon_{\text{nom}}) \tag{2}
\]

Using Eq. (3) the plastic strain-true stress relation can be get, here \( E \) is the Young’s modulus:

\[
\varepsilon^p = \varepsilon_{\text{true}} - \sigma_{\text{true}} / E \tag{3}
\]

Figure 2 show the nominal stress strain curves obtained at different temperatures and strain rates. The results show that the flow stress increased with strain indicating strain hardening. It also represents that flow stress increased with strain rate and decreased with temperature at given strain.

![Nominal stress strain curves](image)

(a) \( \dot{\varepsilon} = 0.01 \text{ s}^{-1} \)  (b) \( \dot{\varepsilon} = 0.1 \text{ s}^{-1} \)

(c) \( \dot{\varepsilon} = 1 \text{ s}^{-1} \)  (d) \( \dot{\varepsilon} = 10 \text{ s}^{-1} \)
Constitutive model is the relation of the von Mises flow stress $\sigma$ varying with strain $\varepsilon$, strain rate $\dot{\varepsilon}$, and temperature $T$, which can be written as Eq(4):

$$\sigma = f(\varepsilon, \dot{\varepsilon}, T)$$  \hspace{1cm} (4)

JC model was proposed by Johnson and Cook [5], which is empirical and can be written as Eq. (5):

$$\sigma_r = \left( A + B\dot{\varepsilon}^n \right) \left( 1 + C \ln \dot{\varepsilon}^s \right) \left( 1 - T^* \right)$$  \hspace{1cm} (5)

Here, $A, B, n, C, m$ are five material constants, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic strain rate, $\dot{\varepsilon}_0$ is the reference strain rate, usually taken as $1 \text{ s}^{-1}$, $T^* = (T - T_r)/(T_m - T_r)$ is the homologous temperature, $T_r$ is the room temperature, $T_m$ is the melt temperature. The strain rate term in JC model can be replaced by a Cowper-Symonds form [10], as a modified JC model:

$$\sigma_r = \left( A + B\dot{\varepsilon}^n \right) \left( 1 + \left( \frac{\dot{\varepsilon}^*}{C} \right)^{1/p} \right) \left( 1 - T^* \right)$$  \hspace{1cm} (6)

Here, $A, B, n, C, m, p$ are six material constants.

3. Results and discussion

3.1. Regress model constants

By nonlinear regression, the material constants are obtained as following:

a) For JC model

$A = 154.5 \text{ MPa}, B = 355.0 \text{ MPa}, n = 0.4515, C = 0.0765, m = 1.125, \dot{\varepsilon} = 14.47 \text{ s}^{-1}.$

b) For modified JC model

$A = 60.4 \text{ MPa}, B = 330.5 \text{ MPa}, n = 0.311, C = 2.84 \times 10^4 \text{ s}^{-1}, m = 1.152, p = 3.3546.$

3.2. Predicted results

The validity of the two constitutive equations for H96 brass, comparisons between the experimental and predicted flow stress were carried out as shown in figure 2-4. The agreements between predicted and experimental results were analyzed by the coefficient, shows that the modified JC model with a Cowper-Symonds term is more suitable for H96 brass.
Figure 3. Comparisons between experimental and predicted results of H96 brass by JC model.
3.3. Discussion
The effects of strain rate on the flow stress under given temperatures and strain was concluded as figure 5(a)(b). The flow stress increases with strain rate and decreases with temperature at given strain. It shows that the flow stress increases with strain rate and slope also increases. So, the Cowper-Symonds term is more suitable to describe the strain rate sensitivity for H96 brass alloy, and higher coefficient (0.9615) was obtained by this modified model as figure 5(c)(d).
Figure 5. The influence of strain rate upon flow stress at given temperatures and strain $\varepsilon = 0.45$
(a) JC model, (b) Modified JC model. Correlations by (c) JC model and (d) Modified JC model.

4. Conclusion
The compression tests of H96 brass, in a wide range of temperatures ranging from 20 $^\circ$C to 600 $^\circ$C and strain rates ranging from 0.01s$^{-1}$ to 6300s$^{-1}$ were employed to study its flow behavior. The conclusions are listed as following:
1) The experimental results show that the flow stress increased with strain indicating strain hardening. The flow stress increased with strain rate and decreased with temperature at given strain.
2) The material constants of two constitutive models are obtained by regression. The related coefficients are obtained and the results show that the modified JC model with a Cowper-Symonds term is more suitable for H96 brass.
3) The effects of strain rate and temperature on the flow stress were analyzed and the results show that the Cowper-Symonds term is more suitable for H96 brass. The validity of the constitutive equations was verified by comparing the experimental results and predicted results, and good agreement was achieved.

References
[1] Junhang Guo, S. D. Zhao and G. H. Yan. 2013 Materials Science and Technology. 29 197-203
[2] Junhang Guo, Shengdun Zhao and Ri-ichi Murakami. 2013 Journal of Alloys and Compounds. 566 62–7
[3] Junhang Guo, Shengdun Zhao and Ri-ichi Murakami. 2013 Computational Materials Science. 71 115–23
[4] Junhang Guo, Li, Y. and Ding, H. 2015 6th International Conference on Manufacturing Science and Engineering
[5] G. R. Johnson and W. H. Cook, 1985 Eng. Fract. Mech 21 31–48
[6] F.H. Abed and G.Z. 2005 Voyiadjis, Acta Mech. 175 1–18
[7] P.S. Follansbee and U.F. Kocks 1988 Acta Met 36(1) 81–93
[8] A. Ghahremaninezhad and K. Ravi-Chandar, 2011 International Journal of Solids and Structures 48 3299–311
[9] B.L. Boyce and M.F. Dilmore 2009 International Journal of Impact Engineering 36 263–71
[10] G. Cowper and P.S. Symonds, 1957 Division of Applied Mathematics, Brown University 28
[11] Zhou, P., Guo, W.G. and Wu, H.H. 2015 Applied Mechanics and Materials 782 130–36