International Journal of Impact Engineering 79 (2015) 65–74

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Comparison of constitutive models for FCC metals over wide temperature and strain rate ranges with application to pure copper

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ARTICLE INFO

Article history:
Available online 22 October 2014

Keywords:
Constitutive models
Plastic behavior characterization
Work-hardening
Thermal-softening
Strain rate effect

ABSTRACT

Applicabilities of several well-known constitutive models for BCC metals have been reviewed in detail previously (Modelling Simul. Mater. Sci. Eng. 20 (2012) 015005; Acta Mech. Solid. Sin. 2012, 25(6): 598–608; Int. J. Plasticity, 2013, 40: 163–184). In this paper, descriptive and predictive capabilities of the same models for FCC metals are investigated and compared systematically, in characterizing plastic behavior of cold-worked pure copper at temperatures ranging from 93 K to 873 K, and strain rates ranging from 0.001 s^{-1} to 8000 s^{-1}. Validities of the established models are checked by strain rate jump tests that were performed under different loading conditions. Flexibilities of the models in describing the effects of work hardening, temperature, and strain rate are also analyzed separately. The results show that these models have various capabilities in the characterization of different aspects of material behaviors, but the precision of prediction relies largely on that of description. Different models should be selected considering the specific details of material behaviors to obtain better performance in the engineering application.

1. Introduction

The plastic behaviors of materials under extreme loading conditions have attracted intensive studies in recent years due to engineering applications in the fields of automotive, aerospace, and military industries. In the deformation process of materials subjected to crash, impact, or explosion, strain, strain rate, and temperature change significantly. In order to describe precisely the thermo-viscoplastic behaviors of metals, an adequate constitutive model is highly desirable that accounts for complex paths of deformation, temperature, and strain rate. With the improvement of experimental techniques and the better understanding of material responses, many state-of-the-art constitutive models have been developed nowadays, which mainly comprise two groups: phenomenological [1–8] and physically based ones [9–23]. For the both groups of models, the simplicity in determination of material constants and the accuracy in material behavior characterization are two crucial determinants of their applicabilities.

In our previous work, the performance of several well-known phenomenological and physically based constitutive models were investigated systematically in their description and prediction of the flow stress for BCC steel [24,25] and WBC [26]. For FCC metals, however, studies regarding comparison of the descriptive and predictive capabilities between different constitutive models are few, and the applicabilities of these models over wide ranges of temperatures and strain rates are not clear due to the diversity of fundamental experimental data. Crystal FCC and BCC structures have much difference in the dependence of strain hardening on strain rate and temperature, and hence many models have different forms for the both structures. In most BCC metals, overcoming Peierls stress resistance is the main phenomenon involved in thermally activated processes [27]. Therefore, the yield stress shows strong dependence on the strain rate and temperature, while the strain hardening is less sensitive to them. In physically based constitutive models for BCC metals, the thermal component of the flow stress is often defined independent of plastic strain. In the case of FCC metals, however, the main rate-controlling mechanism is the overcoming of dislocation forests by individual dislocations; hence strain hardening is strongly dependent on the strain rate and temperature, and the thermal component of the flow stress can be defined as a function of plastic strain. Besides being mathematically and computationally accurate, a successful constitutive model should be able to capture the important aspects of the material behaviors from a limited set of experimental data [20]. For improvement and engineering application of the proposed constitutive models, systematic comparison of them is significant.

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http://dx.doi.org/10.1016/j.ijimpeng.2014.10.003
0734-743X/

The objective of this paper is to study the descriptive and predictive capabilities of the same constitutive models as our previous work [24–26] for FCC metals, with application to cold-worked pure copper over wide temperature and strain rate ranges.

First, uniaxial compressive flow stress of cold-worked pure copper was measured under quasi-static (0.001 s^{-1} and 1 s^{-1}) and dynamic (500 s^{-1}, 3500 s^{-1}, and 8000 s^{-1}) loading conditions, using an MTS servo hydraulic testing machine and the split Hopkinson pressure bar (SHPB) technique, respectively. In quasi-static tests, five temperatures (93 K, 288 K, 473 K, 673 K, and 873 K) were selected for each strain rate; for dynamic tests, four initial temperatures were adopted (288 K, 473 K, 673 K, and 873 K). The samples have a right-cylindrical geometry 6 mm in diameter and 9 mm in height for quasi-static tests; in dynamic tests, the samples are 5 mm in diameter and 4 mm long. The size effect of the samples on the flow stress due to different geometries was not considered in this study. Second, based on the experimental data, two phenomenological (JC [2] and KHL [8]) and five physically based constitutive models (PB [17,28–30], NNL [19], ZA [11], VA [20], and MRK [31]) were established; capabilities of the constitutive models in describing the fundamental experimental data were measured and compared. Then, strain rate jump tests were conducted, and the prediction errors of the models were obtained for the tests to assess the accuracy of each model. The performance of the models in description of work-hardening, temperature, and strain rate effects was also analyzed systematically. In the determination of the material constants, the starting values were first evaluated by physical definition or fitting of the experimental data, and then a constrained optimization procedure was conducted iteratively to minimize the errors between the experimental results and the model prediction. As the detailed procedures of parameter calibration have been introduced previously [25], here the constitutive models will be addressed briefly and the determined material constants will be given directly for each model.

2. Establishment of constitutive models

2.1. JC model [2]

In the JC model, the von Mises flow stress σ is expressed as

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \tag{1}$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic strain rate for $\dot{\varepsilon}_0 = 1\ s^{-1}$, and $T^* = (T - T_r)/(T_m - T_r)$ is the homologous temperature, in which T is the absolute temperature, T_r (=93 K) is the reference temperature, and T_m (=1356 K) is the melting temperature of the material. The five material constants are A, B, n, C, and m. Transition from isothermal to adiabatic conditions is assumed at 10 s^{-1} [31]. The adiabatic temperature rise ΔT is calculated for dynamic tests by

$$\Delta T = \frac{\eta}{\rho C_p}\int \sigma d\varepsilon \tag{2}$$

where ρ is the mass density (8.96 g/cm^3), C_p is the heat capacity (0.383 J/g K), and η is the fraction of plastic work converted into heat. Different values have been used for η in previous studies [16,30–32]. Here η is taken to be 1. The softening in flow stress induced by ΔT is compensated in the optimizing procedure. Accordingly, the calculated flow stress by the obtained model under dynamic loading are converted back to adiabatic condition. Table 1 gives the final values of these parameters after optimization. Comparison of experimental data and JC model description is shown in Fig. 1, for quasi-static and dynamic conditions respectively.

Table 1
Determined values of the JC model parameters.

A (MPa)	B (MPa)	n	C	m
352.1	267.5	0.5299	0.0318	0.6814

2.2. KHL model [8]

In the KHL model, the von Mises equivalent stress is expressed as

$$\sigma = \left[A + B\left(1 - \frac{\ln\dot{\varepsilon}}{\ln D_0}\right)^{n_1}\varepsilon^{n_0}\right]\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^*}\right)^C\left(\frac{T_m - T}{T_m - T_r}\right)^m \tag{3}$$

where $\dot{\varepsilon}^*$ (=1 s^{-1}) is the reference strain rate, and D_0 (=10^6 s^{-1}) is the arbitrarily chosen upper bound strain rate. A, B, n_1, n_0, C, and m are material constants, and the other parameters have the same definition as the JC model. The determined values of the six material constants are shown in Table 2. Fig. 2 shows comparison of experimental data and KHL model description for different loading conditions.

2.3. PB model [17,28–30]

In this model, the flow stress is defined by

$$\sigma = \sigma_a + \sigma^* \tag{4}$$

where σ_a and σ^* represent the athermal and thermally activated parts of the flow stress, respectively.

The stress σ^* is expressed as

$$\sigma^* = \hat{\sigma}\left[1 - \left(-\frac{kT}{G_0}\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1/q}\right]^{1/p} \quad \text{for } T \le T_c \tag{5}$$

where $\hat{\sigma}$ is the threshold stress above which the barrier is overcome without any aid from thermal activation, and $\dot{\varepsilon}_0$ can be seen as a reference strain rate which characterizes the strain rate sensitivity. The parameter k/G_0 represents the temperature sensitivity of the material. The critical temperature T_c, is given by

$$T_c = -\frac{G_0}{k\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)} \tag{6}$$

with $\sigma^* = 0$ for $T > T_c$. The values of p and q in Eq. (5) are defined with $0 < p \le 1$ and $1 \le q \le 2$. In this study, we choose $p = 0.5$ and $q = 1.5$ for the PB model. The same values are also used in NNL and VA models.

The athermal stress σ_a is usually expressed by a power law approximation

$$\sigma_a = a\varepsilon^n \tag{7}$$

where ε is plastic strain, a is the material constant fitting the stress level, and n is the strain hardening exponent, which is also assumed to be constant in this formulation.

Thus, in PB model, the flow stress is given by

$$\sigma = \sigma_a + \sigma^* = a\varepsilon^n + \hat{\sigma}\left[1 - \left(-\frac{kT}{G_0}\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1/q}\right]^{1/p} \tag{8}$$