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A new temperature and strain rate dependent yielding model for iron-based body-centered-cubic metallic materials

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A B S T R A C T

In this paper, a new yielding model integrating temperature and strain rate for iron-based body-centered-cubic metallic materials is developed based on a decoupled modeling idea. The model is verified under different temperatures and strain rates by comparison with experimental data of different iron-based body-centered-cubic metallic materials. Comparisons between this yielding model and Johnson-Cook yielding model are made as well. The predicted results have an excellent consistency with experimental results, and our model could well character yield strength than Johnson-Cook yielding model. Besides, it should be noteworthy that there is only one fitting parameter in our model, while Johnson-Cook yielding model contains three fitting parameters which make it difficult to apply.

1. Introduction

Body-centered-cubic (BCC) metallic materials and alloys mainly presenting BCC structure characteristics always get the attention of researchers owing to their good performances, such as high melting point, good thermal conductivity, high fracture toughness, high strength, good corrosion resistance and weld ability [1]. In practical engineering, especially aeronautics and astronautics, there is no doubt that BCC metallic materials are often inevitable to work in extreme conditions [1,2], for instance, low temperature, radiation, high temperature, high strain rates and repeated thermal impact process etc. Under these circumstances, most of metallic components would experience a deformation process from elastic to plastic flow, and the temperature has a significant influence on the mechanical properties of BCC metallic materials. Therefore, the yield strength of BCC metallic materials under high temperatures or low temperatures is eagerly demand.

Over the past decades, the studies on BCC metallic materials have received a great deal of attention [1–14]. Some studies have showed the effect of ambient temperature, strain rate, and microstructure on their high-temperature yield strength by means of experiment [4–6,9,10]. Large of research results [7,8,11–14] prove that the yield strength of BCC metallic materials is not only temperature but also strain rate dependent. Other close-packed metallic materials, with face-centered-cubic and hexagonal-close-packed crystal structure, do not share these characteristics. The strong temperature and strain rate dependent yield strength results from the thermally activated motion of screw dislocations [1,2,15–18]. The theoretical models have also been developed for metallic materials, such as Johnson-Cook (JC) [3], Zerilli-Armstrong (ZA) [4,5] and Mechanical Threshold Stress (MTS) model [6]. Three classical models are more applicable reasonably well to a number of different materials with different crystal structures. However, these theoretical models are established based on the independence of temperature, strain rate and strain, resulting in a large number of fitting factors, which makes it inconvenient to apply. Besides, the yield strength of BCC metallic materials is influenced by the coupled effect of temperature and strain rate in most cases [12–17], these models could not describe the coupled effect on yield strength of BCC metallic materials. Moreover, much later work [13–15] according to the three models usually needs to introduce some modified parameters to original models. Therefore,

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establishing a yield strength model capable of considering the coupled effect of temperature and strain rate, at the same time, consisting of less fitting parameters, is very important and necessary.

In this study, through a decoupled modeling idea, a new temperature and strain rate dependent yielding model for iron-based BCC metallic materials is developed on the basis of temperature dependent yield strength model [18]. A quantitative relationship of the yield strength, temperature, strain rate, Young's modulus, Poisson's ratio and the specific heat capacity at constant pressure is established. The model expresses the coupled effect of strain rate and temperature on yield strength. The predictions are presented for some iron-based BCC metallic materials, which agree very well with the experimental data. Comparisons between our model and JC yielding model are also presented to analyze the superiority of our model.

2. Theoretical model

As an important index of evaluating metallic material mechanics properties, the yield strength of BCC metallic materials is affected by a number of factors, such as temperature, strain rate and stress state etc. When the strain rate is greater than $10^2\ s^{-1}$, the strain rate sensitivity is evident [19]. Particularly, the coupled effect of temperature and strain rate on yield strength makes it difficult to have a description theoretically.

In our previous work, a temperature dependent yield strength model for metallic materials is developed by our research group, which could be expressed as Eq. (1) [18].

$$\sigma(T) = \left[\frac{(1+\mu_{T_0})E_T}{(1+\mu_T)E_{T_0}}\left(1-\frac{\int_{T_0}^{T} C_p(T)dT}{\int_{T_0}^{T_m} C_p(T)dT}\right)\right]^{0.5} \sigma(T_0) \tag{1}$$

in the Eq. (1), $\sigma(T)$ is the temperature dependent yield strength and $\sigma(T_0)$ is yield strength at reference temperatureT_0. E_T and μ_T are the Young's modulus and Poisson's ratio respectively at temperature T. E_{T0} and μ_{T0} are Young's modulus and the Poisson's ratio at reference temperature T_0. C_P is the specific heat capacity for constant pressure. T_m is the melting point of metallic materials.

In this work, on the basis of temperature dependent yield strength model proposed above [18], the strain rate effect is taken into consideration through a decoupled modeling method. A new yielding model integrating temperature and strain rate for iron-based BCC metallic materials is developed according to the decoupled modeling idea in Eq. (2), $\sigma(T,\dot{\varepsilon}_0)$ is the temperature dependent yield strength under static or quasi static, which is equivalent to $\sigma(T)$, and it should be pointed out that the static strain rate $\dot{\varepsilon}_0$ is less than $10^{-2}\ s^{-1}$ [17]. $\sigma(T_0,\dot{\varepsilon})$ is the strain rate dependent yield strength with respect to reference temperature, which can be equivalent to $\sigma(\dot{\varepsilon})$. And $\sigma(T_0,\dot{\varepsilon}_0)$ is the yield strength at the static state and reference temperature. The term $\sigma(T,\dot{\varepsilon}_0)$ describes the effect of temperature on the yield strength, and the term $\sigma(T_0,\dot{\varepsilon})/\sigma(T_0,\dot{\varepsilon}_0)$ characterizes the effect of the strain rate on the yield strength. The term $\sigma(T,\dot{\varepsilon}_0)\sigma(T_0,\dot{\varepsilon})/\sigma(T_0,\dot{\varepsilon}_0)$ is used to describe the impact of temperature and strain rate on yield strength. Through the detailed analysis to experimental results [12–14], we found it is inadequate to character the coupled impact of temperature and strain rate in the form of $\sigma(T,\dot{\varepsilon}_0)\sigma(T_0,\dot{\varepsilon})/\sigma(T_0,\dot{\varepsilon}_0)$. With the inspiration coming from the Arrhenius Equation [16,19], we believes that the coupled effect of temperature and strain rate could describe not only by temperature but also strain rate separately. Here, the item $[1-\alpha(T-T_0)/(T_m-T_0)]$ is added to characterize the influence of temperature on coupled effect of temperature and strain rate.

$$\sigma_y(T,\dot{\varepsilon}) = \frac{\sigma(T,\dot{\varepsilon}_0)\cdot\sigma(T_0,\dot{\varepsilon})}{\sigma(T_0,\dot{\varepsilon}_0)}\left(1-\alpha\frac{T-T_0}{T_m-T_0}\right) \tag{2}$$

Substituting (Eq. (1)) into (Eq. (2)), the explicit expression of theoretical model could be expressed as follows:

$$\sigma_y(T,\dot{\varepsilon}) = \left[\frac{(1+\mu_{T_0})E_T}{(1+\mu_T)E_{T_0}}\left(1-\frac{\int_{T_0}^{T} C_p(T)dT}{\int_{T_0}^{T_m} C_p(T)dT}\right)\right]^{0.5}\left(1-\alpha\frac{T-T_0}{T_m-T_0}\right)\sigma(T_0,\dot{\varepsilon}) \tag{3}$$

where $\sigma_y(T,\dot{\varepsilon})$ is the yield strength at arbitrary temperature and strain rate. $\sigma_y(T_0,\dot{\varepsilon})$ is the strain rate dependent yield strength at reference temperatureT_0. α is a material constant characterising the strain rate sensitivity. In static or quasi static, the strain rate sensitivity is not obvious and the coupled effect can be ignored. α is equivalent to zero, the temperature and strain rate dependent yielding model degrades into the temperature dependent yield strength model in this case. The material constant α is independent with temperature and could be obtained by fitting easily when the strain rate is higher than $10^2\ s^{-1}$.

In our model, the heat capacity $C_P(T)$ can easily be found in any material handbooks [20], and the Young's modulus under different temperatures could also be obtained through experiment. The only material constant α could be fitted based on the Eq. (3) with the experimental data at arbitrary reference temperature.

3. Results and discussions

Based on the theoretical model above, the temperature and strain rate dependent yield strength of some iron-based BCC metallic materials (pure iron [12], 40Cr steel [13], hardened 45 steel [14]) are predicted. In the calculations, the influence of temperature on the Poisson's ratio is ignored due to its weak dependence of temperature [18]. Comparisons are made between the modeling calculation results and experiment results. A contrast is made between our model and the existing JC yielding model as well. The corresponding results and discussions are as follows:

The temperature dependent Young's modulus E_T of pure iron could be seen in the literature [21]. Reference temperature T_0 was set as 20 °C. The melting point T_m was 1809 K, and specific heat capacity $C_P(T)$ at constant pressure for pure iron could be found in material handbooks [20]. The strain rate dependent yield strength $\sigma_y(T_0,\dot{\varepsilon})$ under reference temperature were 527 MPa, 590 MPa and 630 MPa [12]. The material constant α of pure iron was 1.68.

As shown in Fig. 1, the temperature and strain rate dependent yield strength of pure iron are calculated. Good agreements could be found between the modeling calculations and experimental data, and the yield strength trend with strain rate is characterized admirably. Meanwhile, the theoretical yield strength values of different strain rates under 100 °C and 200 °C are predicted. We believe it would be agreed with experiment.

Temperature dependent Young's modulus E_T for 40Cr steel was taken from experiment [22]. Reference temperature T_0 was set as 20 °C. The melting point T_m was 1809 K, and specific heat capacity $C_p(T)$ for constant pressure was replaced by the specific heat capacity of iron [20]. The reference strength $\sigma_y(T_0,\dot{\varepsilon})$ for different strain rates were 1237 MPa, 1337 MPa and 1490 MPa [13]. The constantα related to the material was 0.39.