Constitutive modeling and prediction of hot deformation flow stress under dynamic recrystallization conditions

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ARTICLE INFO

ABSTRACT

Simple modeling approaches based on the Hollomon equation, the Johnson–Cook equation, and the Arrhenius constitutive equation with strain-dependent material's constants were used for modeling and prediction of flow stress for the single-peak dynamic recrystallization (DRX) flow curves of a stainless steel alloy. It was shown that the representation of a master normalized stress–normalized strain flow curve by simple constitutive analysis is successful in modeling of high temperature flow curves, in which the coupled effect of temperature and strain rate in the form of the Zener–Hollomon parameter is considered through incorporation of the peak stress and the peak strain into the formula. Moreover, the Johnson–Cook equation failed to appropriately predict the hot flow stress, which was ascribed to its inability in representation of both strain hardening and work softening stages and also to its completely uncoupled nature, i.e. dealing separately with the strain, strain rate, and temperature effects. It was also shown that the change in the microstructure of the material at a given strain for different deformation conditions during high-temperature deformation is responsible for the failure of the conventional strain compensation approach that is based on the Arrhenius equation. Subsequently, a simplified approach was proposed, in which by correct implementation of the hyperbolic sine law, significantly better consistency with the experiments were obtained. Moreover, good prediction abilities were achieved by implementation of a proposed physically-based approach for strain compensation, which accounts for the dependence of Young's modulus and the self-diffusion coefficient on temperature and sets the theoretical values in Garofalo's type constitutive equation based on the operating deformation mechanism. It was concluded that for flow stress modeling by the strain compensation techniques, the deformation activation energy should not be considered as a function of strain.

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1. Introduction

Since the computer simulation of metal forming processes is used increasingly in the industry, a proper flow stress description is the preliminary requirement (Gronostajski, 2000). This is especially the case for hot forming processes, which are usually more complex in terms of occurrence of additional microstructural phenomena such as dynamic recrystallization (DRX). Poliak and Jonas (1996) and Mirzadeh and Najafizadeh (2010a) have studied the critical conditions for initiation of DRX. Hot working is an important step in production of materials with required shape, microstructure, and mechanical properties. Therefore, a proper understanding of the microstructural evolution during hot deformation and characterizing the constitutive behavior describing material flow are inevitable (McQueen and Ryan, 2002).

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As a result, considerable research has been carried out to model the flow stress of metals and alloys. Liang and Khan (1999) have reviewed the constitutive models for BCC and FCC metals over a wide range of strain rates and temperatures. Mirzadeh et al. (2011a) have proposed a simple physically-based approach for constitutive analysis in hot working as an alternative for the conventional apparent approach. Lin and Chen (2011) have published a review paper on the constitutive descriptions for metals and alloys in hot working. Mirzadeh et al. (2012) have critically discussed the efficiency of artificial neural network, Arrhenius equation, and a proposed formula in prediction of DRX flow curves. Bhattacharya et al. (2014) have developed some constitutive equations for AZ31 alloy under DRX conditions. Huh et al. (2014) have evaluated the dynamic hardening models of metallic materials for various crystalline structures. Finally, Mirzadeh (2014) has developed a useful approach for comparative hot working and alloy development studies based on constitutive analysis. Generally speaking, the accuracy of a model depends on both the mathematical structure of the model and the proper experimental determination of the material parameters used in the model (Gronostajski, 2000).

A constitutive relationship is a mathematical representation of flow stress of the material as a function of deformation temperature, strain rate, strain, and other factors. A useful form of the constitutive equations can be expressed as $\sigma = f(T, \dot{\varepsilon}, \varepsilon)$. Based on the work of Zener and Hollomon (1944), the coupled effect of temperature and strain rate is incorporated in a temperature-compensated strain rate parameter of the form $Z = \dot{\varepsilon} \exp(Q/RT)$. The basic approach for the modeling of flow stress is the implementation of the classical Hollomon equation by Eq. (1) (Hollomon, 1945) and Ludwik equation by Eq. (2) (Ludwik, 1909):

$$\sigma = K\varepsilon^n \tag{1}$$

$$\sigma = \sigma_0 + K\varepsilon_{plastic}^n \tag{2}$$

where n is called the work-hardening coefficient, K is the stress coefficient, σ_0 is the yield stress, ε is the true total strain and $\varepsilon_{plastic}$ is the true plastic strain. This response is usually called parabolic hardening (Meyers and Chawla, 2009). Obviously, the effects of temperature and strain rate on work hardening and stress level should be incorporated in n and K (Sheng and Shivpuri, 2006) or should be incorporated by adding additional terms (Takuda et al., 2005). A famous form of the latter approach by consideration of the effect of strain-rate hardening has been proposed by Fields and Backofen (1957) in the form $\sigma = K\varepsilon^n \dot{\varepsilon}^m$, where m is known as the strain rate sensitivity. However, the most common form of the latter approach has been proposed by Johnson and Cook (1983) as shown below:

$$\sigma = \left(\sigma_{0r} + K\varepsilon_{plastic}^n\right) \times \left(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_r}\right)$$
$$\times \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^q\right) \tag{3}$$

where $\dot{\varepsilon}_r$ and T_r, T_m, and σ_{0r} are the reference strain rate, reference temperature, the melting point of the material, and the yield stress at reference temperature and strain rate, respectively (Milani et al., 2009). In the Johnson–Cook equation, the three groups of terms in parentheses represent work-hardening (based on the constant n), strain rate (based on the constant C), and thermal (based on the constant q) effects, respectively. It should be noted that the flow softening resulted from the occurrence of DRX has not been considered in simple expressions of Eqs. (1)–(3).

Sellars and McTegart (1966) have proposed another widely applied method in the literature for constitutive analysis, which is based on the expressions which relate Z to the flow stress as shown in Eq. (4). In this equation, Q is the hot deformation activation energy, $\dot{\varepsilon}$ is the strain rate, T is the absolute temperature, and finally A', A'', A, n', β, n, and α are the material's parameters. The power law is preferred for relatively low stresses. Conversely, the exponential law is suitable for high stresses. Finally, the hyperbolic sine law can be used for a wide range of Z parameters. The stress multiplier α is an adjustable constant which brings $\alpha\sigma$ into the correct range that gives linear and parallel lines in $\ln\dot{\varepsilon}$ versus $\ln\{\sinh(\alpha\sigma)\}$ plots and it can be estimated by $\alpha \approx \beta/n'$ (Mirzadeh, 2015a).

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = \begin{cases} A'\sigma^{n'} \\ A'' \exp(\beta\sigma) \\ A[\sinh(\alpha\sigma)]^n \end{cases} \tag{4}$$

Conventionally, the material's parameters are considered to be apparent ones, which makes it impractical to conduct the comparative studies to elucidate the effects of alloying elements (Mirzadeh, 2014) or second phases (Mirzadeh, 2015b). Recently, Mirzadeh et al. (2011a) showed that when the deformation mechanism is controlled by the glide and climb of dislocations, a constant hyperbolic sine power of $n = 5$ and self diffusion activation energy (Q_{sd}) can be used to describe the appropriate stress. This is possible by taking into account the dependences of Young's modulus (E) and self-diffusion coefficient (D) on temperature in the hyperbolic sine law. Accordingly, the unified relation can be expressed as $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^5$. In this equation, $D = D_0 \exp(-Q_{sd}/RT)$, where D_0 is a pre-exponential constant. The constants α' and B are the modified stress multiplier and the modified hyperbolic sine constant, respectively. The consideration of hyperbolic sine power of 5 and self diffusion activation energy gives a physical and metallurgical meaning to this equation and also reduces the number of unknown parameters and constant to 2 (α' and B). However, Mirzadeh et al. (2011a) showed that the occurrence of dynamic recrystallization (DRX) generally exerts an influence on the value of n. Therefore, the unified physically-based relation in its general form can be expressed as $\dot{\varepsilon}/D = B[\sinh(\alpha'\sigma/E)]^n$ and the physically-based equations based on the power, exponential, and hyperbolic sine laws can be summarized as follows:

$$\dot{\varepsilon}/D = \begin{cases} B'(\sigma/E)^{n'} \\ B'' \exp(\beta'\sigma/E) \\ B[\sinh(\alpha'\sigma/E)]^n \end{cases} \tag{5}$$

In these expressions, B', B'', B, n', β', n, and α' are the material's parameters. In Eqs. (4) and (5), the flow stress