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Tensile stress−strain behavior of metallic alloys

Jun CAO, Fu-guo LI, Xin-kai MA, Zhan-kun SUN

State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China

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Abstract: Tensile stress−strain curves of five metallic alloys, i.e., SKH51, STS316L, Ti−6Al−4V, Al6061 and Inconel600 were analyzed to investigate the working hardening behavior. The constitutive parameters of three constitutive equations, i.e., the Hollomon, Swift and Voce equations, were compared by using different methods. A new working hardening parameter was proposed to characterize the working hardening behavior in different deformation stages. It is found that Voce equation is suitable to describe stress−strain curves in large strain region. Meanwhile, the predicting accuracy of ultimate tensile strength by Voce equation is the best. The working hardening behavior of SKH51 is different from the other four metallic alloys.

Key words: constitutive equation; tensile stress−strain behavior; piecewise fitting; coordinate transformation

1 Introduction

It is significant to predict plastic deformation in describing stress−stain curve by using constitutive equation. Furthermore, applying appropriate constitutive equation is especially important to predict tensile properties and to access structural integrity during service [1]. Classical constitutive equations include Hollomon [2], Voce [3], Ludwigson [4] equations and so on. More recently, a "H/V" hardening model [5] was introduced, which combined Hollomon and Voce forms by a linear weight temperature-dependent factor. Many researchers [6−9] took strain rate and temperature into account to study constitutive equations of metallic alloys. Power-law type constitutive equations are more suitable for describing tensile stress−strain curves of body-centered cubic (BCC) metals [5]. Exponential-type constitutive equations are suitable for describing tensile stress−strain curves of most face centered cubic (FCC) metals at room temperature [10]. All classical constitutive equations failed to describe working hardening behavior accurately in two distinct stages, and then a piecewise Ramberg−Osgood equation was proposed [11]. SAMUEL [12] revealed the limitations of Hollomon and Ludwigson equations in assessing strain hardening parameters of stainless steel, aluminum, pure nickel, etc. SAINATH et al [13] studied the applicability of Voce equation in describing tensile working hardening behavior of P92. As the characteristics of working hardening behavior vary during plastic deformation of some materials, empirical and phenomenological constitutive equations may not describe stress−strain curves well.

Efforts were made to study the nature of working hardening behavior [14,15] in plastic deformation. In the course of plastic deformation of a metal, dislocations always move simultaneously and some of them compete with each other. Therefore, dislocations motion is the physical nature of working hardening. MONTEIRO and REED-HILL [16] investigated the two deformation stages in stress−strain curve of pure titanium, and concluded that the growth of uniform dislocation distribution and cell structure formation are responsible for the two deformation stages, respectively. Due to a more complex post-yield behavior, simplified empirical equations cannot precisely describe the stress−strain curve. However, UGent models can successfully describe it by using piecewise fitting [17]. In plain carbon steels, the *n* value depends only on the interparticle spacing of cementite, which is related to two parameters, the volume fraction and the particle size. Strain hardening

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Corresponding author: Fu-guo LI; Tel: +86-29-88474117; Fax: +86-29-88492642; E-mail: fuguolx@nwpu.edu.cn
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and softening processes are competitive during the plastic deformation and the generation and annihilation of dislocation happen. Therefore, metallic alloy presents different hardening stages in the working hardening rate−stress curve [18]. A Kocks−Mecking type curve [14] of strain hardening rate versus net flow stress presents different deformation stages for different materials. These stages occurred in Kocks−Mecking type are related to dislocation mobility, cross-slip of dislocations, dynamic recovery and microstructure characteristics [19]. A very convenient method to distinguish deformation stages in the stress−strain curves is the Crussard−Jaoul (CJ) analysis where $\mathrm{d}\sigma/\mathrm{d}\varepsilon_p-\varepsilon_p$ data are plotted in lg−lg coordinates. Constitutive parameters play a great role in estimating some mechanical properties, such as yield strength (YS), ultimate tensile strength (UTS) and fracture strain. The exponent n plays a crucial role in sheet metal forming. Therefore, microstructure evolution during work hardening is closely related to the manufacture and application of materials.

It is very important to notice that constitutive equation is crucial to predict the plastic deformation. It can be embedded in the finite element method simulations. Therefore, great attention should be given to the constitutive parameters of working hardening behavior. In this work, different deformation stages were distinguished in three coordinate transformations and then piecewise fitting was applied to investigate the working hardening behavior. In addition, the constitutive parameters of three typical constitutive equations for five metallic alloys were investigated. A new working hardening parameter was applied to compare the working hardening behavior in different deformation stages. Furthermore, the predictive accuracy of YS and UTS by using different methods was discussed.

2 Methods

2.1 Constitutive relations

One of the important empirical equations to characterize stress−strain curves of metallic alloy is Hollomon power law:

$$\sigma = K_\mathrm{H}\varepsilon_\mathrm{p}^{n_\mathrm{H}} \tag{1}$$

where K_H is the strength coefficient and n_H is the strain hardening exponent.

If experimental stress−strain curve follows the Hollomon equation, it can be recognized as a straight line in such two equations [11]:

$$\lg \sigma = \lg K_\mathrm{H} + n_\mathrm{H} \lg \varepsilon_\mathrm{p} \tag{2}$$

$$\lg \theta = \lg(K_\mathrm{H} n_\mathrm{H}) + (n_\mathrm{H}-1)\lg \varepsilon_\mathrm{p} \tag{3}$$

where θ is working hardening rate; n_H and K_H can be determined from slope and intercept of ordinate in Eqs. (2) and (3).

Since a good approximation is only restricted to the area of large plastic strain, the Hollomon equation is too simplistic to describe the full-range behavior of some metals. SWIFT [20] proposed another power-law equation, introducing a parameter ε_0, which accounts for a possible pre-strain:

$$\sigma = K_\mathrm{s}(\varepsilon_\mathrm{p} + \varepsilon_0)^{n_\mathrm{s}} \tag{4}$$

where n_s and K_s are strain hardening exponent and strength coefficient. If experimental stress−strain curve follows the Swift equation, the stress−strain curve in a double logarithmic plot of θ against σ related to "modified C−J analysis" [16] is linear, and it is expressed as

$$\lg \theta = \lg(n_\mathrm{s} K_\mathrm{s}^{1/n_\mathrm{s}}) + (1-\frac{1}{n_\mathrm{s}}) \lg \sigma \tag{5}$$

According to this equation, n_s and K_s can be determined from the slope and intercept. However, ε_0 cannot be obtained from linear fitting of Eq. (5).

Hollomon and swift equations both follow power law, while Voce [3] proposed an exponential relation which is fundamentally different from power-law type models. It is expressed as

$$\sigma = \sigma_0 - \sigma_0 A \exp(-\beta\varepsilon_\mathrm{p}) \tag{6}$$

where σ_0 is saturation stress and A, β are material coefficients. In Eq. (6) , the flow curve is deemed as a transient form of the flow stress from some starting value to the saturation value corresponding to some equilibrium structures under a given strain rate and temperature [1]. This equation is applicable to characterize the material that follows a linear relation in a plot of θ−σ referred to Ref. [21]:

$$\theta = \beta(\sigma_0 - \sigma) \tag{7}$$

This equation can determine the coefficients σ_0 and β from the slope and intercept. A cannot be obtained from the linear fitting of this equation. Voce-type models approach a saturation stress at large strain, while power-law models are unsaturated at large strain [2].

The three transformations ($\lg \theta$ vs $\lg \varepsilon_\mathrm{p}$, $\lg \theta$ vs $\lg \sigma$ and θ vs σ) are convenient to distinguish the deformation stages. Since some parameters (ε_0 and A) cannot be determined by linear fitting, the original constitutive equations can be used to piecewise fit experimental stress−strain curves. In order to comprehensively evaluate the working hardening behavior for the power-law relations, we define a working hardening parameter χ_P as

$$\chi_\mathrm{P} = \frac{\partial \sigma^{1/n}}{\partial \varepsilon_\mathrm{p}} = K^{1/n} \tag{8}$$

To predict yield strength (YS) and ultimate tensile strength (UTS), the calculation methods of YS and UTS