STRUCTURAL-TEMPORAL FEATURES OF HIGH-RATE DEFORMATION OF HIGH STRENGTH STEELS

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Abstract

Dynamic yield stress values predicted within the structural-temporal approach based on the incubation time concept and those found from the popular empirical Johnson-Cook and Cowper-Symonds formulas and its known modification are compared with the examples of high strength steels and nickel alloy subjected to high-rate plastic deformation. It is shown that the structural-temporal approach is an efficient and convenient tool for calculations in a much wider range of deformation rates. An advantage of the yield stress calculations based on the incubation time criterion is the minimal number of parameters, which do not require further modifications at high strain rates, in contrast to the empirical Johnson-Cook model and Cowper-Symonds formulas. Experimental curves of the static and dynamic deformation (stress-strain curves) for two high strength steels are analyzed on the basis of the relaxation model of plasticity with a constant characteristic relaxation time definable from the structural-temporal approach. It is shown that the relaxation model predicts an existence of the yield drop phenomenon during high-rate deformation for advanced high strength steel and an absence of this effect in a wide range of strain rates for high strength 2.3Ni-1.3Cr steel.

Keywords: Steel, plasticity, strain rate effect, dynamic yielding, relaxation plasticity model

1. INTRODUCTION

Numerous experiments on metallic nanowhiskers [1, 2, 3], steels [4, 5], nanocrystalline nickel [6] and polycrystalline metals [7] reveal a dependence of the dynamic yield stress on strain rate. In the case of dynamic deformation, caused for example by the shock wave propagation through material, the inertness of plastic relaxation [8,9] reveals itself as a substantial excess of the acting stress of the static yield strength. Strain rate dependent dynamic yield strength is often introduced in order to expand the yielding criterions onto the dynamic loading conditions. This approach turns out to be not very effective and fruitful, because the dynamic yield strength is not a material constant and requires to be represented by the corresponding material function, which in turns is remarkable by its essential instability.

The yield stress of metals subjected to high-rate mechanical treatment is a generally determined in terms of the classical numerical empirical Johnson-Cook [10, 11], Zerilli-Armstrong [12], Steinberg-Cohran-Guinan-Lands [13], Preston-Tonks-Wallace [14] models. The absence of a universal approach for estimating the unstable behaviour of the yield stress leads to an increase in the number of model parameters. In particular, the addition of new empirical parameters to the modified Johnson-Cook model [15] made it possible to expand the range of strain rates to higher values (above $10^{-3}s^{-1}$), at which the classical Johnson-Cook model [10, 11] cannot be used to determine the yield stress at the beginning of plastic deformation.

In this study, we propose to utilize a new phenomenological model for a wide range of strain rates. This model, based on the incubation time concept [16, 17], provides good correspondence with experimental data in the range of external impacts where the Johnson-Cook model is valid. One of the main results of our study is a comparison of the characteristics of the incubation time criterion and the Johnson-Cook empirical approach in the classical and modified statements for determining the dynamic yield stress at the start of plastic deformation.

Considered incubation time approach allows one to predict a phenomena of "higher than normal stress at small deformation" and subsequent relaxation process of whiskers deformation. The main idea of the incubation time concept consists in the consideration of the shear stress relaxation as a temporal process related with the defects motion. The relaxation itself can be realized by various physical mechanisms depending on the particular material. Within the frames of the incubation time approach we do not describe the relaxation mechanism explicitly, but do only state that it can be represented by some characteristic time period. The corresponding relaxation model of plasticity has three parameters; the first two of parameters are the static yield strength and the shear modulus known for most of materials, the third one is the relaxation time of the plastic deformation, which should experimentally or numerically evaluated. Using these parameters, one can predict various theoretical stress-strain curves of metals [18,19]. The temporal parameter can be regarded as a material constant depending only on the state of the defect substructure of material.

2. STRUCTURAL-TEMPORAL APPROACH

Let us consider the behaviour of the yield strength at the initial instant of plastic deformation within the structural-temporal approach based on the incubation time concept [16,17]:

$$Int_p(t) \le 1, \text{ где } Int_p(t) = \frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\Sigma(s)}{\sigma_y}\right)^{\alpha} ds \,. \tag{1}$$

Here, $\Sigma(t)$ is a function describing the time dependence of stress, τ is the incubation time, σ_y is the static yield stress, α is a coefficient of amplitude sensitivity of the material. Note that the onset of macroscopic yield t_* is determined from the condition of equality (1). The introduced time parameter τ, independent of the specific features of deformation and sample geometry, makes it possible to predict the behaviour of the yield strength of material under static and dynamic loads [16]. It was shown in [18,19] that the incubation time can be related to different physical mechanism of plastic deformation. Let us assume the linear elastic deformation law $\Sigma(t) = E\,\dot{\varepsilon}\,tH(t)$, where E is the Young's modulus and $\dot{\varepsilon}$ is the constant strain rate under load, *H(t)* is the Heaviside function. Having written the left-hand side of (1) under the condition that the yield starts at time t_*, one can express the dynamic yield stress $\Sigma_d(\dot{\varepsilon}) = \Sigma(t_*)$ in terms of the strain rate of material:

$$\Sigma_d(\dot{\varepsilon}) = \begin{cases} \left[(\alpha+1)(\sigma_y)^{\alpha} E\dot{\varepsilon}\tau\right]^{1/(\alpha+1)}, & \dot{\varepsilon} \ge \dfrac{(\alpha+1)^{1/\alpha}\sigma_y}{E\tau}; \\ \sigma_y + \left(1 - \dfrac{1}{(\alpha+1)^{1/\alpha}}\right)E\dot{\varepsilon}\tau, & \dot{\varepsilon} < \dfrac{(\alpha+1)^{1/\alpha}\sigma_y}{E\tau}. \end{cases} \tag{2}$$

Thus, the set of parameters (σ_y, τ, α) describes the behaviour of material independent of the plasticity model and the way of impact.

3. JOHNSON-COOK MODEL AND COWPER-SYMONS MODELS

The modified Johnson-Cook [15] without thermal component at the initial instant of plastic deformation can be written as

$$\sigma_y = A\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) + D\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_1}\right)^{k}\right), \tag{3}$$

where A, C, n are the constant parameters of the Johnson-Cook classical model [10,11], $\dot{\varepsilon}$ is strain rate, ($\dot{\varepsilon}_1 = 1000\ \mathrm{s}^{-1}$ по [15]; $\dot{\varepsilon}_0 = 1\ \mathrm{s}^{-1}$ в [10,11]), *D* and *k* are the constant parameters of modified model [15]. A correspondence between parameters of the modified Johnson model and the incubation time model was established in [21]:

$$D = \left((\alpha+1)\frac{E\dot{\varepsilon}_1\tau}{\sigma_0} \right)^{1/(\alpha+1)}, k = \frac{1}{\alpha+1}. \qquad (4)$$

The Cowper-Symonds model [21] is similar to (3) and is given in following form:

$$\sigma_y = A\left(1 + \left(\frac{\dot{\varepsilon}}{B}\right)^{1/q}\right), \qquad (5)$$

where B and q are empirical constants Cowper-Symonds model [22].

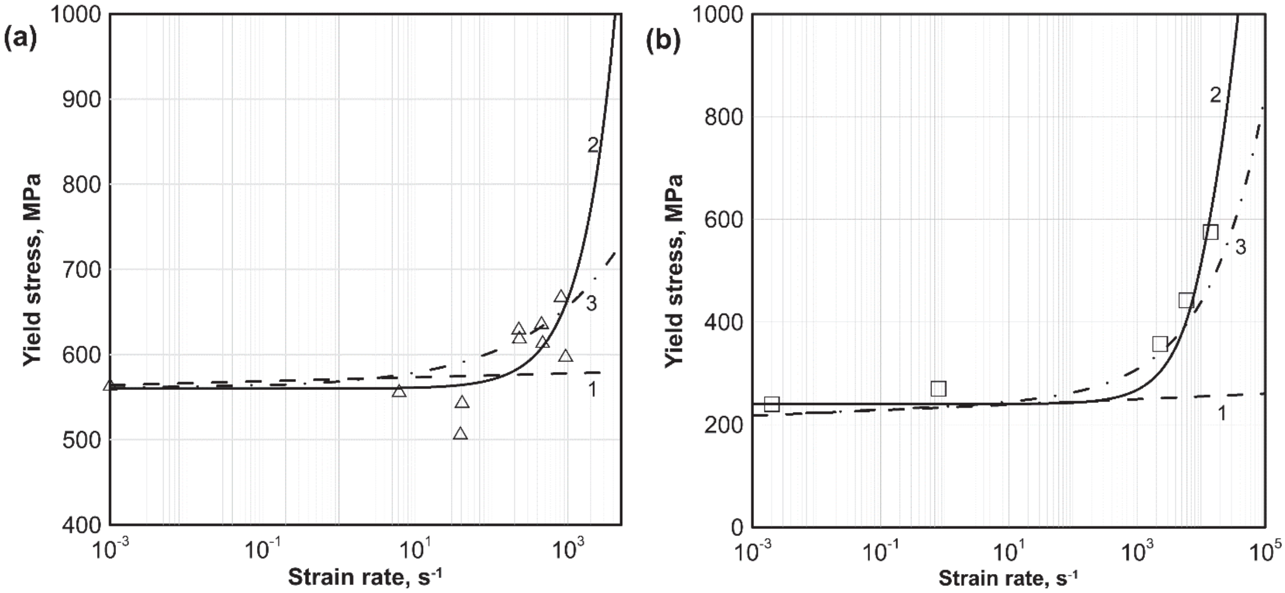

Figure 1 Dependences of the yield stress on the strain rate for: (a) B500A steel [22] (curve 1: classical Johnson-Cook, curve 2: structural-temporal approach, curve 3: Cowper-Symonds model); (b) nickel alloy [23] curve1: classical Johnson-Cook, curve 2: structural-temporal approach, curve 3: Cowper-Symonds model

Figure 1 shows a possibility of prediction of the behaviour of the yield stress in wide range of strain rates using models (2), (3), (5) for B500A steel [23] and nickel alloy [24]. Models (2), (5) and Cowper-Symonds model [22] provide good correspondence with the experimental data (both static and dynamic). As is shown in **Figure 1**, the classic Johnson-Cook model satisfactorily evaluates the yield stress only up to strain rates of the order of $10^3\,s^{-1}$.

4. RELAXATION MODEL OF PLASTICITY

In the present paper we propose a primary version of the relaxation model for the case of a linear increase of the strain with time starting from the zero moment $t = 0$. Let us introduce a dimensionless relaxation function $0 < \gamma(t) \le 1$, defined as follows [18,19]:

$$\gamma(t) = \begin{cases} 1, & Int_p(t) \le 1, \\ \dfrac{1}{\sqrt[\alpha]{Int_p(t)}}, & Int_p(t) > 1. \end{cases} \qquad (6)$$

Condition $\gamma(t)=1$ in Eq. (6) relates with the elastic deformation accumulation before the starting time t_* .of the macroscopic plastic flow. Gradual decrease of the relaxation function in the range $0<\gamma(t)<1$ corresponds to the material transition into the plastic stage of deformation. During the plastic stage of deformation $t \geq t_*$, the relaxation function satisfies the condition for $\gamma(t)$:

$$Int_p(t)\gamma(t)=1. \tag{7}$$

Equality (6) is retained for account of fixing the state at the moment of yield and subsequent relaxation of elastic stress ($0<\gamma(t)<1$). Let us define the actual stress $\sigma(t)$ in a deformed specimen by the following form: $\sigma(t)=E(t)\varepsilon(t),$ where $E(t)=E\gamma^{1-\beta}(t)$ is a coefficient, related with behaviour of stress; β is a scalar parameter ($0 \leq \beta \leq 1$), describing a degree of hardening of material. The case $\beta=0$ corresponds to the plastic deformation without hardening. Considering the stages of elastic and plastic deformations separately, we can obtain the following stress-strain relation:

$$\sigma(\varepsilon(t))=\begin{cases} E\varepsilon(t), & \varepsilon(t)/\dot{\varepsilon}<t_*, \\ E\gamma^{1-\beta}\left(\varepsilon(t)/\dot{\varepsilon}\right)\varepsilon(t), & \varepsilon(t)/\dot{\varepsilon}\geq t_*. \end{cases} \tag{8}$$

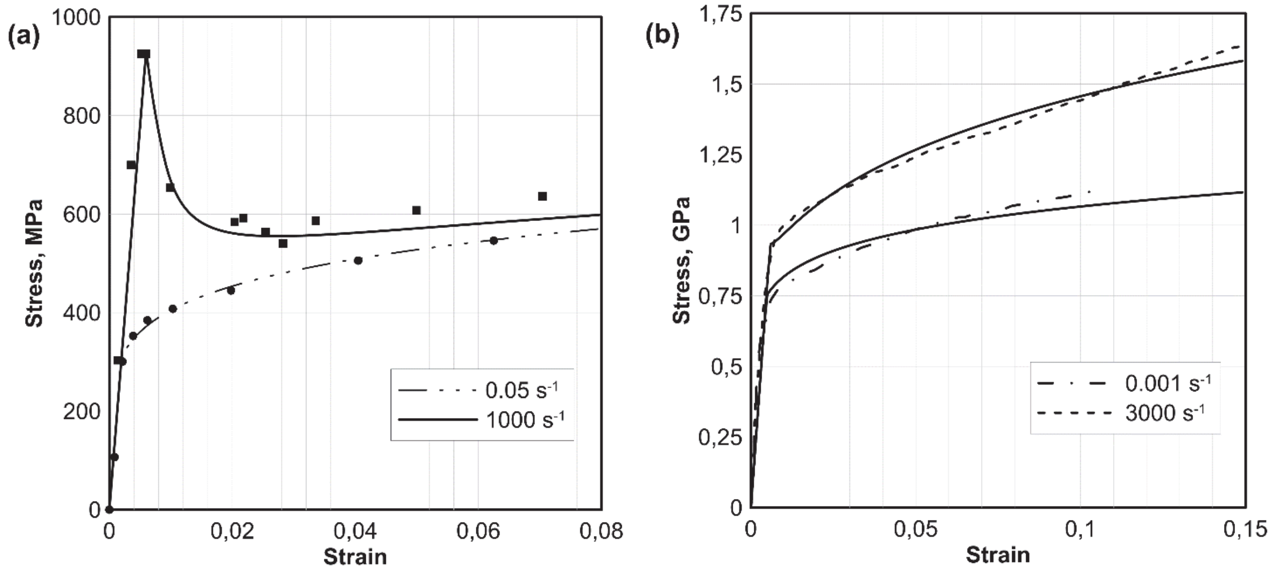

Figure 2 Experimental and theoretical stress-strain diagrams for (a) advanced high strength steel [24]; (b) high strength 2.3Ni-1.3Cr steel

Figure 2(a) presents the simulation of the yield drop phenomena with the subsequent deformation hardening according to the model (6)-(8) in the case of deformation of steel specimens ($\sigma_y=310\,\mathrm{MPa}$, $\alpha=1$). The points correspond to the experimental data given in [25]. In this material, the yield drop phenomena is already not observed at quasi-static strain rates $0.05\,\mathrm{s}^{-1}$ (lower solid curve), but is clearly observed in the case of dynamic deformation at the rates $1000\,\mathrm{s}^{-1}$ (upper solid curve). The points correspond to the recently obtained experimental data [25]. It is remarkable that in this case the obtained value of relaxation time scale is already equal only to 14 microseconds that are still too many. Stress-strain curves of high strength 2.3Ni-1.3Cr steel [26] ($\sigma_y=610\,\mathrm{MPa}$, $\alpha=20$, $\tau=0.76\,\mu\mathrm{s}$) illustrates in **Figure 2(b)**. Absence of the yield drop phenomena for steel [26] is predicted by relaxation model of plasticity (6)-(8). In general case, the plastic deformation of metals is divisible into two types of stress dependence in sample on deformation: a regular transition to the stage of plastic deformation and a sharp transition. In **Figure 2** we deal with two types of diagrams. Thus, the relaxation model of plasticity, opposite, is able to describe various types the deformation curve for one material a wide range of strain rates.

5. CONCLUSION

Characteristic time of plastic relaxation being considered as a material constant is a principal parameter of the integral yield criterion that predicts the dynamic behaviour of the yield strength in a wide range of strain rates. This approach can describe the complicated behaviour of plastic deformation curve, including the yield drop phenomenon.

An essential advantage of the yield stress calculations based on the incubation time concept is the minimal number of parameters, which do not require further modifications at high strain rates in contrast to the empirical Johnson-Cook model. Thus, the relaxation model represented here can be characterized as very convenient for further numerical implementations.

It is shown that the relaxation model predicts an existence of the yield drop effect during high-rate deformation of advanced high strength steel and an absence of such effect in a wide range of strain rates for high strength 2.3Ni-1.3Cr steel.

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