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On the temporal peculiarities of stabilization effect under cyclic deformation for steel

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Abstract

New phenomenological model of accumulation of plastic deformation under repeated cyclic loading for metals based on a notion of the characteristic time as a material property is proposed. Incorporation of the temporal parameter into deformation law allows one to predict the adaptability effect of material at a low-cycle loading, which is defined by the stabilization process of accumulated plastic deformation after multiple loading cycles. Some of the known experimental data for the quenched steel-50 with the observed adaptability effect on the basis of the proposed model are analyzed. Obtained values of the characteristic time for each of the steel grades differ essentially depending on the way of treatment. It is shown that the parameter of temporal sensitiveness of material, presented in the relaxation model of plasticity, can serve as an effective tool for description the stabilization phenomenon and reflection the technological actions towards material.

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Keywords: incubation time, cyclic loading, steel

1. Introduction

The expansion of region of load capacities related to the stabilization deformation phenomenon of elastic-plastic materials under low-cycle loading is a crucial task of engineering analysis. Conventional adaptability theory coupled with numerical methods gives a good correspondence with experimental data for very limited series of experiments.

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In addition to the difficulty of separating simultaneously going processes in an analytical solution for low-cycle deformations, there is a difficulty in choosing a proper approach for describing the behavior of a material beyond elastic adaptability. Increasing of capability of materials to adapt and avoid failure outside of elastic field under cyclic loadings is one of the main tasks of development of modern technologies of treatment of metals. At the same time the universal phenomenological approach for calculation of accumulated plastic deformation is still not formulated.

In this paper a new phenomenological model for the calculation of diagrams of cyclic deformation on the basis of the relaxation model of plasticity, initially developed for the case of single loading (Petrov and Borodin (2015), Borodin et al. (2014), Selyutina et al. (2016), Borodin et al. (2016)), is proposed. In particular, the analytical model of accumulation of plastic strains under one-sided cyclic deformation with arbitrary impulse profile is presented. The main feature of the modified model utilized for the description of cyclic deformation is the characteristic time of stress relaxation, treated as a basic property of the material responsible for its temporal (rate) sensitiveness to the applied load. Approbation of new model is conducted using an example of the modified (nanostructured) steel-50 thoroughly studied by Makarov et al. (2014), that allowed us to model the above mentioned effect of stabilizing of plastic strains and provide estimations of plasticity characteristic times for every type of investigated steels.

2. Modified relaxation model of plasticity

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 (Gruzdkov and Petrov (1999), Gruzdkov, Petrov, Smirnov (2002), Gruzdkov et al. (2009)):

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

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 plastic flow t_* is determined from the condition of equality in (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 Gruzdkov and Petrov (1999). It was shown in Selyutina et al. (2016) 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 step 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 describes the behaviour of material independent on the plasticity model and the way of impact.

One can use an elastic approximation of stress $\Sigma(t) = 2G\varepsilon(t)$ and consider the case of equality in the criterion (1) in order to define the macroscopic time of the plastic flow beginning t_*; here G is the shear modulus. We propose a primary version of the relaxation model in the present paper for the case of a linear increase of strain $\varepsilon(t) = \dot{\varepsilon}\,t\,H(t)$ together with time starting from the zero time moment $t = 0$. Let us introduce a dimensionless relaxation function $0 < \gamma(t) \le 1$, defined as follows