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The definition of characteristic times of plastic relaxation by dislocation slip and grain boundary sliding in copper and nickel

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ABSTRACT

The behaviour of the yield strength of metals is considered from viewpoint of dynamics as a function of the limiting stress and the characteristic time of stress relaxation. Experimental curves of the static and dynamic deformation of the coarse-grained copper, microcrystalline and nanocrystalline nickel are analyzed on the basis of the relaxation model of plasticity (the integral criterion) with a constant characteristic relaxation time. The analytical expressions of the relaxation time as a function of variables that characterizes the internal structure of material are obtained from the model of dislocation slip and grain boundary sliding. The strain rate dependences of the yield strength, which are calculated with the help of both the dislocation model and the integral criterion of plasticity, are compared with the experimental data for copper and nickel in a wide range of strain rates (10^{-3}–10^{11} s^{-1}). It is shown that the proposed analytical expressions give the relaxation time, which order-of-magnitude agrees with the values obtained by fitting the results of the integral criterion. The obtained relations allow us to calculate two separate dependences of the yield strength (one for coarse-grained material, while another for nanomaterial) in Hall–Petch coordinates both for quasi-static and for high-rate deformations.

1. Introduction

Classical definitions of the yield stress and corresponding yielding criterions, such as Mises and Tresca criterions, are applicable only for quasi-static behaviour of metals. In the case of dynamic deformation, for example the shock wave propagation through material, the inertness of plastic relaxation (Krasnikov et al., 2011; Mayer et al., 2013a) reveals itself as a substantial excess of the acting stress the static yield strength. The last one is understood here in traditional sense as the limit stress for the same material in the conditions of quasi-static simple compression. Dynamic yield strength is often introduced in order to expand the yielding criterions onto the dynamic conditions. It is not a fruitful approach, because this dynamic yield strength is not a material constant, it depends on the strain rate and its history. Materials can reveal some specific features typical for the plasticity inertness even in quasi-static conditions. It is observed in the experiments on whiskers made of pure

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metals (Dehm, 2009), nano scale objects (Sedlmayr et al., 2012) and bulk nanostructured metals (Rajaraman et al., 2013; Zhu and Lu, 2012). In spite of different physical mechanisms of plasticity (Dehm, 2009; Sedlmayr et al., 2012; Rajaraman et al., 2013; Khan et al., 2008) in these cases, the stress relaxation down to some yield value occurs not immediately, but gradually during some time. Thus, the relaxation process and the corresponding inertness of the plastic flow development play a key role in the mechanical response of material, at least, in the initial stage of deformation.

There were a lot of attempts to include the temporal aspect into the plasticity description. Kadashevich and Pomytkin (2001) proposed the generalized approach to definition of the history-dependent plastic deformation that analyzed the different ways of unloading or loading for the biaxial stress state and considered the case leading to the classical plasticity theory. Kadashevich et al. (2014) examined the stress relaxation process versus the hardening parameter on the basis of the endochronic theory (Bazant and Shieh, 1978; Wang and Fan, 1991; Bakhshiani et al., 2002; Yeh and Lin, 2006) of inelasticity for large deformations and rotational displacements that took into account the temporal effect. Onuki (2003) offered the elasto-plastic dynamical model with the concept of structural relaxation time (Yamamoto and Onuki, 1997, 1998) based on the phenomenological time-dependent Ginzburg-Landau theory of non-linear plastic deformation in solids. Sudduth (2001) using the characteristic time of creep proposed a mathematical model of the stress relaxation by means of creep that is applied to both short-term and long-term loading.

In this paper, we consider the yielding criterion based on the incubation time concept (Gruzdkov and Petrov, 1999; Gruzdkov et al., 2002; Petrov and Sitnikova, 2005; Petrov et al., 2007; Gruzdkov et al., 2009) as an approach to the maximal shear stress determination at fixed strain rates, as well as more complex conditions of loading. The incubation time approach (Petrov, 2007) was first proposed in fracture dynamics (Petrov and Utkin, 1989) and turned out to be very effective tool to describe the temporal effects of crack growth initiation (Berezkin et al., 2000; Bratov et al., 2004). The characteristic time of plastic relaxation is introduced in the case of plasticity instead of the incubation time used in the case of fracture. 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 material. In the frames of the incubation time approach we do not describe the relaxation mechanism explicitly, but only state that it needs some characteristic time for relaxation. 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 be evaluated. Using these parameters, one can predict various theoretical stress–strain curves of metals. The temporal parameter depends only on the state of the defect substructure of material.

The processes of plastic deformation are connected with the certain types of lattice defects, their densities and motion velocities (Meyers and Chawla, 2009). Particularly, experimental data show the yield stress sensitivity to the grain size (Khan et al., 2008; Zhu et al., 2014) in addition to the strain rate (Khan and Farrokh, 2006) and temperature (Rodriguez-Galan et al., 2015). Therefore, the parameters of purely mechanical plasticity models, such as the considered incubation time model, can be expressed through parameters of the defect structure of material. There are known rheological relations between the strain rate and the applied stresses that were developed for different types of the plasticity mechanisms. In the case of creep, these are the mechanisms of Nabarro–Herring (Herring, 1950), Coble (Coble, 1963) and Harper–Dorn (Harper and Dorn, 1957), first of all. In the case of dislocation plasticity, it is Orowan equation (Hirth and Lothe, 1982; Meyers and Chawla, 2009). In the case of quasi-static loading, the yield stress is connected with the defect structure through well-known Taylor (Suzuki et al., 1991) and Hall–Petch (Dunstan and Bushby, 2014) relations. Similarly, the relaxation time as the parameter of the considered characteristic time model can be expressed through the structural variables of the material. The dependences of the relaxation time on the state of the material microstructure can be obtained with using the structural models of plastic deformation (Krasnikov et al., 2011; Mayer et al., 2013a; Borodin and Petrov, 2014; Borodin and Mayer, 2012) that are based on physical interpretations about kinetics and dynamics of dislocations, grain boundary sliding and other features of the plastic deformation.

2. Relaxation model of plasticity

2.1. General formulation

The classical yield criterion for quasi-stationary processes requires $\Sigma(t) \le \sigma_y^0$ each moment of time, where $\Sigma(t)$ is the current shear stress multiplied by the factor of 2 (or longitudinal stress at simple compression), σ_y^0 is the static yield strength. Suppose that, instead of the current values, the restriction is applied to the values averaged over some period of time, which is denoted as τ

$$\frac{1}{\tau}\int\limits_{t-\tau}^{t} \Sigma(s)ds \le \sigma_y^0. \tag{1}$$

Condition Eq. (1) means that current stress $\Sigma(t)$ can considerably exceed the static yield strength σ_y^0 during short period of time $\Delta t << \tau$, while the averaged value is restricted. Thus, τ has the meaning of a typical time of plastic relaxation. Eq. (1) can be rewritten as