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INCREMENTAL ENERGY BALANCE DURING THE DEFORMATION OF METALS

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Abstract: The incremental balance of the mechanical and thermal energy flows involved in plastic deformation is assessed, via the measurement of the stress, the strain and the surface temperature. The dissipation coefficient is accordingly obtained; a microscopic interpretation in terms of dislocation kinetics is proposed.

Introduction

A thermodynamical approach is adopted to study the plastic deformation of metals [1,2,3]. The aim of this still macroscopic approach is to reach a better understanding of the plastic deformation processes, by carefully accounting for the interplay of mechanical and thermal phenomena which always occur in metals under stress. When a specimen is deformed elastically, the reversible thermoelastic effect is present, which can be described by an 'effective heat source' W_{te}. When the specimen is deformed plastically, a specific plastic power W_p is irreversibly fed into it; the fraction $W_d = fW_p$ is immediately dissipated to heat, the complement $W_i = W_p - W_d$ being stored as internal energy (stored energy of cold work). An experimental method has been developed to derive the instantaneous values of W_p, W_d and W_i for tensile specimens. These data can be exploited to analyze the deformation mechanisms.

Measurements

The experimental method is based on the measurement of the time evolution of the stress, the strain and the temperature field at the surface of the tensile specimen [4]. W_p is readily obtained from the measured tensile stress σ and the measured longitudinal strain ε as $W_p = \sigma\dot{\varepsilon}^p = \sigma(\dot{\varepsilon}^p - \dot{\sigma}/E)$, where $\dot{\varepsilon}^p$ is the plastic strain rate and E is the Young modulus. To measure the thermal energies the Fourier heat equation is exploited; for a solid undergoing elastic–plastic deformations it reads

$$\rho c\, \partial T/\partial t - k\nabla^2 T = W_{te} + W_d = W_{th} \tag{1}$$

where ρc is the heat capacity per unit volume and k is the thermal conductivity. The temperature is measured at several points at the surface of the essentially monodimensional tensile specimen, allowing to estimate the derivatives at the l.h.s. of eq. 1, and to derive W_{th}. W_{te} is deduced from the elastic strain rate, via the Grüneisen parameter; W_d is thus obtained, as well as W_i and the dissipation parameter f.

Results

Measurements are performed on pure (99.5 %) copper, subjected to consecutive loading/unloading cycles, under load control, up to a final plastic elongation of nearly 20 %, within the range of nearly homogeneous deformation. Each yielding is followed by a short easy–glide region, then by a strain hardening regime. At low plastic strains (below 2 %) the dissipation parameter f is below 50 %, but it rapidly reaches a value around 70 % which remains essentially constant up to the highest strains, except for rapid variations in the easy–glide regime; under load control this regime corresponds to peak values of all the energy flows.

Dislocation kinetics interpretation

A simple model of dissipation can be derived from the following hypotheses: (i) the dissipated specific power W_d is entirely due to drag on moving dislocations; (ii) the drag force on dislocations is a viscous one, i.e. proportional to the average dislocation velocity. This model allow to obtain, from the mechanical and thermal data, the average values of the mobile dislocation density and velocity. Yielding and easy–glide turn out to correspond to a high mobile dislocation density, with a low velocity; during strain hardening the density is lower, and nearly constant, while the velocity is higher, and increasing with the stress.

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