LBL-4508

INHOMOGENEITIES IN PLASTIC DEFORMATION THROUGH DISLOCATION GLIDE

by

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ABSTRACT

Recent research involving the direct computer simulation of plastic deformation through planar dislocation glide suggests that plastic inhomogeneities such as the formation and growth of discrete slip bands are an inherent feature of deformation through glide. In this paper we shall describe the sources of glide inhomogeneity and and discuss the influence of temperature, microstructural barriers, and applied stress on the heterogeneity of deformation in idealized crystals.

INTRODUCTION

At moderate temperatures the plastic deformation of a typical crystal involves the planar glide of dislocations against the resistance provided by the microstructure.

In earlier work (1) the statistics of thermally activated glide were developed and useful approximations identified. Recently we have discussed how statistical analysis and computer simulation can be combined to provide new insight into the kinetics of glide in model crystals (2,3). In particular these results suggest that characteristic homogeneities will be observed in deformation through the simplest dislocation mechanism.

BASIC EQUATIONS

We consider the glide of a dislocation, modelled as a flexible, extensible line of constant tension, Γ, and Burgers vector of magnitude, b, through a field of point obstacles, whose density is characterized by the characteristic length ℓ_s. The resolved shear stress, τ, impelling glide is given, in dimensionless form, as

$$\tau^* = \tau \ell_s b/2\Gamma \qquad (1)$$

The obstacles are distributed randomly on the glide plane, and assumed to be identical, localized barriers to the dislocation whose effective range of interaction (d) is small compared to their mean separation. They may hence be treated as point obstacles (4). The force, F_i^k, that the dislocation exerts on the k-th obstacle is simply, in dimensionless form,

$$\beta_i^k = F_i^k/2\Gamma = \mathrm{Cos}(\tfrac{1}{2}\,\psi_i^k) \qquad (2)$$

where ψ_i^k is the included angle between two dislocation arms (Fig. 1). The interaction between obstacle and dislocation is given by the force displacement relation, $\beta(x/d)$, the maximum of which measures the mechanical strength, β_c, of the obstacle.

As discussed in references (2,3), in thermally activated glide the dislocation encounters a sequence of obstacle configurations. Since these "glide paths" change with temperature and stress, the determination of the velocity of glide through a random array of point obstacles is complicated. However, when the temperature (T*) is low or the applied stress (τ^*) is very close to the critical value (τ_c^*) for athermal glide the dislocation tends to follow the "minimum angle" path obtained under the requirement that activation occurs at an obstacle at which the angle ψ_i^k takes on its minimum value (or equivalently, at which β_i^k takes on its maximum value, β_i). In the limit $T^* \to 0$ the velocity is given by the Arrhenius equation

$$\langle v^* \rangle = n^{1/2} \exp[-\alpha(\beta_c - \beta_1)] \qquad (3)$$

where n is the number of obstacles in the glide plane, α is the "dimensionless reciprocal temperature" ($\alpha = (T^*)^{-1} = 2\Gamma d/kT$) and β_1 is the minimum of the β_i, i.e., the maximum force on the most stable configuration encountered during glide. In the limit $T^* \to \infty$ the glide path becomes a "random" path whose configurations are obtained through a random sequence of activation events.

Given the analysis of individual planes one may treat the plastic deformation of an idealized crystal modelled as a stacking of planes of the same type, assuming that each glide plane contains active sources of non-interacting dislocations so that the expected number of dislocations is the same for all planes and all times during steady state deformation. If the glide planes contain a finite number of obstacles, then there may be appreciable scatter in the expected glide velocity from one plane to the other. This will be reflected in an inhomogeneity of the crystal deformation, which will tend to concentrate on these planes over which glide is easiest. As will be shown in the next section, this plane-to-plane variation becomes less pronounced as the temperature is increased or stress is decreased, thus crystal deformation becomes more uniform.

SIMULATION RESULTS AND DISCUSSION

The specific details of the computer code and how the data are obtained are discussed in reference 3. Here we will first discuss the effects of temperature and applied stress on plastic deformation.

The simulation results of an ideal crystal made up of ten parallel glide planes are illustrated in Fig. 2, where we have plotted the glide velocity ($-\ln\langle v^*\rangle$) as a function of α for four values of applied stress τ^*. The light curves show the data for each of the individual glide planes making up the crystal; the heavy line gives the resulting average velocity for the crystal as a whole. Each plane with an area of 10^3 is assumed to contain a uniform distribution of non-interacting dislocations and a Poisson distribution of obstacles with strength of $\beta_c = 0.6$

and an interaction function, $\beta(x/d)$, of simple step form. The glide velocities for the individual planes vary over a range which increases as the temperature is lowered or as the stress is raised. The source of this scatter is straightforward, and may be easily seen from equation 3: when the reciprocal temperature α is large the velocity is quite sensitive to overall plane-to-plane variations in the value of β_I, the maximum force exerted on the most stable configuration encountered in glide along the minimum angle path. In a finite array the variation is significant, and tends to increase with the stress, τ^*. As temperature is raised the properties of the most stable configuration become less dominant. In the high temperature limit the glide velocity is determined by an average over the forces. Unless τ^* is so near to τ^*_c that there are only a few stable configurations in the array this average tends to be independent of the specific array, and the variation of $\langle v^* \rangle$ becomes very small.

The consequences of the plane-to-plane variation in glide velocity are illustrated in Fig. 3, where we show the appearance of a hypothetical bar made of our model crystal and strained 20% in tension at each of the two resolved shear stresses, $\tau^* = 0.4$, at temperatures $T^* = 10^{-3}$ and $T^* = 10^{-1}$. At low stress ($\tau^* = 0.01$) the deformation is markedly inhomogeneous at the lowest temperature ($T^* = 10^{-3}$), but rapidly becomes homogeneous as temperature is raised. At high stress ($\tau^* = 0.4$) the deformation remains inhomogeneous even at $T^* = 10^{-1}$ which roughly corresponds to the highest dimensionless temperature obtainable in a typical metal (Cd at its melting point). Hence, crystal deformation becomes more uniform as stress is lowered at constant temperature or as temperature is raised at constant stress.

The plane-to-plane variation in glide velocity is enhanced by the small array size used in this simulation, 10^3 as opposed to a physical realistic number of perhaps 10^6. Were the array size increased, the variation would become less pronounced. Specific simulations of very large arrays (5) have, however, shown that the plane-to-plane variation remains significant when the number of obstacles is increased to 10^6 or more (Fig. 4). For crystals containing more than one type of obstacle the plane-to-plane variation remains qualitatively the same.

The deformation at constant strain rate becomes rapidly homogeneous as T* is increased, since both the increase in temperature and the decrease in flow stress favor homogeneous slip. Fig. 5 illustrates the variation of flow stress, with temperature. The result depends on the precise value of the average velocity chosen, when $T^* > 0$ the flow stress is an increasing function of strain rate. Since in this simple example there is no athermal component to the flow stress, the flow stress becomes zero at a finite value of T* which increases as strain rate increases.

The effects of temperature and stress on the heterogeneity of deformation discussed above depends on the particular choice of dislocation-obstacle interaction, which was taken to be of simple step form. Introduction of any shape of force displacement diagrams is fairly straightforward and can be handled easily (5). Preliminary results indicate that by taking the interaction to be of the parabolic or triangular form changes the τ^* versus T* curves to become steeper and the temperature at which $\tau^* = 0$ to be lower.

The effects of obstacle distribution and dislocation-dislocation interaction as well as specific details of the effects of temperature on the flow stress are currently being investigated.

ACKNOWLEDGMENTS

This work was done with support from the U. S. Energy Research and Development Administration.

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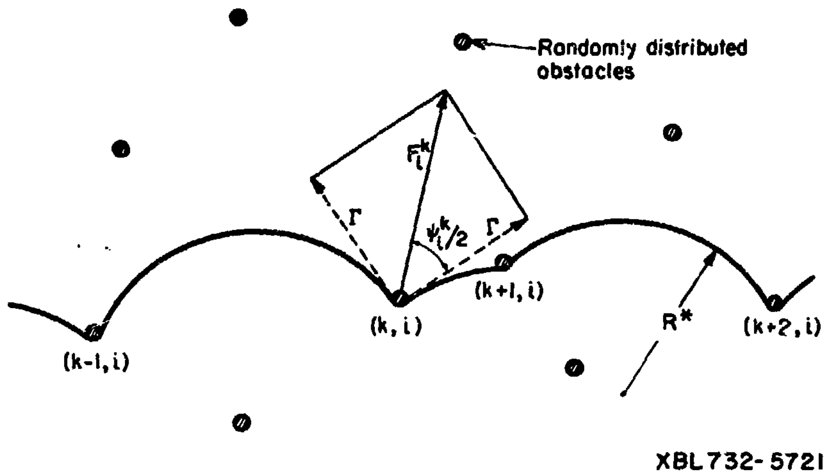

Fig. 1

Equilibrium of a dislocation under stress.

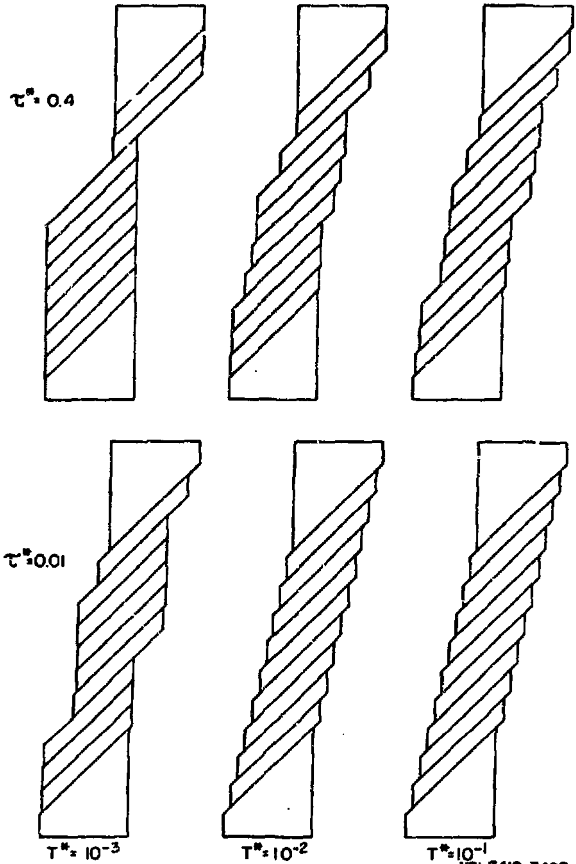

Fig. 3

The effect of temperature and stress on the inhomogeneity of plastic deformation.

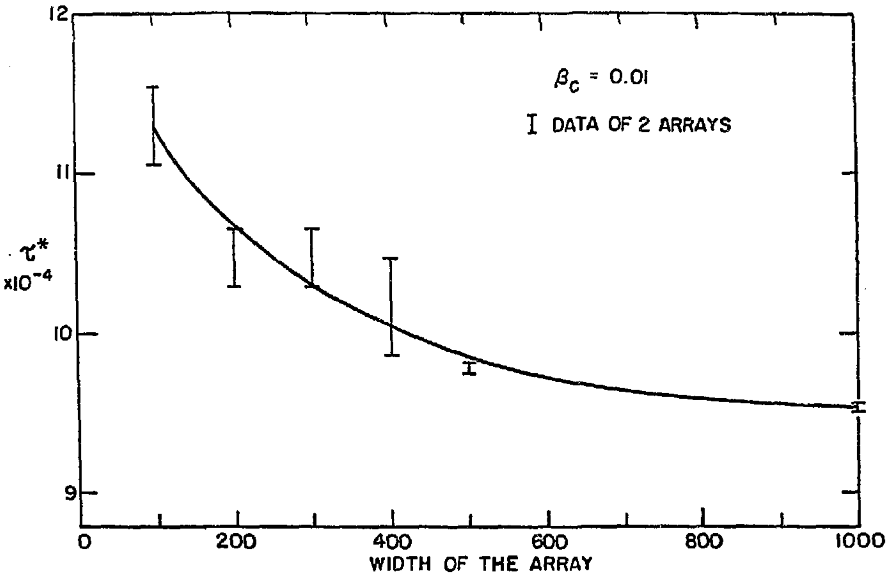

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Fig. 4

Athermal glide stress versus array size for $\beta_c = 0.01$.

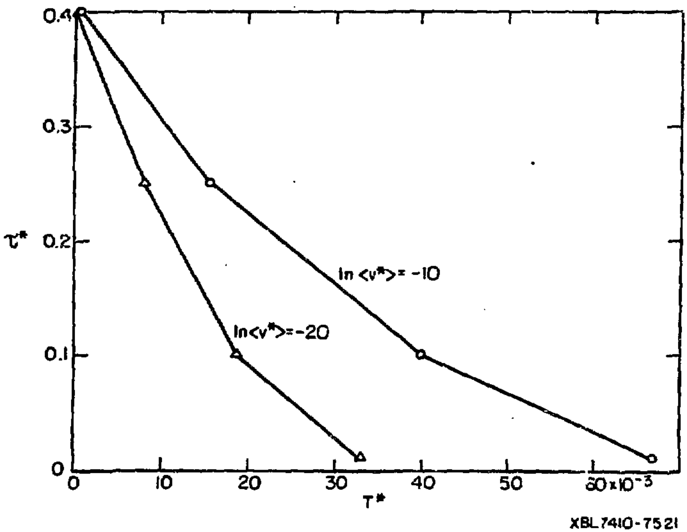

Fig. 5

Flow stress versus temperature at two strain rates.