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The Contribution of Dipole Mechanisms to the Flow Stress and Work Hardening

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The contribution of dislocation dipoles and debris to the work hardening of ionic crystals is investigated by recovery experiments performed on deformed samples. The investigations are supplemented by electron microscope studies. Accordingly, a remarkable part of the work hardening in stages II and III of deformation arises from the short-range interaction of dipole-like defects with the gliding dislocations.

1. Introduction

In the course of the plastic deformation of a material various kinds of defects are generated, which may act as obstacles to successive dislocations. The effect of obstacle structures with long-range stress fields such as piled-up dislocations has been intensively studied and it is generally assumed that they mainly determine the work hardening in stage II of deformation [1]. During deformation also obstacles with a highly localized strain energy may form. Defects of that type are dislocation dipoles or dislocation debris. Because of their short-range interaction with gliding dislocations the defects may generate a thermal stress part [2, 3]. Besides, dipoles can also trap other parallel edge dislocations to form tripoles or multipoles, thus inhibiting the motion of successive dislocations and providing an athermal stress part. Dipole defects may therefore contribute to the flow stress in a very complex manner. A model of work hardening based on dislocation debris has been established earlier by Gilman [4] without considering the details of the interaction. Accordingly, the produced hardening is only important at earlier stages of deformation where the dislocation density is small. On the other hand, a relatively high stress part was related to the interaction of the dislocations with dipoles and debris by the recovery experiments of Davidge and Pratt [5]. To get more information, in the present paper the contribution of deformation-induced dipole defects to the work hardening is studied on ionic crystals by recovery experiments of deformed crystals. The experiments were supplemented by electron microscopy studies of the defect processes.

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2. Experimental Methods and Results

Dislocation dipoles or debris are defects which are realized by a small amount of additional or missing material. Since these differences are easily equalized by diffusion, the defects are less stable against a thermal treatment. This enables the defects to anneal out at relatively low temperatures where the deformation-induced dislocation structure is not yet recovered. The effect of the dipoles on the work hardening may then be estimated by comparing the flow stresses before and after

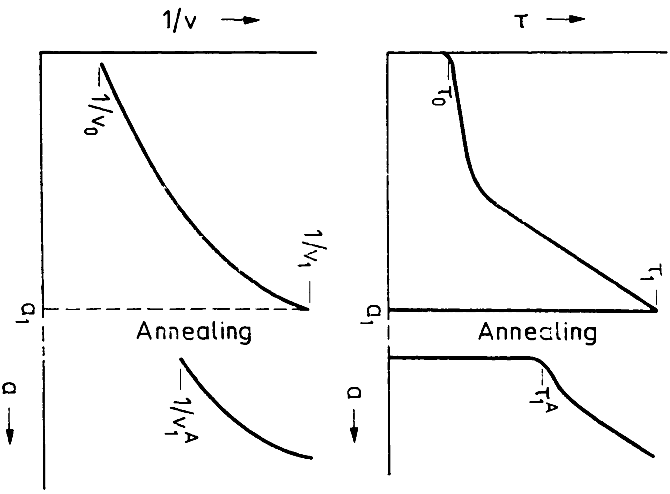

Fig. 1. Recovery experiments of deformed crystals, performed to estimate the obstacle strength of deformation-induced short-range obstacles.

annealing. Fig. 1 shows the scheme of the experiments applied in the present study. The recovery experiments were performed on ⟨001⟩ oriented NaCl single crystals with a total concentration of divalent impurities of 1.7 ppm. The crystals were deformed at room temperature and a shear strain rate $\dot{a} = 1.6 \times 10^{-4}\ s^{-1}$ up to plastic shears of $a_1 = 0.15$ and 0.34, which correspond to stages II and III of the work hardening curve, respectively. The activation volume was determined from the stress increments of strain rate cycling tests [6]. The critical resolved shear stress of the crystals amounts to $\tau_0 = 0.5\ N/mm^2$. At the beginning of deformation the reciprocal activation volume is $1/v_0 = 2.61 \times 10^{15}\ mm^{-3}$, which well corresponds to the impurity concentration. By straining the crystals the flow stress and the reciprocal activation volume typically assume the values τ_1 and $1/v_1$ given in Table 1. After deformation the samples were unloaded and isothermally annealed at $T^A = 481$ and 555 K for $t^A = 15$ up to 240 minutes. Afterwards the deformation was continued at room temperature, and the values τ_1^A and $1/v_1^A$ were determined. Table 1 summarizes the results obtained for a fixed annealing time of $t^A = 60$ min.

TABLE 1
Results of recovery experiments performed on deformed NaCl single crystals according to Fig. 1. T^A = annealing temperature, $f = \tau_1^A/\tau_1$, $g = v_1/v_1^A$, annealing time t^A = 60 min.

T^A (K)	a_1	τ_1 (N/mm^2)	$1/v_1$ (10^{16} mm^{-3})	f	g
481	0.15	7.77	1.35	0.8	0.54
555	0.15	7.35	1.27	0.7	0.39
555	0.34	13.84	2.92	0.58	0.40

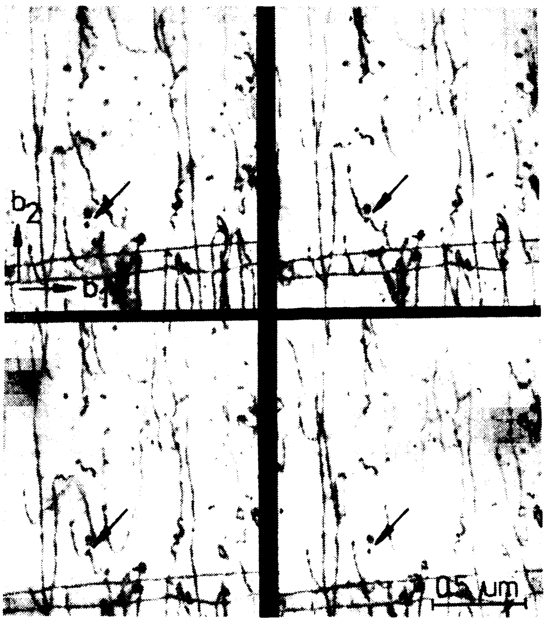

Fig. 2. Dislocation motion during the in situ deformation of an MgO single crystal in the high voltage electron microscope. Interaction of a dislocation gliding downward with a small prismatic dislocation loop (---⟩).

In situ deformation experiments in the high voltage electron microscope were performed on MgO single crystals [7]. The material has the same ⟨110⟩{$\bar{1}$10} slip geometry as NaCl and the processes governing the disloctaion mobility are similar. The experiments show that dislocation dipoles and debris are frequently trailed and terminated behind relatively high jogs in gliding screw dislocations. The jogs are formed by cross-slip, which is often induced by the elastic interaction occurring between intersecting dislocations [8]. Fig. 2 shows numerous small prismatic loops formed by dislocations intersecting on orthogonal ⟨110⟩{$\bar{1}$10} systems. The debris defects strongly impede the motion of successive dislocations.

3. Discussion

The work hardening of NaCl is connected with a strong increase of the reciprocal activation volume. This change of $1/v$ should be attributed to the generation of new short-range obstacles since the structure of the impurity defects determining $1/v$ at the beginning of deformation is certainly not changed by straining. Annealing at relatively low temperatures recovers both τ nad $1/v$. It may therefore be concluded that the recovered defects are dipoles or debris, which contributed with a thermal stress part τ_s^* to the flow stress τ_1. The obstacle strength of the defects may then be characterized in terms of activation parameters of the thermally activated dislocation glide mainly supposing the following two assumptions. First, under work hardening conditions the flow stress τ_1 is linearly composed of the stress parts τ_p^*, τ_s^*, and τ_μ.

(1) $$\tau_1 = \tau_p^* + \tau_s^* + \tau_\mu .$$

τ_p^* and τ_s^* describe the thermal stress parts arising from the impurities and the deformation-induced short-range defects, respectively. τ_μ is an athermal stress part. The total activation volume is then given by

(2) $$1/v_1 = 1/v_p + 1/v_s .$$

The approximation has been proposed by Kocks et al. [9] for the superposition of two thermally activated processes with obstacles being most different in strength. Second, the flow stress change $\tau_1 - \tau_1^A$ is proportional to the change of $1/v_1 - 1/v_1^A$. The flow stress difference may then read [10]

(3) $$\tau_1 - \tau_1^A = [(1/v_1) - (1/v_1^A)]\,[\Delta F_s^* + kT \ln(\dot{a}/\dot{a}_0)] .$$

ΔF_s^* is the total free activation energy for overcoming the deformation-induced defects at a given deformation temperature and strain rate, $\dot{a}_0$ is a constant, and kT has the usual meaning. The quantity $\Delta F_s^* + kT \ln(\dot{a}/\dot{a}_0)$ can be determined from the measured changes of both the flow stress and the activation volume. It describes the energy part $v_s\tau_s^*$ done by the effective stress to overcome the deformation-induced short-range defects. The evaluation of the data yields

$$v_s\tau_s^* = 1.7\ \text{eV} .$$

The energy ΔF_s^* being characteristic of the obstacle strength is given by $\Delta F_s^* = \Delta G + v_s\tau_s^*$. ΔG si the Gibbs free energy of activation. With the value $\Delta G = 0.2$ eV. being typical of NaCl [11] one obtains

$$\Delta F_s^* = 1.9\ \text{eV} .$$

This energy characterizes the dipole defects as very strong obstacles to gliding dislocations.

4. Conclusions

A considerable part of the work hardening of ionic crystals in stages II and III of deformation arises from dislocation dipoles and debris. The defects contribute with athermal stress part to the flow stress and have a high obstacle strength.

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