Effect of a static magnetic field on the rate of macroplastic flow of ionic crystals

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An increase in the rate of plastic flow of ionic crystals, by a factor up to 2, has been observed in a static magnetic field $B=0.7$ T at room temperature. © *1995 American Institute of Physics.*

Research[1-3] on the mobility of individual dislocations in ionic crystals subjected to a static magnetic field with an induction $B \sim 1$ T suggests that the field leads to a detachment of dislocations from certain types of stops of impurity origin.[1,4] During macroplastic deformation, the spectrum of stops for gliding dislocations becomes much broader, the internal stress increases, and the motion of dislocations becomes self-consistent. It is thus impossible to predict beforehand just how important the effect of a magnetic field will be under these conditions. In this letter we are reporting a study of plastic flow of several ionic crystals (NaCl, KCl, and LiF) with impurities (Ca, Pb, and Mn) in various concentrations in a magnetic field $B=0.7$ T.

Test samples with dimensions of $3\times3\times10$ mm were quenched from 800 K and then subjected to uniaxial compression along the [001] direction in an apparatus with quartz shafts. The apparatus created a stress which increased linearly with time: $\sigma = kt$. The strain in the sample, ϵ, and the rate of strain $\dot{\epsilon}$ were recorded by a chart recorder with an induction pickup (the resolution in terms of the displacement was 0.2 μm). A magnetic field was imposed in a direction perpendicular to the compression axis on various parts of the $\epsilon(\sigma)$ curve. The rise time and decay time of the field pulse were about 2 s, so the plastic flow of the crystals could not possibly be influenced by a vortical electric field. Particular care was taken to remove artifacts[5] during the application of the magnetic field. The success of these measures was demonstrated by several independent methods.

In the elastic-strain region (up to the yield point σ_y) the application of the field does not cause a change in the slope of the $\epsilon(\sigma)$ curve, but it does reduce σ_y. At $\sigma > \sigma_y$ the application of the field leads to a rate of plastic flow, $\dot{\epsilon}_f$, higher than the rate before the application of the field, $\dot{\epsilon}_0$ (Fig. 1). This effect was considerably greater in NaCl and KCl crystals containing Ca as an impurity and in LiF crystals containing divalent metals (primarily Mg) as an impurity than in nominally pure crystals. An increased value of $\dot{\epsilon}$ was observed throughout the deformation process in the field (up to ~ 200 s, which corresponded to an increment in the strain in the sample $\Delta\epsilon \approx 0.1\%$). The removal of the field reduced $\dot{\epsilon}$, i.e., the weakening in the field was reversible. The abrupt application of a mechanical load $\Delta\sigma = 30$–40 kPa to a sample during the deformation caused an increase in $\dot{\epsilon}$ comparable to the increase in $\dot{\epsilon}$ in a magnetic field, but only over the first 10 s after the application of the load. After this time, the slope assumed its previous value (Fig. 1). The effect of the magnetic field thus cannot be simply the same as the effect of

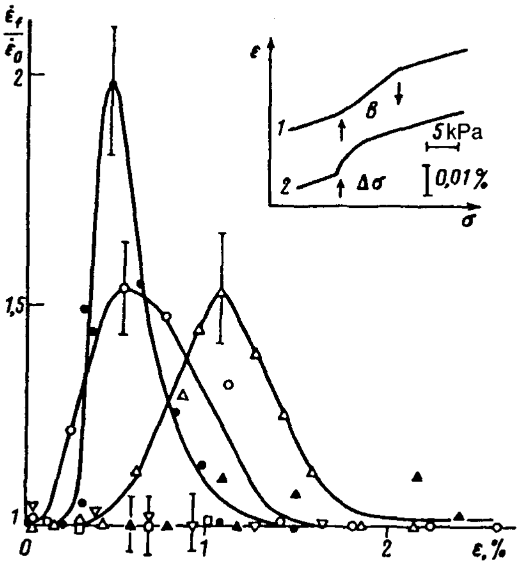

FIG. 1. Rate of plastic strain in a static magnetic field $\mathbf{B}=0.7$ T, $\dot{\epsilon}_f$ (normalized to the flow rate with the field off, $\dot{\epsilon}_0$), versus the total strain in the crystals, ϵ. ●—NaCl:Ca^{2+} (0.1%); ○—KCl:Ca^{2+} (0.03%); △—LiF:Mn^{2+}(<0.01%), dislocation-glide lines $\mathbf{L}\perp\mathbf{B}$; ▽—KCl:Pb^{2+} (0.03%); □—KCl:Mn^{2+} (0.03%); ▲—LiF:Mn^{2+} (<0.01%), $\mathbf{L}\|\mathbf{B}$. The inset shows fragments of the $\epsilon(\sigma)$ curve. 1) During the application of a magnetic field; 2) during an abrupt increment in the mechanical load.

an additional mechanical load. The weakening effect usually reaches a maximum just beyond the yield point, and it decays at $\epsilon > 1-2\%$ (Fig. 1). On occasion the effect is also seen at greater values of the strain, but in such cases it is irregular and not reproducible.

Several experiments were carried out. In these experiments the predominant direction of the dislocation glide with respect to the vector **B** was set by the preliminary creation of stress concentrators. This direction was monitored by etching. These experiments revealed that the weakening was much more pronounced when the dislocation glide lines **L** were perpendicular to **B** than in the case $\mathbf{L}\|\mathbf{B}$ (Fig. 1). The effect of the magnetic field depends on the orientation of **B** with respect to the dislocation line. A possible reason for the irregular dependence of the effect on the strain at $\epsilon > 2\%$ is a change in glide plane. As the concentration of the Ca impurity is increased, the weakening effect increases, up to $C \approx 0.1$ mole % (Fig. 2). As in Refs. 1–3, in which an increase in the range of individual dislocations was observed in a magnetic field, the dependence of the magnitude of the effect on **B** and our own experiments is approximately quadratic (Fig. 3). In crystals with a Pb or Mn impurity, a weakening is not observed. This result agrees with the results of Refs. 1 and 2 regarding the effect of a magnetic field on the mobility of individual dislocations.

The well-studied effects of a magnetic field on macroplastic characteristics of metals (Al, Pb, Ag) have customarily been interpreted on the basis of a change in the viscosity of the electron gas in the magnetic field and its damping properties for moving dislocations.[6–8] Such mechanisms obviously cannot play a role in the motion of disloca-

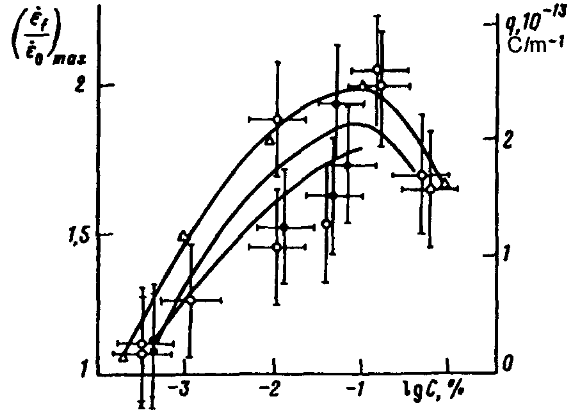

FIG. 2. Magnitude of the weakening at the maximum, $(\dot{\epsilon}_f/\dot{\epsilon}_0)_{\max}$, and dislocation charge per unit length, q, versus the concentration of Ca^{2+} impurity ions in several crystals. ○—NaCl; ●—KCl; △—q in KCl.

tions in ionic crystals. At the same time, the reasons why a magnetic field affects the mobility of dislocations and the plasticity of nonmetallic crystals may be quite general and may be pertinent to a long list of materials.

The fact that the effect is regularly reproducible in only a narrow strain interval indicates that the magnetic field facilitates the surmounting of only a certain fraction of the stops which are important in the initial stage of the plastic flow. These stops are evidently point defects, primarily of impurity origin. The dislocation forest which arises at $\epsilon \geqslant 1-2\%$, and which plays a greater role than impurity centers in slowing gliding dislocations, seems to be relatively insensitive to the effect of the magnetic field, according to Fig. 2. In crystals in which a weakening is observed, the magnitude of the weakening, $\dot{\epsilon}_f/\dot{\epsilon}_0$, is correlated with the dislocation charge per unit length, q (which was measured by a method involving analysis of the dislocation electric polarization[9]; Fig. 2). The absence of the effect from the crystals with a Pb or Mn impurity, which leads to the

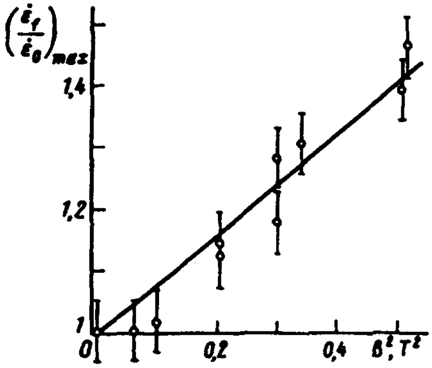

FIG. 3. The weakening effect $(\dot{\epsilon}_f/\dot{\epsilon}_0)_{\max}$ of KCl:Ca (0.03%) crystals versus the magnetic induction.

same dislocation charge as a Ca impurity, does not imply that the magnetic field fails to influence charging features of the dislocation core. The surmounting of impurity centers of various chemical natures (Pb, Ca, Mn) by dislocations can occur by quite different methods. This circumstance may in turn determine the degree of sensitivity of the plastic properties to changes that occur in the dislocation core in a magnetic field. Furthermore, it follows from Ref. 10 that changing the state of the core in a magnetic field requires application of the field for a much longer time ($\sim 10^3$ s at room temperature) than in the present experiments ($\sim 10^2$ s).

An explanation of the magnetoplastic effect in ionic crystals was offered in Refs. 1 and 4. That explanation was based on magnetic-field-sensitive radical reactions, which have been observed on several occasions.[11,12] These reactions can apparently occur both between a dislocation and an impurity as they interact and between elements of a dislocation core, preparing a dislocation for a subsequent easier glide. The observation and study of spin-dependent reactions in solids in magnetic fields might be of interest not only to the physics of strength and plasticity but also to other disciplines (chemistry, molecular biology, etc.).

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