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Magnetoplastic Effect in Nonmagnetic Materials: Experimental Studies and Computer Simulations

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Summary

The magnetoplastic effect manifests itself in a transformation of the structure of the impurity pinning centers in crystals exposed to an external magnetic field which modifies their mechanical properties. As a result, an ordinary nonmagnetic crystal becomes a smart material whose physical properties may be controlled by means of the external magnetic treatment. The basic features of this phenomenon and its established physical mechanisms are discussed. A series of results of experimental studies and computer simulations of the magnetoplastic effect are presented.

Introduction

Magnetoplasticity in nonmagnetic crystals is a very peculiar phenomenon discovered by the experimental group of the first author. It was found [1, 2] that dislocations in alkali halides and metals under the field $B \sim 1$ T, in the absence of loads or any other external actions, moved at macroscopic distances $l \sim 10 \div 100$ μm. Then this phenomenon was studied in details in the same group and by many independent researchers (see review articles [3-7]). The effect manifests itself in a remarkable change of a pinning force on dislocations from point defects under external magnetic field. This change is caused by an elimination of quantum exclusion of some electron transition in the system impurity-dislocation due to an evolution of a spin state in this system under the influence of a magnetic field. After the above transition a configuration of the pinning center becomes completely different and the pinning force also changes. As a rule this leads to a softening of crystals, however for some specific choice of doping there are also known examples of their strengthening. For instance, the hardening of NaCl(Pb) crystals in the magnetic field was revealed. Thus, the magnetoplastic effect provides an example of a quantum phenomenon displaying itself in crystal properties at room temperature.

Manifestations of the magnetoplastic effect were experimentally found both in the mobility of individual dislocations and in such macro-plastic processes as active deformation ($\dot{\varepsilon} = \text{const}$), active loading ($\dot{\sigma} = \text{const}$), creep ($\sigma = \text{const}$), internal friction, microhardness, etc. The effect was observed in alkali halide crystals (NaCl, LiF, CsI, KCl), non-magnetic metals (Zn, Al), semiconductors (InSb, ZnS, Si) and some molecular crystals. In particular, the yield stress of NaCl(Ca) and LiF(Mg) crystals decreased 2-3 times under the magnetic field $B = 0.5$ T.

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The paper presents a short survey of main results obtained in this area. We shall introduce a kinematical model of dislocation motion under the magnetic field based both on experiments and on computer simulations. The particular physical mechanisms of the phenomenon will be also discussed.

Basic experimental features of the phenomenon

It turned out that the change in the polarity of the constant magnetic field is not attended by a change in the direction of dislocation motion. However, the effect somewhat depends on the magnetic field orientation with respect to dislocations and slip planes. In particular, no motion of rectilinear dislocations parallel to the magnetic field is observed in the alkali halide crystals.

The experimental data show that the relative density of dislocations moving in the magnetic field appreciably increases, with an increase in the induction B and the time t of magnetic treatment of the samples and can be as high as $80 \div 100\%$ of the density of freshly introduced dislocations in the alkali halide crystals.

The effect is weakly temperature dependent: lowering of the temperature from 300 to 77 K provides a decrease of the mean dislocation path l only by $15 \div 20\%$, and the value of l at 4 K is practically the same as at 77 K. It was found that the effect in alkali halide crystals is highly sensitive to low doses of X-ray irradiation and to simultaneous action of an electric field and mechanical loading.

There is a lower threshold magnetic induction B_c below which the magnetoplastic effect is practically absent. With a decrease in temperature the magnitude of B_c also decreases. B_c is interpreted as a magnetic induction below which the dislocation depinning time $\tau_{dp} \propto B^{-2}$ exceeds the spin-lattice relaxation time τ_{sl} independent of the magnetic field but sensitive to the temperature.

The mean dislocation path l increases with the magnetic treatment time t and the square of the magnetic induction B. At large values of B^2 a saturation of the dependence $l(B)$ was observed: $l \propto [1 + (B_0/B)^2]^{-1}$. Variations of the Ca impurity concentration C in NaCl crystals showed that $l \propto 1/\sqrt{C}$.

Taking into account that the path l is roughly proportional to the time t of magnetic treatment, one can introduce a mean dislocation speed $v = \Delta l/\Delta t$, which empirically may be characterized by the dependence

$$v \propto 1/\sqrt{C}\,[1 + (B_0/B)^2]\,. \tag{1}$$

The critical frequency ν_c of rotation of a sample in the magnetic field above which the effect disappears was also experimentally found. At ν well below ν_c the mean dislocation path l is almost independent on ν but at $\nu > \nu_c$ the path l is fast decreasing. The value ν_c has proved to be practically insensitive to the concentration C of impurities but quite sensitive to a type of impurity and to the induction B : $\nu_c \propto [1 + (B_0/B)^2]$. The existence of the critical frequency ν_c fits the idea of a

spin precession around the direction of **B** which losses its coherence at sufficiently high frequency ν. Apparently this prevents a spin transition in the system. A direct experimental proof of a spin nature of the magnetoplasticity was given by Golovin & Morgunov [8] who first observed an ESR-type resonance of dislocation mobility in NaCl crystals exposed to the crossed magnetic fields, static and microwave. The analogous resonance was later also found in Si crystals [9].

Kinematic scheme of the dislocation motion

Let us choose such a type of dislocation behavior under the magnetic field which would provide dependencies (1). In accordance with our data the motion of dislocation occurring due to their magnetoinduced depinning has the character of relaxation of the dislocation structure in the internal long-range stress field caused by other dislocations. In described experiments the magnetic field transforms only the pinning centers in dislocation cores, i.e. the transformation process starts just after the direct contact between the dislocation and the point defect, so that the depinning time decreases with an increase in the magnetic induction.

The velocity v of the motion can be expressed as a ratio of the mean distance Δx between local obstacles in the slip plane to the time Δt of dislocation motion between adjacent rows of obstacles. The mean distance can be estimated as $\Delta x \sim 1/\sqrt{C a_l}$, where a_l is of the order of the lattice parameter. The time Δt of dislocation motion to the next row of obstacles can be represented in the form of the product $\Delta t \sim n_{unz}\,\tau_{dp}$, where τ_{dp} is the time of depinning of the dislocation from one impurity atom and n_{unz} is the mean number of atoms being sequentially overcome by the dislocation in its motion from one row of impurities to another in the process of 'unzipping'. For the low internal stresses, the condition for dislocation depinning under the magnetic field is not satisfied at each obstacle and not for each dislocation. This conclusion follows from the observed relay-race character of the dislocation motion. However, if the depinning condition is met on some *active* obstacle ready to spin transformation (say, on a paramagnetic ion Ca^{+}, Mg^{+} or Pb^{+}, instead of ordinary non-magnetosensitive Ca^{++}, Mg^{++} or Pb^{++}) then after unfastening from it, the critical conditions arise on the next stopper etc. That is the so called unzipping regime of dislocation motion. Returning to the velocity $v = \Delta x/\Delta t$, one can estimate it as

$$v \sim 1/n_{unz}\tau_{dp}\sqrt{C a_l}\,. \tag{2}$$

This approximate equation empirically fits Eq. (1) if: i) the product $n_{unz}\,\tau_{dp}$ is weakly sensitive to the impurity concentration C and ii)

$$\tau_{dp} \propto 1 + (B_0/B)^2\,. \tag{3}$$

According to the experimental data, the time τ_{dp} of an elementary step of dislocation depinning from a local obstacle should be virtually independent of the

temperature. In addition, by the physical sense of the depinning time it should be proportional to the inverse critical frequency, $\tau_{dp} \propto 1/\nu_c$, and the latter value is experimentally independent of C. Thus, it is expected that the time τ_{dp} is also independent of C.

The weak sensitivity of n_{unz} to the concentration C results from the following consideration. Evidently, the number n_{unz} is determined by the ratio $n_{unz} = N_s/n_{act}$, where N_s is the total number of pinning points and n_{act} is the number of active centers ready to spin transformation on the dislocation line. The value n_{act} must be proportional to $N_s : n_{act} = wN_s$. Here w is a probability of the definite configuration of the impurity center. Being a local characteristic of a center this factor should be insensitive to the impurity concentration. In these terms, $n_{unz} = N_s/n_{act} = 1/w$. For $w << 1$ we expect n_{unz} to be a large number and independent on C.

The physical mechanism of magnetoplasticity

The physical mechanism of spin evolution in the magnetic field providing the dependence expected from (3) can be attributed to a spin relaxation of a radical pair suggested by Brocklehurst [10]. This mechanism first introduced for a description of chemical reactions under the magnetic field is associated with the anisotropy of the g factor (as a rule, estimated at $\Delta g \sim 10^{-2} \div 10^{-3}$), which leads to the magnetically stimulated transitions between the S and T states of radical pairs. In this case, one has to distinguish the longitudinal and transverse spin relaxations that correspond to the $S \leftrightarrow T_{\pm}$ and $S \leftrightarrow T_0$ singlet-triplet transitions and are characterized by the times τ_1 and τ_2, respectively. Only the former time τ_1, determined by attainment of the equilibrium spin projection onto the magnetic field direction, provides the observed type, (see (3)), of the dependence of τ_1 on B:

$$\tau_1 = \frac{5\tau_c}{(\Delta g)^2}\left(\frac{B_0^2}{B^2} + 1\right). \tag{4}$$

Here τ_c is the correlation time of rotational motion of a radical. When describing the spin relaxation in the paramagnetic center - dislocation system ($\tau_{dp} = \tau_1$), one naturally replaces the correlation time τ_c by the characteristic period of vibrations of dislocation segments pinned by paramagnetic impurities. In our experiments the field $B_0 \sim 1$T corresponds to the time $\tau_c \sim 10^{-10}$ s, which is in agreement with estimates for the eigen-frequency of vibrations of dislocation segments.

Computer simulations

In computer simulations the random internal stresses were replaced by a constant external driving force. Dislocations were considered in a line tension approximation and their interactions with point defects were supposed to be of a contact type. The motion of a dislocation through the point defects "forest" consisted of the individual jumps of its separate segments hooked on the obstacles (pinning points)

and of generations the new configurations. The segment is unlocked from the hook when the angle between the neighbor arcs becomes less than a certain critical value. The algorithm stops when the dislocation line passes over all the obstacles, or when there are no more critical angles between any two neighboring arcs. Thermal and magnetic actions were simulated in terms of their influence on the critical angle.

The motivation for computer simulations, imitating physical experiments, was associated with getting additional information which could not be extracted from real measurements. We were especially interested in distributions of dislocation segments lengths on stationary moving dislocations, in characteristics of unzipping processes and in typical numbers of active pinning points on a dislocation when it moves under the magnetic field. Fig. 1 shows some hidden data of this sort obtained from the computer experiments. For every stop of the dislocation line the

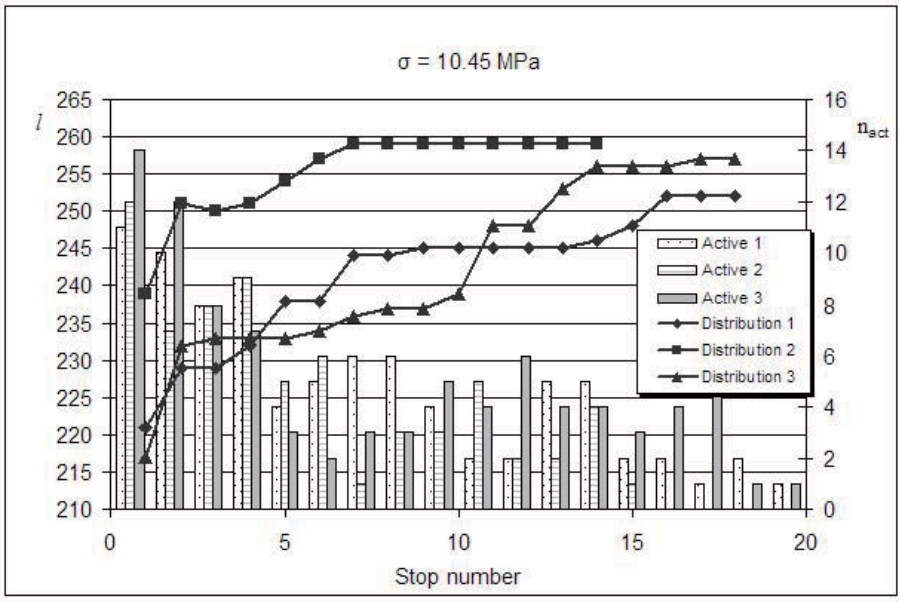

Figure 1: The distance made by the left end of the dislocation and the number of active obstacles on the dislocation line at each its stop for the three realizations of point defect distribution at the fixed external driving stress $\sigma = 10.45$ Mpa

number n_{act} of active stoppers was counted (see the right ordinate axis). The active obstacles were understood as defects which were ready to let the dislocation go due to some magnetoinduced processes after the depinning time τ_{dp} dependent on the magnetic induction B. On the left ordinate axis the distances between the separate stops of the surface dislocation end are given. One can see that stops of dislocations fixed in real experiments by etch pit technique on the surface in fact do not always relate to the absence of the dislocation motion in the bulk. On all three curves in

Fig. 1 one can see the horizontal regions where the number of active centers on the dislocation line is substantial. This means that even on this regions some internal dislocation motions continue.

Conclusions

Thus, the mechanisms and various features of the magnetoplastic effect become more and more clear. Of course, there is not yet a complete understanding of all manifestations of this phenomenon. However, the main grounds of its physical nature are basically understood. The suggested kinematic schemes of magnetoplasticity on micro- and macro levels allows one to describe (sometimes, even quantitatively) almost all specific features of the experimental findings. This concerns the mobility of individual dislocations under the magnetic field in alkali halide crystals, nonmagnetic metals and semiconductors, in particular, the dependencies of the mean dislocation path on the magnetic induction, impurity concentration, temperature etc.

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