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Modelling of the Magnetoplastic Effect

***Abstract**. The basic properties of the magnetoplastic effect in the non-magnetic materials are discussed. The physical model of the phenomenon is proposed. The results of the computer simulations of this phenomenon based on formulated model are presented and the comparison with the experimental observations are given.*

***Streszczenie.** Przedyskutowano podstawowe właściwości zjawiska magnetoplastyczności w materiałach niemagnetycznych. Zaproponowano fizyczny model omawianego zjawiska. Przeprowadzono symulacje komputerowe wykorzystujące skonstruowany model zjawiska, a otrzymane wyniki porównano z danymi doświadczalnymi. (**Modelowanie zjawiska magnetoplastyczności**.)*

Keywords: magnetoplasticity, nonmagnetic materials, computer simulations, modelling.
Słowa kluczowe: magnetoplastyczność materiały niemagnetyczne, symulacje komputerowe, modelowanie.

Introduction

The magnetoplastic effect in non-magnetic materials (MPE) manifests itself in a transformation of the structure of impurity pinning centers of crystal dislocations. This effect appears after the exposition of the probe to an external magnetic field and finally the mechanical properties of the crystal are modified.

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 new results of the experimental studies and parallel computer simulations of the magnetoplastic effect are presented.

Magnetoplasticity in nonmagnetic crystals is a very peculiar phenomenon. It was discovered by the experimental group in the Institute of Crystallography in Moscow [1,2].

It was found that dislocations in alkali halides and non-magnetic metals under the action of the magnetic field of the order of B~1T in the absence of other loads or any other external actions moved at macroscopic distances of the order of ~10-100μm. This phenomenon was studied in details not only by the same group but also by many independent researchers.

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 so that 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. As an example let us note the hardening of NaCl(Pb) crystals in the magnetic field was revealed.

It was found that the magnetoplastic effect provides an example of a quantum phenomenon manifesting itself in crystal properties at room temperature.

Basic experimental features of the phenomenon

The big number of experiments with MPE for different non-magnetic materials and different strengths of magnetic field was done. It was found among others that:

1. the effect 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;
2. 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;
3. the effect is weakly temperature dependent: lowering of the temperature from 300°K to 77°K provides a decrease of the mean dislocation path l only by 15-20%;
4. the value of l at 4°K is practically the same as at 77°K;
5. the effect in alkali halide crystals is highly sensitive to low doses of X-ray irradiation and to simultaneous action of an electric field or mechanical loading;
6. there is a lower threshold magnetic induction B_c below which the magnetoplastic effect is practically absent;
7. with a decrease of the temperature the magnitude of B_c also decreases.

The value of the critical magnetic induction field B_c is interpreted as a magnetic induction below which the time of dislocation depinning $\tau_{dp} \propto B^{-2}$ exceeds the spin-lattice relaxation time τ_{sl} independent of the magnetic field but sensitive to the temperature.

The mean dislocation path l linearly increases with the magnetic treatment time t and the square of the magnetic induction B. At large values of B^2t a saturation of the dependence $l(B)$ was observed

$$l \propto \left[1+\left(\frac{B_0}{B}\right)^2\right]^{-1}. \tag{1}$$

Variations of the Ca impurity concentration C in NaCl crystals showed that

$$l \propto 1/\sqrt{C}. \tag{2}$$

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

$$\Delta x \sim 1/\sqrt{(Ca_i)} \tag{3}$$

For the low internal stresses in our crystals, 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.

If the depinning condition is met on some active obstacle ready to spin transformation like on the paramagnetic ion

$$Ca^+, Mg^+ \text{ or } Pb^+$$

instead of ordinary non-magnetosensitive

$$Ca^{++}, Mg^{++} \text{ or } Pb^{++}$$

then after unfastening from it, the critical conditions arise on the next stopper etc. That is also called the unzipping regime of the dislocation motion.

Computer simulations

In Fig. 1 the main ideas of the computer simulation of the dislocation line walk through the crystal is shown. It is seen that the dislocation line stops between two point defects – these are the pinning point centers. It is assumed that interactions of the dislocations lines with the point defects are of a contact type. The motion of a dislocation through the point defects "forest" consists of the individual jumps of its separate segments hooked to the obstacles and of generations the new configurations.

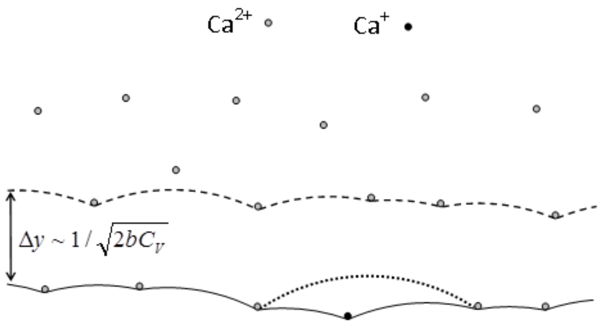

Fig.1. Starting position of the dislocation (solid line) and its position on the second line of obstacles (broken line). Dotted segment represents the first unlocking of the dislocation from the magnetoactive center (black circle) after the magnetic field was switched on and the beginning of the cascade unzipping propagation (to the left and to the right).

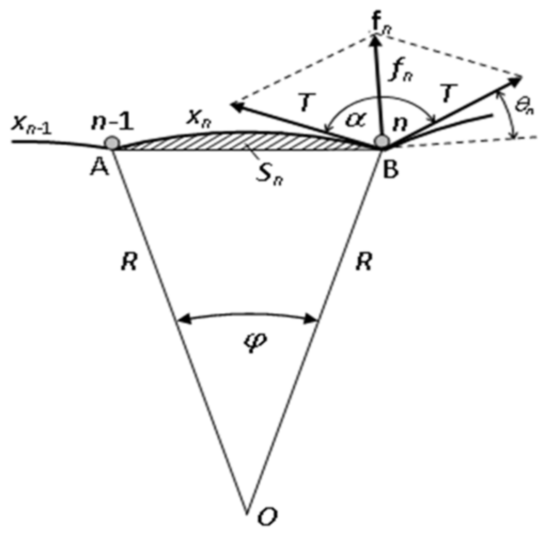

Fig.2. Force $\boldsymbol{f}_n$ acting by dislocation on the point defect n, α_n - opening angle, S_n - area occupied by the dislocation before stop.

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. For every stop of the dislocation line the number n_{act} of active stoppers was counted. The active obstacles are understood as defects which are ready to let the dislocation go due to the some magneto-induced processes after the depinning time τ_{dp} dependent on the value of the magnetic induction B.

The acting force is proportional to $1/R$, where R is the curvature radius of the dislocation segment. When the magnetic field is acting it changes the spin structure of the point defect, the depinning force becomes smaller and the dislocation line can move in the direction of the next point defect.

The all process depends strongly on the density of the point defects in the crystal and on the kind of the interaction of the obstacles with the crystal lattice. This interaction is modelled by value of the critical angle and the results are shown in Fig.3.

In Fig.3 the dependence of the force acting on the dislocation proportional to the inverse of the arc radius of the bended dislocation line on the parameter $\theta_{cr}^{3/2}$, where $\theta_{cr} = 0.5(\pi - \alpha_{cr})$, and α_{cr} – critical angle is shown.

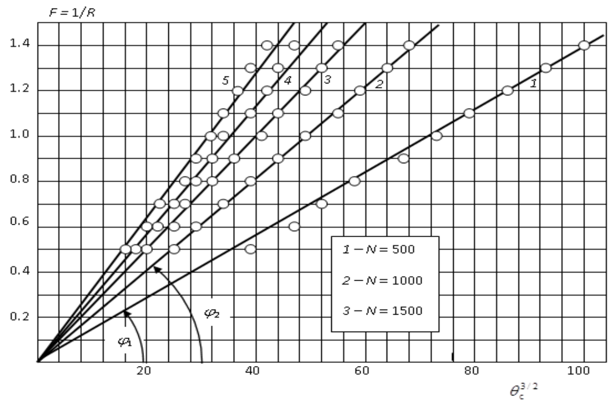

Fig. 3. Dependence of the threshold force F_{cr} on the critical angle for various numbers of the point defects.

It is seen that with growing the point defects density (here described by the number N – the number of the point defects seen on the cut surface inside the crystal) the angle φ (see Fig. 2) is growing too.

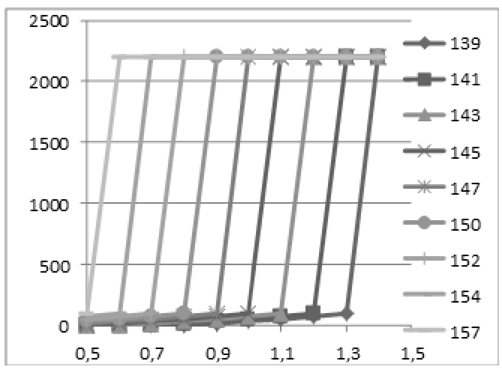

Fig. 4. Dependence of the critical angle α_{cr} on the number of the point defects.

In Fig. 4 the dependence of the critical angle α_{cr} (here from 139° to 157°) on the number of the point defects (it changes here from 0 to 2500) is shown and when the dislocation can move further on with the acting force F_{cr} for the given number of point defects. Here also the interesting regularity is observed what suggest that our assumption on the character of the physical process is confirmed.

The histogram in Fig. 5 represents the frequency of the appearing of arcs with different lengths as a percentage length in respect to the dislocation length on the screen for the number of defects N = 500, acting force F ~ 0.5, and critical angle α_{cr} = 157°. This is an example of a histogram, and it shows typical form of them, the shape of the histogram is asymmetric, it is shifted to the left – the number of the "long" arcs is limited.

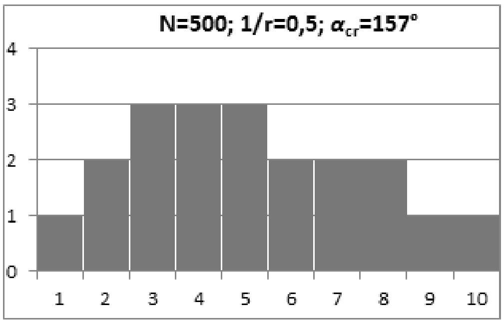

Fig. 5. Histogram of the frequency of arcs of the dislocation line having from 1% to 10% of the length of the total length of the dislocation line, number of defects N = 500, acting force F ~ 0.5, critical angle α_{cr}=157°.

This result is in a very good agreement with the experimental data which are published elsewhere [5].

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