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Magnetoplastic effect in non-magnetic crystals and internal friction*

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Abstract

A new physical phenomenon, the magnetoplastic effect, was found and investigated in a series of non-magnetic crystals (NaCl, CsI, LiF, Zn, Al). The phenomenon manifests itself in dislocation displacements as a result of exposing the specimens to a static magnetic field in the absence of mechanical loading. The effect was studied experimentally as a function of the time of magnetic treatment of the samples, the magnitude and orientation of the magnetic field ($B=0.05$–2 T), the temperature ($T=4.2$–293 K), the type and concentration of impurities, the density of "forest" dislocations and the frequency ($\nu=0$–200 Hz) of the alternating (over orientation) magnetic field. A strong effect of a weak static electric field ($E=2$–30 V cm^{-1}) on the dislocation mobility in NaCl specimens simultaneously exposed to a static magnetic field ($B=0.1$–0.4 T) is found (with no electric influence at $B=0$).

A physical interpretation of the phenomenon is proposed. Possible manifestations of the magnetoplastic effect in the internal friction are discussed.

1. Introduction

The interaction between dislocations and point defects determines a series of different macroscopic processes, including internal friction and modulus defects. Usually for the evaluation of this interaction one uses a very simple estimate based on the idea of dilatational stresses produced by point defects and acting on dislocations. Actually this purely macroscopic mechanical approach looks to be rather naive in view of the microscopic character of the system (*e.g.* an impurity atom in the dislocation core), whereas a quantum mechanical description generally would be much more natural and may even be essential.

The discovery of the magnetoplastic effect [1] has appeared as an important reminder about the fairly complex physical nature of interactions between dislocations and impurities. It was found that exposing NaCl crystals to a static magnetic field without any mechanical loading causes dislocation displacements therein. In further studies of this effect [2–9] it was shown that the phenomenon manifests itself in various crystals (NaCl, CsI, LiF, Zn, Al), being almost temperature independent between 4.2 and 293 K and very sensitive to the impurity type and concentration. In this paper we shall review the main experimental facts related to the magnetoplastic effect, including new unpublished data. On this basis the physical mechanisms of the phenomenon will be discussed and its possible manifestations in the internal friction will be predicted. One will see that the accumulated data leave no room for a dilatational concept of dislocation–impurity interaction.

2. Experimental details

Most of the experimental data have been obtained on NaCl single crystals of several series of different provenances. The phenomenon has been found [1] in NaCl-1 crystals with a yield stress $\tau_y=400$ kPa and a total concentration $C<10$ ppm of impurities. In further experiments we also used NaCl-2 crystals ($\tau_y=500$ kPa, $C\approx10$ ppm) and their modifications: NaCl-2(Ni), with the same values of τ_y and C but with additionally introduced Ni impurities ($C^{\mathrm{Ni}}\leqslant0.06$ ppm), and harder NaCl-2(Cu) crystals ($\tau_y=2.65$ MPa). The third series of NaCl crystals included NaCl-3(Li) ($\tau_y=230$ kPa, $C^{\mathrm{Li}}\approx100$ ppm), NaCl-3(Pb) ($C_1^{\mathrm{Pb}}=5$ ppm and $C_2^{\mathrm{Pb}}=40$ ppm) and NaCl-3(Ca) crystals with various concentrations of Ca impurities: $C^{\mathrm{Ca}}=0.5$ ppm ($\tau_y=150$ kPa), $C^{\mathrm{Ca}}=1$ ppm ($\tau_y=200$ kPa), $C^{\mathrm{Ca}}=10$ ppm ($\tau_y=430$ kPa) and $C^{\mathrm{Ca}}=100$ ppm ($\tau_y=790$ kPa). In addition, we investigated single crystals of CsI ($\tau_y=90$ kPa, $C\approx1.2$ ppm), LiF ($\tau_y=300$ kPa, $C\approx10$ ppm), Zn of purity 99.9979% and Al of spectral purity.

Samples (for details of preparation see refs. 1, 3, 5, 7) with freshly introduced dislocations marked by etching were placed in a uniform static magnetic field $B=0.1$–2

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T (both an electromagnet and a permanent magnet were used) for a time t ranging from several seconds up to 1 h. After switching off the magnet, the crystals were etched again. Experiments were carried out at three temperatures: 293 , 77 and 4.2 K. We observed displacements of both edge and screw dislocations, but for all crystals except LiF sufficient statistics on dislocation paths to construct representative histograms were only available for edge dislocations. For LiF crystals histograms were also obtained for screw dislocations. Histograms of dislocation displacements measured for various combinations of experimental conditions were used to calculate the mean statistical values of dislocation paths l, and their dependences on various physical parameters were determined. The experimental error in the determination of l values was 10%–20%. Apart from the usual etch pit technique, we also used an *in situ* method, namely a slow continuous etching of samples directly in the magnetic field [4]. To study the dislocation mobility in an alternating magnetic field, we rotated the samples in a static field at various frequencies in the range $\nu = 0$–200 Hz at two temperatures, 293 and 77 K.

For the investigation of the electric field ($E = 0.2$–3 kV m^{-1}) influence on the magnetoplastic effect, the electrical contacts were produced from a special paste on the {100} surfaces of NaCl crystals.

3. Experimental results

One can see from Fig. 1 the dislocation displacements in an NaCl-1 crystal as a result of exposing it to a magnetic field $B = 0.5$ T for 5 min. After processing the corresponding histograms, the average dislocation displacement l may be studied as a function of various physical parameters. According to our data, the mean dislocation path l increases linearly with the time t of magnetic treatment (Fig. 2(a)), but at a long enough time t and a sufficiently high density ρ of dislocations the dependence $l(t)$ reaches saturation at a level corresponding to an average distance between "forest" dislocations of $1/\rho^{1/2}$ (Fig. 2(b)). Reversal of the magnetic field orientation ($\vec{B} \rightarrow -\vec{B}$) does not change the direction of dislocation motion. Correspondingly, with increasing magnitude B of the magnetic field the mean dislocation path l changes proportionally to B^2, with subsequent saturation at the same level $1/\rho^{1/2}$ (Fig. 3).

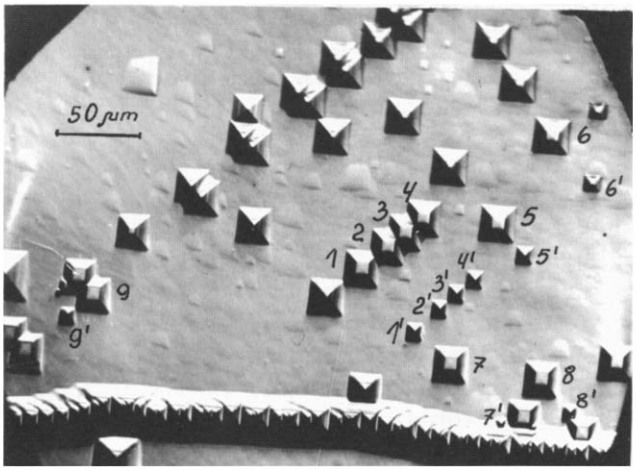

Fig. 1. Dislocation displacements in an NaCl-1 crystal under the action of a magnetic field $B = 0.5$ T for 3 min: 1,2,..., initial dislocation positions; 1′,2′,..., final dislocation positions.

Another physical characteristic which is sensitive to a magnetic field is the density ρ_m of mobile dislocations. In soft enough crystals (such as CsI or pure NaCl) the ratio ρ_m/ρ may reach almost the 100% level (Fig. 4).

One can see from Figs. 2–4 that both l and ρ_m/ρ do not tend to zero as $t \rightarrow 0$ or $B \rightarrow 0$. There are two

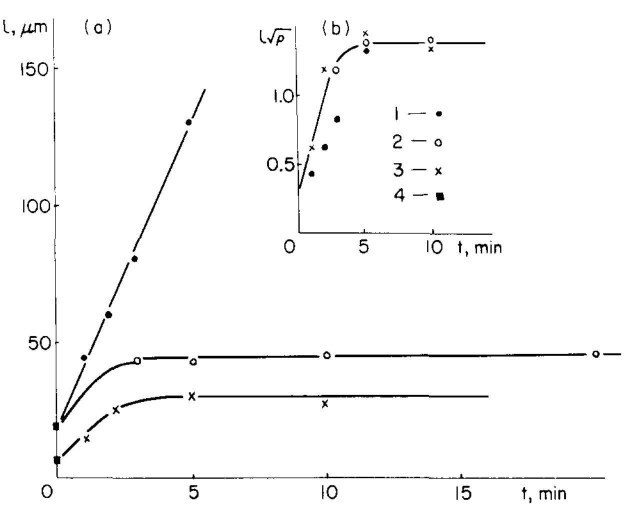

Fig. 2. Dependence of the mean dislocation path l in NaCl-1 crystals on the time t of exposure to a magnetic field $B = 0.5$ T for specimens with various densities of dislocations: 1, $\rho \approx 1 \times 10^4$ cm^{-2}; 2, $\rho \approx 1 \times 10^5$ cm^{-2}; 3, $\rho \approx 2 \times 10^5$ cm^{-2}; 4, dislocation path due to etching.

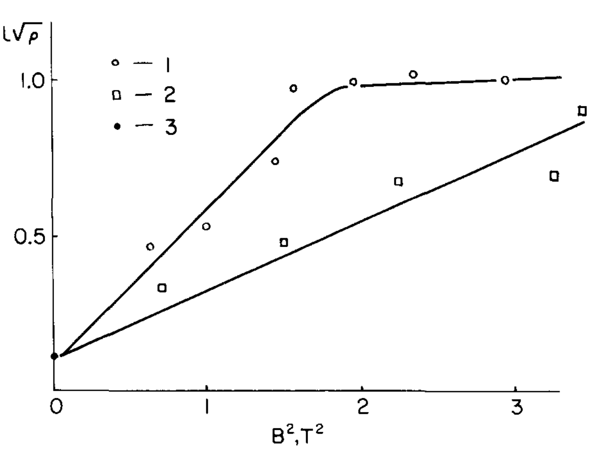

Fig. 3. Dependence of the relative mean dislocation path $l\rho^{1/2}$ on the magnetic induction B in Al and Zn crystals: 1, Al ($t = 15$ min); 2, Zn ($t = 5$ min); 3, dislocation path due to etching.

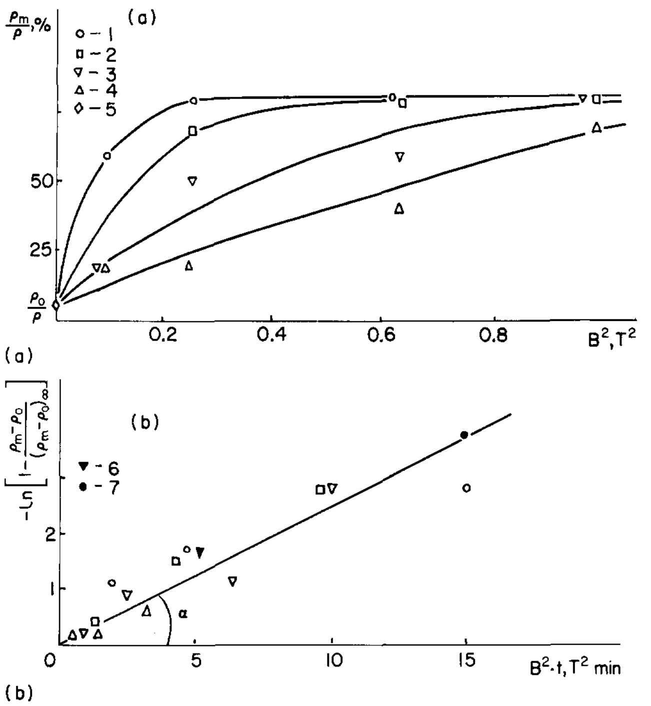

Fig. 4. (a) Dependence of the relative density of moving dislocations, ρ_m/ρ, in CsI crystals on the magnetic induction B and (b) the same dependence for the straightening coordinates: (a) 1, $t=20$ min; 2, $t=15$ min; 3, $t=10$ min; 4, $t=5$ min; 5, the "etching" point; (b) 6, $B=0.5$ T, $t=20$ min; 7, $B=1$ T, $t=15$ min.

different parasitic effects responsible for this peculiarity. The first is related to the etching of pre-surface obstacles on dislocation lines. As a result, dislocations change their positions slightly in the field of internal stresses. This well-known etching effect [10] is not sensitive to the magnetic field and determines the "zero" values of l and $l\rho^{1/2}$ in Figs. 2 and 3. The second parasitic effect is additional to the first and manifests itself upon quick enough switching on of the magnetic field only in some alkali halides (CsI, NaCl).

In situ experiments, where the samples were etched during all the time t of static magnetic treatment, have shown that the real time t_m of dislocation motion is always less than the time t. The dislocation delay at the start may be estimated [4] from the slope of the straight line in Fig. 4(b), which gives the probability of dislocation motion per unit time as

$$W_{st}=B^2 \tan \alpha \qquad (1)$$

According to ref. 4, when $W_{st}t \ll 1$, one should expect $t_m \approx \frac{1}{6}t$, which has been corroborated experimentally.

Figure 5 shows the dependence of the magnetoplastic effect in NaCl-3 crystals on the orientation of the magnetic field $\vec{B}$ with respect to directions of the dislocation line $\vec{L}$ and its Burgers vector $\vec{b}$. Essentially there is no effect for edge dislocations parallel to the magnetic field ($\vec{L} \| \vec{B} \| \{100\}$).

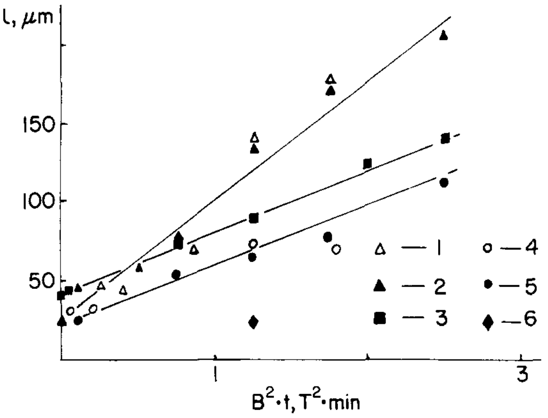

Fig. 5. Dependence of the mean dislocation path l in NaCl-1 crystals on the time t of magnetic treatment and the magnetic induction B for various orientations of the dislocation $\vec{L}$, its Burgers vector $\vec{b}$ and the magnetic induction $\vec{B}$: 1,2, $\angle\vec{B}, \vec{b}=45°$, $\vec{B} \perp \vec{L}$; 3, $\vec{B} \perp \vec{b}, \vec{B} \perp \vec{L}$; 4,5, $\vec{B} \| \vec{b}, \vec{B} \perp \vec{L}$; 6, $\vec{B} \perp \vec{b}, \vec{B} \| \vec{L}$; 1,4, from $l(B)$; 2,3,5,6, from $l(t)$.

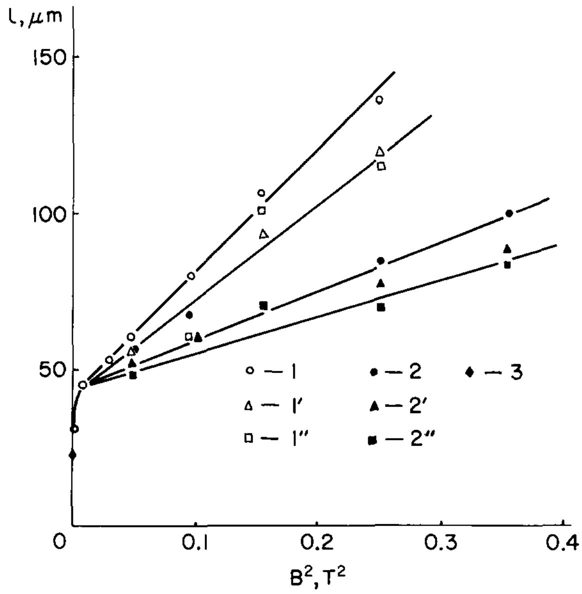

Fig. 6. Dependence of the mean dislocation path l on the magnetic induction B in NaCl-3(Ca) crystals with two different concentrations of Ca impurity for three temperatures: 1,1′,1″, $C=0.5$ ppm; 2,2′,2″, $C=10$ ppm; 1,2, $T=293$ K; 1′,2′, $T=77$ K; 1″,2″, $T=4.2$ K; 3, dislocation path due to etching.

Figure 6 demonstrates an extremely important and quite unexpected experimental fact: the effect is temperature independent in the range $T=4.2$–77 K and grows only by 15%–20% with further increase in T up to room temperature. On the other hand, according to Figs. 6–8, the phenomenon is very sensitive to the impurity content in our samples. In particular, Fig. 7 shows a clear correlation between the mean dislocation path l in NaCl-3(Ca) crystals and the concentration C of Ca impurities: $l-l_0 \propto 1/C^{1/2}$. A slight addition of magnetic Ni impurities to NaCl-2 crystals lends to a paradoxical increase in dislocation mobility (Fig. 8).

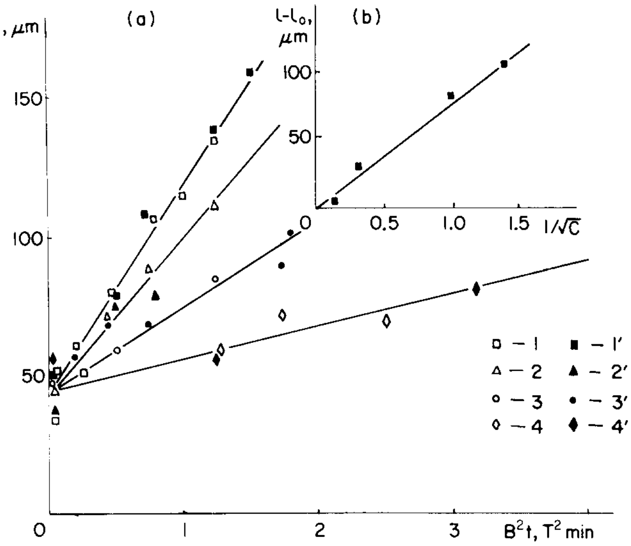

Fig. 7. Dependence of the mean dislocation path l (a) on the time t of magnetic treatment and the magnetic induction B for NaCl-3(Ca) crystals with various concentrations of Ca impurity and (b) on the impurity concentration C ($B = 0.5$ T, $t = 5$ min): 1,1′, $C = 0.5$ ppm; 2,2′, $C = 1$ ppm; 3,3′, $C = 10$ ppm; 4,4′, $C = 100$ ppm; 1–4, from $l(B)$; 1′–4′, from $l(t)$.

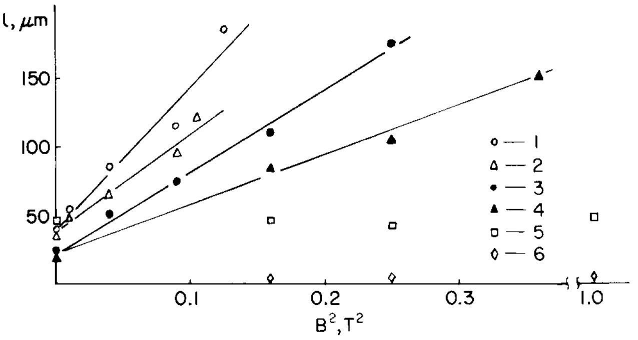

Fig. 8. Dependence of the mean dislocation path l on the magnetic induction B in NaCl-2, NaCl-2(Ni), NaCl-2(Cu) and NaCl-3(Pb) crystals with and without an additional static electric field E: 1, NaCl-2(Ni), $E = 1.2$ kV m^{-1}; 2, NaCl-2, $E = 1.2$ kV m^{-1}; 3, NaCl-2(Ni), $E = 0$; 4, NaCl-2, $E = 0$; 5, NaCl-3(Pb), $E = 0$; 6, NaCl-2(Cu), $E = 0$.

The diamagnetic impurities Pb and Cu "kill" the effect (Fig. 8).

Recently we have found a remarkable effect on the dislocation mobility in NaCl crystals of a weak external electric field ($E \leqslant 3$ kV m^{-1}) combined with a magnetic treatment (Figs. 8 and 9) with no electric influence at $B = 0$. The effect is linear with E (Fig. 9(b)). It is almost the same at 77 and 293 K but differs for different orientations of $\vec{E}$. In particular, an electric field $\vec{E}$ directed parallel to dislocations ($\vec{E} \parallel \{100\}$) and perpendicular to the slip plane ($\vec{E} \perp \vec{b}$) does not lead to a marked difference between the magnitudes $l(E = 0)$ and $l(E \neq 0)$ in Fig. 9. Reversal of the orientation of the electric field ($\vec{E} \to -\vec{E}$) changes the direction of dislocation displacements for an appreciable number of dislocations.

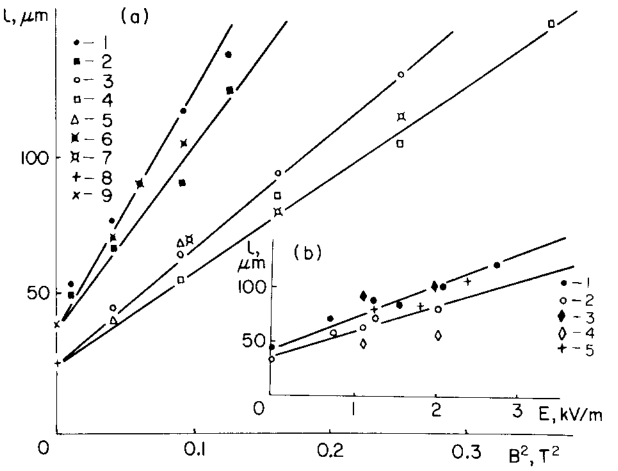

Fig. 9. Dependence of the mean dislocation path l (a) on the magnetic induction B ($t = 5$ min) and (b) on the electric field E ($B = 0.2$ T) for NaCl-1 and NaCl-2 crystals: (a) 1, NaCl-1, $E = 1.2$ kV m^{-1}; 2, NaCl-2, $E = 1.2$ kV m^{-1}; 3, NaCl-1, $E = 0$; 4, NaCl-2, $E = 0$; 5, NaCl-1, $E = 1.2$ kV m^{-1}, $\vec{E} \parallel \vec{L}$; 6, NaCl-1, $E = 1.2$ kV m^{-1}, $T = 77$ K; 7, NaCl-1, $E = 0$, $T = 77$ K; 8, "etching" point; 9, "etching" path plus technological effect (putting of contacts on crystal); 1,2,6, $\angle\vec{E}, \vec{b} = 45°$, $\vec{E} \perp \vec{L}$; (b) 1,5, NaCl-1; 2–4, NaCl-2; 1,2,5, $\angle\vec{E}, \vec{b} = \angle\vec{B}, \vec{b} = 45°$, $\vec{E}, \vec{B} \perp \vec{L}$; 3, $\vec{E} \parallel \vec{b}$, $\angle\vec{B}, \vec{b} = 45°$; 4, $\vec{E} \perp \vec{b}$, $\angle\vec{B}, \vec{b} = 45°$; 5, 77 K.

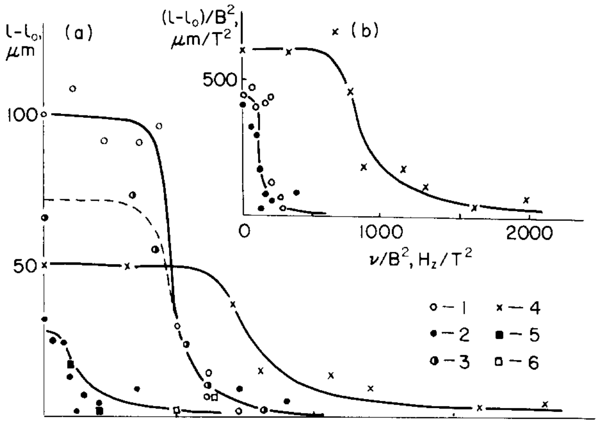

Fig. 10. Dependence of the mean dislocation path l on the frequency ν of specimen rotation for NaCl crystals with various impurity contents for various magnetic inductions B and temperatures T: (a) 1, NaCl-2, $B = 0.5$ T, $T = 293$ K; 2, NaCl-2, $B = 0.3$ T, $T = 293$ K; 3, NaCl-2, $B = 0.5$ T, $T = 77$ K; 4, NaCl-2(Ni), $B = 0.3$ T, $T = 293$ K; 5, NaCl-2, $B = 0.3$ T, $T = 293$ K, $E = 1.2$ kV m^{-1}; 6, NaCl-2, $B = 0.5$ T, $T = 293$ K, $E = 1.2$ kV m^{-1}; (b) dependences 1, 2 and 4 in normalized coordinates.

We have also studied the magnetoplastic effect in the alternating magnetic field produced by rotation of the sample in a static magnetic field. The effect decreases abruptly (Fig. 10) when the frequency ν of rotation exceeds some critical value ν_c which depends only on the magnitude of the magnetic field ($\nu_c \alpha B^2$; see Fig. 10(b)) and on the type of impurity (compare the levels of ν_c for NaCl-2 and NaCl-2(Ni) crystals in Fig. 10(a)). It is also different for edge and screw dislocations (LiF). On the other hand, the critical frequency ν_c proves to be independent of impurity concentration, temperature, electric field E and time of observation.

Control experiments were also carried out in which the dislocation mobility under mechanical loads was investigated. We chose the stress level τ which provided histograms of dislocation displacements similar to those in our "magnetic" experiments. The result was as expected:

$$l \propto \exp\left(\frac{A\tau}{T}\right) \tag{2}$$

i.e. the usual thermoactivated behaviour.

4. Discussion

The presented experimental data give us sufficient material at least to eliminate some physical mechanisms which cannot be the cause of the observed phenomenon. In particular, the driving force for dislocation motion is definitely not related to the magnetostrictional stresses, because they are at least two to three orders of magnitude less than the stress level necessary to provide our histograms. On the other hand, if the magnetic field by any other mechanism produced a sufficient stress $\tau \propto B^2$, we would observe in accordance with (2) not a linear but an exponential dependence of l on B^2 and a strong temperature dependence typical of thermoactivated motion.

The saturation of the dependences $l(t, B)$ at a level corresponding to the average distance between "forest" dislocations ($1/\rho^{1/2}$) leads us to the idea that dislocations move under the action of long-range internal stresses. Then the role of the magnetic field reduces to the depinning of dislocations from local paramagnetic centres (Ca, Ni, Li); diamagnetic impurities (Pb, Cu), as we have seen (Fig. 8), "kill" the effect.

As regards the mechanism of depinning, it must be a destruction of the local barrier rather than a lowering of it, because the mobility of dislocations is observed even at 4.2 K (Fig. 6). In such a scheme the mean dislocation velocity may be estimated as

$$v = \frac{\Delta l}{\Delta t} \tag{3}$$

where Δl is the average distance between paramagnetic centres in a slip plane ($\Delta l \approx 1/(bC)^{1/2}$), which corroborates quite well the experimental dependence $l(C)$ in Fig. 7(b). The value Δt in (3) is the lifetime of the barrier in the magnetic field since the dislocation has come up to it (obviously, in the estimate (3) we may neglect the time of dislocation motion between local barriers, which is several orders of magnitude less than Δt). From our experimental data $\Delta t^{-1} \propto B^2$ and does not depend on the temperature.

Of course, it seems fairly paradoxical to destroy a barrier of height 0.1–1 eV via a magnetic field which modulates the interaction energy between dislocation and impurity by a value of the order $\mu_B B$ (about 6×10^{-5} eV at $B = 1$ T; μ_B is the Bohr magneton). On the other hand, this paradox is rather general for magnetic phenomena in non-magnetic media. For example, it manifests itself in the magnetic influence on chemical reactions [11, 12], on the photocurrent in semiconductors [13, 14] and on the viscosity of amorphous alloys [15]. The theoretical explanation for these phenomena is now generally accepted and is based on the idea that the magnetic field provides not a direct change in interaction energy but a singlet–triplet (S–T) transition in some spin subsystem. The S–T transition eliminates the spin exclusion of some reaction or process which brings about a radical rearrangement of the system configuration, so that given a small change in the total energy, the interaction energy may vanish or even reverse its sign.

Within this theoretical framework we can suppose that in our case the value Δt in eqn. (3) represents the time of some spin transition which provides a change in the spatial configuration of electron states in the dislocation–impurity system and, as a result, a depinning of dislocations. The new state is not necessarily stable: it is sufficient if its lifetime is longer than the time of depinning, $\Delta t_{dp} \approx b/V \approx 10^{-11}$–$10^{-10}$ s (at $b \approx 10^{-8}$ cm, $V \approx 10^2$–10^3 cm s^{-1}).

Recall that the change in electron states of the pinning centres may strongly influence their coupling energy with dislocations. This manifests itself *e.g.* in the photoplastic effect in alkali halides [16] and semiconductors [17].

Note that the behaviour of the magnetoplastic effect in the alternating magnetic field (Fig. 10) fits quite well with the proposed scheme based on the spin transition idea. The critical frequency ν_c obviously corresponds to the inverse lifetime Δt^{-1} of the paramagnetic centres (see eqn. (3)). Indeed, $\nu_c \propto B^2$ is dependent only on the the type of impurity and not on the impurity concentration (*i.e.* it is a characteristic of the elementary barrier). In other words, we can write instead of eqn. (3)

$$v \approx \frac{\nu_c}{(bC)^{1/2}} \tag{4}$$

One can check that the order of magnitude of the velocity v in eqn. (4) fits the slope of the $l(t)$ linear dependence in Fig. 2(a).

The paradoxical effect of the magnetic impurity Ni, which causes not a decrease but an increase in dislocation paths (Fig. 8), may be explained by suggesting that Ni atoms penetrate into the Ca complexes, changing their paramagnetic properties. The remarkable change in the critical frequency ν_c (Fig. 10) corroborates this idea.

The microscopic theoretical expression for $\Delta t^{-1} \approx \nu_c$ is certainly a problem for the future when we have more details about the elementary events (*e.g.* spin transition). However, we can suppose as a pure guess that Δt represents the time of paramagnetic relaxation [11, 18]:

$$\frac{1}{\Delta t} \approx 10^{-1}\left(\frac{\Delta g \mu_B B}{h}\right)^2 \tau_c \qquad (5)$$

Here h is the Planck constant, Δg is the anisotropy of the Landé tensor due to distortions of the crystal symmetry in a dislocation core and to fluctuations of the internal magnetic field on the paramagnetic centre, and τ_c is the correlation time of those oscillations. Inserting in eqn. (5) the estimates $\Delta g \approx 10^{-3}$, $B \approx 0.1$ T and $\tau_c \approx 10^{-13}$ s, one obtains $\Delta t \approx 10^{-1}$ s, which looks reasonable in comparison with our experimental data.

A separate problem is related to the physical reason for the electric influence on the effect. Taking into account its temperature independence, one can exclude the trivial force effect of the electric field on the charged dislocations, the more so since the level of E is too low, at least three orders of magnitude less than in the usual Stepanov effect for the same crystals. However, electric forces may determine together with internal stresses the direction of dislocation motion (we observed this with the change $\vec{E} \rightarrow -\vec{E}$) but not the velocity of the motion. On the other hand, in eqn. (4) the only value which could be sensitive to an electric field is the critical frequency ν_c. However, as we have seen (Fig. 10(a)), ν_c proves to be also independent of $\vec{E}$. Thus the velocity v should be independent of E as well, which leads us to the conclusion that the electric effect on the mean dislocation free path $l = vt_m$ reflects the dependence $t_m(E)$. As already stated, the real time of the motion, t_m, does not coincide with the time of magnetic treatment of the sample. For example, the dislocation delay at the start is characterized by the probability W_{st} in (1) (Fig. 4(b)). According to ref. 4, when $W_{st}t \geqslant 1$, the time of the motion, t_m, is rather sensitive to the level of W_{st}. From our data W_{st} is indeed dependent on E and for our parameters $W_{st}(E)t \geqslant 1$. Thus we can state that the electric influence on the magnetoplastic effect is related to the decreasing of the delay time at the start, which is determined by the dislocation unlocking from "strong" obstacles (*e.g* from "forest" dislocations). The mechanism of the electric influence on this unlocking is not quite clear yet. However, we think that the "switching-on" parasitic effect is a manifestation of the same phenomenon applicable to the eddy electric field arising in an alternating magnetic field.

The considered magnetoplastic effect intimately related to dislocation–impurity interaction may be also important in internal friction phenomena. One should expect, for example, a resonance behaviour of the attenuation and the modulus defect in the vicinity of the critical frequency $f \approx \nu_c \propto B^2$. Taking into account the low level of such frequencies, the proper technique in this case should include as an active element either an appropriate pendulum or a reed. The corresponding experiments are only at the initial stages.

Acknowledgments

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