Mutual self-organization of dislocations, phonons, electrons and photons during plastic deformation of crystals

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Abstract. Periodical structures of dislocations and other structural defects are found in crystals subjected to various kinds of plastic deformation. These periodicities exist in a wide range of scales from tens of millimeters to tens of nanometers. Periodical systems of structural defects are combined with especial resonant systems of phonon, electron and photon excitations due to long-distant interactions between them. This self-organization of mutually bound distortions of regular crystalline lattice, phonons, electrons and photons are capable to influence significantly on the processes of modifications of crystalline structure by mechanical, magnetic, radiation and other external forces.

1. Introduction

It is well known that the most part of the properties of various crystals is dependent rather strongly on the real structure of the crystals [1, 2] i.e. on the composition of crystalline defects. Electrical conductivity at various frequencies, spectra of optical transparency, mechanical properties can be modified in a wide range by variations of the content of the defects. The collection of defects which can influence properties of the crystals includes point defects (vacancies, interstitials, impurities and their combinations), various kinds of dislocations (edge, screw, mixed, partial), twins, stacking faults, inter–grain and inter-phase boundaries, etc.

Regulation of mechanical properties of solids by means of governing of the composition and distribution of structural defects in order to achieve necessary exploitation parameters is one of the most actual branches of the Material Research Science [3–6]. The yield stress, plasticity, mechanical strength, crack resistance belong to the most important mechanical properties. First of all they are determined by the characteristics of dislocations in a given crystal concerning their atomic structures, interactions with other dislocations, point defects and other crystalline inhomogeneities, mobilities, etc. A wide set of physical effects connected with the influences of external factors (temperature [7], electrical and magnetic fields, optical illumination, etc.) are explained by modifications of behaviour of dislocations [8–11] induced by these factors. It should be emphasized that the main features of these mechanisms concern local interactions between individual dislocations and various point defects and local barriers of other kinds (intersections with other dislocations, etc.). For example, mechanisms of the photo-plastic effect (increase or decrease of the yield stress induced by illumination of the semiconductor crystal in the
spectral range of its photoconductivity) is attributed to recharging of several kinds of point defects by photo-excited charge carriers. This recharging modifies the interaction of dislocations with these defects followed by corresponding changes of dislocation mobility [12–14]. The magnetoplastic effect connected with variations of dislocation mobilities in non-magnetic crystals with application of the external magnetic field is explained by the creation of paramagnetic properties of non-magnetic impurities when they are attracted towards dislocations. Hence the external magnetic field modifies their interaction with these dislocations [15].

On the other hand the active interaction of dislocations with the phonon system of crystals is well known. Phonons are emitted by dislocations during their motion [16]. Moreover dislocations can be described mathematically as a singularity of the phonons distribution. Many experimental results about the interaction of dislocations with electron subsystem of crystals are published either for semiconductors or for metals [17]. Our team has collected a wide set of experimental facts about the particularities of scattering, diffraction, focusing of visible photons by dislocations. The most part of these facts are connected with periodical distribution of the density of dislocations in crystals subjected to various kinds of plastic deformation [17, 18]. Moreover the electron microscopy of fine structure of dislocations in metals and semiconductors revealed that individual dislocations are arranging well correlated systems with high periodicity [19, 20]. The periodical natures of electron and phonon states in crystals resulting in several physical particularities are well known. The data presented above show that the systems of dislocations and optical photons interacting with them are periodical as well. Hence one can expect that interactions of dislocations with phonons, electrons and photons due to periodical natures of all of these systems possess several particular features. These features will be considered below.

2. Particularities of Interactions between Systems of Dislocations, Phonons, Electrons and Photons in Crystals Induced by their Periodicities

The periodical natures of phonon and electron systems in crystals provide intense interactions between them working at far distances. One of the most impressive demonstrations of the importance of these long range interactions is the theory of superconductivity by Bardeen–Cooper–Schrieffer involving resonant interactions between electrons and phonons resulting in creation of well-correlated Cooper pairs [16]. These pairs bound by intermediate phonons can propagate through crystalline lattice without scattering and corresponding losses of energy. It is worth noting that the idea of the active influence of intermediate media of neutral atoms and ions on behavior of electrons has been applied earlier by A.A. Vlasov for the analysis of dynamical processes in plasma [17, 18]. He showed that these interactions between electrons and atomic motions in plasma can result in self-organization of periodical structures (stratification of plasma). Periodical structures of dislocations mentioned above are arranged in the dynamical processes of active plastic deformation induced by external load or of internal deformation induced by transformations of crystalline structure [19–22]. The spatial range of the periods of these dislocation structures stretches from several tens of millimeters to several tens of nanometers. It is worth noting that so wide variety of scales of the periodical structures produced by plastic deformation can be analyzed from the common point of view taking into account various interactions between different crystalline quasi-particles. In this analysis dislocations are considered as results of Bose–condensation of acoustical phonons [23, 24]. Even for macroscopic periods of deformation structures (which are attributed to the interaction between the deforming installation and the crystal) the propagation of auto–waves of the plastic deformation are connected with long-wave phonons [25]. As an example of self-organized interaction between the deforming machine and the sample Fig. 1 presents the morphologies of an aluminum and copper discs subjected to ball–rolling. In this case a steel ball (20 mm diameter) was pressed with a force regulated by a spring to the surface of the aluminum disk. The disk was rotating
with the angular speed from 3 to 30 rotations per second whereas the ball was moving in the radial direction with the speed corresponding to the radial displacement about 12 mcm per one rotation. The periodical spiral–like reliefs created by this procedure are explained by non-linear plastic characteristics of the metals. The ball dipped into the subsurface layer is pulling in the direction almost perpendicular to the radius a bulk of the metal. When the plasticity of the metal is high enough the speed of the motion of the bulk corresponds to the speed of the ball. But then due to increasing hardening the plasticity decreases and at a certain moment the ball rolls over the bulk and forming of a new bulk begins. By this way the close to periodical textures of spirals are formed. The periods are regulated by the speeds of the disk and the ball as well as the nonlinearities of plasticity of the metal, force of pressing, diameter of the ball etc.

The left photo of the disk of aluminum demonstrates two kinds of the surface relief. The central zone has not the rough texture of spirals described above. The linear speed of the ball in this zone is small enough. So the bulk before the ball has the possibility of migration together with the ball. But when the radius increases the linear speed increases as well and at last it exceeds the maximal speed of the displacement of the bulk, inducing forming of the spiral texture. In addition to the macroscopic periodicities the ball rolling creates micro- and nano-spic round structures (Fig.2). The left picture presents scanning electron microscopy of a section of the aluminum surface after the ball rolling. The total width of the picture is 3 mcm. The system of straight lines parallel to the direction of rolling is seen distinctly. The computer analysis of spatial Fourier components of the picture made normally to this direction is presented at the right picture demonstrates the submicron periodicity of these lines with the period of about 300 nm.

Transmission electron microscopy of various kinds of crystals subjected to plastic deformation revealed a wide set of dislocation nets with high degree of periodicity at nanoscopic scale (Fig.3). Plastical deformation of optically transparent semiconductors and dielectrics produces dislocation structures with periodicities of the optical scale. Correspondingly these periodicities create a set of optical diffraction phenomena. Fig. 4 presents the transmission diffraction patterns at the exit surface of the zinc sulfide (ZnS) single crystal demonstrating changes in the transmitted light distribution corresponding to variations of the angle of the light beam.

**Figure 1.** Surface view of a) Al and b) Cu samples treated by ball-type rolling from the center to the edge (a) and from the edge to the center (b). The rotation frequency of the Al and Cu samples is 500 and 1600 rpm respectively.
Figure 2. Left – traces of the ball rolling of Al sample. The lines are parallel to the direction of rolling. The length of the black line is 3 mcm. Right – computer Fourier analysis of the structural distribution along the black line at the left demonstrating high periodicity of the structure incidence onto the face of the crystal. These diffraction patterns are induced by the periodical distribution of the stacking faults produced by the deformation of the crystal during its cooling after growth from the melt.

The distinct modulation of the light intensity at the exit surface of the crystal is observed when the angle between the light beam and the planes of the stacking faults corresponds to the Bragg condition:

$$2d \sin \theta = n\lambda.$$  

Here $d$ is the distance between the maxima of the density of the stacking faults, $\theta$ – the angle between the plane of the stacking fault and the light beam, $n$ – an integer, $\lambda$ – the light wavelength. The four pictures of the same crystal correspond to four neighbor values of $\theta$ with the step-like decrease of the distances between the light maxima. These photos are made at the light wavelength of 532 nm. Fig. 5 presents spectral variations of the intensity of the light scattered by the crystal of cadmium sulfate (CdS) subjected to the compressive plastic deformation corresponding to variations of the light wavelength. The maxima of the scattered light correspond to the wavelengths corresponding to the Bragg condition.

These experimental facts demonstrate various scales of periodical superstructures induced in crystals by plastic deformation. The nanoscopic and microscopic periods are comparable with the typical lengths of the free path of electrons and phonons. So resonant states of crystalline phonons and electrons bound with these periodical structures can be created in crystals either during their plastic deformation and after it. When this crystal is illuminated the resonant states of the light photons will be induced as well. These resonances are capable to improve optical, electron, mechanical and other properties of crystals. For example when the surfaces of metal samples are subjected to plastic compression with optically smooth dies the optical reflection of the surface is increased significantly [20]. This increase and corresponding decrease of the absorbed energy of the incident light are explained by creation of resonant states of plasmons in the subsurface layer due to its periodical superstructure produced by deformation.
Figure 3. Transmission electron microscopy of periodical dislocation nets in plastically deformed crystals. At the top – dislocation nets in molybdenum. Bottom left – dislocations in aluminum. Bottom right – dislocations in germanium.

3. Conclusion

Mutual self-organization of periodical systems of structural defects, phonons, electrons and photons can influence rather strongly on dynamical processes in crystals. Due to the main principle of non-equilibrium thermodynamics known as Prigogine theorem about minimal production of entropy [26] these systems will look for the mostly ordered and mutually bound structures. For example dislocations in the process of plastic deformation will form periodical nets which will emit their own resonant phonons. In this case the phonon emitted by one piece of a dislocation will be absorbed by analogous another piece. So the scattering of the mechanical energy will be excluded and the deformation will meet minimal resistance. Analogous situations will take place with scattering of the resonant electrons resulting in mutual exchange of electron energies between dislocations. Hence dislocations, other structural defects taking part in deformation processes, phonons and electrons as well as photons from external light sources will tend to arrange optimally bound super-system with the exchange of the energy.
**Figure 4.** Patterns of light diffraction at the exit surface of a single crystalline ZnS with periodical distribution of stacking faults. Different periodicities correspond to different angles between the planes of the stacking faults and the light beam.

**Figure 5.** Spectral oscillation of the light scattering in the plastically deformed single crystal of CdS.
inside it minimizing the losses to the outer space. By this way a new complex kind of crystalline excitations can be created from mutually bound structural non-homogeneities, resonant phonons, electrons and photons. Further studies of photoplastic, magnetoplastic, electroplastic and other phenomena taking place during deformation of crystals by any external influence can give new fresh information about these states.

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