Experimental investigation of sound emission on annihilation of dislocations in a crystal

V. S. Boĭko, V. F. Kivshik, and L. F. Krivenko

Kharkov Physicotechnical Institute, Ukrainian Academy of Sciences

(Submitted 5 August 1979)
Zh. Eksp. Teor. Fiz. **78**, 797–801 (February 1980)

The angular and spatial dependences of sound emission arising in the annihilation of opposite-sign twinning dislocations are measured. The results are compared with theory and qualitative agreement is observed. The displacements of the dislocations and the sound waves produced by annihilation of two opposite-sign dislocation pile-ups are recorded synchronously. The data are used to estimate the annihilation radius r_a, that is, the distance between approaching dislocations at which each dislocation loses individuality and restoration of a perfect lattice occurs simultaneously throughout the entire path separating the dislocations. For twinning dislocations in calcite, $r_a \sim 10^{-7}$cm.

PACS numbers: 61.70.Ng

1. INTRODUCTION

Emission of sound waves should be observed upon annihilation of opposite-sign dislocations, similar to the radiation of electromagnetic waves upon annihilation of opposite-sign charges.[1] An experimental investigation of sound emission upon emergence of the dislocations to the surface has been carried out in Ref. 2. In the work described in Ref. 2, an experimental method, considered theoretically in Ref. 1 and first observed experimentally in Ref. 3, is used for the study of sound emission in annihilation of dislocations.

Obtaining the characteristics of sound emission of dislocations is difficult because plastic deformation takes place simultaneously in many microvolumes. In the case of electromagnetic radiation of charges, localization of the radiating region is achieved by the creation of collimated fluxes of charged particles. As a spatially localized flux of dislocations, we use an elastic twin that moves under the action of surface tension forces. The collapse of an elastic twin inside a crystal can be regarded as the annihilation, in the crystal, of a pile-up of dislocations of opposite signs, which should lead to sound emission via the annihilation mechanism.[1] For identification of the mechanism, it is important to make clear the spatial and angular dependences of the characteristic radiation. This allows us to make progress in the physical justification of the method of acoustic emission, widely used in modern technology for nondestructive testing. On the other hand, obtaining information on the details of the process of annihilation of dislocations of opposite sign in a crystal is also of general physical interest. We also note that annihilation of the dislocations is the main fundamental channel for dislocation-density reduction within the time of thermal and radiation annealings. The kinetics of these processes is determined to a significant degree by the annihilation radius r_a, by which we mean[4] that distance between the approaching dislocations at which each dislocation loses its individuality and the establishment of an ideal lattice takes place simultaneously along the entire path separating the dislocations. Dislocations approaching in one slip plane within a distance smaller than r_a annihilate without fail.

The aim of the present work is the investigation of the spatial and angular dependences of the emission in the annihilation of dislocations in order to identify the emission mechanism, and also the carrying out of measurements that allow us to determine the annihilation radius.

2. EXPERIMENT

An elastic twin was created in specially cut calcite crystals by a concentrated load. The twin consisted of rectilinear segments of twinning screw dislocations. Its two ends lay inside in the crystal. According to the law of conservation of the Burgers vector, such a twin consists of two pile-ups of dislocations of opposite signs. Actually, under the action of the concentrated stress, plastic polarization of the crystal occurs; on one side of the center of the twin dislocations of one sign pile up, while on the other, those of the opposite sign. Upon removal of the external stress, the twin begins to contract under the action of the surface tension forces, and disappears. At the center of the twin, pairwise annihilation takes place of the rectilinear segments of dislocations, accompanied by sound emission. The center of the twin can be regarded as a linear source of the emission. Movement of a piezo-pickup over the surface of the crystal allows systematic measurement of the emission at points located at various positions relative to the source. For a description of the result of these measurements it is most convenient to use cylindrical coordinates with the Z axis coincident with the source of emission (R is the distance of the source, φ the azimuthal angle) (Fig. 1). The results of measurement of the angular distribution are shown in Fig. 2. The azimuthal

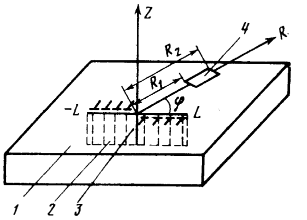

FIG. 1. Arrangement for measurement of the angular and spatial distributions of sound emission in dislocation annihilation: L is the half-width of the twin, R_1, R_2 are the distances from the surface of emission to the ends of the piezo-pickup, 1—calcite crystal, 2—elastic twin, 3—region of localization of the emission source, 4—piezo-pickup.

0038-5646/80/020401-03$02.40

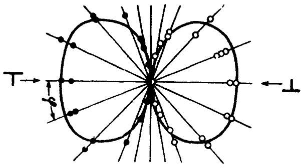

FIG. 2. Angular distribution of the sound emission in dislocation annihilation. The amplitude of the signal is plotted in radial directions in relative units for different values of φ at R = const. In the upper and lower parts of the drawing, dislocations are indicated, moving toward one another in a single slip plane. The white and black circles indicate the signals of different polarity.

coordinate changed from 0 to 360° at R = const.[1)] The results of measurement of the spatial dependence of the emission are shown in Fig. 3, where the dependence of the amplitude of the signal (measured in relative units) on the quantity $(R_1^{-1/2} - R_2^{-1/2})$ is plotted at φ = const = 25°. The necessity of use of just these variables is dictated as will be shown later, by the convenience of juxtaposing the experimental data with the theory.

For direct comparison of the dynamics of contraction of the twin and of the generated annihilation emission, a synchronous recording of these processes was carried out. Several changes were made in the method previously developed.[2] The elastic twin produced inside the crystal be means of the concentrated load was changed to a distributed load applied to the crystal by means of an electromagnet. When the magnet was turned off the twin began to contract. A high-speed camera is activated in synchronism with the turning-off of the magnet, recording the change in the dimensions of the contracting twin. The speed of this camera was 3000 frames per second. The synchronization block simultaneously triggers the sustem of sound emission recording and a flash lamp located near the objective of the movie camera; this allows a recording on the film of the instant of turn-on of the oscillogram. The results of one of the experiments are shown in Fig. 4, where the dependence of the length of the contracting twin on time and the oscillogram of the recorded sound signal are shown on the same time scale. These processes can be compared at an error not exceeding several milliseconds.

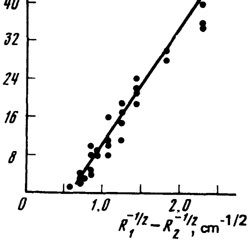

FIG. 3. Spatial distribution of the sound emission in dislocation annihilation. The experimental data are plotted for the case of fixed azimuthal coordinate φ = 25°.

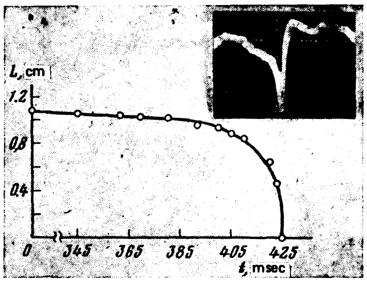

FIG. 4. Graph of the dependence of the length of an elastic twin on the time, plotted on the same time scale as the oscillogram of the acoustic emission signal corresponding to the dislocation annihilations. The instant of switching on the high-speed movie camera is taken to be the origin of the time recording.

3. DISCUSSION OF THE RESULTS

The results obtained on the angular and spatial dependences of the emission accompanying annihilation of dislocations make it possible to compare theory[1] and experiment. In the piezo-pickups used, the amplitude of the signal is proportional to the torsional force. Therefore, by using relation (14) from Ref. 1, we obtain the dependence of the corresponding component of the strain on φ and R in cylindrical coordinates: $\sigma_{z\varphi} \propto \cos\varphi / R^{3/2}$. For the total force P acting on the pickup, with account of its macroscopic dimensions along R, we have

$$P \propto (R_1^{-1/2} - R_2^{-1/2}) \cos\varphi. \tag{1}$$

The emission field was considered in Ref. 1 for the case of annihilation of two complete dislocations. The case realized in the experiment corresponds to the annihilation of two pile-ups of twinning dislocations. Since, from the viewpoint of continuum theory, the elastic fields of the complete and twinning dislocations have the same character (they differ in their Burgers vectors and in the forces acting on them), the emission fields should be similar. Annihilation of not one but many pairs of dislocations is observed in the experiment, but this does not in practice change the angular and spatial distributions of the emission, because the zone of dislocation annihilation is localized in a region of space with dimensions that are much smaller than the distances from it to the measurement point.

The comparison of (1) with experimental data on the angular (Fig. 2) and spatial (Fig. 3) dependences of the emission that accompanies the annihilation of the dislocations makes it possible to conclude a qualitative agreement of the theory of ref. 1 with experiment. The deviation of the experimental curves in Fig. 2 from the circles predicted by experiment is obviously due to the anisotropy of the crystal; an isotropic approximation is used in Ref. 1.

We proceed to the analysis of the connection of the emission with the characteristics of motion of the twin. It is shown in Fig. 4 that, although the entire process of contraction of the elastic twin to its complete disappearance lasts 100 msec the intense sound emission is observed only during the last 10 msec. According to Ref. 5, upon disappearance of an elastic twin in a region of dimension $2d$ and with high dislocation density is formed at the center of the twin. The dislocations enter this region with small velocities. As is known,[1] the intensity of the annihilation emission is proportional to the velocity of the approaching dislocations. This can explain the absence of contraction of the twin in the initial states. As the twin contracts, d decreases. At $d\sim r_a$ (r_a is the annihilation radius), the dislocations begin to enter into the reaction with high velocity, which leads to the appearance of intense sound emission. Using the experimental data and the results of Ref. 5, we can obtain an estimate of the annihilation radius:

$$r_a\sim(MA/\mu)L_u^{1/2}, \tag{2}$$

where M is the phenomenological parameter of the theory of Ref. 6 and characterizes the surface tension, A is a dimensionless constant, μ is the shear modulus, L_u is the half-length of the twin, corresponding to the appearance of sound emission [$M\sim1$ kg/cm$^{3/2}$ (Ref. 6), $A\sim10^{-1}$ (Ref. 5), $\mu\sim10^5$ kg/cm^2]. Taking it into account that, according to the experimental data, the sound emission begins at $L_u\sim10^{-1}$ cm, we obtain the results that the annihilation radius of twinning dislocations can be estimated at $r_a\sim10^{-7}$ cm. This result agrees with the data of the mathematical model.[4] It should be noted, of course, that this is a lower-bound estimate.

In conclusion, we take this opportunity to express our deep gratitude to R. I. Garber for discussion of the results, and also V. D. Natsik for useful discussions.

[1)] The direction of arrival of the sound wave is kept fixed at such a placement of the pickup relative to the emission source.

[1] V. D. Natsik and K. A. Chishko, Fiz. Tverd. Tela (Leningrad) **14**, 3126 (1972) [Sov. Phys. Solid State **14**, 2678 (1973)].

[2] V. S. Boĭko, R. I. Garber, V. F. Kivshik, and L. F. Krivenko, Zh. Eksp. Teor. Fiz. **71**, 708 (1976) [Sov. Phys. JETP **44**, 372 (1976)].

[3] V. S. Boĭko, R. I. Garber, and L. F. Krivenko, Fiz. Tverd. Tela (Leningrad) **16**, 1233 (1974) [Sov. Phys. Solid State **16**, 798 (1975)].

[4] V. S. Boĭko, in sbornik (collection) Defekty v metallkh i ikh modelirovanie na ÉVM (Defects in metals and their modeling on a computer) Yu. A. Osip'yan, ed., Nauka, 1980, Ch. 8.

[5] V. S. Boĭko and A. A. Slutskin, J. Phys. Chem. Sol. **38**, 1221 (1977).

[6] A. M. Kosevich and V. S. Boĭko, Usp. Fiz. Nauk **104**, 201 (1974) [Sov. Phys. Uspekhi **14**, 286 (1971)].

Translated by R. T. Beyer

Diffraction focusing by a bent perfect crystal

O. I. Sumbaev and E. G. Lapin

Leningrad Institute of Nuclear Physics, USSR Academy of Sciences

(Submitted 8 August 1979)
Zh. Eksp. Teor. Fiz. **78**, 803–812 (February 1980)

The diffraction focusing effect described by Afanas'ev and Kon [Sov. Phys. Solid State **19**, 1035 (1977)] for an undeformed perfect crystal is considered for the more general case of an elastically bent ideal crystal with reflecting planes that are bent as a result of the anisotropy [O. I. Sumbaev, Crystal-diffraction gamma spectrometry, Atomizdat (1963); Sov. Phys. JETP **27**, 724 (1968)] within the framework of the Kato eikonal dynamic theory [J. Phys. Soc. Jpn., **19**, 1971 (1964)]. An experiment performed in the geometry of a two-crystal x-ray spectrometer has confirmed the presence of substantial dynamic effects, and yielded quantitative agreement with calculation. By way of applications, the following are calculated: a Cauchois focusing diffraction spectrometer; "point-into-point" focusing of the type considered by Petrashen' and Chukhovskii [Preprint, Crystallography Institute, USSR Academy of Sciences, 1975; JETP Lett. **23**, 347 (1976)], and "point-into-parallel beam" focusing.

PACS numbers: 78.70.Ck, 61.10.Dp

INTRODUCTION

Authier *et al.*[1] and Ibdenbom and co-authors described the effect of focusing of diffracted x-ray (or neutron) radiation inside a perfect flat crystal. Petrashen' and Chukhovskii[3] described an analogous effect in an elastically bent crystal. Recently Afanas'ev and Kon[4] considered theoretically, and others soon observed experimentally,[5,6] the effect of focusing of x radiation diffracted by a flat perfect crystal at a distance of several meters behind the crystal. After studying Refs. 4–6, we noted that the described effect can be easily generalized to include the case of an elastically deformed perfect crystal, including one with bent reflecting surfaces, within the framework of the Kato eikonal theory.[7]

1. DERIVATION OF FUNDAMENTAL RELATIONS

We consider (Fig. 1) diffraction, by a crystal, of radiation emitted by a point source S located near the crystal surface. We shall consider the symmetrical case of Laue diffraction, when the diffracting planes in question coincide with the normal cross sections of the initial (prior to the elastic bending) plane-parallel single-crystal plate. If the crystal is elastically bent into a cylindrical surface of radius ρ, the reflecting planes also are bent, generally speaking, into cylinders (parabolas) of radius ρ' given by (see, e.g., Refs. 8 and 9)

$$\rho'=\frac{1}{2k},\quad k\approx\frac{1}{2\rho}\frac{a_{34}-a_{45}a_{35}/a_{55}}{a_{33}-a_{35}^2/a_{55}}. \tag{1}$$