ARCHIVES OF ACOUSTICS
15, 1-2, 211-226 (1990)

ACOUSTIC EMISSION DURING TENSILE DEFORMATION OF COPPER SINGLE CRYSTALS AND DISLOCATION ANNIHILATION PROCESSES

A. PAWEŁEK[(a)]*, W. STRYJEWSKI[(b)], H. DYBIEC[(a)], W. BOCHNIAK[(a)]

Institute for Metal Working and Physical Metallurgy, Academy of Mining and Metallurgy
(30-059 Kraków, Al. Mickiewicza 30)[(a)]
Institute of Molecular Biology, Jagiellonian University
(30-059 Kraków, Al. Mickiewicza 3)[(b)]

The behaviour of acoustic emission (AE) during the two first stages of the tensile deformation of copper single crystals is investigated using the broad-band piezoelectric transducer for the measurement of AE energy rate $\Delta E/\Delta t$, AE event rate $\Delta N/\Delta t$ (event density) and energy per one AE event $\Delta E/\Delta N$. The existence of some essential correlation between the AE intensity (proportional to $\Delta E/\Delta t$ or $\Delta N/\Delta t$ patterns) and the plastic flow features has been stated. Two large maxima of AE intensity have been observed: the one correlated with the onset of easy glide region and the other one with the onset of stage II of the deformation. Moreover, the mean level of the AE intensity is high in the whole easy glide region and considerably greater than the mean one at the advanced stage II of the deformation, whereas the high mean level is the smaller the smaller is the length of the easy glide region. It has been shown that the observed correlations can be qualitatively quite well explained in terms of the dislocation annihilation component of the transition acoustic radiation.

1. Introduction

The application of acoustic emission (AE) technique to the investigation of the various aspects of the mechanical properties of metals and alloys (mainly plastic deformation, fracture, phase transitions) has already been developing for nearly twenty years [1]. Today there exist many experimental observations of the AE behaviour during tensile deformation of crystals [1, 2] and a common feature of their interpretations is the opinion that the AE during plastic flow is, in general, caused by the dislocation motion. However, these interpretations differ from each other in details and so far there exists no good enough model which would explain most of the experimental observations. The difficulties in their interpretation consist in the fact that there is still no possibility of a quantitative comparison of the results obtained in various laboratories because of the lack of standard engineering devices, and hence no possibility to secure identical conditions for the calibration of the

---

* Present address: Aleksander Krupkowski Institute for Metals Researche, Polish Academy of Sciences (30-059 Kraków, ul. Reymonta 25)

piezoelectric sensors [1, 3, 4]. Nevertheless, the results obtained using the same apparatus always give some additional information on the nature of plastic deformation, and thus they are interpreted mostly qualitatively.

The first more extensive investigations of the AE during tensile testing of various metals have been carried out by FISHER and LALLY [5]. They suggested that AE was a consequence of the fast collective motion of a large number of dislocations. Similar suggestions appeared in some models proposed later. SEDGWICK [6] has considered two possible AE sources: the operation of the fast dislocation sources and the sudden release of dislocation pile-ups. He discussed the former one in detail and pointed out that there existed a correlation between the length distribution of the dislocation segments (being potential Frank-Read sources) and the observed distribution of the AE intensity as a strain function.

Another model has been proposed by JAMES and CARPENTER [7]. They suggested that the AE event rate is proportional to the rate of the mobile dislocation density increase, $d\varrho_m/dt$. The $d\varrho_m/dt$ rate is, in turn, imposed by the stimulated processes of the dislocation breakaway from the pinning points and to a less degree by the dislocation multiplication. A similar conclusion has been drown by HIGGENS and CARPENTER [8], who suggested that the AE at the yield point is caused also by dislocation unpinning. On the other hand, IMANAKA et al. [9] have observed the increase of the AE intensity with increasing strain rate. They suggested that this was due to the dynamic operation of the Frank-Read sources, and the assumption of the constancy of mobile dislocation density during strain rate change should be reconsidered. Unfortunately, they have not developed their idea in detail. Likewise, KIESEWETTER and SCHILLER [10] suggest that the main cause of the AE is also associated with the operation of Frank-Read sources. A common feature of all the models discussed above as well as of other more recent interpretations of various experimental data [11, 12] (see also [1, 2]) is the supposition that during plastic deformation the AE is induced by non-stationary dislocation motion ("bremsstrahlung" type of accoustic radiation).

On the other hand the series of excellent experiments carried out by BOIKO et al. [13 to 17] strongly suggest that AE should be considered on the basis of the so-called transition type of acoustic radiation, the main component of which arises from the dislocation annihilation processes occuring inside the crystal and at the surface. Likewise our recent experimental observations of the AE behaviour [18, 19], and particularly those of the increase (decrease) of AE intensity induced by increasing (decreasing) strain rate changes [18] during copper single crystals tensile deformation have been also interpreted in terms of dislocation annihilation component of the transition type of acoustic radiation. The annihilation of dislocation at a crystal surface is recently also discussed in [20] as the one of possible causes of AE during the fracture of metals.

Therefore the main aim of this paper is to find further experimental evidences for the dislocation annihilation origin of the acoustic radiation during plastic flow of metals using as an example the tensile deformation of copper single crystals.

2. Theoretical background

The first theoretical predictions on a possibility of acoustic radiation due to the non-stationary dislocation motion was reported much earlier [21 to 27]. The theory was developed by ESHELBY [28] for acoustic radiation by an oscillating dislocation kink (recently see also [29]), and later by KOSEVICH [30–32] for a system of accelerating dislocation loops.

It is interesting to notice here that according ESHELBY [28] the rate of acoustic energy radiation is proportional to the mean value of the square of time derivative of the dislocation kink linear velocity, quite analogously to the electromagnetic radiation from an accelerated electron.

A similar result has been obtained by KOSEVICH [30–32] on the basis of the dislocation model in a continuous medium. The analogy between Kosevich and Eshelby treatment follows from the fact that the second time derivative of the dislocation moment tensor is just proportional to the dislocation loop acceleration. However, Eshelby treatment is of microscopic character and describes rather the high-frequency radiation due to the non-stationary dislocation kink motion since the kink vibration frequency is related with atom vibration in the dislocation core. Kosevich approach, is of macroscopic character and describes rather the low-frequency radiation due to the non-stationary motion of the system of many dislocation loops.

One can see that the acoustic emission induced by non-stationary dislocation motion is of an analogous nature as the electromagnetic bremsstrahlung radiation induced by the charged particles. Thus this type of the AE may be called the "bremsstrahlung" acoustic radiation. It should be noted here that in literature also the Čerenkov type of acoustic radiation is being discussed [33 to 35]. Unfortunately, none of these types of AE has a sufficiently explicit experimental evidence.

On the other hand, NATSIK et al. [36 to 38] were the first to analyse theoretically the acoustic radiation due to the dislocation escape from a crystal or due to the dislocation annihilation. Moreover, NATSIK [36] pointed out, basing on the results obtained by GINZBURG and FRANK [39], that the acoustic radiation due to the dislocation escape from a crystal, again per analogy to the classical electrodynamics, is similar to the transition electromagnetic radiation by a charged particle going through the boundary between two media differing from each other in a dielectric constant. Therefore he called this type of AE the transition acoustic radiation, and this name is accepted at present [40]. Since dislocation escape from a crystal may be considered as the annihilation of dislocations with their virtual images, hence the acoustic radiation due to the dislocation annihilation (irrespective whether it occurs inside the crystal or due to the dislocation escape) is always of a transition character. Moreover, the escape of edge dislocations from a crystal induces additionally the Rayleigh surface waves which are absence, however, in the case of screw dislocation escape.

Furthermore, Natsik and Chishko [37], using the methods of the dislocation theory in a continuous medium, proved that the energy E per unit length, which is released after the annihilation of dislocations is given by

$$E = \alpha \cdot u^2 \ln \frac{L}{b} \tag{1}$$

where u is the relative velocity of dislocations at a time moment of their collision, L is of the order of crystal size and α is the coefficient depending on the medium density, the dislocation species and the magnitude of the Burgers vector b.

In the next sections we shall present briefly the experimental procedure as well as our further experimental results and interpretations which confirm quite well the dislocation-annihilation concept of the acoustic emission.

3. Experimental procedure

The equipment for AE measurement and the method of crystals growth were the same as described in [3, 4] and used in [19, 41]. Some of the obtained crystals were oriented for easy glide (orientations 1, 1′ and 2, 2′) and the others were oriented for multislip (orientation 3). The crystals of a length 50 mm and of rectangular cross section 10 mm × 1 mm for the orientations 1, 1′ and 4 mm × 4 mm for the orientations 2, 2′ and 3 were deformed at a constant strain rate $\dot{\varepsilon} = 1.6 \times 10^{-4}\ \mathrm{s}^{-1}$, $\dot{\varepsilon} = 1.7 \times 10^{-5}\ \mathrm{s}^{-1}$ and $\dot{\varepsilon} = 3.0 \times 10^{-4}\ \mathrm{s}^{-1}$, respectively to the orientations 1, 2, 3. For all the specimens the tensile force F and the following AE parameters: rate of AE events counting $\Delta N/\Delta t$, rate of energy released in events $\Delta E/\Delta t$, and mean energy per one event $\Delta E/\Delta N$, were simultaneously recorded as the strain function. The AE parameters were measured at an amplification of about 88dB and at a threshold voltage $U_d = 1.0$ V, except insolated cases when the values $U_d = 0.75$ V or $U_d = 0.5$ V were used. Moreover, the piezoelectric sensor used was of a broad-band type what allowed to record the AE signals in the frequency range from about 50 to 600 kHz, in contrary to the resonance type of the transducers where only a narrow frequency band (about 20 to 50 kHz) may be recorded. The use of the treshold voltage U_d from 0.5 V to 1.0 V allowed to eliminate the apparatus noise, whereas the minimum frequency (50 kHZ) and the maximum one (600 kHz) ensured in turn the elimination of the noises arising from the tensile machine and radio waves, respectively.

The AE event rate $\Delta N/\Delta t$ was measured by the counting of each events which exceeded the threshold level of the discriminator. Thus the AE detected in our experiments, with regard to the resolution of the apparatus, was always of the burst character. The energy of AE events was measured by using the formula

$$E = \int_0^T f^2(t)\, dt \tag{2}$$

where $f(t)$ describes the shape of the AE signal and T is the duration of the event. The rate $\Delta E/\Delta t$ is thus determined in arbitrary units and therefore only its relative changes during the deformation may be useful for the interpretation. Each of the AE parameters ($\Delta N/\Delta t$, $\Delta E/\Delta t$ and $\Delta E/\Delta N = (\Delta E/\Delta t)/(\Delta N/\Delta t)$) was measured within two-second time periods during each tensile test.

4. Experimental results

Fig. 1 and 2 show the strain dependences of the tensile force F and the AE parameters $\Delta N/\Delta t$, $\Delta E/\Delta t$ and $\Delta E/\Delta N$ for two crystals of type 1 orientations (slightly differing from each other). Within the whole easy glide region the AE intensity, proportional to the $\Delta E/\Delta t$ (or $\Delta N/\Delta t$) parameter, remains at a high mean level, and the onset of the decrease of AE intensity takes place nearly at a strain value corresponding to the point of transition from the easy glide region to the stage II of the deformation. One can observe that in the advanced stage II of the deformation (Fig. 2) the level of the AE is much lower and the curve of AE intensity is of a more discrete character than in the case of easy glide region. A more smooth character of the AE intensity curve within the easy glide region follows from the use of the logarithmic scale.

Fig. 3 and 4 show the dependences similar as in Fig. 1 and 2 for the crystals of type 2 orientations, which also differ in their cross-sections and strain rates from those of the orientations 1. One can see that the difference between the orientations as well as between the cross-sections and strain rates of the crystals leads only to quantitative changes, whereas qualitative features of the AE patterns remain the same.

A comparison of the patterns of the AE intensity illustrated in Fig. 1 to 4 leads to the conclusion that there exists a correlation between a high level of the AE intensity and the length of easy glide region. Moreover, Fig. 1 to 4 reveal two appreciable maxima of the AE intensity. In Fig. 4 these maxima are more clearly visible owing to the decrease of the threshold voltage from 1.0 down to 0.75 V (they are very weekly visible in Fig. 1 and 2 as they are masked due to the use of logarithmic scale). Thus the second maximum is in a quite good correlation with the strain value corresponding to the transition from easy glide region to stage II of the deformation.

Fig. 5 shows also the strain dependence of the force and the AE parameters but merely for a crystal of the multislip orientation 3. One can say that the AE from a multislip oriented crystal behaves quite similarly to the one from single slip oriented crystals if we mentally reject the easy glide region in Fig. 1 to 4. This means that in the case of single slip oriented crystals the first maximum of the AE is related with the onset of the easy glide region and the second maximum of the AE is indeed related with the onset of stage II of the deformation. Therefore in the case of

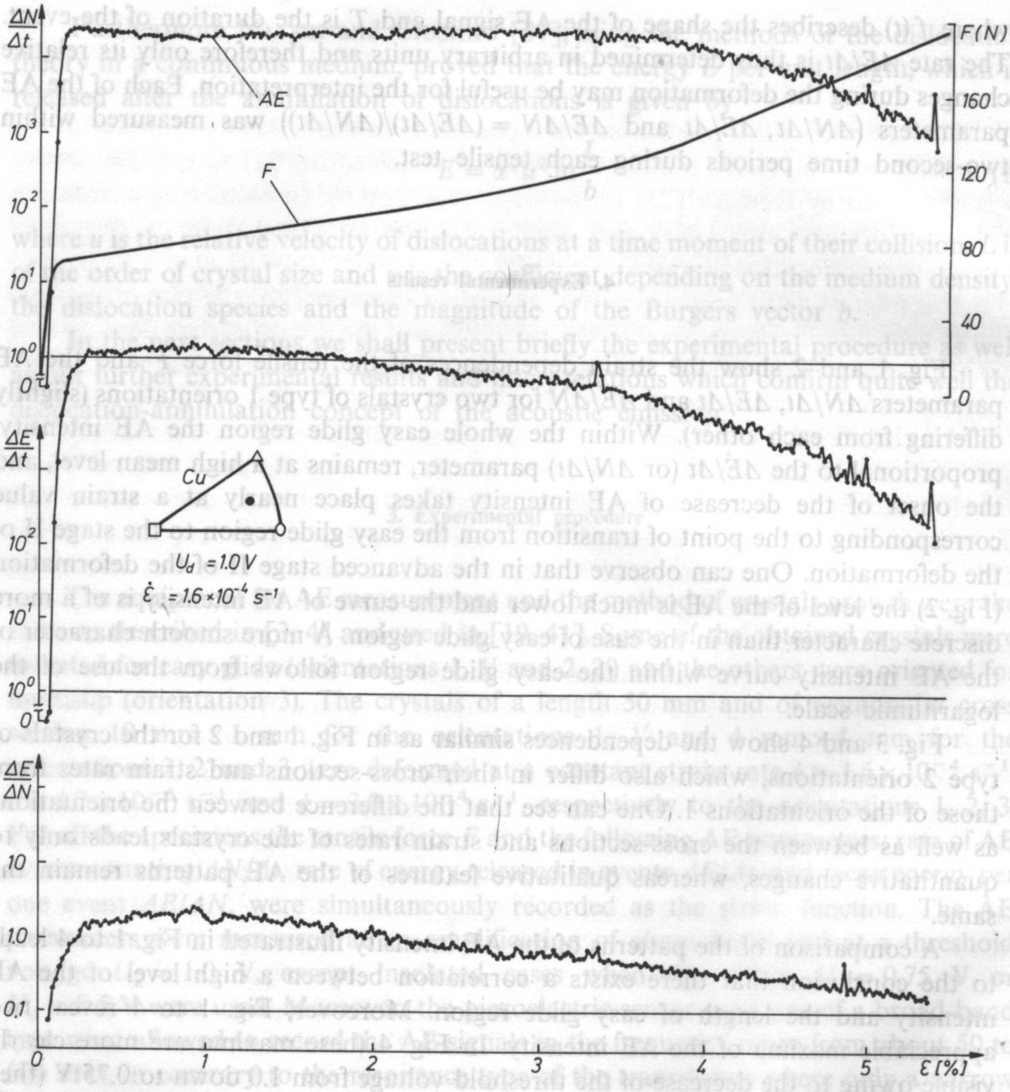

FIG. 1. Strain dependence of the tensile force F and the AE parameters for an easy glide oriented copper single crystal of orientation 1 and of cross-section 10 mm × 1 mm

a multislip oriented crystal, where at least two slip systems are operating from the beginning of the deformation, there exists only one maximum of the AE.

Moreover, the behaviour of the AE within stage II of the deformation is similar for all crystals of various orientations used here. The AE intensity decrease the faster the more advanced is the stage II of the deformation, to attain the mean level which is, however, considerably smaller than the one related with the easy glide region, Fig. 5 brings an additional illustration of the behaviour of the AE intensity during sudden strain rate decrease from $\dot{\varepsilon} = 3.0 \times 10^{-4}\ \mathrm{s}^{-1}$ down to $\dot{\varepsilon} = 3.0 \times 10^{-5}\ \mathrm{s}^{-1}$ (or increase

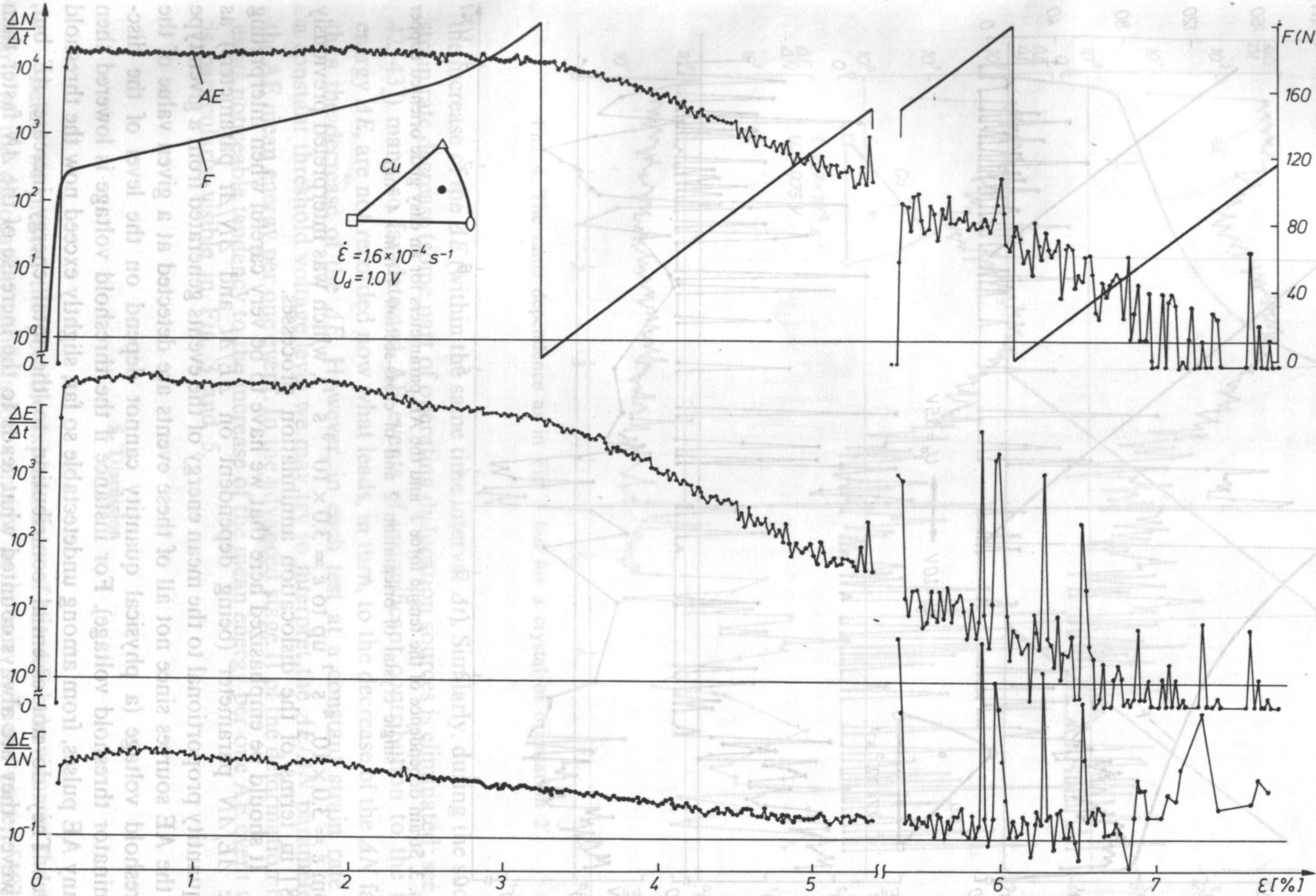

FIG. 2. The same dependence as in Fig. 1 but for a crystal of orientation 1′

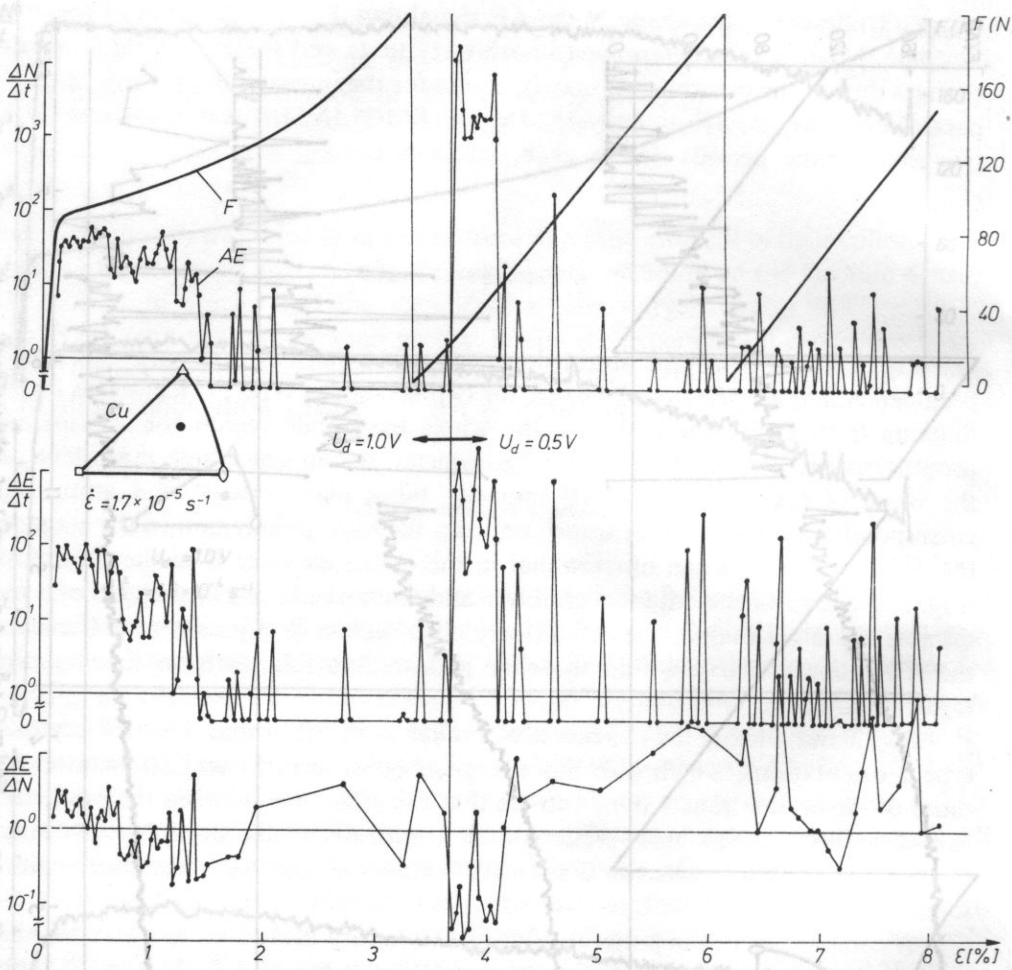

FIG. 3. Strain dependence of the tensile force F and the AE parameters for an easy glide oriented copper single crystal of orientation 2 and of cross-section 4 mm × 4 mm

from $\dot{\varepsilon} = 3.0 \times 10^{-4}\ \text{s}^{-1}$ up to $\dot{\varepsilon} = 3.0 \times 10^{-3}\ \text{s}^{-1}$), which was interpreted previously [18] in terms of the dislocation annihilation processes.

It should be emphasized here that we have to be very careful when interpreting the $\Delta E/\Delta N$ parameter (being dependent on $\Delta E/\Delta t$ and $\Delta N/\Delta t$ parameters) as a quantity proportional to the mean energy of the events generated from a given type of the AE sources since not all of these events are detected at a given value of the threshold voltage (a physical quantity cannot depend on the level of the discriminator threshold voltage). For instance if the threshold voltage is lowered then many AE pulses, from among undetectable so far, slightly exceed now the threshold level. They do not essential contribution to the total energy increase ΔE but, however, they are always counted what leads to the increase of the ΔN faster than

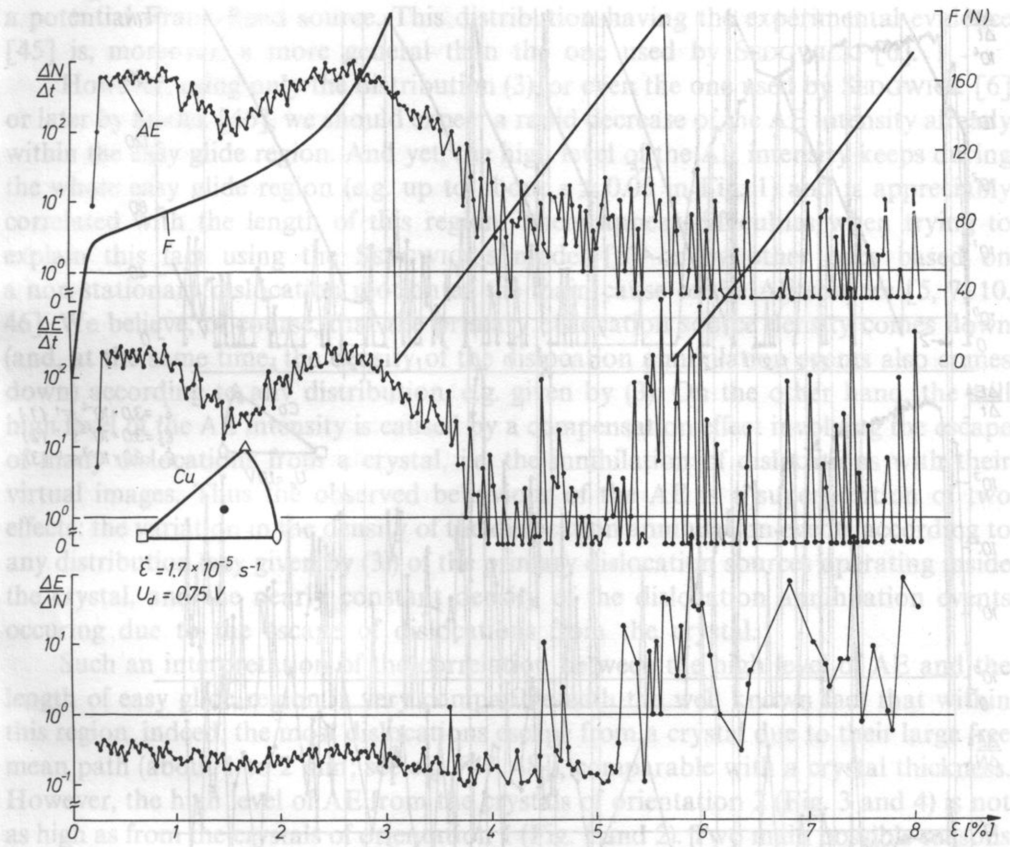

FIG. 4. The same dependence as in Fig. 3 but for a crystal of orientation 2′

the increase of the ΔE (within the same time interval Δt). Similarly, during the sudden strain rate decrease (some part of operating dislocation sources is eliminated; see [18, 42, 43]) many so far detected AE events of insignificant contribution to the total energy ΔE, are not recorded now what leads, in turn, to the decrease of the ΔN faster than the decrease of the ΔE. However, in each test at a constant strain rate and a constant threshold voltage level we may try to interpret the $\Delta E/\Delta N$ parameter as the AE mean energy per one event. In the advanced stage II of the deformation there exists noticeable tendency to the increase of the mean energy per one AE event what is particularly visible in Fig. 3 and 5.

5. Discussion

Below we present the possible explanations of the AE behaviour in the same spirit of the dislocation annihilation concept as in our previous paper [18].

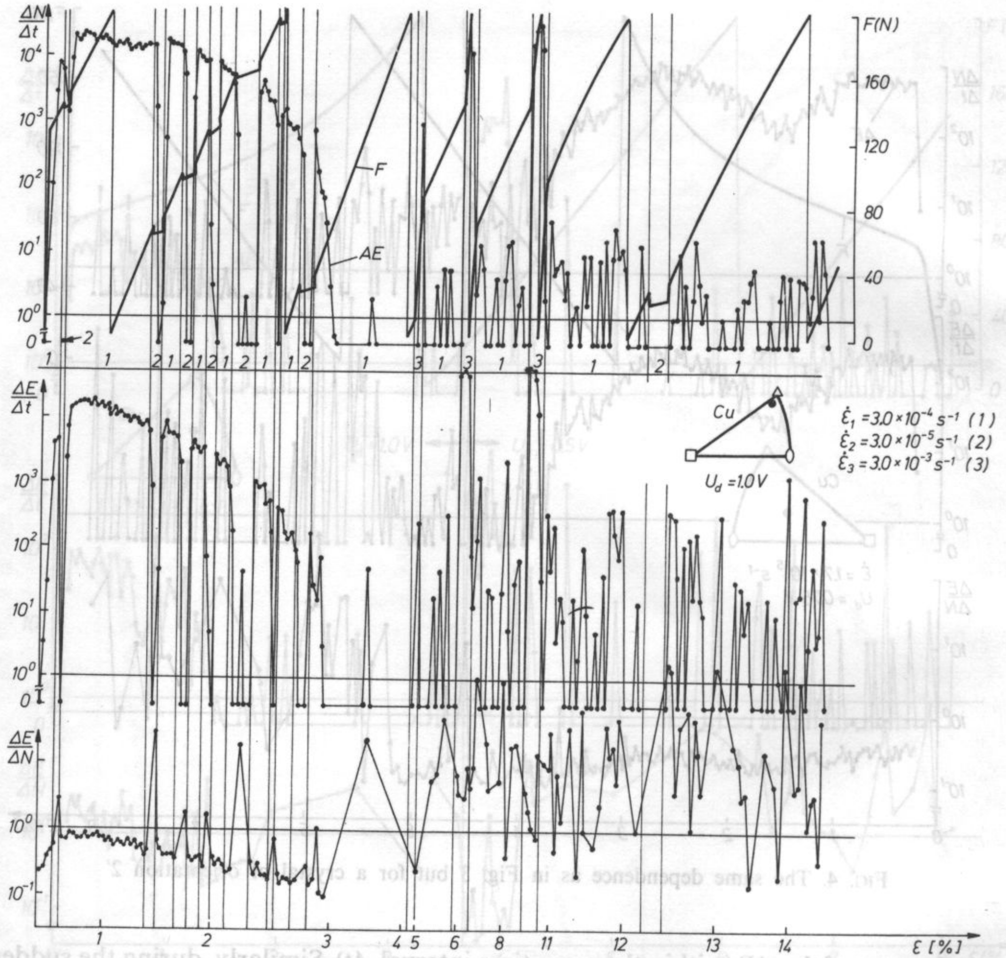

FIG. 5. Strain dependence of the tensile force F and the AE parameters for a multislip oriented copper single crystal of orientation 3 (see also [18])

Let us assume firstly that the high level of the AE intensity at the beginning of the easy glide region (Fig. 1 to 4) may be ascribed only to the high density of the events of the dislocation segment annihilation which proceeds during the closing of each dislocation loop generated due to the start of many dislocation sources of the Frank-Read type. Assume that the primary source density distribution is similar to the one given by GASCA-NERI and NIX [44]

$$N(l) = \frac{n^{n+1}}{n!}\,\varrho_0^{(n+3)/2}\, l^n \exp(-n\sqrt{\varrho_0}\, l) \tag{3}$$

where n determines the abruptness of the distribution curve, ϱ_0 is the total initial density of primary dislocations and l is the length of a dislocation segment being a potential Frank-Read source. This distribution having the experimental evidence [45] is, moreover, a more general than the one used by SEDGWICK [6].

However, using only the distribution (3), or even the one used by SEDGWICK [6] or later by SIEGEL [46], we should expect a rapid decrease of the AE intensity already within the easy glide region. And yet, the high level of the AE intensity keeps during the whole easy glide region (e.g. up to about $\varepsilon \cong 0.05$ in Fig. 1) and is appreciably correlated with the length of this region. There appear difficulties when trying to explain this fact using the SEDGWICK's model [6] or by other ones based on a non-stationary dislocation motion as the main cause of the AE sources [5, 7, 10, 46]. We believe, of course, that the primary dislocation source density comes down (and, at the same time, the density of the dislocation annihilation events also comes down) according to any distribution, e.g. given by (3). On the other hand, the still high level of the AE intensity is caused by a compensation effect involving the escape of many dislocations from a crystal, i.e. the innihilation of dislocations with their virtual images. Thus the observed behaviour of the AE is a superposition of two effects: the variation in the density of the dislocation annihilation events according to any distribution (say given by (3)) of the primary dislocation sources operating inside the crystal, and the nearly constant density of the dislocation annihilation events occuring due to the escape of dislocations from the crystal.

Such an interpretation of the correlation between the high level of AE and the length of easy glide region is very compatible with the well known fact that within this region, indeed, the most dislocations escape from a crystal due to their large free mean path (about 1 to 2 mm; see e.g. [47, 48]), comparable with a crystal thickness. However, the high level of AE from the crystals of orientation 2 (Fig. 3 and 4) is not as high as from the crystals of orientation 1 (Fig. 1 and 2). Two main possible reasons may be accounted for it. First, there is another well known fact that the length of easy glide region decrease with increasing crystal thickness (e.g. [48]). Thus it is clear that the density of dislocations escaping from the crystals of 2 type orientation is smaller than this density in the case of the crystals of 1 type orientation. Second, the lower strain rate of crystals 2 yields the lower density of dislocation annihilation events inside the crystal since the density of operating Frank-Read sources decreases with decreasing strain rate [18, 42, 43].

In the same spirit we can try to explain the appearance of the second maximum of AE, corresponding to the transition from the easy glide region to the stage II of the deformation. This maximum is followed by the local minimum, especially visible in Fig. 3 and 4 (reproducible in Fig. 1 and 2 too, but masked there due to the use of logarithmic scale). Thus the second maximum can be ascribed in turn to the operation of new dislocation sources in the secondary slip systems, i.e. also to the variation of the events of dislocation segments annihilation inside the crystal according to the distribution analogous to that given by (3) for the primary source density.

Moreover, a further decrease of the AE intensity in the advanced stage II of the deformation to a much lower mean level in comparison to the one in the easy glide region can be explained in the following way. It is a well known fact that the mean free path of dislocation decreases considerably with increasing strain within stage II of the deformation (e.g. [47]). Thus the number of dislocations escaping from a crystal becomes now considerably limited since the most dislocation remain inside a crystal forming the pile-ups against the Cottrell-Lomer barriers.

We can explain quite similarly the behaviour of AE from the multislip oriented crystal of greater thickness (orientation 3, Fig. 5). However, the high mean level of the AE intensity at the beginning of the deformation, comparable to the one for the crystals of smaller thickness, is mainly as a result of the superposition of the dislocation annihilation events due to a simultaneous operation of primary and secondary dislocation sources.

Using the Eq. (1) obtained by NATSIK and CHISHKO [37] we may try to give an analytical description of our experimental results. Let $\Delta\varrho_i$ and u_i ($i = 1, 2, 3$) denote, respectively, the mean densities and velocities of annihilating dislocations, corresponding to the operation of primary ($i = 1$) and secondary ($i = 2$) sources as well as to the escape ($i = 3$) from a crystal. Then for each of these processes the rate of elastic energy $\Delta E_i/\Delta t$ released per unit volume may be written in the form

$$\frac{\Delta E_i}{\Delta t} = \alpha \frac{\Delta\varrho_i}{\Delta t} u_i^2 \ln \frac{L}{b}. \tag{4}$$

Thus the total rate of acoustic energy radiation, $\Delta E/\Delta t = \Delta E_1/\Delta t + \Delta E_2/\Delta t + \Delta E_3/\Delta t$, varies with increasing strain according to the superposition rule illustrated schematically in Fig. 6.

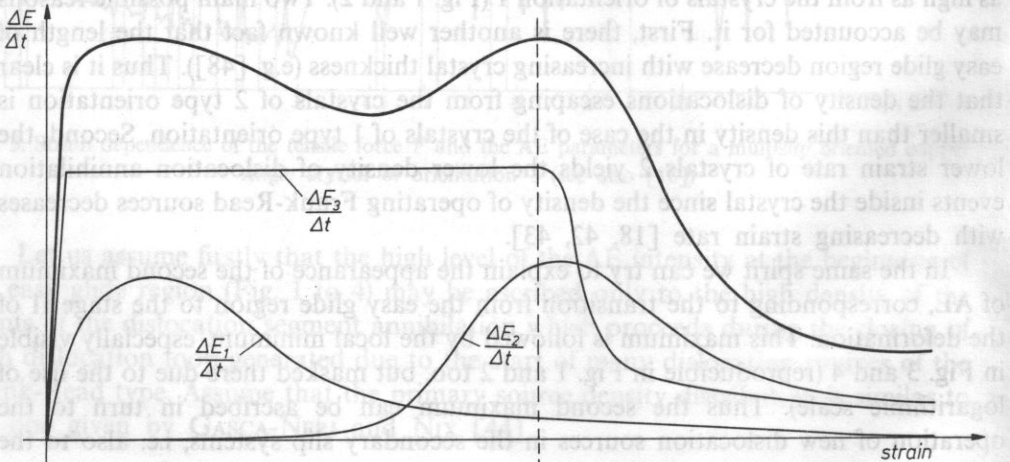

FIG. 6. Schematic illustration of the resultant pattern of the AE behaviour as a superposition of three effects: dislocation annihilation inside a crystal induced by primary ($\Delta E_1/\Delta t$) and secondary ($\Delta E_2/\Delta t$) dislocation source operations, and dislocation annihilation due to the escape of dislocations from a crystal ($\Delta E_3/\Delta t$)

In a similar way we can describe the mean energy $\Delta E_i/\Delta N$ per one event

$$\frac{\Delta E_i}{\Delta N} = \alpha \cdot \Delta d_i \cdot u_i^2 \ln \frac{L}{b} \tag{5}$$

where Δd_i is the mean length of the annihilating segments of dislocation corresponding to each of three discussed processes. Assuming that in the first approximation the mobile dislocation density, ϱ, and the mean dislocation velocity, v, are constant in the easy glide region ($\dot{\varepsilon} = b\varrho v = \text{const}$) then the density of the dislocations escaping from a crystal is constant, too, and thus the mean energy of AE events generated by the corresponding annihilation events is also constant. A slight decrease of the $\Delta E/\Delta N$ till the onset of stage II of the deformation may be related with the decrease of mean dislocation segment length with increasing strain. The lower the segment length the lower is the length of the annihilating dislocation segments during the closing of the dislocation loop generated by the source, what leads to the decrease of the mean energy per one event according to Eq. (5). However, the behaviour of $\Delta E/\Delta N$ parameter is modulated by the appearance of the second maximum (visible in Fig. 3 and 4, but again masked in Fig. 1 and 2). It may be also explained according to Eq. (3) since the lengths of the secondary sources operating at the beginning of stage II are greater than the lengths of primary sources operating at the same time.

Moreover, assuming that in the advanced stage II of the deformation the mobile dislocation density is smaller, and thus the mean dislocation velocity is greater than the corresponding values in the easy glide region, we may suppose that the noticeable increase of the mean event energy is related mainly with the increase of the mean dislocation relative velocity during the annihilation events induced inside the crystal as well as at the surface.

Eventually, we would like to emphasize here once again that there are difficulties in explaining the decrease of the AE intensity during the sudden strain rate decrease (additionally illustrated in Fig. 5; see also [18]) by using any model based on a non-stationary dislocation motion as the main cause of the AE, since the assumption of the "bremsstrahlung" nature of acoustic radiation leads, in this case at least, to the conclusion that a sudden decrease of strain rate should also result in an increase of the AE intensity what is contrary to experimental observations. Nevertheless, we cannot exclude any contribution of this type of acoustic radiation to the AE intensity observed in our experiments. On the other hand, theoretical results obtained not long ago by MALÉN and BOLIN [49] and more recently by JASZCZEWSKI [50], basing after all on the formalism developed by KOSEVICH [30 to 32] and MURA [51], still suggest the possibility of the detection of the "bremsstrahlung" type of acoustic radiation. Also the estimations carried out by JAMES and CARPENTER [7] and also by JASZCZEWSKI [50] show that the dislocations of about 10^2 to 10^3 m length when accelerated simultaneously enough should give a detectable AE signal. And though the annihilation of dislocation at a crystal surface is also considered in terms of non-stationary movement of dislocation (i.e. as a very particular case of dislocation stopping over the distance corresponding to the length of the step formed at the surface [20]), nevertheless there is still very difficult to state experimentally how much is the part of the observed AE signal which originates from the non-stationary dislocation motion. We believe, however, that more precise measurements of the possible deviation from the symmetrical behaviour of the AE during sudden strain rate jumps and drops should reveal the contribution of the "bremsstrahlung" acoustic radiation to the detected AE signals.

Moreover, we cannot exclude the Rayleigh surface waves contribution to the detected AE signals, either. However, under the conditions of our present experiments it was not possible to extract the Rayleigh wave component. And yet we believe that its contribution, if it exists, should be always additive and the qualitative pattern of the AE behaviour is determined only by the dislocation annihilation component of the transition acoustic radiation.

7. Conclusion

The present observations on the AE intensity patterns during two first stages of the tensile deformation of copper single crystals, reveal some essential correlations with the dislocation mechanisms of plastic flow. They can be qualitatively quite well explained in terms of the dislocation annihilation component of the transition acoustic radiation. Namely:

(i) The correlation between a high level of the AE intensity and the length of the easy glide region (large mean free path of dislocations) is related with the escape of the dislocations from the crystal (annihilation of dislocations with their virtual images).

(ii) The high mean level of AE from single slip oriented crystals of greater thickness deformed at smaller strain rate is much lower than the high mean level of AE from those crystals of smaller thickness deformed at greater strain rate. It is related, firstly, with a smaller density of dislocation annihilation events at the surface of the crystal of greater thickness and, secondly, with a smaller density of dislocation annihilation events induced by the Frank-Read source operation inside the crystal deformed at a smaller strain rate.

(iii) The two maxima of the AE intensity correlate by turns with the onset of the easy glide region and onset of stage II of the deformation. They are related with the dislocation annihilation events inside the crystal induced by the operation of the primary and secondary dislocation Frank-Read sources, respectively (started successively according to any distribution, e.g. similar to the one given by Gasca-Neri and Nix).

(iv) The resultant pattern of the AE intensity is a superposition of the dislocation annihilation effects occuring inside the crystal and due to the dislocation escape from the crystal.

(v) The decrease of the AE intensity to a low mean level within the advanced stage II of the deformation is related with the considerably limited dislocation escape from the crystal (small mean free path of dislocations).

(vi) The explanation of the high level of AE and the existence of only one maximum of the intensity of AE from the multislip oriented crystal, where at least two slip systems are operating simultaneously from the beginning of the deformation, follows from previous conclusions being thus a quite good confirmation of the presented interpretation.

(vii) The proposed qualitative explanation of the strain dependence of event mean energy is also compatible with this interpretation.

This work was supported by the Institute for Fundamental Technical Researches at the Polish Academy of Sciences under the contract CPBP 02.03.

References

[1] H. N. G. Wadley, C. B. Scruby and J. H. Speake, Int. Met. Rev., **249**, 41 (1980).

[2] A. Pawełek, W. Bochniak, H. Dybiec and W. Stryjewski, Archives of Metallurgy, **33**, 645 (1988).

[3] W. Stryjewski and G. Zapalski, Rep. Institute of Nuclear Physics, No. 1204/E, Cracow 1983.

[4] W. Stryjewski, G. Zapalski and A. Pawełek, Archives of Metallurgy, **33**, 485 (1988).

[5] R. M. Fisher and J. S. Lally, Can. J. Phys., **45**, 1147 (1967).

[6] R. T. Sedwick, J. Appl. Phys., **39**, 1728 (1967).

[7] D. R. James and S. E. Carpenter, J. Appl. Phys., **42**, 4685 (1971).

[8] F. P. Higgens and S. H. Carpenter, Acta metall., **26**, 133 (1978).

[9] T. Imanaka, K. Sano and H. Shimizu, Crystal Lattice Defects, **4**, 57 (1973).

[10] N. Kiesewetter and P. Schiller, Phys. Stat. Sol. (a) **38**, 569 (1976).

[11] S. Mintzer, R. Pascual and R. M. Volpi, Scripta metall., **12**, 531 (1978).

[12] C. H. Caceres and H. R. Bertorello, Scripta metall., **17**, 1115 (1983).

[13] V. S. Boiko, R. I. Garber, L. F. Krivenko and S. S. Krivulya, Fiz. tverd. teła, **11**, 3624 (1969).

[14] V. S. Boiko, R. I. Garber, L. F. Krivenko and S. S. Krivulya, Fit. tverd. teła, **12**, 1753 (1970).

[15] V. S. Boiko, R. I. Garber, L. F. Krivenko and S. S. Krivulya, Fiz. tverd. teła, **15**, 321 (1973).

[16] V. S. Boiko, R. I. Garber and L. F. Krivenko, Fiz. .tverd. teła, **16**, 1233 (1974).

[17] V. S. Boiko, R. I. Garber, V. F. Kivshik and L. F. Krivenko, ZhETF, **71**, 708 (1976).

[18] A. Pawełek, W. Stryjewski, W. Bochniak and H. Dybiec, Phys. Stat. Sol. (a), **90**, 531 (1985).

[19] A. Pawełek, H. Dybiec, W. Bochniak and W. Stryjewski, Archives of Metallurgy, **34**, 239 (1989).

[20] S. Pilecki, Arch. Akustyki, **21**, 109 (1986).

[21] J. D. Eshelby, Proc. Roy. Soc. London, **A197**, 396 (1949).

[22] G. Leibfried, Z. Phys., **127**, 144 (1950).

[23] F. R. N. Nabarro, Proc. Roy. Soc. London, **A209**, 278 (1951).

[24] J. D. Eshelby, Philos. Trans. Roy. Soc. London **244**, 87 (1951).

[25] A. Seeger, A. Donth and A. Kochendörfer, Z. Phys., **134**, 173 (1953).

[26] A. Seeger, Z. Naturforsch., **8a**, 47 (1953).

[27] J. D. Eshelby, Phys. Rev., **90**, 248 (1953).

[28] J. D. Eshelby, Proc. Roy. Soc. London, A **266**, 222 (1962).

[29] A. Pawełek, Report of the International Centre for Theoretical Physics, ICTP (87) 136, Trieste, Italy 1987; J. Appl. Phys., **63**, 5320 (1988).

[30] A. M. KOSEVICH, Usp. Fiz. Nauk, **84**, 579 (1964).
[31] A. M. KOSEVICH, *Dislocations in elasticity*, Nauk. Dumka, Kiev 1970 (in Russian).
[32] A. M. KOSEVICH, *Dislocations in solids*, vol. 1, [Ed.] F. R. N. Nabarro, North-Holland Publ. Co, Amsterdam 1979, p. 33.
[33] J. D. ESHELBY, Proc. Phys. Soc., **B 69**, 1013 (1956).
[34] D. ROGULA, Bull. Acad. Pol. Sc., Sèrie sc. techn., **13**, 337 (1965).
[35] D. ROGULA, Bull. Acad. Pol. Sc., Sèrie sc. techn., **14**, 159 (1966).
[36] V. D. NATSIK, ZhETF Pis. Red., **8**, 324 (1968).
[37] V. D. NATSIK and K. A. CHISSHKO, Fiz. tverd. teła, **14**, 3126 (1972).
[38] V. D. NATSIK and A. N. BURKHANOV, Fiz. tverd. teła, **14**, 1289 (1972).
[39] W. L. GINZBURG and I. M. FRANK, ZhETF, **16**, 15 (1946).
[40] V. I. PAVLOV and A. I. SUHORUKOV, Usp. Fiz. Nauk., **147**, 83 (1985).
[41] J. A. GOLCZEWSKI and W. STRYJEWSKI, Phys. Letters, **92A**, 397 (1982).
[42] A. PAWEŁEK, Phys. Stat. Sol., (a) **85**, K117 (1984).
[43] A. PAWEŁEK, Archives of Metallurgy, **30**, 295 (1985)
[44] R. GASCA-NERI and W. D. MIX, Acta metall., **22**, 257 (1974).
[45] A. ORLOVA, Scripta metall., **16**, 1133 (1982).
[46] E. J. SIEGEL, Phys. Stat. Sol., (a), **5**, 607 (1971).
[47] F. R. N. NABARRO, Z. S. BASINSKI and D. B. HOLT, *The plasticity of pure single crystals*, Advances in Physics, **13**, 193 (1964).
[48] R. W. K. HONEYCOMBE, *The plastic deformation of metals*, Ed. A. Arnold Cambridge 1968.
[49] K. MALÉN and L. BOLIN, Phys. Stat. Sol., (b) **61**, 637 (1974).
[50] M. JASZCZEWSKI, Rep. Institute of Nuclear Physics, No 1149/PS Cracow 1984.
[51] T. MURA, *Advances in materials research*, vol. 3 Ed. H. Herman, Wiley 1968 p. 1.

Received on April 6, 1988