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THE INFLUENCE OF ORIENTATION ON THE BEHAVIOUR OF THE ACOUSTIC EMISSION IN FACE CENTERED CUBIC METAL SINGLE CRYSTALS COMPRESSED IN A CHANNEL-DIE

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The influence of the crystallographic orientation on the behaviour of the acoustic emission (AE) in face centered cubic (FCC) metal and alloy monocrystals compressed in channel-die is investigated using five differently oriented copper single crystals ({100} < 001 >, {011} < 112 >, {112} < 111 >, {111} < 123 > and {001} < 110 >). The results obtained are also compared to the AE behaviour in silver and to the low-temperature AE behaviour in copper and copper-aluminium alloy single crystals of identical {112} < 111 > orientations. It has been stated that the orientation of crystal affects the final stage of the microstructure evolution (shear bands of the V or X shape or the bands of complex structure), and the orientation dependence of the AE behaviour is only a consequence of the orientation dependence of the deformation mechanisms. In general, however, the AE behaviour is strongly correlated with strain localization related to twinning and shear band formation, and is of universal character since it is similar in all the orientations applied.

The observed correlations between the AE and the strain localization mechanisms are discussed on the basis of the dynamic and nonlinear (solitary wave) properties of dislocations. Consequently, it has been stated that the dynamics of shear band formation is markedly weeker than that in the case of twinning seems to indicate the crystallographic character of the shear band propagation since the non-crystallographic slip should be accompanied by strong acoustic effects.

1. Introduction

Recent investigations of the phenomenon of acoustic emission (AE) are, in general, conducted in two directions. The first one, dealing with the AE phenomenon itself, concentrates mainly on the spectral analysis of the measured AE parameters [1]. However, the phenomenon of AE is more often used as an experimental method in various investigations in the materials science [2–6]. The AE method, in particular, has been used for some years by the authors of the present study in the investigations of the processes of plastic deformation of metal and alloy single crystals of face centered cubic (FCC) lattice subject to a channel-die compression, where a model of strain in plain state is realized [7–10]. The aim of these investigations was to determine and explain the observed correlations between the behaviour of AE and the strength properties (strain hardening curve) of the material, the evolution of its microstructure and texture, and the mechanisms of strain localization connected with the processes of twinning and formation of shear bands [11, 12]. A particular aim of this work was to establish the influence of crystallographic orientation on the AE behaviour in metal and alloy single crystals of FCC lattice subjected to channel-die compression. The investigations were carried out on the example of copper single crystals of five different orientations (I – {111}<001>, II – {112}<110>, III – {112}<111>, IV – {111}<1123> and V – {001}<110>) and compared with the results of investigations of channel-die compression of single crystals of silver, copper and copper-aluminium alloy (CuAl2) of identical orientations {112}<111>. The results obtained in the present work by means of the AE method have been discussed on the basis of the dynamic and nonlinear (solitary waves) properties of dislocations [13–16]. In particular, these results enabled to formulate a more precise opinion on the still disputable problems referring both to the dynamics of the formation and the possibility of non-crystallographic propagation of shear bands.

2. Investigation methods

Channel-die compression tests were carried out using the tensile testing machine INSTRON-6025, equipped with an additional installation containing a channel-die, which ensured the plastic flow of the metal in the parallel direction only, i.e. along the channel axis, and in the vertical direction, i.e. perpendicular to the channel axis. This is a simple model of the channel-die compression in which the plane state of strain is realized since in the lateral direction (also perpendicular to the channel axis) plastic deformation does not occur. Monocrystalline samples were obtained by means of the Bridgeman's method (in the case of silver and copper) or by the method of zone crystallization at a natural temperature gradient (in the case of copper and copper-aluminium alloy). Samples, having the shape of cubes of a 10 mm edge, were subjected to compression tests by the multi-stage method with the purpose to obtain the final reductions as well as the intermediate reductions of an appropiate value. After each stage, the samples were appropiately cropped so as to make the ratio of the actual value of elongation to that of height not greater than 2. In order to minimize the effects of the sample friction against the channel walls, a teflon foil was used. The speed of the testing machine travers was all the time equal to 0.05 mm/min. Simultaneously with the measurement of the work-hardening curve in the terms of force vs. time, the basic AE parameter in the form of the rate of events $\Delta N_z/\Delta t$ was registered. The number of events ΔN_z was measured in the time interval $\Delta t = 4$ s. A broad-band piezoelectric sensor enabled to register acoustic pulses of a frequency from some tens to some hundreds of kilohertzs, while suitable filters eliminated the frequency of free vibrations of the testing machine, as well as the higher frequencies connected, e.g. with the noise of broadcasting stations. The contact of the sensor with the sample at the ambient temperature occurred through a steel rail which formed a pad in the channel-die, and at the liquid nitrogen temperature – by means of a wave-guide especially formed from a quartz rod. The total amplification of the apparatus registering the AE signals was 88 dB, and the suitably chosen threshold voltage of the discriminator had a value of 1.20 V. After each compression test, the microstructure was observed using the standard technique of optical microscopy.

3. Investigation results and discussion

In Figs. 1–5 is shown the AE behaviour during the channel-die compression of copper monocrystals of five various crystallographic orientations: I – {100} <001> (Fig. 1), II – {112} <110> (Fig. 2), III – {112} <111> (Fig. 3), IV – {111} <123> (Fig. 4) and V – {001} <110> (Fig. 5). On each of these figures as well as on the following ones, besides the graphs of AE and force (to the left), there are also presented the microstructures (to the right) corresponding to the reductions obtained at the given compression stage. It should be noted that the initial course of AE, illustrating, on each figure, the AE behaviour in the time interval up to about 200 – 300 s, will not be discussed here since, this interval comprises also beside the transition from the elastic to the plastic state (already fairly accurately examined), effects connected with the mechanical adjustment of the sample to the channel walls in the range of elastic strains. For the purpose of comparison, in Figs. 6–8 there has been presented the behaviour of the AE (for selected compression stages) also in other single crystals of FCC lattice of identical orientation III subjected to channel-die compression at the liquid nitrogen temperature. Consequently, in Fig. 6 is illustrated the AE behaviour in Cu single crystals, in Fig. 7 – in Ag single crystals, and in Fig. 8 – in CuA12 alloy single crystals. Moreover, in Fig. 7 is illustrated the transition from the deformation mechanism, associated with twinning, to the deformation mechanism connected with the formation of shear bands.

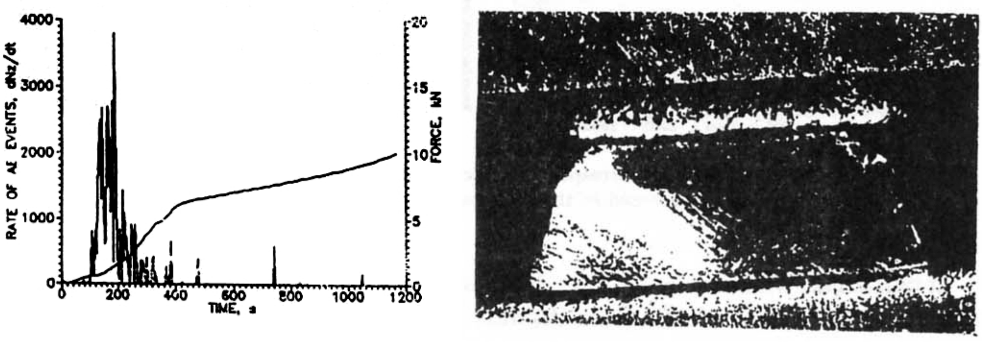


Fig. 1. Behaviour of the acoustic emission (AE) and the external force in copper monocrystals of cubic orientation {100} <001> during a channel-die compression at the ambient temperature. Besides is the corresponding microstructure after a $z = 90.4\%$ reduction; magnified ×31.

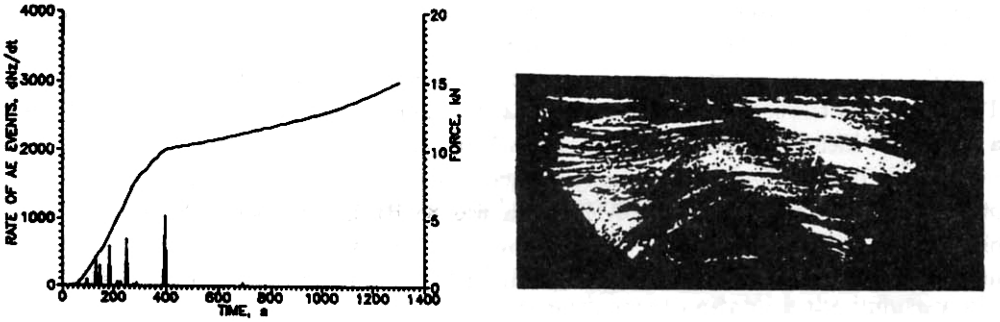


Fig. 2. AE, external force and the corresponding microstructure in Cu monocrystals of {112} <110> orientation compressed in the channel-die ($z = 86.8\%$, $T = 293$ K, ×25).

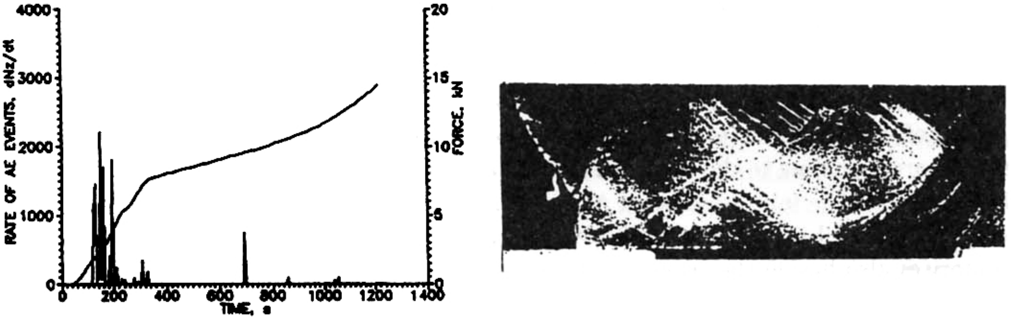


Fig. 3. AE, external force and the corresponding microstructure in Cu monocrystals of {112} <111> orientation compressed in the channel-die ($z = 80\%$, $T = 293$ K, ×31).

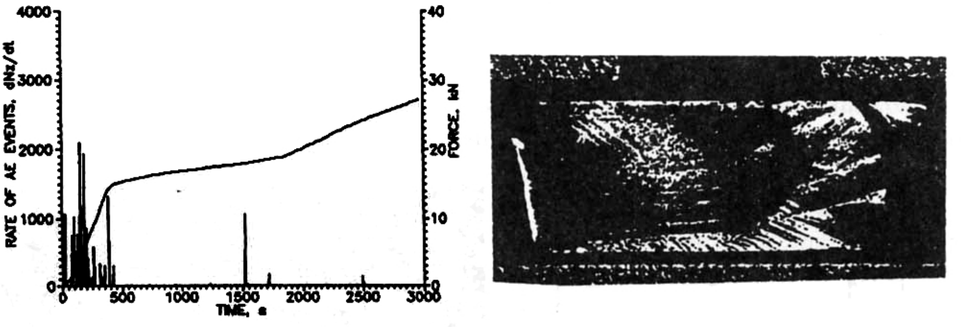


Fig. 4. AE, external force and the corresponding microstructure in Cu monocrystals of {111} <123> orientation compressed in the channel-die ($z = 70\%$, $T = 293$ K, ×10).

In particular, when analyzing Figs. 1 – 5 one can observe that there exists a tendency of universal character indicating that the final stage of the evolution of the microstructure in the process of channel-die compression (high reductions) is the occurrence of a second family of shear bands formed in the secondary activated slip systems; together with the previous family of shear bands formed in the primary activated slip systems, these bands

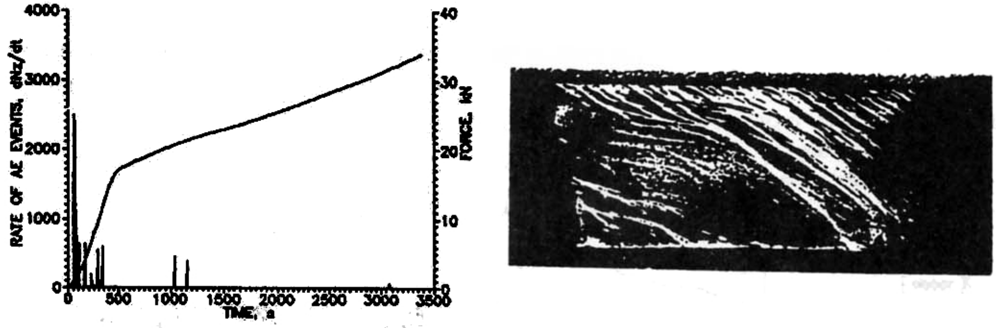


Fig. 5. AE, external force and the corresponding microstructure in Cu monocrystals of {001}<110> orientation compressed in the channel-die ($z = 75\%$, $T = 293$ K, ×31).

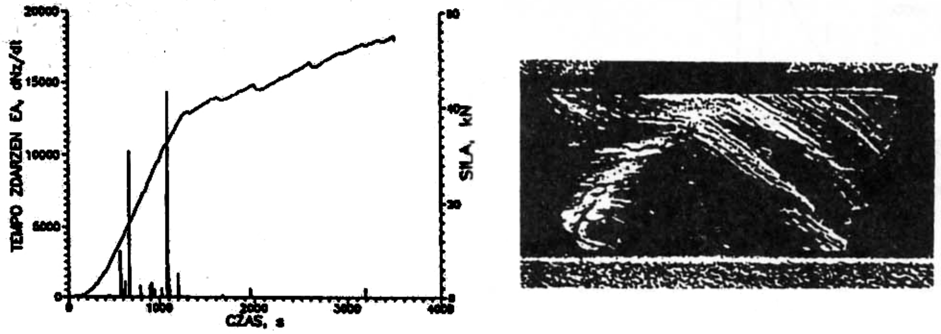


Fig. 6. AE, external force and the corresponding microstructure in CuAl2 single crystals of {112}<111> orientation compressed in the channel-die at the liquid nitrogen temperature ($z = 73\%$, ×20).

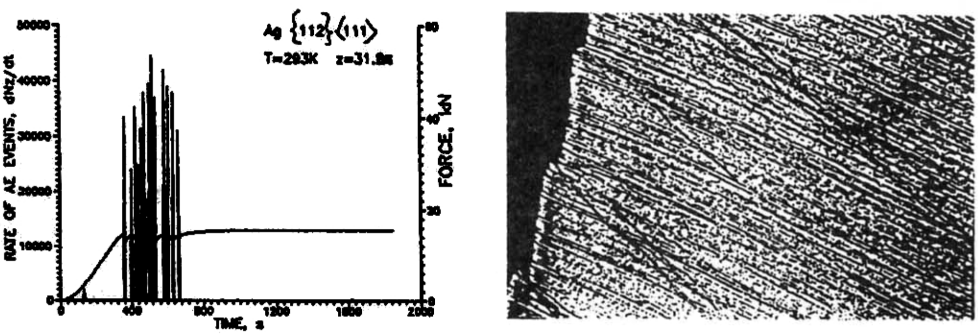


Fig. 7. AE, external force and the corresponding microstructure in silver single crystals of {112}<111> orientation compressed in the channel-die ($z = 31\%$, $T = 293$ K, ×200).

have the shape of the letter *V* (stright or reversed). This can be observed distincly for the orientations I, II and V (Figs. 1, 2 and 5, respectively). In the case of the orientations III and IV (Figs. 3 and 4, respectively), the pattern is more complex due to the influence of the orientation. In the case of the orientation {112}<111>, the bands form a shape resembling the letter *X* (Fig. 3), and in the case of orientation {111}<123>, the effect of cooperation of both the tendencies to form bands of V and X type can be observed (Fig. 4). However, in each case (including those shown in Figs. 6 and 8) the formation of shear bands of V type (as they have been called earlier [7, 9]) is always accompanied by a series of a few, more or less regular, AE peaks.

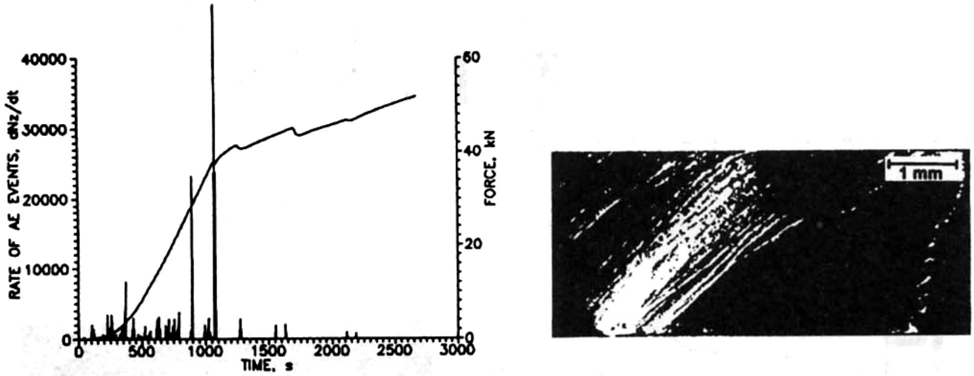


Fig. 8. AE, external force and the corresponding microstructure in Cu single crystals of {112}<111> orientation compressed in the channel-die ($z = 73\%$, $T = 77\,\mathrm{K}$, ×20).

From the presented graphs and microstructures it can be seen that in the case of each orientation there exists a direct correlation between the AE behaviour and the deformation mechanisms, while the influence of orientation is indirect in the sense that the AE depends on the deformation mechanisms determined, in general, by the initial crystallographic orientation.

The above correlations may be interpreted, at least qualitatively, basing on the dynamics of the dislocation configurations (Figs. 9 and 10) and the theoretical concept which seeks the origin of the AE just in the dynamic dislocation phenomena connected chiefly with the acceleration and the processes of dislocation annihilation. It must be taken into consideration that acoustic effects are proportional both to the square of acceleration (including the acceleration in the vibration movement of kinks) and to the square of the relative velocity of annihilating dislocations (see e.g. [14, 15]). In the scheme in Fig. 9 is shown a simple propagation mechanism of a slip band (thus at the first approximation corresponding to the initial phase of shear band formation, Fig. 9a), a wave image of this propagation (solitary wave, Fig. 9b) and the spatial mechanism of the operation of the dislocation sources of the Frank–Read type in the primary activated slip systems (Fig. 9c). In Fig. 10, on the other hand, is illustrated the solitary wave character of the propagation of a group of dislocations generated by a Frank–Read source in a single slip plane (Fig. 10a), a one-dimensional approximation of this propagation (Fig. 10b), and a wave representation (Fig.10c), evidencing the soliton-like character of this propagation (see also [13, 16]). Speaking in general, the observed AE peaks may be the result of a superposition of the effects of acceleration and annihilation of the dislocations both inside a crystal (in the case of the closing of the dislocation loops during the operation of the Frank–Read sources) and also on its free surface (in the case of the formation of the steps on the crystal surface).

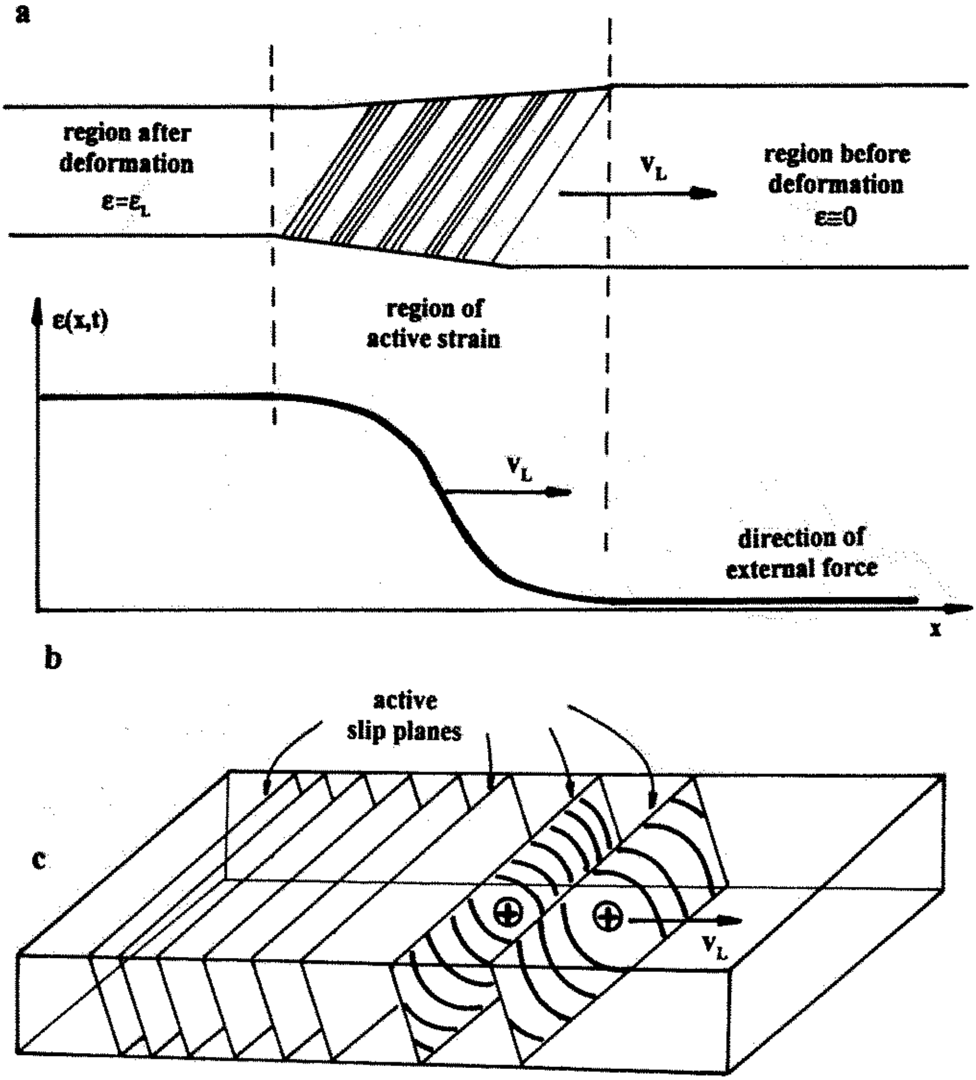
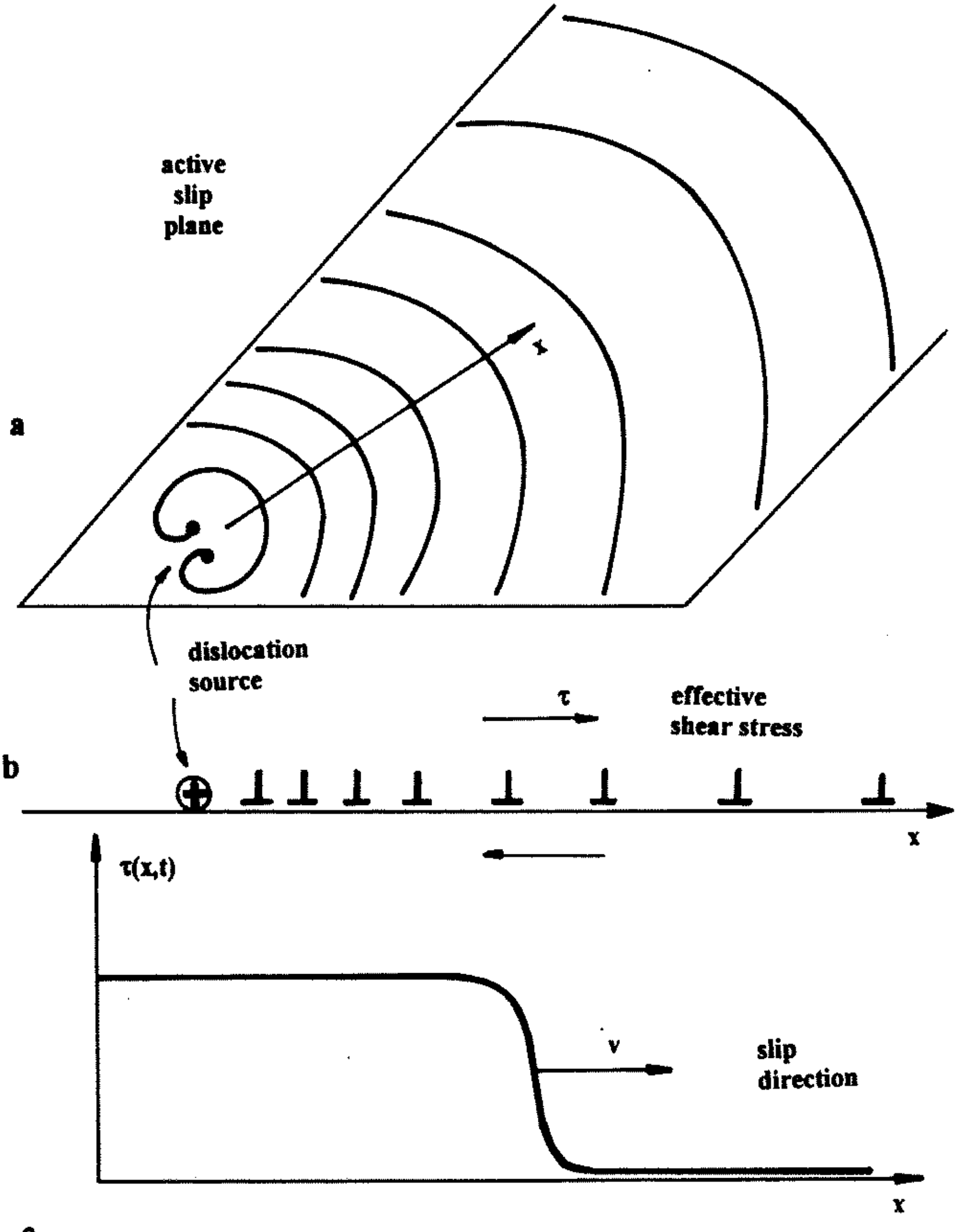


Fig. 9. Schematic illustration of a simple model of shear band propagation (a), its solitary wave representation (b) and the dislocation dynamics in active slip systems (c).

Thus, the high rate of the AE events in the case of twinning, reaching the values of the order of 4×10^4 (in the range from 350 to 650 s in Fig. 7), is due to the fact that the formation of a single twin – assuming the polar mechanism of twinning (see e.g. [15]) – may be associated with the escape to the crystal surface of tens of thousands of dislocations (more accurate estimation has been presented in [17, 18]). The effects of dislocation acceleration may also participate to a great extent in it since it is known that the velocity of twinning dislocations in a given crystal may reach values of the order of the speed of sound. On the other hand, the dynamics of the gliding dislocations (Figs. 9a



$$\tau(x, t) = \text{const} \quad [1 - \tanh \tfrac{1}{2}(x - vt)]$$

Fig. 10. Schematic illustration of the dynamics of dislocation sources in a single slip plane (a), the corresponding configuration of dislocations at the one-dimensional approximation (b), and the soliton-like character of the propagation of dislocations (c).

and 10a) is smaller than that of the twinning dislocations (at least in the sense of the possibility of attaining very high velocities in comparable periods of time). Moreover, shear bands occur in the sample volume considerably less frequently than the twins (Fig. 7). As a result, the shear bands produce much weaker acoustic events of the order of 10^3, i.e. they can be estimated to be at least by one order of magnitude smaller than in the case of twinning.

The considerably more distinct and stronger acoustic effects, accompanying the formation of shear bands at low temperatures (Figs. 6 and 8), can be explained in a similar way. In this case the dynamics of the gliding dislocations is much greater than that occurring at the ambient temperature (higher flow stress since higher dislocation velocity). On the other hand, a quite similar situation occurs when shear bands of type V are formed at the ambient temperature (Figs. 1–5) and at the temperature of liquid nitrogen. The beginning of the formation of shear bands in the secondary activated slip systems (similarly as in the case of the primary activated slip systems) would be associated with the engagement of some tens to some hundreds of dislocation sources (a more accurate assessment is presented also in [17, 18]) operating in parallel slip systems (Fig. 9c); each of them (Fig. 10a) would generate tens or even hundreds of dislocations. In this way each single AE peak, within an advanced range of the work-hardening curve (Figs. 1–5), signalling the beginning of the formation of shear bands and the formation of a step on the crystal surface, would be associated, at the first approximation, with the escape to the sample surface of a number of dislocations of the order from some hundreds (in relation to the ambient temperature) to some thousands (in relation to the low temperature). The number of AE events of this order, observed in Figs. 1–5 and 6 and 8, suggests that in the case of shear bands, independently of the crystallographic orientation, the contribution of the surface annihilation to the AE may be much greater than the that from the internal annihilation and that deriving from the effects of the acceleration of dislocations.

4. Conclusions

1. The observed correlations (very distinct especially at the temperature of liquid nitrogen) between the behaviour of the acoustic emission (AE) and the course of the channel-die compression of monocrystals of metals and alloys of a FCC lattice occur for all the examined orientations being mainly connected with twinning and the formation of shear bands.

2. Single twins, independently of the crystal orientation, are associated with single AE peaks to which the number of AE events of the order of tens of thousands corresponds.

3. The initiation of the formation of shear bands is connected with single AE peaks, to which, however, a smaller number of events correspond – in general, of the order of some hundred to a few thousands – independently on the crystal orientation.

4. Depending on the crystal orientation (although not to a great extent), the final stage of the microstructure evolution (high reductions) are the shear bands, either of type V (most often) or of type X (as in the case of the orientation {112}<111>) or of a

more complex type, being always accompanied by a series of a few, more or less regular, AE peaks.

5. The observed correlations between the AE behaviour and the progress of the compression deformation can be interpreted basing on the dynamic properties of dislocations connected mainly with acceleration and the dislocation annihilation occurring especially on the crystal surface.

6. As a consequence, the dynamics of the formation of shear bands is distinctly weaker than the dynamics of the formation of twins which is an additional evidence of the crystallographic nature of shear bands propagation since a non-crystallographic slip should be accompanied by very strong acoustic effects.

Acknowledgement

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