ON THE NATURE OF STRESS RELAXATION IN DEFORMED CRYSTALS

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ON THE NATURE OF STRESS RELAXATION IN DEFORMED CRYSTALS

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Plastic deformation of crystals is described by dislocation theory in terms of "sources" of dislocations (multiplication or nucleation) and "obstacles" to their displacement (motion). The contribution of each of these processes to the plastic deformation of a crystal differs at different stages of deformation and under different deformation conditions. The difficulties arising in the dislocation theory of plasticity are connected with the fact that the mechanism controlling plastic deformation under various conditions is unknown ([1]). It is usually assumed that the rate of multiplication of dislocations in most crystals is sufficient ([2,3]), deformation is controlled by the motion of dislocations, and dislocation multiplication is a phenomenon accompanying motion ([4]). However, for example, in the plastic deformation of calcite by twinning, the controlling factor proves to be multiplication ([5]). A consistent explanation of a number of experimental facts in plastic deformation by slip (strain bursts, etc.) turns out to be possible only if one assumes that, in slip as well, dislocation multiplication is the factor controlling plastic deformation.

Setting ourselves the task of experimentally determining the role of the process of dislocation multiplication during slip, we undertook a study of stress relaxation in plastically deformed KCl crystals at various stages of plastic deformation. Specimens for the study, of dimensions $\sim 5 \times 5 \times 10$ mm, were cleaved along cleavage planes. The average dislocation density was $\sim 3 \times 10^4$ cm^{-2}. Measurements were carried out at room temperature under compression on a rigid deformation machine (rigidity $\sim 2 \cdot 10^3$ kg/mm) with direct recording of stress as a function of time ([6]), as in ([7]). Dislocations were observed by the etching method in a saturated solution of $PbCl_2$ in ethanol ([8]).

In the first series of experiments the crystals were loaded to a definite value of the acting shear stress τ, after which deformation was stopped and stress relaxation was measured for a certain time (a stop from 0.5 to 2 min.). Then deformation was resumed and relaxation was again measured, and so on up to a deformation of $\sim$ 10%. Stress relaxation is a consequence of the fact that the elastic deformations in the crystal-relaxometer system pass into plastic deformation of the crystal through the motion of dislocations in the crystal.

The dependence of the magnitude of stress relaxation $\Delta\tau$ at each stop on the magnitude of the initial stress τ is presented in Fig. 1. It is seen that in the region up to the yield point ($\sim$ 100 g/mm^2) the magnitude of the relaxation increases, then remains practically constant in the easy-slip region, and again increases regularly in the work-hardening region. The general tendency for the magnitude of relaxation $\Delta\tau$ to increase with increasing τ is evidently connected with an increase in the number of moving dislocations in the crystal as plastic deformation proceeds.

In the second series of experiments, multiple repeated relaxation was measured (for details see ([9])), i.e., after relaxation for a specified time the crystals were loaded to the initial value of the stress τ and relaxation was again measured. This cycle was repeated many times (up to several tens of times). Multiple repeated relaxation was measured at various characteristic portions of the plastic-deformation curve of the crystal (before the elastic limit, before the yield point, at the stage of easy glide, and at the stage of hardening). Figure 2 shows the deformation curve of the crystal. At points A, B, C, and D multiple repeated relaxation was measured; its time curves are shown schematically there as well. It is seen that in the region before the elastic limit (point A) the complete relaxation in each cycle very rapidly decays to zero as the number of cycles increases. This means that the number of moving dislocations in the crystal decreases to zero, while their multiplication practically has not yet occurred. Stress relaxation ceases when the dislocations stop at an obstacle or leave the crystal. The motion of dislocations is the only process controlling plastic deformation at this stage. The result of the experiment depends very strongly on the presence of random dislocations introduced into the specimen during manipulation. Etching shows—

Fig. 1. Dependence of the magnitude of stress relaxation $\Delta\tau$ on the value of the initial acting shear stress τ reached in the course of deformation of the crystal by compression (relaxation time 0.5 min).

Fig. 2. Deformation curve $OABCD$ and the stress-relaxation curves, superposed on it, as a function of time. A —before the elastic limit, B —before the yield point, C —at the stage of easy glide, D —in the hardening region.

Fig. 3. Dependence of the magnitude of residual stress relaxation $\Delta\tau$ under multiple repeated relaxation on the number of cycles N.

—shows that during deformation only such dislocations move, while the dislocations that were already present in the crystal do not move. At this stage, apparently, relaxation in a single-crystal specimen would be absent altogether if "fresh" dislocations had not been introduced into the specimen.

In the region before the yield point (point B, Fig. 2), complete relaxation in each cycle also at first decreases strongly with increasing number of cycles N, but not to zero; rather, it decreases to a certain constant value (Fig. 3, curve b). This means that the number of moving dislocations in the crystal does

Fig. 4. Varieties of stress-relaxation curves, illustrating the unstable character of relaxation at the stage of easy slip

Figure 1: Fig. 4. Varieties of stress-relaxation curves, illustrating the unstable character of relaxation at the stage of easy slip

not decrease—it is maintained constant owing to the appearance of new moving dislocations in the crystal as a result of multiplication. Etching of crystals shows that at this stage, after multiple

during repeated relaxation, "thin slip lines" arise (rows of dislocations that have not left the crystal).

At the stage of easy slip (point C, Fig. 2), repeated multiple relaxation decays little with increasing number of cycles. Relaxation in this region is characterized by instability, i.e., a sudden, jump-like increase in the relaxation rate at certain moments in time. Figure 4 shows typical varieties of relaxation curves. Curve a in Fig. 4 is smooth, usually observed $^{(10)}$, when the relaxation rate decreases monotonically with time.

Fig. 4. Varieties of stress-relaxation curves, illustrating the unstable character of relaxation at the stage of easy slip

On curve b, the relaxation rate is very large at first, then changes abruptly to a small value. On curve v, the relaxation rate, large at first, drops abruptly practically to zero, and then the curve again undergoes a break and takes the usual form. On curve g a peculiar delay of relaxation is visible. The observed instability of relaxation is associated with avalanche-like multiplication of dislocations. The presence of a peculiar "delay time" of relaxation indicates that the process of dislocation multiplication has a fluctuation, probabilistic character. The delay time is a consequence of the insufficient magnitude of the probability of the multiplication process at a given level of stress in the crystal. One might think that jumps in the relaxation rate are connected with the simultaneous release of a large number of dislocations held up by an obstacle. But a relaxation jump of ~ 10 g/mm^2 corresponds to a plastic deformation of $\sim 10^{-5}$ cm, which corresponds to the simultaneous displacement of no fewer than $\sim 4 \cdot 10^2$ dislocations. Such large accumulations of dislocations at an obstacle are never observed experimentally. It is also difficult to imagine that in the crystal there would simultaneously occur a breakthrough of obstacles by dozens of pile-ups at once. Therefore the assumption of obstacle breakthrough must be rejected.

The jump-like character of relaxation is due to the fact that, at stresses corresponding to the stage of easy slip, the process of dislocation multiplication proceeds intensively. Since dislocation multiplication is localized at the edge of the expanding slip band, the "daughter" dislocations are easily carried away by the acting stress from the place of generation (from the "source"), propagating in an almost perfect crystal—on the relaxation curve a break is observed (Fig. 4b) when all the dislocations that have been generated finish their motion, leaving the crystal or stopping in it. In the "late" cycles of repeated multiple relaxation, when the majority of the previously created moving dislocations have already been exhausted, and the number of generation sites is small, each act of multiplication (generation) manifests itself distinctly, leading to a jump in deformation and, correspondingly, in stress. Thus, plastic deformation at the stage of easy slip is controlled by the process of dislocation multiplication.

At the stage of hardening (point D, Fig. 2), repeated multiple relaxation decreases in the same way as at the stage before the yield point, but the residual relaxation has a large value, as is seen in Fig. 3 (curve d), and the process proceeds stably.

The motion of dislocations at this stage, when the dislocation density in the crystal is $\sim 10^9$ cm^{-2}, is very difficult; evidently, they move freely only over short distances. Therefore each act of multiplication cannot lead to a large deformation—the "daughter" dislocations cannot easily move away from the "source" —relaxation proceeds stably,

practically without jumps. Since the magnitude of the residual relaxation is considerable, this means that the crystal has a "reserve" of free dislocations, or that a large number of "sources" —nucleation centers—are operating (the role of such "sources" may be played, for example, by dislocation dipoles present in abundance at this stage of deformation).

A common phenomenon for all relaxation measurements proved to be the hardening of the crystal as a result of relaxation (single or repeated). This shows that after a considerable number of relaxation cycles, at each definite value of the initial stress the relaxation must decrease to zero (all the curves in Fig. 3 must approach the abscissa axis as $N \to \infty$), i.e., the process of dislocation multiplication will cease.

In the experiments carried out on stress relaxation at different stages of plastic deformation, the contribution of the dislocation-multiplication process to stress relaxation was found. The phenomenon of unstable relaxation indicates the controlling role of the dislocation-multiplication process at the stage before the yield point and at the stage of easy glide.

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