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On the Investigation of Temperature Fields Arising During Plastic Deformation of Crystals

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Thermosensitive cholesteric liquid crystals have been used for the study of the inhomogeneity of temperature fields during the plastic deformation of AgCl, NaCl crystals. Regions of local heat releasing have been found that were associated with glide bands. The experimental data obtained are in good agreement with the estimated results.

It is well known that during the plastic deformation and destruction of materials a considerable portion of mechanical work converts into heat. Because of the inhomogeneous nature of plastic deformation of crystals the heat release is not uniform throughout the volume of the deformed crystal. A. V. Stepanov had even proposed[1] that the released heat may be sufficient for local melting of the active glide plane. This hypothesis failed,[2] but the experimental data obtained are indicative of a considerable increase of temperature in the region of intensive plastic deformation: in glide bands, near crack tips and so on.[3–5] However, the problem of the temperature rise in glide bands under different experimental conditions and of its possible role in the manifestation of serrated deformation and anomalies of plastic properties of superconductors is still open to discussion. The problem is very acute; nevertheless, no reliable methods have been worked out as yet for analysis of the inhomogeneity of temperature fields in crystals under deformation. The estimation of temperature fields when using either superconducting coils[3] or thermocouples[6] does not allow us to consider in detail the temperature distribution in the sample. In this respect, more promising are the methods involving the use of thermovision systems and thermosensitive liquid crystals;[5] such methods were employed, for example, when determining the temperature distribution at the tips of growing cracks in polymers. It should be noted, however, that in glide bands formed during plastic deformation of crystals, the thermal effects may be substantially weaker than those appearing at the tips of cracks, and the study of such effects would require the application of more sensitive methods of temperature measurement.

EXPERIMENTAL PROCEDURE

In order to determine the temperature fields that arise during plastic deformation of crystals, mixtures of cholesteric liquid crystals (CLC) have been developed that are very sensitive to temperature and have a property of selective reflection of light (the colour of these mixtures changes as the temperature increases or decreases).

The specially prepared CLC compounds with the selective reflection at room temperatures enabled us to get a sharp colour contrast in the narrow temperature range (1.5–2°C). The mixtures of several cholesteryl esters proved most convenient. The initial cholesteric substances have been subjected to chromatographic purification to remove the organic impurities that might weaken the thermosensitivity of CLC. As a compulsory component of the compound, some cholesteric substances were applied capable of increasing the intensity of the selective reflection of the CLC mixture and narrowing the temperature interval of the selective reflection.

The samples for the mechanical tests by compression had the form of rectangular prisms ($4 \times 4 \times 8\ mm^3$). The samples of sodium chloride crystals were cleaved out on the cleavage planes $\{100\}$ and the samples of cesium iodide were cut out of the crystals on the same planes. The samples for the tensile tests were cut out of rolled plates of silver chloride single crystals and had the form of a shovel. A thin CLC layer was deposited on the surface of samples just before their testing. The change of CLC colour during sample deformation was registered on colour film. The tests were carried out at room temperature; the loading rate varied between 0.0003 and 0.008 sec^{-1}.

EXPERIMENTAL RESULTS

At first we carried out the investigation of the heating of sodium chloride samples in the process of deformation by tension. The form of the samples made it possible to obtain a region of increased heating at the central part of the sample neck (Figure 1). In these experiments, comparison of the observed results and calculated data on local heat release was made. A temperature

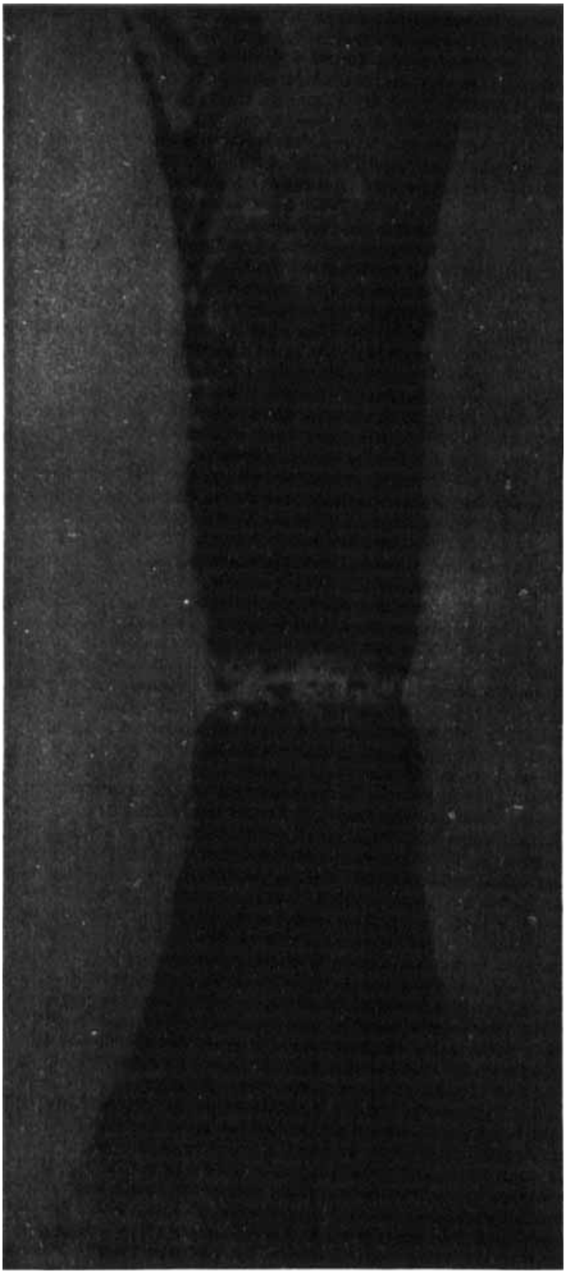

FIGURE 1 The picture of thermal perturbations in the AgCl crystal that has been subjected to the tensile deformation. The negative imprint. The extent of deformation $\varepsilon = 1\%$. The temperature is equal to 19.9°C near the clamps and 20.3°C at the center of the "neck."

field was estimated in the one-dimensional approximation using the equation

$$c\rho\dot{T} = \lambda\left(\Delta T - \frac{2h}{d}T\right) \tag{1}$$

where c is the heat capacity, ρ—the density, T—the temperature, λ—the thermal conductivity, h—the relative surface heat transfer coefficient, and d—the sample thickness. The last term in Eq. (1) accounts for the heat transfer from the side faces according to Newton's law. The solution of Eq. (1) is the following expression:

$$T = \int dx' \int_0^t dt' \frac{\sigma\dot{\varepsilon}}{c\rho}\frac{1}{2}\exp\left\{\frac{2hk}{d}(t - t') - \frac{(x - x')^2}{4\kappa(t - t')}\right\}\bigg/\sqrt{\pi\kappa(t - t')} \tag{2}$$

where t is the time, σ—the stress, $\dot{\varepsilon}$—the deformation rate, $k = \lambda/c\rho$ is the thermal diffusivity. The integral is taken over the region of the local heat release. The length of this region is assumed to be substantially less than the length of the neck. At the center of the heat release region we have:

$$T(0, t) = \int_0^t dt' \frac{\sigma\dot{\varepsilon}}{c\rho}\, l\tfrac{1}{2}R^{-(2h/d)\kappa(t-t')}\Big/\sqrt{\pi\kappa(t - t')}$$

Here l is the size of the deformed area.

From Eq. (3) it follows that during the initial period of time (at $t < d/2hk$) the temperature increases according to the following law:

$$T(0, t) \approx \frac{\sigma\dot{\varepsilon}}{c\rho}\, l\sqrt{\frac{t}{\pi\kappa}} \tag{4}$$

whereas at $t \gg d/2hk$ the temperature tends asymptotically towards the limiting values:

$$T = \frac{\sigma\dot{\varepsilon}}{2c\rho}\frac{l}{\sqrt{2\kappa h\lambda/d}} \tag{5}$$

To obtain the quantitative estimates of the thermal conductivity the data of Ref. 7 have been used. The estimate of h that takes into account the radiation and convective heat exchange gives values of the order of 0.1–0.2. The characteristic time for the establishment of the thermal equilibrium is equal to

$$t_0 = \frac{d}{2hk} = 16 \text{ sec.} \tag{6}$$

Since the duration of the experiments did not exceed 5 sec, the heat transfer from the side surfaces of the sample was disregarded. In Figure 2 the theoretical curves of the temperature rise in the neck as calculated from formula (4) is compared to the experimental data that have been obtained on the basis of

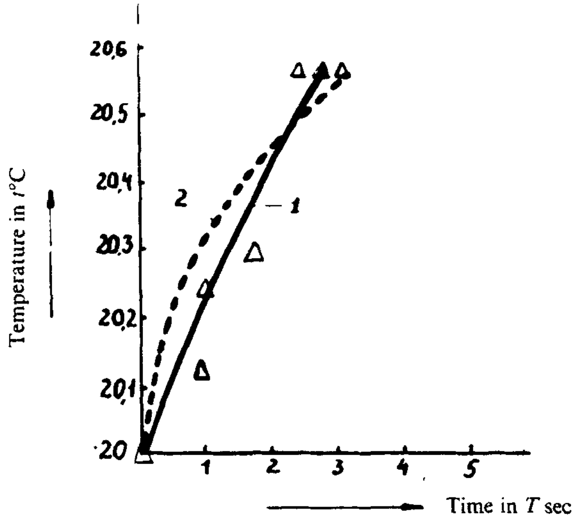

FIGURE 2 The dependence of temperature at the center of the "neck" on the time of deformation for the AgCl crystal that has been deformed by tension. 1—the experimental curve obtained from the analysis of the cinegrams: 2—the curve estimated from Eq. (4).

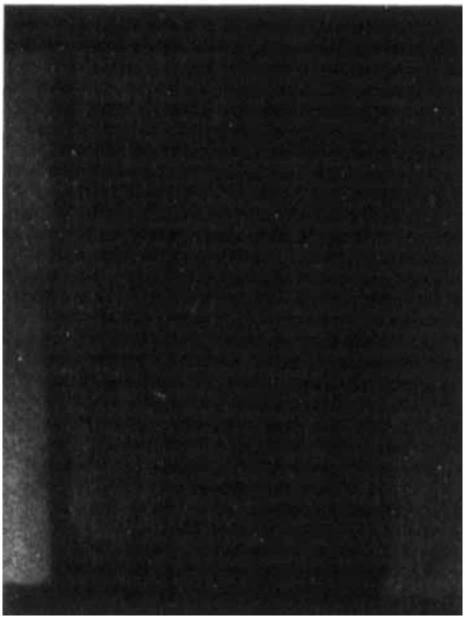

FIGURE 3 The picture of thermal perturbations in the NaCl crystal that has been subjected to the compressive deformation. The negative imprint. The extent of deformation is 2.4%. The temperature of the sample is equal to 22.9°C, in the glide bands the temperature is increased to 24°C.

the cinegram for the case of $\dot{\varepsilon} = 0.003\ \text{sec}^{-1}$ and $\sigma = 1\ \text{kg/mm}^2$. The fact that the theory is in satisfactory agreement with the experiment gives evidence of the sufficient reliability of the temperature control with the aid of CLC mixtures that possess a series of colour transitions.

The compression tests of sodium chloride and cesium iodide crystals revealed the regions of local heat release that were connected with glide bands (Figure 3) and kink interlayers. The results obtained show that the application of CLC with high sensitivity to temperature changes is a very promising method for solving the problem of the role of thermal effects in dislocation motion. This method may also be useful for the elucidation of the causes that give rise to plastic deformation in some local areas of the sample. For example, when comparing the dislocation structure of the initial sample as revealed by the selective etching method and the cinegram obtained during sample loading.

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