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Abstract

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CHANGE IN THE STRENGTH OF CERTAIN SUBSTANCES IN THE REGION OF POLYMORPHIC TRANSITIONS UNDER PRESSURE

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Experiments on uniaxial loading of various materials at high hydrostatic pressure have established that, under the action of all-round compression in a polycrystalline substance, the reserve of plasticity increases and the resistance to fracture rises; certain features of the manifestation of this general tendency in materials of different types have also been investigated experimentally. At the same time, the literature contains only isolated data on the relation between phase (and, first of all, polymorphic) transformations occurring under pressure and changes in the mechanical properties of solids. This question was raised in our preceding paper, devoted to the study of the effect of pressure on the plasticity of a bismuth-tin alloy in connection with its phase diagram (1).

In the present work, rubidium chloride, silver nitrate, and natural limestone (lithographic stone) were taken as objects of investigation. In these three substances (which belong to the class of ionic crystals), polymorphic transformations occur under pressure. The transformation pressure in rubidium chloride is 6000–7000 kg/cm^2 at room temperature. In silver nitrate, transformation into a dense modification occurs at a pressure greater than 10,000 kg/cm^2 (2). Lithographic stone is a highly homogeneous isotropic rock consisting mainly of $CaCO_3$. The grains composing this rock have average dimensions of 3–5 μ. As is known, in $CaCO_3$-based minerals, in the range 3000–30,000 kg/cm^2, several phase transformations occur, the parameters of which depend on a number of factors (chemical composition, crystalline state, etc.). In the material studied by us, phase transitions are observed in the regions of 7500; 15,000 and 21,000 kg/cm^2. In the region of room temperatures, the first two transformations proceed sluggishly and indistinctly; they are not accompanied by measurable jumps in volume (3).

The specimens were tested in axial compression at high hydrostatic pressure. They were short cylinders 8 or 10 mm in diameter with a length-to-diameter ratio from 1 to 1.5; RbCl specimens were made by pressing the powder of the "pure" reagent; $AgNO_3$ specimens by melting the "analytically pure" salt into a steel mold; a radial texture was noticeable in the melted specimens. Cylinders of lithographic stone were turned on a lathe.

Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

Compression was carried out in a special device between polished supports of hardened steel, with the tested material protected by rubber tubes from contact with the pressure-transmitting liquid in the chamber. In the course of the experiment, a hydrostatic pressure was first created in the chamber, and then an axial compressive force was applied to the specimen; unloading was carried out in the reverse order (the deformation rate was $10^{-3} \div 10^{-4}$ $\sec^{-1}$). After completion of the test, the residual deformation of the specimen and the maximum value of the axial force were determined. For the latter, load cells were used, which likewise fit in the high-pressure chamber.

Thus, at each pressure a compression curve could be constructed*. Figure 1 gives an example of such an experimental curve in the coordinates maximum nominal stress—residual relative shortening, obtained for lithographic stone at a pressure of 8000 kg/cm^2. This and similar curves obtained by the Crespi method do not differ from ordinary nominal compression diagrams in those cases where, during the test, the stress does not decrease as the deformation increases. In our experiments this condition was fulfilled.

Fig. 1. Nominal compression diagram of lithographic stone under a hydrostatic pressure of 8000 kg/cm^2. The different symbols correspond to different specimens. The arrows indicate the failure of the given specimen. F is the axial force, S_0 is the initial cross section of the specimen.

Before presenting the results of determining the strength characteristics of the materials studied, it is necessary to dwell on the effect observed in RbCl specimens of the combined action of plastic deformation and polymorphic transformation, which may be interpreted as the phenomenon of "healing" of cracks. At small deformations ($\sim 1\%$), thin cracks appear in RbCl specimens, visible as light threads in the translucent body of the specimen (Fig. 2a and c). After further deformation under conditions of polymorphic transformation, these cracks remain only at the ends and disappear in the bulging regions (Fig. 2b) or vanish altogether (Fig. 2c). In specimens that underwent deformation in the high-pressure phase

Fig. 2. Rubidium chloride specimens after tests at pressures of 6000-6700 kg/cm^2 (a, b, c) and 8000 kg/cm^2 (d, e, f). a—$\delta = 1.5\%$; b—22.8%; c—54.4%; d—1.3%; e—16.7%; f—$\delta = 44.4\%$.

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* During compression of the specimen, the hydrostatic pressure was kept constant with an accuracy of up to several hundred kilograms per square centimeter;

Figure 3

Figure 3: Figure 3

Figure 4

Figure 4: Figure 4

the test pressure was taken to be the maximum pressure value established for the given experiment.

pressure, cracks persist up to the very largest deformations (Fig. 2d and e). On the bulged portions of these specimens, oblique cracks are visible, which are usually associated with shear phenomena in low-plasticity materials. It should be assumed that if such cracks could arise during deformation in the course of a polymorphic transformation, then they did not subsequently develop and were "healed" during further flow of the material, whereas cracks formed after completion of the transition into the

Fig. 3. Compression diagrams at various pressures ($p = \text{const}$).
a—rubidium chloride: 1—1 atm; 2—2000 kg/cm^2; 3—5300; 4—6000; 5—6700; 6—8000; 7—10,500 kg/cm^2.
b—silver nitrite: 1—1 atm; 2—3000 kg/cm^2; 3—6000; 4—9000 and 16,000; 5—12,000 and 14,000 kg/cm^2.
c—lithographic stone: 1—2000 kg/cm^2; 2—5000; 3—8000; 4—10,500; 5—12,500; 6—15,000; 7—17,000 kg/cm^2.

dense modification persist also during the reverse transformation occurring after removal of the axial load.

Fig. 4. Dependence of the reduced stress on pressure at constant residual deformation ($\delta = \text{const}$).
a—rubidium chloride: 1—$\delta = 3\%$; 2—$\delta = 10\%$;
b—silver nitrite: 1—$\delta = 2\%$; 2—$\delta = 10\%$;
c—lithographic stone: 1—$\delta = 2\%$; 2—$\delta = 5\%$; 3—$\delta = 10\%$.

Specimens of all the tested materials, at relatively small deformations (up to 10-15%), deform uniformly, so that

can be calculated as the value of the reduced stress $\bar{\sigma} = F/S$, where F is the maximum, for the given experiment, value of the axial force, and S is the cross-sectional area of the specimen after the experiment. At large deformations the effect of friction at the ends leads to the formation of local bulging, and the value of $\bar{\sigma}$ does not reflect the strength of the material.

As a result of several series of experiments, for each material it was possible to construct curves of the dependence of the reduced stress on the residual deformation at several constant pressures covering the regions of polymorphic transformations (Fig. 3). Processing these curves makes it possible to compare the strength properties of the high- and low-pressure phases. Figure 4 gives graphs of the dependence of the reduced stress on hydrostatic pressure for several constant values of residual deformation, at which local bulging has not yet occurred. In Fig. 4a it is seen that during the polymorphic transition in RbCl there is a jump-like increase in the stress required to obtain a given residual deformation of the specimen; it is also seen that the strength of the dense phase increases with pressure more rapidly than the strength of the low-pressure phase.

In contrast to RbCl, in the case of $AgNO_3$ (Fig. 4b), in the region of the polymorphic transformation there is a cessation of the growth of strength with pressure, and one may even speak of a certain decrease in it upon formation of the high-pressure phase.

In lithographic stone, in which the polymorphic transformations in $CaCO_3$ in the range 7500–15 000 kg/cm^2 are diffuse in character, there is a stepwise increase in the resistance to plastic deformation (Fig. 4c). This character of the dependence of strength on pressure is especially noticeable at small ($\delta = 2$ and 5%) deformations, whereas the bends in the dependence $\bar{\sigma}(p)$ at $\delta = 10\%$ are less pronounced, although the curve itself runs more steeply than the first two. The fan of curves in Fig. 4c may serve as confirmation of the observation made by Bridgman in studying metals, that the effect of hydrostatic pressure on strength is manifested more strongly in the region of large deformations than of small ones (^{4}).

The experiments carried out show that, with the general strengthening of a material under the action of pressure, during polymorphic transitions there may occur both an increase in the resistance to compression in the plastic region (RbCl), and a slowing of its growth with pressure (lithographic stone), and even phenomena of weakening ($AgNO_3$).

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