EFFECT OF PROGRAMMED LOADING ON THE CHANGE IN THE ELECTRICAL RESISTIVITY OF BISMUTH SINGLE CRYSTALS UNDER UNIFORM LOW-TEMPERATURE COMPRESSION CONDITIONS

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Nonhydrostatic conditions arise in various investigations of the effect of pressure on solids in freezing media,and mechanical properties of the investigated objects play an important role in this effect. To obtain more stable characteristics, to suppress hysteresis, and to improve reproducibility of the results, a preliminary programmed hardening of bismuth single crystals was carried out. Bismuth single crystals, hardened by increasing the load at 3 kg/mm^2 per hour, showed practically no hysteresis and no residual changes in the electrical resistivity when pressures up to 7.5 kbar were applied via solid nitrogen. Untreated samples, as well as samples deformed without this preliminary hardening, exhibited a residual change in the electrical resistivity when pressure was removed,and this change amounted to 40% after two tests in a high-pressure chamber.

1. Investigations of the influence of the rate of preliminary loading on various properties of crystalline bodies demonstrate the effectiveness of programmed loading, consisting of a gradual increase of a load at a constant rate of deformation [1]. Hardening by programmed loading is due to the diffusion displacement of defects present in a crystal to energetically more favorable sites and the relief of local overstresses near various inhomogeneities in a crystal. This produces a more uniform structure in a metal, increases the yield point and strength, improves the resistance to creep and to the change in shape during heating, and reduces the temperature at which cold brittleness appears [2-4].

Investigations of properties of program-hardened metals have been carried out so far mainly under conditions of uniaxial stretching or compression and, therefore, it seemed interesting to investigate the behavior of program-hardened crystals under uniform pressure in freezing media. It is known that nonhydrostatic conditions may appear in such media and the conditions are strongly affected by the mechanical properties and the degree of uniformity of the structure of the investigated objects.

Bismuth of the V-00 grade was used in the present investigation. The samples were in the form of single-crystal rods of square (3 × 3 mm) cross section grown by the Shubnikov method, with the trigonal axis parallel to the sample axis. The programmed loading of the samples was carried out in a special device on the object table of an IZA-2 horizontal comparator which made it possible to follow very accurately the changes in the distance between two marks on a sample during stretching. The samples were loaded gradually at a certain rate by pouring water into a container suspended from the sample; this was done at room temperature. The pressure-induced change in the electric resistivity of bismuth single crystals was measured in apparatus

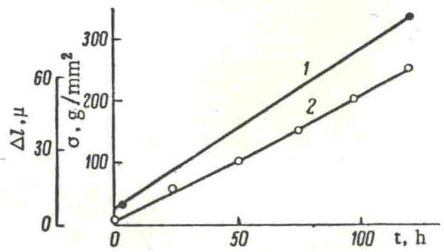

Fig. 1. Programmed loading of bismuth single crystals at room temperature and atmospheric pressure.

described earlier [5], using samples cut from the middle parts of the single-crystal rods. The pressure in the apparatus was raised up to 10 kbars at 77.3°K by means of a piston moving in a medium of solid nitrogen.

2. We can see from Fig. 1 that an increase of the applied stress at a rate of 3 g/mm^2 per hour up to 330 g/mm^2 resulted in a practically linear increase in the length without discontinuities in the "elongation-time" dependence. Discontinuous deformation has been observed [2, 3] at high loading rates of large crystals and during programmed loading of single-crystal samples of bismuth of small transverse cross section or in the presence of surface macrodefects. The discontinuities in the "elongation-time" curve, due to the appearance of twinned layers, were observed in the usual tests of bismuth single crystals at loads beginning from 160-200 g/mm^2. Increase of the resistance of single crystals to deformation and the absence of deformation discontinuities in our case (Fig. 1) could be explained by the diffusion hardening of weak points in the crystals, in which usual tests caused local overstresses comparable with the critical shear stresses required in twinning.

Program-hardened samples were used to investigate the change in the electrical resistivity due to uniform compression at low temperatures and the results were compared with the measurements carried out on the original (untreated) crystals.

Since the pressure in the solid nitrogen medium was not fully hydrostatic and since the structure of the untreated crystals was not uniform, irreversible shear was observed in these samples from 2-3 kbars, when a certain value of the tangential stress of the medium on the samples was reached. This increased the resistivity and destroyed the reversibility of the dependence of the electrical resistivity on pressure (Fig. 2a). When the load was increased, the electrical resistivity of a single crystal increased, but when the pressure was removed the resistivity remained about 30% higher than the initial value. Repetition

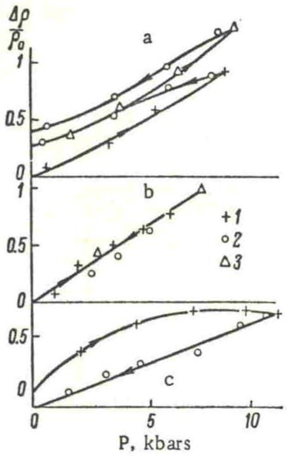

Fig. 2. Relative change in the electrical resistivity. $\Delta\rho/\rho_0$ of bismuth single crystals subjected to pressure at 77.3°K. a) Initial state; b) after programmed loading to 330 g/mm^2; c) after programmed loading to 500 g/mm^2. 1) Pressure increasing; 2) pressure decreasing; 3) second increase in pressure.

of the application of pressure up to 9 kbars and the subsequent removal of the load continued to increase the residual electrical resistivity.

In the case of a single crystal subjected to a preliminary programmed loading up to 330 g/cm^2, the electrical resistivity increased linearly with pressure up to 7.5 kbars and when the load was removed, the resistivity returned to its initial value (Fig. 2b). When pressure was applied again, the pressure dependence of the electrical resistivity coincided with the dependence obtained initially and after unloading no increase in the residual resistivity was observed.

Increase of the residual electrical resistivity after uniform compression of untreated bismuth single crystals was the consequence of the generation of a large number of defects, particularly in the first loading cycle. A preliminary programmed harding of bismuth single crystals produced a diffusion redistribution of point defects and dispersed local overstresses; this increased the structural uniformity of the whole crystal and reduced the probability of formation of new lattice defects in microvolumes.

The pressure dependence of the electrical resistivity was somewhat different for a single crystal which was slowly loaded first to 500 g/mm^2 until a residual deformation of 0.4% was observed. Figure 2a shows that when pressure was applied, the electrical resistivity of this crystal increased,

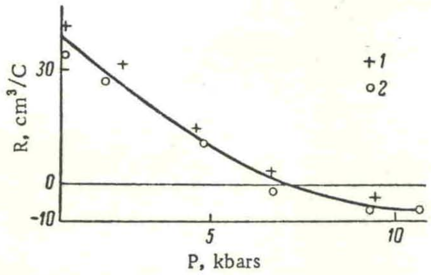

Fig. 3. Pressure dependence, at 77.3°K, of the Hall coefficient R of a bismuth single crystal subjected to programmed loading up to 500 g/mm². 1) Pressure increasing; 2) pressure decreasing.

reaching a maximum value at 7-8 kbars, and then it tended to decrease. When the load was removed the resistivity of this single crystal decreased by about 14% compared with the initial value. We measured the magnetoresistance and the Hall coefficient of this sample when pressure was increased and decreased. It was found that the pressure dependence of these properties for a program-hardened crystal differed from the dependence obtained for untreated bismuth single crystals at low temperatures and from those obtained in a hydrostatic medium at room temperature in the same range of pressures [6]. Figure 3 shows that the Hall coefficient of a program-hardened crystal even changes its sign at 7 kbars. The change of the sign of the Hall coefficient in bismuth single crystals has been observed earlier by one of the present authors, but this observation was made at a higher pressure (about 16 kbars), applied through the medium of silver chloride [6]. The unusual nature of the pressure dependence of the Hall coefficient was probably governed not by the properties of carriers in bismuth but by a redistribution of defects during programmed loading.

The reversible changes in the electrical resistivity during low-temperature uniform compression and the increase in the resistance to plastic deformation confirmed the possibility of improvement of the structural uniformity of crystals by programmed loading to very low degrees of deformation.

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