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Figure 1

Figure 1: Figure 1

Abstract

Full Text

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PHYSICS

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THE INFLUENCE OF THIN MERCURY COATINGS ON THE STRENGTH OF METALLIC SINGLE CRYSTALS

A decrease in the surface energy of a metal under the influence of adsorption of surface-active substances leads to a reduction in its strength ([1,2]). These very general effects of adsorption-induced strength reduction have been studied in detail on metals during adsorption of organic surface-active substances under various conditions ([2–4]). However, liquid metallic media can cause a considerably greater decrease in strength, lowering the solid/liquid interfacial surface energy almost to zero. It is precisely by this effect that the phenomena studied by S. T. Kishkin, Ya. M. Potak, and also by a number of other authors ([5–7])—the reduction in the strength of metals, especially at high temperatures, under the influence of low-melting metallic melts—are explained.

P. A. Rebinder, V. I. Likhtman, and L. A. Kochanova ([1]) showed that the effects of adsorption-induced strength reduction under the influence of liquid surface-active metals saturated with the metal under investigation are very sharply expressed in perfect single crystals.

These studies were carried out at elevated temperatures; it was of interest to investigate the influence of a surface-active metallic coating on the strength of single crystals at room temperature.

Fig. 1. Dependence of the true stress $P = P_0(1 + \varepsilon/100)$ on the relative elongation ε for amalgamated (a) and non-amalgamated (b) zinc single crystals. $\chi_0 = 40^\circ,\ \lambda_0 = 40^\circ$. Tensile rate 15% min^{-1}.

The objects of our investigation were single crystals of zinc, tin, cadmium, and lead with a content of the base metal of 99.99%, diameter 0.5 mm and length $\sim$ 10 mm. The surface-active substance was mercury, which was applied in

Figure 2

Figure 2: Figure 2

the form of a thin film by immersing the specimen in a solution of $Hg_2(NO_3)_2$, followed by washing with water. The mercury covered the single crystal with a uniform layer about $0.1\,\mu$ thick and rapidly became saturated with the metal under investigation. The extremely small amounts of applied mercury, as well as the comparatively low solubility in it of the metals studied (2.2% for Zn and 0.6% for Sn at 20°), ruled out any appreciable corrosive action of the mercury.

The investigation of the strength properties of amalgamated single-cryst—

of the samples under tension at a constant rate showed that the strength of zinc and tin single crystals coated with mercury is several times lower than the strength of non-amalgamated single crystals (Figs. 1 and 2).

Such a sharp decrease in strength is apparently connected with a considerable reduction of the surface tension at the metal/mercury boundary and with a decrease in the work required to form the new surface of the fracture crack. The development of such fracture cracks, lying in the slip plane, is apparently promoted by the rapidly occurring surface migration of mercury along the developing defects of the crystal lattice.

Fig. 2. Dependence of the stress P_0 on the relative elongation ε for amalgamated (a) and non-amalgamated (b) tin single crystals, $\chi_0 = 58^\circ$, $\lambda_0 = 74^\circ$. Tensile rate 15% min^{-1}.

Investigation of polished sections in the axial cross-section of amalgamated zinc single crystals after their deformation showed that cracks may form both on the surface and in the volume of the single crystal, as is seen when axial polished sections are examined (Fig. 3 I). The formation of internal cracks may be associated with appreciable diffusion of mercury into zinc at room temperature, followed by a decrease in the surface tension on the internal interfaces that arise.

The study of the temperature dependence of the adsorptive action of mercury showed that raising the temperature to 160°C eliminates, in amalgamated zinc single crystals, the described phenomena of catastrophic brittleness, leading to complete restoration of plasticity and strength (Fig. 3 I). In the 40-degree temperature interval (120—160°) of transition from the brittle state to the plastic one, phenomena of "partial brittleness" are observed (Fig. 3 II), when the single crystal is found to be covered with a number of more or less deep, partly opened cracks, around which the material is strongly hardened. These phenomena of a sharp temperature dependence are completely reversible, i.e., they are not connected with removal of mercury by evaporation. A decrease in the deformation rate causes phenomena analogous to an increase in temperature.

The mechanism of crack formation, considered in detail in a number of works ($^{9-11}$), is usually associated with the accumulation of groups of dislocations near various obstacles. The stress P_c, sufficient for the formation of a crack at the head of such a group, according to Stroh' s calculations (^{6}), is equal to

$$P_c \simeq \frac{12\sigma_{12}}{nb}.$$

Here σ_{12} is the surface tension at the single-crystal—medium interface; n is the number of dislocations arrested at the obstacle, depending on the penetrability of the obstacle; b is the magnitude of the Burgers vector. Thus, the strength of a body decreases with a lowering of the surface tension on the newly formed crack surface and increases when conditions are created that impede the accumulation of large avalanches of dislocations near possible potential barriers. A body proves to be brittle if the yield point P_1 is higher than the stress P_c ensuring the appearance of a crack, i.e., if the condition $\sigma_{12} < \alpha b P_1$ is satisfied, where α is a theoretically estimated constant, in order of magnitude close-

To the article by V. N. Rozhanskii, N. V. Pertsov, E. D. Shchukin, P. A. Rebinder, p. 769

I

II

up to 110°

130°

150°

above 160°

Fig. 3. *I* —axial section; *II* —fracture of amalgamated zinc single crystals at various temperatures. Tensile rate 15% min^{-1}

To the article by Yu. S. Zuev, S. I. Pravednikova, p. 813

a *b*

Fig. 3. Photographs of ozone cracks formed at large deformations: *a* —sodium nitrite; *b* —NK. The arrow indicates the direction of stretching.

···close to unity, and $P_1 \simeq nP_f$ is the local stress necessary for overcoming the obstacle, i.e., for the propagation of shear.

According to the temperature dependence of the probability of crack formation calculated by Stroh (^{9}), the probability that an obstacle will be overcome by a pile-up of dislocations, i.e., the probability of plastic flow, can be expressed by the relation

$$W(T) = 1 - \exp\left(-\frac{\nu l t_0}{b} e^{-U/kT}\right), \qquad (1)$$

where ν is the natural frequency of thermal vibrations of the atoms; l is the length of the arrested dislocation front; t_0 is the accumulation time, sufficiently long for the formation of a crack, of a group of dislocations; U is the activation energy for a dislocation to overcome the barrier.

Such a dependence causes a sharp transition of $W(T)$ from 0 to 1 in a small temperature interval near

$$T_c = \frac{U}{k \ln \frac{\nu l t_0}{b}}. \tag{2}$$

The quantities under the logarithm can be estimated approximately; then, according to (2), for the experimentally found transition temperature, U proves to be equal to ~ 1 eV at the given deformation rate ($15\%\,\mathrm{min}^{-1}$). Substitution of these quantities into the expression $W(T)$ gives the temperature dependence of the transition from the brittle state to the plastic state, which is in good agreement with the experimental data (Fig. 4). Similar experiments with the amalgamation of cadmium and lead single crystals did not produce so sharp a decrease in strength. In this case the lowering of surface tension by mercury coatings, at the sufficiently small value of the yield stress P_f for these metals, apparently did not ensure fulfillment of the inequality $\sigma_{12} < \alpha b P_1$ under the conditions of our experiments.

Fig. 4. A—dependence of the ultimate elongation before fracture for amalgamated (a) and non-amalgamated (b) zinc single crystals on temperature; **B** —dependence of the probability that dislocations overcome an obstacle for an amalgamated zinc single crystal on temperature.

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