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Abstract

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ON THE BRITTLE FRACTURE OF ZINC SINGLE CRYSTALS

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One of the fundamental problems of the physicochemical mechanics developed by P. A. Rebinder and his collaborators is the problem of the effect of temperature, the character of the stressed state, and an active external medium on the mechanical properties of metals (1).

In our investigations of the influence of low-melting metallic melts on the mechanical properties of more refractory metals, very significant adsorption effects of reduction in strength and plasticity were discovered (2). Similar results were also obtained in works of great importance (3,4).

A study of the regularities of the adsorption-induced reduction in strength and plasticity of zinc single crystals coated with the thinnest film of liquid tin showed that these effects are fully reversible and are not connected with the action of the melt along grain boundaries (2), as had been assumed by many authors (5–7).

In work (8) it was established that mercury, like tin, behaves with respect to zinc single crystals as a very strong surface-active substance, sharply reducing their strength and, especially, their plasticity.

Since molten metals greatly reduce the strength and plasticity of more refractory metals, bringing them into a brittle state, it becomes necessary to carry out a comparative study of the regularities of deformation and fracture of metals in strongly surface-active melts with the analogous regularities for the same metals in a brittle state, but in inactive media.

Such a comparison of properties was carried out by us in the present work on zinc single crystals, using mercury as a surface-active substance and liquid nitrogen as an embrittling but inactive medium.

Single-crystal specimens were prepared from pure zinc (99.99%) by the zone crystallization method developed in our laboratory (9). The regularities of brittle fracture of zinc single crystals with different initial orientations of the basal plane relative to the wire axis ($13^\circ \leq \chi_0 \leq 80^\circ$) were studied by uniaxial tension

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

at a constant elongation rate ($\sim 12\%\ \text{min}^{-1}$) of the specimens in inactive and surface-active media.

Figure 1 presents the results of experiments with zinc single crystals at the temperature of liquid nitrogen. It follows from this figure that the magnitude of the plastic shear preceding fracture is the greater, the smaller χ_0 is. At the same time, the normal tensile stresses in the basal plane (the slip plane) decrease sharply with decreasing initial orientation angle χ_0 of this plane, or, what is the same thing, with increasing plastic shear preceding separation. Conversely, the magnitude

the shear stresses increase with increasing deformation, which is associated with shear hardening.

For a proper understanding of these regularities it should be pointed out that the crystallographic conditions of deformation of zinc single crystals, in combination with the law of independence of the critical shear stress from the orientation angle of the basal plane, lead to the fact that at small χ_0 the normal stresses on the basal plane are comparatively small, whereas at large χ_0 these stresses increase considerably.

Fig. 1. Dependence of the limiting plastic shear (a_m), the tensile normal (N_m), and shear (S_m) stresses on the initial orientation angle of the basal plane (χ_0) of zinc single crystals at $-196°$.

Fig. 2. Decrease of the normal fracture stresses along the basal plane N_m for zinc single crystals fractured at $-196°$, with increasing prior deformation at $20°$.

Thus, brittle separation along the basal plane is facilitated by preceding shear along this plane. In the region of comparatively high normal stresses on the basal plane (large χ_0), even a small shear along this plane is sufficient for brittle separation to occur, whereas with decreasing normal stresses the magnitude of the shear deformation preceding separation increases continuously.

It follows from the experimental data obtained that the so-called Sohncke law on the constancy of the tensile normal stresses is not valid for zinc single crystals in the brittle state. It also follows from the data obtained that plastic shear leads to the appearance of defects in the crystal structure which are embryos of fracture. These structural defects, already at early stages of their development, lead to brittle separation along the slip plane (the basal plane) at large χ_0. At small χ_0, however, the development of the defects to the critical value corresponding

Fig. 3. Dependence of the limiting plastic shear (a_m) of non-amalgamated (1) and amalgamated (2) zinc single crystals on the initial orientation of the basal plane (χ_0) at 20°

Figure 3: Fig. 3. Dependence of the limiting plastic shear (a_m) of non-amalgamated (1) and amalgamated (2) zinc single crystals on the initial orientation of the basal plane (χ_0) at 20°

to the given level of normal stresses is attained at a larger magnitude of plastic shear.

In this connection it should be pointed out that the effect of "hardening under tension," indicated by Polanyi (10) and rather widely accepted (11–13), was not observed in our experiments on zinc single crystals. Figure 2 shows the dependence of the normal separation stresses along the basal plane for zinc single crystals fractured at −196° on the prior deformation of these single crystals at room temperature. As can be seen from this figure, the magnitude of the normal separation stress along the basal plane falls with increasing prior deformation, i.e., it obeys the same regularity as in tension in liquid nitrogen. It follows from this that slip along the basal plane in zinc single crystals at room temperature does not lead to hardening under tension, but, on the contrary, lowers the level of the normal separation stresses along this plane. The absence of brittle separation along the basal plane at room temperature in those cases where the normal stresses on this plane exceed its brittle strength should be explained by the fact that

under these temperature conditions it is energetically more favorable for the crystal to continue slipping than to tear. The dislocation criterion for the transition from plasticity to brittleness, developed by E. D. Shchukin (14), determines the temperature boundary of this transition, which for zinc single crystals lies at about 200°K.

The regularities of brittle fracture of zinc single crystals at low temperatures are reproduced completely also in the case when the transition to the brittle state is achieved not by lowering the temperature, but by the action of a strongly surface-active medium—mercury—in which deformation of the crystals takes place. Mercury was applied to the surface of zinc single crystals in a thin layer (of thickness $\sim 5\mu$) by immersing the crystals in a saturated solution of mercurous nitrate (oxide) with a holding time in the solution of about 1 min.

Fig. 3. Dependence of the limiting plastic shear (a_m) of non-amalgamated (1) and amalgamated (2) zinc single crystals on the initial orientation of the basal plane (χ_0) at 20°.

Fig. 4. Dependence of the limiting shear value (a_m), the tensile normal (N_m), and shearing (S_m) stresses on the initial orientation of the basal plane (χ_0) of amalgamated zinc single crystals at 20°.

Fig. 4. Dependence of the limiting shear value (a_m), the tensile normal (N_m), and shearing (S_m) stresses on the initial orientation of the basal plane (χ_0) of amalgamated zinc single crystals at 20°

Figure 4: Fig. 4. Dependence of the limiting shear value (a_m), the tensile normal (N_m), and shearing (S_m) stresses on the initial orientation of the basal plane (χ_0) of amalgamated zinc single crystals at 20°

Figure 3 gives the dependence of the limiting plastic shear a_m, preceding fracture of non-amalgamated and amalgamated crystals, on the initial orientation χ_0 of the basal plane. Whereas in the absence of mercury this limiting shear increases with increasing χ_0, i.e., with a more transverse arrangement of the base the crystals prove to be more plastic, the amalgamated specimens show a directly opposite regularity. Such a radical change in the character of the dependence $a_m(\chi_0)$ under the action of mercury is associated with the transition of zinc single crystals in the presence of mercury from the plastic to the brittle state and with the resulting appearance of new regularities of deformation and fracture.

Indeed, as can be seen from Fig. 4, the dependence of the limiting shear value, and of the normal and shearing stresses at the moment of rupture, on the orientation of the basal plane is entirely analogous to the same dependence for zinc single crystals at low temperatures (Fig. 1). The essential difference, however, between these brittle states is that in the surface-active medium—mercury—the brittle strength of the single crystals (the magnitude of the normal tensile stresses) is sharply reduced (by a factor of 3-5), whereas the magnitude of the shear stresses practically does not change.

Consequently, mercury, as a surface-active substance, causes a brittle state in zinc single crystals characterized by the same

general regularities of deformation and fracture as is the brittleness caused by lowering the temperature in the absence of surface-active substances. The sharp decrease in the normal tensile stresses in the presence of mercury is determined by a considerable decrease in the interfacial surface tension at the boundary saturated solution of zinc in mercury—zinc. The structural defects formed during deformation—microcracks—are rapidly filled with mercury by the mechanism of two-dimensional migration, and thereby their further development up to brittle fracture under the action of even small normal stresses is substantially facilitated. The high mobility of mercury atoms, which allows them to penetrate sufficiently rapidly into the microcracks that form, is a necessary condition for observing the effect of a decrease in strength and plasticity. At low temperatures, when mercury atoms are deprived of mobility, an increase in the brittle strength of zinc single crystals coated with a mercury film is observed; this is associated either with alloying of zinc by mercury or with impeded shear and fracture introduced by the film itself.

As is known, with an unfavorable orientation of the basal plane, brittle separation in zinc single crystals at low temperatures can occur along a prism of the first order. The normal tensile stresses for separation along this plane considerably exceed the corresponding stresses for the basal plane, but at sufficiently small angles χ_0 such separation may nevertheless occur more easily than along the base. Experiment shows that preliminary stretching of zinc single crystals at room temperature (the slip plane is the basal plane) considerably increases the normal tensile stress for separation along the prism plane at the temperature of liquid nitrogen [15]. This result is associated with strengthening against shear of the latent slip planes, which may be even more significant than the strengthening of the active slip system.

Table 1

Influence of preliminary stretching of zinc single crystals at 20° on the normal tensile stresses for separation along the prism plane

Preliminary stretching ε at 20° (%)	Normal tensile stress of separation N_m for zinc single crystals (kg/mm^2), non-amalgamated (at −185°)	Normal tensile stress of separation N_m for zinc single crystals (kg/mm^2), amalgamated (at 20°)
0	1.8	0.8
50	2.6	2.0
150	4.8	4.2
300	7.6	5.2
450	9.6	5.4

Table 1 gives these data for non-amalgamated and amalgamated specimens.

It follows from the data of Table 1 that in the presence of mercury brittle separation along the prism plane (at room temperature) is also facilitated, and the effect of strengthening of fracture caused by preliminary stretching along the basal plane is considerably reduced after amalgamation.

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