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Abstract

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ON CERTAIN FEATURES OF BRITTLE FRACTURE OF METALLIC CRYSTALS

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In our earlier experiments on the brittle rupture of amalgamated zinc single crystals along the basal plane (0001) ([1,2]), a noticeable scatter was found in the values of the rupture stresses (and, correspondingly, of the limiting strains attained by the moment of rupture) for completely identical specimens with the same angle of inclination χ_0 of the basal plane to the specimen axis, cut from one and the same long single crystal. If the minimum values of the true tensile stresses at rupture of specimens with a given χ_0 are denoted by $P_{c\,\min}(\chi_0)$, and the maximum values by $P_{c\,\max}(\chi_0)$, then it turns out that the relative magnitude of the scatter $(P_{c\,\max} - P_{c\,\min})/P_{c\,\max}$ increases substantially as the angle χ_0 decreases: for single crystals with $\chi_0 > 50°$ it usually does not exceed 10%, whereas for specimens with $\chi_0 < 30°$ it reaches 25% and more. Since the section of a crystal, of diameter L_0, by a slip plane is an ellipse with axes L_0 and $L_0/\sin\chi_0$, single crystals with large angles χ_0 differ substantially from specimens with small χ_0 in that in the former the outlines of the slip planes (0001) are close to a circle, whereas in the latter the length of the planes (0001) in the direction of the major axis of the ellipse noticeably exceeds the diameter of the specimen. It could be assumed that precisely this geometrical feature is associated with the increase in the scatter of the values of rupture stresses at small angles χ_0.

To clarify this question, in the present work a microscopic study was carried out of cleavages along the basal plane obtained upon rupture of numerous specimens of amalgamated zinc single crystals of diameter $L_0 \sim 1$ mm with different orientations χ_0 in the interval approximately from 20 to 70°. After applying a mercury coating of thickness $\sim 5\,\mu$, the specimens were brought to rupture at a constant rate of extension $\sim 10\%$ min^{-1} at room temperature; the following were recorded: the limiting strain $\varepsilon_{\max}$, which makes it possible to find the final angle of inclination χ of the basal plane to the specimen axis, and the magnitude of the true tensile stress at rupture $P_c = P_0(1 + \varepsilon_{\max})$ (P_0 is the rupture stress referred to the initial cross section).

Microscopic examination of the cleavage pattern showed that cleavages are never perfectly smooth and mirror-like: with suitably sufficiently contrast illumination, numerous steps can always be found in the field of view, caused by a series of successive transitions of the fracture crack from one given plane (0001) to other, adjacent parallel planes as the crack propagated through the crystal section. Among these numerous faintly distinguishable small steps, sometimes curving in a fanciful manner and forming a peculiar pattern of branches on the cleavage, there is usually sharply distinguished one (more rarely, several) distinct, considerably deeper "main" step with more or less rectilinear outlines. Several characteristic microphotographs of cleavages obtained on specimens with orientation χ_0 about 30° are given in Fig. 1 (see the insert facing p. 1053), where the aforementioned main steps are indicated by arrows. The pattern shown in Fig. 1a we called a cleavage of type A: here the main step is located closer to the sharp end of the ellipse and is arranged approximately perpendicular to the direction of the major axis. The pattern shown in Fig. 1b we ···

called a type B cleavage—here the main step lies closer to the end of the minor axis of the ellipse and runs approximately perpendicular to the minor axis. Figure 1c shows a microphotograph of a cleavage of mixed type.

When the values of the rupture stresses P_c were compared with the character of the cleavages obtained, it turned out that the **minimum** P_c usually corresponds to a **type A cleavage**, whereas the **maximum** P_c corresponds to a **type B cleavage**. Additional investigations showed that the main step most probably corresponds to the site of **nucleation** of the fracture crack.

To explain the results obtained, one should proceed, as we believe, from general ideas about the nucleation of fracture cracks at places with high stress concentrations caused by inhomogeneities of plastic deformation (for example, by the formation of dislocation pile-ups). Such ideas were developed by us in papers ([3]) and are applicable to various specific dislocation models of the appearance and development of microcracks ([4]). We have shown that rupture of differently oriented specimens occurs upon reaching a certain critical ratio between the normal stresses p_c applied to the basal plane and the shear stresses τ_c (or the limiting crystallographic shear a_c, which changes with the orientation of the single crystals in approximately the same way as τ_c). It is precisely these quantities that correspond to the approximate condition of constancy of the product: $p_c\tau_c = \gamma^2 G\sigma/L$, or $(p_c\tau_c)^{1/2} = \text{const}\cdot L^{-1/2}$, where L is the maximum size of the region of localization of plastic-deformation inhomogeneities (in particular, of incomplete shear).

It is natural to assume that, in the case of rupture with the formation of a type A cleavage, the extent L of such a region of accumulation of incomplete shear in front of an obstacle, in the vicinity of which the main step arose during crack opening, should be regarded as a quantity close to the dimensions of the major axis of the ellipse, i.e. $L_A \approx L_0/\sin\chi_0$. Accordingly, in the case of rupture with the formation of a type B cleavage we have $L_B \approx L_0$. Hence it follows that, for identical specimens with the same initial orientation χ_0, which in one case exhibited a type A cleavage and in another case a type B cleavage, the relation $(p_c\tau_c)_A^{1/2}/(p_c\tau_c)_B^{1/2} = (L_B/L_A)^{1/2} = \sin^{1/2}\chi_0$ should hold; or, since $(p_c\tau_c)^{1/2} = P_c \sin^{3/2}\chi\cos^{1/2}\chi$,

Fig. 2

Figure 1: Fig. 2

$$(p_c\tau_c)_A^{1/2}/(p_c\tau_c)_B^{1/2} = (P_c \sin^{3/2}\chi \cos^{1/2}\chi)_A/(P_c \sin^{3/2}\chi \cos^{1/2}\chi)_B = \sin^{1/2}\chi_0. \tag{1}$$

The difference between the factors $\sin^{3/2}\chi\cos^{1/2}\chi$ in cases A and B corresponds to the circumstance that in case B the crystal is stretched to larger values of $\varepsilon_{\max}$; since, with increasing deformation, the angle χ decreases, we obtain $\chi_B < \chi_A$. However, in the specific interval of values of χ_0 and $\varepsilon_{\max}$ under consideration this difference is relatively small, and therefore approximately we have $P_{cA}/P_{cB} \approx \sin^{1/2}\chi_0$. In other words, the relative magnitude of the scatter of rupture stresses is $(P_{c\max} - P_{c\min})/P_{c\max} = (P_{cB} - P_{cA})/P_{cB} \approx 1 - \sin^{1/2}\chi_0$.

The corresponding experimental data for six different orientations χ_0 are given in Fig. 2, where the value $\sin^{1/2}\chi_0$ is plotted along the abscissa axis, and along the ordinate axis are the values of the left-hand side of equality (1), i.e. the ratios of the quantity $(p_c\tau_c)^{1/2}$ for those crystals with the given χ_0 which in some cases showed a fairly clearly expressed type A cleavage and in others an equally clearly expressed type B cleavage. The straight line in this figure corresponds to exact fulfillment of equality (1). Figure 2 shows that relation (1), within the accuracy of an individual experiment (about 10%), is fulfilled over a wide range of orientations; thus, the dependence of the magnitude of the scatter of the values of P_c on χ_0 can indeed be explained by differences in the geometrical conditions of formation of deformation inhomogeneities.

From the point of view of dislocation theory, such inhomogeneities, in the case of formation of cleavage of type A, are clusters of edge dislocations approximately parallel to the minor axis of the ellipse and arranged in a row along the major axis, whereas in case B one may speak of a cluster of screw dislocations approximately parallel to the major axis and forming a row along the minor axis of the ellipse. (The corresponding considerations concerning the difference in the length of clusters of edge and screw dislocations have already been expressed in works ([5–7]).) It follows from this that if, under the given experimental conditions, the breaking values p and τ for different χ strictly obey the condition $(p_c\tau_c)^{1/2} = \text{const} = K$, then the principal role in the process of formation of the fracture crack may be ascribed to screw dislocations; in this case the graphs of the dependence of p_c and τ_c on χ form symmetric branches $p_c = K \operatorname{tg}^{1/2}\chi$, $\tau_c = K \operatorname{ctg}^{1/2}\chi$.

Fig. 2

Close to this are, in particular, the conditions of fracture of zinc single crystals at low temperatures and of gallium-plated zinc single crystals at room temperature ([1–4,8,9]). If, however, the predominant role belongs to edge dislocations, then the dependence of the breaking stresses on orientation should be closer to the condition $(p_c \tau_c)^{1/2} = K \sin^{1/2}\chi_0$, or, what is the same, $p_c = K \operatorname{tg}^{1/2}\chi \sin^{1/2}\chi_0$, $\tau_c = K \operatorname{ctg}^{1/2}\chi \sin^{1/2}\chi_0$. In this case the branch $p_c(\chi)$ rises considerably more steeply than the branch $\tau_c(\chi)$ falls. Similar conditions occur, in particular, in the fracture of gallium-plated cadmium single crystals ([8,9]). For amalgamated zinc single crystals, as already noted above, a considerable scatter of the data is observed; it is limited, however, by the region between the two named dependences $(p_c \tau_c)^{1/2} = K \sin^{1/2}\chi_0$ and $(p_c \tau_c)^{1/2} = K$, which, by analogy with the preceding, may be called dependences of type A and type B.

The data presented make it possible to assert that in studying the mechanism of brittle fracture one should take into account the difference in the role of edge and screw dislocations. It is known that the mobility of edge and screw dislocations changes differently with temperature and rate of deformation ([10]). In this connection one may expect that similar objects under different deformation conditions may exhibit both a dependence of type A and one of type B. It may therefore be supposed that further analysis of the relation between normal and shear stresses in the fracture of crystals will make it possible to clarify in greater detail a number of questions connected with the temperature-rate dependence of the conditions of brittle fracture ([11]).

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Note: Figure translations are in progress. See original paper for figures.