Fracture in Hexagonal Closed Packed Metals, Zinc and Beryllium

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ABSTRACT: - A study has been made of the fracture behavior of zinc and beryllium at 77°K. The energy to propagate a crack, ϕ_p, on the basal plane (0001) in monocrystals was determined using the double cantilever cleavage technique. The energy to initiate a cleavage crack on the (0001) plane, ϕ_I, was determined using the tensile fracture data from mono and asymmetric bicrystals and a fracture criterion derived for Bullough-Gilman-Rozhanskii model of crack initiation. It is shown that $\phi_I \simeq \phi_p \sim \gamma$, where γ is the surface energy of the cleavage plane. These results are in agreement with the condition for nucleation controlled fracture derived by Stroh and Smith from theoretical considerations. Accordingly, it is concluded that fracture in zinc and beryllium is initiation controlled.

1. INTRODUCTION

It is known that hexagonal closed packed metals zinc and beryllium are brittle and fracture by cleavage (0001) after a limited amount of basal slip. Cleavage initiates in the basal plane via one of several mechanisms of crack initiation and subsequently propagates in the same plane. If the energy expended by plastic relaxation processes at a barrier during crack initiation or at the tip of a crack during crack propagation is small, then ϕ_I, the energy to initiate a crack in the basal plane, should be equal to ϕ_p that to propagate the crack in the same plane. If $\phi_I \simeq \phi_p \sim \gamma$, where γ(0001) is the cleavage surface energy of the basal plane, then following Stroh (Adv. Phys. 1957, 6, 418) and Smith (Acta. Met., 1966, 14, 985) fracture in zinc and beryllium may be considered nucleation controlled. The purpose of this paper is to demonstrate the validity of above relationship for zinc and beryllium and to show that fracture in these metals is nucleation controlled and is independent of the nature of the barrier from which fracture nucleates.

2. EXPERIMENTAL

2.1 Determination of ϕ_p and ϕ_I for zinc: - ϕ_p and its variation with temperature, fig. 1, for zinc has been determined earlier by Westwood and Kamdar (Phil. Mag., 1963, 8, 787) using the double cantilever cleavage technique. The primary objective, therefore, is to determine reliable values of ϕ_I at 77°K. The values of ϕ_I can be computed by substituting published fracture data from 6 mm and 1 mm dia. zinc monocrystals of various orientations, χ (where χ is the angle between the cleavage plane and tensile axis and χ_F is this angle at fracture) tested in tension at 77°K, fig. 2, into a fracture criterion,

$$(\tau_F - \tau_C)\ \sigma_{NF}\ L_F = 4\ \phi_I\ [EG/(1-\nu)]^{1/2}/\pi \qquad \text{Eq. (1)}$$

derived for Bullough-Gilman-Rozhanskii model of crack nucleation. Here τ_F and σ_{NF} are respectively the resolved shear and normal stress along the basal plane, τ_C is the critical resolved shear stress for basal slip for zinc at 77°K, L_F is the length of the fractured slip plane, E and G are Young's and shear modulus, respectively, and ν is Poisson's ratio. The computed values of ϕ_I and its variation with χ_F and the crystal diameter is shown in Fig. 3. It is seen that ϕ_I is 100 ± 20 ergs/cm^2 and does not vary with χ_F or the diameter of the monocrystals.

2.2 Variation of P_F with D: Although ϕ_I does not vary with χ_F or crystal diameter, equation (1) predicts that the fracture stress, P_F, of zinc crystals having different diameters but identical orientations χ_F should vary inversely with diameter. The data presented in Fig. 2 illustrates the validity of this prediction. Alternatively, the product, $[(\tau_F - \tau_C)\ \sigma_{NF}]^{1/2}$ should vary linearly with the reciprocal of the square root of the fracture (slip) plane length, L_F. The data presented in Fig. 4 when L_F varied from 1.03 to 14 mm ($L_F^{-1/2}$ = 1.0 to 0.26 mm$^{-1/2}$) seem to be in accord with the prediction. This relationship is equivalent to the well known Petch fracture stress-grain size relationship.

2.3 Fracture initiation in asymmetric zinc bicrystals at 77°K: Zinc monocrystals deform by single slip (basal) at 77°K and hence it is not known what would constitute a fracture nucleation barrier at 77°K in these crystals. Therefore, it was decided to examine the effects of the presence of a grain boundary on fracture initiation in zinc crystals. Accordingly, asymmetric zinc bicrystals of χ = 65° to 75° were prepared and using $\dot{\varepsilon}$ = 0.005"/min were tested in tension to fracture at 77°K. The bicrystals fractured within the gauge length via basal cleavage. The cleavage crack initiated in the monocrystal which was specifically oriented for pile up of dislocations against the grain boundary. The average value of ϕ_I computed from four tests was 100 ± 15 ergs/cm^2 (M. H. Kamdar, Met. Trans., 1971, 2, 485), in agreement with that determined for monocrystals, Fig. 3.

2.4 Determination of ϕ_p for beryllium: - The double cantilever cleavage technique of Gilman (J. Appl. Phys., 1960, 31, 2208) was used to study crack propagation in monocrystal specimens prepared from high purity beryllium. The details of specimen preparation and test procedures, etc., are described elsewhere (R. K. Govila and M. H. Kamdar, Met. Trans., 1970, 1, 1011). Specimens (see inset, Fig. 1) were partially cleaved at 77°K and subsequently the cleavage crack was propagated at various temperatures. Using the fracture data and the equation given in the inset, Fig. 1, ϕ_p was determined. The variation of ϕ_p with temperature is shown in Fig. 5.

2.5 Determination of ϕ_I for beryllium: - Crack initiation studies were carried out on small, damage-free tensile test specimens of χ = 30° to 60°. Prior to testing, a series of three Vickers microhardness indentations were made at room temperature in the center of the gauge length of several of the specimens. Indentation was intended to provide a barrier for slip dislocations, either in the form of a bend plane or twins as required by the fracture criterion. After indenting, the specimens were electrolytically polished and were given a recovery annealing heat treatment. Cracks were not observed in the vicinity of the indentation. The specimens were then tested at 77°K in tension to fracture using $\dot{\varepsilon}$ = .005"/min. The non-indented specimens fractured in or near the grips after 30-80% plastic strain. The indented specimens fractured within the gauge length via basal cleavage in a catastropic manner after 7-20% strain. The fracture data and the fracture criterion,

$$\phi_I = (\tau_F - \tau_C)\ \sigma_{NF}\ L_F\ (1 + \cos\chi_F)\pi\ \ (1-\nu)\ 4G \sin\chi_F \qquad \text{Eq. (2)}$$

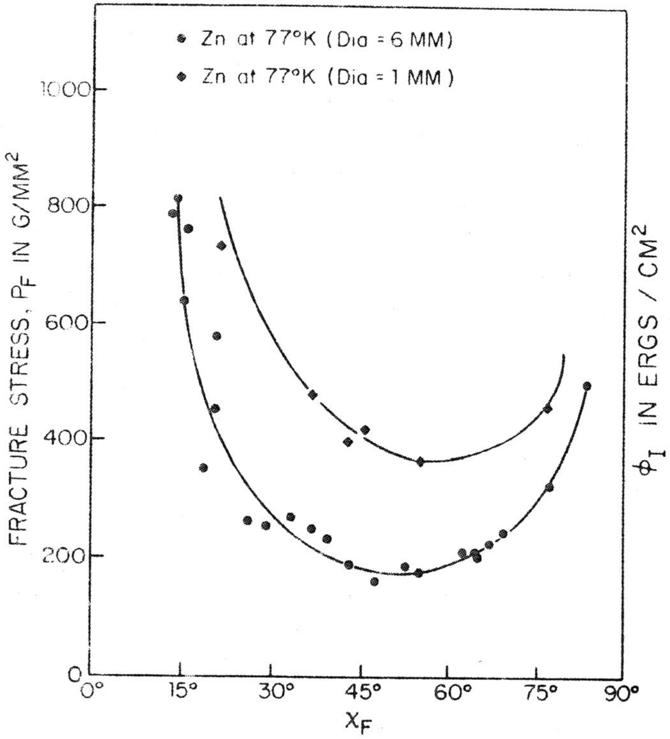

Fig. 2

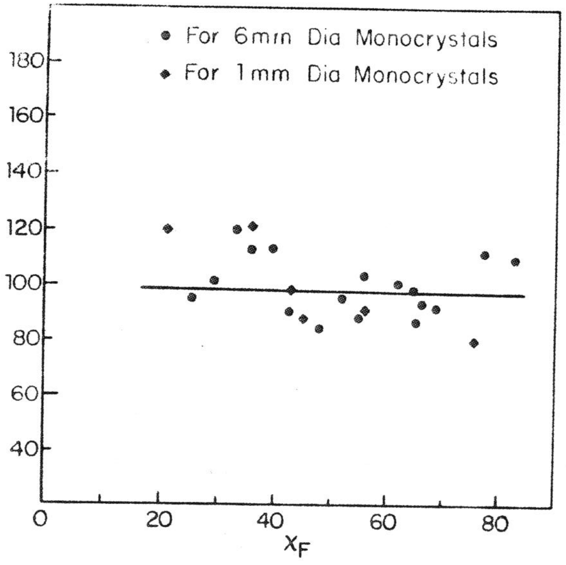

Fig. 3

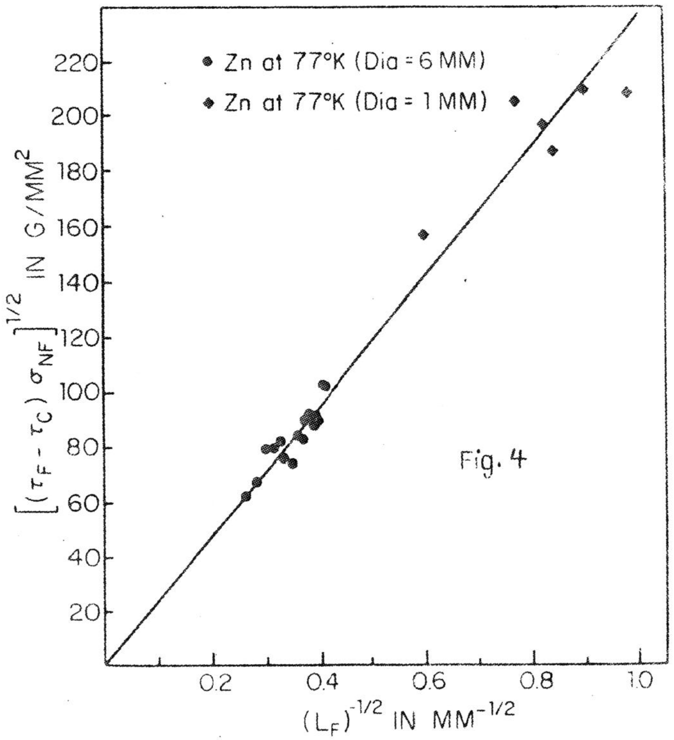

Fig. 4

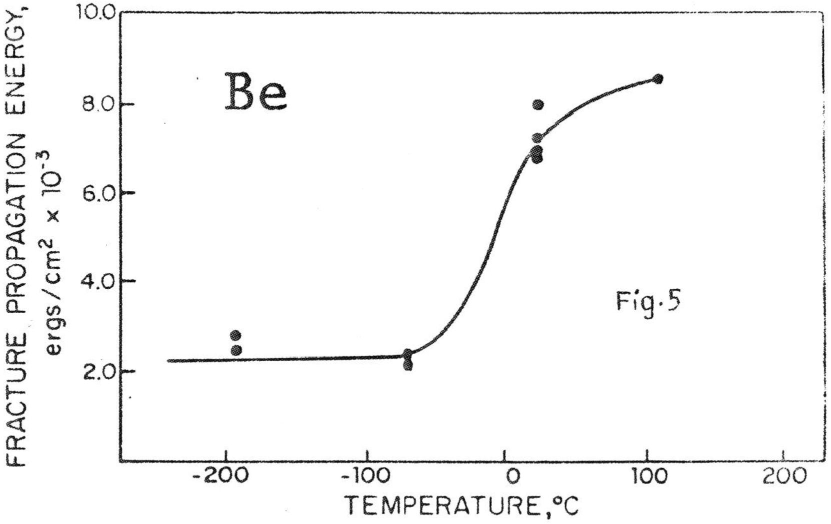

Fig.5