Influence of Grain Boundary Carbide on Brittle Fracture

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Introduction

In their theory of brittle fracture Cottrell [1] and Petch [2] start from the idea that a crack is initiated by a pile-up at the grain boundary. This model, however, does not consider the fact that, in some steels, the crack may be initiated by the fracture of grain boundary carbides.

The present paper proposes an energy balance for a crack which, starting from two pile-ups, is passing through a rigid particle into the ferrite. Two equations describing the dependence of the true fracture stress on the friction stress, the grain size, and the thickness of the grain boundary carbides will be presented.

Proposed Model

Similar to the model of Cottrell dislocations are assumed to pile up on 2 intersecting planes against the grain boundary carbide, the thickness of which is D. In the grain boundary carbide a crack of length c is initiated by the high stress concentration at the tip of the pile-ups. When making up the energy balance, we have to consider two different cases, because the surface energy of the ferrite γ is greater than the surface energy γ_A of the carbide.

$c < D$

If the tip of the crack is within the carbide, the energy of the growing crack will be

$$E(c) = \frac{\mu n^2 b^2}{4\pi(1-\nu)} \ln\left(\frac{4R}{c}\right) - \frac{\sigma n b c}{2} - \frac{\sigma^2(1-\nu)\pi c^2}{8\mu} + 2\gamma_A c \qquad (1)$$

σ being the applied normal stress, μ the shear modulus, nb the width of the crack, R the cut-off radius and ν Poisson's ratio.

$c \geqq D$

If the tip of the crack is within the ferrite, the energy of the growing crack will be

$$E(c) = \frac{\mu n^2 b^2}{4\pi(1-\nu)} \ln\left(\frac{4R}{c}\right) - \frac{\sigma n b c}{2} - \frac{\sigma^2(1-\nu)\pi c^2}{8\mu} + 2\gamma_A D + 2\gamma(c-D) \quad (2)$$

The discussion of $E = E(c)$ which has been discribed in detail elsewhere [3] yielded results which are independent on any assumption concerning nb. The fracture stress and the critical length of the crack are independent on the thickness D of the grain boundary carbide as long as D does not surpass a certain critical value. After this critical value has been surpassed, the critical crack length equals D and the fracture stress σ_z decreases.

In order to be able to quantitatively discuss the results of the energy balance, nb has to be given as a function of measurable or well-known variables. In the present paper, nb is given as a function of the grain size d by the equation

$$nb \doteq \frac{(\sigma-\sigma_0)\,d}{4{,}4\mu} \quad (3)$$

which corresponds to an equation proposed by [4] neglecting the additive therm 3.1 b. σ_0 takes into consideration the fact that [4] postulates a state of equilibrium between external stress and the number of piled-up dislocations, which does not exist in case of a usual tensile test. If e. g. the elongation necessary for brittle fracture is approx. 0.1 %, the effective shear stress on the mobile dislocation will be strong enough to cause this plastic deformation. The stress necessary for the movement of the dislocations equals the $\sigma_{0.1}$-yield point of the single crystal.

In equations (1) and (2) nb is eliminated by means of equation (3). According to [3] σ_z is evaluated as a function of the new variable $x = \sqrt{4{,}4\pi(1-\nu)D/d}$

In the case of $$x^2 < \frac{8{,}8\gamma\mu}{d} \Big/ \left\{\frac{\sigma_0}{2} + \sqrt{\frac{\sigma_0^2}{4} + \frac{8{,}8\gamma\mu}{d}}\right\}^2 \quad (4)$$

$$\sigma_z = \frac{\sigma_0}{2} + \sqrt{\frac{\sigma_0^2}{4} + \frac{8{,}8\gamma\mu}{d}} \quad (5)$$

$$\sigma_z = \frac{\sigma_0}{2} + \sqrt{\frac{2\gamma\mu}{\pi(1-\nu)D} + \left(\frac{\sigma_0}{2x}\right)^2} \cdot x \quad (6)$$

In the case of $$x^2 \geq \frac{8{,}8\gamma\mu}{d} \Big/ \left\{\frac{\sigma_0}{2} + \sqrt{\frac{\sigma_0^2}{4} + \frac{8{,}8\gamma\mu}{d}}\right\}^2$$

$$\sigma_z(x) = \frac{\sigma_0}{x^2+1} + \sqrt{\frac{8{,}8\gamma\mu}{d}} \cdot \frac{2x}{x^2+1} \quad (7)$$

$$\sigma_z(x) = \frac{\sigma_0}{x^2+1} + \sqrt{\frac{2\gamma\mu}{\pi(1-\nu)D}} \cdot \frac{2x^2}{x^2+1} \quad (8)$$

Discussion

Fig. 1 shows σ_z as a function of $\sqrt{D}$ for constant grain size according to equations (5) and (7). As can be seen, σ_z is constant for small x (see equation (4)) or D. This is in very good agreement with the results of the three-point-bend-test of Holzmann and Man [5] (fig. 2). In case d is varied while D remains constant, $\sigma_z(x) = \sigma_z(d^{+1/2})$ is given by equations (6) and (8). A comparison with results of tensile tests executed by Reiff and Lücke [6] with mild steel at temperatures of 4°K and 30°K (fig. 3) shows that these results may easily be explained by means of equation (6), i. e. the dashed line in fig. 3. The experiments of Dahl, Hengstenberg, and Behrens [7] showed, in agreement with equation (6), that the brittle fracture behaviour of mild steel, in contradiction to Cottrell's model, is independent of k_y, the slope of the line in the Hall-Petch plot.

Almond, Timbres and Embury [8] increased the carbide size of Armco iron from 0.3 to 2.5μ by using special heat treatments. The max. value thus obtained for x^2 was 1.6. According to fig. 1 this results in a decrease of σ_z by 10% or more. The somewhat problematical comparison with Low's results [8] shows that this presumption has at least qualitatively been fulfilled. As Almond et al. and the author of the present paper use different logarithmic terms in their energy balance, it is rather difficult to compare these two models.

References

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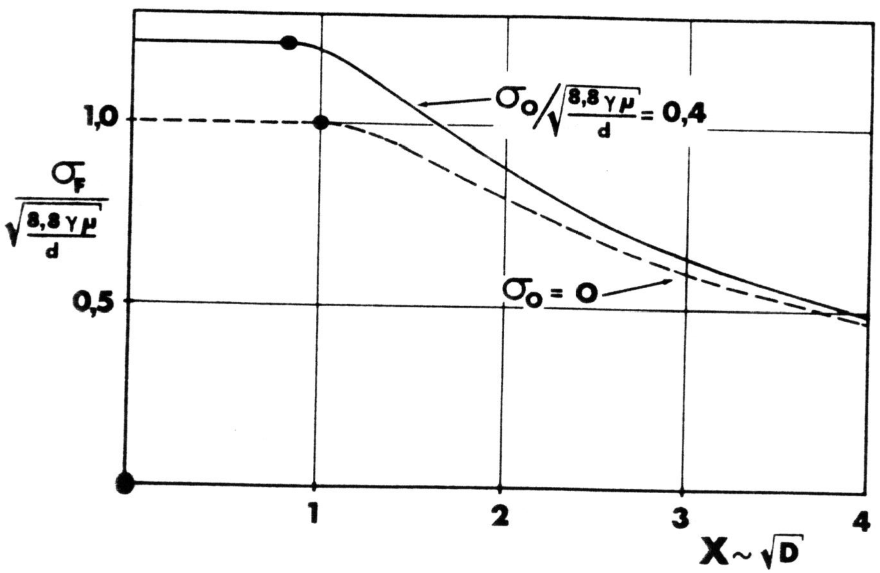

Fig. 1: σ_z as a function of $\sqrt{D}$ according to equations (5) and (7)

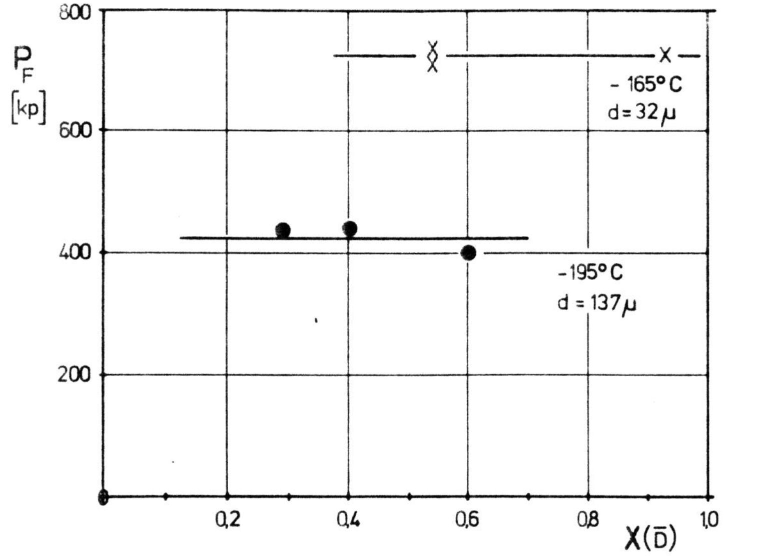

Fig. 2: Fracture load P_F measured in the three-point-bend-test [5] plotted as a function of X ($\bar{D}$) ($\bar{D}$ = average carbide size).

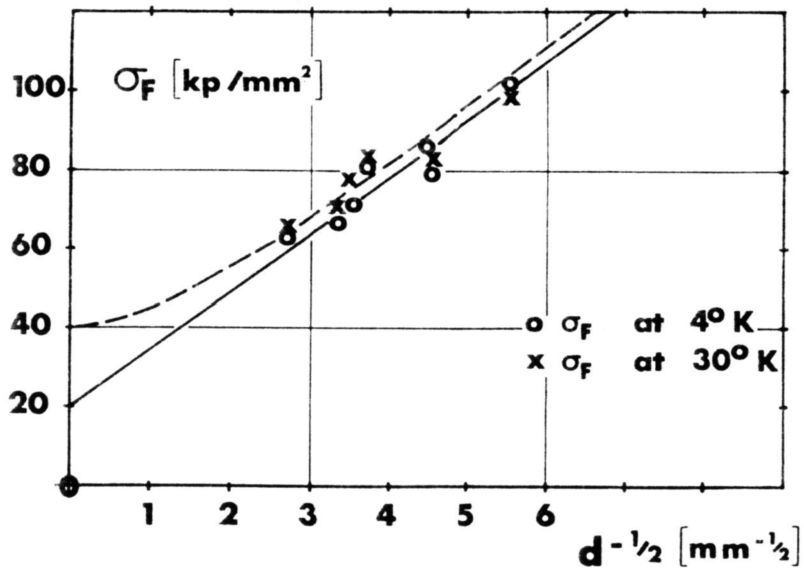

Fig. 3: σ_F ($d^{-1/2}$) measured at 4°K and 30°K [6].