INFLUENCE OF GRAIN SIZE AND THICKNESS OF PRECIPITATIONS ON THE BRITTLE FRACTURE OF STRUCTURAL STEELS

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In the investigation of brittle fracture of polycristalline metals a distinction has to be drawn between the nucleation and propagation of cracks. A crack can be nucleated according to A. H. Cottrell [1] by the intersection of two glide bands within a ferrite grain, or, according to K. H. Reiff [2], by the pile-up of dislocations against a brittle second phase particle. When the crack is formed, the dislocations of the pile-up run into the crack and extend it by a value given by n . b (n = number of dislocations; b = Burgers vector). K. H. Reiff [2] has formulated the energy of a crack of length c which is formed in grain boundary cementite of the thickness D, and which has grown into the ferrite:

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

In this formula the lower surface energy γ_A is used for that part of the crack length in the cementite, and the surface energy of ferrite γ for that part of the crack length in the α-iron. If the precipitates are small, so that the crack length in the precipitates in relation to the total length is negligible, formula (1) becomes identical with Cottrell's equation. Both authors calculated the critical crack length and stress at which the crack is propagated unstably with energy gain. The width of the crack is given by equation (2) if all dislocations of the pile-up run into the crack.

$$n \, . \, b = \left(\frac{\sigma - \sigma_i}{4\mu}\right) d \qquad (2)$$

In this equation μ is the shear modulus, σ the stress, σ_i the friction stress, and d the grain diameter. According to Cottrell the following relation is valid between fracture stress σ_f and grain size:

$$\sigma_f \, (\sigma_f - \sigma_i) = \frac{8\mu\gamma}{d} \qquad (3)$$

Cottrell puts the fracture stress σ_f equal to the yield stress σ_y, which is given by the Hall-Petch-equation as a function of the grain size, and obtains the relation (Figure 1):

$$\sigma_f = \sigma_y \, (T_t) = \frac{8\mu\gamma}{k_y} d^{-1/2} \qquad (4)$$

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with T_t = transition temperature. The results of Reiff's theory, in which the influence of the brittle grain boundary carbides is taken into consideration are shown in Figure 2. These results are identical with Cottrell's if the ratio D/d does not exceed a critical value. For larger carbides the fracture stress becomes lower with increasing thickness of the carbides.

EXPERIMENTAL METHODS

Tensile tests were carried out with double notched rectangular and unnotched specimens (Figure 3) made from unalloyed structural steels with carbon contents of the range 0.09% - 0.69%C. To correlate a well defined plastic zone with a stress in the load-elongation diagram the elongation of the notched specimens was measured by means of a linear variable Displacement Transformer (LVDT) of very high sensitivity.

RESULTS

For the evaluation of the load-elongation graphs a similar principle was adapted as in the case of the notched bending specimens of A. Kochendörfer and H. D. Schulze [3]. As a result of the high sensitivity of the dilatometer deviations from the elastic line can be observed prior to general yield, which is detected in the load-elongation diagram by a rapid increase of the elongation value, without or with only a small rise in load. At the load P_1, where the deviation from the elastic line can be first seen, a small plastic zone is formed in front of the notch, which increases in size with rising stress up to general yield (Figure 4). The plastic elongations of the specimen of 0.72 µm and 1,2 µm correspond to the forces P_3 and P_5. Since the dimensions of the specimens and the precision of measurement remain constant during all tests, these elongations give an indication of the size of the plastic zone in front of the notch. The fracture stress of a specimen which breaks before reaching general yield is associated with a certain amount of plastic deformation. In addition to Cottrell's criterion of brittle fracture ($\sigma_f = \sigma_{gy}$) any other criteria can be applied as $\sigma_f = \sigma_1$, $\sigma_f = \sigma_3$, $\sigma_f = \sigma_5$.

In Figure 5 the influence of testing temperature on yield and fracture stress is shown for steel C 10 and 21 µm grain size. The yield stresses σ_1 to σ_{gy}, which with increasing index correspond to greater plastic zones, rise with decreasing temperature. The course of the fracture stress can be divided into three typical regions. At high temperatures (region III) the specimen fractures after large plastic deformation and at a stress which is clearly higher than the stress at general yield σ_{gy}. With decreasing temperature the fracture stress approaches σ_{gy} and the transition from shear to cleavage takes place. In region II the specimen fractures during general yield, the fracture stress rising as σ_{gy} with decreasing temperature. In this region the condition for fracture is as follows

$$\sigma_1 = \sigma_f^* = K_{pl}^{max} (\sigma_y + \Delta\sigma) \tag{5}$$

Here the maximum plastic stress concentration factor K_{pl}^{max} is constant, and, for the local tensile stress σ_1 to reach the temperature independent microscopic cleavage stress σ_f^*, a certain amount of strain hardening ($\Delta\sigma$) must take place. Strain hardening and consequently plastic deformation in the plastic zone decreases with decreasing temperature due to the increasing yield stress σ_y.

At still lower temperatures the fracture stress falls steeply and the specimen fractures before reaching general yield (region I). The size of the plastic zone decreases continuously in this region. The condition for fracture is as follows:

$$\sigma_1 = \sigma_f^* = K_{pl} \cdot \sigma_y \tag{6}$$

To satisfy this condition a lower plastic stress concentration and thus a small plastic zone is required with decreasing temperature, due to the increasing yield stress σ_y. The increase in yield stress counterbalances the decrease in the plastic zone and thus K_{pl}, so that the microscopic cleavage stress will be reached locally. With brittle specimens at very low temperatures there is a renewed increase in the fracture stress. It is assumed that at the temperature of the lowest fracture stress a minimum plastic zone is reached which is necessary for nucleation of a micro-crack. At still lower temperatures the size of this plastic zone remains constant, and the influence of temperature on the fracture stress is the same as on the yield stress.

The influence of grain size on the yield stresses σ_1 to σ_{gy} can be described very well by the Hall-Petch-equation (Figure 6). The slope of the lines (Figure 6) increases with increasing size of the plastic zone from σ_1 to σ_{gy}. This means that the influence of grain size becomes more pronounced with increasing volume of material deformed, and thus with increasing number of grain boundaries crossed. The temperature is of minor influence.

The fracture stress at the different sizes of plastic zones, as defined above, is shown as a function of $d^{-1/2}$ in Figure 7. By extrapolation of the straight lines a fracture stress is obtained as intercept for very large grains which is largely independent of the size of the plastic zone. The slope of the lines again increases with the size of the plastic zone.

The influence of the thickness of grain boundary cementite is represented in this figure by the value $\Delta\sigma_{carbide}$. Carbides which are thicker than 1/25th of the grain size reduce the fracture stress but have no influence on the yield stress. Here there is a good agreement between the theory of Reiff and the present experimental results.

The influence of grain size on the microscopic cleavage stress σ_f^*, which was calculated by equation (6) at general yield, is shown in Figure 8. The microscopic cleavage stress follows a straight-line relationship similar to Hall-Petch, and an intercept is again found for very large grain diameters. The slope is 8 kp/mm$^{3/2}$, i.e., four times the value of k_y, calculated for yield stress from unnotched specimens.

Following Cottrell's proposal the fracture stress may be put equal to the yield stress at different sizes of the plastic zone, but in so doing, some discrepancies arise:

a) the fracture stress is not zero for $d^{-1/2} \rightarrow 0$, as predicted by Cottrell,
b) the dependence of fracture stress and yield stress on grain size changes uni-directionally with increase in size of plastic zone, in

contradiction to the Cottrell theory.

c) The value of effective surface energy γ calculated from the slope of the lines in Figures 7 and 8 is smaller by a factor 10^3 than the values from fracture mechanics tests. This means that the theory cannot explain the influence of grain size on fracture stress. For the interpretation of the present results, the following is proposed.

The effective surface energy, as calculated from the slope of the straight lines in Figures 7 and 8, represents only that part of the energy necessary for the crack to overcome the grain boundaries. The remaining energy, i.e. the energy required to build up the minimal plastic zone and the elastic energy is contained in the stress at very large grain diameters and/or small plastic zones. Therefore, there must be a new interpretation of this stress.

REFERENCES

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2. REIFF, K. H., Arch. Eisenhüttenwes., 43, 1972, 567/570.
3. SCHULZE, H. D. and KOCHENDÖRFER, A., Arch. Eisenhüttenwes., 44, 1973, 853/860.

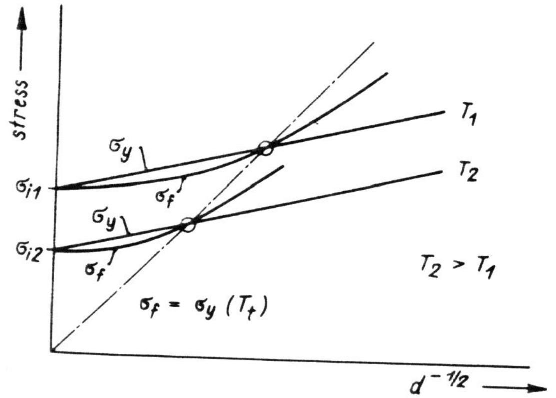

Figure 1 Theoretical Relations Between σ_f, σ_y, Grain Size and Temperature, According to Cottrell [1]

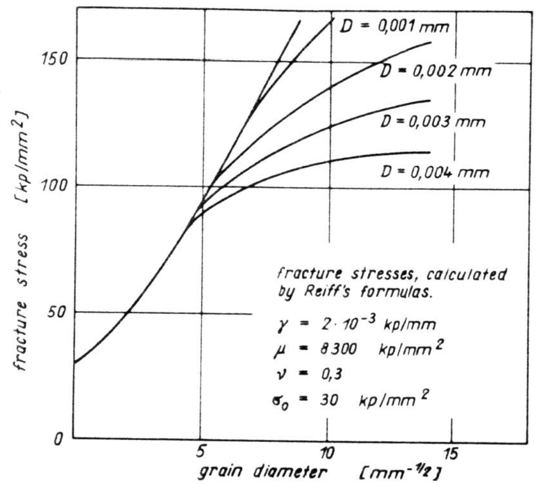

Figure 2 Influence of Grain Boundary Carbides and Grain Diameter on Brittle Fracture Stress, According to Reiff [2]

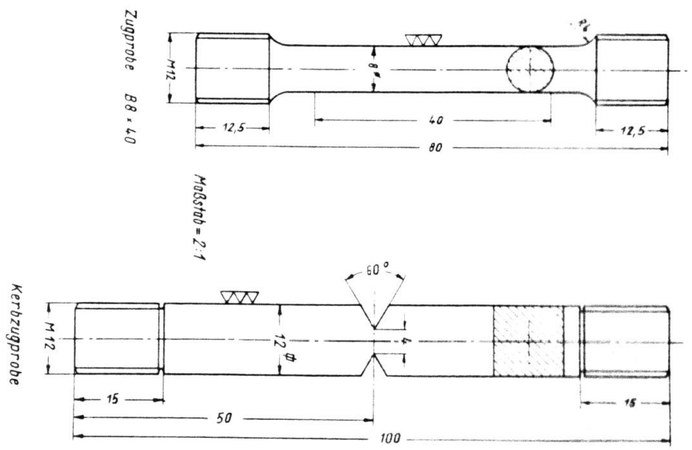

Figure 3 Tensile Specimen Used

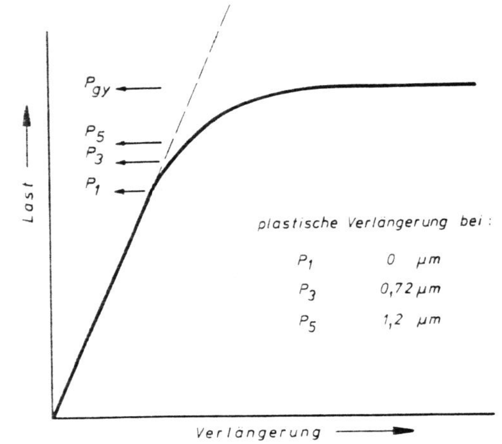

Figure 4 The Evaluation of the Load-Elongation Graphs

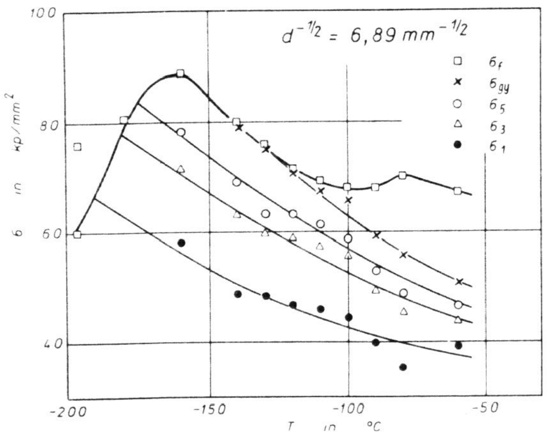

Figure 5 Influence of Temperature on the Fracture and Flow Stress of Steel C 10, Grain Diameter 21 µm

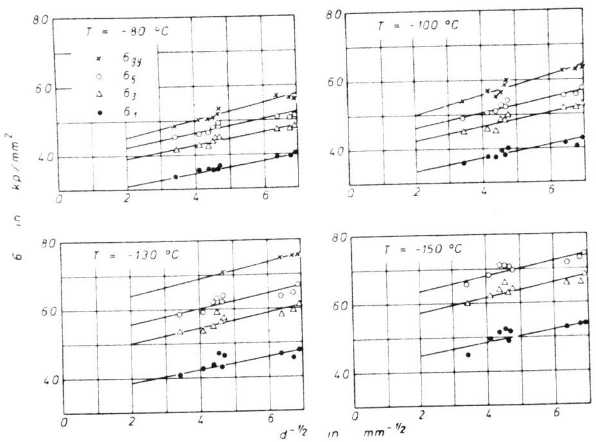

Figure 6 Influence of Grain Diameter on the Flow Stresses of Steel C 10

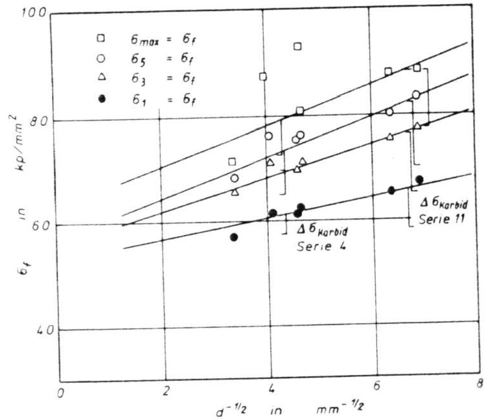

Figure 7 Influence of Grain Diameter and Cementite Thickness on the Fracture Stress of Steel C 10

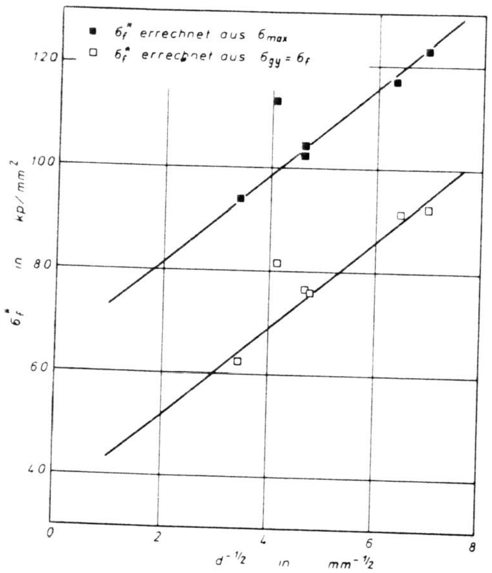

Figure 8 Influence of Grain Diameter on the Microscopic Cleavage Stress of C 10