The Transition of the Brittle Fracture at Full Scale Yielding to that at Small Scale Yielding

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The aim of the present paper is to analyse experimental results on this transition by the theory of brittle fracture of Stroh and Cottrell+). Some new relations between the yielding and fracture behavior at different plastic zones are derived.

Experimental procedure and results

We have made bending tests under a constant bending moment along the specimen length with unnotched and notched specimens with a cross section of 10 mm x 10 mm of a normalized structural steel St 37 (UTS about 37 kgf/mm^2) with grain sizes from 0.02 mm to 0.1 mm. We have not only measured the macroscopic (index m) yield stress σ_y^m at which full scale yielding just has taken place, but also the flow stress σ_y^δ at which the plastic zone extends only over a part of the cross section, with the lower limit case of small scale yielding. In another paper (Kochendörfer, Saito, Hagedorn, this book, paper II-324; cited as (1)) we could reveal the plastic zone by proper light reflection of the glide lines on the electropolished side surfaces. With the present small specimens this was not possible and also the etching method, used for example by Knott and Cottrell was not successful. As a measure of the length of the plastic zone we therefore have taken the notch opening δ, measured by a COD-clip gauge. The measured value of δ becomes zero at a certain stress σ_y^e though the real value of δ (= e) and the length of the plastic zone are not zero. As we plotted log δ versus the stress σ_y^δ we found a straight line in the measure-

+) Because of the limited space we cannot give full references. They all are contained in the papers (1), (2) and in Kochendörfer, Z.Metallkde. 62, 1-12, 71-85, 173-185, 255-269 (1971).

able range of δ, and as we extrapolated these lines to lower δ it resulted that for the stresses σ_y^e (for which δ (measured) = 0) the real $\delta = e$ had a fixed value independent of temperature and grain size (Fig.1). We assumed this to be the case also for lower values of δ and took from a curve in Fig.1 the value $\delta < e$ at the stress σ_y^δ for a certain temperature and grain size (how to obtain this see below).

Fig.2 shows σ_y^δ versus test temperature T for a sharply single notched specimen for $\delta = m$ and $\delta = e$. The curves are limited to low temperatures by the occurence of the fracture (index f). Along the curve $\sigma_f^\delta = \sigma_f(T)$, given by $\sigma_f^\delta = \sigma_y^\delta$, the temperature has the signification of a transition temperature (index t) in the sense that for given $\delta = \delta_t$ the fracture occurs at $\delta > \delta_t$ for $T > T_t^\delta$ and at $\delta < \delta_t$ for $T < T_t^\delta$. At a certain $\delta = c$ the stress σ_f becomes no longer smaller than σ_{ft}^c but increases somewhat with decreasing temperature. Within the scattering of the measured points this part $\sigma_{f_c} = \sigma_f(T)$ appears to be the continuation of the curve $\sigma_y = \sigma_y^c(T)$ for the flow stress with $\delta = c$. Using the curves of Fig.1 we have obtained the dashed curve in Fig.2 in the manner described above. It fits indeed in the course of the other curves. It is the curve for the flow stress at small scale yielding and the transition temperature T_t^c is that at which the fracture occurs at small scale yielding. In the strong sense the linear elastic fracture mechanics is only applicable as a sufficient approach at temperatures below T_t^c, at higher temperatures it becomes soon inaccurate though the measured value of the notch- or crack-opening remains zero for a longer range of temperature or stress.

Analysis of the results

We have tried to analyse these results in terms of the Stroh-Cottrell theory of brittle fracture. Stroh presumes that a dislocation source within a grain is anchored by Cottrell atmospheres of foreign atome or fine precipitations and that at a certain stress, the local upper yield stress, the source is unpinned and can produce a large

number of dislocations. The first dislocation is arrested at the next grain boundary and the following dislocations pile-up. The stress field near the piled-up group may by its normal stress component overcome the lattice cohesive strength and thus generate a crack. Stroh has calculated the energy of this not completely stress free crack. Cottrell has calculated if such a crack becomes unstable by adding to the crack term the Griffith term and the surface energy term. The result is an equation for the fracture stress σ_f^m in dependence of the grain size with a quantity k_f^m which is proportional to the square root of the shear modulus G and the specific effective surface energy γ.

The stress field near a piled-up group of dislocations may by its shear stress component activate dislocation sources nearby and thus continue the gliding at the lower yield stress stress. The calculation gives a grain size dependence of this stress according to the Hall-Petch relation with the parameters k_y^m and σ_{yi}^m.

From both relations for the fracture stress and for the yield stress results a relation for the transition temperature as implicite variable in dependence of the grain size, containing the parameters k_f^m, k_y^m and σ_{yi}^m. It can be numerically solved if k_y^m and σ_{yi}^m are evaluated as functions of the temperature and if the value of k_f^m is calculated by using the measured transition temperature for one grain size. The measured grain size dependence of the transition temperature T_t^m for our steel is well fitted by this way as well as it has been the case in an earlier investigation with a similar steel (Kochendörfer and Schreiner, Stahl u. Eisen 89, 1053, 1969; cited as (2)). This was not only the case for unnotched specimens, for which the theoretical conception has been at first developped, but also for notched specimens.

We have applied the results of the Stroh-Cottrell theory not only to the yielding and fracture at full scale yielding but also at partial scale yielding till small scale yielding. We have found that this frame is also then applicable. It resulted that the fracture parameter k_f^δ decreases with decreasing δ and reaches a minimum value k_f^c for $\delta = c$. According to the mentioned connection of k_f and the effective surface energy γ the latter depends in the same way of δ. From the experiments we could deduce the following relations

$$\frac{\sigma_y^{\kappa\delta}}{\sigma_y^{\kappa m}} = \frac{\sigma_y^{\kappa\delta}}{\sigma_{yi}^{\kappa m}} = \frac{k_y^{\kappa\delta}}{k_y^{\kappa m}} = \left(\frac{k_f^{\kappa\delta}}{k_f^{\kappa m}}\right)^2 = v^{\kappa\delta}$$

The index κ for a multiaxial stress state shall include the specimen and notch geometry and the kind of loading (tension or bending), i.e. $v^{\kappa\delta}$ depends on the test conditions but is independent of the temperature and of the grain size. Therefore, if we have measured for one temperature the function $v^{\kappa\delta}$ we can connect the yielding and fracture behavior for arbitrary values of δ with the behavior at full scale yielding, $\delta = m$. If we know furthermore the constraint factor b_y^m for $\delta = m$, for example from the papers of Hill, Green and Dundy, we can reduce the necessary measurements on unnotched specimens which give $k_y^{om}(T)$, $\sigma_{yi}^{om}(T)$ and k_f^{om}. The results obtained by this way for the conditions indicated are shown in Fig.3. It represents the curves for the flow stress $\sigma_y^{\kappa\delta}$ and the fracture stress $\sigma_{ft}^{\kappa\delta}$ versus the test temperature T, calculated in the just mentioned manner. The circles indicate the measured points. The agreement is good and the same is the case for all other specimens and grain sizes.

We shall continue these investigations with CT-specimens and hope to obtain a physical interpretation of K_{Ic}.

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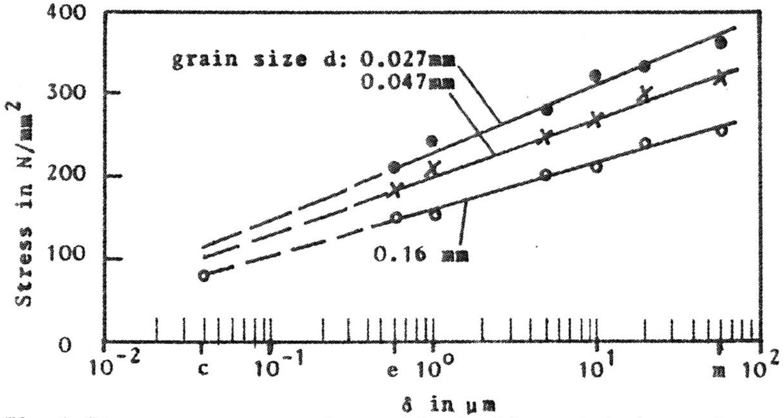

Fig.1 Stress σ_y versus δ; weakly double notched specimens

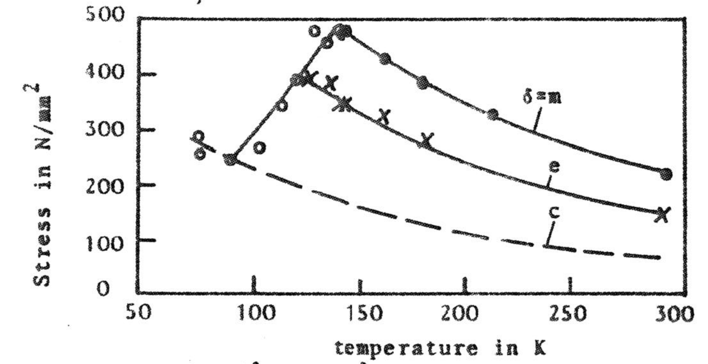

Fig.2 Stresses $\sigma_y^{\kappa\delta}$ and $\sigma_{ft}^{\kappa\delta}$ versus test temperature; sharply single notched specimens, grain size d=0.16mm

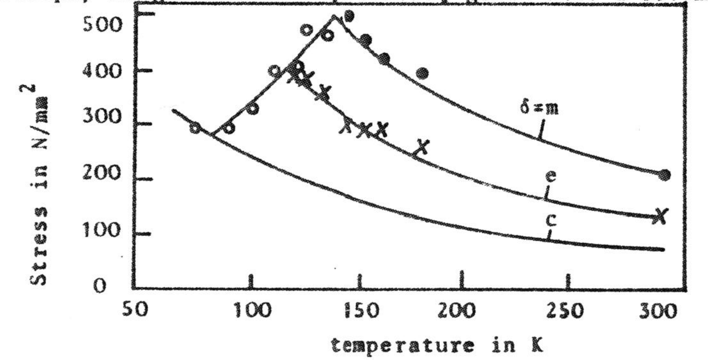

Fig.3 Calculated curves: Stress vers. test temperature Weakly single notched specimens, grain size d=0.16mm