Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

INTERMEDIATE FRACTURE STRESS AND FRACTURE INITIATION MODE TRANSITIONS IN THE BRITTLE FRACTURE OF STRUCTURAL STEELS

A. Kochendoerfer*

PRELIMINARY REMARKS

An increase or decrease of a quantity with respect to the test temperature T always relates to decreasing T. The nominal stress σ is taken as a measure of the load P or the bending moment M. It is irrelevant which of the definitions of σ (see [1]) is used. In the ratio σ/σ_{gy} the proportionality factor cancels out and so $\sigma/\sigma_{gy} = P/P_{gy}$ or M/M_{gy}. Slip line field calculation is abbreviated by SLFC and finite element calculation by FEC.

INTRODUCTION

In Figure 1a the nominal fracture stress σ_f decreases steadily below the general yield temperature T_{gy}. Such a result is for instance obtained from bending tests with notched specimens of an annealed unkilled steel U St 37-1 [2]. If this steel were tested after it had been deformed or strain aged [3] the curve $\sigma_f(T)$ would exhibit an intermediate increase between an upper temperature T_u and a lower temperature T_l as shown in Figure 2a. Metallographic investigations have revealed that below T_l many twins are present near the notch root but that above T_u no twins are present. Therefore, it has been concluded that between T_u and T_l the transition from slip initiated to twin initiated cleavage fracture would take place. The difference in behaviour of the annealed and the pre-treated steel was considered to be due to the fact that T_{gy} was so strongly increased by the pretreatments (from about 150K to about 300K by strain ageing) that the slip initiation temperature range extended well below T_{gy} for the pre-treated steel whilst if went no lower than T_{gy} for the annealed steel.

These findings suggested that an intermediate transition should frequently be found for mild steels and the literature has been reviewed. It has become evident that such a transition should be analysed by means of the local fracture stress concept [4, 5, 6] as outlined in the next section.

INTERMEDIATE TRANSITION AND THE LOCAL FRACTURE STRESS CONCEPT

Graphs for a steel without and with an intermediate transition are presented in Figures 1 and 2, respectively. Figures 1a and 2a show σ_f and the general yield stress σ_{gy} versus T. In the transition range T_u to T_l the ratio σ_f/σ_{gy} is constant, i.e., the curves $\sigma_f(T)$ and $\sigma_{gy}(T)$ increase in a similar manner. The same holds at a given (specimen and loading) geometry for σ_f and the uniaxial yield stress σ_y, since σ_y and σ_{gy} are connected by $\sigma_{gy} = b_{gy}\sigma_y$ where b_{gy} is the constraint factor [1]. In Figures 1 and 2 the numerical value $b_{gy} = 1.25$ is used, which holds for

---

* Department of Metal Physics, Max-Planck-Institut fuer Eisenforschung, Duesseldorf, Federal Republic of Germany

sufficiently sharp notched bend specimens.

For the analysis it is necessary to know the variation of the normal stress σ_{yy} with respect to the middle plane y = 0 of the notch versus the length coordinate x for each ratio σ/σ_{gy} taking into account the plastic zones. Then the stress intensification factor $R(\sigma/\sigma_{gy}) = \sigma_{yy}^{max}(\sigma/\sigma_{gy})/\sigma_y$ is known and the local fracture stress is given by

$$\sigma_F(T) = R(\sigma_f/\sigma_{gy}(T)) \cdot \sigma_y(T) \ . \qquad (1)$$

The exact calculation of R is the crux of the problem. There are differences between the results of a SLFC and those of a FEC for the same geometry (four point bend specimens, notch flank angle 45°, notch radius 0.25mm) as may be seen from Figure 11 of [7]. Knott [9] used R(1) according to Green and Hundy and calculates $R(\sigma_f/\sigma_{gy})$ from the measured values of σ_f/σ_{gy} and σ_y assuming that σ_F has the constant value $R(1) \cdot \sigma_y(T_{gy})$. The resulting curve agrees qualitatively with the FEC curve of Griffiths and Owen [7].

In Figure 1b, $R\sigma_y$ (= σ_{yy}^{max}) versus σ/σ_{gy} is plotted for the two values σ_{y1} and $\sigma_{y2} < \sigma_{y1}$ corresponding to the points 1 and 2 in Figure 1a, for temperatures T_1 and $T_2 > T_1$. For the chosen curves of $\sigma_{gy}(T)$, $\sigma_f(T)$ and $R(\sigma/\sigma_{gy})$, the latter being qualitatively in accordance with that of Griffiths and Owen [7], σ_F takes a constant value. For a given plot of $R(\sigma/\sigma_{gy})$ the decrease of $\sigma_f(T)$ depends upon the increase of $\sigma_{gy}(T)$ and the stronger (or weaker) the increase of σ_{gy} the stronger (or weaker) the decrease of σ_f. If the relation is different from this, or if $R(\sigma/\sigma_{gy})$ varies differently, σ_F becomes dependent on σ_f/σ_{gy} or T.

These conclusions hold as long as the initiation mechanism of the cleavage fracture remains unchanged. The properties associated with an intermediate transition are shown in Figure 2b. Since σ_f/σ_{gy} now has a constant value between T_u and T_l and σ_{gy} is lower for T_u than for T_l, σ_F must increase between T_u and T_l or make a jump at $\sigma_f/\sigma_{gy}(T_u) = \sigma_f/\sigma_{gy}(T_l)$. This follows immediately from equation (1).

EXAMPLES OF INTERMEDIATE TRANSITIONS

Figure 3 shows the results of Griffiths and Oates [8] as evaluated by Griffiths and Owen [7]. The differences between σ_F(FEC) and σ_F(SLFC) follow from the differences in $R(\sigma/\sigma_{gy})$.

The full curve $\sigma_F(T)$ in Figure 3 has a concave-convex path between 170K and 100K and this corresponds to the slight increase of σ_F(FEC) in this temperature range. An intermediate transition is threfore weakly indicated by this curve. The dashed curve which represents the scatter of the experimental points as well as the full curve shows this transition very closely.

A distinct intermediate transition is shown in Figure 4. The curve of σ_F(SLFC) is calculated in this case from the curve $\sigma_F(T)$ which has been taken as a basis. The calculated curve runs somewhat above the experimentall points below T_l. If these points had been used for the calculation of $\sigma_F(T)$, this quantity would first decrease below T_l but then increase to the value at the lowest temperature in Figure 4b.

A further well pronounced intermediate transition is shown in Figure 5. If the upper of the three points at 153K were absent the transition would be clearer. An example having many points at each temperature which demonstrates the relatively high scatter of these points for mild steel specimens with small notch radii is shown in Figure 6. Here some doubt may indeed exist as to whether the curve exhibits an intermediate transition. However, the upper point at 173K were omitted the transition would appear conclusively.

CORRELATION WITH FRACTURE INITIATION MECHANISM TRANSITION

It is not an easy matter to identify the initiation mechanism of cleavage fracture in notched specimens of a structural steel. In iron single crystals it is possible to state whether or not a fracture is initiated by twins because twins are long and broad and can be detected easily in scanning electron micrographs as well as in photographs of etched sections [11]. In steels they have different degrees of extension and careful etching is necessary to make them all visible [12]. At small scale yielding fracture is initiated near the notch root and it is often possible to observe its initiation by interacting twins, e.g., Figure 17 of the paper by Knott and Cottrell [13]. In other cases it is simply assumed that where twins are observed, cleavage is twin initiated, and where they are not it is slip initiated. In the present case it is significant that the upper temperature for twin initiated fracture in this sense coincides with the lower transition temperature T_l as indicated in the figures by Tw. The symbol Sl for slip initiated fracture is not put immediately beyond Tw but beyond T_u.

FRACTURE INITIATION MECHANISM TRANSITION AT GENERAL YIELD

If an intermediate transition below T_{gy} exists the curve $\sigma_f(T)$ goes through T_{gy} continuously. Fracture may be slip initiated cleavage up to 50% reduction in area [14]. If no such transition exists the transition from twin initiated to slip initiated fracture begins at $T_l = T_{gy}$ with $\sigma_f = \sigma_{gy}$. In the transition range from $T_l = T_{gy}$ to $T_u > T_{gy}$, $\sigma_f \approx \sigma_{gy}$, eventually σ_f becomes larger than σ_{gy} for $T > T_u$, as indicated in Figure 1. Uebags and Dahl [15] have investigated the influence of microstructural parameters (grain size, carbide lamella thickness) and of the manganese content on these properties and have found a shift of T_u and T_l to lower temperatures if the microstructure becomes finer and if the Mn content increases.

DISCUSSION AND CONCLUSIONS

The examples demonstrate unambiguously the existence of intermediate transitions. If the transition is obscured by the experimental scatter knowledge of its existence may help to reveal it. The fact that σ_f and σ_F increase in the temperature interval T_u to T_l indicates that within this interval both initiation modes operate.

Because of some uncertainty in the variation of $\sigma_f(T)$ due to experimental scatter and in the variation of $R(\sigma/\sigma_{gy})$, definite conclusions on the temperature dependence of σ_F cannot be drawn and the concept of a constant local fracture stress for a given fracture initiation mechanism may be rather more a qualitative than a quantitative concept. The increase of σ_F within an intermediate transition is, however, a necessary consequence as outlined in the preceding sections. Furthermore it seems that σ_F initially decreases below T_1 but then increases again sufficiently below T_1. By experiments down to the temperature of liquid helium many of these questions might be clarified in more detail.

ACKNOWLEDGEMENT

I am grateful to The Deutsche Forschungsgemeinschaft for financial assistance.

REFERENCES

1. KOCHENDOERFER, "Fracture 1977", (editor, D. M. R. Taplin), University of Waterloo Press, 1977.
2. SCHULZE, H. D., KOCHENDOERFER, A. and BAUER, G., Archiv Eisenhuettenwes, 44, 1973, 853.
3. RUEDIGER, U. and KOCHENDOERFER, A., Archiv Eisenhuettenwes, 46, 1975, 455.
4. OROWAN, E., Rep. Progr. Phys., 12, 1948, 185.
5. KNOTT, J. F., J. Iron Steel Inst., 204, 1966, 104.
6. WILSHAW, T. R., RAU, C. A. and TETELMAN, A. S., Eng. Fracture Mech., 1, 1968, 191.
7. GRIFFITHS, J. R. and OWEN, R. J., J. Mech. Phys. Solids, 19, 1971, 419.
8. GRIFFITHS, J. R. and OATES, G., Proc. 2nd Int. Conf. Fracture, Chapman and Hall, London, 1969, 229.
9. KNOTT, J. F., J. Mech. Phys. Solids, 15, 1967, 97.
10. KOCHENDOERFER, A., KOBAYASHI, K., SCHULZE, H. D., HAGEDORN, K. E. and RUEDIGER, U., Eng. Fracture Mech., 1976, in press.
11. JOERGENS, H. and KOCHENDOERFER, A., Z. Metallkde., 64, 1973, 204.
12. KOCHENDOERFER, A. and SCHOLL, H., Archiv Eisenhuettenwes., 28, 1957, 483.
13. KNOTT, J. F. and COTTRELL, A. H., J. Iron Steel Inst., 201, 1963, 249.
14. FINK, W., Thesis, University of Cologne, 1973, -KOCHENDOERFER, A., Grundlagen des Festigkeits-und Bruchverhaltens, editor, W. Dahl, Stahleisen, Duesseldorf, 1974, 129.
15. UEBAGS, M. and DAHL, W., Meeting of the Fracture Research Group of the Verein Deutscher Eisenhüttenleute, Duesseldorf, April 8, 1976. To be published in Archiv Eisenhuettenwesen.

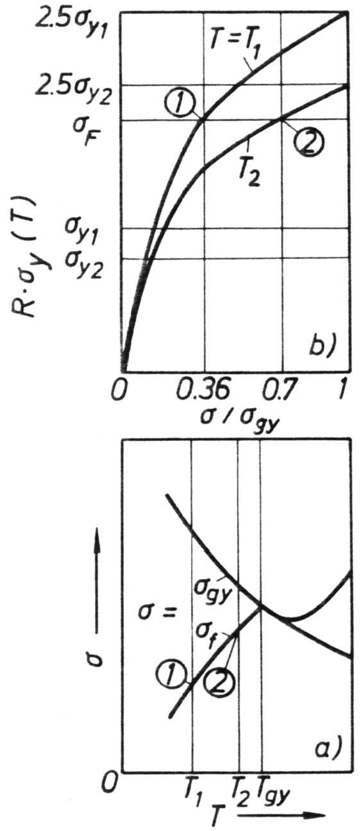

Figure 1 No Intermediate Transition below T_{gy}

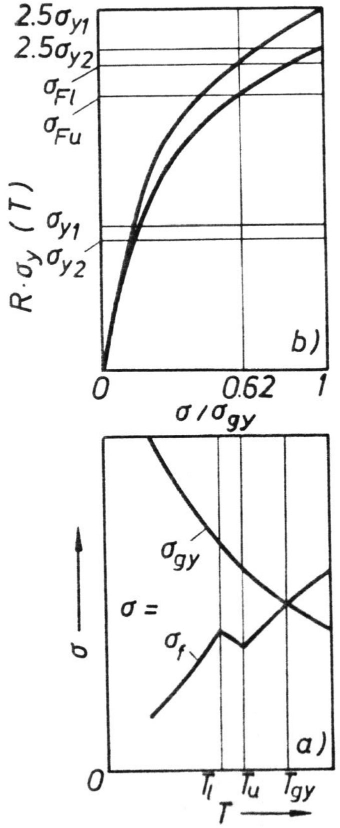

Figure 2 An Intermediate Transition Below T_{gy}

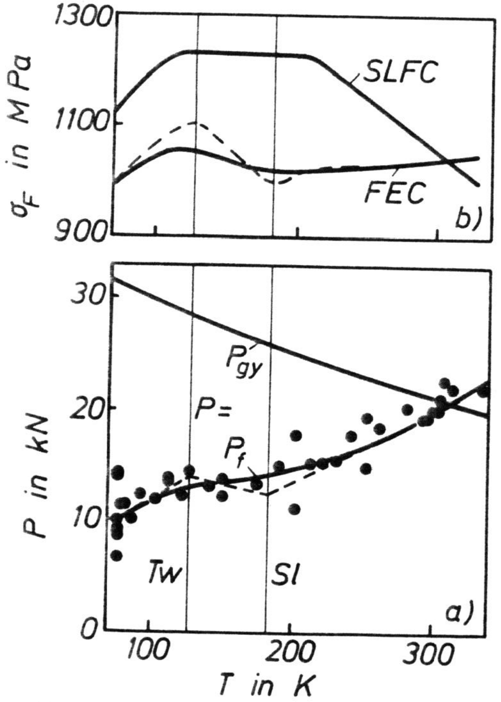

Figure 3 Intermediate Transition of a Steel with 0.033%C, 3.09%Si, 0.07%Mn, Experimental Values from [8], Evaluated Full Lines from [7]

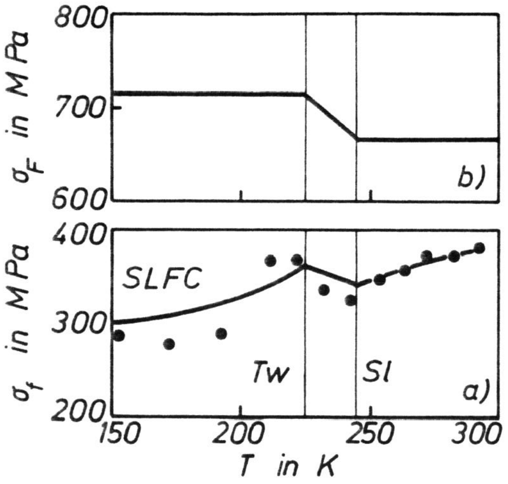

Figure 4 Intermediate Transition of a Steel with 0.15%C, 0.01%Si, 0.44%Mn, 0.015%N, Strain Aged (10% Strained, 30 min 523K, Air Cooling). From [3]

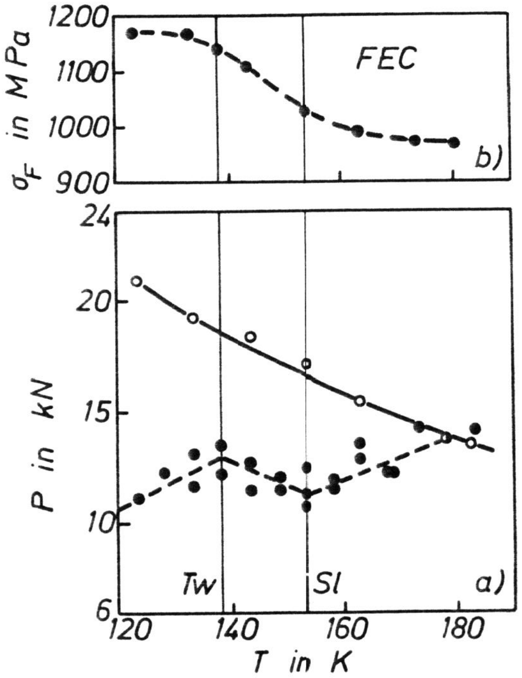

Figure 5 Intermediate Transition of a Steel with 0.07%C, 0.33%Mn, 0.021%N. Experimental Points from [9]

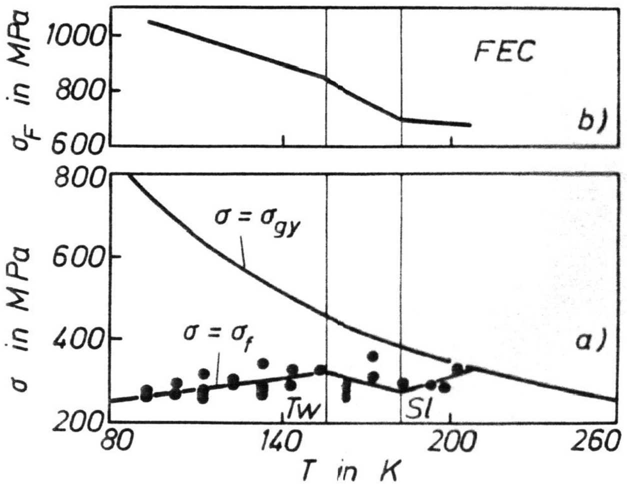

Figure 6 Weakly Indicated Intermediate Transition of the Same Steel as in Figure 4, but Annealed. From [10]