Investigations on Cleavage Fracture Below and at General Yield

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ABSTRACT

Investigations were made with the low carbon steel C 10 to study cleavage fracture occuring below and at general yield. The microscopic cleavage fracture stress σ_f* was determined with double-edge notched tensile (DENT) specimens of varying size and 3-dimensional finite element calculations, which were regarded as necessary due to the considerable amount of plasticity at general yield. A significant influence of temperature on σ_f* was found, also after taking a critical distance x_c into account, according to the Ritchie, Knott and Rice (RKR) model. This result is contrary to the general understanding of σ_f* as a temperature independent material parameter. It is discussed, whether a temperature dependence of σ_f* might be regarded as physically reasonable. A possible explanation is seen in terms of the thermal activation of dislocation movement, which is needed to produce the critical conditions for fracture.

KEYWORDS

Low stress cleavage, cleavage at general yield, specimen size, 3-D finite element calculations, microscopic cleavage fracture stress

INTRODUCTION

Notched specimens exhibit purely cleavage fracture surfaces if fracture occurs below or at general yield. The original Orowan criterion (Orowan, 1948) proposes that cleavage is induced when the maximum tensile stress below the notch root reaches a critical stress σ_f* , which is nearly independent of temperature and strain rate. Investigations by Kühne and Dahl (1982) with double-edge notched tensile (DENT) specimens and 2-dimensional finite element calculations yielded temperature dependent values for σ_{yy}^{max}. Beneath T_{gy}, in the region of low stress cleavage, the influence of temperature was reduced by considering a characteristic distance x_c over which σ_{yy} must be exceeded (Ritchie et al., 1973). Between T_{gy} and T_i, where the fracture and general yield stress coincide, the temperature dependence of $\sigma_f* = \sigma_{yy}(x_c)$

subsisted. If plane strain conditions are no longer valid in this range of higher plasticity, 3-D finite element calculations would be necessary for a correct description of material behaviour. The aim of this study was to find out, whether the temperature dependence of $\sigma_{yy}(x_c)$ is physically reasonable or due to the simplifying assumption of plane strain.

EXPERIMENTAL

A low carbon steel C 10 (Table 1.), supplied as 55 mm square hot rolled bars, was chosen for the investigation. The steel was heat-treated for 5h at 1200°C (air cooled), followed by 2 x 920°C/1h/furnace cooled. The ferrite grain size was determined to be ≅45 µm.

TABLE 1. Composition in wt-% of the material employed

C	Si	Mn	P	S	Al	Cu	Cr	Ni	V	N
.091	.190	.373	.027	.025	.003	.030	.045	.026	.010	.004

Test-pieces were machined according to Fig. 1. (ρ = 0.25 mm, ω = 60°). Specimen width, thickness and notch depth were varied for analyzing the influence of test-piece dimensions on fracture and general yield stresses (Table 2.).

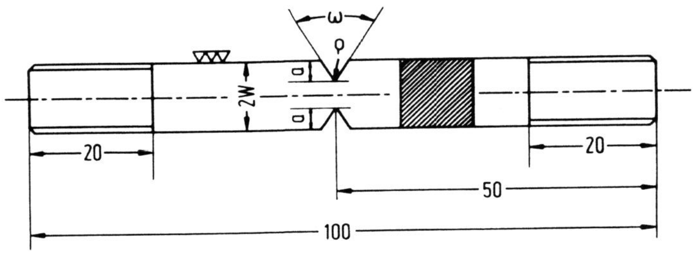

Fig. 1. Geometry of a DENT-specimen

TABLE 2. Dimensions of DENT-Specimens and Transition Temperatures

Specimen (a 2W-2a a - B)	Thickness B [mm]	Width 2W [mm]	Notch Depth a [mm]	T_{gy} [K]	T_i [K]
4 4 4 -12	12	12	4	123	173
4 10 4 -18	18	18	4	153	198
6 6 6 -18	18	18	6	153	198
7.5 3 7.5 -18	18	18	7.5	123	173
8 8 8 -24	24	24	8	173	198

The specimens were tested between 77 K and 293 K at a crosshead speed of 5 mm/min. Uniaxial tensile properties were obtained by testing smooth cylindrical specimens over the same temperature range.

FINITE ELEMENT CALCULATIONS

The microscopic cleavage fracture stress σ_f* is determined from the distribution of the maximum local tensile stress σ_{yy} below the notch root, which is computed with the finite element method (FEM). The computations were performed by the general purpose finite element program ABAQUS (Hibbitt et al., 1984) using the von Mises yield criterion and isotropic strain hardening. Isoparametric 20-noded elements with reduced integration were employed for the three-dimensional calculations allowing for geometric non-linearities. To assure high accuracy of the finite element calculations, several convergence studies were carried out concerning a good discretization of the investigated geometry. These preliminary studies discussed in detail by Twickler et al. (1986) led to a finite element model for one quarter of the DENT-specimen consisting of 550 elements with about 8000 degrees of freedom.

RESULTS

DENT-tests

The fracture and general yield stresses σ_f and σ_{gy} plotted as a function of temperature yield characteristic curves as shown in Fig. 2. for the specimen size 444-12. The specimen sets 444-12, 666-18 and 888-24 are geometrically similar regarding width, thickness and notch depth, but the notch root radius was kept constant. Increasing specimen size leads to a decrease in fracture stress, whereas the general yield stress is hardly influenced.

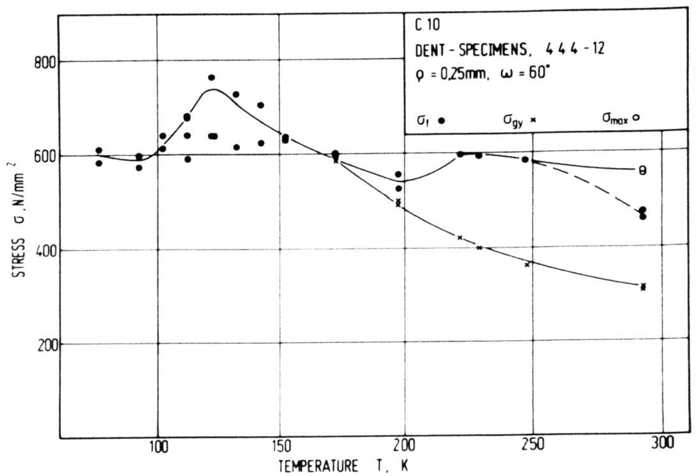

Fig. 2. Influence of temperature on fracture and general yield stresses

The transition temperatures T_{gy} and T_i are shifted to higher values, with T_{gy} being more strongly affected. The specimen sets 4 10 4-18, 666-18 and 7.5 3 7.5-18 are characterized by increasing failure lengths. Due to the rising amount of constraint with increasing a/W-ratio, σ_f and σ_{gy} are both raised to higher stresses. The specimen sizes 4 10 4-18 and 666-18 show identical transition temperatures, whereas T_{gy} and T_i are reduced by 30 K and 25 K respectively for 7.5 3 7.5-18 (Table 2.).

Finite element results

In the following the response of the DENT-specimen will be discussed in terms of local stress and strain distributions. In the perspective graphs only one half of the net cross-section is plotted for the specimen size 444-12 tested at a temperature of 173 K (T_i). Figure 3 shows the σ_{yy}-stress distribution in front of the notch at fracture, the integral of which represents the load applied to the specimen. The shape of the plotted distribution is mainly influenced by a constraint in thickness direction, which leads to a local elevation of the tensile stress σ_{yy}. Since this constraint increases from the surface to the mid-plane, the maximum tensile stress σ_{yy}^{max} occurs in the mid-plane. Therefore the solution in this plane will be used for the subsequent investigation (see Fig. 5.). In order to demonstrate the necessity of 3-D calculations in a range of higher plasticity in which fracture is associated with greater deformations, the distributions of the tensile strain ε_{yy} at fracture load are compared for a plane strain and the 3-D calculation (Fig. 4.). The highest values are found at the notch root, decreasing from about 7% in the mid-plane to about 3% at the surface; the plane strain model only produces a maximum value of about 3%. This comparison points out a significant difference of the state of deformation which has to be taken into account.

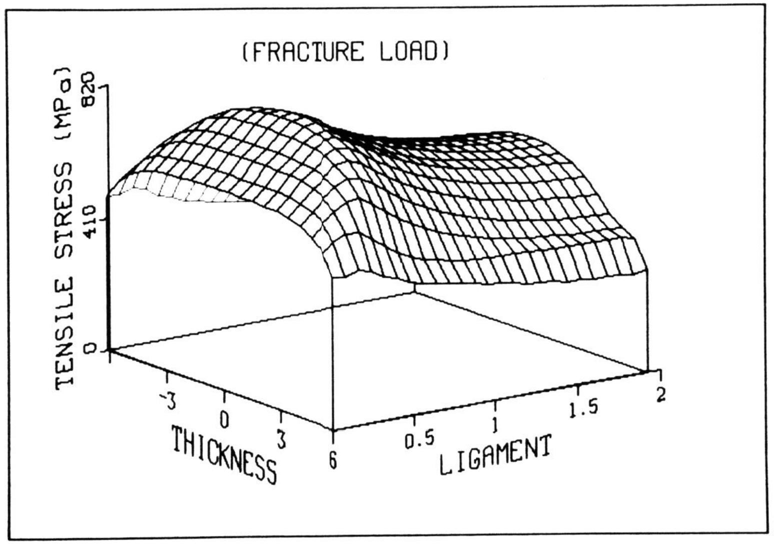

Fig. 3. σ_{yy}-stress distribution in the net cross-section at fracture load

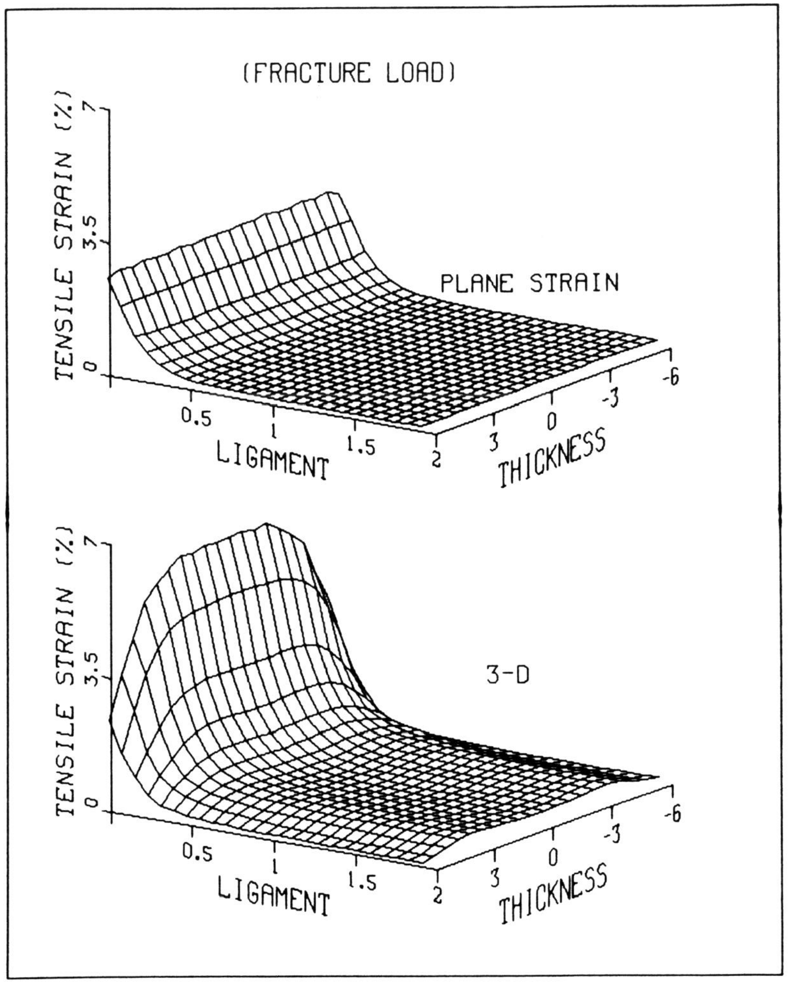

Fig. 4. ε_{yy}-strain distribution in the net cross-section at fracture load (plane strain and 3-D solution)

Figure 5. shows the σ_{yy}-stress distributions in the mid-planes of 444-12 specimens at fracture. The maximum σ_{yy}-values decrease with increasing temperature, gradually moving further into the ligament. A significant

influence of specimen size on σ_{yy}^{max} was not observed (Fig. 6.).

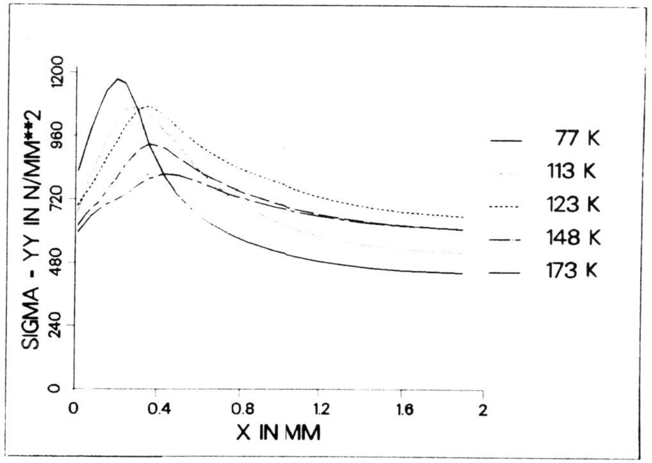

Fig. 5. σ_{yy}-stress below the notch root

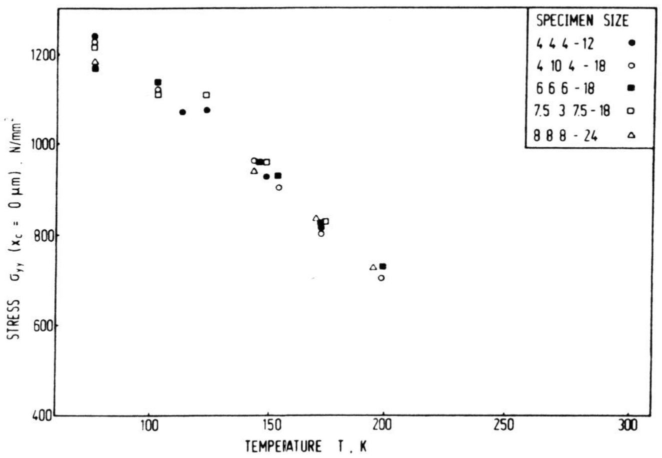

Fig. 6. Influence of temperature on $\sigma_{yy}^{max} = \sigma_{yy}(x_c = 0\mu m)$

According to the RKR-criterion, the microscopic cleavage fracture stress σ_f^* must be exceeded over a characteristic distance x_c ($\sigma_f^* = \sigma_{yy}(x_c)$). Since x_c cannot be calculated, it is fitted in correlation with some microstructural unit. Kühne and Dahl (1982) chose x_c to render temperature independent $\sigma_{yy}(x_c)$-values in the range of 100% cleavage. For the present results, $\sigma_{yy}(x_c)$-values were calculated with x_c varying from one to five grain diameters.

This is illustrated in Fig. 7. for the specimen size 444-12 and x_c = 90 μm (2d) and 180 μm (4d). As temperature rises, the effect x_c has on $\sigma_{yy}(x_c)$ is reduced, since the σ_{yy}-stress distribution gets flatter. σ_{yy}^{max} and $\sigma_{yy}(x_c)$ increase nearly linearly with decreasing temperature, the slope becoming less with increasing x_c. It was not possible though to achieve a temperature independent value for $\sigma_f^* = \sigma_{yy}(x_c)$ with a sensible x_c. Figure 7. demonstrates further that $\sigma_{yy}(x_c)$ and R_{eL} do not intersect, even when extrapolated to T = 0 K.

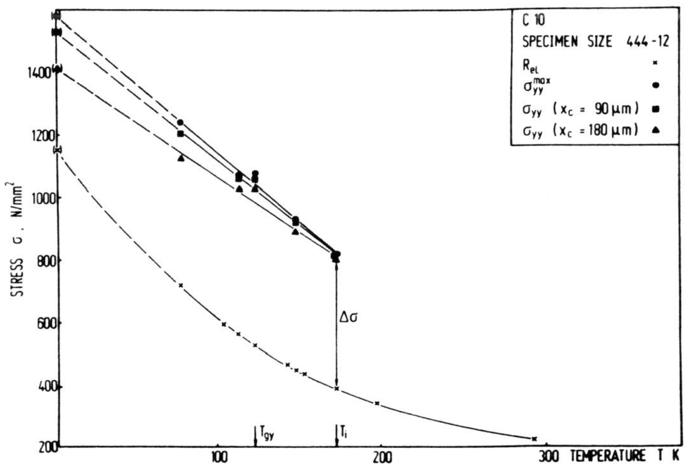

Fig. 7. Influence of temperature on $\sigma_{yy}(x_c)$ and R_{eL}
(() → extrapolated values)

DISCUSSION

The present results are not conform with the generally acknowledged assumption that σ_f^* is a temperature independent material parameter. But on the other hand, a temperature effect on the cleavage fracture stress has already been observed in several earlier investigations (e.g. Curry, 1982).

Thermal activation of cleavage fracture is imaginable in connection with dislocation movement. Considering that cleavage is always preceded by some amount of plasticity, it could be postulated that dislocation movement is an important part of the failure process. According to Fig. 7., the uniaxial yield stress is exceeded by an additional stress $\Delta\sigma$ before cleavage occurs.

Within this stress interval the dislocations seem to produce the critical conditions for fracture. $\Delta\sigma$ decreases slightly as temperature is reduced, perhaps because less dislocation movement becomes sufficient for failure initiation. This could be attributed to a decrease in critical crack length under the influence of elevated local stresses. Furthermore, smaller and more frequent carbides may serve as potent crack nuclei because of rising stress intensification at lower temperatures. Smaller particles might then be cracked by less dislocations, which could lead to a decrease of $\Delta\sigma$.
An effect of sampling volume can also provide an explanation for the observed temperature dependence. As temperature increases, a rising amount of specimen volume is affected by high stresses. The probability of finding a cleavage inducing capacity becomes larger, so that the stress needed to initiate failure is reduced. At this point it is not possible to state whether the temperature dependence of σ_f^* is primarily controlled by sampling, or if an actual thermal activation is given.

A considerable temperature dependence of σ_f^* was also found for line-pipe steels with bainitic microstructures (Dünnewald-Arfmann et al., 1988). Compared to the C 10, the line-pipe steels showed $\Delta\sigma$-values which were about twice as high, indicating that increasing strength and toughness result in higher $\Delta\sigma$.

CONCLUSIONS

1. The strongest influence on σ_f and σ_{gy} is achieved with varying a/W-ratios. Increasing notch depth shifts the transition to brittle fracture to lower temperatures, if a/W > 0.6.

2. The results indicate that cleavage obeys the same critical stress criterion below and at general yield. The transition temperature T_{gy} is influenced by specimen size; it does not characterize a transition in fracture mode. A temperature dependence of σ_f^* was observed. Further investigations will be needed to confirm whether σ_f^* is actually thermally activated.

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