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ASSESSMENT OF FLAWS IN STRUCTURAL COMPONENTS ON THE BASIS OF A HYPOTHESIS FOR CLEAVAGE FRACTURE

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INTRODUCTION

Many components made of structural steels, e.g. pressure vessels, containers, boilers etc. with wall thicknesses up to about 50 mm are operating in ranges of temperature where the application of fracture mechanics toughness parameters such as K_{Ic}, δ_c or J_{Ic} for the assessment of flaws is still somewhat doubtful, because of gross yield and initiation of ductile thumbnail crack which can propagate in a brittle manner. An alternative criterion for the assessment of flaws in such components is based on a hypothesis for cleavage fracture. This has been proposed by several authors [1 to 3], and has some confirmation by experiment [4,5]. The authors use the normal stress hypothesis in combination with a yield hypothesis for cleavage fracture:

$$\bar{\sigma} = \sigma_y = \frac{\sigma_{fc}}{\beta^{-1}} \qquad (1)$$

where $\bar{\sigma}$ is the equivalent stress (after Tresca or v. Mises), σ_{fc} the cleavage fracture stress, which is supposed to be relatively independent of temperature and β^{-1} the maximum plastic stress concentration factor. An essential condition is that at stress gradients this criterion must be met simultaneously in the same volume element. The physical meaning of this criterion is that plastic deformation is necessary for cleavage fracture.

The nominal fracture stress depends on the ratio σ_{fc}/σ_y, on the geometry of the component and the configuration of the cracks or notches. With regard to the operating temperature of such components experience has demonstrated that the range of

$$\frac{\sigma_{fc}}{\sigma_y} > \beta^{-1} \qquad (2)$$

is of special technical interest. In this range general yield or gross yield occurs before fracture so that the nominal fracture stress

$$\sigma_{fn} \geq L \cdot \sigma_y \qquad (3)$$

(L = constraint factor ≈ 1 to 3). Technical rules for design of components are based on the condition

$$\bar{\sigma} = \frac{\sigma_y}{S} \qquad (4)$$

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(S = safety factor, usually about 1.1 to 2). Therefore, failure can be excluded if

1) $$\sigma_y \beta^{-1} \leq \sigma_{fc} \quad \text{(see equation 2)} \tag{5}$$

2) $$\frac{A_c}{A_o} < 1 - \frac{1}{s} \tag{6}$$

(A_c = area of a crack or a notch, A_o = cross section without crack or notch). The second condition takes into account the cross section reduction by cracks or notches in view of the net fracture stress. The maximum value of β^{-1} is achieved at cracks or parallel sided notches under plane strain conditions; it is about 2.6 after the Tresca criterion or 3.0 after the v. Mises criterion.

Some years ago the Verein Deutscher Eisenhüttenleute (VDEh) initiated a test program for comparison of several brittle fracture test methods, to which many institutes and companies contributed results.* Wide plate tests, among others, were carried out by the authors and Soete and co-workers. The results of these tests were used to check the validity of the above mentioned fracture hypothesis and to evaluate the significance of such tests in terms of the assessment of flaws under general yield conditions.

TEST METHODS

The form and dimensions of the test plates plus the notch configuration are shown in Figure 1. The notch of 0.2 mm width was cut by hand with a jeweller's saw. The essential instrumentation was as follows:

- Two devices for measuring the overall deformation over a gauge length of 400 mm or 370 mm
- COD-meter, placed at a distance of 2 mm from the notch tip inside the 1 mm notch
- Thermo-couples for controlling the test temperature.

During the test

- Temperature
- Load vs. elongation
- Load vs. crack opening displacement

were plotted.

In addition tensile tests were carried out with small unnotched specimens (Figure 1) at temperatures down to about 13 K to establish the cleavage fracture strength, and tests with Hill-specimens were performed at room temperature to determine the fracture strain under plane strain condition at ductile fracture. The width of the Hill-specimens was equal to the sheet thickness of 30 mm.

MATERIALS

This paper deals with the results of tests on the following steels: St 37 - 2, St 52 - 3, StE 47, 22 NiMoCr 3 7. The chemical composition of these materials is listed in Table 1, the mechanical properties are shown in Table 2. The microstructure of these steels was ferrite-pearlite or ferrite-bainite. All specimens were loaded perpendicularly to the rolling direction.

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*The program has been subsidized by EC.

RESULTS

The results of all the tests are collected in Figures 2 to 5. If the cleavage fracture strength is defined as the uniaxial tensile stress $\sigma = \sigma_y = \sigma_f$, one can see that even at 13 K in no case was this condition satisfied. Therefore the highest fracture stress was regarded as the cleavage fracture strength, notwithstanding that the true values are somewhat higher.

In the temperature range up to about 50 K plastic deformation and cleavage crack nucleation occurs mainly by twinning, often in an abrupt manner.

With the wide plate tests at low temperatures the fracture stress is below the yield point and the "plastic displacement" of the notch flanks $\delta_p \approx \delta_c - \delta_e < 0{,}1$ mm (δ_c = displacement at fracture, δ_e = elastic displacement). This "plastic displacement" can be determined with sufficient accuracy from the load-displacement plot only if stable crack growth does not occur. At the cleavage fracture temperature T_{fc} the fracture stress equals the general yield stress σ_{Gy}. The constraint factor L = 1 for an internal notch, and so $\sigma_{Gy} = \sigma_y$. As one can see, at T_{fc} the maximum stress concentration factor β^{-1} of all steels is about 2.4 to 2.5, whereas the theoretical value on the Tresca criterion is about 2.6. The difference may arise from an underestimate of the cleavage fracture strength from the uniaxial tensile tests.

At all higher temperatures fracture occurs after general yield. The plastic elongation $\Delta\ell_p$ and the "plastic displacement" δ_p (Figures 2 and 4) increase with increasing temperature by similar amounts. This is illustrated more clearly in Figure 6. This correlation may be a consequence of the formation of a pair of wedge shaped zones ahead of the notch tips, which move towards the tips by plastic flow on slip lines. The notch flanks, as well as the ends of the plate, are moved apart by these wedges. This relation should hold up to the initiation of a ductile crack, but in practice, as one can see from Figures 2 and 4, it holds afterwards also.

With Hill-specimens the fracture strain for ductile fracture under plane strain condition can be determined. The max principal deformation at fracture ε_{pf1} was calculated from the reduction of area. Its value was about 0.25. If the width of the 1 mm wide notch is taken as initial gauge length ℓ_o, the "plastic displacement" at the origin of a ductile crack is $\delta_{pd} = \exp \varepsilon_{pf1} - 1$. The exact values are marked for the respective materials in Figures 2 to 5. As one can see, ductile cracks occur in all materials at test temperature where $\delta_p \approx \Delta\ell_p > \delta_{pd}$. The ductile thumbnail cracks become longer with increasing temperature. Finally the plate fracture is completely ductile at temperatures near room temperature.

DISCUSSION

The approximate agreement of theroetically and experimentally determined values of max plastic stress concentration factor β^{-1} gives an indication of the validity of the proposed fracture hypothesis for cleavage fracture. Therefore, this fracture hypothesis can be used as a basis for assessment of flaws in components. Suppose the design of a component is based on

$\bar{\sigma} < \sigma_y$, the lowest working temperature of a component is the cleavage fracture temperature T_{fc}, if the component is free of residual stresses. As Kihara, et al. [6] have shown by tests with pressure vessels, residual stresses can cause fracture stresses below σ_{Gy} also at temperatures where the fracture stress is equal or above σ_{Gy} without residual stresses. Residual stresses should not reduce the fracture stress below σ_{Gy} if they are released by plastic deformation. The extent of plastic deformation necessary to remove the influence of residual stresses will be evaluated by another test program. A limiting operating temperature in case of residual stresses could be T_{fd}, because plastic deformation far away from the notch or crack tip is considerable. The influence of residual stresses on fracture stress will certainly disappear at temperatures where the fracture is completely ductile.

For this method of assessment of flaws the crack or notch size is of importance in so far as it has an influence on the net stress.

The temperature T_{fc} could be determined theoretically by tests with small unnotched specimens by evaluating the cleavage fracture strength and the temperature dependence of the yield point. But the variation in yield stress is so small in the temperature range of interest, that this method would be rather inaccurate. Therefore wide plate tests are required to evaluate critical temperatures for components, especially when they are welded. These tests can also be carried out in bend.

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Table 1 Chemical composition of the steels investigated in wt. %

Steel	C	Si	Mn	N	Al	Ni	Cr	Mo
St 37-2	0,11	0,24	0,52	0,0027	0,005			
St 52-3	0,22	0,40	1,37	0,0074	0,037			
StE 47	0,15	0,35	1,51	0,0108	0,040	0,53		
22NiMoCr 3 7	0,19	0,36	0,75		0,083	0,85	0,35	0,62

Table 2 Mechanical properties of the steels investigated at room temperature

Steel	σ_y	UTS	δ_5*
	MPa	MPa	%
St 37-2	257	386	33
St 52-3	373	567	31,3
StE 47	470	668	25,5
22NiMoCr 3 7	508	663	23,9

*Fracture strain for a gauge length of l_o = 5 x specimen diameter

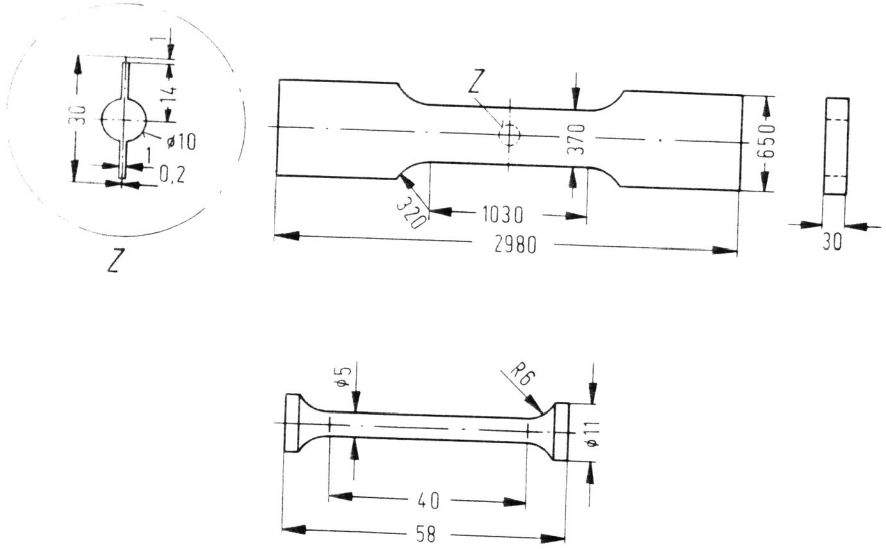


Figure 1 Form, dimensions in mm and notch configuration of the test plates, and the small unnotched specimens.

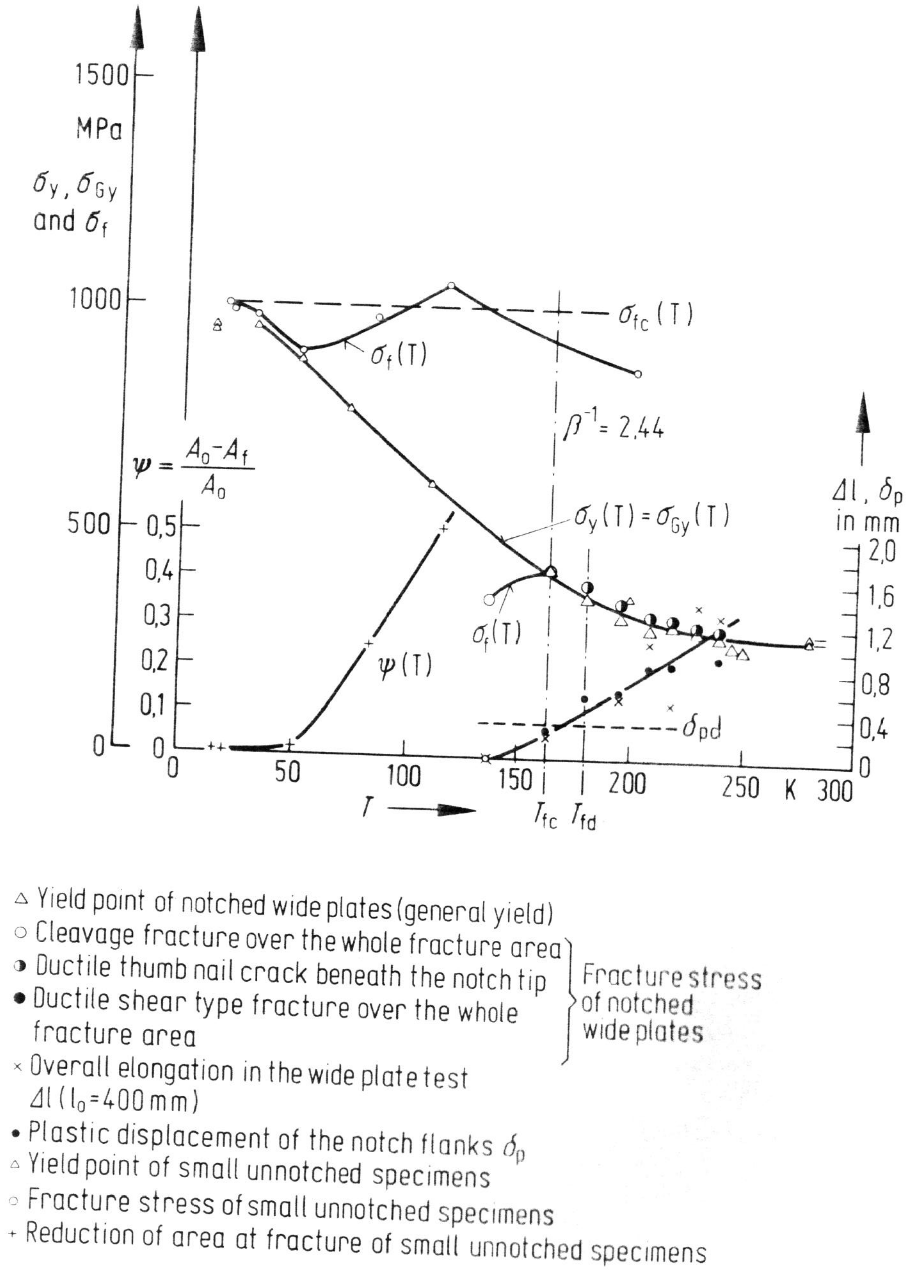
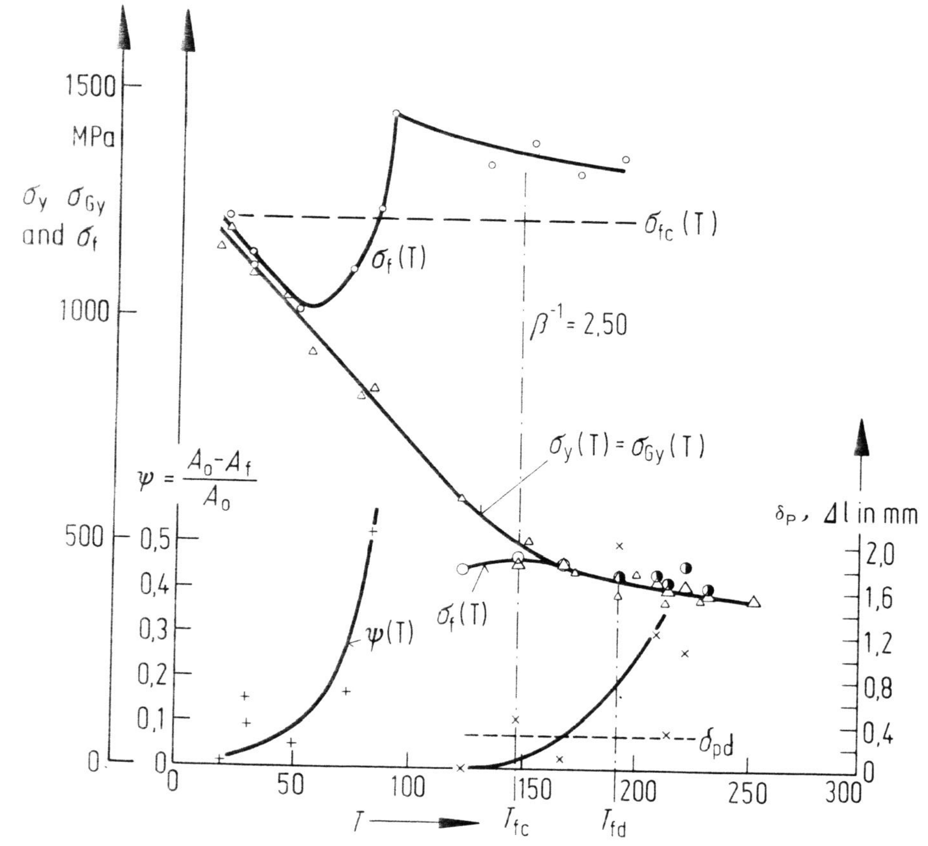


Figure 2 Fracture behaviour of the steel St 37-2, illustrating particularly the variation of yield stress and fracture stress with temperature.

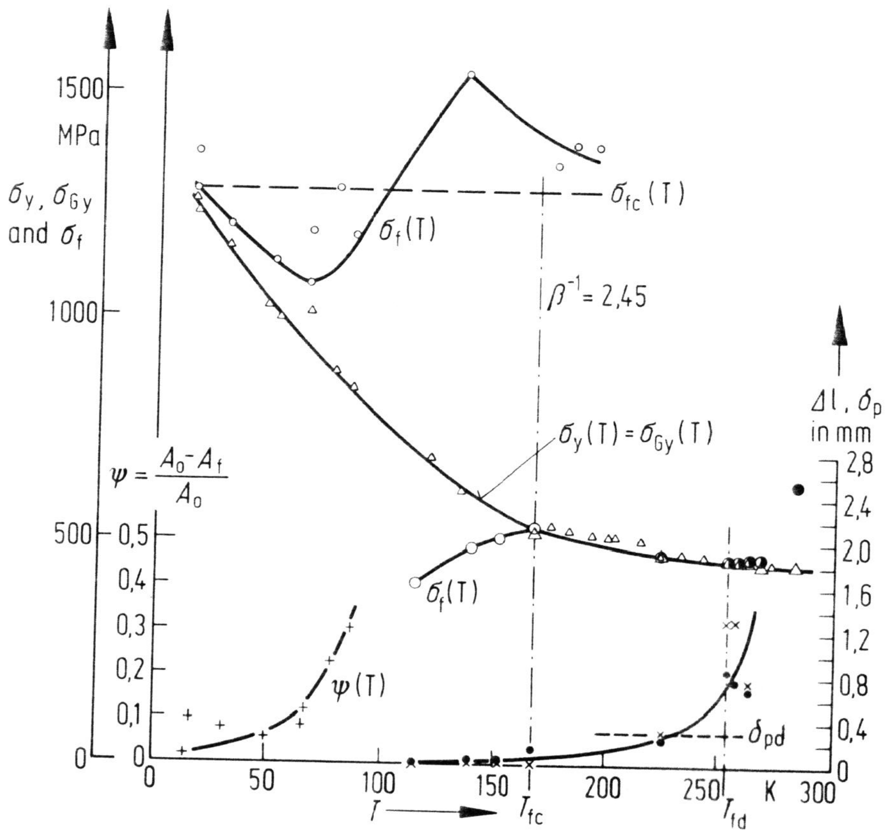


Results from Soete et. al.:
- △ Yield point of notched wide plates (general yield)
- ○ Cleavage fracture over the whole fracture area
- ◑ Ductile thumb nail crack beneath the notch tip
- ● Ductile shear type fracture over the whole fracture area
- × Overall elongation in the wide plate test $\Delta l (l_0 = 370\ \mathrm{mm})$

Fracture stress of notched wide plates (○, ◑, ●)

- △ Yield point of small unnotched specimens
- ○ Fracture stress of small unnotched specimens
- + Reduction of area at fracture of small unnotched specimens

Figure 3 As Figure 2 for steel St 52-3.



- △ Yield point of notched wide plates (general yield)
- ○ Cleavage fracture over the whole fracture area
- ◑ Ductile thumb nail crack beneath the notch tip
- ● Ductile shear type fracture over the whole fracture area

Fracture stress of notched wide plates (○, ◑, ●)

- × Overall elongation in the wide plate test $\Delta l (l_0 = 400\ \mathrm{mm})$
- • Plastic displacement of the notch flanks δ_p
- △ Yield point of small unnotched specimens
- ○ Fracture stress of small unnotched specimens
- + Reduction of area at fracture of small unnotched specimens

Figure 4 As Figure 2 for steel St E47

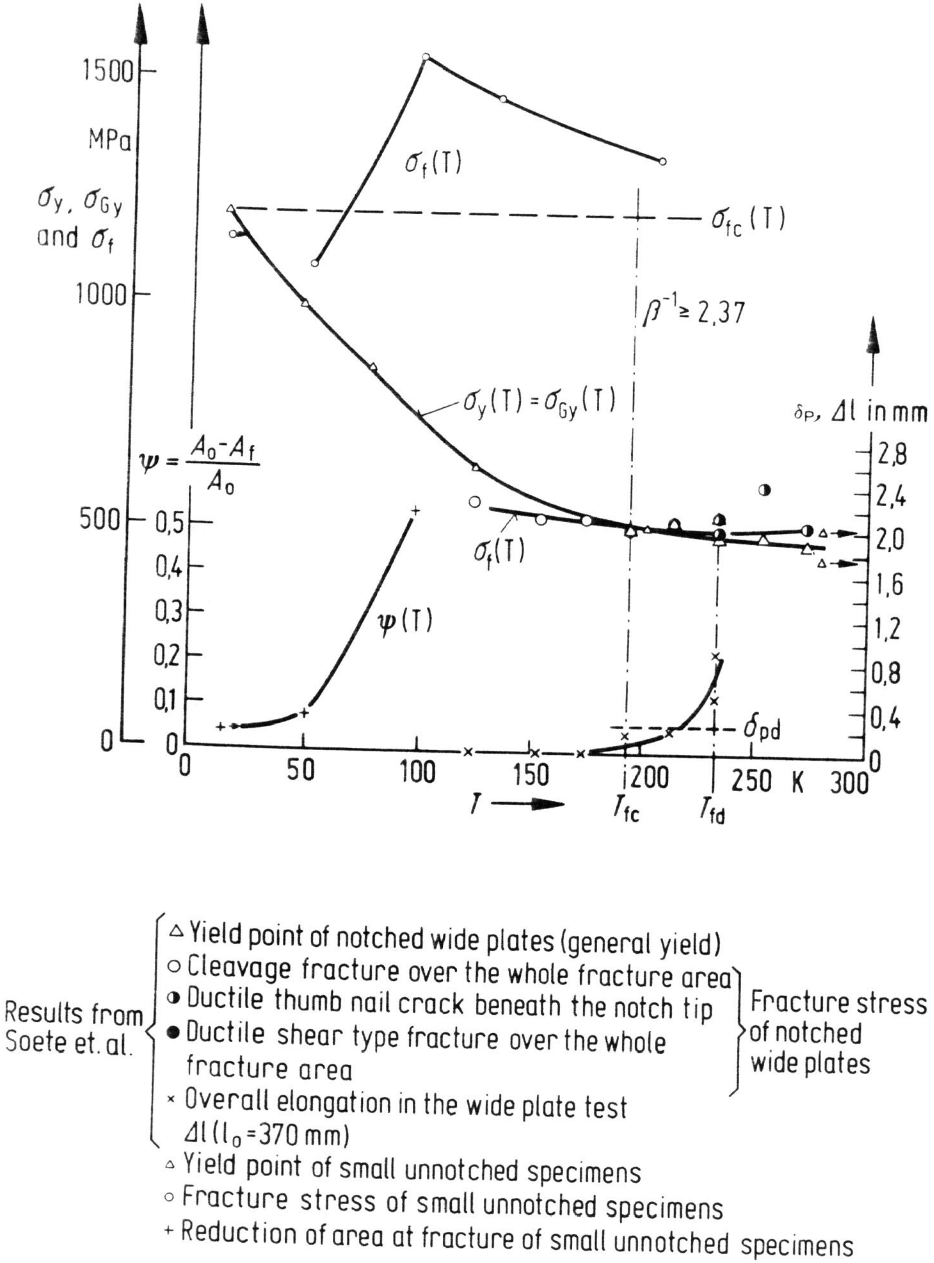


Figure 5 As Figure 2 for steel 22 Ni Mo Cr 37

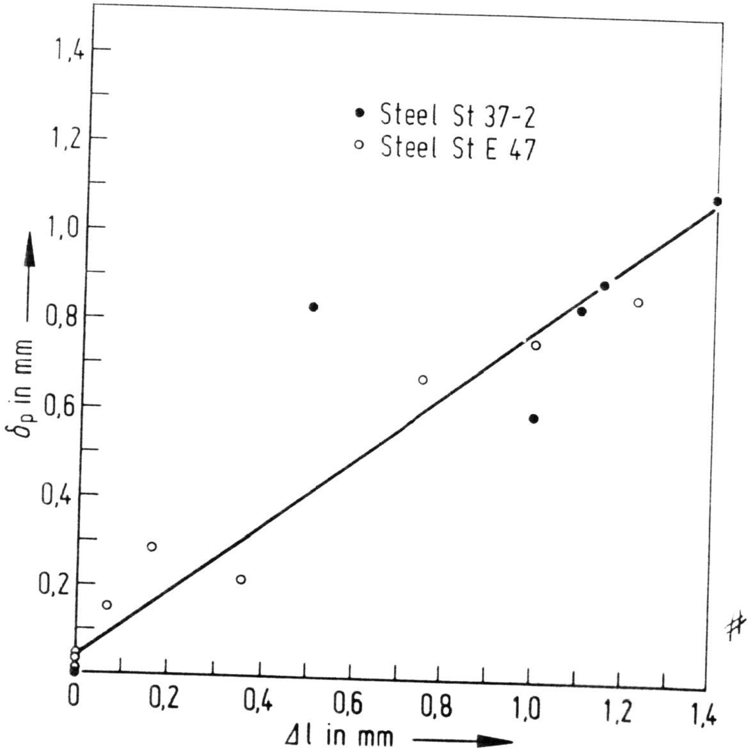


Figure 6 Plastic displacement of the notch flanks at the instant of unstable fracture versus overall elongation in the wide plate test.