TEST ON A PRESSURE VESSEL WITH FLAWS OF DIFFERENT LENGTH AND COMPARISON OF THE RESULT OF SPECIMENS

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Axial flaws of 100...453 mm length were cut in the high strength steel Ste460 as well as in the HAZ of a pressure vessel of 1500 mm diameter and a wall thickness of 40 mm with a jeweller saw. The vessel was pressurized up to a COD where a considerable stable crack growth could be supposed. Attaining the COD the pressure was dropped and a hollow auger specimen was taken including the crack tip in order to obtain the amount of crack growth. The results in terms of critical CTOD and J_{c}(Aa) were compared with critical CTOD-values of 3-point bend specimens and wide-plate specimens as well as with J_{c}-curves of CT specimens with fatigue cracks as well as with saw cuts with and without side grooves.

INTRODUCTION

This work is part of a project entitled "Investigations on the assessment of safety against cleavage fracture of welded steel structures with the aid of the results on small specimens and wide plates". Results of small tensile specimens, wide plate specimens CCP as well as 3-point bend specimens SENB with various thicknesses, widths, notch angles and notch root radii were already published (1 - 6). Fig. 1 shows test parameters and results of the used specimens. The chemical composition and the mechanical properties of the test material Ste460 (German Standard) are plotted in Tab. 1. Furthermore two welded joints with heat inputs of 20 kJ/cm and 50 kJ/cm were tested (Table 2). Finally tests on pressure vessels had to be carried out in order to check the validity of a safety analysis based on elastic-plastic fracture mechanics using the test results of various specimens.

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TABLE 1 - Steel StE 460: Chemical composition (mass %) and mechanical properties at 20 °C

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>0.28</td>
<td>1.52</td>
<td>0.009</td>
<td>0.009</td>
<td>0.62</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Lower yield point \( R_{el} \) 480 N/mm²
Ultimate tensile strength \( R_m \) 633 N/mm²
Elongation in % D \( \Delta L \) 23 %
Reduction of area Z 60 %
Charpy (upper shelf) energy \( A_{V} \) 135 J

TABLE 2 - Welded joints

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Double U 2/3 - 1/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding process</td>
<td>Submerged arc</td>
</tr>
<tr>
<td>Wire</td>
<td>S₂Ni2,5(Ø 4 mm)</td>
</tr>
<tr>
<td>Flux</td>
<td>LW 330</td>
</tr>
<tr>
<td>Heat input</td>
<td>20 kJ/cm, 50 kJ/cm</td>
</tr>
<tr>
<td>Preheating temperature</td>
<td>175 °C ± 20 °C</td>
</tr>
<tr>
<td>Heat treatment</td>
<td>No</td>
</tr>
<tr>
<td>Retreatment</td>
<td>No straightening</td>
</tr>
</tbody>
</table>

The parameters of the pressure vessel tests were:

- type and size of flaws: through wall flaws or cracks respectively, semielliptical surface notches (cracks) of various dimensions,

- microstructure in the vicinity of the flaws: base metal and heat affected zone HAZ produced by 20 kJ/cm heat input,

- loading by internal pressure \( P \) until initiation or limited extension of a stable crack respectively.
PRESSURE VESSEL TESTS

The test temperature was 22 °C and the length \( (2c_0) \) of the through wall flaw varied from 100 mm to 453 mm, it was located in the base metal as well as in the HAZ 0,3 mm beside the fusion line of the 20 kJ/cm welded joint respectively. Criteria for crack initiation and limited stable crack growth were the crack tip opening displacement \( \Delta a \) and the J-integral.

Fig. 2 shows the dimensions of the vessel. The flaws were located inside round I and II of 650 mm diameter, which were welded to the middle of the cylindrical part and aligned parallel to the vessel axis. At the end of a test procedure hollow auger specimens around the crack tip were taken for metallographic examination. Different flaw lengths were produced by extension of the slot by sawing after the tests. Fig. 3 demonstrates the dimensions and orientation of a flaw in the HAZ of the 20 kJ/cm welded joint. The significant parts of the flaw were the 0,2 mm wide slots on each side.

The following data were measured:
- during the pressure test:
  - internal pressure,
  - notch opening displacement \( V \) in a distance of 3 mm from the notch tip,
  - the strain distribution in front of the crack (notch) tip,
- test temperature
after the test:
  - investigation of hollow auger specimens (diameter 10 mm) at the crack tip:
    - stable crack extension \( \Delta a \) as a function of the position in the vessel wall,
    - crack (notch) opening displacement and crack (notch) tip opening displacement as a function of the position in the vessel wall
  - notch position and crack extension in the HAZ-microstructure in the case of the welded joint.

RESULTS

Fig. 4 - 6 shows results obtained from hollow auger specimens. Flaw and crack contours were measured at least at 6 cross sections, which were prepared for metallographical examination. The crack (notch) opening displacement values were obtained at the notch tip as well as in a distance of 3 mm away from it.
Fig. 4 demonstrates stable crack extensions in the vessel wall in front of flaws of different length. It is remarkable, that for the same internal pressure crack growth on either side of the slot was different. Compare both curves for equal pressure 15.6 MPa and 19.6 MPa.

Fig. 5 shows the measuring procedure for the notch resp. crack tip displacement. For the determination of $d_e$, the plastic and elastic parts of the notch (crack) tip displacements were added, whereby $d_e$ was obtained according to BS 5762 (7).

Fig. 6 demonstrates examples of the distributions of notch opening displacement $V_0$ in the vessel wall. Again a different behavior at the two notch tips of a flaw is evident.

Fig. 7 and 8 compare the critical notch (crack) displacements at stable crack initiation obtained at $T_1$ with SENB specimens (5), CCP specimens (6) and the pressure vessel. For SENB $d_c$ was determined in accordance to BS 5762 (7) and for CCP it was measured after the test.

Fig. 7a shows for SENB the interdependence of the critical notch (crack) tip opening displacement at $T_1$ on the notch root radius. Obviously there is no influence of the notch position (T-L or T-S) on $(d_c)_{T_1}$.

Fig. 7b compares the results of SENB, CCP and pressure vessel tests. There is a rather good agreement between the results of the vessel and SENB-tests whereas the results of the wide plate tests are different. The reason of the deviation is not quite clear. But it must be kept in mind, that for wide plates with an a/W-ratio of 0.08 the flaws were relatively small.

In Fig. 8 results obtained with welded joints notched in the HAZ 0.3 mm beside the fusion line are plotted. Compared to the base metal $d_c$-values for stable crack initiation, the HAZ-values are smaller for the vessel as well as for the wide plate. Thus, the 20 kJ/cm welded joint seems to have somewhat lower $d_c$-values than the base metal. Generally welded joint and base metal behave rather similar concerning initiation of stable cracks. The same statement is valid for the 50 kJ/cm welded joint with $(d_c)_{T_1}$-values only slightly above the base metal values (Fig. 8b).

In the following we compare results concerning $J$-integrals obtained with CT25 specimens, wide plates (6) as well as for the vessel.
Fig. 9 shows crack resistance plots which were determined with CT25-specimens of different dimensions according to ASTM E 813-81. Single specimen tests using a DC-potential method for crack extension measurement yielded comparable $J_R-\Delta a$-plots. The $J_R$-curves of specimens without side grooves were nearly identical, whereas side grooved specimens obviously had a different slope.

Fig. 10 again includes a comparison between CT25, wide plate and vessel tests concerning $J_R-\Delta a$-plots. Since the $\Delta a$-values of the vessel and wide plate tests are related exclusively to stable crack extension in the following diagrams, the $J_R$-curves of CT25-specimens were shifted 0.1 mm (width of the stretch zone) to the left.

$J_{\text{applied}}$ of the vessel was determined using the equation of Paris and Johnson (8) with $\beta = 2$:

$$J_R = \frac{R \Delta a}{E} = \frac{\pi (P/P_k)^2}{1 - \frac{1}{\beta} (P/P_k)^2}$$

$\beta = 2$, plane stress condition
$\beta = 6$, plain strain condition

Fig. 10 shows that only one value of vessel tests 2 and 4 respectively deviates remarkably from $J_R$-curve of side grooved CT25-specimens. The $J_R-\Delta a$ value of wide plates determined according to (9) yielded relatively large deviations in comparison to the other tests.

Fig. 11 shows the same functions as Fig. 10 for a notch root position in the HAZ. Only the results of vessel tests 1 and 2 clearly lie below the reference curve of side grooved CT25-specimens. For these experiments the flaws were relatively short. Therefore it can be assumed that residual stresses caused by shrinkage which had been produced during welding of the round were added to the circumferential stress produced by the internal pressure. It was estimated that a tensile residual stress of 50 N/mm² would be sufficient to explain the observed deviations. Whether there are really tensile residual stresses will be proven by further tests. The $J_R-\Delta a$ value of the wide plate again is too high, but the deviation is smaller than for the notch position in the base metal (compare Fig. 10 and 11).

Fig. 12 gives a survey of $J_R$-values as a function
of flaw length, determined by vessel tests with notch positions in the base metal and HAZ of the 20 kJ/cm welded joint. The hatched columns referred to \( J_R \)-values determined by the vessel tests with the aid of equation 1. The unhatched columns had been calculated by using the \( \Delta a \)-values of the vessel tests in connection with the \( J_R \)-curve of the side grooved base metal CT25-specimens. Assuming tensile residual stresses of 50 N/mm², the \( J_R \)-values would be increased as shown by arrows.

CONCLUSIONS

The results show, that values of initiation and extension of stable cracks determined with SENB-specimens and CT25-specimens can be transferred to vessel with through wall flaws. But with specimen values alone the assessment of the vessel behaviour is not very conservative.

In several cases wide plate tests (CCP) are not useful to simulate the behaviour of vessels with through wall flaws. The reason of this is not quite clear. Further experiments are necessary to find out whether increasing the \( a/W \)-ratio will improve the correspondence to the vessel tests. A further argument could be, that for wide plates crack initiation always occurred after general yield, whereas for vessels initiation took place, below the limit load for plastic collapse.

ACKNOWLEDGEMENTS

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SYMBOLS USED

\(a, c\) = notch length, crack length

CCP, vessel: one-half the total length of notch resp. crack (mm)

\(\Delta a\) = stable crack extension (mm)

\(A_v\) = charpy energy (J)

\(B\) = specimen thickness (mm)

BM = base metal (StE 460)

CCP = centre cracked tensile panel specimen

COD = crack (notch) opening displacement (mm)

CTOD = crack (notch) tip opening displacement (mm)

CT25 = compact specimen (ASTM E 813-81)

\(E\) = Young's modulus (N/mm²)

FL = fusion line

HAZ = heat affected zone of welded joint

\(J_I\) = Rice's J-integral, modus I (N/mm)

\(J_R\) = fracture resistance (N/mm)

\(P\) = pressure (MPa)

\(Q\) = heat input (kJ/cm)

\(R_{el}\) = lower yield point (N/mm²)

\(s\) = distance from external surface (mm)

SENB = 3-point bend specimen with single edge notch

SG = side grooves on CT-specimen (0.258)

\(T\) = temperature (°C)

\(T_f\) = fibrous/cleavage transition temperature (\(\Delta a \geq 0\) mm)

T-L, T-S = crack (notch) plane orientation (ASTM E 399-81)

\(V\) = crack (notch) opening displacement (mm)

\(W\) = specimen width,

CCP: one-half the total width (mm)

\(b\) = numerical value

\(\delta, \delta_t\) = crack tip opening displacement (mm)

\(\gamma\) = notch root radius (mm)

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$\sigma_c$ = tensile residual stress (N/mm²)
$2\omega$ = notch angle (°)

Indices

c = critical value

e = elastic

i = at initiation of stable crack

k = at plastic collapse

p = plastic

REFERENCES


(7) British Standards BS 5762, 1972, "Methods for Crack Opening Displacement(COD)Testing"


Figure 1 Investigated specimens and results

Figure 2 Test vessel

Figure 3 Round I, flaw in HAZ
\[ \delta_{hp} = \delta_{pt} + \delta_e \]
\[ \delta_{pt} = V_0 - V_R - 0.2 \]

Figure 4 Stable crack extension in the vessel wall

Figure 5 Determination of CTOD resp. \( d \_t \)

Figure 6 Notch root opening displacement in the vessel wall
Figure 7 Ste 460: Critical values of crack opening displacement vs. notch root radius

Figure 8 Ste 460, notch root in HAZ 0.3 mm by FL: Critical values of crack opening displacement vs. notch root radius
Figure 9  Ste 460: $J_R(\Delta a)$-curves measured at 25 °C

Figure 10  Ste 460: $J_R(\Delta a)$-values of different specimens

Figure 11  $J_R(\Delta a)$-values of different specimens
Figure 12  $J_R$-values of the vessel with flaw length $2c_0$