Stable Crack Growth of Axial Surface Flaws in Pressure Vessels

W. Brocks, G. Künecke, K. Wobst

Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, FRG

INTRODUCTION

Crack initiation and stable crack growth in ductile materials are usually described by J-resistance curves which are obtained from standard specimens. Whereas the initiation value, J_i , is found to be quite independent on the specimen geometry, $J(\Delta a)$ -curves may vary with shape and size of the specimens (Garwood, 1979, McCabe, Landes & Ernst, 1983, Julisch & Stadtmüller, 1985). Still, no reliable criteria exist how to apply these curves to surface flaws in components. Experimental investigations (Wobst & Krafka, 1988) and elastic-plastic finite element (FE) analyses (Brocks & Künecke, 1988) of a test vessel containing an axial surface crack, have been performed for two different materials and crack configurations to analyze the transferability of J_R -curves from specimens to structures. The variation of the J-integral along the crack front as well as the stresses in the vicinity of the crack tip have been evaluated to study the dependency of the local crack resistance on the local stress state. Continuing earlier considerations (Brocks & Noack, 1988), the ratio of the hydrostatic to the von Mises effective stress is introduced to characterize the triaxiality of the stress state.

EXPERIMENTAL INVESTIGATIONS

Two different tests, VT1 and VT2, are reported here, some of the data are summarized in Table 1. Both tests have been performed on the vessel shown in Fig. 1. The axially orientated flaws were located in a round of 650 mm diameter which had been welded into the cylindrical part of the vessel. The vessel was annealed for stress relief afterwards. The flaws were fatigue precracked, starting from a machined notch. After that, the vessel was subjected to internal pressure which was increased up to p_{max} , when ductile crack growth had occurred. The DC-potential method was used to measure the increase of the crack area both during fatigue and static loading. Notch opening displacement, V, and pressure, p, were recorded during the static test. A much larger extension has been obtained in VT2 than in VT1, see Table 1.

Two German standard steels, 20MnMoNi55 and StE 460, whose mechanical properties are also given in Table 1, were used as test materials for the round. J_R -curves have been determined from a number of different specimens, see Table 2, some of them being side grooved (sg) to 20 % of their thickness. The J_i -values given in Table 1 were obtained by the standard test procedure of ASTM E 813. No significant differences could be found between the J_R -curves of T-L and T-S orientation.

NUMERICAL INVESTIGATIONS

The shaded part of the vessel shown in Fig. 1 was modeled by finite elements, see Fig. 2. Profit was taken from some symmetry conditions in order to reduce the number of degrees of freedom. For the same reason, the spherical heads have not been modeled but been replaced by axial tensile forces. A rather fine mesh was necessary in the vicinity of the crack front, which has been modeled according to the shape of the fatigue crack, because the evaluation of stresses and strains at the crack tip was intended. The non-linear FE analysis with ADINA (Bathe, 1984) bases on the incremental theory of plasticity by von Mises, Prandtl and Reuß and allows for large strain in the vicinity of the crack.

No crack growth was simulated in the FE model. Thus, all the calculated values refer to the configuration of the initial fatigue crack, a_0 and c_0 , only. This appeared to be a severe handicap in the analysis of VT2.

RESULTS

The FE calculations as well as a limit analysis by means of the Folias factor showed that the initiation of crack growth occurred near or beyond full yielding of the smallest ligament, see Table 1. A large plastic zone had developed at $p_{\max}$, see Figs. 3a,b. Beside von Mises effective stress, σ_e , the hydrostatic stress, σ_h , is of great importance for fracture as it is a measure of the local triaxiality of the stress state. The isolines of $\sigma_h = \sigma_y$ are plotted in Figs. 4a,b.

Figs. 5a,b show a comparison of the pressure vs. notch opening displacement curves obtained in the vessel tests and in the FE analyses, respectively. The curves indicate a slightly higher plastic limit load in the experiment than in the FE calculation but they coincide rather good at the initiation pressure, p_i . As no crack growth was simulated, the numerical results will necessarily deviate from the experimental data beyond initiation. Consequently, the calculated J-integral will deviate from the "real" J values with increasing pressure. This deviation can be eliminated approximately by remembering that J is related to the work of external forces where the latter may be calculated from the area, A, under the load vs. load line displacement curve. Evaluating A for both experimental and numerical data, a "revised" J is obtained and plotted in Figs. 6a,b vs. the crack front angle Φ which is 0° at the deepest point of the crack and $\pm 90^\circ$ at the penetration points of the crack front to the vessel surface. J shows a maximum at $\Phi = 0^\circ$ as in linear elastic fracture mechanics but, with increasing plastification, develops a second local maximum at $\Phi = \pm 55^\circ$ and $\Phi = \pm 65^\circ$ for VT1 and VT2, respectively. The dotted lines denote the initiation values, J_i , for the respective materials.

Contrary to the variation of J along the crack front, the maximum crack extension, Δa , is observed at $\Phi = 70^\circ$ and $\Phi = 80^\circ$, respectively, see Figs. 7a,b. The crack propagation in axial direction is three to four times larger than the crack growth in wall thickness direction at $\Phi = 0^\circ$. An attempt to explain this phenomenon has been made by Brocks & Knecke, 1988, for VT1 by introducing the local ratio of triaxiality of the stress state $\chi(\Phi) = \max(\sigma_h / \sigma_e)$. This quantity has proved to be a parameter characterizing the stress state in various specimen geometries (Brocks, Knecke, Noack & Veith, 1987). Its physical significance for void growth in elastic-plastic materials is well-known. Indeed, the variation of this ratio along the crack front as shown in Figs. 8a,b reveals that the maxima of crack growth occur close to the maxima of triaxiality.

Local R-curves for the surface cracks are obtained by taking $\Delta a(\Phi)$ from Figs. 7a,b and $J(\Phi)$ at $p_{\max}$ from Figs. 6a,b and assuming that J_i is a material constant. As the progress of $\Delta a(\Phi)$ under increasing J is unknown, the R-curves have been approximated by straight lines, simply connecting the point of initiation with the point at maximum pressure, see Figs. 9a,b. For comparison, the resistance curves of various specimens, which are summarized and explained in Table 2, are plotted by dashed and dotted lines.

CONCLUSIONS

- The local crack resistance depends on the local stress state. Any assessment of stable crack growth which does not account for this dependency but bases on J_R -curves of compact specimens, only, may lead to unconservative leak-before-break estimates, see Figs. 10a,b where this kind of predictions is denoted by dashed curves.
- Introducing dJ/da curves which depend on the ratio of triaxiality, χ , for predicting the local crack growth (Brocks, Veith & Wobst, 1988) gave better results in the case of VT1 but did not bring much better results in the case of VT2, see solid lines in Figs. 10a,b, respectively.

Some unsolved problems are

- Due to the limit conditions for "J-controlled" crack growth, the J_R -curves of the specimens do not cover the amount of crack growth which was reached in the vessel tests.
- The R-curves of the side grooved compact specimens do not yield a lower bound: the minimum dJ/da in VT2 is only half of the slope of the J_R -curve obtained from the compact specimen #3.
- As the present FE analysis did not account for the changes of the flaw configuration during crack growth, the corresponding reaction of the J distribution is not known.
- Nothing is known either from the experiment about the progress of the local ductile extension of surface cracks under increasing pressure.

REFERENCES

- Bathe, K. J. (1984). ADINA, A finite element program for automatic dynamic incremental nonlinear analysis. Report AE84-1, ADINA Engineering Inc., Watertown (USA).
- Brocks, W. & Knecke, G. (1988). Elastic-plastic fracture mechanics analysis of a pressure vessel with an axial outer surface flaw. 14th MPA-Seminar, Vol. 2, Stuttgart (FR Germany), paper 42.
- Brocks, W. & Noack, H. D. (1987). J-integral and stresses at an inner surface flaw in a pressure vessel. Int. J. Pres. Ves. & Piping, Vol. 31, pp. 187 - 203.

- Brocks, W., Künecke, G., Noack, H. D. & Veith, H. (1987). On the transferability of fracture mechanics parameters to structures using FEM. 13th MPA-Seminar, Vol. 1, Stuttgart (FR Germany), paper 3.
- Brocks, W., Veith, H. & Wobst, K. (1988). Experimental and numerical investigations of stable crack growth of an axial surface flaw in a pressure vessel. IAEA Specialists' Meeting, Stuttgart (FR Germany).
- Garwood, S. J. (1979). Effect of specimen geometry on crack growth resistance, ASTM STP 677, Philadelphia (USA), pp. 511 - 532.
- Julisch, P. & Stadtmüller (1985). Valuation of a ductile vessel rupture by R-curve analysis with CT specimens and wide plate tests. Trans. 8th SMIRT Conf., Vol. G, Brussels (Belgium), paper G 3/1.
- McCabe, D. E., Landes, J. D. & Ernst, H. A. (1983). Prediction of heavy section performance of nuclear vessel steels from surveillance size specimens. Trans. 7th SMIRT Conf., Vol. G, Chicago (USA), paper G 2/4.
- Wobst, K. & Krafka, H. (1988). Experimental investigation of stable crack growth of an axial surface flaw in a pressure vessel. 14th MPA-Seminar, Vol. 2, Stuttgart (FR Germany), paper 41.

Table 1: Vessel test data

	vessel test	
	VT1	VT2
<u>vessel geometry</u>		
inner diameter r_i (mm)	1500	
wall thickness t (mm)	40	
length of cylindrical part L (mm)	3000	
<u>flaw geometry</u>		
crack length $2c_o$	180.4	192.12
crack depth a_o	21.6	28.04
<u>material</u> (round)	20MnMoNi55	StE 460
yield strength σ_y (MPa)	460	490
ultimate stress σ_u (MPa)	604	642
hardening exponent n	7.3	6.0
crack initiation J_i (N/mm)	120	110
<u>loading</u>		
initiation pressure p_i (MPa)	22.4	20.0
maximum pressure p_{max} (MPa)	24.2	22.4
pressure at ligament yielding (FE)		
p_y (MPa)	17.5	21.0
FOLIAS' collapse pressure p_F (MPa)	21.2	19.2
<u>ductile crack growth</u>		
maximum Δa (mm)	2.91	8.0
at Φ (deg)	71	82

Table 2: Specimen geometries

No	type	material	B mm	W mm	a_o/W
1	CT, sg	20MnMoNi55	25 (20)	50	≈ 0.5
2	CT		25	50	≈ 0.5
3	CT, sg	StE 460	25 (19)	50	≈ 0.5
4	CT		25	50	≈ 0.5
5	CCT, sg		20 (16)	50	≈ 0.5
6	CCT		40	125	≈ 0.1
7	CCT		40	125	≈ 0.5
8	CCT		40	125	≈ 0.8
9	DECT		40	125	≈ 0.8

Fig. 1: Geometry of the test vessel

Fig. 2: FE model of the test vessel

Fig. 3: Plastic zones at $p_{\max}$, effective stress $\sigma_e = \sigma_Y$
a) VT1 b) VT2

Fig. 4: Hydrostatic stress $\sigma_h = \sigma_Y$ at $p_{\max}$
a) VT1 b) VT2

Fig. 5: Pressure vs. mouth opening displacement, experiment and calculation
a) VT1
b) VT2

Fig. 6: Variation of J along the crack front at p_l and p_{max}
a) VT1
b) VT2

Fig. 7: Ductile crack growth at p_{max}
a) VT1
b) VT2

Fig. 8: Variation of the ratio of triaxiality along the crack front
a) VT1
b) VT2

Fig. 9: Local J_R -curves for the surface flaw and various specimens
a) VT1
b) VT2

Fig. 10: Ductile crack growth, prediction and experiment
a) VT1
b) VT2