COMPLEX COMPONENT FAILURE WITH LARGE DUCTILE CRACK GROWTH – HIGH QUALITY PREDICTION BY DAMAGE MECHANICAL SIMULATION AND EXPERIMENTAL VERIFICATION

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ABSTRACT

A basic problem within the safety assessment of flawed components is the question of how to deal with large amounts of ductile crack growth. Conventional fracture mechanical concepts fail as their validity is restricted only to small amounts of ductile crack growth. The assessment tools for the elastic plastic material and component behaviour have been significantly improved by the development of micromechanical material models. Advantages of these models are geometry independent material parameters and their validity even with large amounts of ductile crack growth.

In the present study the micromechanical damage model of Gurson, Tvergaard and Needleman implemented in the FE code ABAQUS was applied to predict the complex crack growth and leakage behaviour of a large thinwalled pipe with 90°-external circumferential surface flaw under fourpoint bending (nominal pipe dimensions: length × outer diameter × wallthickness = 2000 × 273 × 17 mm³). The threedimensional elastic-plastic numerical simulation of the pipes failure behaviour including ovalization and leakage was performed up to ductile crack growth of about 200 mm in circumferential direction. A series of experimental pipe tests was carried out up to final cleavage failure after significant stable leak growth in order to gain detailed data on the failure behaviour for the verification of the FE simulation.

The numerically determined results were nearly identical to the respective experimental results. That especially applies to the crack front shapes, crack length, displacements and the leakage opening area. Therefore, it is outlined that even complex failure mechanisms of components with large ductile crack growth can be well assessed by application of damage models.

KEYWORDS

Component failure, large ductile crack growth, damage mechanical simulation, experimental verification

INTRODUCTION

A wellknown and basic problem within the safety analysis of components is the lack of valid crack resistance curves for large amounts of stable crack growth due to the validity limits in the relevant standard procedures and the uncertainty of how to extrapolate the curves correctly. Therefore, the present study

deals with the question of how to describe and predict complex component failure behaviour with large ductile crack growth by means of application of micromechanical damage simulation.

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS

Material

The material under investigation was the german 15NiCuMoNb5 ferritic-bainitic high-temperature structural steel (WB36) in the form of thinwalled seamless pipes with nominal dimensions of length × outer diameter × thickness = 2000 × 273 × 16 mm³. Table 1 shows mechanical and fracture mechanical properties of the investigated material at ambient temperature together with Charpy impact energy values. Crack initiation toughness values J_i were determined on the basis of the critical stretch zone width from crack resistance curves of fatigue precracked and 20%-sidegrooved C(T)6.25 specimens in L-S orientation with an initial crack length ratio of 0.5 according to the ESIS P2-92 guideline [1] (L – axial direction in the pipe, T – tangential direction, S – wallthickness direction).

TABLE 1
MECHANICAL AND FRACTURE MECHANICAL PROPERTIES OF THE INVESTIGATED 15NiCuMoNb5 STEEL AT AMBIENT TEMPERATURE

	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	K_V [J]	K_{VH} [J]	J_i [N/mm]
L- direction	515	672	27	-	-	-
T-L-position	-	-	-	105 [1]) (20 °C) 98 [2]) (20 °C)	159	-
L-S-position	-	-	-	133 ± 15 (22 °C, 8 specimens)	176	126

[1]) mean value of 3 specimens, [2]) lowest single value

Pipe Bending Tests

The pipe test program [2] covered tests on a pipe with no flaw and pipes with 90°- as well as 60°-external circumferential surface flaws each of which with an initial flaw depth ratio of 0.5 (Figure 1). Figure 1 gives a schematic outline of the test setup for pipe bending tests that was built up in a 20 MN servohydraulic testing machine. The pipes had been extensively instrumented with inductive linear position transducers and clip gages in order to provide a large set of purposefully determined data of deflection, ovalization and crack opening displacement (COD) that was needed for the development and verification of finite element models. Furthermore, a number of non-destructive testing methods were applied focussing on the investigation of the crack growth and leakage behaviour of the pipes. Ultrasonic testing, acoustic emission testing, direct current potential drop technique and an optical analysis delivered detailed data on the experimental pipe failure. Additionally, several engineering approaches were used to provide and to compare analytical predictions of the experimental pipe failure: Plastic Limit Load Concept, Concept of Local Flow Stress, R6 Procedure and Engineering Treatment Model. These investigations are reported in detail in [2].

Finite Element Analysis

All simulations of the component failure behaviour were performed by three-dimensional elastic plastic finite element analysis (FEA) with the FE code ABAQUS using the damage model of GURSON modified by NEEDLEMAN and TVERGAARD [3] for the simulation of ductile crack growth. With BAM division V.3 this model has been used very successfully for the simulation of ductile crack growth within a variety of problems during the past few years such as for instance different specimens geometries, structures and materials [4].

Table 2 summarizes the geometry independent material parameters of the applied damage model for the investigated steel 15NiCuMoNb5 at ambient temperature. These parameters were determined by fitting to experimental results of tensile tests on notched bars with different notch radii as well as to one fracture mechanics test on a C(T)6.25 specimen.
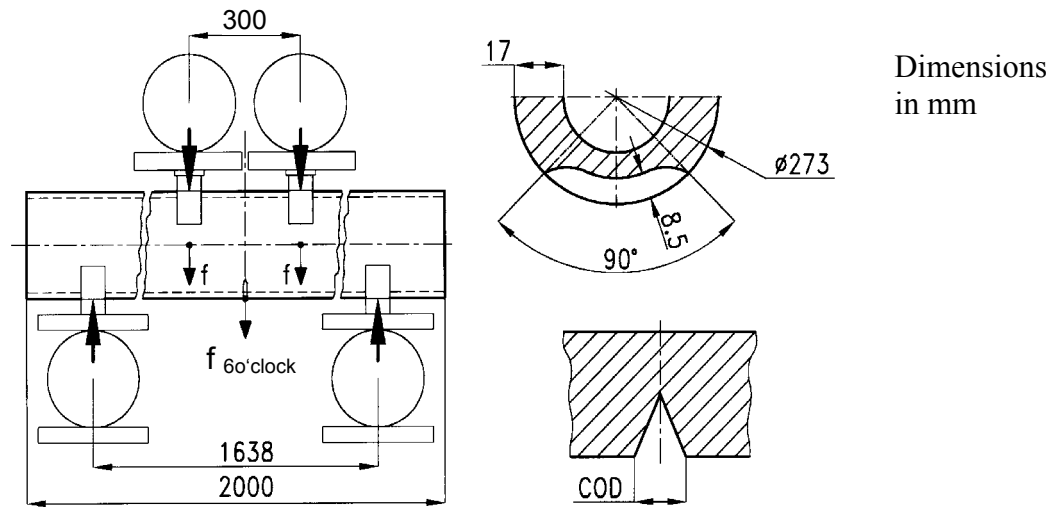

Figure 1: Schematic outline of the test stand for pipe bending tests and position of selected gauging points (f – deflection, COD – crack opening displacement)

TABLE 2
MATERIAL PARAMETERS DETERMINED FOR DUCTILE DAMAGE AND FAILURE OF 15NiCuMoNb5 STEEL
AT AMBIENT TEMPERATURE

f_a	f_n	ε_n	s_n	f_c	f_f
0.0001	0.008	0.25	0.1	0.022	0.19

The geometry of the pipe and the bearings had to be modelled very exactly to achieve the experimentally measured forces and displacements and had therefore been optimized by experimental data of the test with an unflawed pipe. Due to the absolutely up-to date but limited available computer capacity the pipe with the 90°-flaw had to be meshed by relativ large elements compared to the model of the C(T)-specimen. The pipes mesh consisted of 14208 nodes and 10713 three-dimensional elements with linear shape functions and approximate edge length of 0.25 mm in radial (y) as well as axial (x) direction and 2.2 mm in tangential direction (z), see Figure 2.
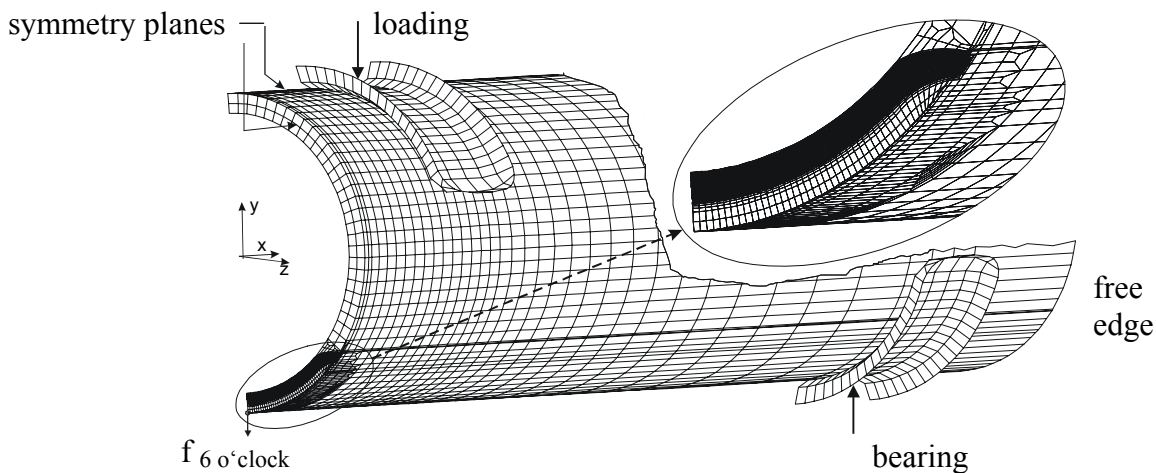

Figure 2: Finite element mesh of pipe no. 2 with 90°-external circumferential surface flaw, rigid bearings and contact

RESULTS AND DISCUSSION

The experimental failure behaviour of the pipes in the displacement controlled tests was characterized by ductile crack growth until full penetration of the wall thickness (leakage), stable growth of the leak and final instability by brittle fracture. The analysis of the fracture surfaces proved that stable crack growth in circumferential direction beyond the angle of the machined initial flaw did not occur. The cleavage fracture initiation region was always located in the area in front of the initial flaw angle.

The finite element analysis of the pipe with an 90°-external circumferential surface flaw was performed until a maximum displacement of about 18 mm at which the experimental failure by cleavage fracture was observed, see Figure 3. Due to the relativ stiff FE-mesh in the flaw region the simulation slightly overestimates the experimental maximum force. The experimental and numerical force records nearly coincide after the leakage had been initiated and thereby most of the comparable stiff elements in as well as near the ligament have failed. Furthermore, the start ot the leakage is remarkably well predicted by the simulation.
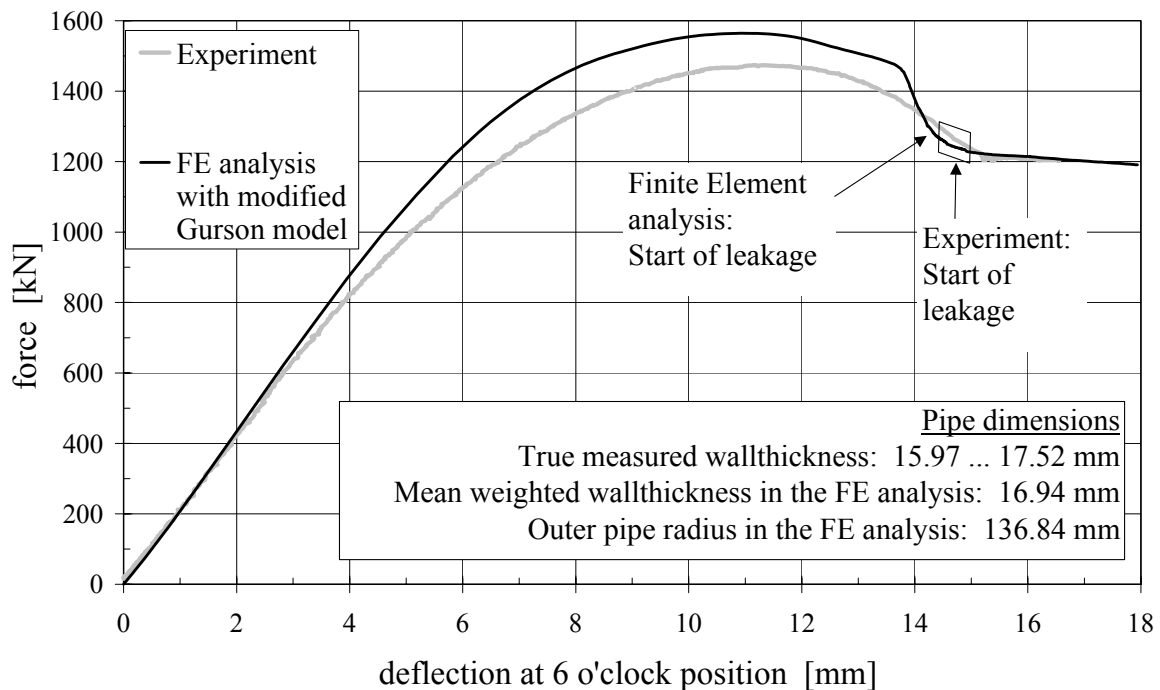

Figure 3: Experimental and numerical force - deflection at the 6 o'clock position - records

Within the FE analysis limits the simulated ductile crack growth led to a total leakage angle of about 70 ° in circumferential direction what equals the experimental result. It was proven by this that the experimental crack initiation and crack growth behaviour as well as the leakage behaviour of the flawed pipe was very well reproduced by the finite element analysis both in terms of the amounts of crack growth and the crack front shape. Figure 4 shows the leakage opening at the internal surface of the pipe in dependence on the circumferential angle at several levels of deflection at the 6 o'clock position. Under the conditions of increasing deflection the maximum of the leakage opening at 0 ° (6 o'clock position) increases up to a value of about 1.8 mm and the leakage enlarges up to an angle of 35 ° in circumferential direction. The numerically determined leakage opening profile in the moment of experimental failure at $f_{6o'clock} = 17.94$ mm corresponds very well to the experimentally determined profile.

At a numerically determined leakage size of 36 ° ($f_{6o'clock} = 17.94$ mm) there was the very high level of stress triaxiality in the ligament of about 4 determined in front of the end of the crack in the area of a circumferential angle of 40 to 45 °. This value of stress triaxiality was only determined at this position in the simulated structure and not until this stage of the simulation of the test. All other values determined are

significantly lower. As can be seen from Figure 5, the position of the highest stress triaxiality perfectly coincides with the area on the fracture surface, where cleavage fracture was initiated as indicated by the performed fracture surface analysis. Therefore, it is concluded that on the applied side the high stress triaxiality is responsible for the cleavage fracture that was initiated in the area in front of the crack at a circumferential angle of 40 to 45 °.
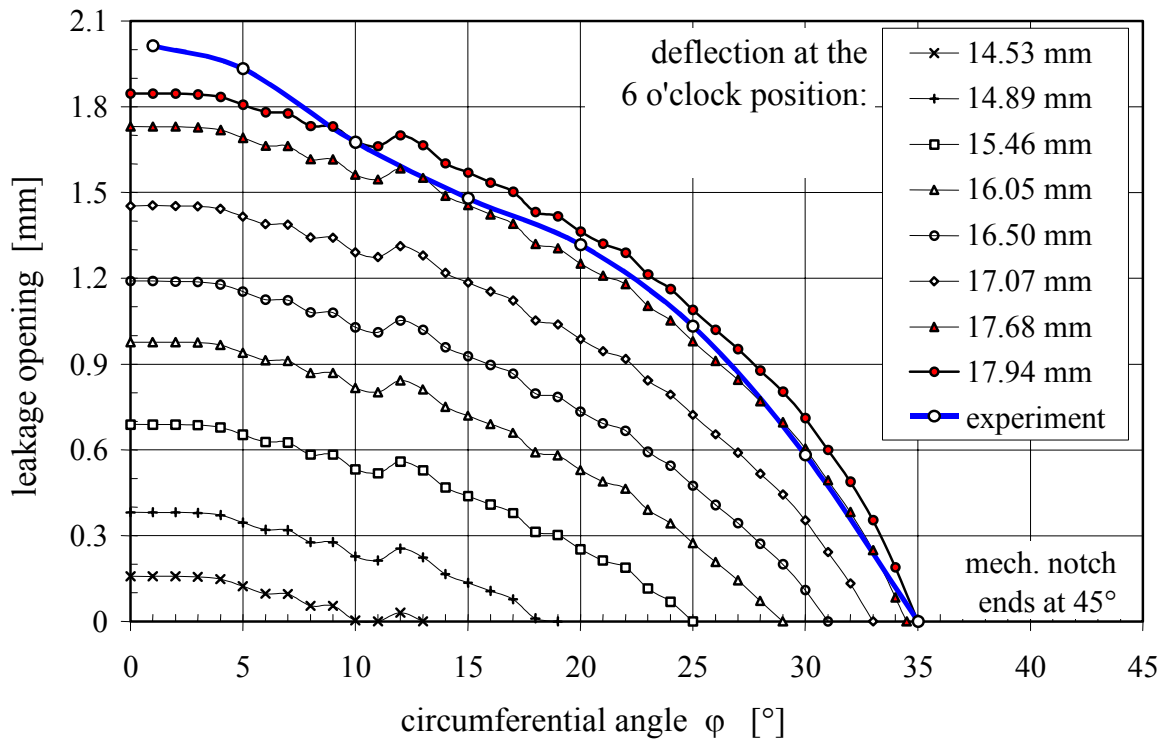

Figure 4: Pipe no. 2 with 90°-external circumferential surface flaw,
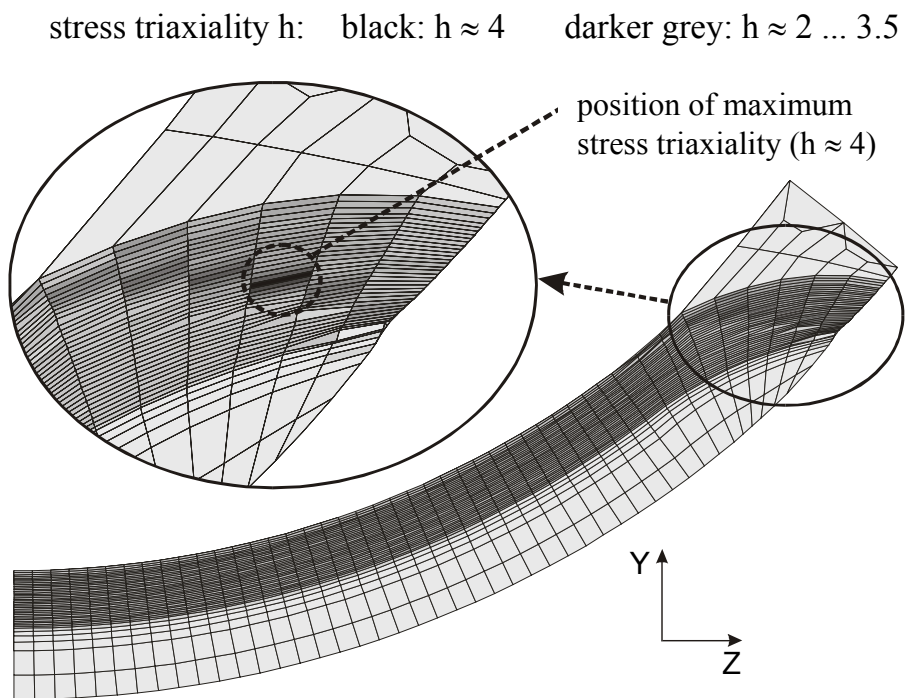leakage opening profiles at different load levels in terms of deflection at the 6 o'clock position

Figure 5: Pipe no. 2 with 90°-external circumferential surface flaw, maximum stress triaxiality in the ligament σ_h / σ_v at a deflection of $f_{6o'clock} = 17.94$ mm, where experimental cleavage failure was observed

CONCLUSIONS

In the present investigations it could be shown by finite element analysis of large ductile crack growth that even complex failure of components can be modelled with high quality by use of damage mechanical simulation. It is pointed out that the problem could only be solved by damage models with geometry independent material parameters as conventional fracture mechanics concepts are not suited to be applied to large ductile crack growth. The high quality of the finite element analysis is underlined because experimental and numerical results are nearly identical, which applies especially to the crack opening area. For instance, this is regarded as an important prerequisite for the realistic assessment of effusion rates in damage cases and for the safety assessment of components in the field of power generating plants.

NOMENCLATURE

A	elongation at rupture
COD	Crack Opening Displacement
$f_{6o'clock}$	deflection at the 6 o'clock position
φ	circumferential angle (half of the total flaw angle)
J_i	crack initiation toughness
K_V	Charpy impact energy
K_{VH}	upper shelf of Charpy impact energy
L	axial direction (x-direction)
$R_{p0,2}$	0.2% offset yield strength
R_m	ultimate tensile strength
S	wall thickness direction (y-direction)
σ_h	hydrostatic stress
σ_v	Mises effective stress
T	tangential direction (z-direction)
f_n	volume fraction of void nucleating particles
ε_n	average plastic equivalent strain at which the nucleation of new voids reaches its maximum
s_n	standard deviation of the distribution which controls the nucleation of new voids
f_a	initial void volume fraction
f_c	critical void volume fraction
f_f	final void volume fraction

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