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CRACK INITIATION AND CRACK GROWTH OF LARGE DIAMETER PIPES UNDER CYCLIC BENDING LOAD

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Abstract

Pipes of 706 mm inner diameter, 47 mm wall thickness and up to 5500 mm in length were provided with circumferential surface defects and loaded by internal pressure of 15 MPa whilst being simultaneously subjected to an alternating external bending moment. Usually a load ratio R of -1 (M_{min}/M_{max}), in one case $R = 0.1$, was applied. The pipes were fabricated of two types of ferritic steel: one, grade 20 MnMoNi 5 5, with a high upper shelf impact energy of > 150 J and one, MnMoNiV–special melt, with a low upper shelf impact energy of about 60 J. Deformation, crack initiation and crack growth in the wall thickness and circumferential direction were determined.

Introduction and Aims

In the following a test programme is introduced which shall contribute to verify the safety of piping including the dimensions of the main coolant piping system of a 1300 MW_e pressurized water nuclear power plant. It is the logical continuation of tests carried out in Phase I and II of the research project "Phenomenological Pressure Vessel and Pipe Burst Tests", in which the failure and fracture behaviour of pipes containing longitudinal or circumferential defects were investigated in detail and which already furnished important results for the proof of integrity / 1 /. FIGURE 1 gives an overview of the main objectives investigated within the research programme.

In Phase III of this research project, promoted by the Federal Minister of Research and Technology, Bonn, it is now intended to enlarge the knowledge about the failure behaviour of circumferentially cracked pipes loaded by a static internal pressure and simultaneously applied cyclic external bending moment. FIGURE 1 also represents the aims of investigation of this part of the project. For the design, calculation and construction of primary cooling systems of light water reactors the KTA–rules 3201.1 and .2 are applicable and demand also a fatigue analysis, which is limited to the determination of a maximum permissible number of load cycles based on linear–elastic or simplified elasto–plastic calculated stress amplitudes. Should upset conditions occur then loadings can arise which cause local plastic deformations in the components. In the case of earthquakes or water hammers etc. additionally low cycle fatigue crack growth has to be considered. Therefore the projected tests focus on the determination of the fatigue life of artificial cracked pipes subjected to high loads which cause an overall nominal equivalent strain range up to 20 mm/m. Furthermore

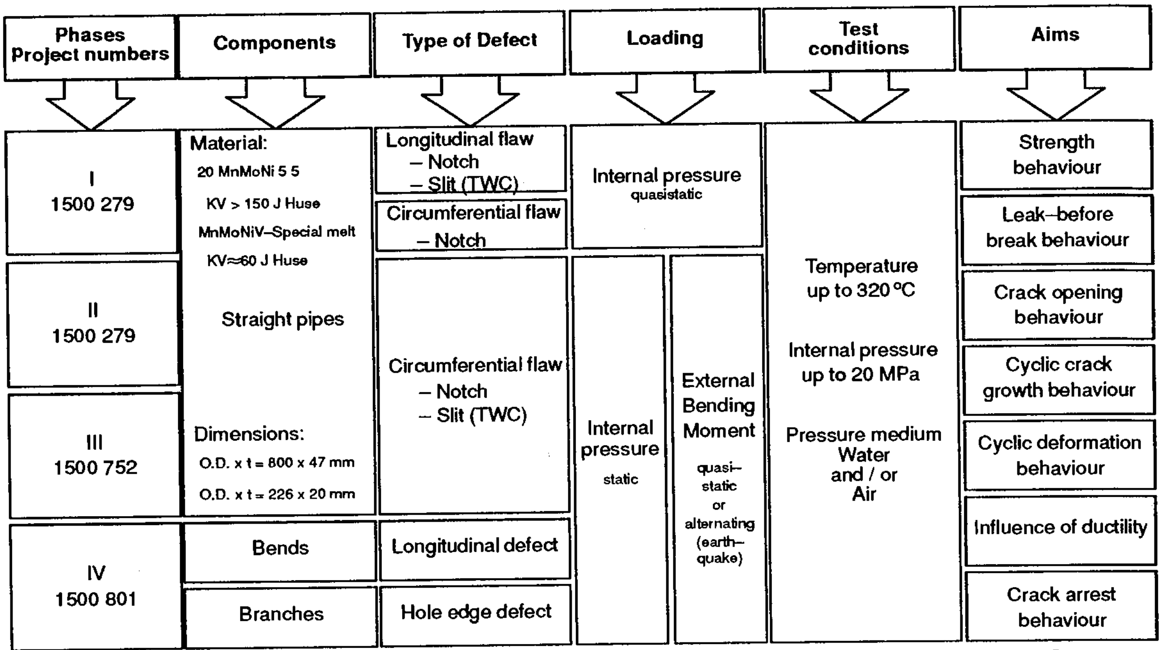


FIGURE 1: Research Project "Phenomenological Pressure Vessel and Pipe Burst Test"; Phase III Subject of Actual Investigation

the rules governing the transferability of material properties obtained from small specimens to components are to be determined.

Test Equipment, Test Pipes, Test Parameters and Material Properties

In order to investigate crack initiation and crack growth during slow cyclic bending in the frequency range between 1 load cycle per 3 hours ($\approx 10^{-4}$ Hz) and 30 cycles per hour (≈ 0.01 Hz) the four point bending device shown in FIGURE 2 was constructed and taken into operation. Both ends of the test pipe are provide with cylindrical bearings which are mounted into slide blocks supported by the upper and lower plate of the machine frame. Two servo–hydraulically controlled actuators, having a maximum stroke of 700 mm, generate a bending moment of up to 12 MNm. The force to the pipe is applied by means of two load distributing saddles. Because of the symmetry of both the system and loading at the pipe centre, a constant bending moment results over a distance of 500 mm of the centreline.

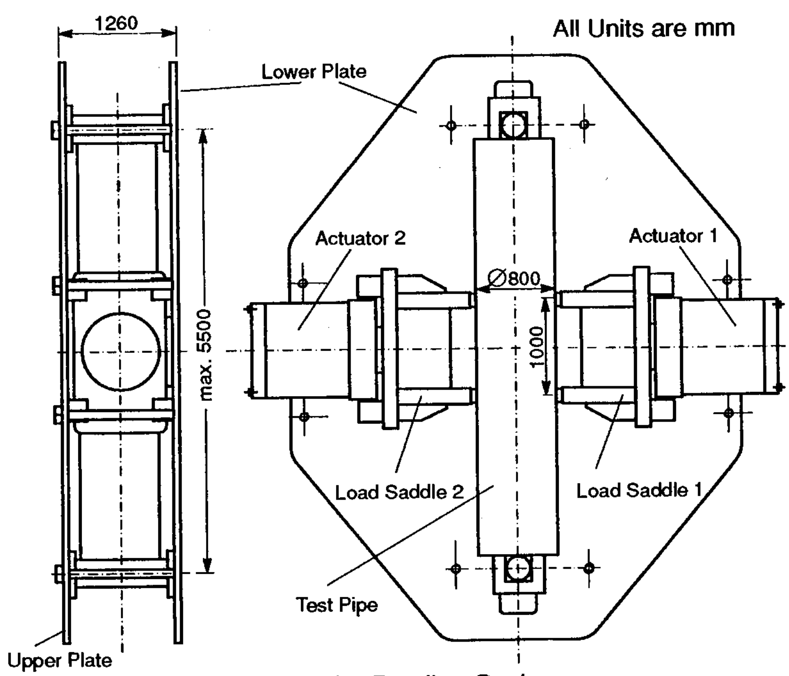


FIGURE 2: 12 MNm Four–Point Bending Device

For the fatigue bending tests with the 12 MNm bending device pipes with an inner diameter of 706 mm and a wall thickness of 47.2 mm were used. To avoid geometrically influenced effects, both the inner and outer surface had been turned by means of a lathe. Therefore the pipes showed little standard deviations in diameter (0.175 mm) and wall thickness (0.24 mm). The pipes were fabricated of two types of ferritic steel. One was grade 20 MnMoNi 5 5 (similar to steel A 533 Cl 2) with a high upper shelf impact energy of > 150 J. The pipes of this material were seamless. To produce pipes with a low upper shelf impact energy of 60 J with nearly the same strength and deformation properties a special melt with a special heat treatment was used (20 MnMoNi 5 5: Yield Strength $R_{p0.2}$ = 529 MPa, Tensile Strength R_m = 662 MPa, at 20 °C; MnMoNiV– Special melt: $R_{p0.2}$ = 529 MPa, R_m = 701 MPa; all values are mean values). The pipes of this material were made of rolled plates with the rolling direction in circumferential direction. The two longitudinally welding joints were positioned in the neutral axis during the fatigue bending tests. The pipes were weakened by artificial circumferential cracks by means of spark eroding (electric discharge machining). Growth behaviour of cracks with various lengths, depths and under various loadings (described in the test parameters, FIGURE 3) was investigated. It should be mentioned here, that in an other part of the programme, not covered in this paper, pipes with smaller dimensions are loaded by resonance excitation / 2 /, / 3 /. The test parameters for this part of the programme are also included in FIGURE 3.

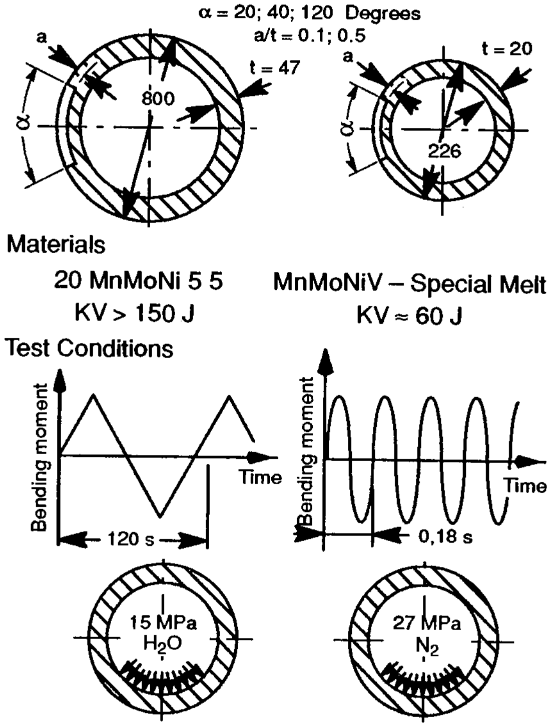


FIGURE 3: Test Parameters for Slow Cycle Fatigue Tests (Left) and Resonance Frequency Excitation (Right)

Test Results

The calculated component bending moment – equivalent strain curve / 4 / for the unweakened pipe, shown graphically in FIGURE 4, agree very well with the experimentally determined nominal equivalent strain at the maximum bending moment. The equivalent strain due to internal pressure is not taken into consideration in this plot. The equivalent strain is calculated from the principle strains using v. Mises equations. The range of bending moment, resp. the

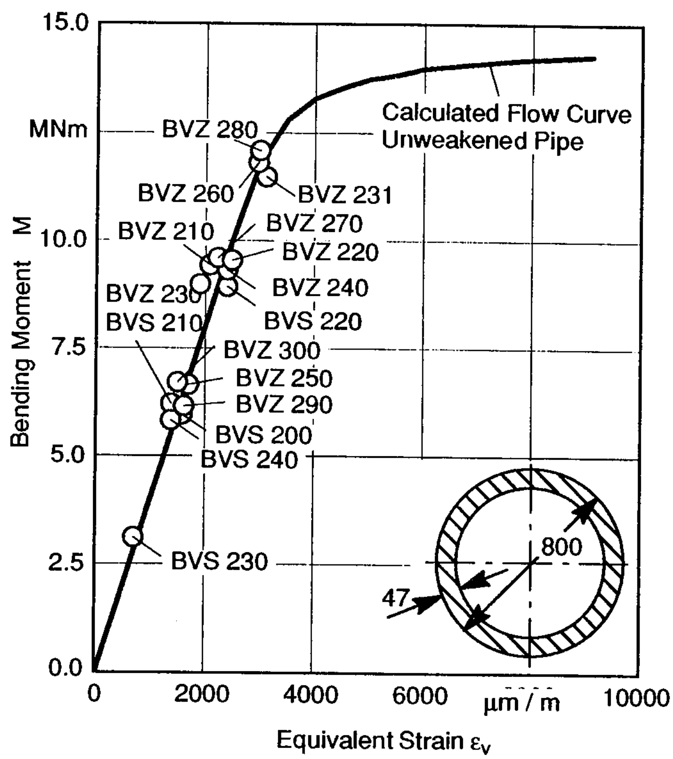


FIGURE 4: Bending Moment – Equivalent Strain Curve

range of equivalent strain was chosen with respect to the failure moment of the considered crack for a steadily increasing moment. The range of the strain $2\varepsilon_a$ in the unweakened cross section at the mostly stressed fibre serves as a basis for the assessment of the crack growth behaviour. The strain range $2\varepsilon_a$ is determined from the bending moment–equivalent strain curve, FIGURE 4, and the range of the bending moment applied in the fatigue test. The tests were performed at a temperature when the upper shelf impact energy level was reached, i. e. 20 °C for the high and 80 °C for the low toughness material. The results of 16 fatigue bending tests together with the test parameters such as crack size and shape and level of loading are listed in TABLE 1 and plotted in FIGURE 5 as a function of the number of load cycles to through cracking and equivalent strain range. Also plotted is a scatterband (load cycles to incipient crack) determined of smooth fatigue specimens of various materials which is known from published works / 4 /. The test results for smooth fatigue test specimens of the two here applied materials also lie within this scatterband.

Test	Defect depth (mm)	Defect length (mm)	Defect position (Spark eroded)	Temperature (°C)	Internal pressure (MPa)	Bending moment (MNm) Max.	Min.	Equivalent strain range (mm/m)	Load cycles N_B	Remarks
BVZ 210 ◆	4.7	292	outer + inner	20	0	+ 9.5	− 9.5	4.00 4.00	2197 2308	Outer notch: Through crack Inner notch: defect depth = 35 mm
BVZ 220 ◆			outer		15			4.80	1007	Through crack
BVZ 230 ◆							+ 0.50	1.80	8027	Test discon. defect depth = 9.8 mm
BVZ 231 ■	9.8	294				+ 11.5	+ 0.25	2.80	722	Test discon. defect depth = 12.8 mm
BVZ 240 ●	23.6	292				+ 9.5	− 9.5	4.80	32	Through crack
BVZ 250 ●						+ 6.5	− 6.5	3.16	238	
BVZ 300 ●									321	
BVZ 260 ●						+ 11.9	− 11.9	5.71	4	
BVS 200 ○				80		+ 6.0	− 6.0	2.92	70	
BVS 240 ○									60	
BVS 210 △		140							663	
BVS 220 △						+ 9.0	− 9.0	4.60	41	
BVZ 270 ▲				20		+ 9.5	− 9.5	4.80	275	
BVZ 280 ▲						+ 12.1	− 12.1	5.96	13	
BVZ 290 ▼		838				+ 6.0	− 6.0	2.92	84	
BVS 230 ▽				80		+ 3.0	− 3.0	1.45	606	
BVZ ... Material: 20 MnMoNi 5 5					BVS ... Material: MnMoNiV – Special melt					

TABLE 1: Results of Cyclic Bending Tests on Pipes with Circumferential Defects, Dimensions O.D. x t = 800 x 47 mm

The tests in which the circumferential crack in the pipe had an initial depth of 4.7 mm (a/t = 0.1) and a length of 292 mm (42 degrees) gave through crack cycle numbers which lie about one decade below the incipient crack growth curve for smooth fatigue test bars. There was also no significant difference conceming the number of load cycles to through crack starting from a crack on the outer or inner surface (test BVZ 210). On the other hand for pipes with deeper notches, e. g. a/t = 0.5, the numbers of cycles to through cracking lie up to three decades lower than the incipient crack curve for smooth fatigue test bars.

The number of load cycles for through cracking are influenced by the crack length. Comparing the results of pipes with a crack length of 40 degrees, resp. 20 degrees there is a one decade shift of the fatigue life curves. But for length more than about 40 degrees the fatigue life curve is not affected anymore (test BVZ 290 and BVS 230, crack length: 120 degrees).

The test results of BVZ 250, BVZ 270, BVS 200 and BVS 220 imply an influence of the material toughness to the number of load cycles to through cracking. Temperature effects may negligible

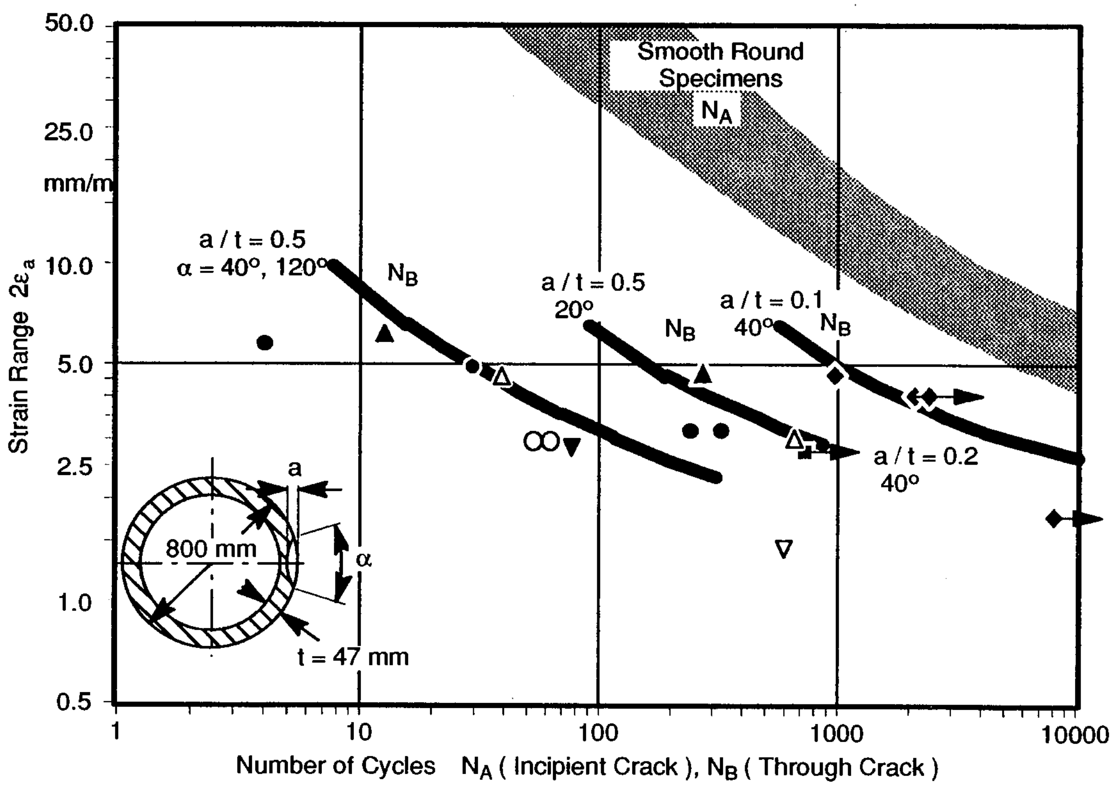


FIGURE 5: Crack Initiation and Through Crack Characteristic Lines of Notched Pipes and Smooth Round Specimens made of Materials 20 MnMoNi 5 5 and MnMoNiV – Special Melt

in this case. But it could be also an effect of the natural scattering of the test results, which we have to face in this range of low cycle fatigue tests. Further investigations should prove this special point.

Crack initiation in the starter notch was determined by means of an endoscope. It could be proved that in most tests (BVZ 270, BVZ 280, BVZ 300 etc.) the crack initiation took place during the first load cycle below the maximum bending moment. For example FIGURE 6 shows characteristic pictures of a video recording from a notch with a length of 292 mm (42 degrees) and an initial depth of 23.6 mm (a/t = 0.5). The top left picture shows the crack tip prior to initiation of the first loading of the pipe by bending moment. The top right picture represents the first visual macroscopic crack initiation. It took place at a moment of 5.3 MNm, the maximum moment was 12.1 MNm, FIGURE 6, RIGHT MIDDLE. The picture, FIGURE 6, RIGHT MIDDLE AND BOTTOM shows the cracked starter notch at the moment of the maximum bending loading.

Tests were also performed with pipes having an internal diameter of 186 mm FIGURE 3 right. In the case of equivalent strain ranges and flaw geometries (relation flaw depth to wall thickness, flaw length related to pipe circumference) the obtainable number of cycles can be compared with the results of the pipes with 706 mm inner diameter.

Summary

Low cycle fatigue life curves were experimentally determined with pipes (inner diameter: 706 mm, wall thickness: 47.2 mm) of the dimensions of main cooling pipes of a 1300 MW_e–PWR. The pipes were provided with spark–eroded cracks with a length between 20 degrees and 120 degrees and a depth between 4.7 mm (a/t = 0.1) and 23.6 mm (a/t = 0.5). The pipes were subjected to a statically internal pressure of 15 MPa and superimposed an alternating bending moment with an ampli-

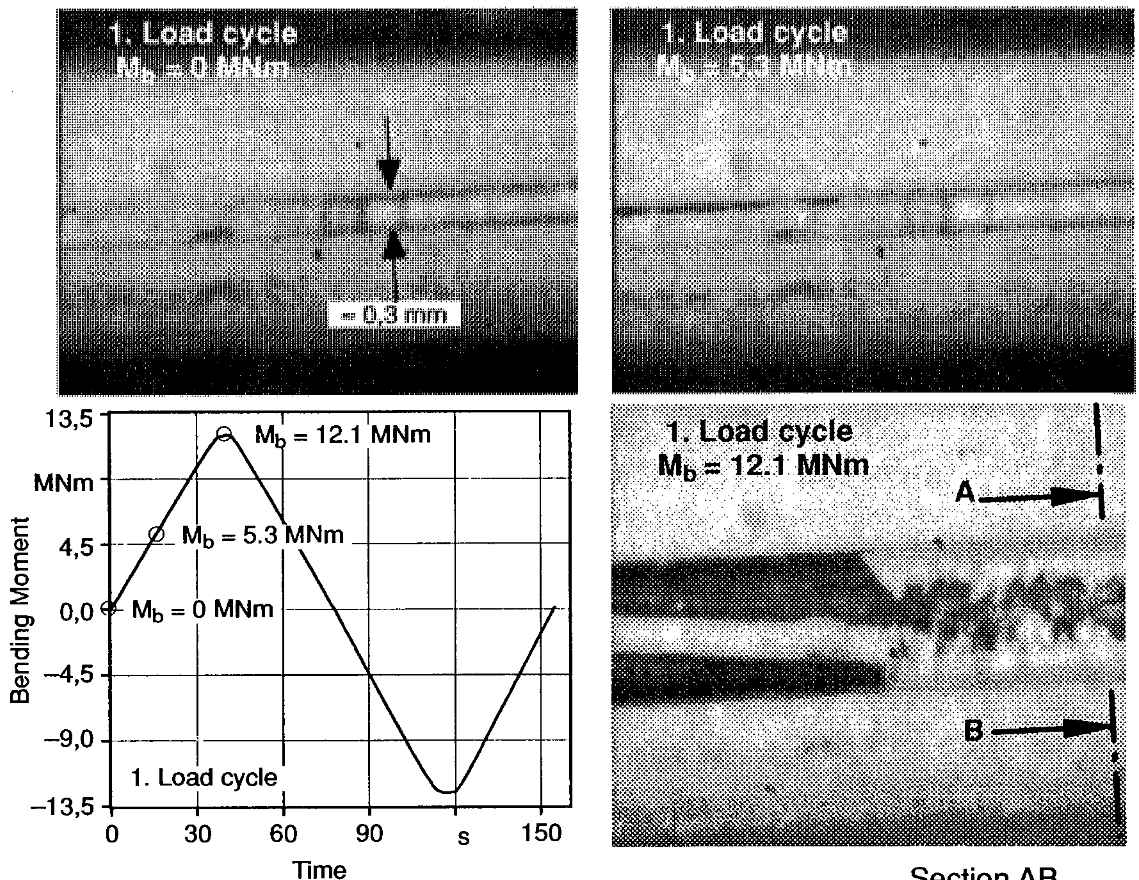
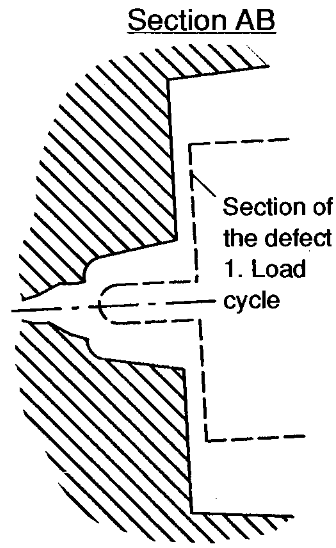


FIGURE 6: Crack Initiation Detected with an Endoscope



tude between 3 MNm and 12 MNm. To investigate the influence of material toughness the pipes were fabricated of two types of ferritic steels: one, grade 20 MnMoNi 5 5, with a high upper shelf impact energy of > 150 J and one, MnMoNiV–special melt, with a low upper shelf impact energy of about 60 J.

References

/ 1 / Sturm, D. und W. Stoppler, 1989, "Phenomenological Pipe and Vessel Burst Test, Final Report, MPA – Contract No.: 8180 00 000", MPA Stuttgart.

/ 2 / Kerkhof, K., W. Stoppler, D. Sturm and R. Zirn, 1990, "Resonant Excitation of Pipe Section", *Nuclear Engineering and Design*, Vol. 119, pp. 361–370.

/ 3 / Stoppler, W., D. Sturm, K. Hippelein und A. de Boer, 1992: "Rißwachstum und Bruchverhalten von rohrförmigen Komponenten mit Umfangsfehlern bei Innendruckbelastung und überlagertem wechselnden äußeren Biegemoment", 18. MPA–Seminar, Stuttgart.

/ 4 / Wellinger, K. und H. Dietmann, 1968, "Festigkeitsberechnung", A. Kröner Verlag Stuttgart.