Fatigue and Failure Behaviour of a Mechanically Loaded Ferritic Pipe Bend in High Temperature Water With Elevated Oxygen Content

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INTRODUCTION

The loading history of nuclear piping is composed of start up, standby, steady state and shutdown phases. The reaction of mechanical and thermal loading is represented through strain and stresses in the component. Environmental conditions, such as temperature and coolant chemistry, might have a decisive influence with regard to resistance against crack formation and crack growth /1, 2/. Stress corrosion cracking, therefore, remains a generic issue not only for the non-stabilized austenitic piping but also for respective piping made of ferritic steels.

The corrosive impact is a function of the level of loading, the temperature and, first of all, the rate of loading in terms of frequency and strain rate. The individual parameters which influence corrosion assisted crack growth are being studied in many laboratories worldwide /3, 4/. However, experiments performed in Phase II of the German HDR Safety Program have shown that the laboratory results might not represent real service conditions of the structural component. For this reason, close-to-reality experiments made on close-to-reality systems constitute a major contribution to understanding the complex interaction of the decisive stressors.

Therefore, experiments are being performed within group E21 of Phase III of the HDR Safety Program /5/, which pursue the following objectives:

- Generation of global static and/or cyclic thermal loading originating from suppressed thermal expansion and thermal striations.
- Generation of incipient cracking of a pipe bend under cyclic in-plane bending load.
- Generation of corrosion assisted crack growth under conditions of close-to-reality thermal and mechanical loadings.
- Verification of the capability to transfer analytical and numerical as well as experimental results obtained from laboratory specimens to real structural components.

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The trial delineated relates to cracks with an axial orientation at a pipe bend of DN 425 nominal width.

2 EXPERIMENTAL SETUP AND BOUNDARY CONDITIONS OF LOADING

The experiment E21.1, Figure 1, was set up in analogy with experiment T20.2 during Phase II of the HDR Safety Program /6/. The pipe bend is made of low alloy ferritic material 20 MnMoNi 5 5 similar to ASTM A508 Cl. 3. The major dimensions are: external diameter D_a = 482,2 mm, wall thickness t = 28,7 mm and a radius of curvature R = 686 mm. The bend is considered to belong to the category of thin-walled components which means a pronounced cross-sectional oval as a result of bending. At T = 240 °C the material used for the pipe bend has its yield strength at 440 N/mm^2 and an ultimate strength of 599 N/mm^2. The corresponding strain to the ultimate strength is $19,5 \cdot 10^{-2}$ m/m. At the test temperature (240 °C) the pipe bend is in the upper shelf of the charpy energy. The value of the charpy energy in the direction of dismounting TS which is relevant to crack loading is 136 J at 240 °C. The load is applied by two hydraulic cylinders in a parallel arrangement. Their movement in the test is displacement controlled. The level of loading during the first loading phase is a specified strain range of $\pm$ $2,5 \cdot 10^{-3}$ m/m (roughly corresponding to $\pm R_{p0,2}$) so that incipient cracks can be generated at the pipe bend.

The operating conditions selected are as follows: temperature T = 240 °C and internal pressure P_i = 10,6 MPa. The pressurizing agent was stagnant deionate with 8 ppm oxygen content. Temperature and pressure sensors were used to monitor the operating parameters. Besides, the cylinder force, the the vibration force and the cylinder stroke were measured. The global response of the piping system to the external load was recorded with displacement transducers, the resulting stress with strain gauges (DMS). On the outer surface of the pipe bend 54 appropriate foil strain gauges were applied to record high vibration amplitudes and high numbers of stress cycles. Acoustic emission probes which recorded the onset of cracking were attached to the pipe bend. Off the bend, temperature and moisture sensors were provided for early detection of a starting leakage. A survey of the measuring instruments used at the pipe bend is given in Figure 2.

3 SEQUENCE OF TESTING

The test was performed in two stages because the total testing time of approx. 4 weeks was rather long, Figure 3. In the first stage, the already mentioned formation of incipient cracks was studied together with the subsequent cyclic crack growth and the first phase of the so-called "corrosion cycles". During the corrosion cycles the frequency was 1 cycle per 15 minutes with a rise time of 14,5 min. The mode of loading was sawtooth-shaped cyclic loading. The R-ratio was R = 0,5 which led to a theoretical strain rate at the point of maximum loading of the bend (related to the nonweakened structural component) of $\dot{\varepsilon}$=

$1{,}5 \cdot 10^{-6}$ m/m·1/s. In the first phase of testing 315 sawtooth cycles were carried out. After 500 hours of testing in the second stage of the experiment another 1358 sawtooth-shaped cycles were applied to the pipe bend. Since at the end of these 500 hours no through-wall crack was achieved as a result of the corrosion cycles, the pipe bend was finally loaded with a monotonously rising load until failure. During this process a leak occurred in the vicinity of the bend flank. The length of the through-wall crack was 235 mm. By parallel connection of the RPV and pressurizer the system pressure could be kept constant over 5 minutes following leak occurrence. Approximately five minutes later the hydraulic system failed. Until the end of the experiment about 80 to 90 m³ of water escaped into the containment through the gap of the crack.

4 ANALYSIS OF THE FAILURE ZONE

Following the termination of the experiment, the pipe bend damaged by a longitudinal through-crack at the bend half-shell 0°-90°-180°, Figure 4, was cut off and subjected to metallographic and fractographic examination at MPA Stuttgart. An examination of the bend inner surface using magnetic particle showed pronounced crack fields on both flanks. The macroscopic crack length at the leak point was 235 mm on the external side, and approx. 640 mm on the inner side. Transverse microsections from the bend flank yielded 103 to 298 single cracks with an assumed threshold of evaluation of a = 0,1 mm, Figure 5.

The fracture surface around the primary leak point at $\alpha = 38°$, Figure 6, exhibits clear features with the individual phases in the test differing from each other. Up to approx. a/t = 0,31 the fracture surface is characterized by major indications assigned to the test phase involving bending loads opening and closing the bend (R = -1). Up to a/t = 0,36 striations can be recognized on the fracture surface. The mean crack growth rate in this area is about 1μm/cycle. The range from a/t = 0,36 to a/t = 0,74 includes crack growth during the corrosion cycles. From a/t = 0,74 to a/t = 1,0 dimples can be seen on the fracture surface which suggest stable crack growth with monotonously rising ultimate loading of the pipe bend.

5 SUMMARY

During the first experiment of the experimental group E21 - behaviour of crack growth of piping components at operating pressure and cyclic bending load in a corrosive medium - performed within phase III of the HDR Safety Program a pipe bend made of ferritic material 20 MnMoNi 5 5 was the object investigated. During the test incipient cracks were generated by cyclic bending on the inner surface around the bend flanks. In various phases of the test characterized by sinoidal and sawtooth modes of loading and different load frequencies (1 cycle per minute and 1 cycle per 15 minutes) the cracks were further extended. At the end of the phase of cyclic testing the maximum crack depth of the macrocrack embedded in a crack field was approx. 21 mm. In the final load test with monotonously rising bending moment the pipe bend failed in the form of a leak.

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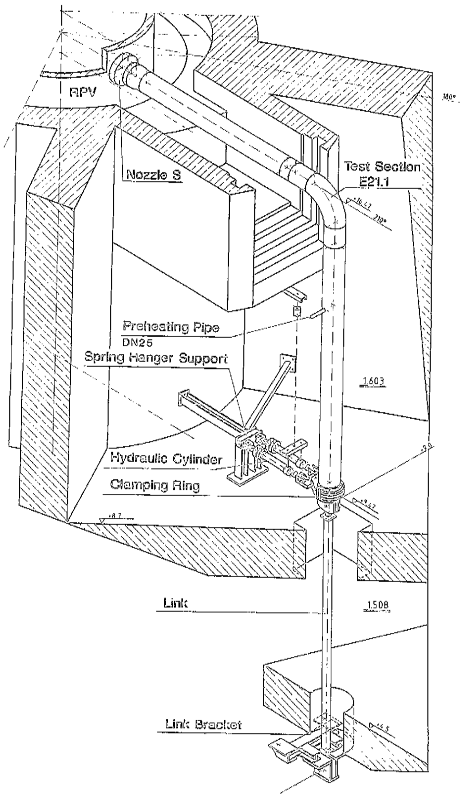


Fig. 1: Test piping E21.1

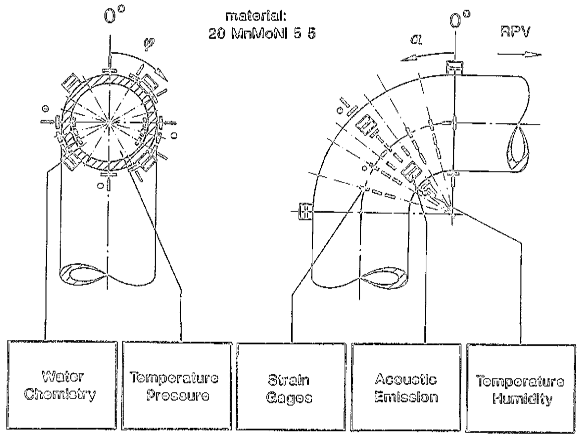
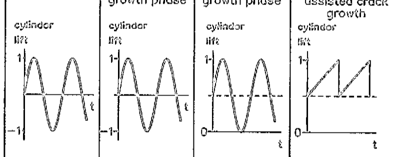


Fig. 2: On-line measurement instrumentation during test

1. Test Phase

Test	incipient crack	1. crack growth phase	2. crack growth phase	environmentally assisted crack growth
1 Test cycle at ambient temperature / 1 Test cycle at temperature 240°C				
	8500 load cycles		1500 load cycles	315 load cycles
	Sinus ν = 1/min	Sinus ν = 1/min	Sinus ν = 1/min	Sawtooth ν = 1/15 min
	$\varepsilon_n = -2{,}5..+2{,}5 \cdot 10^{-3}\,\frac{m}{m}$ R = −1	$\varepsilon_n = -2{,}5..+2{,}5 \cdot 10^{-3}\,\frac{m}{m}$ R = −1	$\varepsilon_n = 0...2{,}5 \cdot 10^{-3}\,\frac{m}{m}$ R = 0	$\varepsilon_n = 1{,}25...2{,}5 \cdot 10^{-3}\,\frac{m}{m}$ R = 0,5
	crack depth ~ 0	crack growth Δa = 8,8mm	crack growth Δa = 1,4mm	
Time	5,9 d		1,04 d	3,28 d

27 days test interuption

2. Test Phase

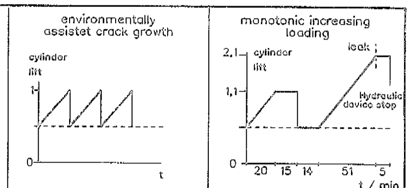
	environmentally assistet crack growth	monotonic increasing loading
1 Test cycle at ambient temperature / 1 Test cycle at temperature 240°C		
	1358 load cycles	
	Sawtooth ν = 1/15 min	
	R = 0,5	
	crack growth Δa = 10,8mm	stable crack growth, reduction area, Δa ~ 7mm
Time	14,14 d	

Fig. 3: Loading history E21.1

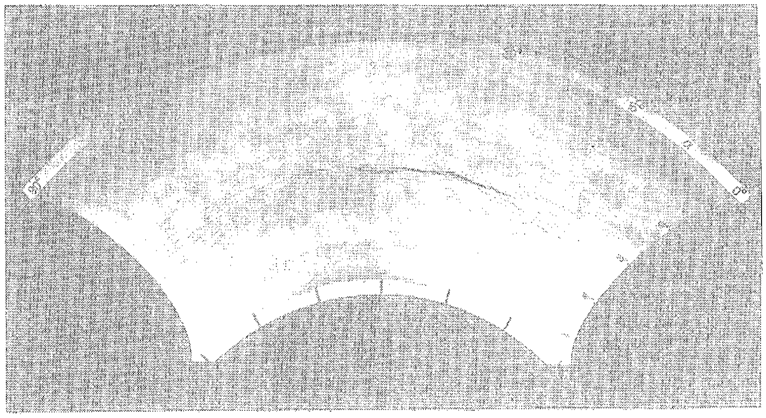


Fig. 4: Multiple crack field, Bend shell 0°-90°-180°

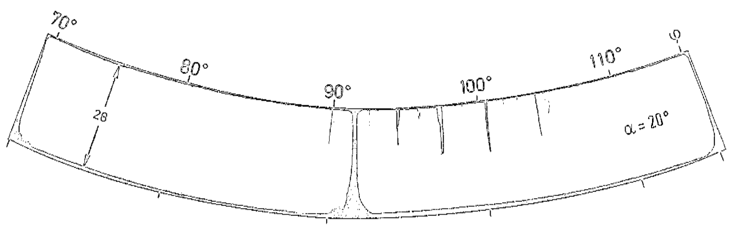


Fig. 5: Multiple crack field at position α=20°

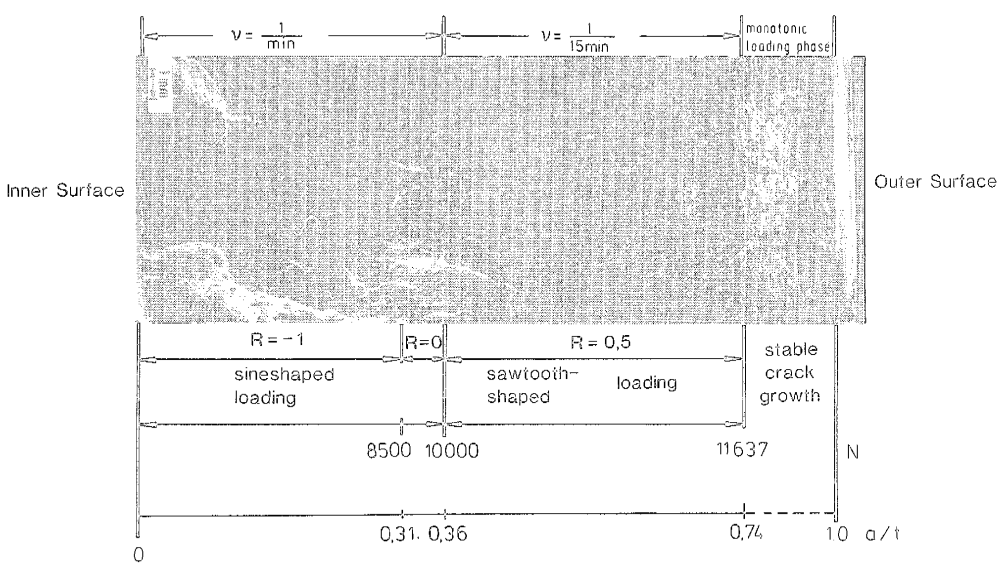


Fig. 6: Fracture surface at the leckage position