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Pressurized thermoshock tests on model pressure vessels of VVER 440 RPV steel

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ABSTRACT

The main objective of the research program was to create experimental knowledge of the crack behaviour under pressurised thermal shock (PTS) loading, as well as specific material property data for CrMoV type VVER-440 pressure vessel steel in simulated brittle condition for validation of different fracture assessment methods. The program consisted of four parts: pressure vessel tests with two model pressure vessels (cladded and non-cladded), material characterisation, computational fracture analyses and evaluation of the results.

Three PTS tests were carried out on the second, cladded model pressure vessel. The vessel material was in under-tempered condition to simulate the decrease of base material fracture toughness due to irradiation embrittlement in a real reactor pressure vessel. Both under-clad and through-clad axial cracks in the outside surface were tested. Comparison of experimental and computed results together with the fracture surface of the sub-clad crack gives consistent evidence for crack initiation and growth.

1 INTRODUCTION

Pressurised thermal shock (PTS) tests were conducted on two model pressure vessels with outer diameter of 980 mm and wall thickness of 150 mm. The first model pressure vessel with circumferential weld seam was without cladding and the second model vessel was cladded.

Seven pressurised thermoshock tests were carried out on the non-cladded model pressure vessel. After the tests, the vessel was sectioned and material characterisation as well as post-test analyses were performed. The results have been presented in the previous SMIRT conference and in [1]. This paper summarises the results for the second part of the program.

Three tests were carried out on the cladded model vessel. Before the first PTS test the vessel ruptured in the pre-test pressurisation. So the first thermoshock test was performed without pressure and the behaviour of under-clad crack was examined. After the first test, the vessel was repaired and a new surface crack was manufactured. Two other PTS tests were performed using different crack configurations.

The cladded vessel was sectioned after the three tests. The fracture surface of the under-clad crack 2, which existed through the whole testing history, revealed several initiation and arrest locations and considerable amount of crack growth.

2 MANUFACTURING AND MATERIAL

The idea was to manufacture the model vessel so that the material is in brittle condition simulating the irradiation embrittlement and the residual stress condition in the tough cladding is as close as possible to the real residual stress state. The vessel was thermally degraded by tempering at a lower temperature (610°C) than normally (~660°C). The final material state is very sensitive to the exact value of the tempering temperature, which was noticed in the case of the first model vessel [1] causing large scatterband of material properties.

The pressure vessel base material was a VVER-440 type reactor pressure vessel steel 15Kh2MFA. The austenitic cladding was welded in three layers using submerged arc welding. The welding material of the first layer was Sv-07Kh25N13 and the second and third layer Sv-08Kh19N10G2B, respectively.

Material testing has been performed only for uncladded vessel 1 material. Based on the toughness test results, "master curves" describing the temperature dependence of fracture toughness and arrest toughness have been determined. The curves corresponding confidence level of 50% and thickness of 25 mm (statistical size correction included) are for the base material [4]

$$K_{JC} = 30 + 70\, e^{0.019(T-T_0)} \ . \qquad (1)$$

The transition temperature T_0 (corresponds to fracture toughness of 100 MPa√m) of fracture toughness varied from 81 to 163°C [1], depending on the location of interest.

3 MODEL VESSEL, CRACKS AND TEST PARAMETERS

The geometry of the cladded model vessel is presented in Fig. 1. The artificial flaws were all axial flaws located at the midlength of the vessel.

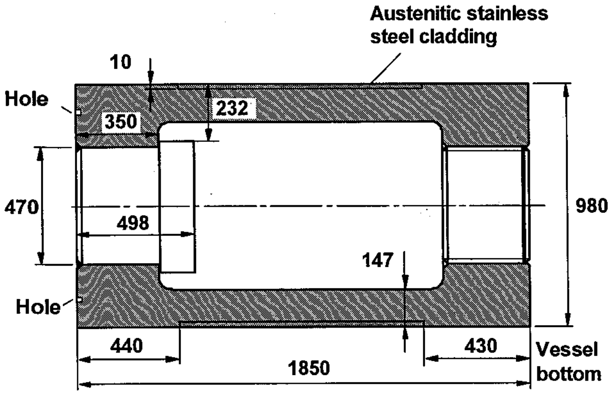

Fig. 1. The geometry of the model pressure vessel.

The testing history of the cladded model vessel comprised three tests, Table 1. The vessel had in the first test two cracks located 180° from each other. These cracks were manufactured by a special welding technique [2]. Initially both were axial under-clad cracks located at the mid-length of the vessel. Before the first test the cladding above the crack 1 was removed by grinding so that a through-clad crack was produced. The trough-clad crack initiated in the first pre-test pressurisation, however, and consequently vessel rupture occurred.

The under-clad crack (crack 2) remained through the whole testing history.

Table 1. Different tests and flaws in the case of the cladded model vessel. T_c is coolant (water) temperature and T_{ini} is initial temperature of the vessel.

Test.	1	2		3		
Pressure (bar)	0	>600		>300^a		
T_{ini} (°C)^b	295	300		300		
T_c (°C)	10	10		10		
Crack no.	2^c	2^c	3	2^c	3	5
Crack type	sub-clad	sub-clad	through-clad	sub-clad	trough-clad	trough-clad

^{a}Due to leak constant pressure was not maintained. ^{b}Approximated initial temperature at vessel midlength. ^{c}Crack 2 remained through the whole testing history.

After the first test the vessel was repaired from ruptured crack 1 area by welding and a new through-clad crack (crack 3) was manufactured 90° from the previous through-clad crack 1. Crack 3 was manufactured in a similar manner as the two previous cracks. After the repair welding of vessel and the crack 3 manufacture, a tempering heat treatment was performed.

After the second test two new through-clad cracks (crack 4 and 5) were manufactured. A trial was made to produce a fatigue crack (crack 4) by local pressurisation. However, a very deep crack (3/4 of wall thickness) was accidentally obtained. This was partly repaired by welding before test 3. Finally, crack 5 was manufactured by the special welding technique.

In the PTS tests the pressure vessel was first heated to approximately 300°C using resistors. Simultaneously the pressurisation of the vessel was realised in the closed system due to steam generation and water expansion. Just before the test the heating resistors were lifted up. The vessel was subjected to sudden flow of cold (0...20°C) tap water around the outside surface.

4 COMPUTATIONAL MODELS

The computational analyses were made using finite element method, and Abaqus 5.5 code. In the thermal analysis a densely meshed line model was used. The temperature field was assumed to be rotationally symmetric and constant along the vessel length.

The values of the heat transfer coefficient on the cooled outside surface varied from 0,5 to 40 kW/(m^2°C). Considering the formation of residual stresses in the cladding, the stress relief heat treatment of the vessel was taken into account simply by adding calculation steps corresponding the uniform heat treatment temperature (610°C) and uniform room temperature (20°C) before the actual thermal shock. The temperature field for the three-dimensional mechanical model with a crack was generated from the results of the line model.

The through-clad and under-clad cracks (cracks 1 and 2) were analysed separately by using a three-dimensional slice model, which describes actually an infinitely long crack. In the case of the under-clad crack crack growth of 31...53 mm was simulated by releasing displacement constraint boundary conditions.

A three dimensional model was created to analyse crack 3 opening (cutting of cladding) before the second test and crack 3 behaviour in the second test. The crack 3 shape was based on the NDT results. The cutting of cladding was simulated in the computation by gradually removing the displacement boundary conditions in the area of cladding.

5 RESULTS

5.1 Crack behaviour

Table 2 summarises crack behaviour during different testing phases. Two pressurisations were made before the first test. The vessel ruptured in the second pressurisation at the pressure of 259 bar. As there was a leak through crack 1, the first test was performed without pressure. In the test, the crack 1 initiated again and extended. Due to the complex crack geometry (rupture in the pre-pressurisation), an examination of the events related to crack 1 behaviour would be a difficult task.

The maximum pressure was 166 bar in the first pressurisation and 259 bar in the second pressurisation, respectively. The strains in the crack 1 plane during the first pressurisation are shown in Fig. 2. From the CMOD gage (S2, S3 and S4) values crack initiation at pressure of 95 bar is clearly visible.

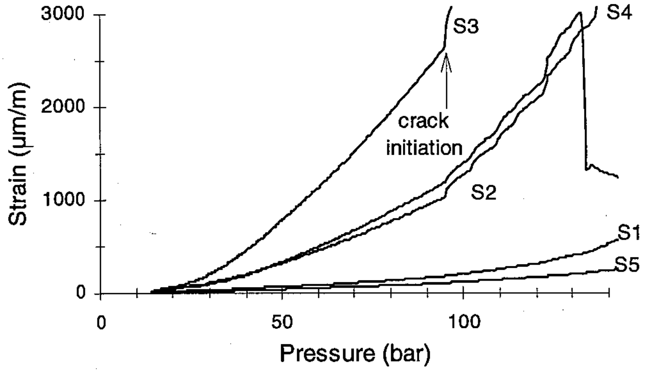

Fig. 2. Measured strains over in the surface crack (crack 1) in the first pre-pressurisation. CMOD gage S3 is located near the middle of the crack length, and CMOD gages S2 and S4 are located near the crack ends. Gages S1 and S5 are ordinary strain gages located on the vessel surface near the crack ends.

Table 2. Summary of the crack behaviour in the different phases of testing.

Event	Pre-pressurisation	Test 1	Test 2	Test 3
surface crack 1	Initiation and rupture		Repaired before test by welding	Leak in the repair weld
sub-clad crack 2	Initiation and arrest	Initiation and arrest	Initiation and arrest	Initiation and arrest
surface crack 3	-	-	No initiation	No initiation
surface crack 4	-	-	-	In manufacture uncontrolled growth, repaired by welding
surface crack 5	-	-	-	No initiation
LOADING	Pressure	Thermal shock (TS)	Pressurised TS	Pressurised TS
REMARKS	Rupture of vessel, repaired before test 2	No pressure in thermal shock	New heat treatment before test	Many cracks in pressure vessel ⇒ interaction?

The NDT measurements of cracks 1 and 2 before test and pre-pressurisation show that crack 1 has grown under the cladding in the vessel length direction in the manufacturing phase of the model vessel.

The initial and final depth of crack 2 were determined visually from the fracture surface. There is a reasonable agreement between NDT measurements and the final crack depth, Fig. 3. In Fig. 4 part of the fracture surface selected for a more detailed examination is shown. The fracture surface after initial crack reveals brittle, cleavage type morphology. Several initiation and arrest zones can be visually found from the fracture surface. This crack growth has occurred gradually during the pre-test pressurisation's.

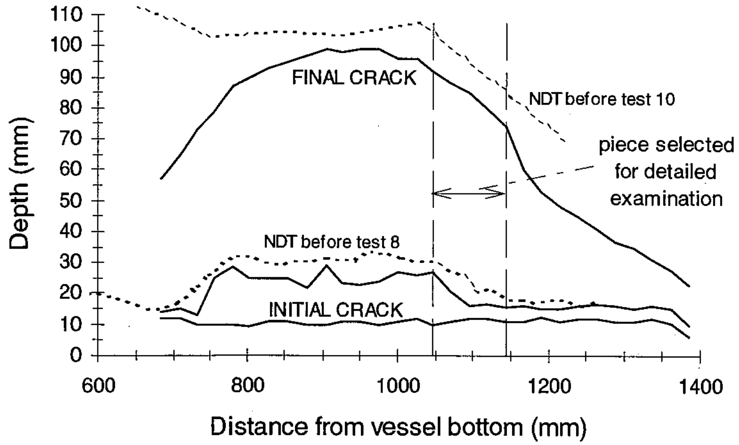

Fig. 3. Comparison of measured (NDT) and real crack geometry.

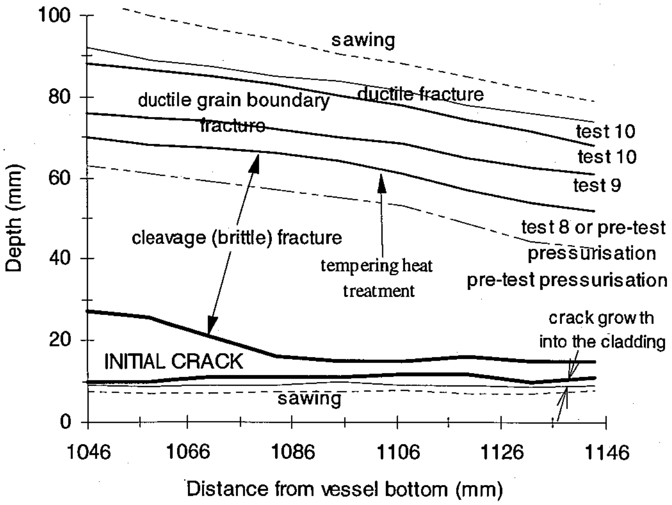

Fig. 4. Schematic presentation of a part of the sub-clad crack (crack 2) fracture surface. The location is a section of 1046...1146 mm from the vessel bottom.

After the first thermoshock test a tempering heat treatment was performed. There is a clearly visible line in the fracture surface showing crack location during tempering. The crack growth up to this line has occurred probably during the pre-test pressurisation.

In the last two PTS tests crack initiation, propagation and arrest occurred. The fracture surfaces reveals ductile intergranular fracture. This type of fracture gives explanation for the measured quite rapidly growing strains without specific jumps. The final crack extension has been ductile in the last test.

5.2 Comparison of computed and measured values

Sub-clad crack 2 initiated and extended in pre-test pressurisation. Fig. 5 compares measured and computed strain on the cladding above crack 2. Crack propagation was also roughly modelled in the later stage of computation. The computed strain at the point of strain maximum located 10 mm from the crack plane should overestimate the measured strain, because strain gage integrates the strain over its length. The computed strain shows almost linear behaviour. On the contrary the measured strain behaves nonlinearly.

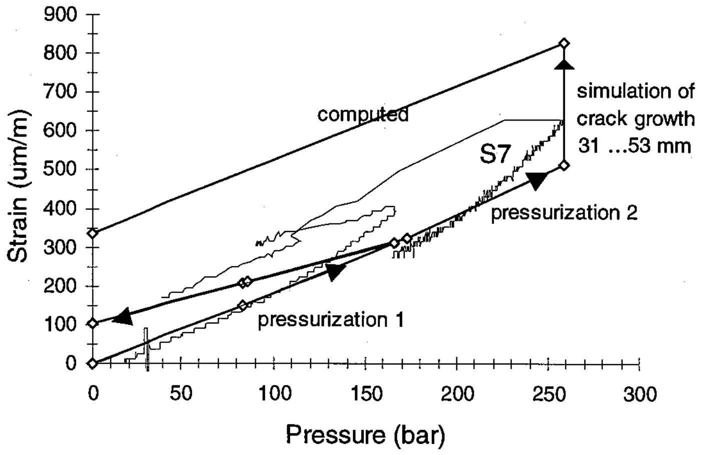

Fig. 5. Comparison of measured and computed circumferential strain (10 mm from the crack plane) in the cladding above the sub-clad crack (crack 2).

At the final time step, 402 s, cleavage crack extension (31...53 mm) was also simulated in the computation, Fig. 6. The crack growth causes an immediate jump in the computed strain value. The strain maximum occurs at a distance of 10 mm from crack centerline. There is a close correspondence between the computed and measured strain values at time values less than 50 seconds. There are no sharp changes in the measured strain curves. According to the slip line field theory, the maximum strain at the free surface should occur at an angle of 45° from the crack tip (at the distance of 10 mm from crack plane). Very similar results has also been presented by Talja [3]. The higher measured strain values reveal deeper crack than modelled in the computation.

Fig. 7 presents the computed stress intensity factor together with the fracture toughness limits of the PTS 1 base material. The whole calculation history is shown including the cooling and warming phases, pre-pressurisations and the thermoshock. Crack initiation is not predicted in the deepest point of the crack. It is, however, possible, that somewhere else in the crack front the toughness curve is exceeded. To study this a full 3D model would be needed.

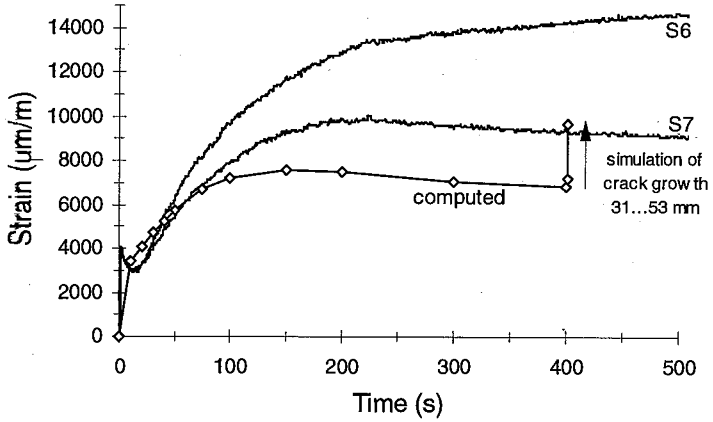

Fig. 6. The computed maximum strain above the sub-clad crack together with measured strains S6 and S7.

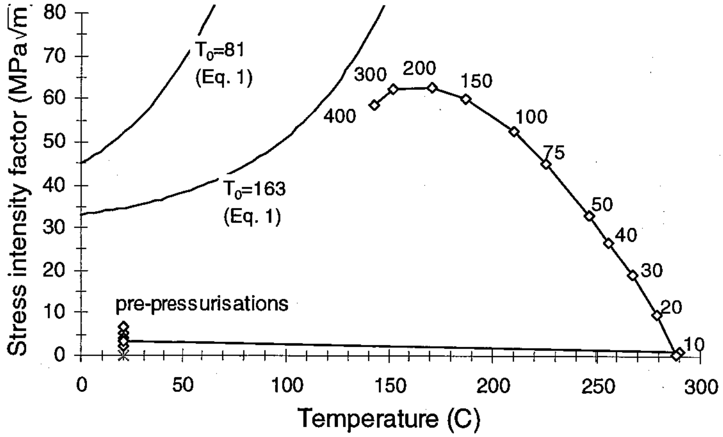

Fig. 7. The computed stress intensity factor (crack 2) during the first thermoshock test together with the fracture toughness limits of the base material. The whole calculation history is shown.

6 SUMMARY AND CONCLUSIONS

The cladded model vessel was manufactured of VVER-440 reactor pressure vessel steel. The vessel was under-tempered to simulate irradiation embrittlement. The behaviour of the vessel was studied under pressurised thermal shock (PTS) loading. Three tests were carried out on the model pressure vessel using different axial crack geometries.

Rupture of the vessel occurred through initiation and growth of the surface crack (crack 1) in pressurisation before test 2. The opening of the sub-clad crack into a surface crack already caused a rather high crack loading owing to cladding residual stresses. Thus the second pre-pressurisation caused loss of integrity (leak through crack 1).

The under-clad crack (crack 2) initiated and arrested several times in the pre-test pressurisations. Considerable amount of cleavage crack extension occurred.

The extended under-clad crack initiated and arrested in the last two tests (tests 2 and 3). Crack extension type was ductile grain boundary fracture. The last (minor) part of the crack extension in test 3 was ductile.

The real geometry of the surface crack 3 was far from ideal; several branches of crack existed and a single crack could not be identified. The crack branching prohibited crack initiation.

In the last test the possible interaction of the cracks and repaired locations may have influenced the test behaviour. The residual stress state in the cladding differs from that in the other tests.

The testing of a cladded model pressure vessel with cracks is not a simple task. Furthermore, the tests have been realised with limited instrumentation and NDT. For example, additional NDT between different stages of testing and additional strain gage measurements during testing might have helped in the result interpretation.

Material characterisation and computation of the behaviour of the extended under-clad crack in test 2 including crack initiation, propagation (ductile grain boundary fracture) and arrest will be probably performed in the near future.

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