PRESSURIZED THERMAL SHOCK TESTS WITH MODEL PRESSURE VESSELS

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ABSTRACT

From the safety point of view, a reactor pressure vessel may be exposed to the most severe loading during its operational life, when cold water is injected in emergency cooling into the vessel. The very high thermal stresses combined with the stresses due to internal pressure may cause initiation of an existing crack and its propagation into the pressure vessel wall which in the worst case leads to catastrophic failure.

In the Prometey Institute pressure vessel tests are carried out in the scope of a joint research programme between three partners: the Prometey Institute from Russia, the Imatran Voima Oy (IVO) from Finland and the Technical Research Centre of Finland (VTT). The main objective of the research programme is to increase the reliability of the reactor pressure vessel safety analysis. This is achieved by providing the material property data for the pressure vessel steel and by producing experimental knowledge of the flaw behaviour in pressurized thermal shock loading for the validation of different fracture assessment methods.

The programme is divided into three parts: pressure vessel tests, material characterization and computational fracture analyses. The testing programme comprises tests on two model pressure vessels with axial outer surface flaws. The Prometey Institute conducts the pressure vessel tests, IVO is responsible for the instrumentation and VTT performs the material characterization and the computational analyses. In this paper the experimental details and the preliminary results of the tests with the first vessel are discussed.

KEYWORDS

Fracture tests, fracture properties, pressurized thermal shock, pressure vessels, reactor vessels.

INTRODUCTION

Seven pressurized thermoshock tests were made with the first model pressure vessel (Fig. 1) using five different flaw geometries, Table 1. The initial flaws have all been shallow, outer-surface, axially oriented flaws at the midlength of the vessel, partially in the base metal and in a circumferential weld. In the first three tests the flaw was actually a blunt notch. In the following tests a sharp pre-crack was used.

The pressure vessel material is VVER 440 reactor type Russian pressure vessel steel 15X2MFA. The circumferential weld has been made by submerged arc welding using wire Sv-10XMFT and flux AH-42. The model vessel has been subjected to thermal heat treatment to simulate the radiation embrittlement of the steel: annealing 1000 °C, holding 4 hours, cooling in oil, tempering 620 °C 10 hours, cooling in air. The estimated material property values for the preliminary analyses were obtained from the Prometey Institute, Table 2.

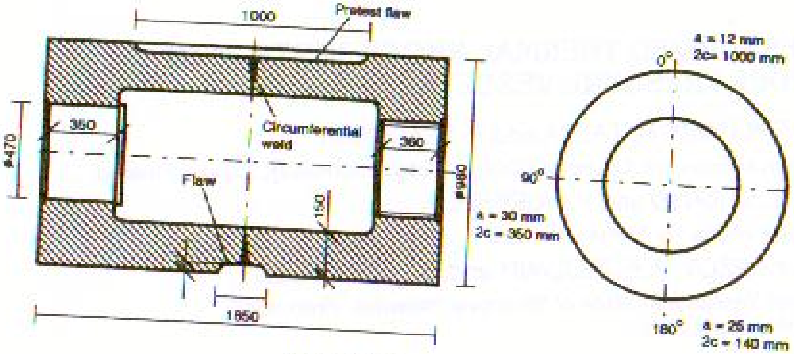

Fig. 1. The first model vessel.

Table 1. Different tests and flaw geometries. a is crack depth, 2c is crack length, p is pressure, T_c is coolant (water) temperature and T_{ini} is initial temperature.

Test nr.	1	2	3	4	5	6	7
a (mm)	12	12	25	26	30	30	↵
2c (mm)	1000	1000	250	140	350	350	↵
Flaw nr.	1	1	-	2	3	3	4
Type	notch[a]			crack[b]			
p (bar)	60	300..90[c]	335	300..40[c]	560..0[c]	600	600
T_{ini} (°C)	240	262	266	266	280	300	300
T_c (°C)	13	13	20	9	7	15	15

[a] *Mechanical notch.* [b] *Sharp crack produced by a special crack initiating welding technique (Rintamaa et al. 1988).* [c] *Due to leaks constant pressure was not maintained.* ↵ *The old (extended) flaw was used.*

TEST CONFIGURATION

The pressure vessel is first heated to approximately 300 °C using resistors. At the same time the vessel is pressurized by water. Just before the test the heating resistors are lifted up and the vessel is subjected to sudden flow of cold (0...20 °C) water around the outer surface. Due to the capacity of cooling water tanks the coolant flow is effective during the first two minutes. The test configuration is presented in Fig. 2.

MEASUREMENTS DURING THE TESTS

The measurements were performed by the Imatran Voima Oy (Nurkkala 1991a, 1991b). Temperatures were measured on the outside surface of the vessel and inside the vessel wall using thermocouples. Strains were measured on the outside surface using weldable strain gages. In addition, crack opening displacement and pressure were measured in tests 6 and 7. All the transducers were set to zero after pressurization just before the beginning of the thermal transient.

Table 2. Preliminary material property values. T is temperature, E is Young's modulus, ν is Poisson's ratio, α is thermal expansion coefficient, λ is thermal conductivity and d is thermal diffusivity.

T (C°)	20	150	300
E (GPa) (base and weld)	206.0	197.5	187.0
ν (base and weld)	0.3	0.3	0.3
Yield stress (MPa) (base/weld)	980/532	958/532	868/532
Tangential modulus (MPa) (base/weld)	664/833	383/833	406/833
α (10^{-6} 1/°C) (base and weld)	11.7	12.15	12.7
λ (W/(m°C)) (base and weld)	37	37	37
d (mm^2/s) (base and weld)	9.970	9.775	9.550

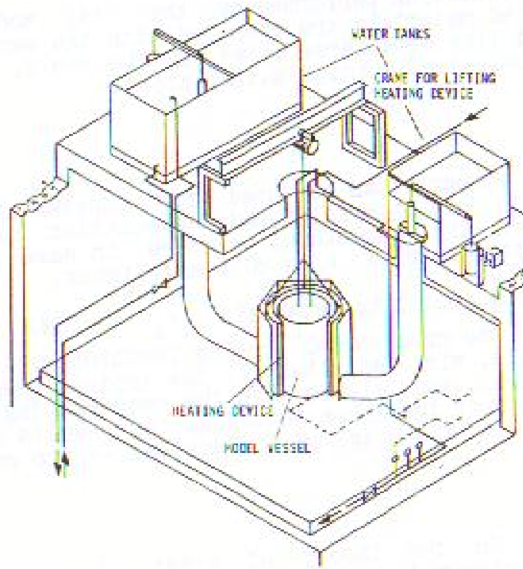

Fig. 2. The PTS test configuration.

PRELIMINARY CALCULATIONS

Preliminary numerical post-test calculations were made for studying especially the case of test 6, in which the crack initiated to grow and arrested. In the finite-element calculation the ADINA-T and ADINA codes were used. The VTTVIRT code (Talja 1987) was used to calculate J-integral values.

The temperature field was calculated using a fine meshed line model. The inside surface of the vessel was assumed to be insulated. The heat transfer between the vessel wall and the coolant was modelled for the outside surface. The heat transfer coefficient h between the cooling water and the vessel outside surface is presented in Table 3. The calculated temperatures are compared to measured ones in Fig. 3.

Table 3. The heat transfer coefficient between the cooling water and the vessel wall.

T (°C)	0	100	200	400
h (kW/(m²°C))	5	5	30	30

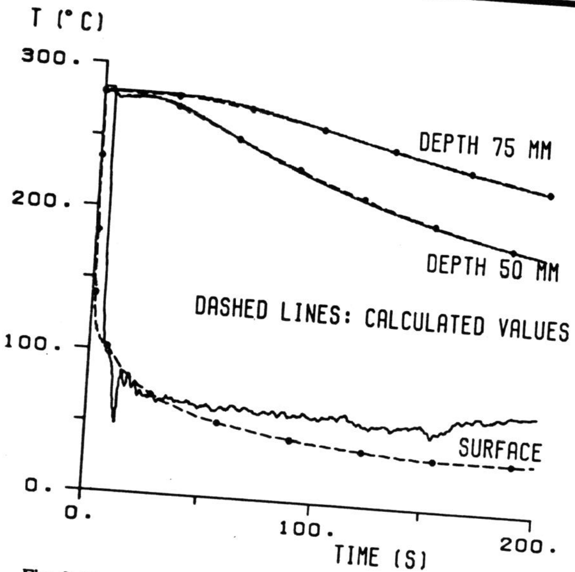

Fig. 3. Comparison of calculated temperatures to measured ones, test 6.

In the three dimensional model only the straight part of the vessel was modelled (the length of the model was 385 mm), because the end effects were small (Talja & Keinänen 1991). The axial crack was modelled having a constant depth and quarter-circular ends and located in the middle of the the vessel. Due to appropriate symmetry boundary conditions one quarter of the vessel was modelled. The axial traction due to internal pressure was modelled and the measured pressure-time-dependency was used. The three dimensional finite element model is presented in Fig. 4.

Fig. 5 compares the calculated crack opening displacement to the measured one in the middle of the crack. Fig. 6 shows the location of strain gages in test 6 and corresponding points of the calculation model. Fig. 7 compares the calculated strains to the measured ones.

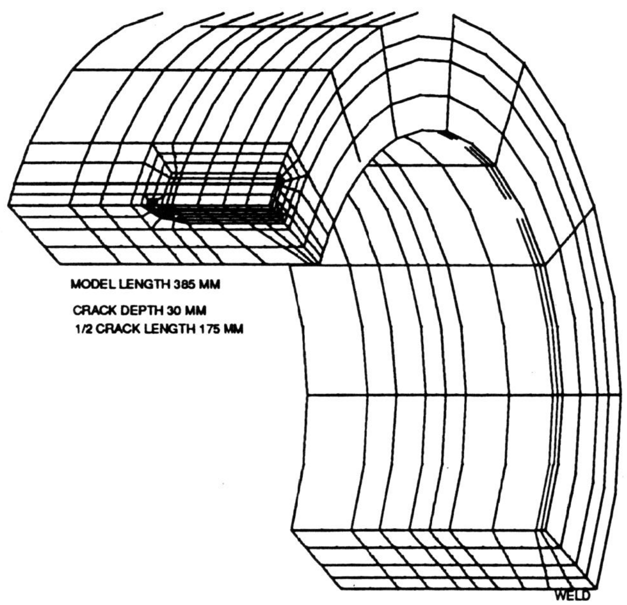

Fig. 4. The three dimensional finite element model.

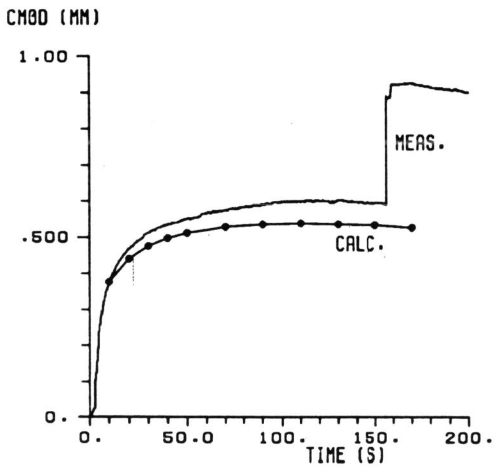

Fig. 5. Comparison of calculated and measured crack mouth opening displacement in the middle of the crack.

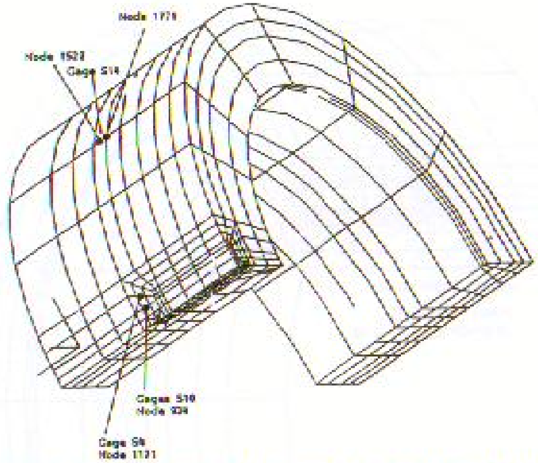

Fig. 6. Location of strain gages in test 6 and corresponding points of the calculation model.

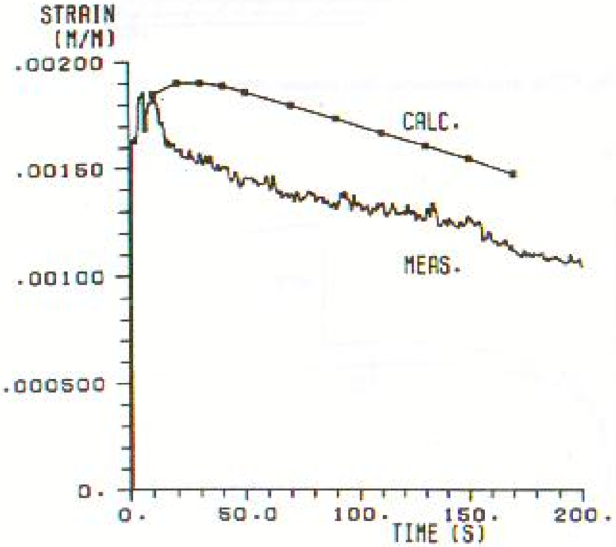

Fig. 7. Comparison of calculated and measured hoop strain far from the crack.

J-integral values were calculated using the VTTVIRT-code (Talja 1987) in which the calculation of the J-integral is done by the virtual crack extension method. The stress intensity factor was calculated assuming a plane strain condition and small scale yielding, thus

$$K = \sqrt{\frac{E}{1-\nu^2} J} \qquad (1)$$

The calculated stress intensity factors in two locations along crack front are compared to the preliminary material fracture toughness data in Fig. 8.

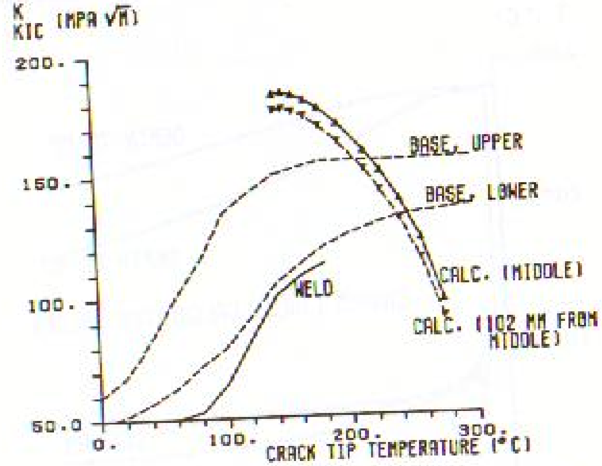

Fig. 8. Calculated stress intensity factors (tests 6) and the preliminary material fracture toughness data.

DISCUSSION

The rapid quenching of the vessel outer surface results in rather steep temperature gradients through the vessel wall and high tensile stresses in the outer portion of the wall. The reduction in temperature tends to reduce the fracture toughness of the vessel material. In addition, the simulated fast-neutron fluence (radiation embrittlement) also reduces the fracture toughness. The combined effect of a high stress intensity factor due to high stresses and low fracture toughness may result in propagation of the existing crack. However, the steep positive gradient in toughness across the wall tends to provide a mechanism for arresting the crack. The initiation of the growth of the crack may also be prevented by the warm prestressing (WPS) effect. This is due to plastic deformations and crack tip blunting "locking" the crack.

According to the measurements and other observations, no crack initiation occurred in tests 1 - 5. In tests 1, 2 and 3 the crack was actually a blunt notch. In tests 4 and 5 a sharp crack was inroduced but constant pressure was not maintained during the tests due to leaks.

According to the measured strain and crack mouth opening displacement values the crack initiated and propagated in test 6. According to the measurements crack initiation occurred at the time of round 155 s from the start of cooling. This corresponds the time of the maximum calculated stress intensity factor value. The uncertainties in the available material fracture toughness data limits further conclusions.

When the calculated temperatures and crack mouth opening displacement are compared to measured ones, a good agreement is observed. However small differences could be seen in the surface temperatures. The reason may be changes in the coolant flow rate resulting in variations in the heat transfer coefficient and uncertainties in initial and coolant temperature values.

Post-test studies will include comprehensive material property characterization as well as fractographical studies to determine the real initial crack geometry and the location and amount of crack growth. The three-dimensional thermo-elastic plastic finite element calculation will be repeated using the real crack configuration and the measured material properties. Until these studies have been completed the question regarding the accuracy of the fracture assessment methods remains open.

SUMMARY AND CONCLUSIONS

The behaviour of a model pressure vessel made of Russian reactor vessel steel 15X2MFA has been studied in a pressurized thermal shock loading. Seven PTS tests were performed with the same model pressure vessel using five different flaw geometries. According to the measurements and a post-test ultrasonic examination of the crack front, the successful sixth test led to remarkable crack extension followed by crack arrest. Due to the lack of the relevant material property data and the real flaw geometry only some preliminary conclusions can be made:

- Good agreement was observed between the calculated and measured wall temperatures and crack mouth opening of the flaw
- The initiation time corresponded the time at which the calculated stress intensity factor reached its maximum

ACKNOWLEDGEMENT

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