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CRACK INITIATION AND ARREST IN A PTS TEST FOR A MODEL PRESSURE VESSEL MADE OF VVER-440 REACTOR PRESSURE VESSEL STEEL

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ABSTRACT

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

A joint pressure vessel integrity research programme between three partners has been under way since 1990. The partners are 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 VVER-440 reactor pressure vessel safety analysis. This is achieved by producing material property data for the VVER-440 pressure vessel steel and by producing experimental knowledge of the crack behaviour in pressurized thermal shock (PTS) loading for the validation of different fracture assessment methods.

1 TEST CONFIGURATION AND MODEL PRESSURE VESSEL

The PTS tests are performed by the Prometey Institute. First the pressure vessel (Fig. 1) is heated to approximately 300 °C using resistors, and simultaneously the vessel is pressurized by water up to approximately 600 bar. Just before the test the heating resistors are lifted up. The vessel is subjected to sudden flow of cold (20 °C) tap 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.

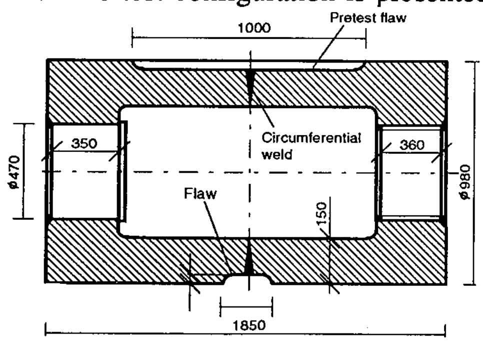
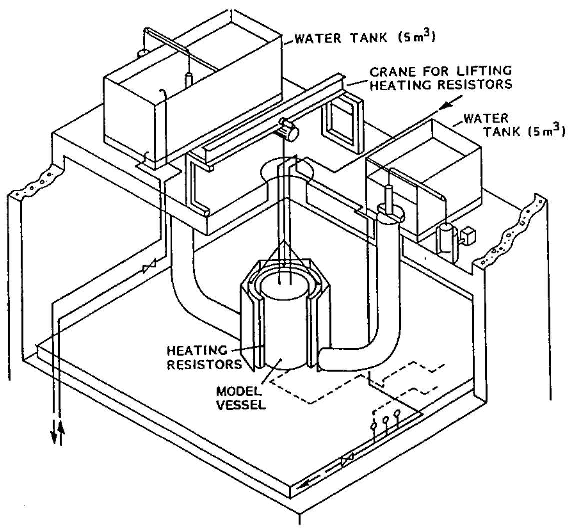


Fig. 1. The model pressure vessel.



PTS TEST FACILITY AT THE PROMETEY INSTITUTE

Fig. 2. The PTS test configuration.

The pressure vessel material is VVER-440 type reactor pressure vessel steel 15H2MFA. The circumferential weld has been made by submerged arc welding using wire Sv-10HMFT and flux AH-42. The 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 thermal material property values for the analyses were provided by the Prometey Institute, Table 1. The measured stress-strain curves for both base and weld material are presented in Fig. 3. The material fracture toughness was determined utilizing the maximum load or the load at 'pop-in' during J-R testing (Keinänen et al. 1993). The transition curves are of the form (Wallin 1992)

$$K = 20 + (11 + 77\, e^{0.019(T-T_0)}) \left(\log\frac{1}{1-p} \right)^{\frac{1}{4}} , \qquad (1)$$

in which p is fracture probability, T is temperature and T_0 is the temperature where fracture toughness has a value of 100 MPA√m. In this case T_0 is 152 °C for base material and 50 °C for weld material.

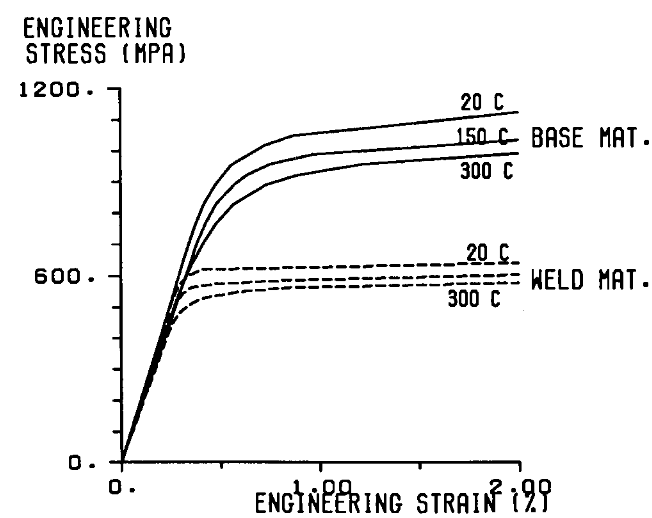


Fig. 3. Stress-strain curves for the base and weld materials.

Table 1. Thermal material property values. T is temperature, α is thermal expansion coefficient, λ is thermal conductivity and d is thermal diffusivity.

T (C°)	20	150	300
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

The initial flaw was a shallow, outer-surface, axially oriented flaw at the midlength of the vessel, partially in the base metal and in a circumferential weld. The sharp crack was manufactured by filling the grinded notch by weld deposites which produced a cold crack in the middle of the weld.

The measurements during the test were performed by Imatran Voima Oy. 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, the crack opening displacement and the internal pressure were measured.

2 FLAW BEHAVIOUR DURING THE TEST

According to the measured strain and crack mouth opening displacement values the crack initiated and propagated in the test. The crack initiation and arrest occurred at the time of round 157 second from the start of cooling. The experiment was later continued with the propagated crack. In the continued test no observations of crack initiation could be done on the basis of the CMOD measurements.

On the basis of the macroscopic examination of the fracture surface following conclusions can be made:

- The initial depth of the crack was approximately 30-40 mm in the middle length of the crack. The initial crack length was 350 mm.
- The crack initiated and arrested during the test. The fracture surface revealed brittle and brittle/ductile crack growth morphology.
- Considerable amount of crack propagation was found in both ends of the crack ('tunneling').
- The crack has grown mainly in the base material.

3 COMPUTATIONAL ASSESSMENTS

Numerical post-test calculations were made for studying the crack initiation and arrest. 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 applying the virtual crack extension method. The stress intensity factor was calculated assuming the plane strain condition and small scale yielding.

The temperature field was calculated using a fine meshed line model. The heat transfer coefficient h between the cooling water and the vessel outside surface is presented in Table 2. These values were determined on the basis of pre-test experiments (Prometey) and the measured surface temperatures. The values are consistent with those presented in literature (e.g. Kordisch et al. 1990). The calculated temperatures are compared to measured ones in Fig. 4.

Table 2. The heat transfer coefficient between the cooling water and the vessel wall.

T (°C)	40	80	90	95	100	105	110	300
h (kW/(m^{2}°C))	2.5	3.3	6.0	8.0	15.0	20.0	30.0	40.0

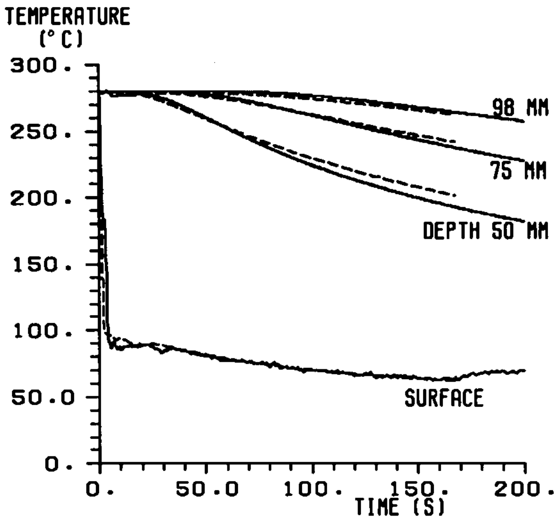


Fig. 4. Comparison of calculated temperatures (dashed lines) to measured values (solid lines).

The three dimensional finite element model for the crack initiation study is presented in Fig. 5. Only the straight part of the vessel was modelled (length of the model was 385 mm), because the end effects were small (Talja & Keinänen 1991). The measured pressure-time-dependency was used and the axial traction due to internal pressure was modelled.

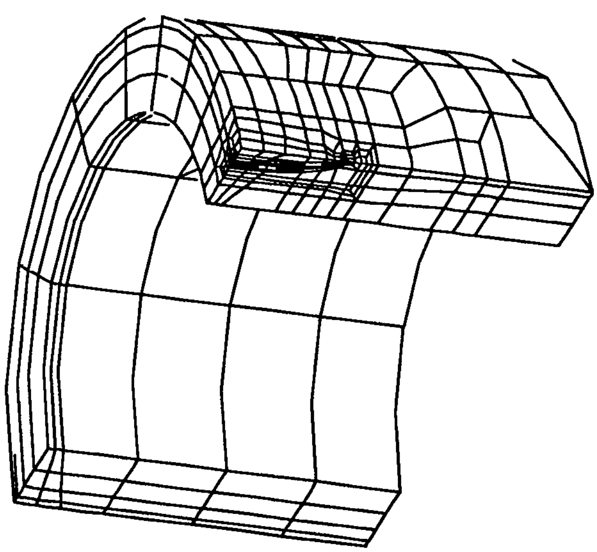


Fig. 5. The three-dimensional model for the crack initiation study.

In the base material near the crack end the calculated stress intensity factor exceeds the material fracture toughness approximately at a time of 30 second from the beginning of the transient (calculated stress intensity factor 115 MPA√m, temperature 161°C, measured toughness 113 MPA√m). The calculated stress intensity factor reaches its maximum in the base material at a time of 155 second (165 MPA√m). In the weld material the calculated stress intensity factor values are lower than the measured touhgness during the whole period.
In Fig. 6 the modelled crack geometries are compared with the real crack shapes defined from the fracture surface. The crack arrest analysis has not yet completed.

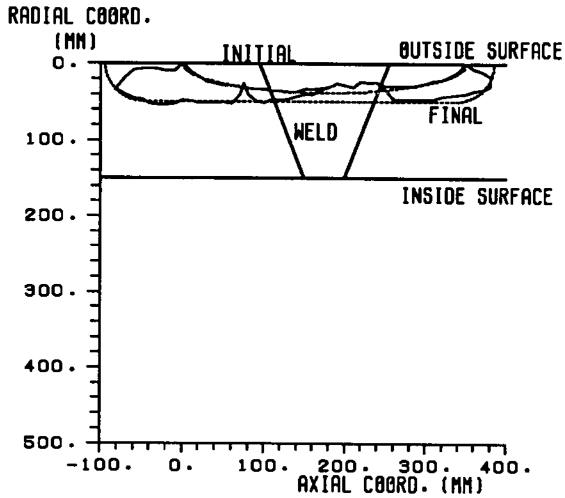


Fig. 6. Comparison of modelled crack geometries to the real ones.

4 DISCUSSION AND FUTURE PLANS

The behaviour of a model pressure vessel made of VVER-440 reactor pressure vessel steel 15X2MFA has been studied in a pressurized thermal shock loading. The test led to remarkable crack extension followed by crack arrest. Following conclusions can be made on the basis of the results:

- The weld material was tougher than the base material. This is not the situation in VVER-440 reactor pressure vessels.
- The test lead to crack initiation and extension in the base material. Main crack extension occurred near crack ends.
- Good agreement was observed between the calculated and measured temperatures, strains and crack mouth opening displacements.
- The crack initiation corresponded the point at which the calculated stress intensity factor reached its maximum.
- The most remarkable crack extension occurred in the crack front portion where the calculated stress intensity factor first reached the critical value.
- The actual initial temperature was not uniform along the vessel length. Thus there is a need to model the whole vessel in order to simulate this effect.

The experimental programme is continued with a PTS-test using a cladded model vessel. The results of the test and analyses will be available by the end of 1993.

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