THERMAL SHOCK EXPERIMENTS ON CRACKED CLADDED PLATES

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To investigate the effect of the cladding on the behaviour of postulated near surface cracks in the wall of a nuclear pressure vessel under thermal shock transients, two model experiments on cladded plates with artificially introduced cracks were performed. A comparison of observed crack initiation and arrest events for subclad and for surface cracks with results of analytical and FE analyses shows good agreement.

INTRODUCTION

To investigate the effect of the cladding on the behaviour of postulated cracks in circumferential welds of a nuclear pressure vessel model experiments on cladded plates with cracks were performed. The vessel loading by emergency core cooling was simulated by liquid nitrogen cooling and bending. The real material conditions being characterized by an irradiation embrittlement of the welds were simulated by a corresponding temperature shift.

After material characterization pre-test calculations for the assessment of the crack initiation have been done using the same analytical methods as in actual safety analyses (Blauel et al (1)).

In a 4-point bending set-up the central part of the cladded surface of the specimen was cooled for several minutes before the load was increased to initiate crack growth. After an initiation and arrest event the specimen was separated in two parts by fatigue loading to allow fracture surface evaluation.

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The experimental findings have been analysed and compared with analytical and complete 3D finite element (FE) calculations.

MATERIALS AND SPECIMENS

A large plate (1400 x 16 00 x 80 mm^3) with a longitudinal SAW butt weld manufactured from RPV steel 20 MnMoNi 55 (corresponding to ASTM A533B) was cut in 400 mm wide strips (Fig. 1), two of which were used for the model experiments. In these two plates cracks were introduced in the weld region using spark erosion and fatigue loading before and after applying the 2 layer band cladding, respectively. Fig. 1 shows the locations and geometry of the cracks.

Tensile properties of the ferritic parent and weld materials and of the austenitic cladding were measured a as function of temperature. At RT the yield stress is 529 MPa and 340 MPa for weld and austenite, respectively. At -80° C values of 615 MPa and 390 MPa have been measured. From the C_v-T curves of the ferritic weld a transition temperature T_{68J} = -50 °C was obtained. The temperature T_{68J} -33 °C is used instead of RT_{NDT} (Pellini tests

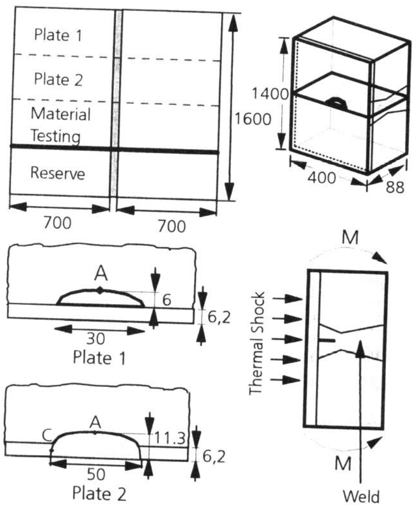

Figure 1 Geometry and loading of cracked plates.

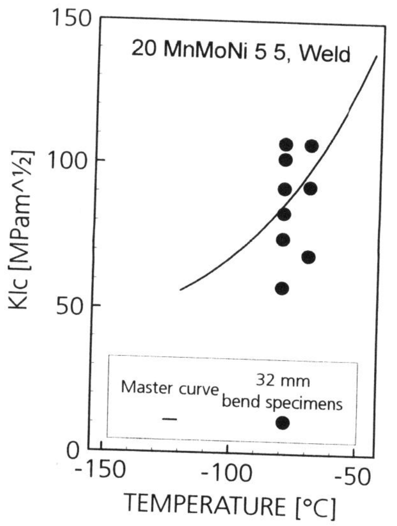

Figure 2 Fracture toughness and „master curve".

have not been done) to define the ASME reference fracture toughness K_{Ic} and K_{Ia}. The real fracture toughness of the weld was measured at -70 and -80° C on bend specimens with a thickness of 32 mm. The results are shown together with a „master curve" fit according to Wallin (2) for 32 mm crack front length. Based on an analysis by Wallin (3) for a similar material the crack arrest toughness is assumed to be shifted by 27 °C.

EXPERIMENTS

The precracked plates were instrumented with strain gauges and thermocouples on both surfaces. In a 4-point bending set-up an area of 65 x 225 mm^2 over the crack location was cooled by liquid nitrogen for about 12 minutes. Then the load was slowly increased.

Plate 1 with the subclad crack had to be loaded far beyond the linear part of the load-displacement curve until small crack extensions have been indicated by the strain gauges. After some additional load increase the experiment was terminated and the fracture surface was open up by fatigue. Fig. 3 shows crack blunting at the deepest part of the crack front but no crack extension into the ferritic material. There is some crack growth into the first layer of the cladding which obviously has been damaged (dark areas)

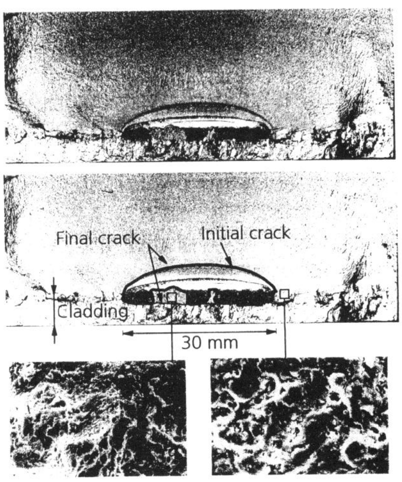

Figure 3 Fracture surface of plate 1.

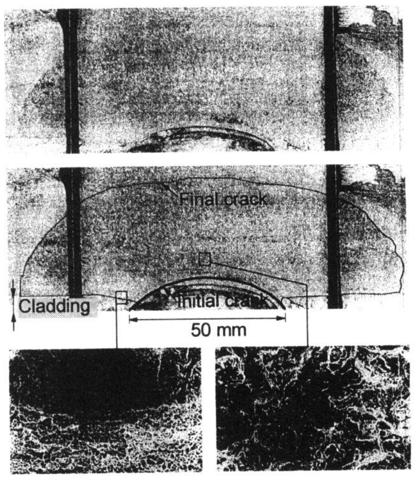

Figure 4 Fracture surface of plate 2.

already during the cladding process. This crack extension is the result of the locally high loading of the crack front due to irregular shape.

For plate 2 with through the cladding crack a major event was indicated in the linear part of the load-displacement curve. The experiment was terminated at the displacement of 0.6 mm. The fracture surface in Fig. 4 shows an extended brittle (see quasi cleavage facets in the right partial picture) crack jump into the depth and length direction in ferrite, while in the cladding no crack extension in the length direction was observed („tunnelling" under the cladding). The main crack has also entered the cladding from the back side, but was stopped by the high toughness of the ductile cladding (Fig. 4, bottom, left).

CALCULATIONS

FE calculations of temperature transients simulating a preliminary thermal shock experiments on specimens instrumented for the measurement of temperature through the wall thickness were done to determine thermal properties of the ferritic and austenitic materials. On this basis temperature distributions in plates 1 and 2 were calculated. Stresses were determined both in linear-elastic and elastic-plastic FE analyses. As an example temperature and stress distributions in the plane of the crack of plate 2 (half plate) for the observed time of the crack jump are shown in Fig. 5 together with contours of the initial and the final crack.

The stress intensity factor K for cracks which are partially located in a plastically deformed region is calculated as proposed in reference (4) $K=\sqrt{K_{LE}K_{EP}}$, where K_{LE} and K_{EP} are SIFs based on stresses from linear-elastic and elastic-plastic FE analyses, respectively. For surface cracks the weight function method (Shen, Glinka (5)), for subclad crack a modified weight function method (Hodulak and Siegele (6)) was used. Figures 6 a 7 show good agreement of SIF values calculated analytically and by the FE method, with the exception of evaluations for plate 2 under high loads, where the entire crack is in the plastically deformed surface layer and the SIF concept is no longer valid.

For plate 1 (Fig. 6) the analytically calculated SIF value for the deepest part of the subclad crack reaches the middle of the K_{Ic} scatter band at the end of the experiment, but it is out of the validity range of the linear-elastic fracture mechanics. Despite of the very high K_J value from the FE analysis there was only crack blunting (Figure 3). For plate 2 (Fig. 7) the SIF value at the crack jump lies within the K_{Ic} scatter band and is much higher than the ASME predicted K_{Ic}.

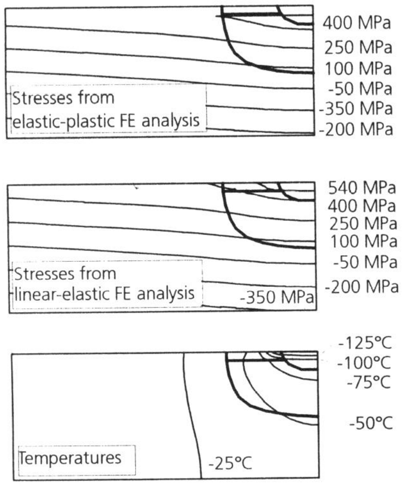

Figure 5 Temperature, stresses, and cracks in plate 2 at load F = 755 kN.

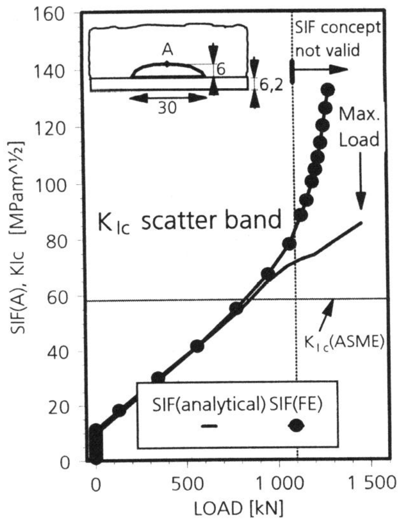

Figure 6 SIF for crack depth direction in plate 1, and fracture toughness.

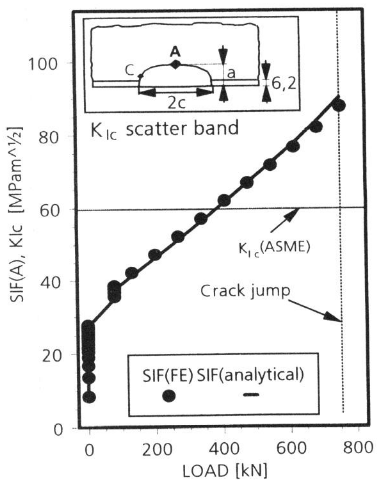

Figure 7 SIF for crack depth direction in plate 2, and fracture toughness.

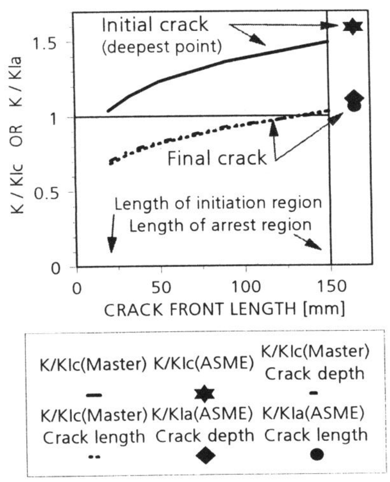

Figure 8 Crack initiation and arrest. Calculations and experiment.

Using the „master curve" approach to estimate the fracture toughness and the quantification of the influence of the crack front length on the probability of fracture (Wallin (2)) a very good agreement between calculated and observed crack initiation and arrest conditions in plate 2 is obtained (Figure 8). Following the experimental findings in Fig. 4 it is assumed that initiation occurred over a limited part of the initial crack front (possibly 20 mm) only, but equal arrest conditions were found for the whole arrest crack front (ca 150 mm). For these crack front lengths both K/K_{Ic} and K/K_a approach the value of 1.

CONCLUSIONS

1. The evaluation of the behaviour of cracks in cladded components under thermal shocks using FE temperature and stress analyses and analytical calculation of SIFs can be done with sufficient accuracy.

2. Using a crack front length dependent fracture toughness concept improves the agreement of calculated and observed initiation and arrest conditions.

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