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Research of stainless steel cladding on crack initiation

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ABSTRACT: Tests with cladded beams were performed on VVER-440 reactor pressure vessel steel at 20°C. The base material of these beams was artificially embrittled after quenching by annealing the beams at 620°C for four hours. This paper summarizes the most interesting test and calculation results of seven destructive bending tests.

1. INTRODUCTION

The effect of cladding on the initiation of a crack has been studied jointly by IVO International and the Central Research Institute of Structural Materials Prometey, St. Petersburg. Tests with three point bending specimens have been carried out during this program. The dimensions of these specimens were 450x100x50 mm (length x thickness x width) and they were cladded on one 50 mm wide side. A crack was introduced on the same side in the mid-length position at each specimen. Manufacturing and heat treatments of these specimens have been performed at PROMETEY.

2. PREPARATION OF BENDING SPECIMENS

The specimens were made of 15X2MΦA steel having three layers of stainless steel cladding corresponding to normal cladding production. The chemical composition of steel 15X2MΦA measured (Rajamäki 1994) from four beams was analogous to that of VVER-440 reactor pressure vessels. The embrittlement treatment was performed after quenching from 1000°C for two hours in oil followed by a low temperature annealing of the beams at 620°C for four hours.

For calculational simulations, the stress-strain curves of 15X2MΦA and cladding were measured at 20, 300, 475 and 620°C after successful beam tests. The nonlinear behaviour of base metal and cladding below the yield limit (0.2%) was also recorded and taken into account in the calculations (Rajamäki 1994).

3. TEST RESULTS OF CLADDED BEAMS

After annealing the beams were fractured by three point bending load at 20°C. All the beams designated PTS32, 33, 44, 36, 37, 38 and PTS39 broke in two parts with a brittle mode in base metal. The test results are given in Table 1. PTS32 and 33 are single-edge notch specimens with surface cracks, PTS44 is a subsurface crack, the crack depth was constant in these three beams through the width of the specimens. PTS36, 37, 38 and PTS39 are semi-elliptical surface cracks, and the crack front penetrates the cladding/base metal interface.

Table 1. Test results of cladded beams. 2c = crack length, a = crack depth (=2a for subsurface crack), t = thickness of cladding and F = failure load.

BEAM	2c, mm	a, mm	t, mm	F, kN
PTS32		17.0	8.5	376
PTS33		16.0	10.0	202
PTS44		10.6	13.7	647
PTS36	44.5	16.4	7.2	371
PTS37	45.3	16.2	7.1	546
PTS38	33.4	12.1	10.7	432
PTS39	33.4	12.0	7.4	300

4. FEM CALCULATIONS FOR THE TESTED BEAMS

Cooling from 620°C to 20°C and mechanical bending up to beam fracture were simulated using the BERSAFE finite element system. Stress-free temperature was 620°C. The finite element meshes for PTS32, 33 and 44 are presented in Fig. 1. The cladding thickness was not constant in PTS44; it was 13.7 mm within the distance of 27 mm from the crack plane and 8.5 mm outside this region. Very small crack tip elements, 0.01 mm, were used in the meshes of PTS32 and PTS33. The meshes of Fig.1 are engineering plane strain models. The appropriateness of these models was confirmed by a full three-dimensional analysis.

Three-dimensional finite element meshes for PTS36, 37 and 39 are presented in Fig.2. Node 77 is the deepest point of the crack, node 1272 is at a distance of 1.0 mm from the cladding/base metal interface and node 733 is at a distance of 3.1 mm from this interface(PTS36,37). According to Table 1, the crack dimensions of PTS36 and 37 are almost identical. The same mesh was therefore used for both beams. For PTS39 this mesh was modified. Crack tip element length normal to the crack front was 0.1 mm. The mesh for PTS38 is shown in Fig.3. The J-integrals for PTS32 and 44 after cooling and as a function of the mechanical load are given in Fig.4. The J integrals of PTS36 and 37 are given in Fig.5 and those of PTS38 in Fig.6. The calculated J-integrals for PTS36 at nodes 77, 733, 1272 and 2173 with fracture load were equal to 25.8, 37.5, 41.3 and 43.9 N/mm, respectively.

5. SHALLOW-CRACK EFFECT

The shallow-crack effect was studied by comparing crack opening-mode stresses (Dodds) of cladded beams with those of a reference beam which had the same main dimensions and base metal material properties as the cladded beams, but the surface crack depth was 50 mm.

The shallow-crack effect in PTS32 was studied in detail. In order to achieve the same opening-mode stress as in PTS32, this reference beam had to be loaded so that the J integral at the 50 mm deep crack was 77 N/mm. The J integral in PTS32 with fracture load was 58 J/mm. According to this result, the K(J) values of PTS32 should be increased by a factor of $\sqrt{(77/58)}$ = 1.15. Normally this factor is <1.0 for shallow cracks. Two factors may have an effect on this reverse result, very high yield strength (Rajamäki) of the base metal, 935 MPa, and high residual stresses in the cladding layer ~400 MPa.

On the basis of this tentative study, the calculated K(J) values of PTS32, 33 and 44 were not corrected with the shallow-crack effect.

In case of semi-elliptical surface cracks, the shallow-crack effect was taken into account. The K(J) values of PTS36 with fracture load at nodes 733 and 1272 were equal to 90.8 and 95.3 MPa$\sqrt{m}$, respectively (section 4, $K(J) = \sqrt{\{0.001\} x \sqrt{\{Jx200000\}/\{1-\upsilon^2\}}}$). In order to achieve the opening-mode stress of node 733, the reference beam had to be loaded so that the J-integral was equal to 36.4 N/mm. The corrected K(J) at 733 was $\sqrt{(36.4/37.5)}$x90.8 = 89.5 MPa$\sqrt{m}$. Similar comparison for node 1272 was performed and the corrected K(J) for it was $\sqrt{(29.5/41.3)}$x95.3 = 80.5 MPa$\sqrt{m}$.

Analogous corrections were also performed for PTS37, 38 and 39, the most critical nodes, shallow crack factors and modified K(J) values are presented in table 2.

Table 2. Calculation results for cladded beams. K(J) in MPa√m.

BEAM	PTS32	PTS33	PTS44	PTS36	PTS37	PTS38	PTS39
NODE				733	733	72	733
FACTOR				0.99	0.83	1.0	1.1
K(J)	112.9	79.8	117.8	89.5	102.8	80.5	67.9

6. FRACTURE TOUGHNESS OF BASE MATERIAL IN TESTED BEAMS

One or two CT specimens were cut from the tested beams. 25 mm thick specimens were cut from PTS32, 33 and 44, and 40 mm thick from PTS36, 37, 38 and 39. The measured K_{IC} values are presented in the upper row of table 3. These values are much lower than the calculated K(J) values. Irwin´s plastic-zone correction was also made for the measured K_{IC} values (middle row), but this did not decrease the difference. The most important reason for this difference is a toughness gradient in the base metal. This gradient was discovered on the basis of charpy tests, Fig.7.

Table 3. Measured (upper row), Irwin´s plastic-zone corrected (middle row) and toughness modified (lower row) K_{IC} values in MPa√m.

PTS 32		PTS 33		PTS 44		PTS 36		PTS 37		38	39
94	47	74	84	74	92	80	56	72	59	58	51
96	47	75	86	75	94	81	56	72	59	58	51
116	57	90	103	90	113	98	68	87	71	70	61

At a distance of 5.5 mm from cladding interface, the average value of charpy results is 37.7 J, and at a distance of 37.5 mm it is 26 J. The crack tip position in cladded beams varied from 1.4 to 10.6 mm from this interface, while the crack tip positions of CT specimens were 40-50 mm from the interface. The results presented in the middle row of table 3 were therefore modified by a factor $\sqrt{(37.7/26)}$, and the modified K_{IC} results are presented in the lower row. These modified K_{IC} values and the calculated K(J) values are presented in Fig.8. The results are presented in an ascending sequence regarding the K(J) values. The range of the calculated values is close to the scatter of the measured material properties.

7. CONCLUSIONS

The yield limit of the base material was very high after embrittlement heat treatment. This, together with the lower yield limit of the cladding, complicates calculational analyses. Toughness gradient close to base metal/cladding-interface and large scatter in toughness values also make the assessment of results difficult. In spite of these difficulties, the calculated results were in good agreement with the toughness properties of the bending specimens studied.

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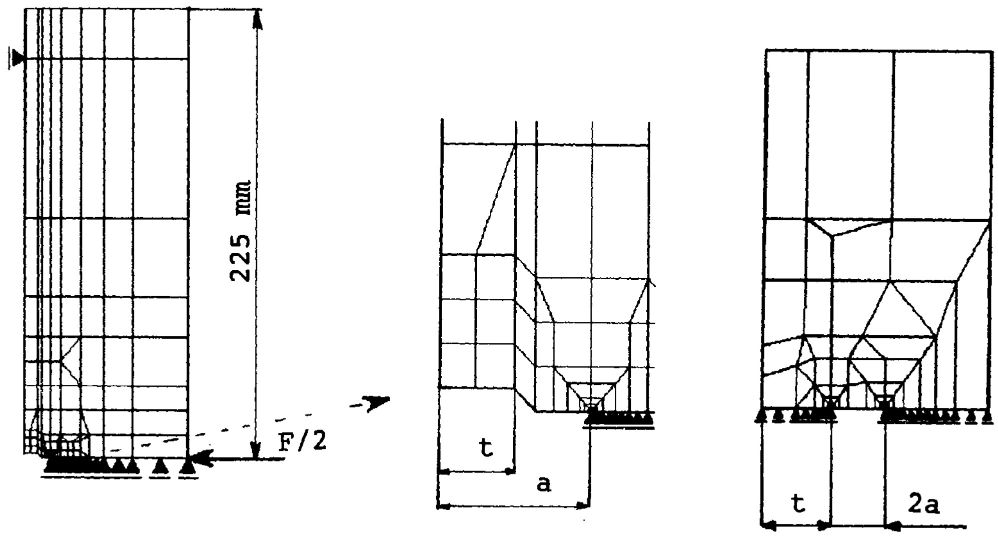

FIG. 1. FE MESHES FOR PTS32, 33 AND 44.

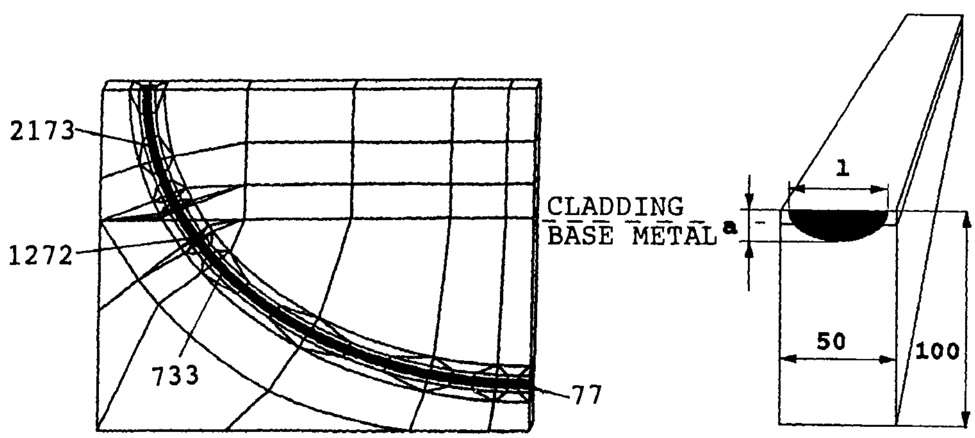

FIG. 2. FE MESHES FOR PTS36, 37 AND 39.

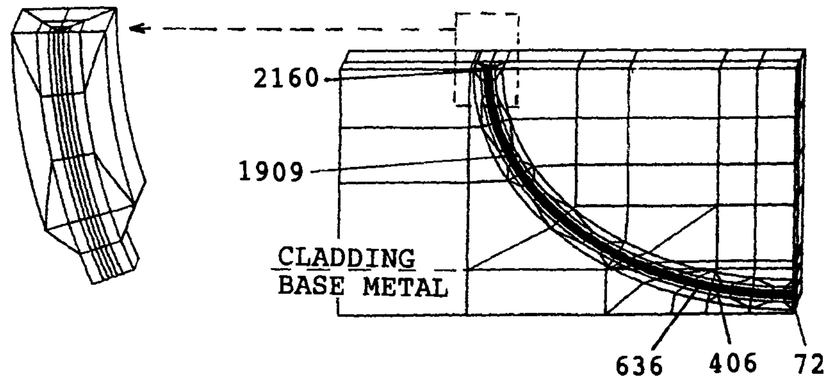

FIG. 3. FE MESH FOR PTS38.

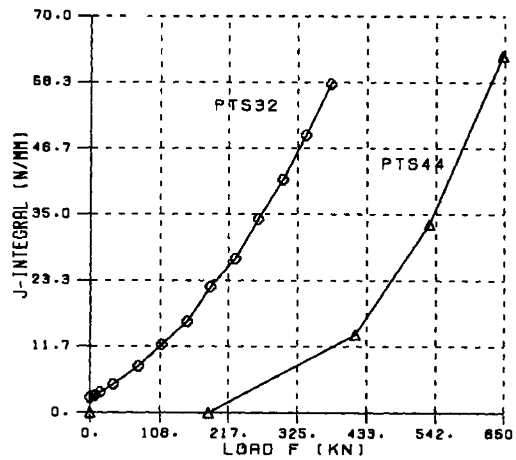

FIG. 4. J-INTEGRALS FOR PTS32 AND PTS44.

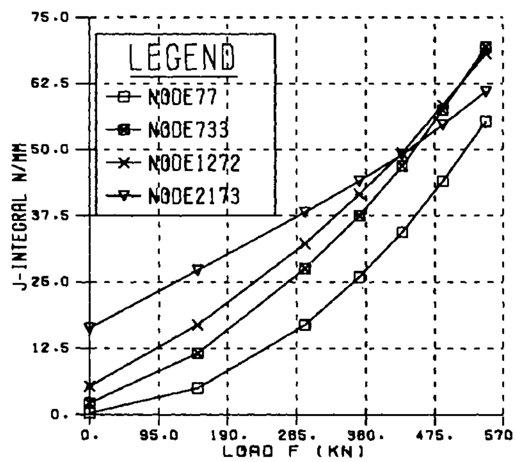

FIG. 5. J-INTEGRALS FOR PTS36 AND PTS37.

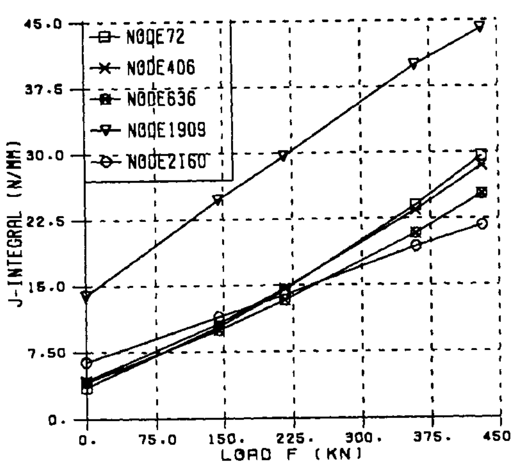

FIG. 6. J-INTEGRALS FOR PTS38.

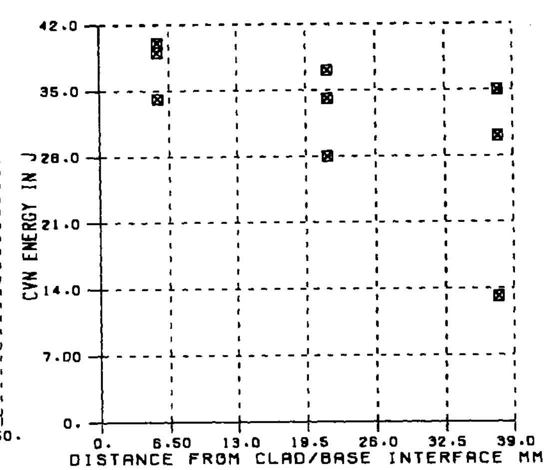

FIG. 7. CHARPY RESULTS.

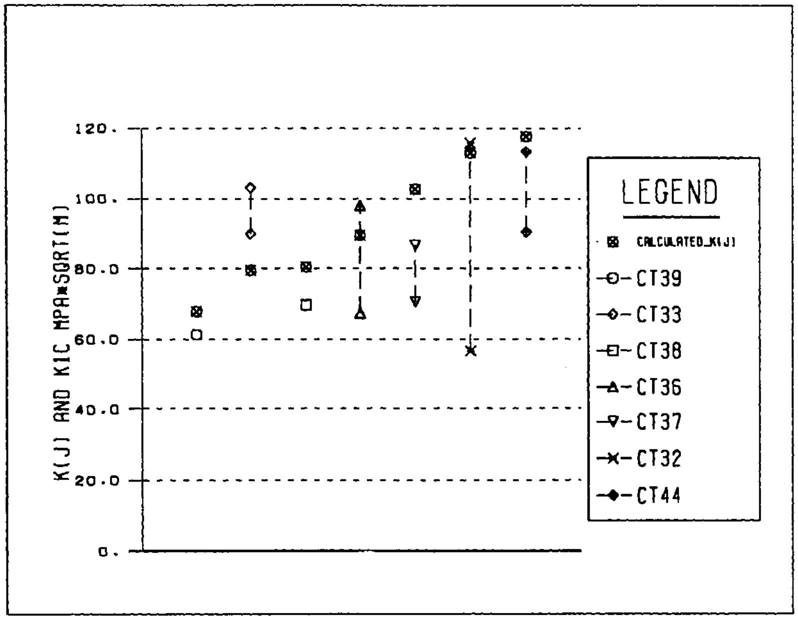

FIG. 8. COMPARISON OF CALCULATED K(J) VALUES WITH BASE METAL FRACTURE TOUGHNESS CLOSE TO CLADDING INTERFACE.