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Assessment of Cracking in Dissimilar Metal Welds

Paper presented at the 10th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 2001, Lake Tahoe, Nevada, USA

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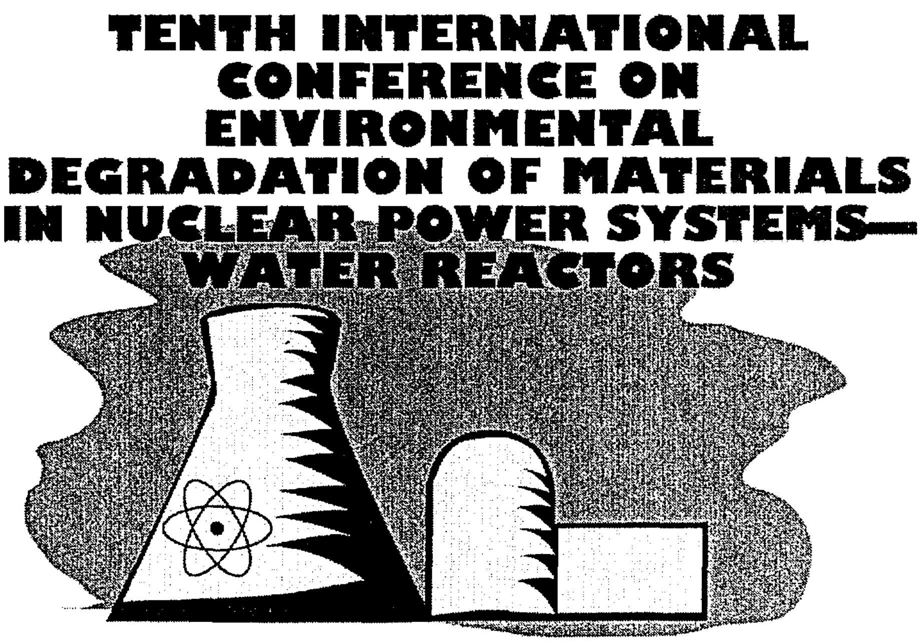

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Assessment of Cracking in Dissimilar Metal Welds

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Abstract

During the refueling in 2000, indications were observed by non-destructive testing at four locations in the reactor pressure vessel (RPV) nozzle to safe end weld in Ringhals 4. All indications were confined to the outlet nozzle (hot-leg) oriented at 25°, a nozzle with documented repair welding. Six boat samples were removed from the four locations, and the samples were subsequently subjected to a metallographic examination. The objectives were to establish the fracture morphology, and if possible the root cause for cracking. The examination revealed that cracks were present at all four boat sample locations and that they all were confined to the weld metal, alloy 182. Cracking extended in the axial direction of the safe-end. There was no evidence of any cracks extending into the RPV-steel or the stainless steel safe-end. All cracking was interdendritic and significantly branched. Among others, these observations strongly suggested crack propagation mainly was caused by interdendritic stress corrosion cracking (IDSCC). In addition, crack type defects and isolated areas on the fracture surfaces suggested the presence of hot cracking, which would have been formed during fabrication. The reason for crack initiation could not be established based on the boat samples examined. However, increased stress levels due to repair welding, cold work from grinding, and defects produced during fabrication, e. g. hot cracks, may alone or in combination have contributed to crack initiation.

Introduction

Ringhals 4 is a 915 MW PWR of Westinghouse design. The reactor was commissioned in November 1983. During the refueling outage of year 2000, several indications were observed by non-destructive testing in the reactor pressure vessel (RPV) nozzle to safe end weld. All indications were confined to the outlet nozzle (hot-leg) oriented at 25°. Boat samples were removed from the locations where indications were detected. These boat samples were shipped to Studsvik Nuclear where metallographic and fractographic examinations were carried out. The objectives of these examinations were to establish the fracture morphology, and if possible the root cause for cracking.

Nozzle Fabrication and Materials

Fabrication

The RPV was manufactured by Uddcomb Sweden AB in accordance with the ASME Boiler and Pressure Vessel Code, Section III for Class 1 Vessel, 1971 Edition. The RPV nozzle to safe end weld where the indications were found was produced in the workshop. A schematic of the weld is shown in Figure 1. The inner diameter of the safe end is 736 mm, and the nominal wall thickness is 79.5 mm.

Prior to welding the safe-end to the RPV nozzle, a weld buttering was applied on the nozzle. After various inspections (ultrasonic, dimensional check, and X-ray radiography), resulting in acceptable results, the nozzle was machined to final dimension. Subsequently, the safe end was welded to the nozzle. When the weld was completed, it was ground, dye penetrant tested, and inspected by X-ray radiography. The latter inspection technique revealed defects in the weld, both porosities and longitudinal cracks. The defects were located between 0° to 135°, 180° to 225°, and 315° to 0°, using the same references for position in the weld as for the boat samples, see Figure 2. Repair was made by grinding out the indications and then filling the area with weld metal. The weld was repaired three times, with intermediate X-ray radiography followed by grinding, before an acceptable result was achieved. It is noted in the documentation that the defects have been ground out to at least 32 mm in depth. Finally, the safe end was machined to final dimensions, followed by dye penetrant testing.

It may be worth noting that the X-ray radiography of the safe-end weld was carried out using a Co-60 source. Normally, a linear accelerator was used for this type of inspection, as was the case for the buttering. The linear accelerator has a better resolution for detecting cracks than a cobalt source.

Materials

The RPV nozzle is welded to the upper shell course, and it is made of ASME SA-508, cl 2, clad on the inside with 3.2 mm thick weld deposited austenitic stainless steel, A7-E23.12-1/A7-E19.9L-1. To the outer end of the nozzle, a safe-end made of forged austenitic stainless steel, ASME SA-182 F316 (Type 316 SS), is attached by welding. This weld was made by manual arc welding, using A43-EniCrFe-3-1 (alloy 182) as filler metal. The buttering applied on the RPV nozzle was also made by manual arc welding, using alloy 182 as filler metal.

Compositions of the weld filler metals used for the buttering and the nozzle to safe end weld are shown in Table 1. All heats of weld filler metal were produced by Inco. As the weld was repaired three times, several heats of filler metal were used. Table 1 indicates which heats were used for the original weld and which heats were used for the repairs. For one of the repairs performed, information about the weld material used is missing in the documentation.

Non-Destructive Testing and Boat Sampling

Non-Destructive Testing

An in-service inspection (ISI) of the weld in question was carried out during the refueling outage of 1993. Both ultrasonic (UT) and eddy current (ET) techniques were employed. This inspection detected no reportable indications.

During the refueling outage of the year 2000, the same techniques as in 1993 (i. e. UT and ET) were used to inspect the nozzle to safe-end weld. Four defects, interpreted as cracks, were detected during the latter inspection. In addition, a number of indications arising from pores and inclusions were also detected. At this time, the inspection results from 1993 were re-evaluated, with the objective to clarify if the defects existed already at the time of the first inspection. In this context, it should be noted that the detailed procedures between the two inspections were different, and thus, a direct comparison of the two inspections is not straightforward.

The results from the inspection in 2000 indicated that all four defects were oriented in the axial direction of the safe-end, i. e. in the transverse direction of the weld. According to the ISI qualification [1], the techniques employed have, for transverse defects, a resolution for surface length and depth of ±13 mm, and ±3.0 mm, respectively. The respective sizes of the four defects, as determined by the ISI, are shown in Table 2.

Boat Sampling

In all, six boat samples were removed from four locations of the weld, see Figure 2 for positions and denominations of the samples. In order to remove one surface breaking defect and one defect which ISI had indicated was just below the surface, two boat samples were taken out in positions 305° and 330°, respectively. Based on the results from the metallographic examination of the defect located at 330° (Boat Samples B and C), it was decided to remove two other defects (91° and 124°, Boat Samples F and E, respectively).

Electro discharge machining (EDM) was used to take out the boat samples. A low machining speed was used in order to achieve a fine surface. Subsequently to machining, all EDM surfaces were inspected by ET. Decisions on any further repair, other than removing the defects by EDM, will be taken at a later stage.

As indicated in Figure 2, two boat samples were removed from each of the locations at 305° and 330°. At the location 305°, two boat samples were required to remove all of the crack, i. e. the first sample (A) did not cover the entire depth of the crack. Regarding the location at 330°, a second sample had to be removed since the location of the first sample (B) was not properly positioned in relation to the indication.

Results

The various boat samples were cut in smaller pieces and prepared for examination by light optical microscopy (LOM). Some samples were broken open and the fracture surfaces were investigated by stereo microscopy and scanning electron microscopy (SEM). Energy dispersive X-ray analysis (EDS) in SEM was used to determine compositional variations in the samples.

Boat Sample Location at 305°

The crack in this boat sample is oriented in the axial direction of the safe end. Figure 3 shows a crack in Boat Sample A extending through the entire thickness of the boat sample. This means that the crack is deeper than 16.1 mm, which is the thickness of the boat sample in this cross section. In order to determine the crack depth, as well as to verify that no part of the crack remained in the plant, Boat Sample D was examined. Examination of this sample revealed the presence of thin, short crack tips on the surface facing Boat Sample A. These crack tips are in the order of 1 mm deep, and they disappeared after light polishing. Considering that about 5 mm of the material is removed during the EDM process, and provided that the crack tips observed in Boat Sample D are continuations of the main crack in Boat Sample A, this means that the total crack depth is approximately 22 mm (16 +5 +1 mm).

Both the cross section of Boat Sample A (Figures 3 through 5), and examination by SEM of the fracture surface (Figure 6), reveal that the crack morphology is interdendritic. Evidence of repair welding was observed, see Figure 4. Cracking is significantly branched, and the crack extends in the dendrite as well as recrystallized boundaries, see Figure 5. Examination of Boat Samples A and D verified that no cracks extend into the RPV steel or the stainless steel safe end. Analysis by EDS of Boat Sample A showed some areas of the fracture surface with high silicon levels.

Boat Sample Location at 330°

No cracks could be observed in Boat Sample B. The crack in Boat Sample C is oriented in the axial direction of the safe end, and all cracking is confined to the weld metal alloy 182. Examination by LOM of Boat Sample C shows that the crack morphology is interdendritic, see Figure 7. The crack depth in this section is 22 mm. As in Boat Sample A, the crack is heavily branched. Adjacent to the main crack shown in Figure 7, at least four other, shallow, cracks have initiated at the surface in contact with primary water. No attempts have been made to investigate if other areas of Boat Sample C, or any other boat sample, contain additional cracks of similar kind.

The interdendritic nature of the cracking is also evident from the fractographic examination, see Figure 8. Similar to Boat Sample A, the fracture surface is uneven, and shows that the crack extends in different planes. Ductile fracture (dimples) were observed in some areas where the dendrites protrude from the fracture surface, which is a further indication that the cracks extend in different planes. The fracture surfaces are covered by a brownish oxide, except the few areas where ductile fracture occurred. A defect caused by incomplete penetration during welding exists in Boat Sample C at the surface in contact with primary water, see Figure 8. As in Boat Sample A, areas with elevated silicon content were detected on the fracture surface of Boat Sample C. However, the silicon rich areas are less in extent in the latter sample.

Boat Sample Location at 124°

Cracking in Boat Sample E is oriented in the axial direction of the safe end, and is confined to alloy 182. Examinations by LOM reveal that the crack morphology is interdendritic, see Figure 9. The crack depth in this cross section is 6.1 mm. As in the other samples, cracking in Boat Sample E is significantly branched. At the surface in contact with primary water, there is clear evidence of cold work, see Figure 9. The depth of the cold worked layer is in the order of 0.1 mm. Examination of the fracture surface confirms that cracking is interdendritic and oxidized. No silicon rich areas were detected in this sample.

Boat Sample Location at 91°

Examination of Boat Sample F revealed an 8.8 mm deep crack extending in the axial direction of the safe end. Similar to the other cracks investigated, cracking in Boat Sample F is interdendritic and branched.

Another crack found in Boat Sample F is entirely enclosed in the weld, i. e. it is not in contact with primary water. It runs almost parallel to the surface in contact with primary water, at a distance of 8.2 to 9.6 mm from the same, see Figure 10. The length of the crack is 4.4 mm. Analysis by EDS shows enrichment in silicon. Several other non-surface breaking defects exist in this sample.

Discussion

Examination of six boat samples removed from four locations in the nozzle to safe-end weld show that cracks are present at all these locations. All cracks are confined to the weld metal alloy 182, and they extend in the axial direction of the safe-end. From the examinations performed, it is not entirely clear whether or not any of the cracking extends to the alloy 182 buttering. However, there are no indications that any cracks extend into the RPV steel. In addition, there is also evidence that cracking is present in the weld close to the stainless steel safe-end, but does not extend into it.

All cracking observed is interdendritic, showing significant branching. The extent of branching tends to increase when moving from the surface in contact with primary water towards the bulk of the pipe wall. These observations strongly suggest that crack propagation was caused mainly by interdendritic stress corrosion cracking (IDSCC). This is supported by the close resemblance of the boat sample fracture surfaces to those from crack growth specimens tested in laboratory [2]. These laboratory investigations demonstrated that alloy 182 is susceptible to IDSCC in PWR primary water.

The interdendritic surfaces examined are probably not entirely caused by IDSCC, as areas indicating hot cracking have been observed. These defects represent cracking occurring during fabrication, caused by the formation of a low melting liquid eutectic during cooling between the solidifying dendrites. Some regions of the fracture surfaces of Boat Sample A, and to a lesser extent Boat Sample C, were rich in silicon. In addition, several non surface breaking crack-like defects are present in Boat Sample F. Silicon enrichment was observed in one of these non surface breaking defects. These silicon rich regions and defects probably cracked during welding as a result of hot cracking. It has been noted that silicon is particularly damaging to the hot cracking resistance of chromium bearing high-nickel alloys [3]. In addition, it has been shown that fracture surfaces resulting from hot cracking reveal enrichment in niobium, manganese and silicon [4]. Thus, this may suggest that cracking of those areas high in silicon occurred during fabrication.

The reason for, or location of, crack initiation can not be established based on the boat samples examined. According to documentation from the fabrication, repair welding was performed at the cracked regions. Evidence of this is observed in Boat Sample A. This may increase stress levels adjacent to repair welds. In addition, there is evidence of cold work at the surface of Boat Sample E, which may stem from grinding after repair welding. Grinding has the possibility to induce local tensile stresses, although compressive stresses may also be produced. Another factor that may have played a role in the crack initiation process of Boat Sample C is the defect caused by incomplete penetration. There is also a possibility that hot cracks not detected during the original inspection assisted crack initiation. All these factors, alone or in combination, may have contributed to the crack initiation process.

An insight into the crack initiation mechanism may be gained by more detailed examination of the shallow cracks adjacent to the main crack in Boat Sample C. An examination to establish if further, similar cracks, are present in Boat Sample C (as well as the other boat samples), might present additional information as regards crack initiation.

The previous inspection in 1993 did not reveal any defects in the weld. It is not possible to determine if any part of the cracks discussed here (with the exception of the non-surface breaking cracks in Boat Sample F) existed at the time of this inspection. However, provided the stress levels are high enough, crack propagation rates for alloy 182 are sufficiently high [2] to produce cracks of the sizes observed in the recent inspection from small, non-detected, defects, during the time period from 1993 to 2000.

Whilst, the non-destructive inspections appear to have been successful in detecting all the defects examined and providing an indication of the size of the cracks, there is a consistent tendency to underestimate the maximum crack depth, by between 15 and 40%. The underestimate of crack depth is not surprising in view of the tighter nature of the crack tip region.

Conclusions

Six boat samples removed from the nozzle to safe end weld in Ringhals 4 have been subjected to metallographic and fractographic examination. Cracks are present at all four boat sample locations, and they are all oriented in the axial direction of the safe-end. All cracks are confined to the weld metal 182. Some cracking may have occurred in the weld buttering of alloy 182, but there is no evidence of any cracks extending into the RPV steel or the stainless steel safe end.

All cracking is interdendritic and significantly branched. These observations strongly suggest that crack propagation was caused mainly by interdendritic stress corrosion cracking (IDSCC).

Non surface breaking defects, rich in silicon, have been observed, as well as silicon rich areas on some of the fracture surfaces. These observations suggest the presence of hot cracks, which would have been formed during fabrication.

The reason for crack initiation cannot be established based on the boat samples examined. However, increased stress levels due to repair welding, cold work from grinding, and defects produced during fabrication, e. g. hot cracks, may alone or in combination have contributed to crack initiation. Further examination of the boat samples may present additional information as regards crack initiation.

Despite the success of the ultrasonic inspections to detect the defects, there was a tendency for the technique to somewhat underestimate the size of the cracks.

Acknowledgements

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Table 1 Compositions and diameters of weld filler metal wires used to produce the nozzle to safe end weld

Heat	Diameter mm	Used[1)]	C	Si	Mn	S	Cr	Ni	Cu	Fe	Ta	Ti	Nb	Co	$\overline{N}$ [2)]
3996	4	Buttering	.04	.43	7.06	.005	14.12	69.40	.04	6.73	.02	.50	1.61	.02	8.5
4557	3.25	Original and Rep. 1	.04	.41	6.67	.004	14.23	68.53	.27	7.73	.01	.39	1.67	.05	8.0
4384	4	Original	.05	.32	6.16	.008	13.85	68.87	.12	8.67	.03	.34	1.53	.05	5.7
4436	4	Original	.04	.38	6.88	.005	13.70	67.85	.11	8.97	.01	.34	1.67	.04	7.6
4628	5	Original	.04	.32	6.11	.007	14.31	68.54	.13	8.73	.02	.34	1.41	.04	6.8
4868	5	Original	.04	.43	6.21	.006	14.78	68.02	.14	8.44	-	.40	1.50[3)]	.03	7.5
4356	4	Rep. 1	.04	.48	6.58	.006	14.79	67.09	.16	8.70	.01	.46	1.64	.04	8.3
4872	5	Rep.1 and Rep. 2	.03	.45	6.03	.006	13.72	69.42	.40	8.13	.01	.46	1.50	.04	10.5
4370	3.25	Rep. 2	.04	.50	6.38	.008	14.21	67.92	.29	8.57	.01	.43	1.60	.04	8.0
4535	4	Rep.2	.04	.46	6.66	.006	14.73	67.17	.11	8.60	.01	.48	1.69	.04	8.6

1) Indication on where the respective heats of weld filler metal was used during the fabrication. Rep. 1 and Rep. 2 denote the first and second documented repair, respectively.

2) Carbide stabilization parameter defined as: $\overline{N} = 0.13 \cdot \frac{Nb + 2 \cdot Ti}{C}$, where Nb, Ti and C are the concentrations of the respective elements in weight percent.

3) Concentration of Nb + Ta

Table 2 Sizes of indications according to the in-service inspection

Location of defect[1)]	Lenght[2)] mm	Depth mm	Distance from surface[3)] mm
91°	12	6	4
124°	8	5	4
305°	28	13	0
330°	28	14	2

1) Location of indication in weld according to Figure 2
2) Length of indication on inner surface of safe-end weld
3) Distance of indication from inner surface of safe-end weld, i. e. 0 means the indication was surface breaking

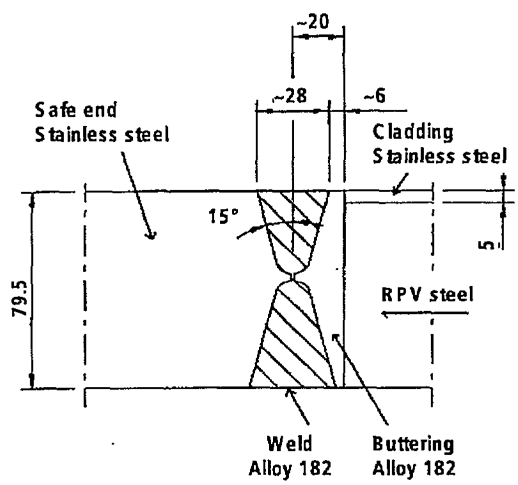

Figure 1. Schematic showing the nozzle to safe end weld. All dimensions are in mm.

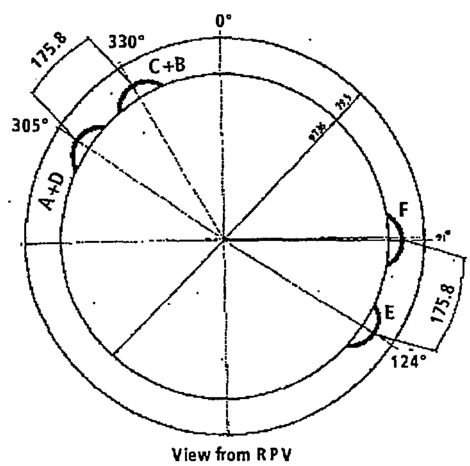

Figure 2. Cross section of nozzle to safe end weld. 0° is in the direction of the RPV head. Letters denote location of boat samples.

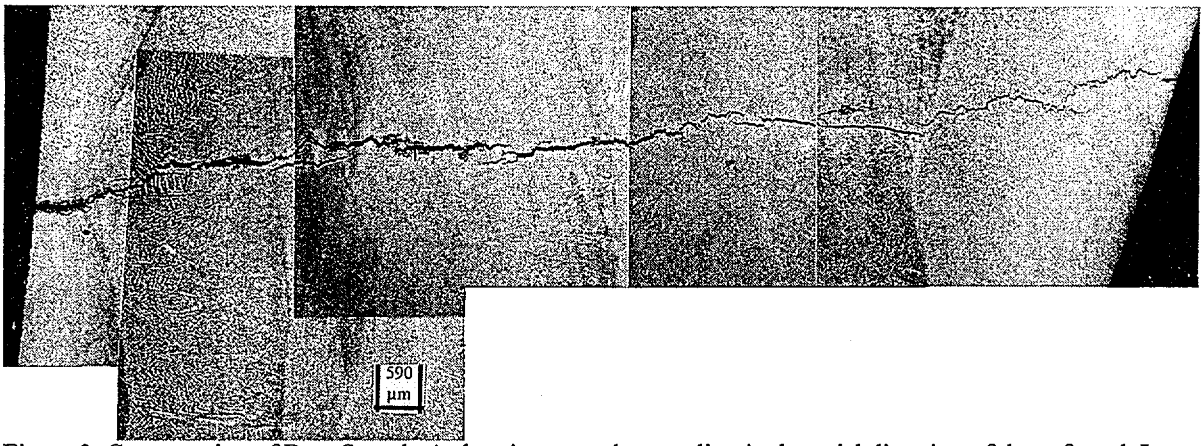

Figure 3. Cross section of Boat Sample A showing a crack extending in the axial direction of the safe end. In this cross section the crack exceeds the thickness of the boat sample. The surface in contact with primary water is to the left.

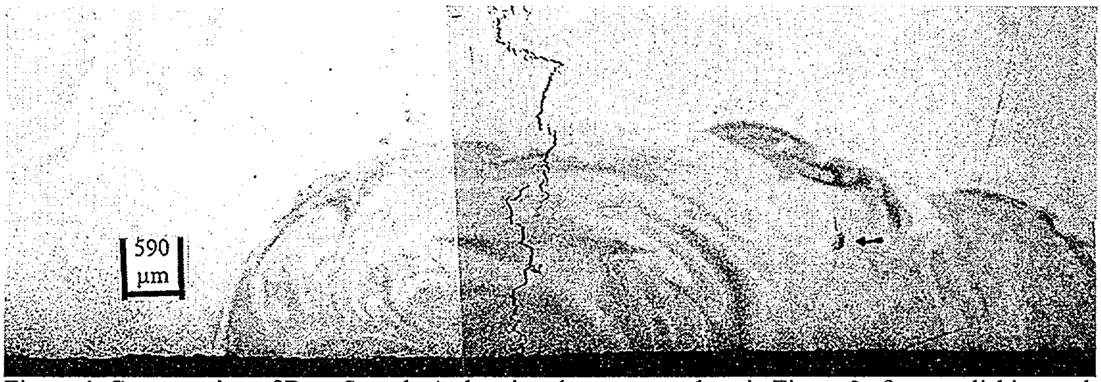

Figure 4. Cross section of Boat Sample A showing the same crack as in Figure 3 after repolishing and etching in 10% chromic acid. Part of the repair weld is visible. Note the short crack indicated by the arrow.

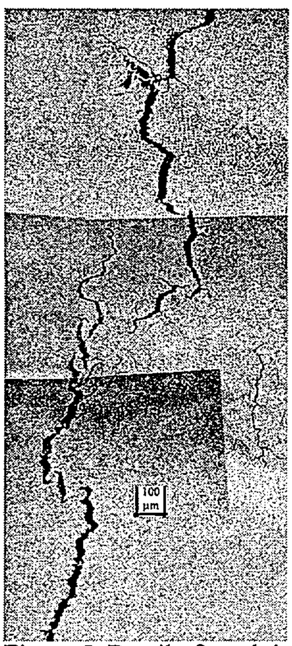

Figure 5. Detail of crack in Boat Sample A. Etched in 10% chromic acid

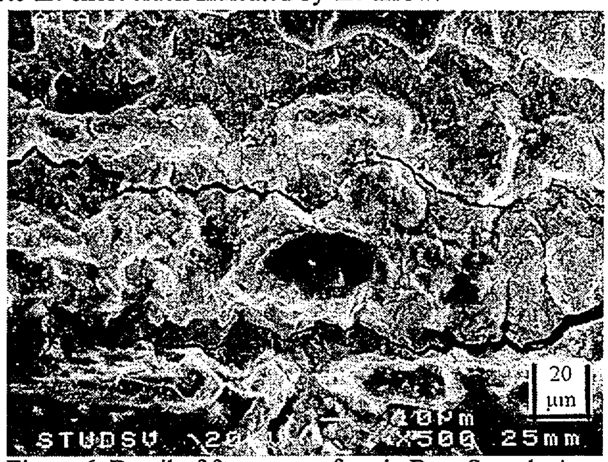

Figure 6. Detail of fracture surface in Boat Sample A showing interdendritic cracking. Note the transverse cracking.

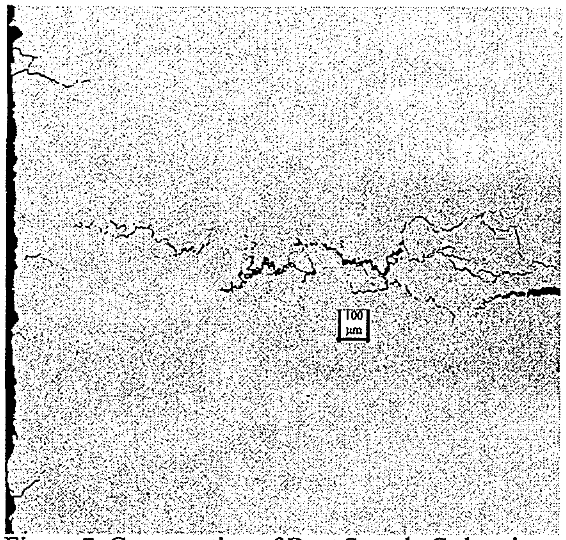

Figure 7. Cross section of Boat Sample C showing a crack extending in the axial direction of the safe end. Note the shallow cracks adjacent to the main crack. The surface in contact with primary water is to the left.

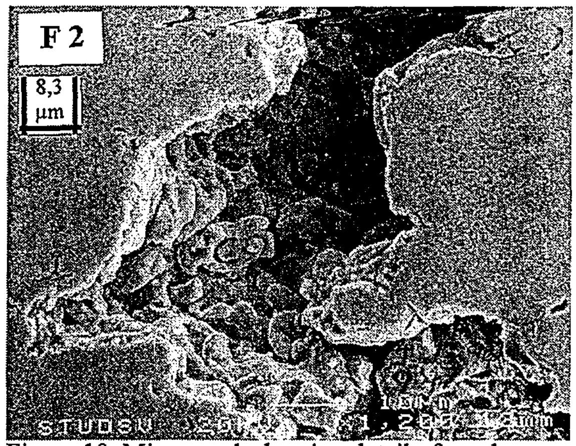

Figure 10. Micrograph showing detail of crack entirely enclosed in the weld, i. e. it was not in contact with primary water. The surface of the crack is high in silicon.

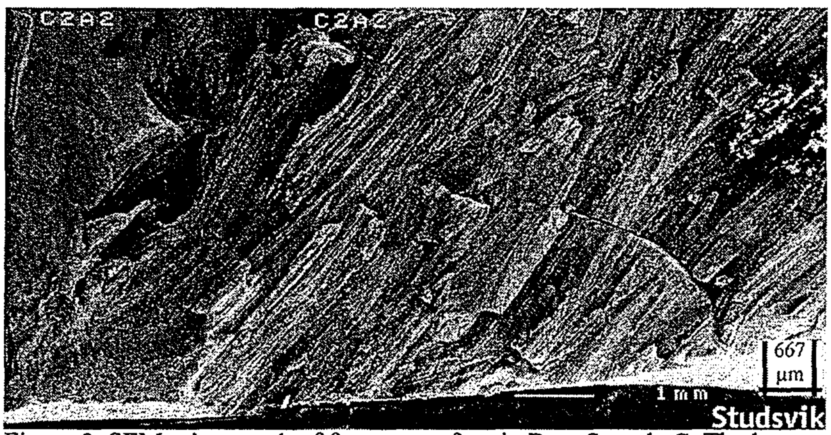

Figure 8. SEM micrograph of fracture surface in Boat Sample C. The lower edge of the fracture was in contact with primary water. Note the incomplete penetration in the lower right-hand corner

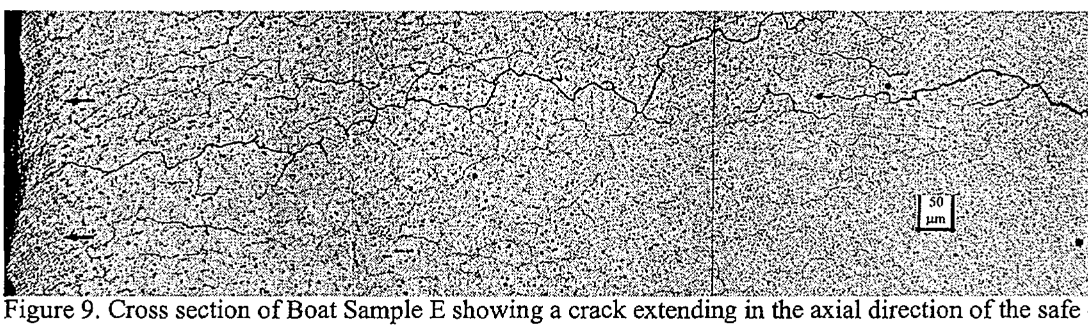

Figure 9. Cross section of Boat Sample E showing a crack extending in the axial direction of the safe end. Surface cold work is indicated by arrows. Electrolytically etched in Chromic acid.

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