81094

THE STRESS CORROSION CRACKING OF $2\frac{1}{4}$ Cr–Mo FERRITIC STEEL IN CAUSTIC ENVIRONMENTS

P. HURST and H. C. COWEN *U.K. Atomic Energy Authority*
Risley Nuclear Power Development Laboratories
Risley, Warrington, Cheshire WA36AT, United Kingdom

Received October 20, 1980
Accepted for Publication May 21, 1981

Stress corrosion studies in caustic environments have been carried out on the ferritic $2\frac{1}{4}$ Cr–Mo steel, with particular reference to its use in the evaporators of the U.K. prototype fast reactor. The quench-hardened steel has been found to be susceptible to stress corrosion cracking (SCC) throughout the temperature range of 50 to 300°C. In 30% caustic soda at 116°C, this susceptibility extends over the potential range −900 to +100 mV (Hg/HgO). On tempering, SCC occurs at −900 to −700 mV, but only at more positive potentials when preceded by an overheating treatment. Mechanisms by which cracking occurs under the different conditions studied are discussed. Cracking can occur in hard tube-to-tube-plate welds exposed to caustic environments as a consequence of fabrication stresses, but it has been shown that this can be avoided by shot-peening.

INTRODUCTION

The evaporators of the U.K. prototype fast reactor (PFR) were fabricated from the ferritic $2\frac{1}{4}$ Cr–Mo steel, and the present paper is an account of some of the stress corrosion studies performed on this material by Risley Nuclear Laboratories (RNL). Particular attention has been given in this work to testing the steel in the hard condition, since a post-weld heat treatment (PWHT) was not possible for the evaporator tube-to-tube-plate joints. The use of shot-peening as an alternative to heat treatment to reduce the stress corrosion cracking (SCC) hazard associated with the welds has also been investigated, and is described in this paper. Two environments have been covered: good quality water, characteristic of normal operation of the evaporators, and caustic soda solutions, which could arise under fault conditions or during a sodium removal operation. The first of these environments is not dealt with here, beyond stating that the hard material in some circumstances has been found to be capable of undergoing intergranular cracking in water, and that this is relevant to the interpretation of observations made on welds removed from the plant, as reported in Ref. 1. The caustic studies have been carried out at temperatures in the 50 to 300°C range and concentrations up to 30%, and are described below.

EXPERIMENTAL

Materials and Specimens

Three types of $2\frac{1}{4}$ Cr–Mo specimen were used for the stress corrosion tests: U-bends made from strip material, tensiles (flat or round), or tube-to-tube-plate welds, exposed either individually or as a multitube block assembly (Fig. 1). All the materials originated from air-melted stock and the compositions are shown in Table I. No differences were noted in this work between the behavior of stabilized and unstabilized material, the former having been used for the tubing of the PFR evaporators. A particular form of U-bend specimen was used in some of the tests aimed to simulate the tube-to-tube-plate weld. This was produced by welding longitudinally sectioned and flattened tube to the grooved edge of a relatively massive piece of plate (Fig. 2) to produce a high hardness weld; excess plate was removed to leave a composite sheet, which was then divided into strips each with the weld at the center, and subsequently formed into a U-bend.

Stress Corrosion Tests

The stress corrosion work was initially performed at the corrosion potential, mostly using 30% caustic soda solution under refluxing conditions (116°C). Tests at the corrosion potential were also conducted at lower concentrations and higher temperatures, the associated pressurized conditions being achieved by the use of welded nickel capsules. Figure 3 shows the apparatus used for measuring or controlling the corrosion potential, or determining polarization curves in the refluxing 30% caustic soda solution. The polytetrafluorethylene (PTFE) cell was heated by means of an externally wound heating tape, and fitted with a condenser. It contained a cylindrical platinum sheet as counter-electrode, and a thermocouple. The coupon, U-bend, or tensile specimen acted as the working electrode, and a cold, external mercury-mercuric oxide reference electrode was located in a side-arm. The multitube block assemblies were tested wholly immersed in refluxing 30% caustic soda at 116°C, the solution being contained in a nickel-lined mild steel test vessel. The complex shape and large surface area precluded the control by a potentiostat in the case of these assemblies, and recourse was made to sodium chromate as a passivating agent: addition of 0.5% maximum was made to maintain potentials up to approximately −300 mV. (Note: All potentials quoted refer to the Hg/HgO electrode, unless otherwise stated.) In other tests, SCC was induced in single tube-to-tube-plate welds exposed to a 10% caustic soda solution at 200°C without the necessity for chromate additions.

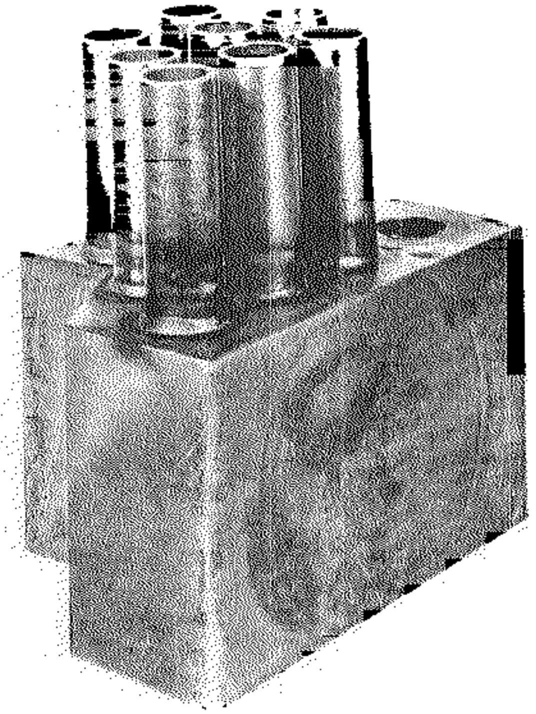


Fig. 1. Multitube block test assembly.

TABLE I

Composition of Materials

Element (wt%)	Tube (stabilized)	Tube (unstabilized)	Plate[a]		
			(A)	(B)	(C)
Carbon	0.08	0.097	0.10	0.08	0.12
Chromium	2.6	2.3	2.64	2.3	2.4
Molybdenum	0.96	1.09	0.92	1.0	1.0
Niobium	1.1	<0.02	<0.02	ND[b]	<0.05
Silicon	0.31	0.29	0.19	0.19	0.31
Manganese	0.52	0.47	0.58	0.56	0.50
Sulfur	0.007	0.014/0.024	ND	0.007	0.013
Phosphorus	0.006	0.009	ND	0.010	0.014
Tin	0.003	0.075	ND	0.0135	0.016
Arsenic	0.004	0.0165	ND	0.0288	0.042
Antimony	0.0009	0.002	ND	0.0027	0.005
Nickel	0.60	0.14	0.23	0.25	0.15
Copper	0.02	0.07	ND	0.20	0.21
Iron	Balance	Balance	Balance	Balance	Balance

[a] (A) is used in stabilized tube-to-tube-plate welds, (B) is used in unstabilized tube-to-tube-plate welds, and (C) is used to make U-bend specimens.

[b] ND = not determined.

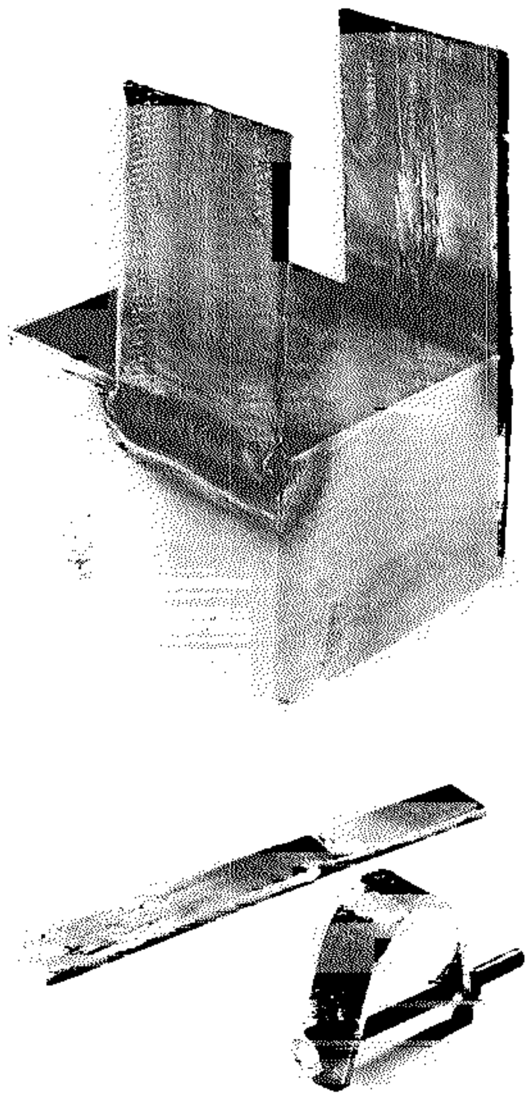


Fig. 2. Weld assembly and U-bend specimen.

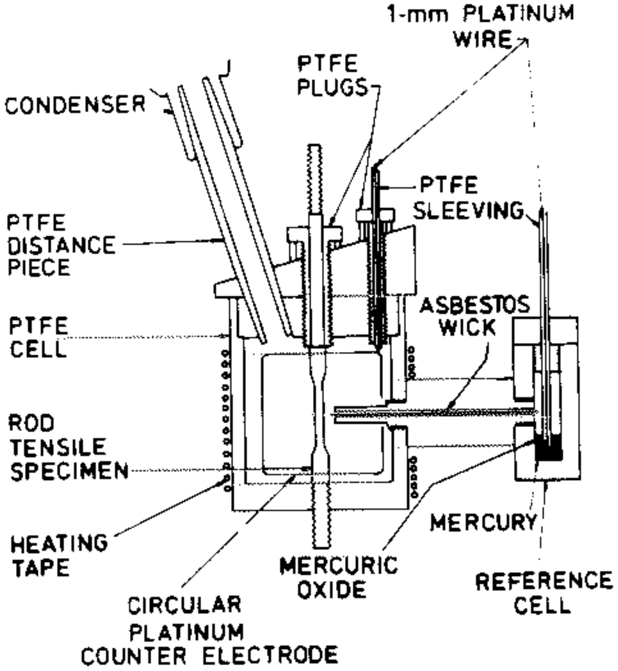


Fig. 3. Cell used for electrochemical experiments in caustic solutions at 116°C.

Shot-Peening

Shot-peening of the tube-to-tube-plate welds (both bore and exterior surfaces) was performed by Metal Improvement Company, Derby. The shot was to their specification QCO 01-11A/M1 230 H, namely, cast high carbon steel, 90% of which is >0.58 mm in diameter and 2% >0.84 mm, with high hardness (600 to 800 VPN). The Almen intensity was 0.016 to 0.020 A. Experiments were carried out to determine the effect of metal removal from the bore of a peened weld on susceptibility to SCC. Chemical dissolution was chosen for this purpose, in preference to a mechanical process. Specifically, an electrolyte consisting of 10 wt% sulfuric acid at 20°C was used. The weld itself acted as the containment vessel and the working electrode in a conventional three-electrode cell arrangement, and was maintained at an active potential of −200 mV (SCE). A platinum gauze counter-electrode with a profile that accurately matched the contour of the weld was located centrally in the bore; the potential was controlled by a high current potentiostat. X-ray photoelectron spectroscopic examination of the surface of a weld subjected to metal removal revealed no obvious change in composition (although results were not entirely conclusive), but a separate experiment demonstrated that the electrolytic dissolution process did not itself (for any reason) lessen the susceptibility of welds to SCC in a caustic environment. The amount of metal removed was determined by diameter measurements made on either side of the weld, and confirmation that the weld itself had sustained the same metal loss was obtained by careful measurements on methacrylate resin replicas made before and after metal removal.

RESULTS

U-Bends and Tensile Specimens

In tests performed at the corrosion potential, U-bend specimens failed in times ranging from a few hours to 2 to 3 weeks in the 30% refluxing caustic soda solution at 116°C. The shortest times were shown by specimens made from hard material (heat-treated 1050°C for 0.5 h, and water quenched), and the U-bends containing just a hard weld failed almost as readily; in the latter case the weld itself was not subjected to the yield point stress corresponding to hard material, since the deformation involved in forming the U-bend has mostly occurred in the adjacent soft material. Attempts to induce temper embrittlement by step cooling from 590°C resulted in intermediate times to failure. The U-bend specimens containing a hard weld were tested also in 0.01, 0.1, 1, 5, 10, and 92% caustic soda solutions at 300°C. No SCC was observed in the highest and three lowest concentrations but through-cracks were formed within 21 days in the 5 and 10% solutions. However, in the 10% solution it was found that extremely rapid cracking could occur at 200°C, so that these results could not be taken as indicative of the higher temperature. Results for 300°C could thus only be obtained by controlling the electrochemical potential to prevent cracking during the heating and cooling cycles. At the time, suitable equipment for this purpose was not available at RNL, but tests performed on our behalf by the Central Electricity Generating Board (CEGB) Central Electricity Research Laboratories (Leatherhead) gave the results shown in Table II, indicating that U-bend specimens containing a hard weld will still crack at 300°C within 10 days in the 10% solution. Returning to 200°C, the very short failure times shown by U-bends in this solution are shown in Table III. Cracking in all these tests was predominantly intergranular.

Prior to carrying out controlled potential tests with U-bend specimens in the refluxing 30% solution (116°C), polarization curves were obtained for materials in a range of conditions, using fast and slow sweep rates (1000 and 20 mV/min). The anodic currents showed an appreciable dependence on sweep rate for all materials between −700 and −900 mV; an example is shown in Fig. 4. Exposure of U-bends for seven days (longer in some instances) was then made at selected potentials in the −1200- to +400-mV range, and metallography used to determine the morphology of any cracks, and the proportion of the section occupied by them. Results are shown in Figs. 5 and 6. The metallurgical conditions covered were

TABLE III

U-Bend Specimens Exposed to 10% NaOH at 200°C

Material	Heat Treatment	Failure Times (days)
Weld (stabilized tube/plate C)	---	0 to 0.5
	700°C for 1 h, water quenched	0 to 4
Plate C	As received	4 to 8
	700°C for 1 h, water quenched	8 to 12
Plate B	As received	4 to 8
	700°C for 1 h, water quenched	0.5 to 4
Stabilized tube	As received	>10
	700°C for 1 h, water quenched	>10

TABLE II

Stress Corrosion of U-Bend Weld Specimens in 10% NaOH

Specimen Number	Temperature (°C)	Experimental Conditions	Time (h)	Result
7	300	Control experiment under galvanostatic control (−5 mA)	16.5	No cracking
4	300	Corrosion potential	16.0	No cracking
5	150	Corrosion potential	17.4	Failed just adjacent to weld in tube plate steel
13	300	Potentiostatically controlled (+300 mV)	18.0	No cracking
11	200	Corrosion potential	27.0	Failed in weld fusion region
6	250	Corrosion potential	20.0	Failed in weld fusion region
2	300	Potentiostatically controlled (+20 mV)	20.5	Failed in weld fusion region
3	300	Corrosion potential	21.0	No cracking
1	300	Corrosion potential	240.0	Failed in weld fusion region

Note: Specimens in all experiments heated and cooled while being polarized at −5 mA (0.15 mA·cm^{-2}). All potentials with reference to polarized platinum electrode (−200 μA·cm^{-2}).

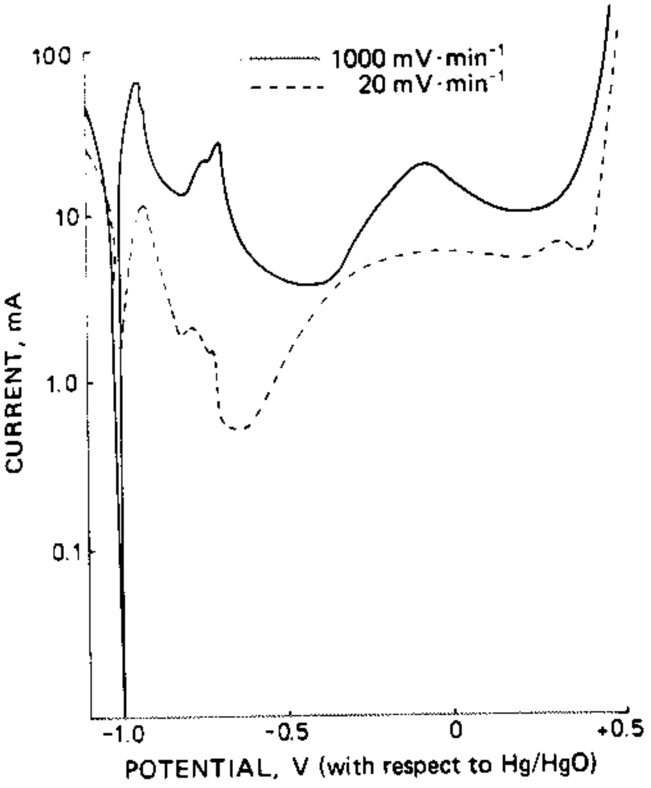


Fig. 4. Anodic polarization curves—refluxing 30 wt% NaOH (116°C) ($2\frac{1}{4}$ Cr—Mo—Nb tube water quenched from 1050°C).

1. 700°C, water quenched to produce soft material, free of any temper embrittlement
2. step cooled from 590°C, in an attempt to induce temper embrittlement
3. air cooled from 1400°C followed by water quenching from 700°C, to produce an overheated structure with soft material
4. water quenched from 1050°C to produce hard material, again free of any temper embrittlement.

The overheated structure arising from heat treatment (step 3) gave intergranular facets when fractured in air at 200°C, revealed by scanning electron microscopy (SEM) to consist of fine ductile dimples nucleated by 0.5- to 1.0-μm particles (Fig. 7), shown by energy and wavelength dispersive x-ray analysis to be manganese sulfide (Fig. 8). It is uncertain whether heat treatment (step 2) did in fact induce temper embrittlement: the ductile-to-brittle transition temperature was increased by some 50°C, but there was considerable scatter in the observations, and SEM examination revealed only small intergranular areas on the fracture surfaces.

All the above results refer to U-bend specimens. The results obtained from tensile specimens (flat or rod-type) in the range of 50 to 116°C are listed in Table IV. These tests were all performed in 30% caustic soda at potentials of −800, −400, or −100 mV at a number of stress levels, using material in the metallurgical conditions described previously.

Tube-to-Tube-Plate Welds

The multitube block assemblies (Fig. 1) tested in refluxing caustic soda at 116°C (with chromate additions made in an attempt to avoid excessive general corrosive attack) cracked readily in the region of the welds when no PWHT had been performed. Circumferential cracks visible on the "sodium" side are illustrated in Fig. 9; some circumferential cracks were also apparent on the "water" side (but may have initiated from the "sodium" side), and some longitudinal cracks were also visible on the bore without any preferred location with respect to the runoff zone. Cracking in such tests was intergranular, and eliminated by heat treating the welds at 650°C for 24 h. Similar results could be obtained from single tube-to-tube-plate welds providing a sufficient proportion of the ligament to the neighboring welds was included (to avoid any stress relief). These single welds were also tested in 10% caustic soda at 200°C, when (in the absence of PWHT) cracking occurred even more readily (a matter of hours), as in the case of U-bends.

Shot-Peening

By contrast, single as-fabricated welds that had been shot-peened on both "sodium" and "water" sides remained uncracked in the 200°C/10% caustic test for 21 days (the maximum exposure), and crack resistance was maintained as metal was progressively removed (by the technique described above) to a depth of 0.5 mm; a specimen from which 0.7 mm of metal had been removed, however, was found to have cracked (see Table V). A heat treatment (750°C for 0.5 h) designed to cause recrystallization of the worked layer (resulting from the peening operation) revealed this to be ~0.1 mm deep, so that crack protection to five times this depth is at first sight surprising. The observation is believed to be consistent, however, with available information on the likely stress profile in a peened tube-to-tube-plate weld from x-ray diffraction or the hole drilling technique. This indicates that the compressive stress induced by the peening process is present to a greater depth than the worked layer, and, in fact, reversion to a tensile stress does not apparently occur within a distance of ~0.5 mm from the surface. Tests have also been performed on peened tube-to-tube-plate welds with simulated pits, introduced by spark erosion. These also were found to be resistant to cracking in the

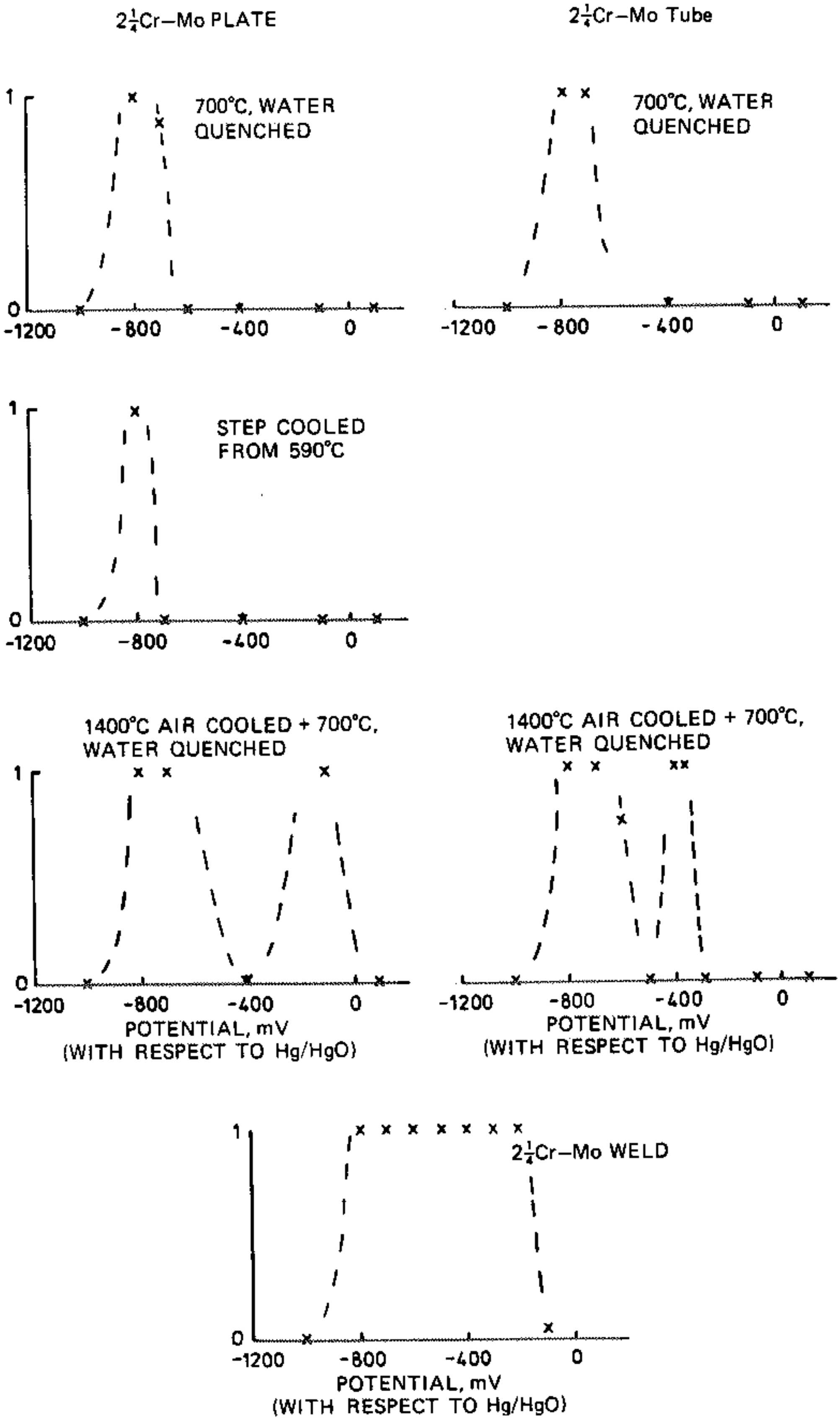


Fig. 5. Extent of SCC (expressed as a fraction of specimen thickness) as a function of potential refluxing 30% NaOH at 116°C.

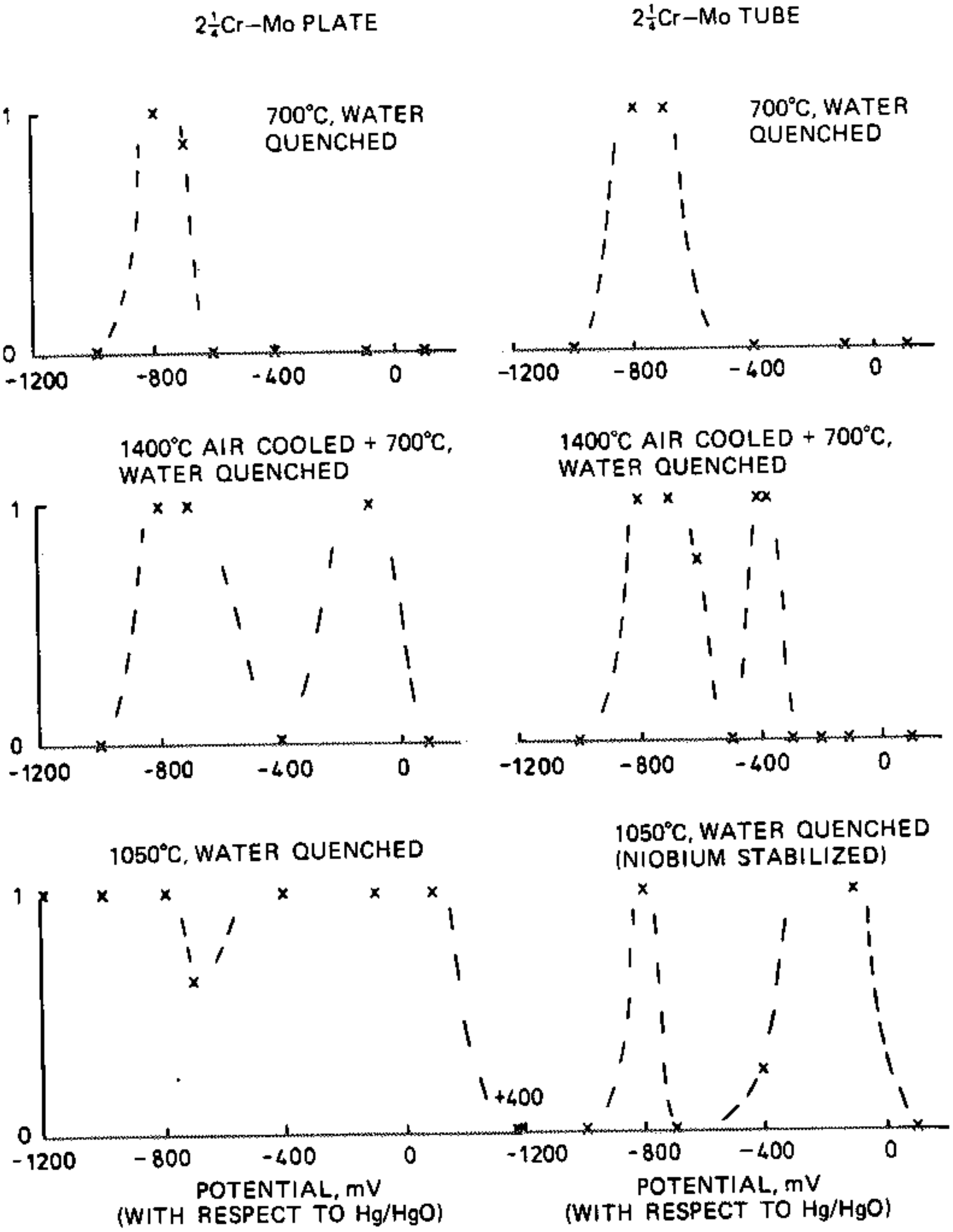


Fig. 6. Extent of SCC (expressed as a fraction of specimen thickness) as a function of potential refluxing 30% NaOH at 116°C.

200°C/10% caustic test, providing the base of the pit was within ~0.5 mm from the surface. Likewise, aging of peened welds for seven days at 400°C, or three days at 450°C to simulate the relaxation that could occur after 10 000 or 250 000 h, respectively, at the service temperature of ~350°C did not cause a return to a crack-susceptible condition. The effect of the peening process on the response of tube-to-tube-plate welds to chemical cleaning with citric acid was also investigated: no cracking occurred, and resistance to pitting was found to be slightly greater than for unpeened welds.

DISCUSSION

The SCC of the 2¼ Cr–Mo steel in caustic environments has been reported by Dahl et al.,[2] Isaacs (as cited by Indig[3]), McIlree and Michels,[4] Indig,[5] and Spalaris and Ring.[6] The work in the last two references (in common with our own) was undertaken in the context of the use of this steel for fast reactor steam generators, and included weld samples tested at the free corrosion potential as either tensile specimens or U-bends. At 316°C, Indig found no evidence for SCC in 10% caustic soda in constant load or constant extension rate tests, whereas this did eventually occur at 300°C with U-bend specimens containing a hard weld in the work reported here; however, Indig's specimens had received a PWHT. At 232°C, Spalaris and Ring[6] reported that as-welded U-bends and tensile specimens cracked in 20% solution provided these were made from air-melted stock, and tensile specimens made from such stock also failed with a PWHT. The electroslag remelt and in particular vacuum arc remelt material was, however, reported to be superior. The present work, of course, has covered only air-melted stock, and U-bend specimens containing a weld failed readily with or without PWHT at the corrosion potential at 200°C in 10% caustic soda solution. Providing such cracking could also have been expected at the slightly higher temperature and concentration used in the work reported by Spalaris and Ring,[6] the U.K. and U.S. information on air-melted material is consistent in this regime; it would, however, appear desirable to check the proviso concerning the difference in experimental conditions.

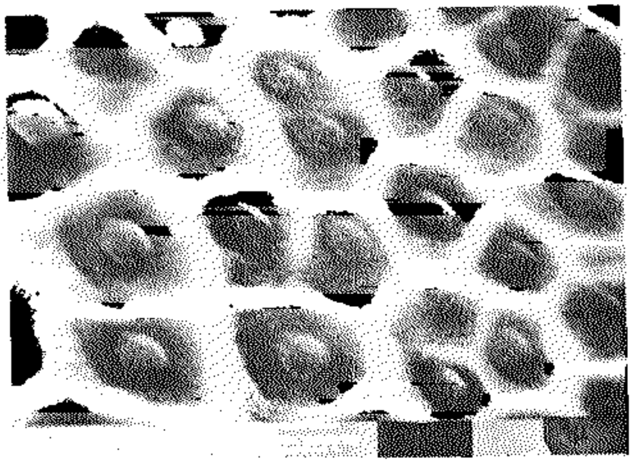
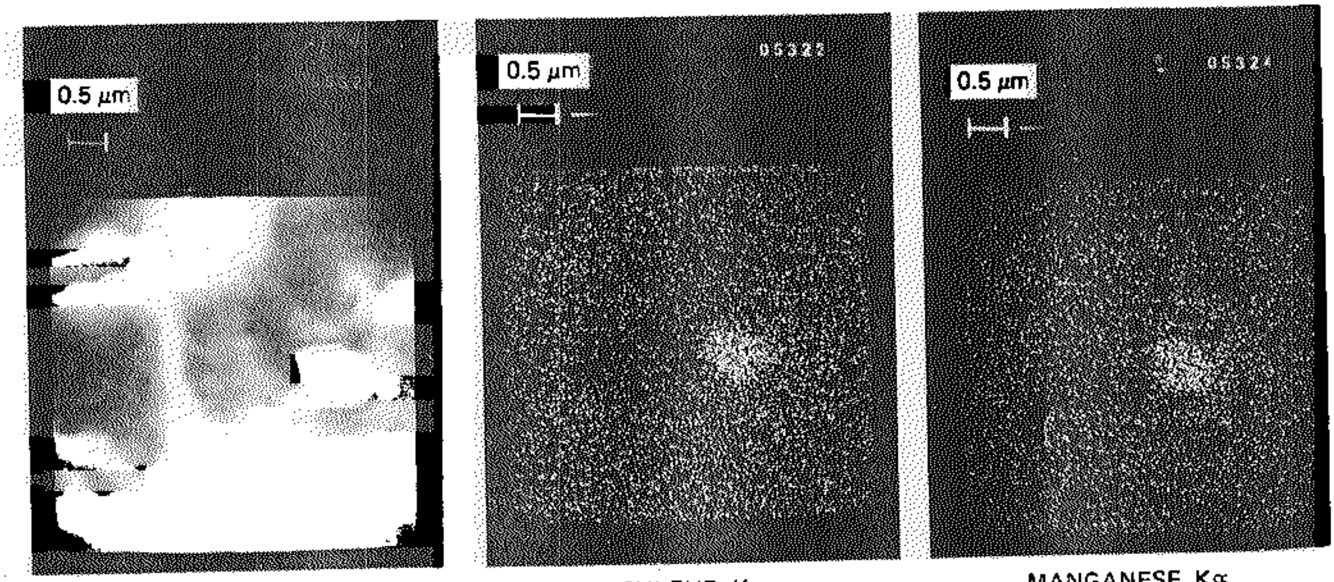


Fig. 7. Detail of overheating facet showing intergranular array of small inclusions.

The RNL tests in refluxing 30% NaOH at 116°C in which potentiostatic control was exercised showed that the metallurgical condition had a marked effect on the range of potential over which susceptibility to SCC was observed. As-fabricated welds and material hardened by quenching from 1050°C, although in some instances showing a reduced susceptibility at intermediate potentials, cracked at all values from −900 to at least +100 mV, whereas the 700°C quenched condition only cracked at potentials in the region −900 to −700 mV within the duration of the tests (U-bends 28 days, tensile specimens 42 days). Stress corrosion at potentials around −800 mV appears to be generally exhibited by carbon and low alloy steels in caustic solutions, and is probably associated with dissolution and repassivation of iron at the crack tip. The observation that the polarization curves (Fig. 4) show a maximum sweep-rate dependence in this region would also support the view that



SULFUR Kα   MANGANESE Kα

Fig. 8. X-ray element images for grain boundary inclusion in overheated structure.

TABLE IV

$2\frac{1}{4}$ Cr–Mo Tensile Specimens Exposed to 30% NaOH

Material	Heat Treatment	Stress	Temperature (°C)	Time to Failure Potential (h)		
				−800 mV	−400 mV	−100 mV[a]
Plate	*N* + *T*	100% of 0.2% PS	116			NF[b] 507
Plate	700°C, water quenched	100% of 0.2% PS	116	175		NF 1006
Plate	700°C, water quenched	60% of 0.2% PS	116	847		NF 681
Plate	1050°C, water quenched	100% of 0.2% PS	116	1.0		7.4
Plate	1050°C, water quenched	60% of 0.2% PS	116	3.9		
Plate	1050°C, water quenched	30% of 0.2% PS	116	9.0		
Plate	1050°C, water quenched	20% of 0.2% PS	116	13.7		
Plate	1050°C, water quenched	100% of 0.2% PS	100	2.5	2.2	3.0
Plate	1050°C, water quenched	100% of 0.2% PS	75	13.0	7.5	9.5
Plate	1050°C, water quenched	100% of 0.2% PS	50	53.0	69.3	70.9
Unstabilized	1400°C +	75% of 0.2% PS	116	3.4		6.4
Tube	1050°C, water quenched	60% of 0.2% PS	116	4.8		24.4
Tube	1050°C, water quenched	20% of 0.2% PS	116	18.6		
Unstabilized Tube	1400°C + 700°C, water quenched	75% of 0.2% PS	116	117.1		NF 335

[a] Potentials refer to the Hg/HgO electrode.

[b] NF = not failed.

the associated SCC is primarily associated with the bulk properties of the alloy.

The nature of the cracking at the more noble potentials is, however, more uncertain. A secondary active peak has been observed in the anodic polarization curve, and Agrawal et al.[7] has related a similar feature (in the case of more highly alloyed materials) to loss of integrity of the passive film due to the formation of CrO_4^-. Poulson[8] has also shown that molybdenum extends the potential range over which the cracking of carbon steels occurs. At Harwell, Marsh[9] has reported that both $2\frac{1}{4}$ Cr–Mo and 9 Cr–Mo steels in a quenched and tempered condition are susceptible in two potential ranges: −900 to −700 mV and −300 to +100 mV. However, cracking in the latter range was not found in the present work for soft $2\frac{1}{4}$ Cr–Mo, produced either by tempering or water quenching from 700°C (the latter also ensuring freedom from temper embrittlement). It occurred, however, at potentials extending to −100 mV with material heat treated at 1400°C to form an overheated structure containing grain-boundary sulfide, and then softened; tensile specimens made from such material, however, require appreciably longer times to fail than quench-hardened material. Although the latter cracked readily over a wide range of potential, this is unlikely to be associated with hydrogen uptake at potentials up to which soft, overheated material cracked. Thus, the susceptibility of $2\frac{1}{4}$ Cr–Mo to cracking at more positive potentials may well be related to the high temperature solution-annealed structure, perhaps involving segregation of sulfur or some other element, and the degree to which it is retained.

A hydrogen mechanism may well be responsible for the cracking of hard material, however, at the more negative potentials (−1000 to −1200 mV). Transgranular cracking was observed in this regime for U-bend specimens made from uniformly hard strip; the fact that U-bend specimens hard only in the vicinity of a weld did not crack at potentials more negative than −1000 mV can probably be ascribed to the fact that the stress was limited by the deformation in forming the U-bend occurring primarily in adjacent soft material.

It was found in this work that the corrosion potential (measured at 116°C in 30% caustic soda) varied from about −950 up to (ultimately) −300 mV, and this is within the range over which hard material is susceptible to cracking. The results shown in Table IV indicate that the susceptibility of material quenched from 1050°C does not vary markedly (at least at the 0.2% PS) over this range, and that although a reduction of stress and/or temperature is helpful, failure of hard material still occurred in these tests in a matter of days under the least severe conditions investigated. Although the results in terms of times to

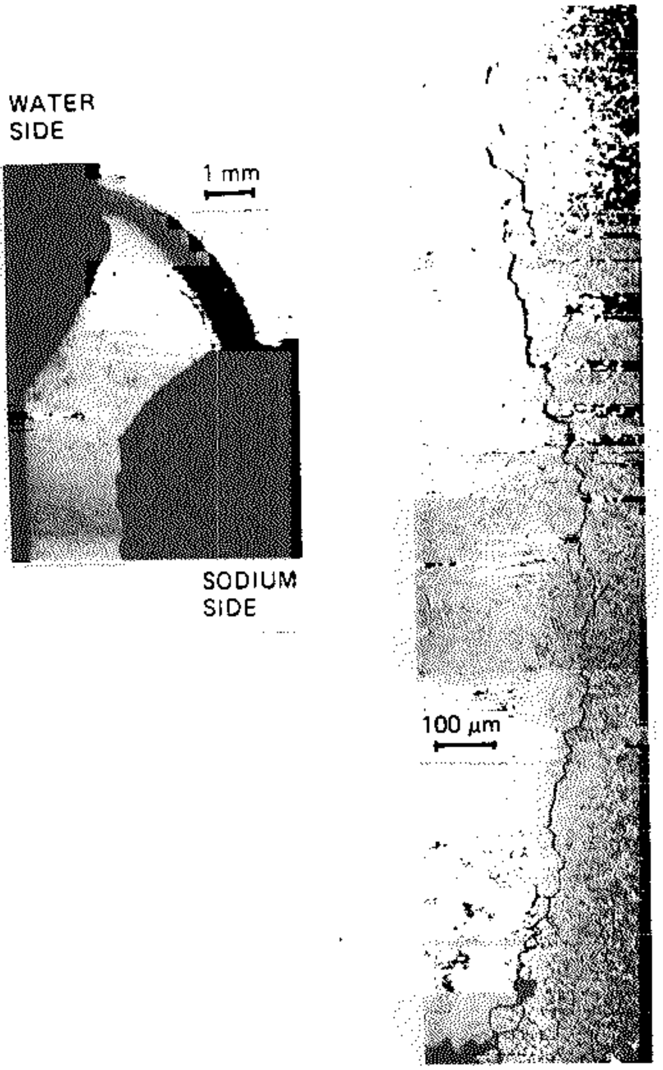


Fig. 9. Circumferential crack propagating along the fusion line on the plate side of a weld.

failure are not necessarily representative of hard tube-to-tube-plate welds, some caution is evidently required if sodium removal from such regions involved the creation of caustic conditions.

The effectiveness of shot-peening in preventing SCC of the 2¼ Cr-Mo steel due to fabrication stresses has emerged clearly in this work, and (though not reported here) it has been shown also to prevent the cracking of hard material that could otherwise occur in good quality water. Although caustic conditions were created on one occasion in the vicinity of a number of welds in one of the PFR evaporators (and were shown by the present work to have been responsible for circumferential cracking), the probability of a further occurrence of this type has been effectively discounted.[10] Shot-peening is planned, however, for the bores of these welds to prevent crack initiation from the water side.[10] The RNL work indicates that even after some degree of general or localized metal loss, it should remain effective for this purpose. It might also be noted that some of the reservations that sometimes need to be borne in mind before advocating this treatment are not relevant here. Thus, the peening is to be applied to a surface that has yield point tensile stresses in the initial condition, as a result of the fabrication process; the peening replaces them by compressive stress to a depth of ~0.5 mm. This is in contrast to a situation in which an initially stress-free surface is peened as a protection against SCC. The surface compressive stress that is then created is accompanied by the formation at a greater depth of a tensile stress that did not previously exist, and could represent a new hazard. Balancing tensile stresses can in principle also be created at the surface in untreated regions adjacent to those that have been peened. No evidence for this has been found in the development work for the present application, but in any case the intention is to locate the boundary in soft material in the plate and tube, where water side cracking is known not to be a hazard.

TABLE V

Response of Peened Tube-to-Tube-Plate Welds to Exposure to 10 wt% NaOH at 200°C After Uniform Metal Removal

Specimen Number	Depth of Metal Removed from Bore (mm)	Stress Corrosion Cracks
1	0.05	No
2	0.10	No
3	0.15	No
5	0.25	No
6	0.35	No
4	0.43	No
8	0.50	No
11	0.70	Yes
Unpeened control	0.13	Yes

CONCLUSIONS

The main conclusions arising from these studies, which were performed exclusively on air-melted material, are as follows:

1. Quench-hardened 2¼ Cr–Mo is susceptible to SCC in caustic environments throughout the temperature range studied (50 to 300°C).

2. In 30% refluxing caustic at 116°C, this susceptibility of hardened material extends over a wid range of electrochemical potentials, encompassing th

variation in free corrosion potential which increases from about −950 to −300 mV.

3. Tempered material undergoes SCC at −900 to −700 mV, but in the present work has only cracked at more positive potentials when preceded by a high temperature overheating treatment.

4. At the most negative potentials studied (−1000 to −1200 mV), hydrogen cracking is possible for hardened material, while at about −800 mV (where caustic cracking is exhibited also by mild steel and other low alloy steels) the cracking mechanism is probably related to the dissolution/repassivation kinetics of iron at the crack tip. At the more positive potentials, the possibility of cracking appears to be associated with the high temperature solution-annealed structure (perhaps involving some form of segregation), and the degree to which it is retained.

5. The vulnerability of hard tube-to-tube-plate welds to cracking as a consequence of fabrication stresses can be eliminated by shot-peening, which remains effective after general or localized removal of metal to a depth of 0.5 mm.

ACKNOWLEDGMENTS

The authors wish to thank C. W. Pennington and G. R. Kirkland for assistance in carrying out these studies and the CEGB Central Electricity Research Laboratories, Leatherhead, for carrying out the controlled potential tests at 300°C.

REFERENCES

1. G. R. KIRKLAND, E. R. DAVIES, M. E. LAMBERT, and E. J. KENNET, "Metallurgical Examination of Tube to Tube Plate Welds Removed from Dounreay PFR Evaporators," *Nucl. Technol.*, **55**, 289 (1981).

2. L. DAHL, T. DAHLGREN, and N. LAGMYR, "The Caustic Stress Corrosion Cracking of Alloyed Steels—an Electrochemical Study," *Proc. Int. Conf. High Temperature High Pressure Electrochemistry in Aqueous Solutions,* Guildford, Surrey, U.K., January 7-12, 1973, CONF-730105.

3. M. E. INDIG, "Stress Corrosion Behaviour for the Clinch River Breeder Reactor Steam Generator," GEAP-14118, General Electric Company (June 1976).

4. A. R. McILREE and H. T. MICHELS, "Stress Corrosion Behaviour of Fe-Cr-Ni and Other Alloys in High Temperature Caustic Solutions," *Corrosion,* **33**, *2*, 60 (1977).

5. M. E. INDIG, "Stress Corrosion Studies of $2\frac{1}{4}$CrMo Steel," *Proc. BNES Conf. Ferritic Steels for Fast Reactor Steam Generators,* London, June 1977.

6. C. N. SPALARIS and P. J. RING, "Welding for the CRBRP Steam Generators," *Proc. BNES Conf. Welding and Fabrication in the Nuclear Industry,* London, April 1979.

7. A. K. AGRAWAL, K. G. SHETH, K. POTEET, and R. W. STAEHLE, "The Polarisation Behaviour of Fe-Ni-Cr Alloys in Concentrated Sodium Hydroxide Solutions in the Temperature Range 25° to 150°," *J. Electrochem. Soc,* **119**, *12*, 1637 (1972).

8. B. POULSON, Clarke Chapman, Gateshead, England, Private Communication (1978).

9. G. P. MARSH, Atomic Energy Research Establishment, Harwell, Private Communication (1978).

10. A. M. BROOMFIELD and J. A. SMEDLEY, "Operating Experience with Tube to Tube Plate Welds in PFR Steam Generators," *Proc. BNES Conf. Welding and Fabrication in the Nuclear Industry,* London, April 1979.