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RUPTURE OF REAR TUBE SHEET AT THE CIRCUMFERENTIAL WELD OF A HIGH PRESSURE BOILER

by

D. E. PARSONS

PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

This boiler failed by rupture at the welded circumferential seam between the furnace and the rear tube sheet after about 8 months of actual service.

The original brittle failures, in the form of toe cracks, were believed to have occurred at the time the seam was welded. During subsequent service the expanded tube ends were girth-welded to the rear tube sheet, and it is believed that the application of this additional stress under conditions of restraint caused rapid intercrystalline propagation of the cracks, resulting in failure of the seam.

Design changes have since been made whereby this part of the boiler has been flanged, thereby allowing some stress relief by deformation.

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(8 tables, 15 illus.)

INTRODUCTION

On December 19, 1957, a section of rear tube sheet and furnace plate, welded in the form of a 5 in. x 12 in. angle and containing cracks at the toes of the girth weld (water side), was submitted by Mr. L. Jehu, Welding and Research Engineer, Dominion Bridge Company Limited, Lachine, Quebec, to the Physical Metallurgy Division, Mines Branch, Ottawa, for metallurgical examination. (For purposes of this report this angle sample has been designated specimen "E".)

Specimen E was covered by a letter dated December 19, 1957, from Mr. L. Jehu referring to Dominion Bridge Company Contract No. Y-1360, Drawing No. H-205-D1-OH.

Subsequently, four additional angle samples similar to E, identified as specimens "A", "B", "C" and "D", were submitted by Mr. A.M. Bain, Plate and Boiler Engineer, Eastern Division, Dominion Bridge Company, Lachine, and were covered by a letter dated February 25, 1958. Also, on April 1, 1958, two samples of plate which had been stress-relieved by Dominion Bridge Company were received from Mr. L. Jehu. These samples, covered by a letter dated April 1, 1958, were a 3/8 in. x 9 in. x 9 in. plate and a "sandwich" specimen 3 in. square and 3/8 in. thick. The plate samples were designated specimens "F" and "G", respectively.

The December 19, 1957, letter covering sample E identified the 12 in. length as furnace plate and the 5 in. length as rear tube sheet material. The drawing (No. H-205-D1-OH) indicated that in other areas of the boiler the crack at the girth weld was continuous and had resulted in complete separation of the weld from the furnace plate.

This letter also stated that the boiler from which the sample was taken was installed during the winter of 1956 and had been in actual service for about 8 months. It was fired by means of an intermittent oil burner, which is estimated to have been lit about fifty times per day, indicating a life of about 12,000 cycles. During the spring of 1957, leaks developed around some of the tubes in the rear tube sheet. As a result, the owner had all the tube ends welded to the tube sheet, to avoid further trouble. Recently (winter 1957/58), a fracture occurred completely through the furnace plate. This crack was about 18 in. long, ran from the top centre line toward one side, and was adjacent to the toe of the fillet weld.

Closer examination revealed additional cracks partly through the thickness of the plate in both the furnace and tube sheet plates. In all cases the cracks were adjacent to the toe of the fillet weld.

The letter of December 19, 1957, stated that because the boiler was fabricated during the winter months, their first thought was of brittle failure during hydrostatic testing, since the water could have been between 40° and 50°F. Therefore, they performed Charpy V impact tests with the following results:

Tested at 34°F	-	12.1 ft-lb (average of 5 specimens)
" " 50°F	-	20.2 ft-lb (" " 5 ")
" " 70°F	-	38.1 ft-lb (" " 4 ")

These impact results indicated that 15 ft-lb would be obtained at a temperature of 40°F and therefore, on the basis of the ASME Code, the material should have been satisfactory for service at that temperature. (In addition, reports on welded ship failures have shown that cracks initiated only when Charpy V values of the material were below 10 ft-lb at the temperature at which failure occurred.)

Feeling that the Charpy V results were not conclusive, the Dominion Bridge Company made four drop weight tests (Pellini's method) which gave the following results:

Tested at 20°F	-	fractured
" " 30°F	-	fractured
" " 40°F	-	no fracture
" " 40°F	-	no fracture

The drop weight tests suggested a Nil Ductility Temperature of about 35°F.

In his December 19, 1957, letter Mr. Jehu further stated:

> It was doubtful that the test water temperature was at or below the suggested N.D.T. point, therefore we more closely examined the fracture face of the sample. It was noted that the fracture consisted of a series of steps in cross-section and had a stratified appearance in the front view. This suggested a fatigue failure. If this were so, then, as a crack propagates we would expect to find symptoms of cold work at its root.

He then requested that the Mines Branch examine the fracture microscopically for evidence of cold work and that comment be made concerning the specimen.

Also mentioned by Mr. Jehu was the presence of a scale deposit about 3/64 in. thick, on the furnace plate and a portion of the tube sheet, which might or might not have caused inequalities in local temperature during operation.

For information, the Dominion Bridge Company provided a copy of the Mill Test Report, for the furnace and tube sheet material supplied to ASTM-A-285/C, showing the following properties for the furnace and head plates. These details are shown in Tables 1 and 2.

TABLE 1

Mechanical Properties of Tube Sheet and Furnace Plate
(per Dominion Bridge Company)

Heat No.	Bar Size	Yield Pt. p.s.i.	Ultimate Strength (bottom longitudinal) p.s.i.	Ultimate Strength (top longitudinal) p.s.i.	Elongation % 8 in.	RA %	Material
66157	1.560 x 0.715 in.	39,500	56,900	58,100	29.0	57.6	Head
66148	1.550 x 0.783 in.	37,800	55,000	55,500	31.0	62.0	Furnace

TABLE 2

Chemical Analysis of Tube Sheet and Furnace Plate
(per Dominion Bridge Company)

Sample	Carbon	Manganese	Phosphorus	Sulphur
	Percent			
Head Plate	0.22	0.35	0.010	0.038
Furnace Plate	0.18	0.38	0.011	0.030

PROCEDURE

Examination of the various samples was carried out as follows:

Sample E:

(1) Visual magnaglo and penetrant inspections were made.

(2) The angle was sectioned and the fracture surface was examined.

(3) A section 3/8 in. thick, transverse to the crack, was cut, polished and etched with 6% nital solution.

(4) X-ray diffraction examinations were made on boiler deposits

and scale taken from the water and furnace sides of the plates.

(5) Chemical and spectrographic analyses were made on metal samples from the head and furnace plates. The boiler deposit was analyzed for Ca^{++} and Na^{+} by flame photometer, and was analyzed spectrographically for other elements. Spectrographic and wet analyses were made on the 5-pass and 2-pass weld deposits.

(6) Microspecimens taken in the weld and crack regions were examined.

(7) A Rockwell B hardness survey was made on a section cut through the weld-crack region.

(8) Tensile tests, Charpy V notch tests and Hounsfield slow bend tests were carried out on the head and furnace plates.

Samples A, B, C and D:

In addition to the tests carried out on sample E (items 1-8 inclusive) four angle samples, A, B, C and D, taken from other positions along the fracture, and submitted later than E, were examined as follows:

(9) Slices, 1/2 in. thick, were cut from each angle and were surface ground and etched for evidence of weld overlap.

(10) Oxide samples were obtained from the crack.

Main Fracture Sample:

(11) A section of furnace plate containing the main fracture close to its point of origin was also supplied later by Dominion Bridge Company, and the fracture was examined metallographically.

Samples F and G:

A plate sample, F, and a sandwich sample, G, were prepared from plate after removal of all mill scale and were heat treated by the

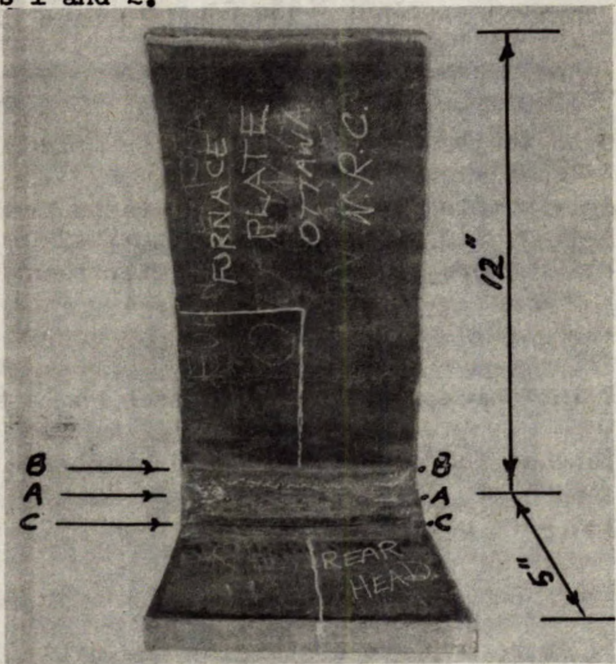
Dominion Bridge Company at 1150°F to provide X-ray samples in the stress-relieved condition. Examination of the oxides from the surface of sample F and the crevice of sample G was carried out.

(12) X-ray diffraction patterns were obtained on oxides developed on samples F and G and the patterns were compared with oxide patterns obtained on scale removed from the cracks present in samples A-E.

RESULTS ON SAMPLE E

(1) Visual, Magnaglo and Penetrant Inspection

The appearance of the cracked boiler sample "as-received" is shown in Figures 1 and 2.



(X 1/5)

Fig. 1. - Cracked angle, Sample E (furnace plate at top; rear head sheet at bottom). This view illustrates the water surface and fillet weld, "A-A". The cracks in the specimen submitted were located at the toe of the fillet weld, principally in the axis "C-C", although a 1/8 in. 45° crack was also observed at the toe of the weld on the furnace side, axis "B-B".

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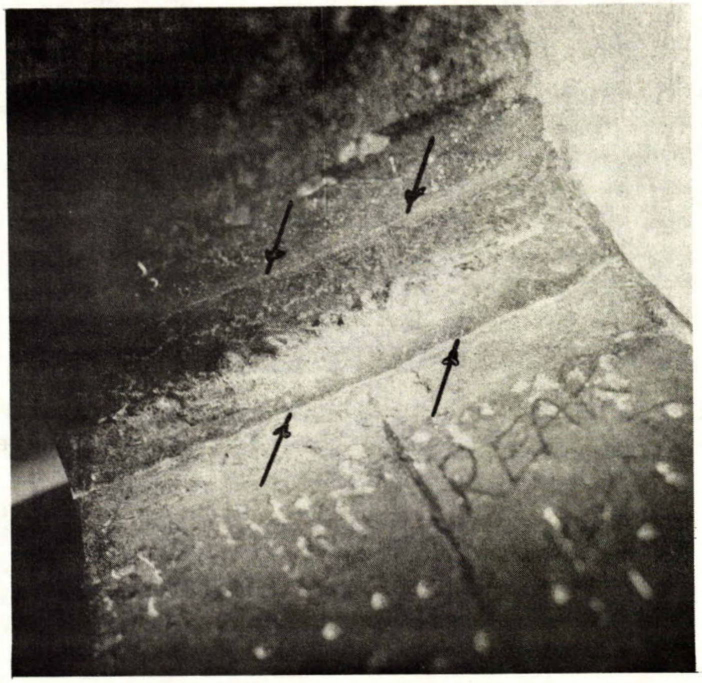
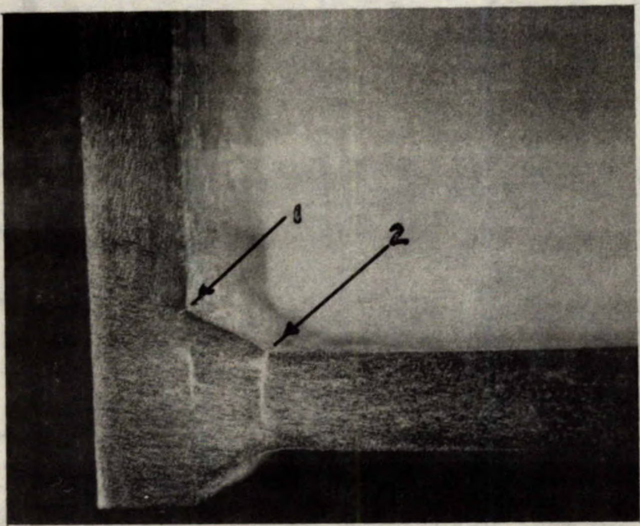


(X 1/2)

<u>Fig. 2</u>. - Enlarged area of Figure 1, showing the fillet weld. Viewed under fluorescent light with the toe cracks outlined by magnetic particles (arrows).

In the particular sample submitted, the crack at the rear tube sheet had extended through four-fifths of the plate section (arrow 2, Figure 3) and the crack at the fillet weld adjacent to the furnace plate was relatively small (arrow 1, Figure 3).



X 2/3

Fig. 3. - *Cross-sectional view of cracks, outlined with magnetic particles and viewed under fluorescent light. The furnace plate is shown at the left of the picture, the tube sheet at the right of the picture. Both cracks opened to the water surface, arrows 1 and 2.

As illustrated in the drawing supplied by the Dominion Bridge Company, in other areas the crack marked by arrow 1, Figure 3, had completely penetrated the furnace plate.

(2) Appearance of Fracture, Sample E

The section oulined in Figure 1 was cut from the angle and was broken open to allow inspection of the fracture surface. The appearance of the fracture, opened at the larger crack, is shown in Figure 4.

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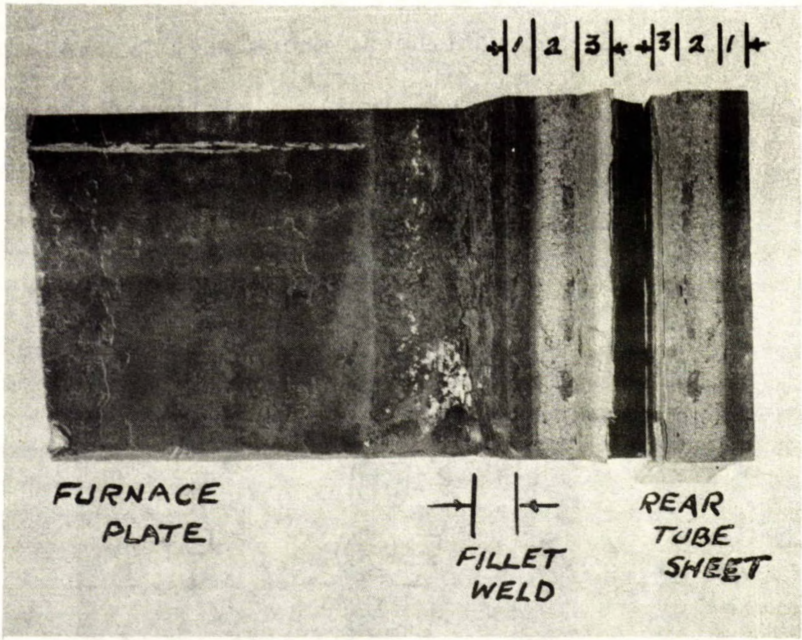
*This section, when inspected by fluorescent penetrant oil, ZL-1-B, "Zyglo", gave crack indications identical to those shown in Figure 3.



(X 2/3)

Fig. 4 - Fracture broken open for inspection.

Three zones are visible on the fracture surface. Zone 1 was adjacent to the water side; the fracture was smooth and was covered with black oxide. Zone 2 was a more recent part of the fracture and appeared ragged but had been tightly* closed, evidenced by its bright appearance when opened. Zone 3 was fibrous and tough-appearing; this part of the fracture was made at the Mines Branch when the crack was opened.

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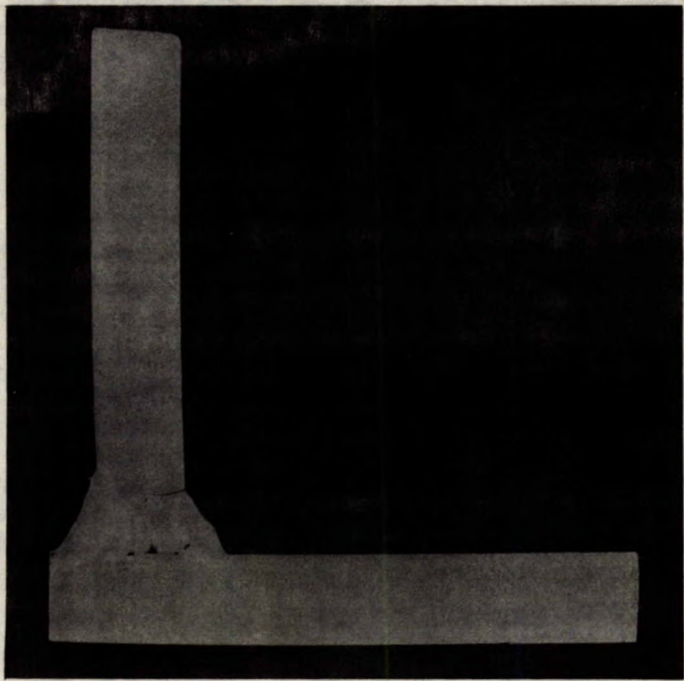
*A few patches of oxidation were visible when this part of the fracture was examined.

(3) Appearance of Section Cut Transversely Through the Fillet Weld, After Etching with 6% Nital

This section was cut, polished, and etched by swabbing with 6% nital to reveal the weld structure in the vicinity of the cracks (see Figure 5).



(X 2/3)

Fig. 5. - Transverse section through the weld.

The tube sheet is illustrated at the left, the furnace plate at the bottom of the picture. The water side and cracked 2-pass fillet weld are shown at the top and right, respectively. A 5-pass fillet weld is shown fastening the combustion side of the tube sheet to the furnace plate.

Note that the fillet weld, toe areas, provide notches where the cracks originate, also that the geometry of the fillet weld approximates a 60°, 30°, 90° section rather than a 45°, 45°, 90° deposit. The older part of the crack has opened, while the newer part remained tightly closed.

(4) X-Ray Diffraction Analysis of Scale and Boiler Deposit, Sample E

X-ray diffraction studies were carried out on 6 specimens from sample E identified as follows:

(a) Black Scale (Water Side) - from surface of furnace plate.

(b) Brown Boiler Deposit (Water Side) - from head sheet.

(c) Black Scale from Crack (Water Side) - black oxide from surface of older part of crack.

(d) Boiler Deposit - boiler deposit sample from Dominion Bridge Company.

(e) Sample of Black Oxide - taken from beneath the superficial brown deposit which overlay the 2-pass weld on the water side.

(f) Combustion Side - sample of black, high temperature oxide taken from the combustion side of the furnace plate.

The results of the x-ray analyses identify the boiler deposits b and d as anhydrite ($CaSO_4$), Plaster of Paris ($CaSO_4\frac{1}{2}H_2O$), and an amorphous constituent. The black oxide samples a and c contained $CaCO_3$, $CaSO_4$ and amorphous material with traces of hematite and magnetite present on the water side and on the old part of the crack surface. Sample e was identified as hematite and anhydrite with traces of calcite. Sample f was identified as magnetite (Fe_3O_4), high temperature oxide.

The significant result is believed to be the presence of traces of Fe_3O_4, high temperature oxide, on the darkened part of the crack surface.

(5) Chemical and Spectrographic Analysis of Furnace and Head Plate, Sample E

TABLE 3

Mines Branch Analysis (Wet Analyses)

Sample E Identification	Element (%)								
	C	Mn	Si	S	P	Cu	Ni	Cr	Mo
Furnace	0.18	0.38	<0.01	0.036	0.013	0.26	0.10	0.08	0.03
Rear Head	0.17	0.34	<0.01	0.040	0.014	0.28	0.12	0.09	0.04

The trace silicon content identifies the steel as rimmed steel. The chemical composition conforms to the requirements of ASTM-A-285/C for Firebox quality steel plate. (The rim is visible on both the head plate and furnace plate etched with 6% nital, Figure 5.)

TABLE 4

Mines Branch Semi-Quantitative Spectrographic Analyses

Sample E Identification	Element (%)								
	Ni	Cr	Mo	Co	V	Al	Cu	Sn	As
Furnace Plate	0.09	0.09	0.07	0.005	N.D.	0.004	0.3	0.015	N.D.
Head Plate	0.07	0.09	0.05	0.005	N.D.	0.004	0.3	0.015	N.D.

N.D. - not detected.

Flame Photometer Tests for Ca^{++} and Na^{+}: When taken on the brown boiler scale these gave a strong calcium flame and a result which showed practically no Na^{+} in the deposit.

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TABLE 5

Chemical and Spectrographic Analysis of Weld Deposits*

Sample	Element (%)										
	C	Mn	Si	S	P	Cr	V	Mo[x]	Ni[x]	Al[x]	B[x]
5-pass weld	0.10	0.82	0.58	0.024	0.022	0.07	0.02	<0.02	0.09	0.01	N.D.
2-pass weld	0.10	0.72	0.51	0.021	0.053	0.06	0.02	<0.02	0.09	0.009	N.D.

* - Weld deposits on sample E.
x - Spectrographic analysis.
N.D. - Not detected.

The weld deposits contain residual quantities of chromium, nickel and vanadium, but are considered normal for metal of 60,000 psi ultimate strength except for the relatively high phosphorous content, 0.058%, of the cracked weld.

TABLE 6

Spectrographic Analysis of Boiler Deposits, Sample E (Semi-Quantitative)

(In percent)

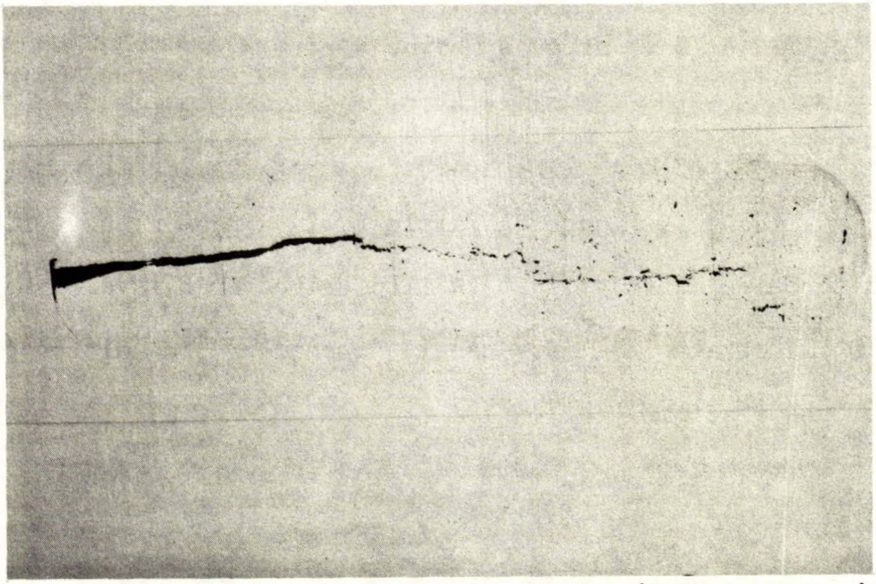
Element	Boiler Deposit Adjacent to Weld	Boiler Deposit from Inside of Crack (Oxidized Zone)	Boiler Deposit from Surface of Rear Head
Fe	15.0	P.C.	4.5
Ca	P.C.	10.0	P.C.
Mg	9.0	2.0	7.5
Na	N.D.	N.D.	1.0
Ba	0.04	1.0	0.04
Si	1.0	0.8	1.5
Mn	0.3	1.5	0.3
Al	0.4	0.2	0.4
Cu	0.05	0.6	0.03
Zn	0.3	N.D.	0.3
Sr	0.3	N.D.	0.3
Ni	0.04	0.5	0.02
Ti	0.15	N.D.	0.2
Pb	0.15	N.D.	0.15
Cd	0.005	0.3	0.005
B	0.005	N.D.	0.005
Cr	0.03	0.15	0.02
V	0.008	N.D.	0.009
Zr	0.003	N.D.	0.004

N.D. - not detected P.C. - primary constituent

(6) Metallography, Sample E

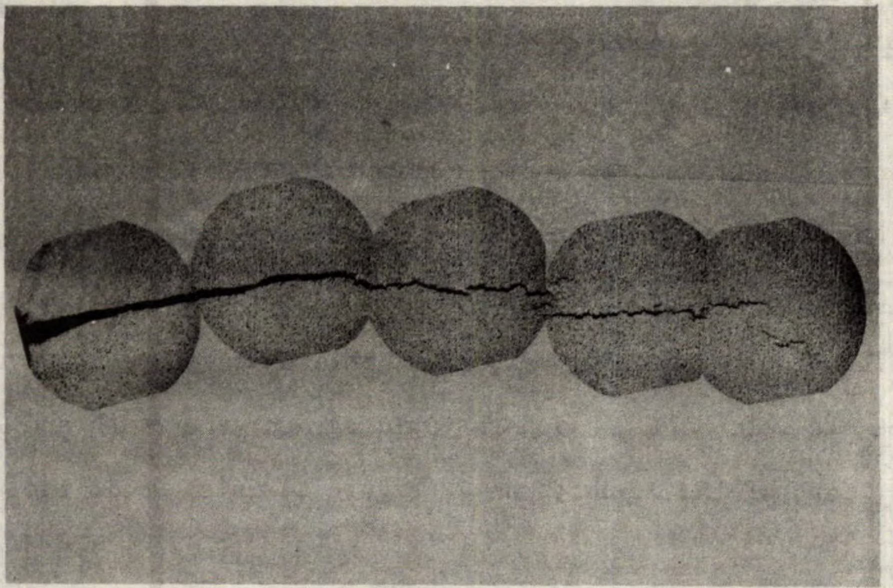
Composite photomicrographs, Figures 6 and 7, illustrate the appearance of a transverse section through the larger crack at the toe of the 2-pass weld on specimen E. The crack originated in the spheroidized area of the head plate at the toe of the fillet weld.

The smooth and oxidized part of this crack (Zone 1, Figure 4) occupies the left half of each photomicrograph; the rough and intergranular part of the crack (Zone 2, Figure 4) is shown in the right half.



(X18, unetched)

Fig. 6. - Transverse section through crack adjacent to the head plate, Sample E.



(X18, etched in 2% nital solution)

Fig. 7. - Same area as above.

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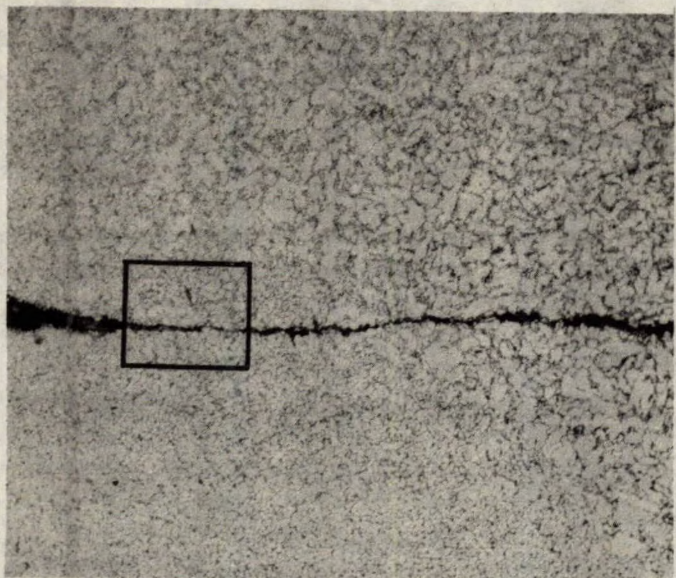
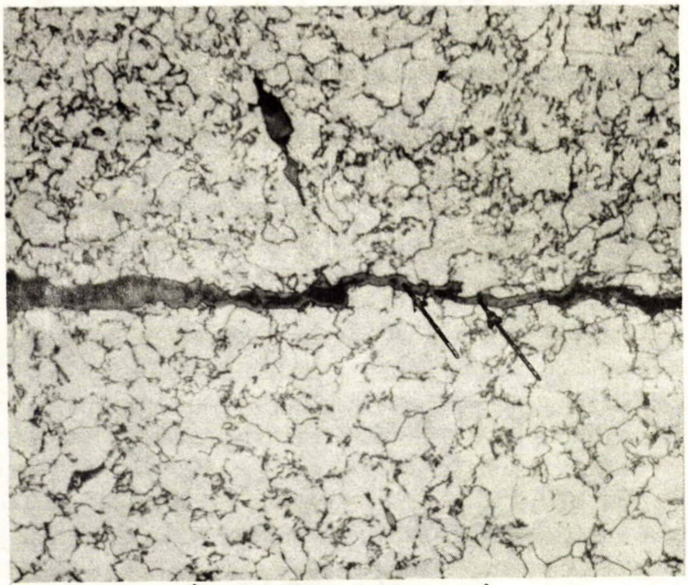
The transcrystalline appearance of the oxidized part of the larger crack (Zone 1, Figure 4, Sample E) in a region where it happened to be relatively tight is illustrated in Figures 8 and 9. Figure 10 illustrates the more usual, "opened-up", condition of this region of the fracture.



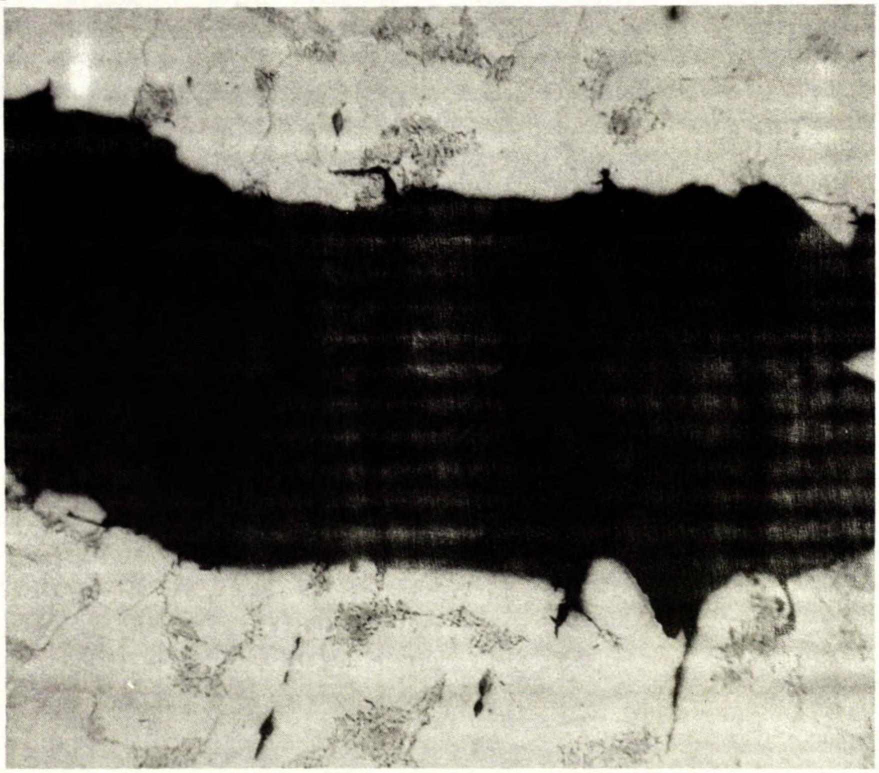
(X100, etched in 2% nital solution)

Fig. 8. - Transverse section through larger crack adjacent to head plate (2-pass weld, Sample E).



(X500, etched in 2% nital solution)

Fig. 9. - Same sample as Figure 8, with the area outlined in Figure 8 magnified to show (arrows) the transcrystalline path of the fracture in zone 1.



(X200, etched in 2% nital solution)

Fig. 10. - Transverse section, old part of larger crack, adjacent to head plate, Sample E.

-

Figure 11, below, illustrates the appearance of the smaller crack adjacent to the furnace plate at the toe of the 2-pass weld on sample E. This smaller crack appeared to be mainly transcrystalline.

(X750, etched in 2% nital solution)

<u>Fig. 11</u>. - Transverse section, tip of smaller crack, adjacent to furnace plate, Sample E. This crack has not propagated past the heat-affected zone.

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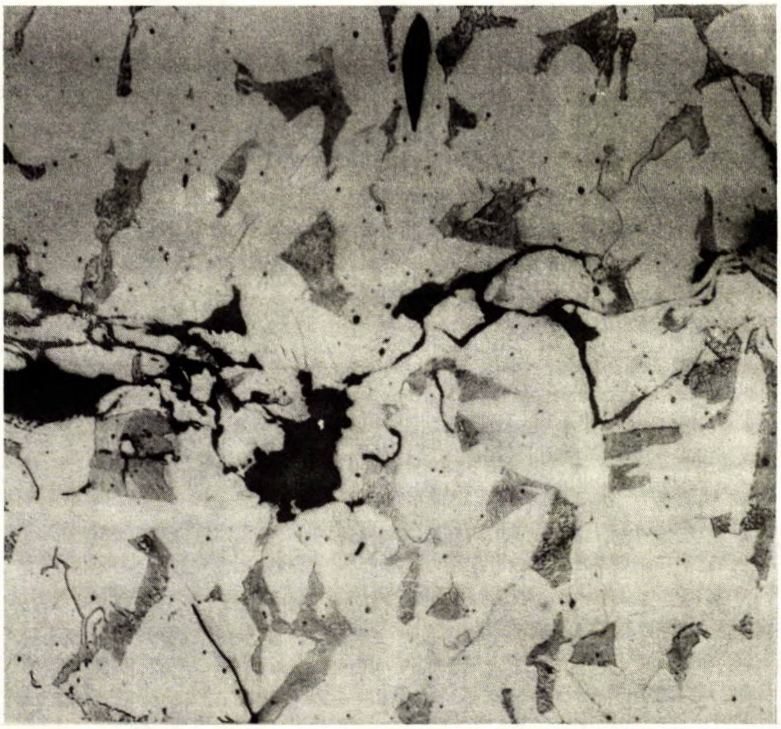
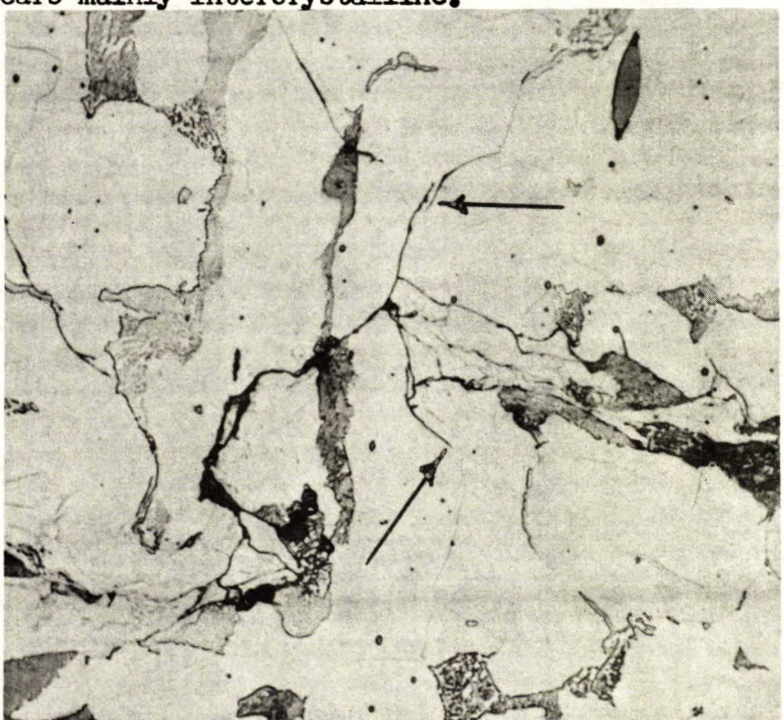
The appearance of typical areas of the intercrystalline part of the larger crack (Zone 2, Figure 4) of sample E is illustrated in Figures 12 and 13.



(X200, etched in 2% nital solution)

Fig. 12. - Transverse section, newer part of larger crack adjacent to head plate, Sample E. In this region the crack appears mainly intercrystalline.



(X750, etched in 2% nital solution)

Fig. 13. - Same sample as above, magnified to show intercrystalline path of the fracture in the deep part of the crack (arrows).

(7) Hardness Survey, Sample E

The results of a hardness survey taken on the plates and in the weld region, using the Rockwell "B" hardness tester, are shown in Figure 14.

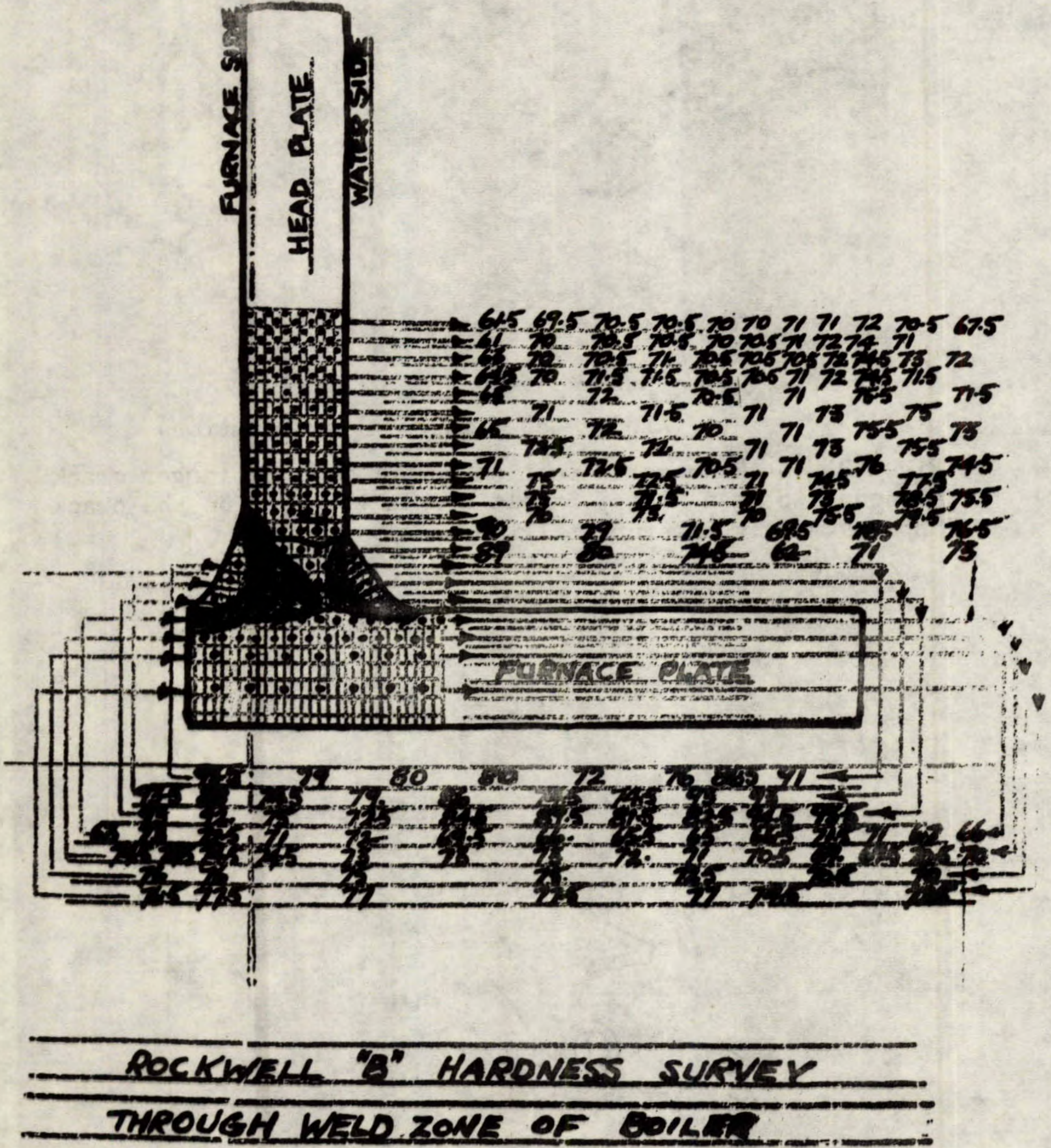


Fig. 14. - Rockwell "B" hardness survey through weld zone of boiler, Sample E. The cracks are located at the toes of the 2-pass weld in the soft parent metal adjacent to the hardened zones beneath the weld deposits.

(8) Mechanical Test Results (Mines Branch), Sample E

TABLE 7

Tensile Tests

Sample No.	*Bar Size	Ultimate Tensile Strength, (psi)	Yield Point (psi)	Elongation (%)	Red. of Area (%)	Brinell Hardness
Furnace Plate #1	0.505 in. dia. 2 in. gauge	59,800	40,000	37.0	60.6	123
Furnace Plate #2	0.505 in. dia. 2 in. gauge	60,000	37,000	37.5	58.6	123
Rear Head Plate #1	0.125 in. dia. 4D . gauge	66,400	38,900	27.6	61.4	128
Rear Head Plate #2	0.125 in. dia. 4D . gauge	66,000	34,800	27.6	61.4	126

*All test bars were taken in the plates normal to the weld.

TABLE 8

Charpy V Notch Impact Tests (ft-lb)

Sample No.	(20°F)	(34°F)	(50°F)	(70°F)	(100°F)
Head Plate	5*	6**	12**	16*	38*
Furnace Plate #1	8*	11**	17*	32**	54**
Furnace Plate #2	8**	12*	16**	23*	38*

*Notches normal to plate surface. **Notched parallel to plate surface.

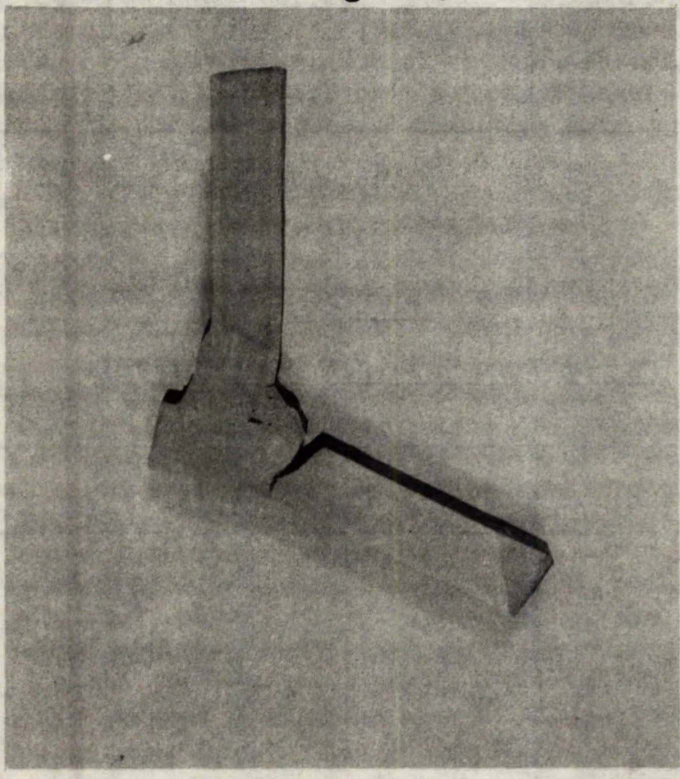
Note: The 15 ft-lb transition temperature of the furnace plate is of the order of 40°F; the 15 ft-lb transition temperature of the head plate appears to be of the order of 65°F.

Three Hounsfield slow-bend bars were taken, two from the furnace plate and one from the head plate (5/16 in. diameter x $1\frac{3}{4}$ in. length, unnotched) and were bent 90° on a 3/32 in. radius without fracture or surface checks.

RESULTS ON SAMPLES A, B, C AND D

(9) Weld Overlap (Observed by Examination of Slices Cut from Samples A, B, C and D)

Examination of slices cut from samples A, B, C and D revealed some overlap of the welds in sample A. The appearance of this overlapping area is illustrated in Figure 15.



(X½; 6% nital etch)

Fig. 15 - Slice of sample A, etched to show overlap of weld deposits.

-

In sample A, extra weld passes, made at the time of welding, are visible on the head plate above both fillet welds. The heated zones of the 5-pass welds (left) overlap the deposits of the weld where toe cracks were present, proving that the smaller weld at the right of the picture was made first. (The angle has been bent to open the crack for inspection.)

It will be noted that in this sample, A, unlike sample E, the crack at the toe of the 2-pass weld adjacent to the furnace plate is considerably larger than the crack next to the head plate. Also, the rim present on the plates is visible in Figure 15.

(10) Identification of Oxide Present in Old Part of Fracture Surface

The results of X-ray diffraction examination of oxides taken from the cracks of samples A - D confirmed the previous results on sample E.

RESULTS ON ORIGINAL FRACTURE SAMPLE

(11) Examination of Fracture Surface at Origin

In appearance, this fracture resembled all the other large cracks, having a smooth, transcrystalline aspect on the water side with intercrystalline attack evident in the deeper part of the crack. From the tip of the crack final rupture had completely severed the furnace plate, leaving a 45° shear zone between the intercrystalline crack and the combustion surface of the furnace plate.

Also, like all the crack specimens examined, the crack originated in the soft, spheroidized parent metal at the toe of the weld adjacent to the hardened weld zone.

Except for the presence of the 45° shear fracture, caused by the final rupture, the appearance of this fracture was identical to that of the cracks previously discussed (samples E - A).

RESULTS ON SAMPLES F AND G

(12) X-Ray Diffraction Examination of Samples F and G

X-ray diffraction analysis of the red oxide formed on the 9 in. x 9 in. x 3/8 in. plate sample identified this material as hematite. However, in the crevice of the 3 in. x 3 in. x 2 in. sandwich sample, a black oxide formed and this constituent was identified as pure magnetite. The magnetite pattern obtained from the oxide, formed in the crevice during stress relief treatment at 1150°F, matched the pattern obtained on oxide scrapings taken from the old part of the crack surfaces in samples A - E.

DISCUSSION

Materials:

Mechanical test results, Charpy V notch impact tests, bend tests, chemical analysis, spectrographic analysis, and metallographic examination show that the plates conform to the requirements of ASTM-A-285/C, although the ultimate strength results obtained on head plate material, using 0.125 in. diameter tensile bars, was slightly above the 65,000 psi maximum. Also, the Charpy V notch results on the head plate suggest a 15 ft-lb transition temperature of 65°F, whereas that of the furnace plate is of the order of 40°F.

Both steels were of rimming grade and had well developed rims and silicon contents of less than 0.01%. The ferrite grain sizes of the head and furnace plates were, respectively, No. 8 and No. 7. The Mn/C ratio of the plates was 2:1, phosphorus contents were low, and sulphur contents were of the order of 0.040%.

Analysis of the weld deposit metal showed that this material was normal for a type 60 (60,000 psi ultimate) rod, except that the residual content of chromium nickel and vanadium, together with the manganese present (0.80%), would increase the hardenability of the weld deposit. Also, in the cracked weld the phosphorus content of 0.058% was higher than normal.

Cracks:

The cracks were located at the toe of the fillet weld adjoining the head and furnace plates and originated on the water side. All the cracks started in the soft spheroidized metal immediately adjacent to the hard zone beneath the weld deposit (i.e., in the metallurgical notch, in the presence of a mechanical notch). Failure had occurred without deformation of this metal adjoining the weld. No evidence of cold work was observed when the cracks were examined under the microscope. All the cracks could be classed as brittle, and occurred in ductile material suggesting that the weld was restrained at the time of failure and that the welding stresses were not relieved by deformation.

While the weld deposit metal was stronger than the plate material and had hardness zones as high as Rockwell B 94, this condition is considered normal, and without restraint the welding stresses should have been relieved by plate deformation. The relatively high phosphorus content (0.058%) was, however, higher than normal.

Examination of the larger crack present in samples A to E showed that the crack consisted of two aspects, one of which, an older part, was open to the boiler water and was black and oxidized in appearance.

On this part of the crack, striations normal to the plate surface were observed and the fracture appeared brittle. Beneath the oxidized part of the crack the newer part of the fracture was rough and intergranular in appearance and had remained tightly closed so that oxidation had only occurred in a few patches on the fracture surface.

Examination of the main fracture showed that it also had the two aspects mentioned and, in addition, had an area where final rupture had occurred leaving a 45° shear failure. The origin of this crack, like all other cracks examined, was located in the soft parent metal immediately adjacent to the hardened metal at the toe of the fillet weld.

Examination of the weld deposits showed that the cracked weld had been made before the heavy 5-pass fillet weld was made.

Oxides:

Several types of oxidation product were identified by X-ray diffraction. For example, on the furnace side of the samples, black, magnetic, high temperature Fe_3O_4 was present.

On the water side of the plate the oxide was mainly hematite with traces of magnetite detected after magnetic concentration. Also, in the old part of the crack, hematite and boiler deposit was predominant but, after magnetic concentration of scrapings from the crack surface, magnetite patterns were obtained which matched the magnetite developed synthetically when a sandwich sample was cleaned and heat-treated at 1150°F in the Dominion Bridge Company stress-relief furnace.

The X-ray diffraction and metallographic evidence, while not conclusive, led to the suspicion that, in addition to boiler deposit and corrosion products, traces of high temperature Fe_3O_4 from the stress-relief treatment were present on the older surface of the weld toe cracks.

The brown boiler deposit was essentially $CaSO_4$ or $CaCO_3$, and flame photometer results did not detect Na^+, hence nothing was observed to explain the presence of intercrystalline corrosion in the deeper part of the cracks.

Hypothesis re Origin of Cracks:

Based on the location and appearance of the cracks and on the scale observations, the following hypothesis is postulated for the origin of the cracks:

The original cracks formed by brittle failure in the mechanical-metallurgical notch between strong weld metal and weak parent metal. These cracks formed without deformation under conditions of restraint, probably at the time the heavy 5-pass weld was made, and because of inaccessibility escaped detection. During stress-relief at 1150°F, magnetite formed in the crack on the "older" part of the crack. The cracks at this stage did not progress until additional stress was applied, probably at the time the tubes were welded to the tube sheets. The application of additional stress in the presence of the pre-existing crack opened the "old" crack and allowed stress corrosion to proceed, forming the "newer" intercrystalline part of the crack, resulting in a reduced section and finally in rupture of the furnace plate.

CONCLUSIONS

1. The oxidized part of the larger crack was believed to be transcrystalline and to have occurred when the heavy 5-pass weld was

made on the combustion side of the rear head plate. This part of the fracture occurred without deformation, leaving traces of the chevron pattern indicative of brittle failure.

2. The newer part of the larger crack was intercrystalline, indicating that the original crack progressed by stress corrosion attack until the section was sufficiently reduced for rupture. This part of the fracture could have been induced by the application of additional stress when the tubes were welded to the head sheet.

3. Failure occurred in every instance in the mechanical-metallurgical notch at the toes of the 2-pass weld.

4. The plate material conformed to ASTM-A-285/C and was considered satisfactory. The weld deposits were considered normal for class 60 rod, except for slightly high residual contents and the presence of 0.058% phosphorus in the 2-pass weld.

5. No evidence of cold-worked metal, suggestive of fatigue failure, was observed in the vicinity of any of the cracks examined.

RECOMMENDATIONS

1. The suitability of the heavy 5-pass weld behind the lighter 2-pass weld may need to be reconsidered under the conditions of restraint present in this design of boiler.

2. Magnaflux inspection, after completion of the weld and the stress-relief treatment, might assist in detecting weld cracks prior to service.

3. Selection of weld metal having lower residual contents, and having mechanical properties and hardness matching those of the boiler plate, might allow some relief of welding stresses by deforma-

tion prior to the stress-relief heat treatment.

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