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METALLURGICAL EXAMINATION OF BOILER SHELL PLATE AND BROKEN RIVETS FROM STARBOARD BOILER OF S. S. WINNIPEG

by

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PHYSICAL METALLURGY DIVISION

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ABSTRACT

Examination of boiler shell plate taken from the steamship "Winnipeg" showed that the plate was semi-killed and had not been stress-relieved before service. The mechanical properties of the steel at the time of testing were satisfactory, but in service the cracks propagated without deformation.

The cracks were predominantly intercrystalline and were filled with corrosion product. Failure appeared to result from stress-corrosion (caustic cracking), possibly assisted by strain-ageing and working of the boiler seam.

Failure originated in radial cracks, present in cold-worked metal at the rivet hole surfaces, which slowly propagated to result in continuous cracking of the ligaments in the two outer rows of rivets.

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(19 pages, 3 tables, 18 illus.)

INTRODUCTION

On January 31, 1958, a section of boiler shell plate, 16 in. x 8 in. x 1 1/16 in. thick, and two broken rivets were submitted to the Physical Metallurgy Division, for metallurgical examination, by Mr. A. Cumyn, Director, Steamship Inspection Service, Board of Steamship Inspection, Department of Transport, Ottawa, Ontario. In an accompanying covering letter, File Nos. 9562-1144 and 9400-43, Mr. Cumyn stated that the plate sample was a section of shell plate removed from the starboard boiler of S. S. Winnipeg, berthed at Toronto.

The plate was severely cracked between the rivet holes and the two rivets had fractured 1/2 in. and 3/4 in. below the points. Mr. Cumyn requested that metallurgical examination be made of the plate and rivets to determine the cause of cracking.

Other information about the boiler is that it is 13 ft. 6 in. diameter by 11 ft. 0 in. long and operates at a working pressure of 185 psi. The boiler was built in 1926 by Richardson Westgart Co., Ltd., West Hartlepool, England. For the last five years the feed water has been treated with a proprietary compound but there is no reliable information about prior treatment, although it is probable that for some years ordinary sal-soda (Na_2CO_3) comprised the only boiler water treatment.

Examination of the plate and rivet samples was carried out as follows:

(1) Visual, magnetic particle and radiographic examination.

(2) Mechanical, tensile and impact tests.

(3) Metallographic examination of plate and rivet specimens.

(4) Chemical and spectrographic analyses.

(5) Hardness surveys of plate metal adjacent to rivet holes and of rivet sections.

INVESTIGATION DETAILS

(1) Visual, Magnetic Particle and Radiographic Examination

The appearance of the water surface and of the outer plate surface is illustrated in Figures 1 and 2 respectively. The cracks have been outlined by the magnetic particle method.

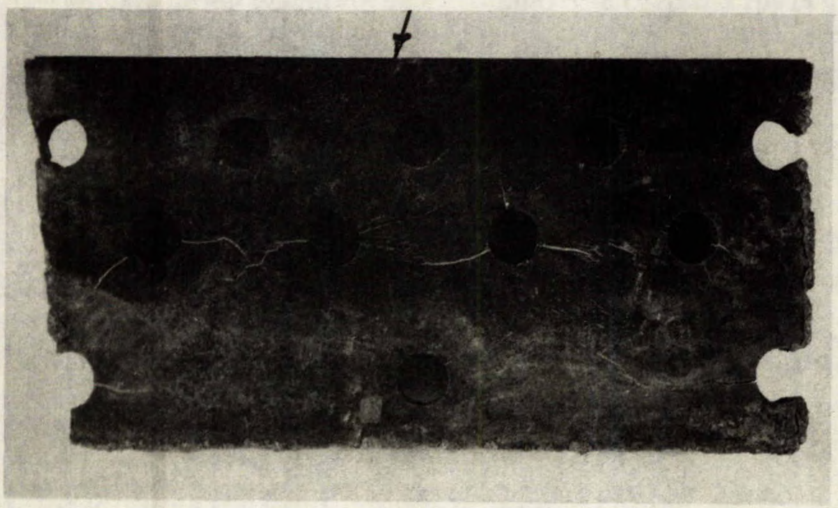

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Figure 1. - Water side of shell plate (concave surface). The longitudinal seam is indicated by the arrow (top). Cracking is most extensive along the two outer rows of rivets.

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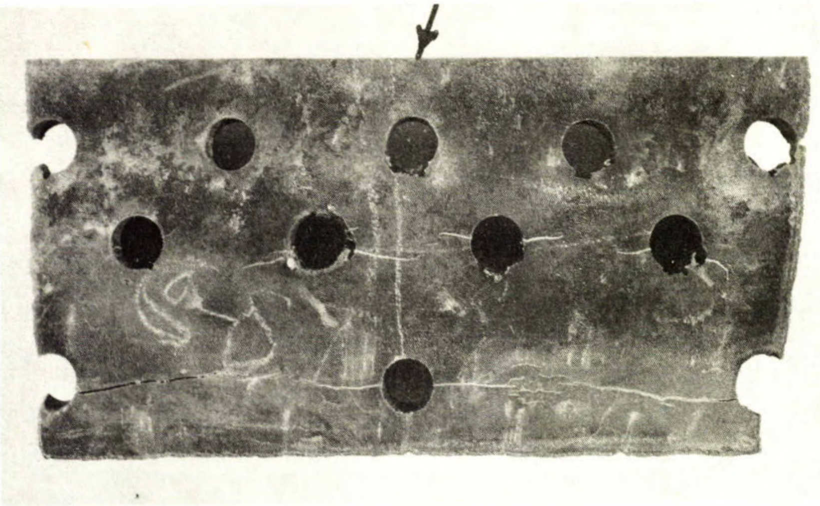

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Figure 2. - Outer surface of shell plate (convex surface). The longitudinal seam is marked by the arrow (bottom). The cracks are continuous in the ligaments of the outer rows of rivets, but are almost completely absent in the ligaments of the inner row of rivets.

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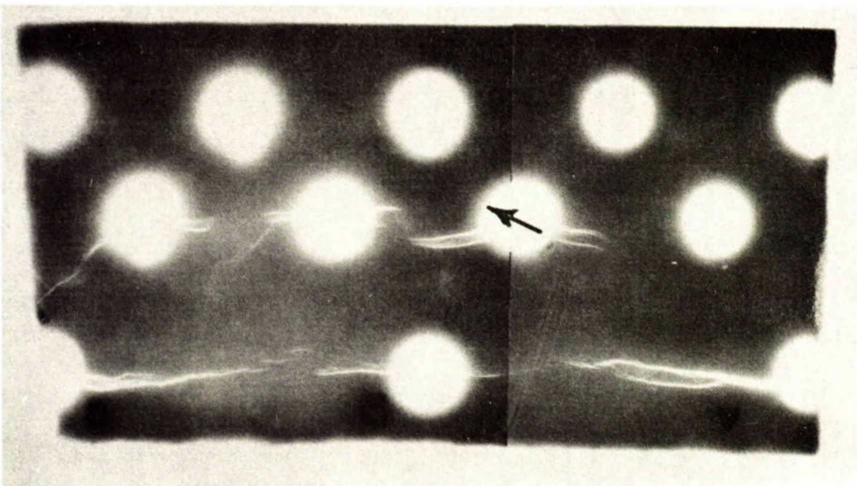
The appearance of a composite X-ray photograph prepared from radiographs in illustrated in Figure 3.



(Approx. 1/4 size)

Figure 3. - Composite X-ray view of cracked shell plate. The larger cracks are clearly visible; the smaller cracks are more difficult to see than on the original radiograph. The arrow marks the location of one of the radial cracks examined under the microscope.

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Figure 4 illustrates the appearance of the plate after sectioning for mechanical tests. The two broken rivets, "D" and "E", are illustrated at the top of the photograph.

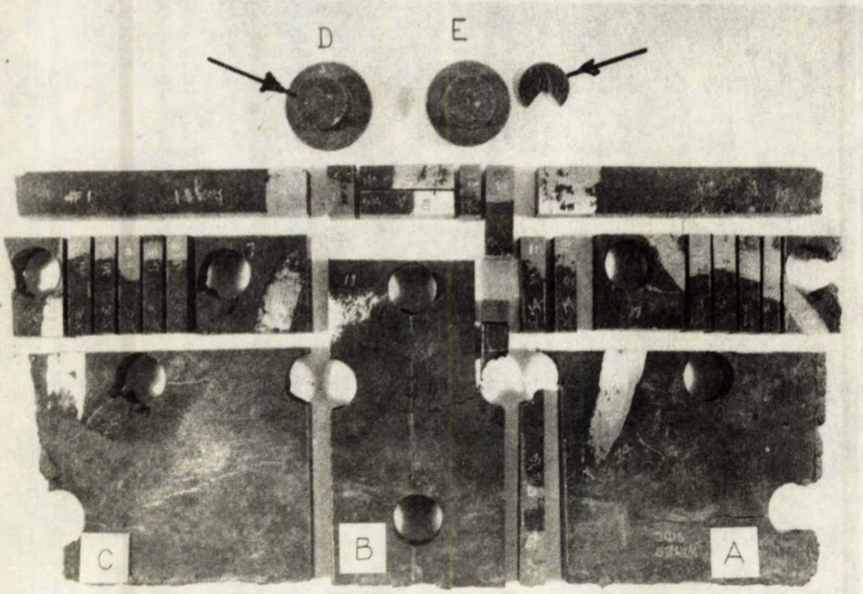

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Figure 4.- Sectioned shell plate and broken rivets D and E. The metal pieces were numbered 1 to 26, and in the case of Charpy bars those taken adjacent to the water surface were marked W and those adjacent to the outer surface were marked 0. The rivet surfaces are indicated by the arrows.

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(2) Mechanical Tests

Sections Nos. 1 and 14, illustrated at the top left and right respectively of Figure 4, were machined into 0.505 in. tensile bars. These test bars were cut from the centre of the plate, adjacent and parallel to the longitudinal seam. Sections 15 and 16 were split in the middle and two substandard Hounsfield tensile bars were taken close to the water surface and two were taken close to the outer surface. These bars were normal to the seam. The substandard bars were identified as 15-0 or 16-0 adjacent to the outer plate surface and 15-W or 16-W adjacent to the water surface of the plate.

The results of the tensile tests are shown in Table 1.

TABLE 1

Results of Tensile Tests.

Bar No.	Location	Area, in^2	Break, lb	U.T.S., psi.	Yield* or 0.2% Proof** Stress, psi	Elongation, %	R.A., %	BHN
	Parallel							
1	to seam	.201	13,760	68,500	42,600*	34% in 2 in.	54.0	126
14	" "	.200	13,500	67,500	37,500**	36% in 2 in.	56.2	128
	Normal							
ᵒ15-0	to seam	.0125	890	71,200	66,800**	22% in ½ in.	40.0	
ᵒ16-0	" "	.0123	900	73,200	51,200**	22% in ½ in.	41.7	
15-W	" "	.0123	858	69,600	———	32% in ½ in.	61.6	
16-W	" "	.0123	872	70,800	48,700**	36% in ½ in.	65.0	

Bars Nos. 1 and 14 were 0.505 in. diameter.

Bars Nos. 15-0, 16-0, 15-W and 16-W were substandard Hounsfield bars.

oFinal rupture occurred through gauge length punch mark; 45° shear fractures in bars 15-0 and 16-0, cup-cone fractures in bars 1, 14, 15-W and 16-W.

The results of the Charpy V notch impact tests are shown in Table 2 and are plotted in Figure 5.

TABLE 2

Charpy Impact Strength (ft-lb) of Boiler Shell Plate.

TESTING TEMPERATURE (°F)							
	-40	0	20	30	40	80	200
(2-W)	2	(3-W) 3	(4-W) 7	(5-W) 5	(6-W) 8	(9-W) 25	(10-W) 48
(2-0)	2	(3-0) 4	(4-0) 8	(5-0) 6	(6-0) 4	(9-0) 24	(10-0) 48
(18-W)	3	(18-0) 4	(19-W) 10	(19-0) 10	(20-W) 8	(20-0) 24	(21-W) 64
Average (ft-lb)	2.3	3.7	8.3	7	6.7	24.3	54

Code:- e.g., 2-W: section 2 (Figure 4), water side,
2-0: " " 2 " ", outer side.

Bar identification numbers are shown inside the brackets.

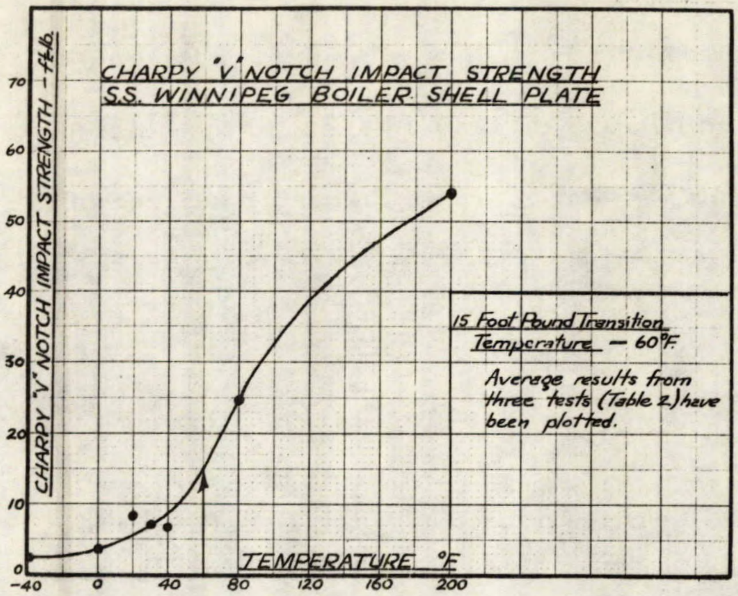


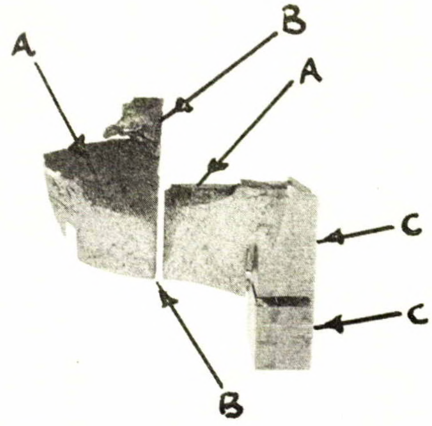
Figure 5. - Charpy V-notch impact strength results, plotted.

The 15 ft. lb. transition temperature measured adjacent to the water side was 60°F and adjacent to the outer side of the shell was 64°F. The transition curves indicate no significant variation in impact strength between the water and outer surface.

The slightly lower impact values obtained at testing temperatures of 30°F and 40°F, compared with values obtained at 20°F, are not considered significant.

(3) Metallographic Examination

The radial crack, marked by the arrow in Figure 3, was cut out of the plate for microexamination. This crack was not visible without use of magnetic particle or radiographic methods but when sectioned the crack was continuous and the metal separated into two pieces. The appearance of this cracked section is illustrated in Figure 6.



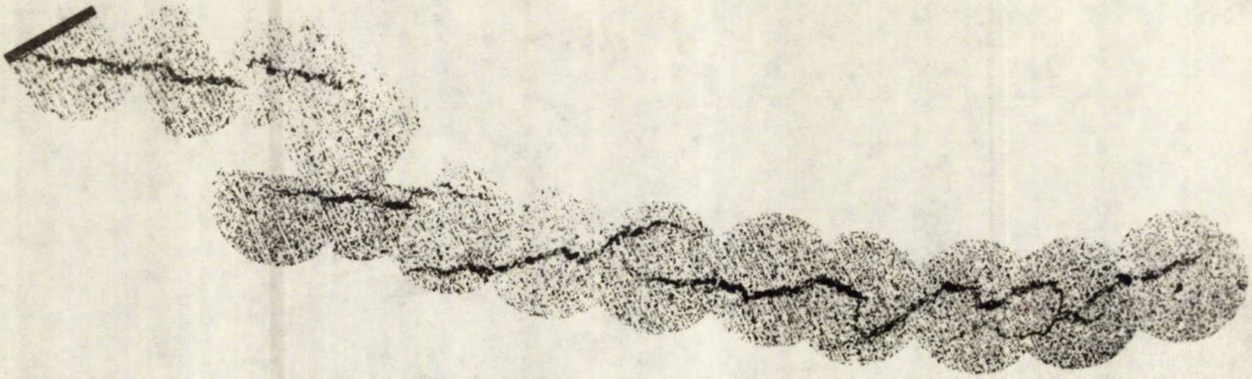
(Approx. 1/2 actual size)

Figure 6. - Radial crack at rivet hole - opened to show crack surfaces. The arrows A indicate the hole surface, arrows B mark the water side of the plate, and arrows C mark the outer plate surface. The crack surface appeared intergranular.

The appearance of a transverse microsection through the radial crack is illustrated in Figures 7 and 8 at 15 diameters. The crack appears discontinuous in the plane illustrated, but is, in fact, continuous and mainly intercrystalline.

(X15)

Figure 7. - "As polished" radial crack at second row rivet hole. The water side of the plate is shown at the extreme left of the plate. This crack is continuous, connected, and mainly intercrystalline.



(X15, etched in 2% nital)

Figure 8. - Same area as Figure 7.

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Figure 9 shows typical intercrystalline secondary cracks adjoining the larger crack illustrated in Figures 6, 7 and 8.

(X750)

Figure 9. - Secondary intercrystalline crack. The intercrystalline path of the crack is illustrated. Carbide attack is also visible.

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Figures 10 and 11 illustrate the appearance of typical radial cracks at rivet holes. The intercrystalline path of a similar crack is illustrated in Figure 11.

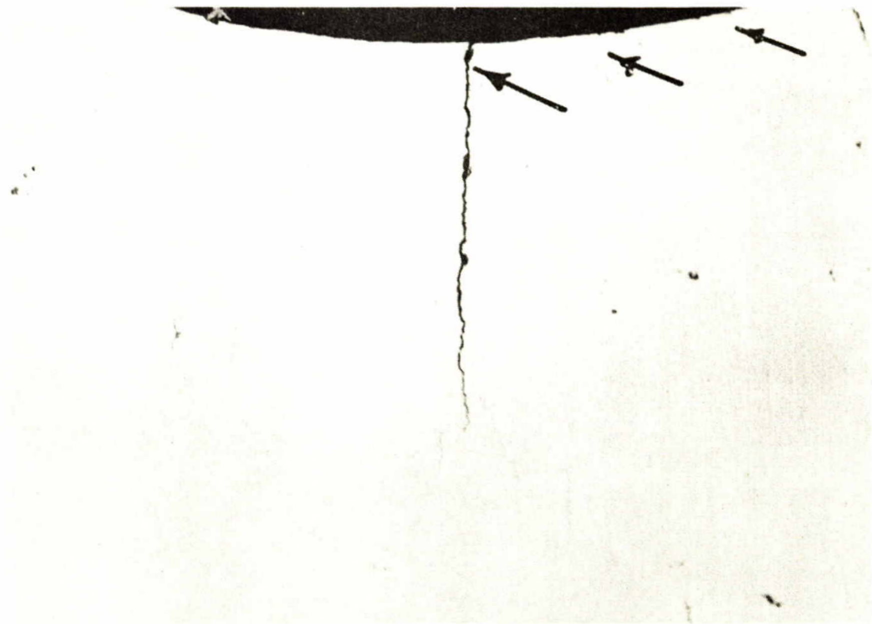
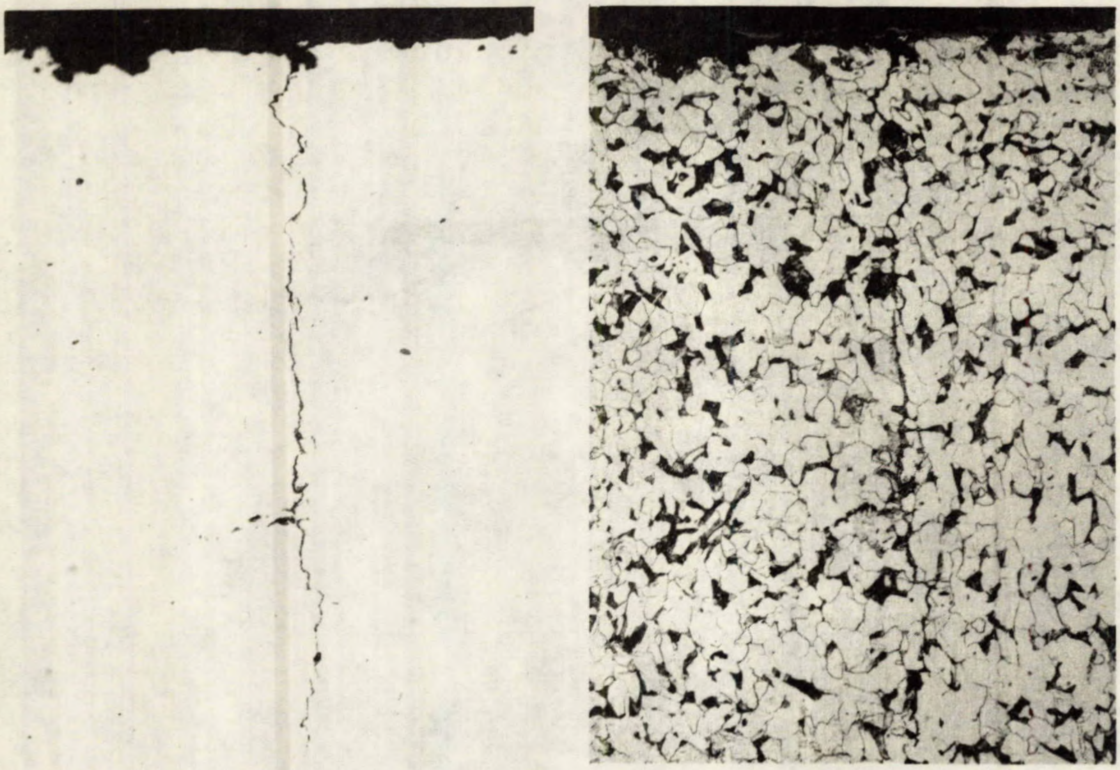


Figure 10. - Radial cracks at rivet hole (arrows). Also, note the numerous small cracks at the tip of the larger crack.



(X100, as polished) (X100, etched in 2% nital)

Figure 11. - Views of a typical intercrystalline crack extending in a radial direction from a rivet hole. This small crack in an early stage of development is believed similar to those which were normal to the applied stress and propagated to form the large ligament cracks.

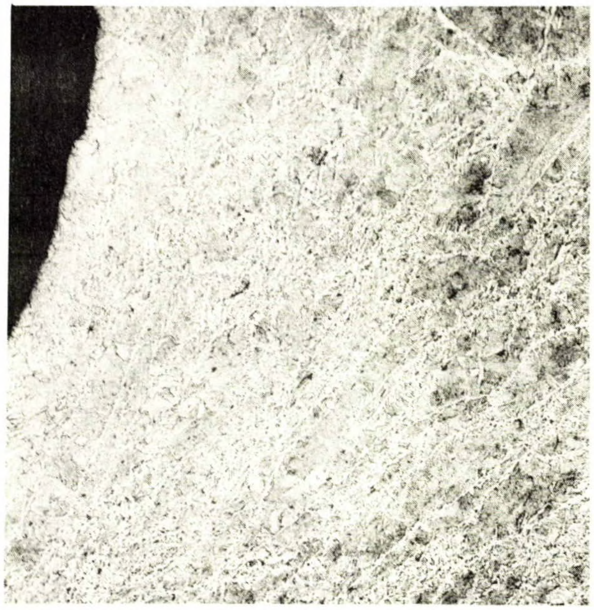
Metallographic examination of secondary cracks associated with the large cracks and of radial rivet hole cracks showed these to be mainly intercrystalline. In the deeper part of the crack there were local areas, situated between branches of the crack, where a few cold-worked ferrite grains were observed. In some areas, adjacent to the crack, occasional twinning of ferrite grains was observed.

The traces of cold-work and twinning, present in the deeper part of the crack, and the appearance of the fracture suggest that the crack advanced by successive stages of corrosion and rupture. Cracking was predominantly intercrystalline.

The microstructure of the two broken rivets, illustrated in Figures 12 and 13, consisted of pro-eutectoid acicular ferrite and fine pearlite. There was practically no evidence of cold-worked metal at the fillets between the shanks and the points. The appearance of the microstructures suggests better than average riveting practice.

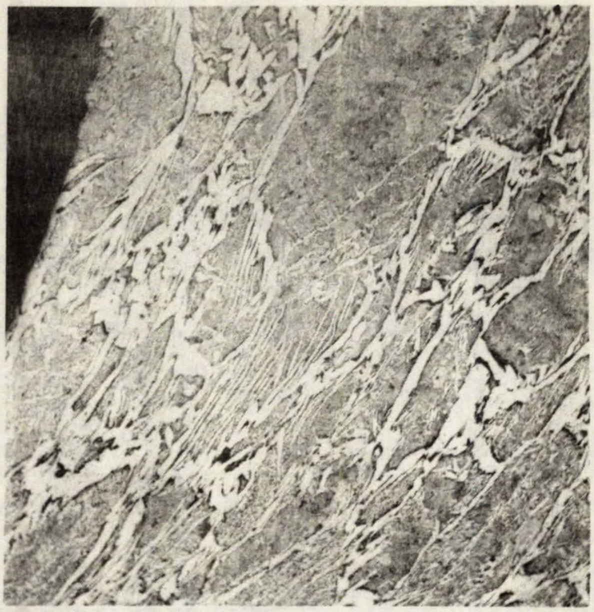
Figure 14 illustrates the quantity of cold-worked metal visible at rivet hole surfaces.

Cracked areas containing twinned ferrite grains are shown in Figures 15 and 16.



(X100)

Figure 12. - Rivet "D" - fillet between point and shank. The driving temperature and the cooling rate after driving were successful in avoiding cold work, grain growth, or a severely quenched microstructure.



(X100)

Figure 13. - Rivet "E" - fillet between point and shank. The structure is similar to that of Figure 12, except that this rivet was probably driven hotter than rivet D, resulting in a slightly coarser grain size.

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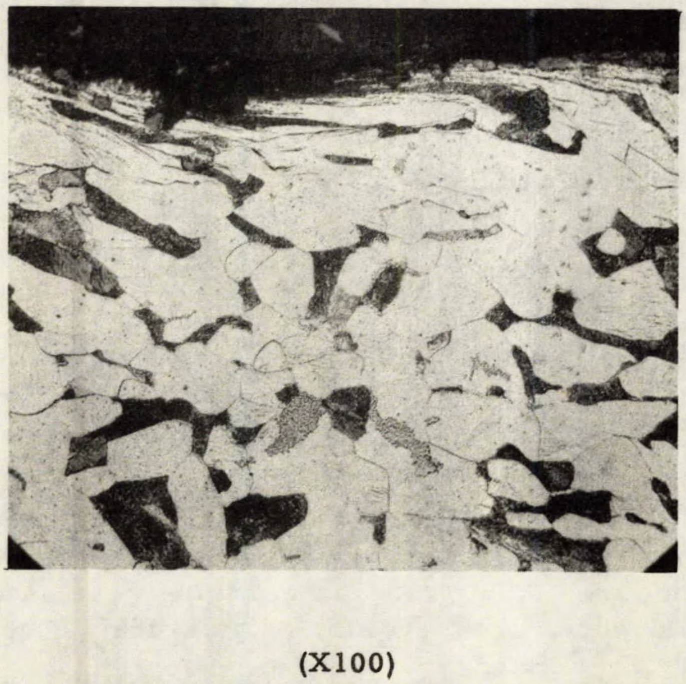

(X100)

Figure 14. - Cold-worked metal at a rivet hole surface. Traces of cold-worked metal are visible at the rivet hole surface. This amount of cold-work is less than is often observed.

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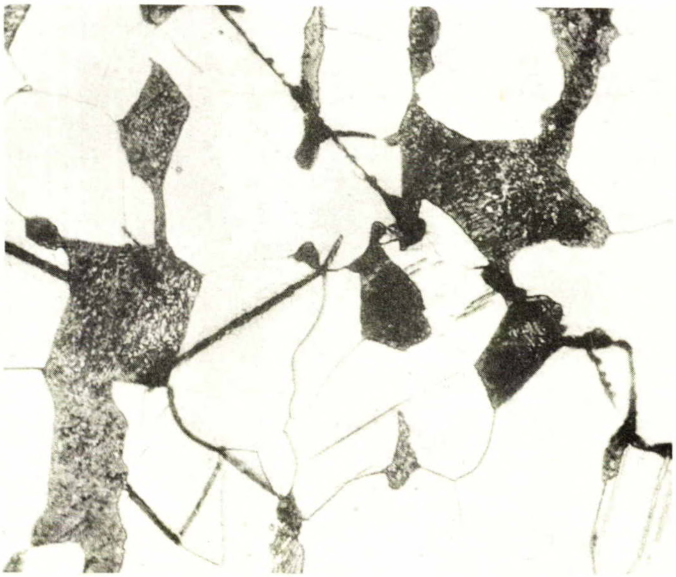
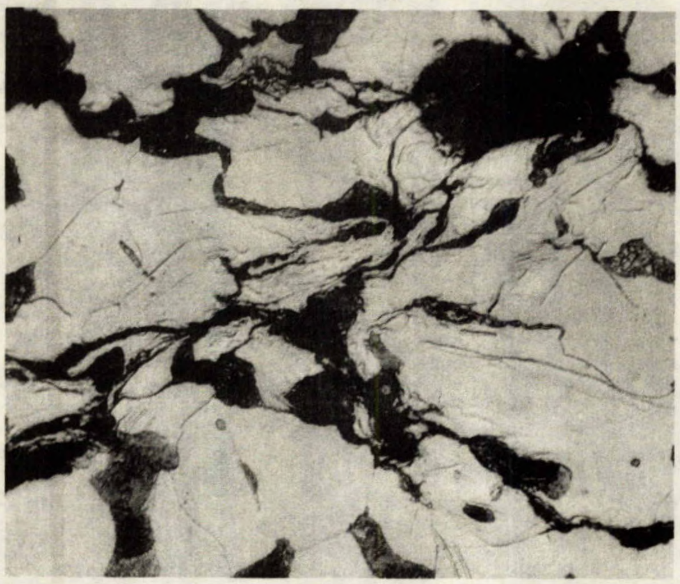
(X750)

Figure 15. - Intercrystalline cracks and twinning of ferrite grains. Twinning of ferrite grains is marked by the arrows.



(X750)

Figure 16. - Twinning and corroded cracks in ferrite grains. The transcrystalline appearance of these cracks in ferrite grains was exceptional.



(X750)

Figure 17. - Cold-worked metal between branches in the deeper part of the crack. The presence of this cold-worked metal suggests working of the plate after crack propagation had severely reduced the ligament section.

(4) Chemical and Spectrographic Analysis

Chemical and spectrographic analyses were made of drillings or powder taken from the boiler plate. The rivets were analyzed by the wet method.

TABLE 3

Chemical and Spectrographic Analyses (%)

	BOILER PLATE	RIVET "D"	RIVET "E"
Carbon	0.25	0.27	0.21
Manganese	0.63	0.71	0.72
Silicon	0.08	0.05	0.05
Sulphur	0.016	0.031	0.029
Phosphorus	0.046	0.044	0.063
Copper	0.04	0.08	0.07
Nickel	0.02	0.05	0.05
Tin	0.003	0.004	0.005
Chromium	0.02		
Molybdenum	0.01		
Aluminum*	0.006		
Vanadium*	0.007		
Tungsten*	N.D.		
Arsenic*	N.D.		

* Spectrographic analysis. N.D., Not detected.

The composition of the boiler plate and rivets conforms to that for AISI-C-1025 steel. The silicon contents, 0.05% to 0.08%, indicate that the plate and rivet steels are "semi-killed" grades.

(5) Hardness Survey of Plate and Rivet Sections

The Brinell hardness of the plate was of the order of 131/134, measured on the transverse section. Surface readings of 134-149 Brinell were obtained. The plate appeared to be slightly harder near the middle and outer rows of rivets than adjacent to the seam, where the tensile test bar hardness was 126-138 Brinell. The results of hardness surveys immediately adjacent to the rivet holes showed slight hardening to 145-149 Brinell.

The results of Rockwell B hardness surveys on longitudinal rivet sections are shown in Figure 18. These hardness values are normal.

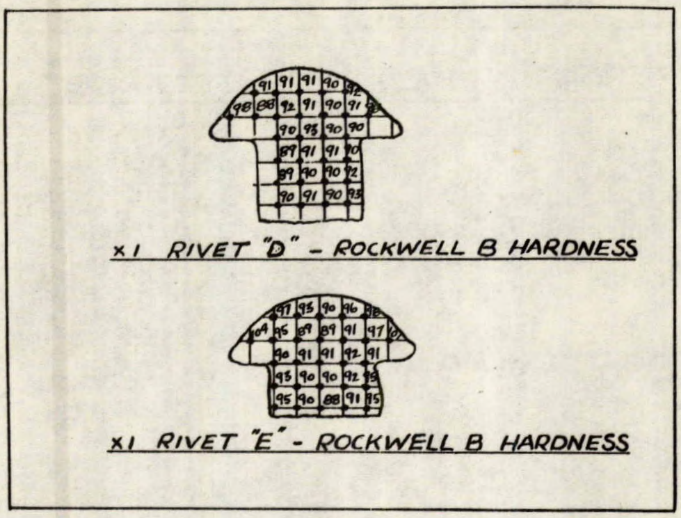


Figure 18. - Rockwell B hardness values on longitudinal sections of of rivets "D" and "E".

DISCUSSION

Cracking in the S.S. "Winnipeg" boiler appeared to be most severe along the outer row of rivets, slightly less severe along the middle row, and practically absent at the inner row of rivets. The direction of the main cracks between ligaments was normal to the principal applied stress (the hoop stress).

Numerous radial cracks were present at rivet holes. Some of these radial cracks, which happened to be oriented at right angles to the stress, appeared to have acted as origins for the large cracks present in the ligaments. The large cracks in the ligaments were generally parallel to the seam. While the original small cracks (present beneath rivet heads in the cold-worked metal at rivet hole surfaces) may have been transcrystalline, subsequent exposure in service has given all the cracks a predominantly intercrystalline appearance.

Secondary cracks, associated with the main cracks, are also predominantly intercrystalline but do show areas, in the deeper part of the cracks, where ferrite grains contain microcracks and show evidence of twinning. Also, in this region between branches of the cracks the metal in local areas is cold-worked. These facts suggest that the cracks have propagated by a combination of corrosion and rupture, where intercrystalline attack occurred and was followed by rapid advance of the crack for a short distance. The areas of rapid advance are marked by twinning and cracked ferrite grains. Presumably, after cracking and relief of the stresses, new surfaces were exposed for corrosion and intercrystalline attack continued. This process, alternating between corrosive attack and local rupture, must have been slow since the boiler has been in service 32 years, and it is probable that the original radial cracks at the rivet hole formed during or soon after the rivets were driven.

The quality of steel used was the usual semi-killed grade which is not classed as "non-ageing", but appeared to retain satisfactory tensile properties in areas which were free from cracks. Some scatter in impact results was observed at temperatures between 0°F and 40°F, but the 15 ft-lb transition temperature was normal for this semi-killed material. The hardness and chemical composition of the plate and rivets appeared to be normal, although the plate was slightly harder at the centre and outer row rivet holes than along the inner row and longitudinal seam.

CONCLUSIONS

1. The chemical composition of the plate and rivets was satisfactory and conformed to the analysis for an AISI-C-1025 grade of "semi-killed" steel.

2. The room temperature tensile strength and tensile ductility appeared satisfactory when measured in areas of metal which were free from cracks.

3. The cracks in the plate are mainly intercrystalline, and typical of caustic cracks. After the cracks extended into the ligaments, local areas of metal adjacent to the cracks were subjected to stresses beyond the yield point, as evidenced by small areas of cold-worked metal adjacent to the deeper part of some cracks.

4. The presence of cracked ferrite grains and ferrite twinning in some crack areas between areas of intergranular cracks suggests that the cracks propagated by corrosive attack followed by local rupture.

5. Failure of this boiler steel plate appeared to result mainly from intercrystalline stress corrosion with working and ageing of the plate as possible contributing factors. Cracking appeared to originate at radial rivet-

<u>hole cracks which were oriented normal to the applied stress and were believed associated with the original riveting of the seam.</u>

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