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OTTAWA March 2, 1946.

REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 2011.

Examination of Welded C.P.R. Locomotive Tube Steel.

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(Copy No. 8.)

Bureau of Mines
Division of Metallic
Minerals

Physical Metallurgy
Research Laboratories

CANADA

DEPARTMENT
OF
MINES AND RESOURCES

Mines and Geology Branch

O T T A W A   March 2, 1946.

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Introduction:

In October, 1945, Mr. A. G. Ralley, Welding Supervisor, Canadian Pacific Railway, Montreal, Quebec, submitted for examination a section of locomotive tube sheet with boiler tubes inserted, which had been flame cut from locomotive No. 3003. The boiler tubes were welded to the tubes sheet by a single pass weld. Nearly every weld showed numerous transverse cracks, some of which extended from one boiler tube hole to another. In several cases it was noted that during the course of service several welds had been made between boiler tube holes, apparently to repair such cracks. These repair welds had been subsequently ground flush to the surface of the tube sheet.

A letter from Mr. Ralley, dated November 2, 1945, (Introduction, cont'd) -

gives the following additional information.

> "The locomotive boiler had a service life of about 15 months during which the locomotive had travelled approximately 130,000 miles. The electrodes used are of the A.W.S. E-6013 type used with A.C. welding equipment. Each weld is made from 6 o'clock to 12 o'clock up both sides. Tube sheets are installed and riveted to the boiler prior to installing tubes which, therefore, will not permit stress relieving. The operating temperature of the weld areas will vary with the amount of scale accumulated on the tube sheet in and around the tube. It will probably vary from 700-900° F. on the fire side. The entire tube area is subjected to residual stresses due to the varying temperatures of the fire box when in operation and standing in the shop. I believe cracks are the result of fatigue due to the number of cycles to which the metal is subjected owing to various fire box temperatures. Railroads in U.S. and Canada are troubled with this condition and considerable research has been done, but, unfortunately no one has found a solution. A number of contributing factors have been set forth, some of which are: water conditions, fatigue, residual stresses caused from welding, scale accumulation on tube sheet and fire box temperatures."

Object of Investigation:

To determine the cause of cracking of welds.

PROCEDURE:

(1) Chemical analysis samples were machined from the sheet and tubes. The results of the analyses are shown below. For the purpose of comparison, C.P.R. Material Specification No. 14-P and No. 5-N are shown for these materials. Since it is not known whether the material submitted was from the front or back of the boiler, both firebox and flange chemical specifications are shown. These specifications are dated Feb. 1/40(No. 5-N) and April 6/42(No. 14-P).

(Continued on next page)

(Procedure, cont'd) -

	Tube Sheet	Tubes	Boiler Tubes, C.P.R. Spec. No. 14-P	Tube Sheet, C.P.R. Spec. No. 5-N Fire box	Tube Sheet, C.P.R. Spec. No. 5-N Flange
		-	Per Cent	-	
Carbon	0.17	0.11	0.08 to 0.18	0.25 max.	-
Phosphorus	0.013	0.042	0.04 max.	0.035 max.	0.04 max.
Sulphur	0.021	0.032	0.045 max.	0.04 max.	0.05 max.
Manganese	0.72	0.66	0.30 to 0.60	0.3/0.5	0.3/0.6
Silicon	0.25	0.06			
Chromium	Trace.	0.24			
Nickel	2.30	None.			
Molybdenum	Trace.	None.			

(2) The sample was photographed in the "as received" condition. To show the number and direction of cracks more readily, they were marked with white ink.

(3) Small tensile test pieces were machined from the tube sheet. Since it was impossible to determine the direction of rolling, the axes of the specimens were maintained parallel to one another and running in an arbitrarily selected direction. Hounsfield Tensometer made by the Birmingham Tool and Gauge Co. for the Tensometer Limited was used for the tensile tests. The machined tensile specimens measured .059 inches in diameter before testing with a gauge length of 3/4 of an inch for percent elongation. The results of these tests are listed below:

Test No.	Yield Strength, p.s.i.	Ultimate Strength, p.s.i.	Elongation, per cent in 3/4 in.	Reduction of area per cent
1	50,000	75,000	30.0	60.0
2	52,500	77,500	32.0	58.0
3	52,500	77,500	35.0	58.0
4	55,000	77,500	35.0	60.0
5	52,500	77,500	32.0	58.0

(4) Transverse weld samples showing characteristic cracks were machined from the material, mounted, polished and etched. One sample, showing numerous cracks of various lengths is shown in Figure 2. The samples were then examined under the microscope.

Figures 3 to 7 show respectively the structures of

(Procedure, cont'd) -

the normal boiler tube material, the normal tube sheet material, the heat affected zone of the tube sheet material, the weld metal and the transition zone of the tube sheet material. Figures 8 to 10 show three stages of crack development, beginning in the weld metal and propagating deeply into the tube sheet material.

DISCUSSION:

A visual examination of the material "as received" reveals numerous weld cracks distributed uniformly around the complete periphery of the weld. In some cases these cracks had propagated from one weld through the tube sheet to an adjacent tube hole. Several machined welds were noted between tube sheet holes. These were apparently areas in which cracks were repaired by welding during the service life of the boiler. In at least one case, a second crack had propagated through the repaired area. It is important to note that there is no preferred direction of cracking and that the area of initiation of cracks is apparently the weld metal.

The chemical analysis of the boiler tubes show it to be a low carbon steel with an appreciable amount of chromium. It is not believed that the chromium is a residual, but has been deliberately added. It will be noted by comparing the analysis obtained with those specified that the manganese content exceeds that of both firebox and flange quality specifications. It will also be noted that our analysis reveals an appreciable nickel content which is not mentioned in either specification. These considerable differences from the specified are inexplicable. Indeed, both chemical analysis and physical properties more closely conform to the A.S.T.M. A 203-44 specification for boiler steel.

The microscopic examination reveals normal structures

(Discussion, cont'd) -

in the boiler tube, tube sheet materials and weld metal. The heat affected and transition zone structures in both cases indicate a normal response to the thermal cycle of welding. A study of various cracks show that they are all transcrystalline, a condition found in cracks resulting from fatigue; and that they are all blunt ended, which is generally indicative of cracks which have been affected by corrosion.[1] It is difficult to assess the relative importance of the two factors of corrosion and fatigue when both are simultaneously in action. Some authorities[2] believe that, for steel, corrosion forms relatively deep surface pits which act as stress raisers and greatly reduce the fatigue strength of the metal. Since there is some degree of correlation between notch-sensitivity of a metal and its resistance to corrosion-fatigue this property of the metal would also be playing a part in the problem. The origin of fatigue cracks in the weld metal is considered to be due to local stress concentration at the irregular weld surface, and not to any inherent weakness of the metal proper. Welds on this type of steel do not seem to show any great difference in resistance to corrosion from that of the base metal.

The use of A.W.S. E-6013 type electrode is subject to the rather obvious criticism that it produces welds of a low order of ductility. A.W.S. E-6011 type electrodes would provide the same mechanical properties, is usable with A.C. equipment and produces welds of a higher ductility. It should be emphasized, however, that there is no certainty that increased weld ductility would increase resistance to corrosion-fatigue. It would appear that this increased ductility would be valuable in dissipating, at least in part, the initial locked-up stresses

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(1) "Changes in a High-Pressure Drum to Eliminate Recurrence of Cracks Due to Corrosion Fatigue." A.E. White, A.S.M.E. Transactions 1939, Vol. 61. pp. 507-519.

(2) "Corrosion Fatigue of Metals." A.S.M. Handbook, 1939 Edition, pp. 147-153.

(Discussion, cont'd) -

when the welds are completed. These stresses may be of considerable importance in view of the method of assembly and impossibility of over-all stress relief. It must be remembered that service stresses are superimposed upon the locked-up stresses in the first stages of service life, and the combined effect may be sufficient to initiate a large number of cracks. It is also true that if the service temperature is in the order of 700 to 900° F. considerable stress relief will take place over a period of time but this will not be nearly as effective as stress relief at 1050° F. Therefore for a considerable period high stress levels may exist in the tube sheet.

The variations in stresses as applied to the material, as a result of working conditions of the locomotive, cannot be materially altered. The more likely approaches to improvement of service life are as follows: reduction of locked-up stresses as a result of welding, increasing fatigue resistance by pre-stressing by cold working and reduction of corrosion. Locked-up stresses may be reduced by high ductility weld metal, local stress relief and peening. Fatigue resistance may be increased by elimination of stress-raisers, such as design changes, to provide a smooth change of section at welds, cold working weld areas by rollers or shot peening to introduce compressive surface stresses. Reduction of corrosion may be brought about by the use of nickel-clad steels or by protective coatings such as sprayed aluminium. Some or all of these suggestions may be inoperable due to shop or service conditions presently unknown or from such efforts already tried and found to be abortive.

Conclusions:

(1) Corrosion-fatigue is the primary cause of cracking. The relative importance of both factors cannot be determined by an examination of this kind.

(Continued on next page)

(Conclusions, cont'd) -

(2) The chemical analyses reveals (1) a small amount of chromium in the boiler tube material which cannot be a residual, (2) a considerable nickel content and a higher than specified manganese content. Both chemical analysis and physical properties differ considerably from the specifications submitted.

(3) Higher weld metal ductility is available in the A.W.S. E-6011 type of electrode.

Recommendations:

1. Due to insufficient knowledge of shop conditions and results of previous experimental work no definite recommendations can be made.

2. As indicated above the major factors concerned are (1) locked up stresses, (2) corrosion and (3) fatigue. Improvement in any of these lines would result in improved service life. There are methods, already available, capable of producing the desired improvement with regard to each of these individual factors. It is felt that further co-operation and interchange of information would be of mutual benefit. Concommitant with these conditions there is every reason to believe that valuable work could be done.

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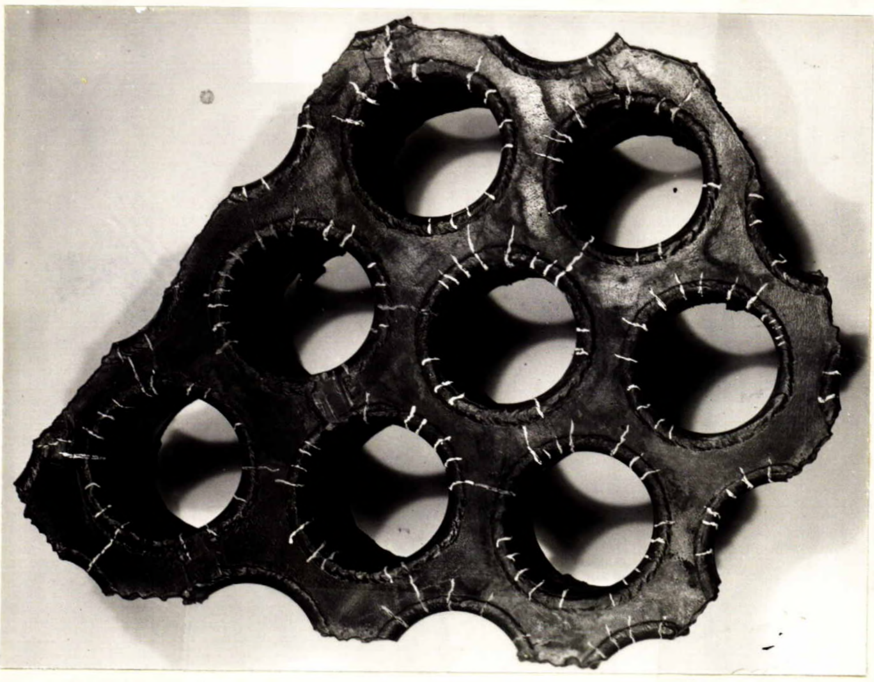
(Figures 1 to 10 follow,)
(on Pages 8 to 13.)

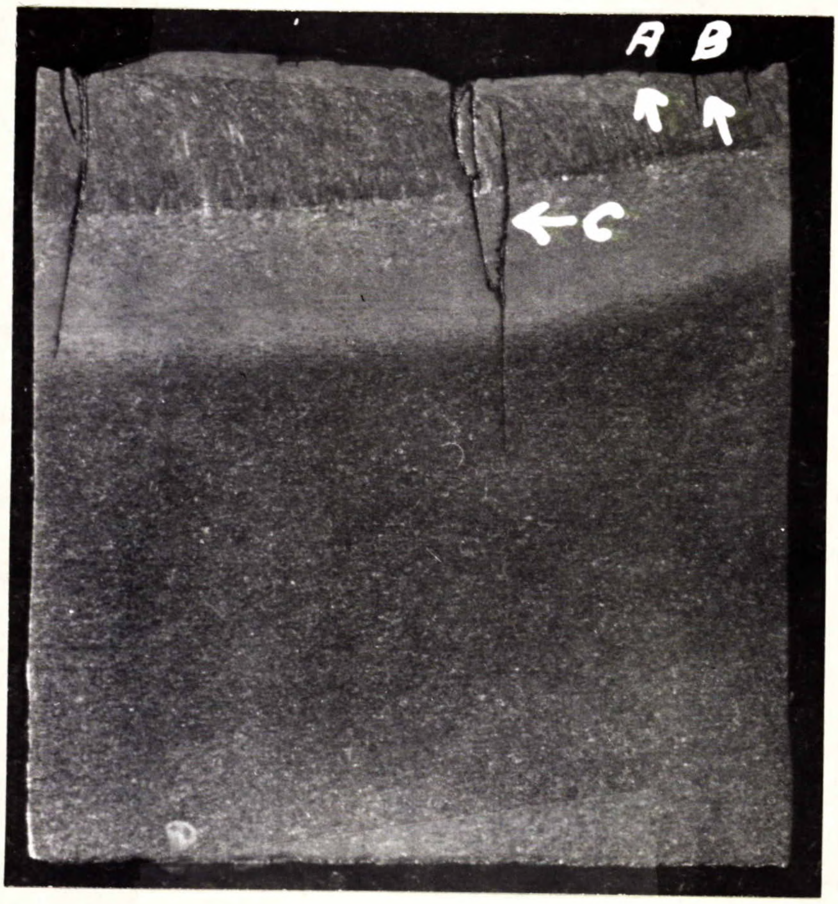
Figure 1.



PHOTOGRAPH OF MATERIAL "AS RECEIVED".

(Cracks outlined in white ink)

Figure 2.



Approximately X8,
deep etch in nital.

MACROPHOTOGRAPH OF CRACKED AREA IN WELD.

Note development of cracks:

A - incipient stage.
B - slight development.
C - deep penetration.

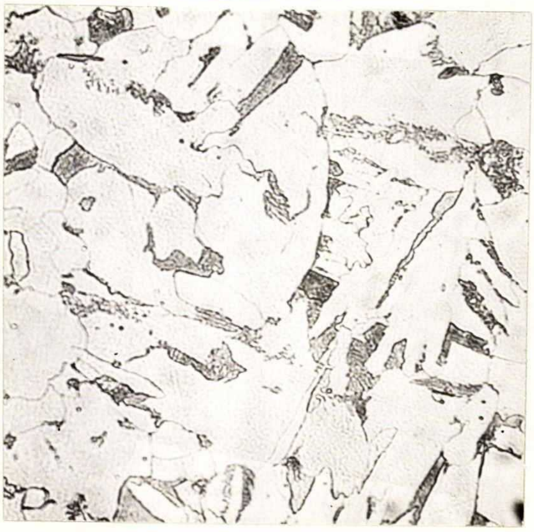
Figure 3.

X500, nital etch.

NORMAL STRUCTURE OF BOILER TUBE MATERIAL.

Pearlite and ferrite matrix.

Figure 4.



X500, nital etch.

NORMAL STRUCTURE OF TUBE SHEET MATERIAL.

Pearlite in a matrix of ferrite.

Figure 5.

X500, nital etch.

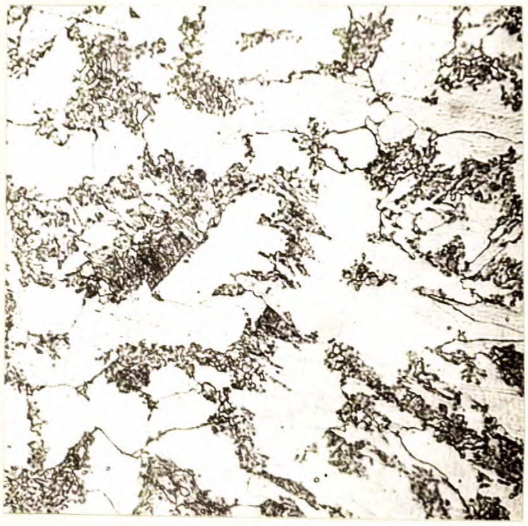
TYPICAL STRUCTURE HEAT AFFECTED ZONE.
Low carbon martensite and ferrite.

Figure 6.

X500, nital etch.

TYPICAL STRUCTURE OF THE WELD METAL.
Mainly ferrite with some fine pearlite.

Figure 7.



X500, nital etch.

TYPICAL STRUCTURE OF TRANSITION ZONE.
Partially spheroidized pearlite in ferrite matrix.

Figure 8.

X100, nital etch.

INCIPIENT CRACK IN WELD METAL.
(See Fig. 2 - crack A. Note oxide and blunt termination)

Figure 9.

X100, nital etch.

CRACK IN THE PARTIALLY DEVELOPED STAGE IN WELD METAL.

(See Fig. 2 - crack B. Note oxide and blunt termination)

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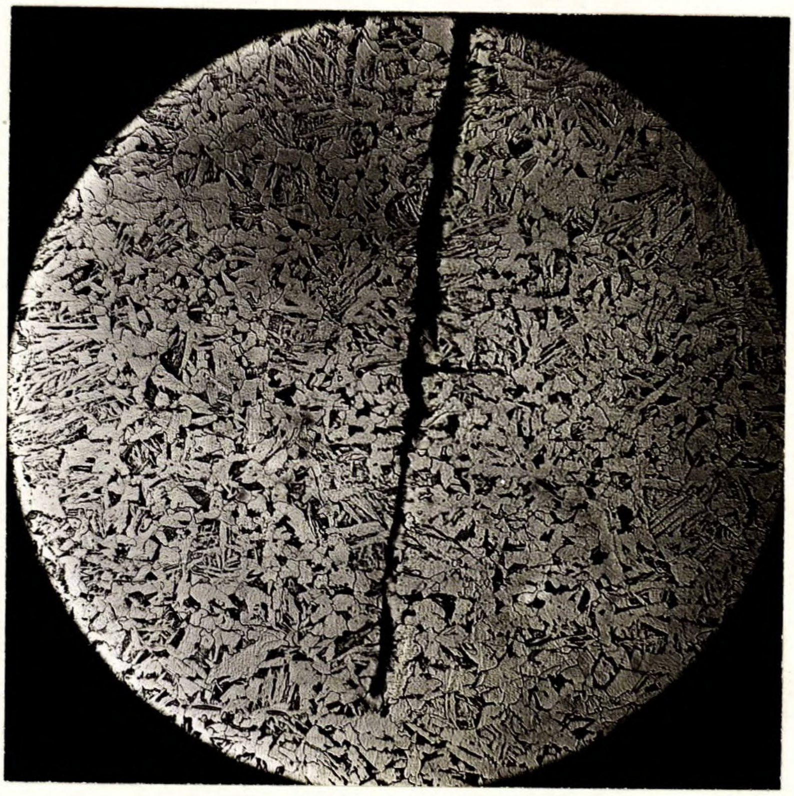
Figure 10.



X100, nital etch.

TERMINATION OF DEEP-SEATED CRACK IN TUBE SHEET.

(See Fig. 2 - crack C. Note transcrystalline nature of crack with blunt termination)

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