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MINES BRANCH INVESTIGATION REPORT IR 58-46

A METALLURGICAL INVESTIGATION INTO THE FAILURE (DECEMBER 1957) OF THE AUBREY-WAVERLEY WATERMAIN BRIDGE WINNIPEG, MANITOBA

by

R. C. A. THURSTON and W. A. MORGAN

PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Samples of steel channel, tie bar and water pipe from a collapsed watermain bridge of triangular construction over the Assiniboine river at Winnipeg were examined. The fractures were essentially of a brittle nature and originated at rivet holes in the channel. The steel conformed to C. S. A. Specification G 40.4 and showed a low level of notch toughness typical of this grade of steel. It is recommended that a grade of steel with greater notch toughness should be used and/or the rivet holes should be reamed.

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INTRODUCTION

Late in December, 1957, a telephone request was received from Mr. W. D. Hurst, City Engineer and Commissioner of Buildings, Engineering Department, City of Winnipeg, Winnipeg, Manitoba, that the Mines Branch investigate the cause of failure of a recently constructed watermain bridge over the Assiniboine river at Winnipeg. It was stated that the Aubrey-Waverley bridge had collapsed while the water main was being filled and that the temperature at the time of failure was about 10°F. Dr. John Convey, Director of the Mines Branch, was asked to send officers of the Physical Metallurgy Division to inspect the site.

On December 31, 1957, Mr. A. J. S. Taunton, Deputy City Engineer, forwarded photographs of the bridge after failure, data covering the temperatures for 10 days prior to the failure, and a statement as to the rate of filling of the watermain.

On January 6, 1958, the writers of the present report visited the site of the failure and selected samples for subsequent metallurgical examination. (Internal Report No. PM-V-58-2)

In the Appendix to this report (pages 26-27), a short discussion is given of the factors which affect the low temperature notch ductility of structural steels.

DESCRIPTION OF SAMPLES

Particulars of the various samples received, and their location in the bridge, together with relevant comments regarding their condition, are given in Table 1.

TABLE 1. - Particulars of Samples.

Sample No.	Heat No.	Description	Location	Comments
EH 1	358915*	32 in. length of 15 in. channel (50 lb) with riveted reinforcing plates 3/4 in. and 3/8 in. thick	Lower chord, east side, between U6 and U7 (centre of bridge)	Brittle fracture through 1 flange and 2 rivet holes (see Figure 2)
EH 2	251217*	37 in. length of 18 in. channel (58 lb) with riveted reinforcing plate 1/4 in. thick	Upper chord, east side, between U10 and U11	Brittle fracture through 5 rivet holes; ductile fracture in plate (see Figure 3)
EH 3	251217*	36 in. length of 18 in. channel (58 lb) with riveted reinforcing plate 1/2 in. thick	Upper chord, west side, between U6 and U7 (centre of bridge)	Brittle fracture through 3 rivet holes (see Figure 4)
EH 4	251217*	Short length of channel containing 1 flange and part of web	Upper chord, east side, opposite sample EH 3	Containing portion of longitudinal crack (see Figure 5)
EH 5	251217*	33 in. length of 18 in. channel (58 lb) with riveted reinforcing plate 1/2 in. thick	Upper chord, west side, between U5 and U6	Undamaged sample
EH 6	358915*	25 in. length of 15 in. channel (50 lb)	Lower chord, east side, between U2 and U3	Undamaged sample
EH 7	(Not stated)	20 in. length of 12 in. channel (20.7 lb)	Pipe support channel at centre of bridge	Undamaged apart from a slight bend in 1 flange
EH 8	(Not stated)	Lateral bracing (23 in. length)	Centre of bridge	Undamaged sample

(Table 1, concluded) -

Sample No.	Heat No.	Description	Location	Comments
EH 9	(Algoma steel)	13 in. length of 15 in. channel (33.9 lb)	Lower chord, west side, between U1 and U2	Mixed fracture through 3 rivet holes (see Figure 6)
10	(Not stated)	About 1 sq. foot of water pipe	Centre of bridge	Brittle fracture along one edge

* Supplied by U. S. Steel Corporation.

A number of high-tensile-strength bolts used in the construction were also supplied.

TENSILE AND HARDNESS TESTS

Tensile tests were carried out on flat longitudinal test-pieces machined from all samples of the U. S. Steel channel, with the exception of #4. The test-pieces were about 16 in. long, with a central test portion 9 in. long and cross-section 1.5 in. by the plate thickness. Two tensile test-pieces were prepared from the web of each sample tested. The yield point was determined by the 'drop in the beam' method, and the elongation was measured after fracture on an 8 in. gauge length.

Diamond pyramid hardness tests, using a load of 30 kg, were made on test-pieces prepared for the Charpy impact test. The hardness values were obtained from the measured diagonals of the impressions and the standard tables.

The results of the individual tensile tests, and the average hardness values, are given in Table 2, together with the corresponding figures for heats 251217 and 358915 taken from the U. S. Steel mill sheets.

TABLE 2. - Results of Tensile and Hardness Tests.

Sample No.	Approx. thickness (in.)	Heat No.	Yield point (psi)	Ultimate tensile strength (psi)	Elongation on 8 in. g.l. %	Average hardness value
EH 1 A	3/4	358915	32,600	67,400	30.3	135
B			32,800	67,100	29.6	
EH 2 A	11/16	251217	33,700	64,700	28.5	141
B			35,300	65,900	28.3	
EH 3 A	11/16	251217	37,000	66,300	27.8	138
B			35,500	65,800	29.7	
EH 5 A	11/16	251217	34,100	70,600	25.2	152
B			37,300	70,400	25.5	
EH 6 A	11/16	358915	36,300	67,300	29.0	142
B			36,900	66,900	30.0	
EH 7 A	5/16	(not	45,600	64,400	19.5*	142
B		stated)	40,900	62,700	28.8	
(Mill sheet)		251217	35,980	70,040	29.5	
(Mill sheet)		358915	35,950	67,280	29.5	

* Fractured outside middle third of gauge length.

The requirements of C.S.A. Specification G 40.4 are as follows:

Ultimate tensile strength	-	60,000-72,000 psi
Yield point (minimum)	-	33,000 psi
Elongation in 8 in. (minimum)	-	21%

With the exception of sample EH 1, which is slightly low on the yield point value, all the samples conform to the requirements of G 40.4.

BEND TESTS

Two specimens, each 9 in. long and 1 1/2 in. wide, were machined longitudinally from the web of each sample channel subjected to tensile tests (EH 1, 2, 3, 5, 6 and 7). The thickness of each specimen was that of the original material, and the edges were rounded with a 1/16 in. radius.

The bend test was started by a four-point loading method and completed by loading the partially bent bar as a strut. All the test-pieces were satisfactorily bent through 180° around a mandrel of diameter equal to half the test-piece thickness. No cracking was observed on the outside of the bent portion in any test.

IMPACT TESTS

Eighteen V-notch Charpy impact test-pieces were machined from the web of channel samples EH 1, 2, 3, 5, 6, 7 and 9. The test-pieces were cut in the longitudinal direction and notched at right-angles to the original surface of the web. In the case of the thicker channel, EH 1, 2, 3, 5, and 6, the Charpy test-pieces were of standard size (0.394 in. x 0.394 in.). In the case of the thinner channel, EH 7 and 9, sub-size test-pieces were used, the width of the notched face being reduced to 0.197 in. All notches were checked on an optical comparator before testing.

The impact tests were carried out in triplicate in a standard machine of 120 ft-lb capacity and a striking speed of 11 feet per second. Tests were made over a range of temperatures from -40°C (-40°F) to 128°C (262°F) in order to determine the ductile-to-brittle transition characteristics of the material. For the low temperature tests, the specimens werepre-cooledin an acetone bath with solid carbon dioxide. For tests above room temperature, a constant temperature oil bath was used. The results of the Charpy impact tests are given in Table 3.

TABLE 3. - Results of Charpy Impact Tests.

Temperature of Test (°C)	Energy Absorbed (ft-lb)	Percentage Shear in Fracture	Temperature of Test (°C)	Energy Absorbed (ft-lb)	Percentage Shear in Fracture
EH 1 - Standard test-piece -			EH 2 - Standard test-piece -		
0	4	2	0	7	2
	7	2		7	2
	9	5		6	2
22	31	20	24	11	25
	20	20		15	25
	18	25		13	25
50	38	25	50	39	65
	48	25		41	70
	39	25		41	65
70	59	70	70	62	95
	63	75		51	90
	62	75		50	85
100	80	>95	100	70	>95
	73	>95		65	>95
	69	>95		61	>95
EH 3 - Standard test-piece -			EH 5 - Standard test-piece -		
0	6	2	0	5	2
	5	2		5	2
	5	2		4	2
24	16	25	24	10	20
	13	25		13	20
	11	25		12	20
50	42	50	70	36	40
	47	50		33	40
	44	50		30	40
70	60	65	100	51	70
	51	60		49	75
	58	70		55	75
100	71	>95	128	54	100
	71	>95		55	100
	74	>95		60	100

(Table 3, cont'd) -

EH 6 - Standard test-piece -

Temperature of Test (°C)	Energy Absorbed (ft-lb)	Percentage Shear in Fracture
-20	3	2
	3	2
	4	5
0	9	15
	6	10
	8	15
21	22	20
	30	25
	23	20
50	47	70
	37	60
	37	65
70	61	75
	56	70
	59	75
100	63	100
	63	>95
	64	>95

EH 9 - Sub-size test-piece -

Temperature of Test (°C)	Energy Absorbed (ft-lb)	Percentage Shear in Fracture
-40	3	0
	6	0
	7	0
-20	6	2
	9	10
	7	5
0	14	25
	15	40
	12	20
24	24	90
	21	75
	27	100
100	28	100
	30	100
	29	100

EH 7 - Sub-size test-piece -

Temperature of Test (°C)	Energy Absorbed (ft-lb)	Percentage Shear in Fracture
- 40	3	0
	4	0
	3	0
- 20	17	40
	9	25
	10	25
0	23	70
	32	75
	23	60
24	35	100
	34	100
	36	100
100	35	100
	34	100
	36	100

The results were plotted as temperature-energy absorbed and temperature-percentage shear curves, and from these curves the following transition temperatures were derived for each sample tested:

(1) 15 ft-lb - the temperature at which the average energy absorbed is 15 ft-lb.

(2) Average Energy Absorbed - the temperature at which energy absorbed is the mean of the maximum and minimum values.

(3) 50% shear - the temperature at which the fracture surface is half crystalline and half fibrous.

The corresponding values are given in Table 4.

TABLE 4. - Charpy V-Notch Transition Temperatures

Sample No.	Web thickness (in.)	Heat No.	Transition Temperature - °C 15 ft-lb	Average energy absorbed	50% shear
EH 1	3/4	358915	11 (52)	45 (113)	60 (140)
EH 2	11/16	251217	27 (81)	45 (113)	40 (104)
EH 3	11/16	251217	26 (79)	45 (113)	50 (122)
EH 5	11/16	251217	35 (95)	65 (149)	80 (176)
EH 6	11/16	358915	10 (50)	35 (95)	40 (104)
EH 7	5/16	(not stated)	-28 (-18*)	-10 (14*)	-10 (14*)
EH 9	3/8	(Algoma steel)	-20 (- 4*)	7 (45*)	10 (50*)

Note: Figures in parentheses are temperatures in °F.
* Based on tests on half-width specimens.

The transition temperatures based on standard test-pieces may be considered typical of the grade of steel examined, and show some superiority for heat 358915 over heat 251217. Since, however, there is a definite size effect in notched-bar testing, they may not be compared directly with the values obtained from the sub-size test-pieces.

CHEMICAL ANALYSIS

Drillings for chemical analysis were taken from each sample of steel, near the fracture surface. The results are given in Table 5.

The steels, with one possible exception (No. 10), were all semi-killed. The Mn/C ratio is not high and in the range 1.6-2.0 for all of the large structural sections in the bridge. The mill and this Division's analyses are in good agreement. The phosphorus content is low in all of the samples. The chemical analysis of the steel is within the G 40.4 and A 373 specifications.

TABLE 5. - Results of Chemical Analysis

Heat No.	ELEMENT, %									Mn/C Ratio
	C	Mn	Si	S	P	Al*	Cu*	Ni*	Cr*	
Mill Analysis -										
251217	0.26	0.49	-	0.035	0.008	-	-	-	-	1.90
358915	0.25	0.49	-	0.032	0.016	-	-	-	-	2.00
Lab. Analysis -										
251217:										
Sample EH 2	0.250	0.480	0.060	0.034	0.013	0.008	0.020	0.020	0.050	1.90
" EH 5	0.280	0.480	0.060	0.037	0.012	0.009	0.020	0.020	0.050	1.70
" EH 3	0.250	0.490	0.080	0.041	0.016	0.009	0.020	0.020	0.050	2.00
" EH 4	0.280	0.540	0.060	0.036	0.014	0.007	0.020	0.020	0.050	2.00
358915:										
Sample EH 1	0.300	0.490	0.050	0.033	0.020	0.005	0.070	0.050	0.070	1.60
" EH 6	0.270	0.510	0.060	0.037	0.020	0.007	0.070	0.050	0.090	1.90
"										
Heat not stated:										
Sample EH 9	0.250	0.420	0.060	0.028	0.008	0.009	0.030	0.020	0.020	1.70
" EH 10	0.250	0.590	0.120	0.036	0.019	0.004	0.080	0.100	0.040	2.40
" EH 7	0.230	0.540	0.030	0.026	0.012	0.009	0.050	0.050	0.040	2.40
" EH 8	0.240	0.450	0.060	0.027	0.012	0.006	0.080	0.040	0.030	1.90

*Determined by spectrographic analysis.

Note: No molybdenum, tin, arsenic, boron or vanadium was detected by spectrographic analysis.

MACROSCOPIC EXAMINATION

Longitudinal and transverse samples of each piece of steel supplied were prepared for sulphur printing and deep etching. A typical sulphur print is shown in Figure 7, which was taken on Sample EH 6. There is evidence of sulphur segregation at the centre of the web of the channel, but this is considered to be normal for semi-killed structural steel purchased to the C.S.A. G 40.4 specification.

The samples after sulphur printing were deep-etched in 1:1 hydrochloric acid solution at 165°C for 20 minutes. The deep-etched surface of sample EH 6 is shown in Figure 8. The deep etch confirms the presence of segregation of sulphide and other non-metallic inclusions into the centre of the web. The rivet holes pass through this segregated zone, and a deep etch of a section through a rivet hole is shown in Figure 9. The inclusions are concentrated around the circumference of the rivet holes in a plane parallel to the longitudinal surface of the web. At points on the interior surface of the rivet hole, several small laps were visible; an example of this is shown in Figure 10.

MICROSCOPIC EXAMINATION

Sections of each steel sample supplied were cut, polished, etched, and examined under the microscope.

Figure 11 shows the microstructure of sample EH 8, a relatively thin member of angle iron; this sample possesses a fine ferritic grain size, indicating that its notch ductility would be good at low temperature.

The structure of channel sample EH 3, however, is much coarser, as shown in Figures 12 and 13. This coarser ferritic structure is due to the higher finishing temperature of rolling of the channel (3/4 in. thick) as compared with that of the angle iron. The thinner the plate section, the lower is the finishing temperature, and thus a fine ferrite grain size is produced. Figure 12 shows a section taken across the fracture surface; the fracture is transcrystalline.

Figure 14 shows the structure of the metal just beneath the inner surface of the rivet hole. The ferrite grains are greatly distorted by the high degree of cold work introduced into this section of the web during the punching of the rivet holes. At the base of the lap shown in Figure 10, fine cracks are present, propagating through this cold-worked region.

The unetched structure of a section taken from the centre of the web of sample EH 6 (sulphur print shown in Figure 7) is shown in Figure 15. The inclusions are mainly sulphides with some oxides.

Figure 16 shows the structure of the water pipe, which consists of a finer ferritic grain size than the channel's and shows marked banding. No abnormalities were evident in the pipe material.

Figure 17 shows the structure of the high tensile bolt which showed no defects that could lead to premature failure.

DISCUSSIONS AND CONCLUSIONS

It will be apparent from Figure 1 that the collapsed bridge could be resolved essentially into three sections:

(1) The south section, from U11 to U14, resting with one end on the pier and the other end under the ice; distortion in this section was slight.

(2) The central section, from U10 to U7, of which the lower chord was below the ice; considerable distortion was evident between upper and lower chords.

(3) The north section, from U6 to U0, resting almost horizontally with the U6 end under the ice; very little distortion was apparent.

The main fractures occurred in the region of U10-U11 and U7. The fractures in the channel were mainly brittle and passed through a number of rivet holes, whereas the reinforcing plate either bent or fractured in a ductile manner. It was also observed that the rivet holes had been punched but not reamed, and a surface layer of cold-worked metal was visible, together with fine cracks.

The punching operation drastically cold-works the material at the edge of the hole, raises its transition temperature, and thus makes the steel more susceptible to brittle fracture. The degree of embrittlement will depend upon the type of steel and the plate thickness. This condition will be enhanced if fine cracks are also formed, and if subsequent strain ageing occurs due to the application of heat in the vicinity of the rivet hole. In order to improve or eliminate such an undesirable condition, the rivet holes should either be drilled, or reamed after punching, to remove the severely cold worked layer.

In the examination of the fractured channel, it was evident from the fracture markings or herringbone pattern (Figure 18) that brittle failure originated at a rivet hole in the web and then propagated in both directions transversely across the channel and through other rivet holes. From the results of the Charpy V-notch impact tests, it can be seen that at the estimated temperature of bridge collapse (10°F), the thicker channel material would not absorb more than 5 ft-lb, and would therefore be very susceptible to brittle fracture at a notch, incipient crack, or other stress raiser.

The chemical compositions of the structural members examined in this report are well within the requirements of the C.S.A. G 40.4 Specification (ASTM A7) and would also meet the ASTM A 373 specification. However, this does not detract from the fact that the steel is a semi-killed grade and possesses a low manganese/carbon ratio, which is of no aid to the notch ductility of the steel. A higher manganese content would be desirable and in special cases a fully killed steel is often necessary. However, these steels are more expensive and are not as readily obtainable as A 7 or A 373. At the present time it appears that the steel manufacturers are not fully set up to produce these higher grades of steel. In the meantime, therefore, great care has to be paid to design and workmanship if failures of structures are to be avoided at low temperatures.

Undoubtedly, many structures have been successfully constructed of A 7 steels, but their factor of safety at low temperatures is generally unknown and may be quite low. The high manganese low carbon and/or fully killed steels will give higher and more consistent factors of safety at low temperatures than will A 7 steel. Therefore, any defect in design or workmanship is more likely to lead to failures by yielding rather than by catastrophic brittle cracking.

In the present case, however, the higher grade steels may not be readily available, so considerable attention should be paid to ensuring good workmanship and the elimination of any design features which may produce regions of stress concentration.

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(Figures 1-18 and an appendix)
(follow, on pages 17-27.)

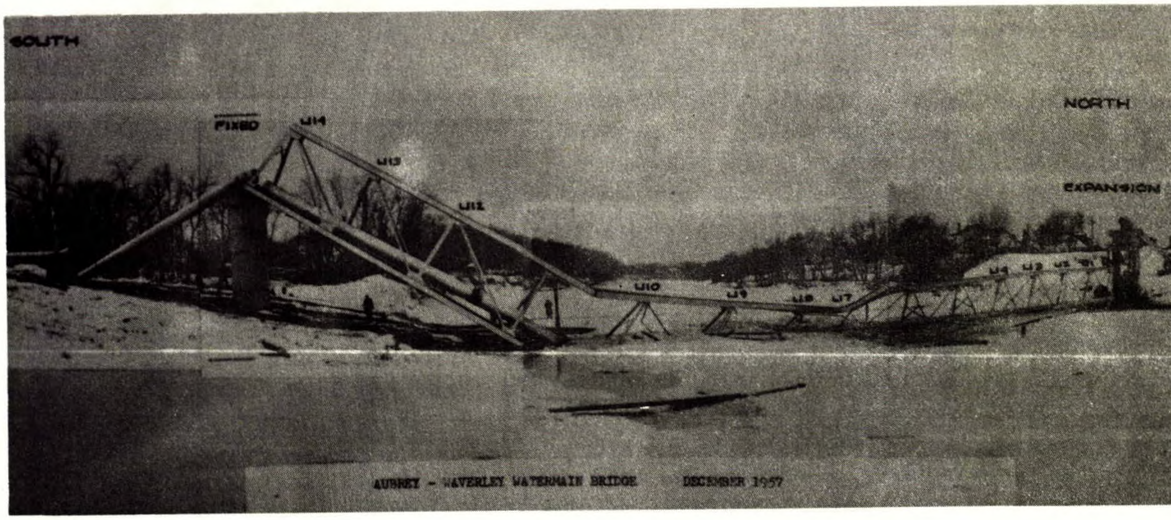

Fig. 1. - Photographs of bridge shortly after failure.

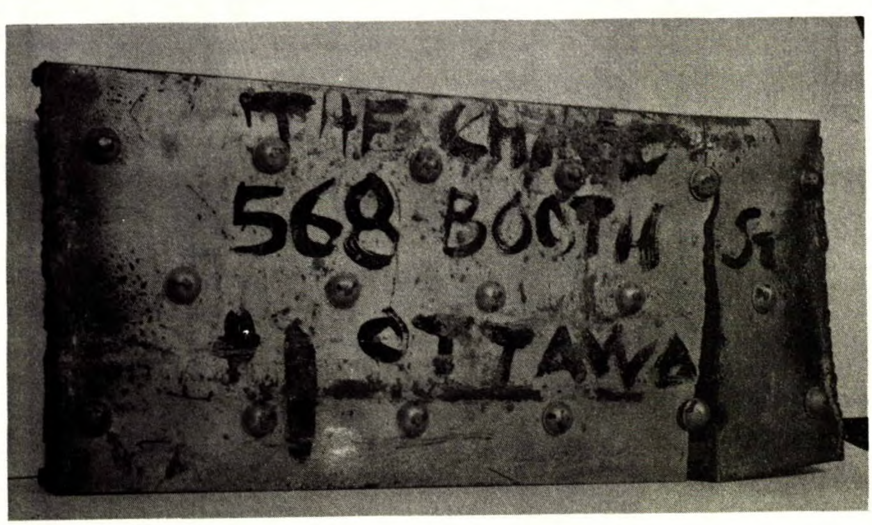

Fig. 2. - Sample EH 1 - 15 in. channel.

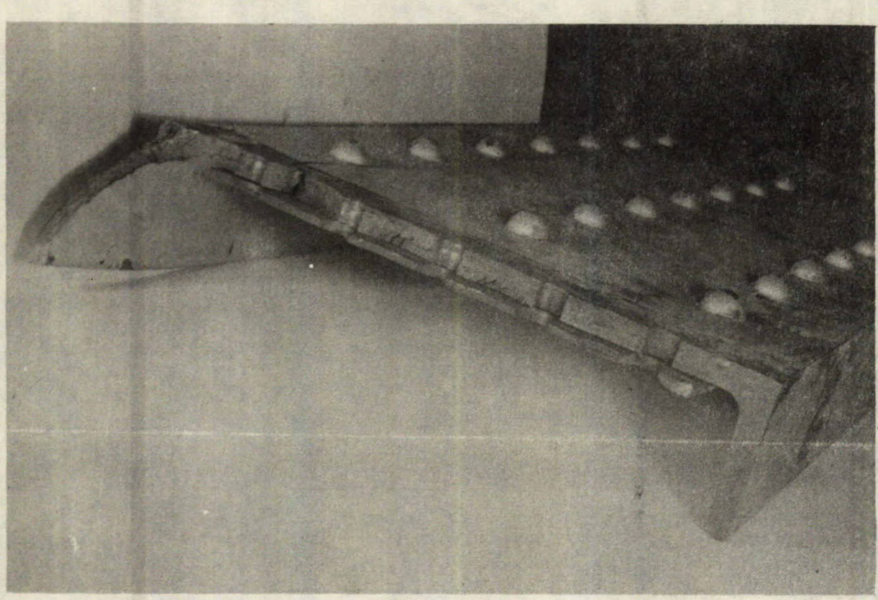

Fig. 3. - Sample EH 2 - 18 in. channel.

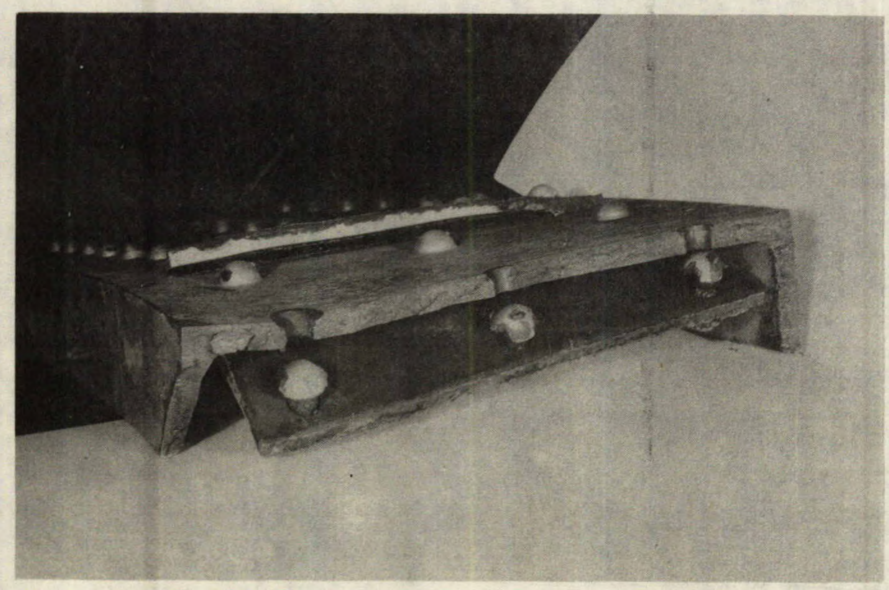

Fig. 4. - Sample EH 3 - 18 in. channel.

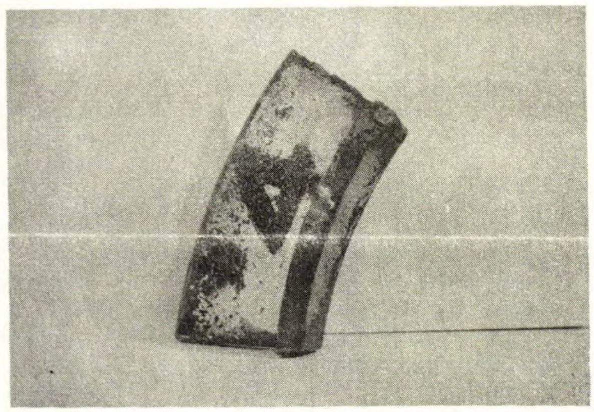

Fig. 5. - Sample EH 4.

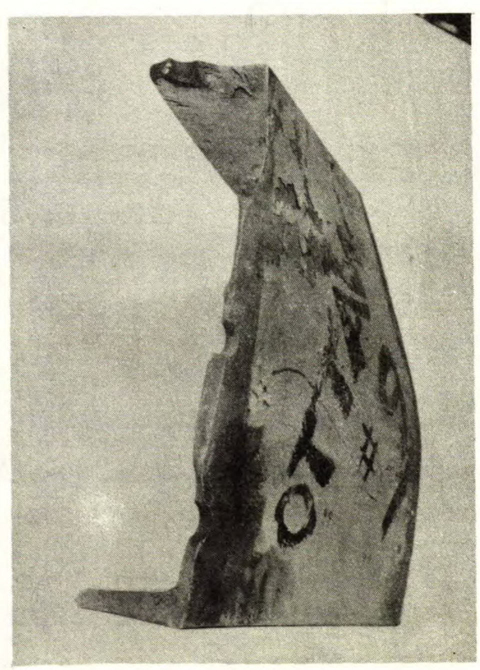

Fig. 6. - Sample EH 9 - 15 in. channel.

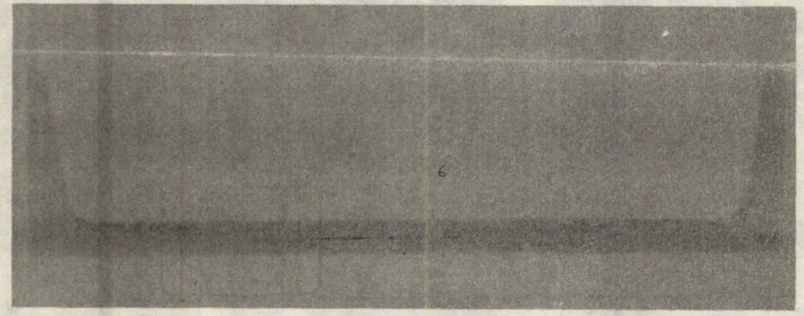

Fig. 7. - Sulphur print of a transverse section of channel EH 6.

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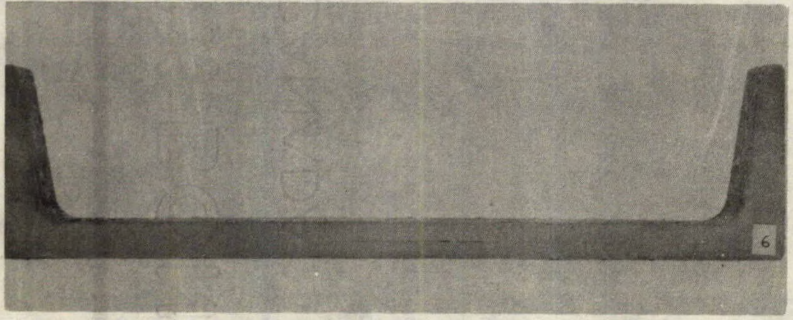

Fig. 8. - Deep-etched structure of transverse section of channel EH 6.

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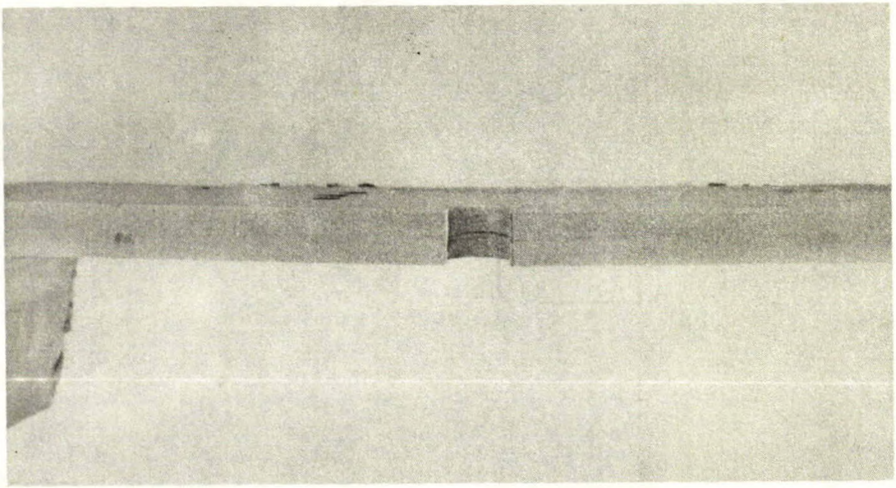


Fig. 9. - Transverse section through a rivet hole, showing the segregated zone.

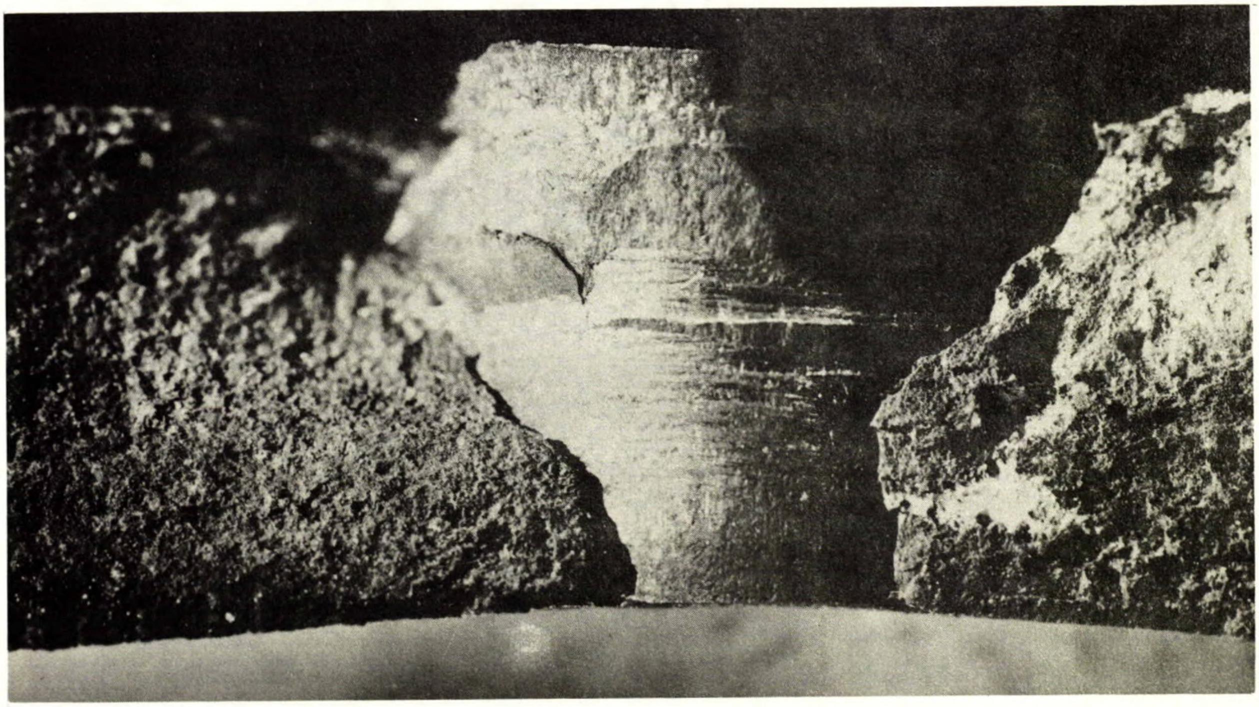


Fig. 10. - Small surface discontinuity in a rivet hole.

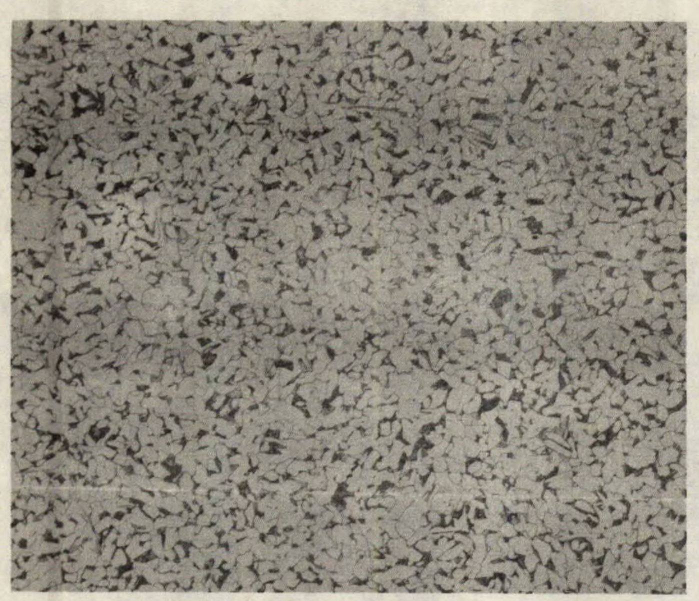


Fig. 11. - Microstructure of sample EH 8.

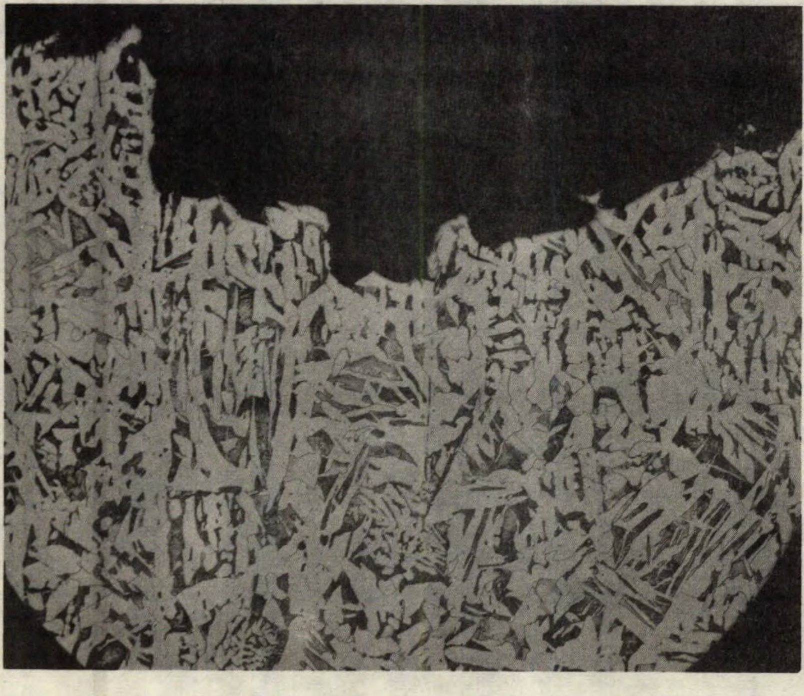


Fig. 12. - Microstructure across fractured surface of Sample EH 3. (X100. Etched in 2% nital.)

Fig. 13. - Microstructure of sample EH 3. (X100. Etched in 2% nital.)

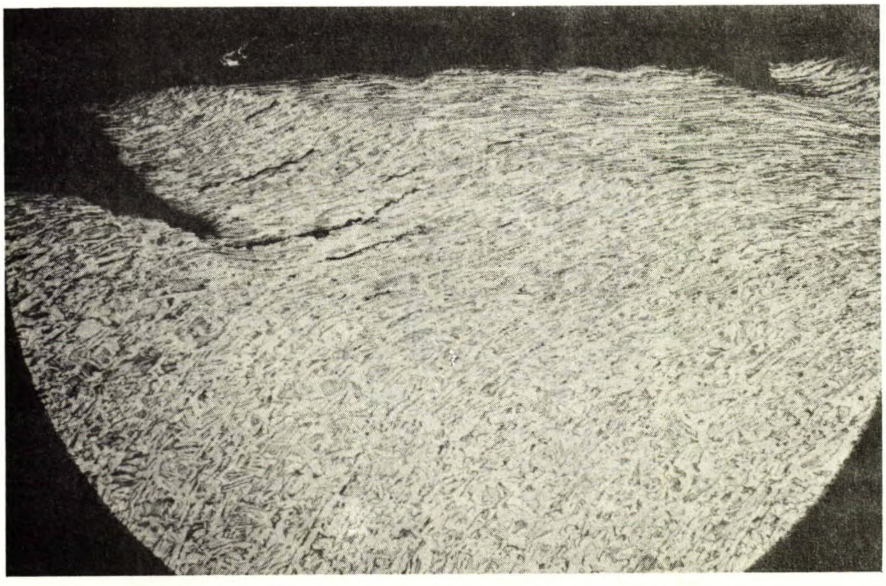
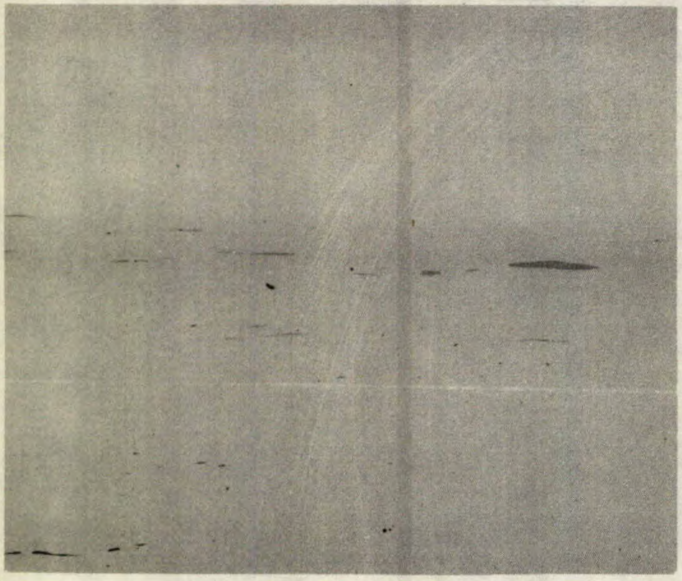


Fig. 14. - Microstructure of cold worked metal at the inside of a rivet hole. (X33. Etched in 2% nital.)



X100.

Fig. 15. - Unetched structure near the segregated zone at the centre of the web.

Fig. 16. - Microstructure of water pipe. (X100. Etched in 2% nital.)

Fig. 17. - Microstructure of high tensile bolt. (X100. Etched in 2% nital.)

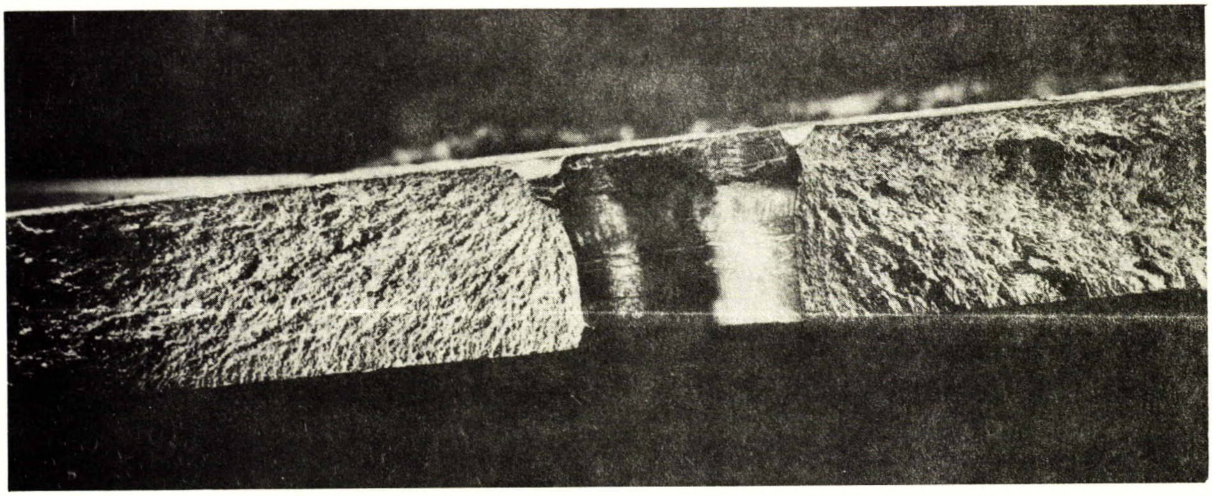


Fig. 18. - Brittle fracture originating at rivet hole. (EH 2)

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APPENDIX

Factors Controlling Notch Toughness.

It has been known for many years that structural steel showing normal ductility in the tensile test may fracture in a completely brittle manner in the presence of a notch at low temperatures. The tendency of a given steel to exhibit this behaviour may be investigated by a number of tests of which the most commonly used is probably the Charpy V-notch impact test. In this test a notched beam-type test-piece is struck behind the notch by a hammer, in a pendulum-type machine, and the energy absorbed to fracture or partially fracture it is measured. The energy absorbed is then plotted against the temperature of test. At the higher temperatures, the fracture is generally completely ductile, fibrous in appearance, and requires a large amount of energy. At the lower temperatures, the fracture is completely brittle, crystalline in appearance, and requires very little energy. In the intermediate or transition zone, the fracture is mixed and the energy absorbed intermediate in value. Certain temperatures in the zone are defined on the basis of selected criteria as transition temperatures, and of these the 15 ft-lb or ductility transition temperature, which is associated with crack initiation, is probably the most important.

The effects of the more common metallurgical factors on the transition temperature, and therefore on the susceptibility of the steel to brittle failure, have been established and are given below:

(a) Factors which lower the transition temperature.

1. Deoxidation.
2. Small ferrite grain size.
3. Higher manganese content) - higher Mn/C ratio
4. Lower carbon content)
5. Low phosphorus content.
6. Increasing silicon content (up to 0.25%).

(b) Factors which raise the transition temperature.

1. Rimming nature of the steel.
2. High finishing temperatures in rolling.
3. Low Mn/C ratio.

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Among other factors which effect the notch toughness of a given material, the most important are the velocity of deformation, the severity of the notch, the state of stress, and the size of the sample or component. Increasing the strain rate, increasing the severity of the notch, increasing the condition of triaxial tension, and increasing the size, all tend to raise the transition temperature.

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