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EXAMINATION OF FAILED SECTION FROM A BAILEY BRIDGE PANEL

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

The fractures in the two side channels of the end piece from a Bailey Bridge panel were brittle in nature and were initiated at small heat-affected zone cracks, which resulted from incorrect welding procedures. The steel contained higher carbon and manganese levels than are desirable for good weldability and had inadequate notch-ductility under low-temperature service conditions.

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INTRODUCTION

In a letter dated February 4, 1963, (Ref. 31-2-66), Mr. B. F. Cummings, Acting Chief, Testing Laboratories, Department of Public Works, Ottawa, Ontario, requested that an examination be performed to determine the cause of failure of a male end section of a panel from a Bailey Bridge. A copy of a letter from Mr. J. E. Kellett, District Engineer, Department of Public Works, Y. T., was enclosed, together with a short report from the Department of National Defence, entitled "Fatigue in Bailey Bridges". The following information was obtained from the letter and report:

(1) The fractured male end section was from a panel installed in a Bailey Bridge over the Hyland River at Mile 65 Nahanni Pioneer Road, Y. T.

(2) The temperature at the time of failure was -55°F.

(3) There appeared to be a defect at the fracture location prior to "collapse" and this was thought to be shown by a spot of rust or paint on the fractured surface.

(4) The Department of National Defence stated that there is a possibility of fatigue failures particularly when Bailey Bridges are used for non-military applications involving heavy loads over a long time period. If fatigue conditions are developing, cracks will first appear at the sway-brace slots at positions of maximum stress in the tension chord.

These cracks spread very slowly and give ample time for detection by visual examination, before becoming dangerous.

In view of the warning about possible fatigue failures, and the observation of an apparent prior defect at the location where fatigue fractures are known to have occurred in some other panels, Mr. Kellet requested that the examination determine if "fatigue or other defects contributed to the collapse of the span".

PROCEDURE

(1) The assembly was examined visually and by magnetic particle inspection. Photographs were taken of the assembly and fractured surfaces.

(2) Chemical analyses of drillings and quantitative spectrographic analyses of pieces were performed on samples taken from the top flange of each of the two channels.

(3) One tensile test was made on specimens machined from the lower flange of each channel.

(4) Impact tests at several temperatures were made on 5 mm x 10 mm bars cut longitudinally from the web of each channel. Each bar had a standard Charpy V-notch cut perpendicular to the surface of the web. Two bars were broken at each temperature.

(5) The following sections were removed from the assembly and examined microscopically after suitable polishing and etching:

(a) longitudinal sections at the initiation points of each of the four fractures

(b) longitudinal sections at the starting points of the two welds joining the lower side of the sway brace slots to the central connecting plate

(c) a transverse section across the welds joining the connecting plate to channel B (see Figure 2)

(d) longitudinal and transverse sections through the fillet weld joining a small steel piece at right angles to the upper flange surface of channel B (see Figure 2).

Several photomacrographs and photomicrographs were taken to illustrate the observations made on the various sections.

RESULTS AND DISCUSSION

As shown in Figures 1 and 2, the failure of the end piece occurred as a result of two fractures forming in each channel; one fracture being above the slot and the other below. The fractures are near the ends of the straight portions of the sway-brace slots. It is evident in these two figures, and also in Figures 4 and 6, that the two lower fractures in each channel are at or very close to the ends of the fillet welds joining the channels to the central connecting plate. Closer views of the four fractures, illustrated in Figures 3-6 inclusive, indicate

that they are of the cleavage type with little evidence of shear. Thus the fractures are typical of metal which has failed in a brittle fashion.

The fractured surfaces exhibit chevron markings which tend to point towards the intersection of the fractures with the slots. This is a definite indication that the fractures initiated at these locations. At the lower fracture in channel B, a dark spot, differing in colour and texture from the major portion of the fracture, is evident in Figure 4 at the fracture initiation point. A similar spot is seen in Figure 3 on the upper fracture in the same channel, although there is no evidence of weld metal, this having been retained with the portion of the end piece not submitted. No similar spots were noted at corresponding locations in channel A, although a small hole was noted at the upper fracture (See Figure 5). A very small amount of weld deposit was seen near this defect.

Figures 7 and 8 illustrate the site of fracture initiation in a section taken through the dark spot shown in Figure 4. It is apparent that the brittle failure was initiated by cracks close to the toe of the weld crater. The dark spot corresponds to the extreme left hand edge of the section, and to a small portion of the main fracture which is just below the right hand crack, with reference to Figures 7 and 8. A close examination of the fracture (See Figure 4) will show that this dark area at

the initiation of the fracture really consists of two spots, at slightly different elevations on the fractured surface. A third crack, seen in Figure 7, between the extreme left edge and the right hand crack, did not extend to any appreciable extent. An examination at higher magnification, of the location on this specimen corresponding to the dark areas in Figure 4, revealed the presence of oxide scale, as seen in Figure 9. Figure 10 illustrates the crack which is in line with the main portion of the fracture, and this crack is also oxidized. Another crack, running parallel to the one just mentioned, was found further away from the fracture. This crack, shown in Figure 11, is intergranular in nature, and so tightly closed that it was not evident in the macro-examination of the section, e.g., it is not apparent in Figure 7. This type of crack probably initiated first as a hot crack at the austenite boundaries in the heat-affected zone at the weld fusion line and then extended as a cold crack when the heat-affected zone became martensitic. Other heat-affected zone cracks, which are transgranular and run more nearly parallel to the weld fusion line, were found a short distance away from the fracture, and are illustrated in Figure 12.

The upper fracture in channel B apparently occurred in a similar fashion. Figure 13 shows that the initiation of the fracture was in a weld heat-affected zone. Although no cracking was seen below the fractured surface, it was evident that a crack had occurred during welding and had been subsequently oxidized. The surface of the fracture immediately adjacent to its inter-

section with the slot, i.e., through the dark spot evident in Figure 3, was similar to that illustrated in Figure 9.

A section is shown in Figure 14 from the upper fracture in channel A illustrated in Figure 5. Some lack of fusion and entrapped slag were present in the small portion of weld metal remaining. No cracking was found in the heat-affected zone, nor was there any evidence of oxidation along the fracture path through this zone. However, it is possible that the fracture was initiated at some weld defect such as shown in this section.

A section through the weld crater and intersecting the lower fracture in channel A (see Figure 6), showed that the weld crater was very shallow and that no cracks were present in the heat-affected zone.

Sections were also examined at the starting point of the two lower welds where no fracture had been initiated in the channels. The heat-affected zones below the start of the welds were quite shallow, thus indicating rapid cooling rates. However, no cracking was found in these zones. The welding arc had melted a small shallow zone in channel A a short distance in advance of the start of weld deposition, as is shown in Figure 15. A very small crack, perpendicular to the edge of the channel, was found in the upper portion of this zone. Such a crack is favourably located to initiate a brittle failure.

Heat-affected zone cracking such as illustrated in Figures 11 and 12 can result in certain steels if the cooling

rate in the heat-affected zone is sufficiently rapid to produce a predominantly martensitic microstructure and if the welding arc atmosphere is sufficiently high in hydrogen. It is evident that the welding procedure was inadequate, at least when some of the welds were made. The microstructure adjacent to most of the weld deposits was predominantly tempered martensite. As these welds were all single pass deposits, it is evident that the assembly must have been subjected to some post-weld heating, probably with the intention of stress-relieving the assembly and of tempering hardened heat-affected zones.

The oxidation found at the initiating points of two of the fractures, and in nearby cracks, as well as on the surface of the welds, supports the view that a post-weld heat treatment had been applied. It is quite possible that some of the heat-affected zone cracks may have been extended due to thermal stressing, as well as being oxidized by this heat treatment.

It is of interest to note that the brittle fractures have been initiated at the same locations from which fatigue fractures have propagated in some other panels. Information on fatigue behaviour is given in the DND report "Fatigue in Bailey Bridges" and in the paper[1] by Whitman and Alder, which is referred to in the DND report. There would seem to be a possibility that at least some of the fatigue failures may have been initiated at heat-affected zone cracks at the ends of the welds. The paper by Whitman and Alder does not indicate that any examination was made to determine if such cracks were present.

However, it is quite possible that there would be sufficient notch effect at the ends of the welds to initiate fatigue fractures even in the absence of heat-affected zone cracks from welding. This may also be true in the case of brittle fractures, but certainly pre-existing cracks will increase the likelihood of brittle failures at low temperatures or of fatigue fractures under prolonged service at normal temperatures.

Prior to removing the various sections from the welds, the assembly was examined visually and by the magnetic particle process. The fillet welds between the lower edges of the slots and the connecting plate were of satisfactory appearance. The small fillets around the ends of the connecting plate, i.e., across the thickness of this plate, were irregular and some were cracked. The vertical fillet welds between the inner surface of each channel web and the 5/8 in. plates, just back of the connecting plates (see Figure 2), appeared to be of poor quality. The fillet welds joining the small steel tabs to the top surface of the channel appeared to be adequate. Magnetic particle examination, after removal of paint with a liquid paint remover, did not provide any additional information about weld quality. It is significant that this inspection did not reveal any of the cracks shown in Figures 7, 8, 10, 11 or 12. This is not surprising as these cracks are actually quite small, and such cracks usually do not extend to the surface being examined. However, in view of the subsequent finding of toe cracks at the ends of the welds, greater emphasis on magnetic particle inspection at

these locations still seems to be warranted.

Some additional sections were examined during the investigation. A transverse section, at the centre of the fillet weld joining the connecting plate to channel B, was uncracked. There was a considerable difference in the microstructure of the heat-affected zones in the channel adjacent to the top and bottom welds. A higher cooling rate in the top weld produced a martensitic heat-affected zone, but a slower cooling rate in the bottom weld produced a microstructure consisting of fine pearlite with ferrite. This illustrates that slight variations in welding energy input can result in significant differences in the heat-affected zone microstructure and properties, as the latter zone would not be susceptible to cracking. Similarly, the microstructure in channel B, adjacent to the fillet welds on the top surface of the flange, indicated that the welds had been made with sufficiently high energy input conditions to avoid the production of martensite.

Figure 16 shows the microstructure typical of channel B, unaffected by welding heat. The microstructure consists of fine pearlite and ferrite. There was some banding in the steel, although this is not evident in the picture.

The results of the chemical analyses of drillings from each channel are given in Table 1 and compared with the requirements of two British Standards Institution specifications.

TABLE 1

Chemical Composition

	Element, Per Cent*						
	C	Mn	Si	S	P	Cr	Ni
Channel A	0.25	1.67	0.14	0.029	0.029	-	-
Channel B	0.25	1.67	0.13	0.030	0.030	-	-
BS968-1941**	0.23 max	1.8 max	0.35 max	0.06 max	0.06 max	1.0 max	0.5 max
BS968-1962***	0.20 max	1.50 max	0.35 max	0.05 max	0.05 max	0.50 max	-

* Internal Report MS-AC-63-56 (Mineral Sciences Division).

** War Emergency British Standard Specification for High Tensile (Fusion Welding Quality) Structural Steel for Bridges, etc., and General Building Construction, June 1941.

***Specification for High Yield Stress (Welding Quality) Structural Steel, April 1962.

The results of quantitative spectrographic analyses are given in Table 2.

TABLE 2

Quantitative Spectrographic Analyses of Channels

	Element, Per Cent*						
	Co	Cu	Ni	Ti	Zr	Cr	Sn
Channel A	0.03	0.06	0.11	0.001	0.001	ND**	ND
Channel B	0.02	0.05	0.12	ND	0.002	ND	ND

* Internal Report SL 63-050 (Mineral Sciences Division).
**Not detected.

Both channels meet the chemical composition requirements of B.S.968-1941 except for having carbon values which are 0.02% in excess of the specified maximum. The spectrographic analyses do not indicate the presence of harmful amounts of residual elements. It should be noted that the 1962 issue of The British Standard specifies lower carbon and manganese levels than in the earlier edition, and that the two channels would definitely fail to meet these requirements. In the foreword to the 1962 specification, it is acknowledged that the earlier composition limits could be too high for satisfactory welding performance and that significant improvement in weldability should be obtained with a steel meeting the 1962 requirements. In this connection, it is relevant to mention that the failure of main girders of The Kings Bridge(2) in Melbourne, Australia on July 10, 1962 was related to brittle failure of steel to the B.S.968:1941 specification, at air temperatures of 35 to 40°F. Apparently, fractures were initiated at hard zones and cracks in highly stressed locations where fillet welds joined the terminating points of cover plates to the lower tension flanges.

The tensile test results of steel from the two channels are given in Table 3, together with requirements of B.S.968:1941 specification.

TABLE 3

Tensile Test Results*

	UTS kpsi	YS** kpsi	%, El***
Channel A	91.4	59.2	25.0
Channel B	96.0	68.4	22.0
B.S.968-1941	78.3-91.8	47.0 min	14 min

* From Internal Report PM-T-1113 (Physical Metallurgy Division)

**The yield strength of steel from the channels was determined at 0.2% offset; B.S.968-1941 requirements are based on the drop-of-the-beam or divider method.

***For the two channels, the per cent elongation was determined in a 2 in. gauge length; B.S.968-1941 requirements are for an 8 in. gauge length.

The ultimate tensile strength of channel A is slightly below and that of channel B is about 4 kpsi above the maximum given in the British Standard. A direct comparison of the yield strength and elongation values obtained for the channels cannot be made with the specification requirements, but it is sufficient to observe that the values obtained indicate adequate tensile properties.

The results of impact testing of 5 mm x 10 mm Charpy V-notch bars, cut from the channel webs, are summarized in Table 4.

TABLE 4

Results* of Charpy V-Notch Impact Tests

Temperature °F	Channel A ft-lb	Channel B ft-lb
212	-	42
140	47	30
100	40	19
82	27	17
32	25	5
0	18	5
-55	5	-

*Internal Reports PM-T-1114 and PM-T-1151 (Physical Metallurgy Division).

Channel B has lower notch ductility than channel A. For example, at 32°F channel B gave only 5 ft-lb compared with 25 ft-lb for channel A. However, at the failure temperature of -55°F, even channel A gave only 5 ft-lb and thus also had little ability to resist brittle fracture. It is apparent that both channels have inadequate notch ductility for a structure exposed to low temperature combined with shock loading.

CONCLUSIONS

1. Failure of the end piece was due to brittle failure of the two channels by fractures that were initiated at cracks, and possibly other weld defects, at the ends of the fillet welds along the edges of the sway-brace slots.

2. Incorrect welding procedures had been used in making these welds, with the result that heat-affected zone cracking occurred. Cracks at the ends of the welds may have been extended as a result of thermal stressing during a post-weld heat treatment.

3. These cracks would be difficult or impossible to detect by any nondestructive testing method. They could act as originating points for fatigue cracks and, if extended by service over a period of time, might become apparent by visual examination. However, exposure to lower temperature service conditions could result in sudden brittle failures long before the small heat-affected zone cracks were extended by fatigue cracking to a point where they could be detected.

4. The steel composition and tensile properties indicate that the channels were intended to conform to the B.S.968-1941 or similar specification. This specification has been superseded by specifications for more weldable steels.

5. Impact testing showed that the steel in the channels had low notch-ductility at the failure temperature. Channel B had poor notch-ductility at temperatures at least as high as 32°F.

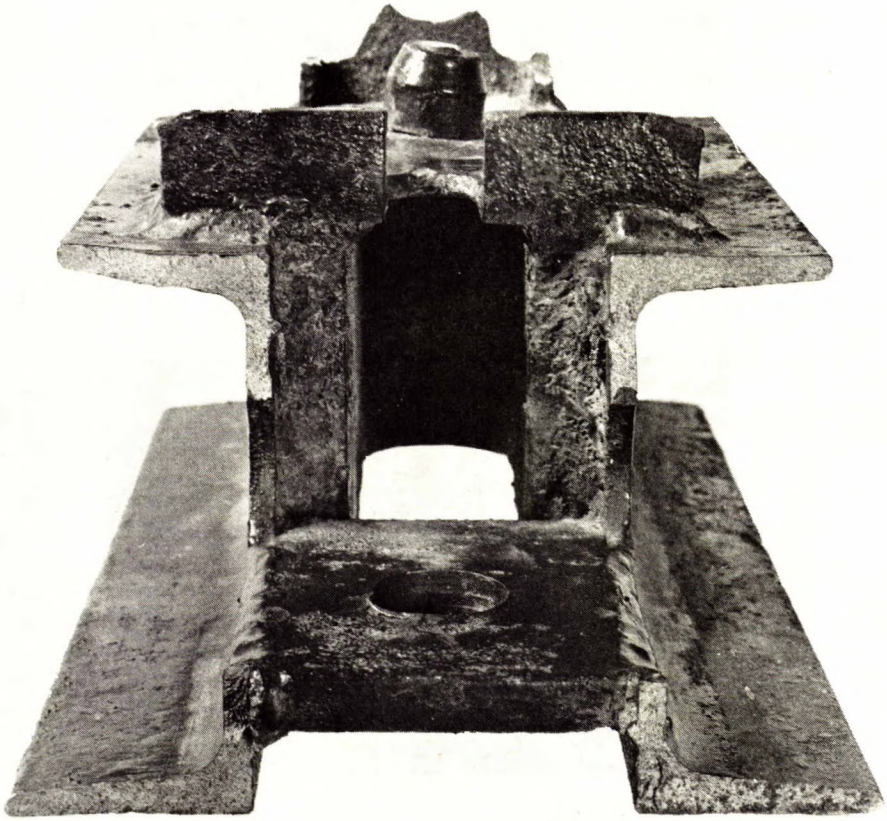
6. There is no assurance that similar failures will not occur in other Bailey Bridge members in service at lower than normal temperatures.

REFERENCES

1. J. G. Whitman and J. F. Alder, "Programmed Fatigue Testing of Full Size Welded Steel Structural Assemblies", British Welding J. 7 (4), 272-280 (April 1960).

2. Abstract of investigation committee, "Report on The Kings Bridge Failure, Melbourne", The Engineer 214, 370-371 (August 31, 1962).

Figure 1 - Side view of fractured end section
About 1/2 scale.



A B

Figure 2 - Looking toward fractured surfaces of end section. Channel A is on the left and channel B on the right.

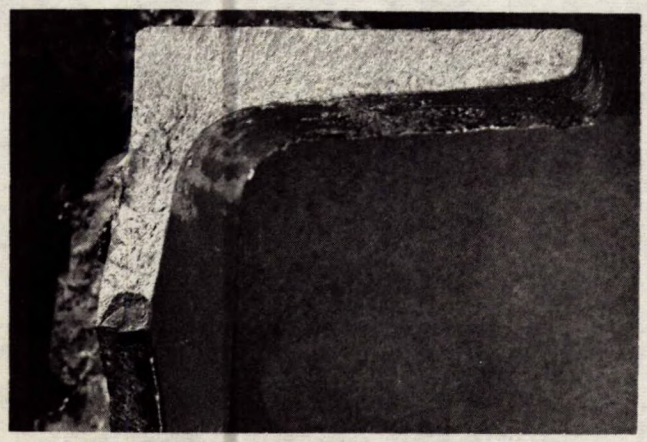


Figure 3 - Upper fracture in channel B.
About full size.

Figure 4 - Lower fracture in channel B.
About full size.

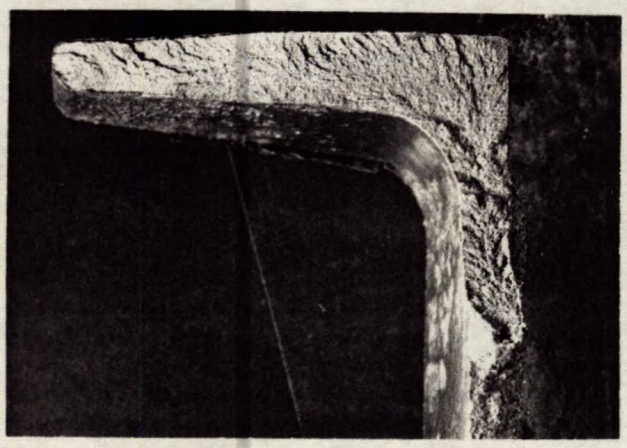


Figure 5 - Upper fracture in channel A.
About full size.

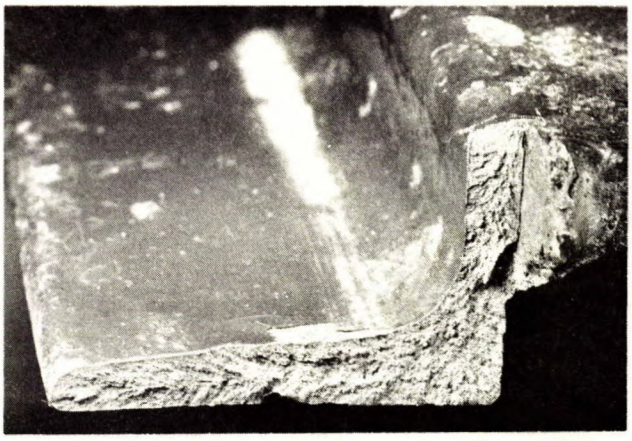


Figure 6 - Lower fracture in channel A.
About full size.

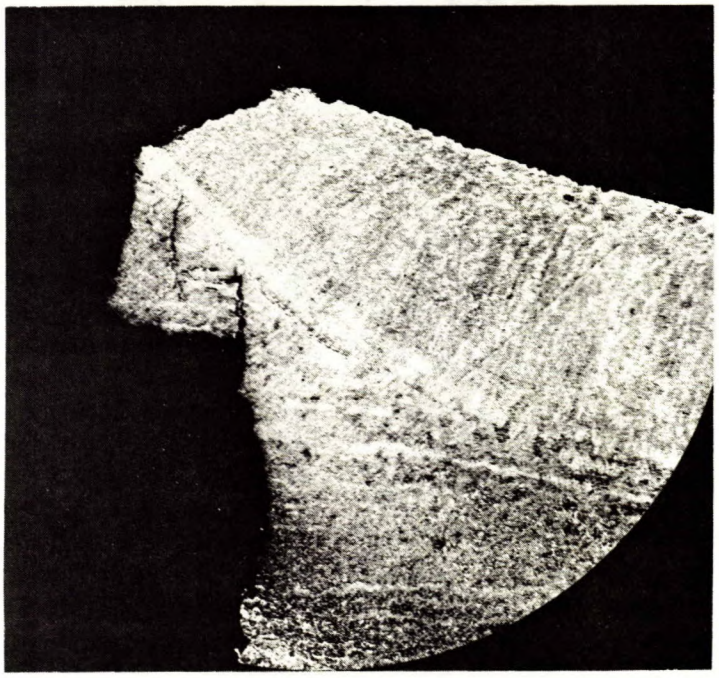


Figure 7 - Cross section at end of weld, and part of brittle fracture in lower part of channel B.
Etched 2% nital. X20.

Figure 8 - Showing initiation point of brittle fracture in lower part of channel B. Etched picric-hydrochloric acids. X75.

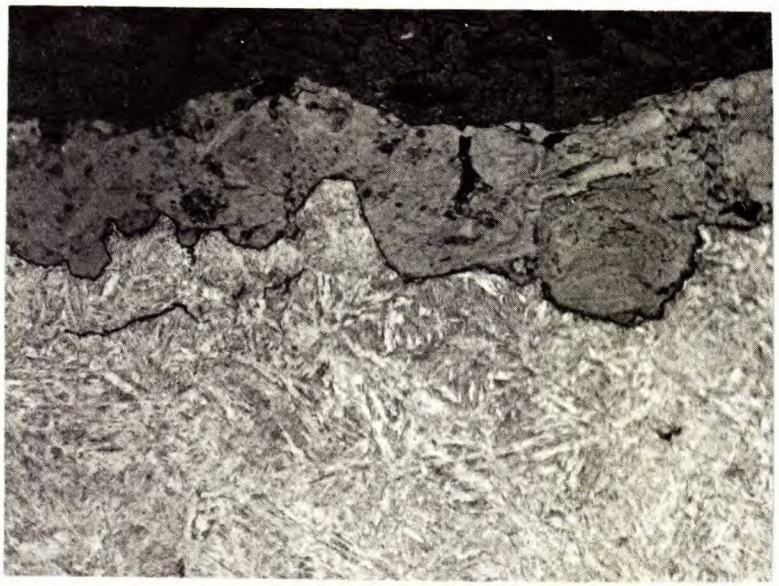


Figure 9 - Showing section through dark areas at initiation of fracture on lower side of channel B. See also Figure 4. Also representative of section through the dark area shown in Figure 3.
Etchant 2% nital. X250.

Figure 10 - Showing oxidized cracks at initiation of brittle fracture at lower side of channel B. The larger crack is in line with the main fracture as seen in Figures 7 and 8.
Etched 2% nital. X250.

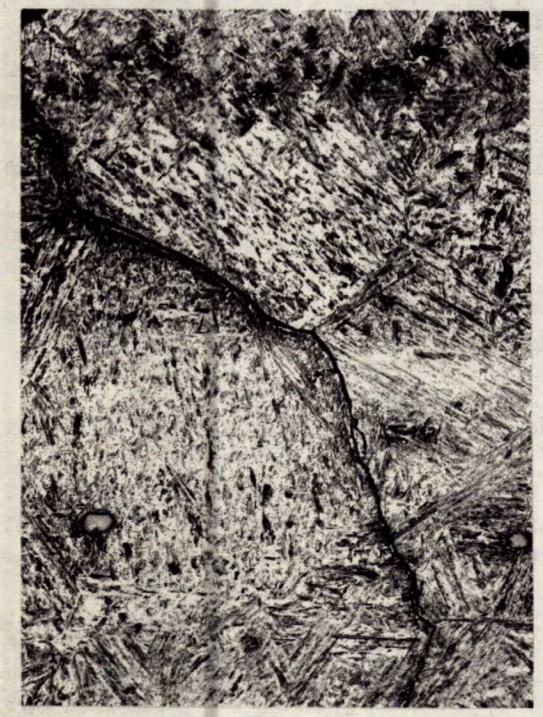


Figure 11 - Intergranular crack in heat-affected zone a short distance away from the fracture and cracks shown in Figures 7-to 10 incl. Weld metal is at top. Etched 2% nital. X250.

Figure 12 - Underbead cracking a short distance to the right of fracture and cracks shown in Figures 7 and 8. Weld metal is at top.
Etched 2% nital. X250.

Figure 13 - Cross section at start of weld, and part of brittle fracture in upper part of channel B seen in Figure 3. Only the heat-affected zone remains, and the fracture extends upwards from its junction with the curve of the slot.
Etched 2% nital X12.

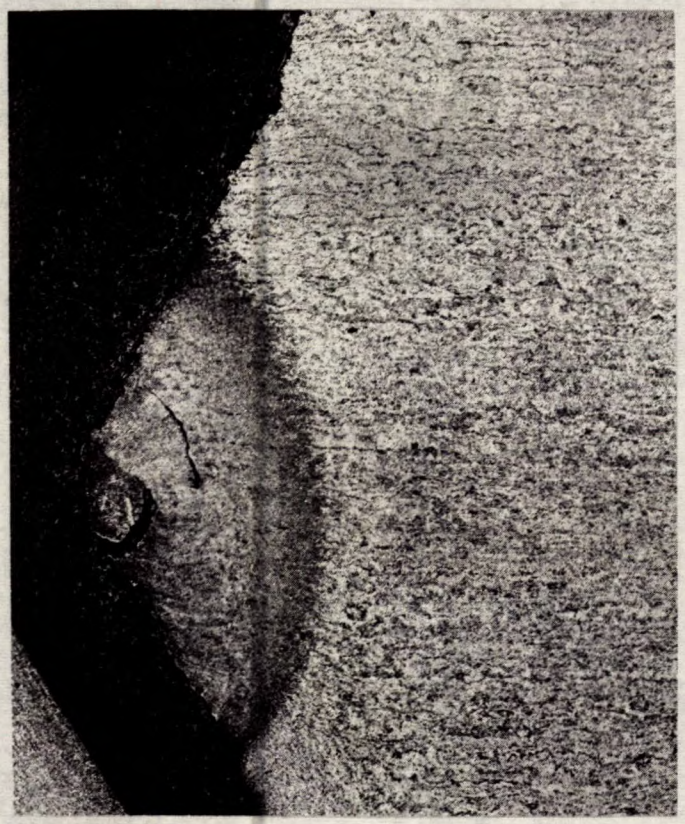


Figure 14 - Cross section at start of weld, and part of brittle fracture in upper part of Channel A seen in Figure 5. Some lack of fusion and entrapped slag is seen in the small portion of weld metal remaining. The fracture extends upward through the weld from its junction with the curve of the slot.
Etched 2% nital. X7.

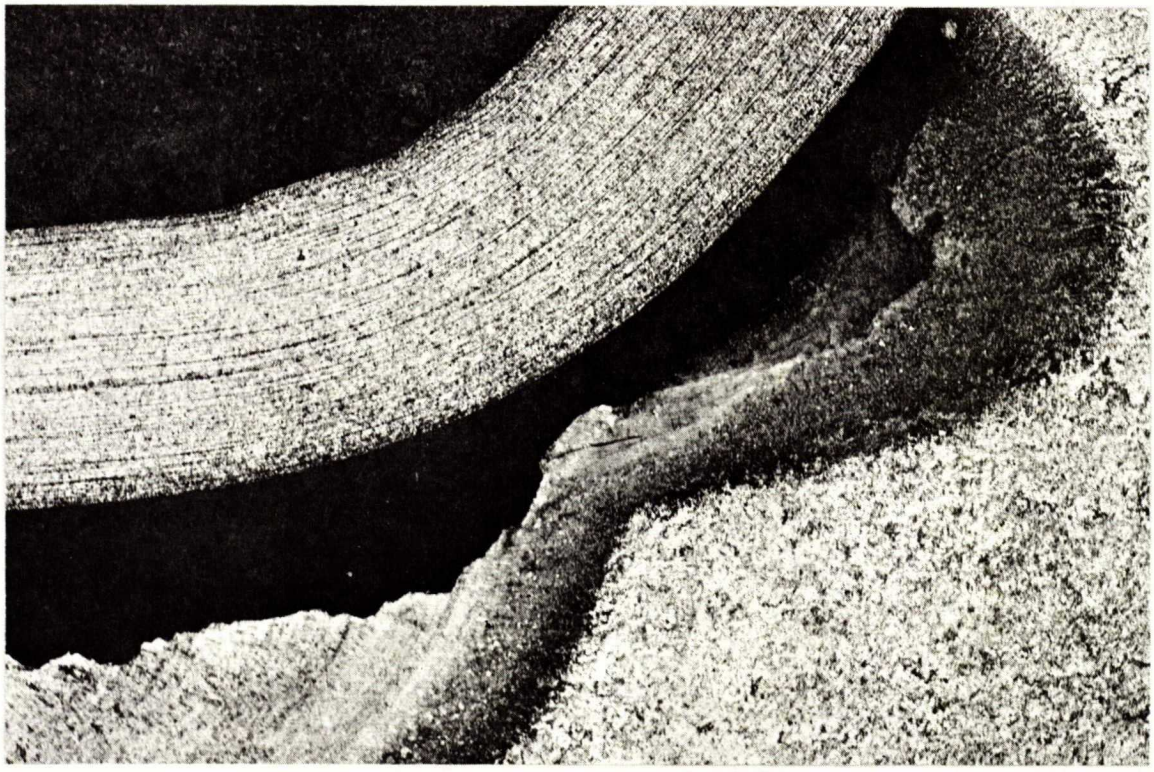


Figure 15 - Cross section at start of weld on lower part of channel A, showing a small arc strike just above the start of the weld deposit which is at lower left. The dark zone in the arc strike is a remelted spot on the channel and contains a very fine crack perpendicular to the edge of the channel slot, extending about 2/3 the depth of the remelted zone. The presence of this crack was established by examination at higher magnification.
Etched 2% Nital. X12.

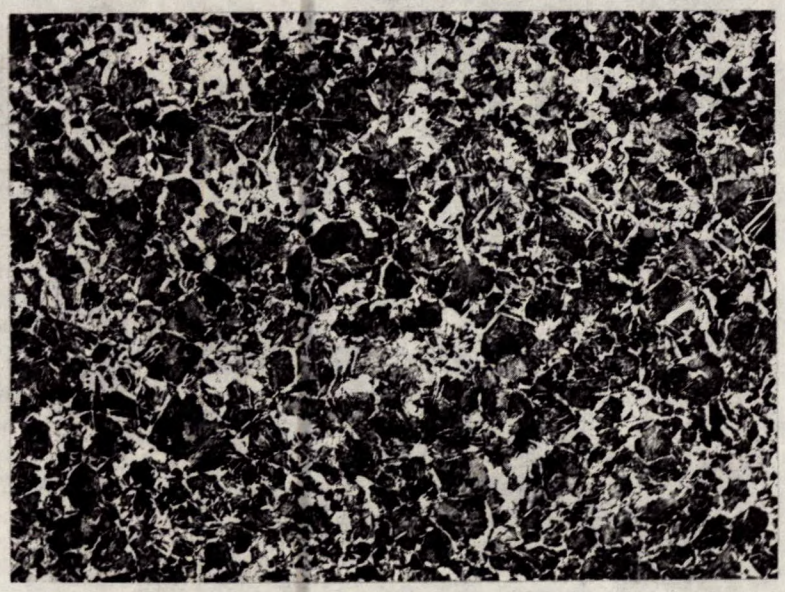


Figure 16 - Microstructure of channel remote from influence of weld deposits. Etched 2% nital. X100.