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INVESTIGATION OF FRACTURE OF 30 IN. WIDE FLANGE I-BEAM FROM WELLAND CANAL BRIDGE NO. 18

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

The fracture was found to have originated in a flame cut notch in the flange of the beam, and to have propagated as a result of high residual stresses in the beam. Recommendations were made to avoid this difficulty.

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(4 tables, 11 illus.)

INTRODUCTION

On March 10, 1958, Mr. J.N. Betournay, Assistant Director, Canal Services, Department of Transport, Ottawa, visited the Physical Metallurgy Division to discuss the failure of a 30 in. wide flange beam. The broken section was submitted for examination, and in a covering letter (File No. 4056-308) dated March 12, 1958, Mr. Betournay requested that comments be submitted as to the possible causes of failure, and recommendations made for any action which might be taken to prevent a recurrence of such failure.

The beam in question, along with three others, had been in use as a temporary support for the counterweight of Bridge No. 18 over the Welland Canal. The beams spanned the bridge tower (24 ft) with an overhang of approximately 12 ft. It was in this overhanging 12 ft that the failure occurred and on which there had been no load other than the beam's own weight. At the time of the fracture the beams were no longer loaded by the counterweight and were being removed from the tower. A sling had been placed round the beam, approximately a foot inside the tower leg. The sling was just taking the strain when there was a loud crack and the top flange of the beam cracked right across, starting at the outer notch which had been cut to allow the beam to sit in close to the tower leg. The crack continued vertically down through the web for about 4 in. and then diagonally downward and outward towards the end of the beam, turning downward again at a point approximately 1 ft 10 in. from the end of the beam and 6 in. up from the bottom surface. The crack stopped partway through the bottom flange, and the whole section rotated upward as though there were a residual stress forcing the section. As the beam was still up some 115 ft in the air, a hole was burned in the end of the broken section through which a sling could be fastened, in order that the broken portion could be completely removed and then lowered separately to the ground. The pieces of beam submitted are shown in Figure 1. A sketch of the orientation of the pieces is shown in Figure 2.

VISUAL EXAMINATION

The flame cut notches were very rough and irregular (Figure 3), with extremely deep grooves cut near and at the internal corners of the notches (Figure 4). The fracture surface was relatively smooth (Figure 5), with very little evidence of the chevron pattern usually associated with brittle fracture. A slight chevron pattern was found on the fracture surface of the upper flange on the side opposite to the notched side (Figure 6). These chevron marks pointed to the flame cut notch as the origin of the failure.

MECHANICAL TESTING

Full thickness, 8 in. gauge length tensile test bars were cut, in the longitudinal orientation, from both flange and web and, in the transverse orientation, from the web. The results of the tensile tests are shown in Table 1. Charpy V-notch bars in both the longitudinal and the transverse orientation were prepared from both the flange and the web. Numerical results of these tests are given in Table 2. The results are shown graphically in Figure 7. The 15 ft-lb transition temperatures, read from the curves of Figure 7, are shown in Table 3.

TABLE 1

Tensile Test Results

Sample	Tensile Strength (psi) Yield	Tensile Strength (psi) Ultimate	Elongation in 8 in., %
Flange, longitudinal	30,500	64,400	30.8
" "	31,700	64,000	32.0
Web, longitudinal	41,900	67,100	29.5
" "	38,700	66,500	30.5
Web, transverse	42,200	67,200	16.0
" "	40,100	67,700	22.0

TABLE 2

Charpy V-notch Test Results (in ft-lb)

Temperature, °F	Impact Energy (Average of 3 tests)			
	Web		Flange	
	Longitudinal	Transverse	Longitudinal	Transverse
212	67.3	38.0	82.3	40.7
160	67.0	36.3	68.3	36.0
110	49.7	30.0	46.7	25.0
77	34.0	21.7	26.7	18.3
50	26.0	16.0	12.7	10.0
32	17.0	12.0	8.3	8.0
0	6.3	6.3	4.7	4.3
-40	2.3	2.0	2.0	2.0

TABLE 3

Transition Temperatures
(15 ft-lb)

Web, longitudinal	-	27°F
Flange, "	-	55°F
Web, transverse	-	45°F
Flange, "	-	70°F

CHEMICAL ANALYSIS

Drillings were taken from web and flange and mixed to obtain a representative sample for chemical analysis. Results of the analysis are as shown below:

TABLE 4

Chemical Analysis

Element		Percent
Carbon	-	0.27
Manganese	-	0.61
Silicon	-	0.07
Sulphur	-	0.031
Phosphorus	-	0.011

MICROEXAMINATION

Longitudinal and transverse samples from both flange and web were prepared for microexamination. No abnormalities in either content or type of non-metallic inclusions were noted. The inclusions were somewhat thicker and shorter in the flange than in the web, as would be anticipated (Figure 8). A very considerable difference in coarseness of microstructure between the flange and the web was found (Figure 9). The fracture was seen to be typical of most brittle fractures, being principally transcrystalline cleavage with some shear and intercrystalline cleavage. A rather extensive heat-affected zone was found adjacent to the flame cut surface (Figure 10). Considerable martensite was found in this zone (Figure 11).

MICROHARDNESS TESTING

The Tukon microhardness tester was used to determine the hardness immediately adjacent to the surface in the heat-affected zone. A 500-g load was used with the Knoop indenter. The results, converted from the Knoop hardness values, show the hardness at 0.001 in. from the surface to rise to a maximum of R_c 46 (BHN 440), from a hardness of approximately R_b 74 (BHN 135) away from the heat-affected zone in the flange.

DISCUSSION

The mechanical properties, chemical analysis, and general microstructure of the beam are normal for as-rolled semi-killed mild structural steel intended to conform to ASTM A-7. The transition temperatures determined were all well above the stated service failure temperature of 11°F, so that brittle fracture could be anticipated under appropriate conditions. The very considerable difference in microstructure between flange and web indicates a considerable difference in cooling rate, caused presumably by the difference in thickness of these two portions of the beam (flange thickness 1 1/8 in., and web thickness 3/4 in.). In turn, this differential cooling rate in such a large beam would be expected to give rise to residual stresses of some magnitude.

The chevron marks, although scant, were sufficient to indicate clearly that the fracture origin was at the corner of the flame-cut notch in the flange. In addition, the presence of brittle untempered martensite in this area is a convincing argument in favour of so locating the fracture origin. It is apparent that the flame cut notch provided the "trigger" for the fracture. It is also evident, from the existence of untempered martensite associated with the notch, that the flame cutting was performed with neither pre- nor post-heating of the area. Also, the extreme roughness of the flame cut surface and the presence of deep grooves in the corners of the notches deserve the most severe condemnation.

However, having condemned, justifiably, the notches and the workmanship displayed there, it must be admitted that this grade of steel characteristically is cut and welded with no special precautions being taken. It is assumed that, under normal conditions, while a thin hard zone of more or less untempered martensite may form and crack, this zone is thin enough, the stress low enough, and the underlying material tough enough, to stop the crack. In this case the crack did not stop. One reason for this is quite clear, i.e. the material was well below the transition temperature at the time of fracture. Even so, some stress was required to propagate the crack. According to the information received, the beam was unloaded at the time of fracture. Even if loaded, the tensile stress in the upper flange due to load and deadweight load of overhang amounted to less than 300 psi in the fracture origin area. While the nominal stress required to propagate a running crack is absurdly low in relation to the yield strength of the material, it does appear to require something in the order of 5,000 to 10,000 psi. Since the crack did propagate and since the loading conditions account for less than a tenth of this stress, it must be assumed that the difference was due to residual stress. The precise reason for such a high residual stress in this particular beam is, of course, unknown. Two possibilities suggest themselves: differential cooling between web and flanges, and cold straightening. It might be pointed out that fracture of wide flange I-beams under conditions of no load (even, in one case, merely lying on the floor on its side) have been reported previously. In brief, fracture was initiated at a severe notch and propagated as a result of low temperature and high residual stress. In considering corrective and/or preventative measures, the appropriate procedures are obvious but their practicability is another matter. Stress relief of the entire beam would, of course, obviate the difficulty but is awkward, expensive, and most probably would result in a warped beam. Returning to the notch itself, preheating the area would prevent to a considerable degree the formation of the hard brittle zone. If possible, a template should be used in order to reduce the surface roughness. The corners should be given a very generous radius of curvature. In fact, the geometry of the notch should approach a semi-circle as nearly as possible. Finally, the flame cut surface should be ground to a depth of at least 0.020 in. to smooth out the surface and to remove the hardened zone. It is suggested that the last two steps be applied to the other beams in which notches have already been cut.

CONCLUSIONS

1. Fracture originated at a flame cut notch in the flange.
2. The fracture propagated as a result of low temperature and the existence in the beam of residual stresses of considerable magnitude.

RECOMMENDATIONS

1. Improve the notch geometry, eliminating sharp internal corners and providing generous radii of curvature instead. The notch should approach a semi-circular form as nearly as possible.
2. Flame cutting technique should be improved, e.g.:
   (a) Use a template to reduce the surface roughness.
   (b) Avoid cutting deep grooves.

(c) Preheat the area, particularly if the ambient temperature is low.

3. Grind off the flame cut surface to a depth of 0.020 in.

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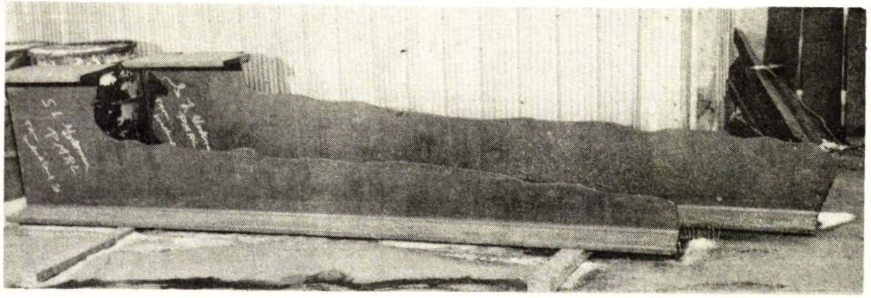

Figure 1. - Pieces of beam, as received.

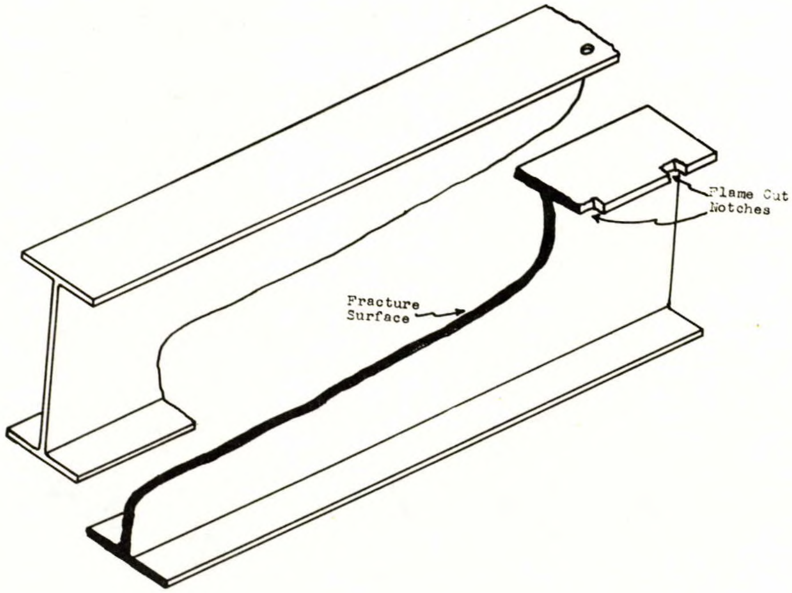

Figure 2. - Sketch of pieces of beam in correct orientation.

Figure 3. - Origin of fracture. Note roughness of flame cut surface. X1.

(X6; etched in 2% nital)

Figure 4. - Section through fracture origin area. Note deep flame cut groove.

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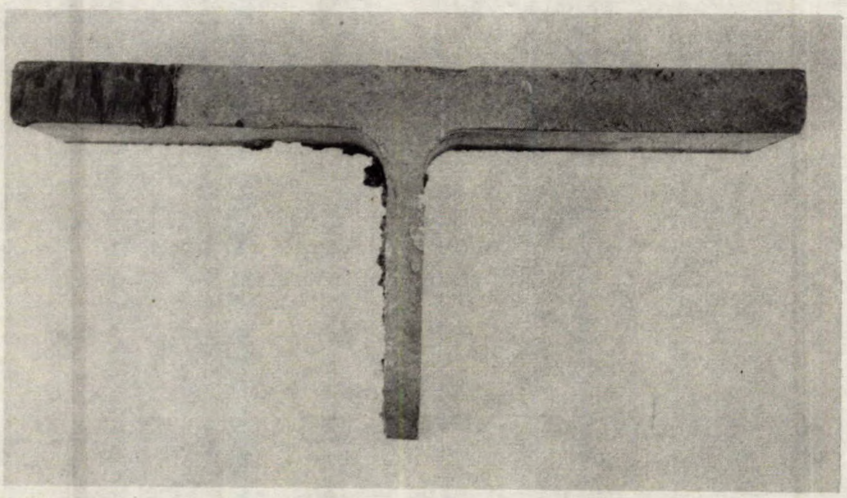

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Figure 5. - Fracture origin at corner of flame cut area at left of flange. Note apparent "fine grain".

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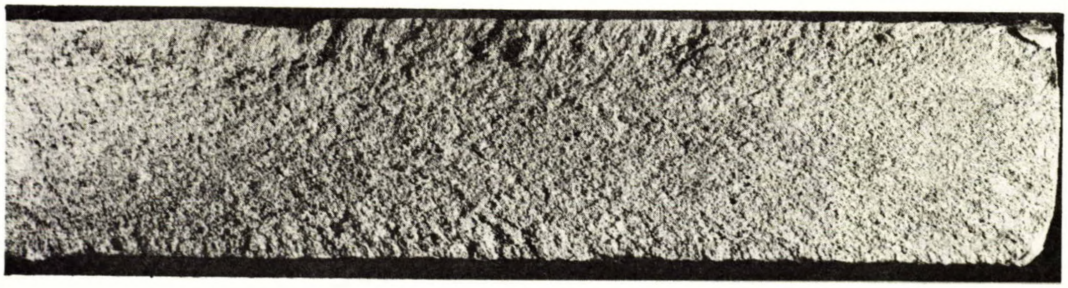

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Figure 6. - Fracture surface on upper flange. Note fine chevron markings pointing to fracture origin on other side of flange.

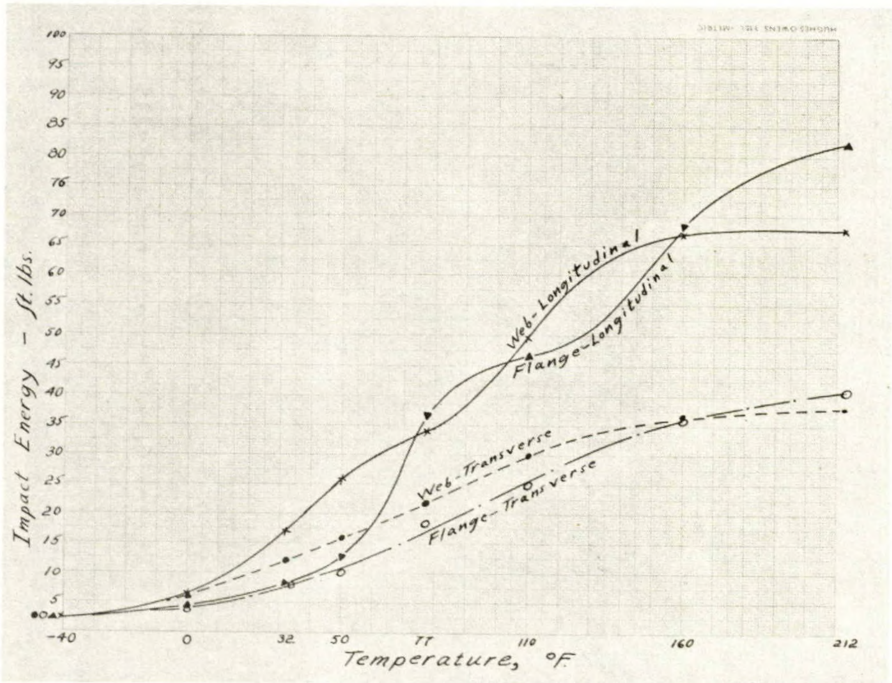
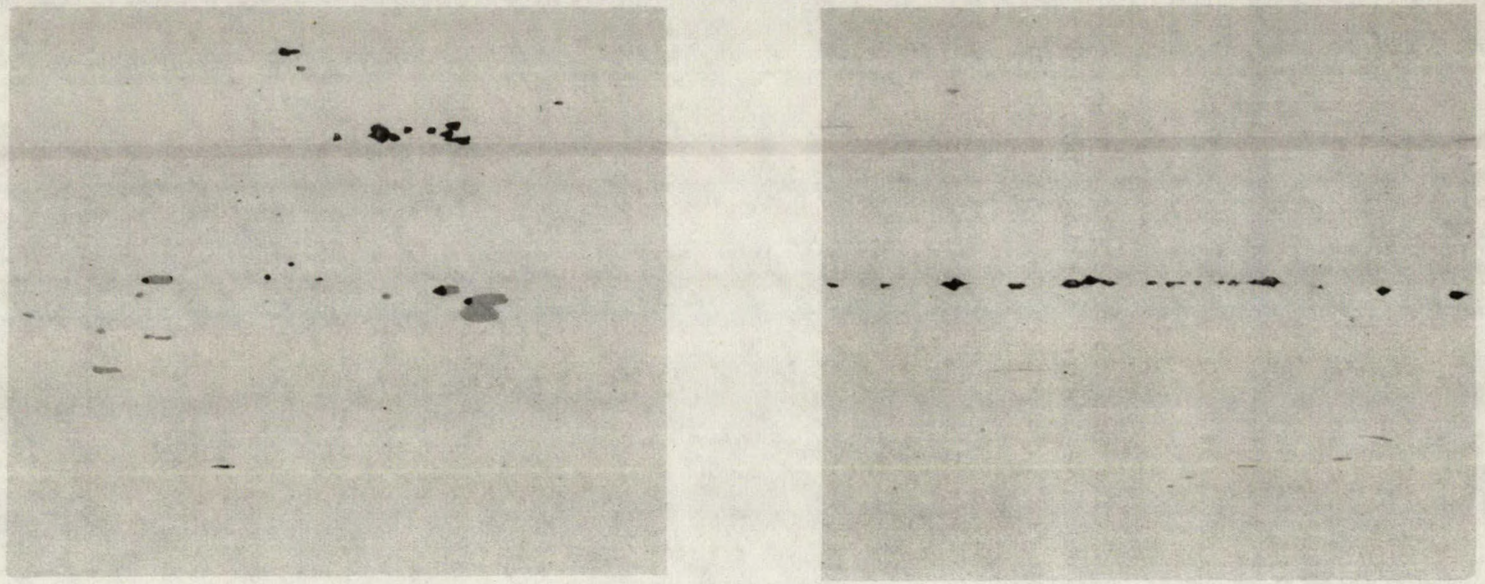


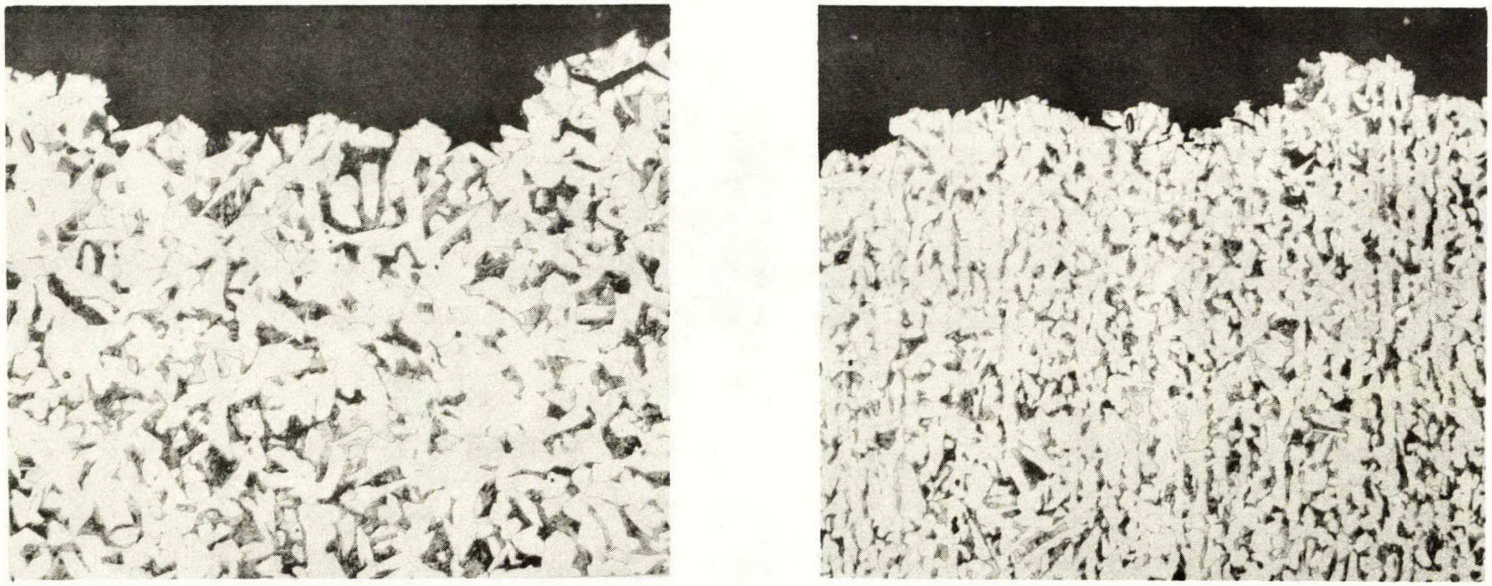
Figure 7. - Charpy V-notch impact test results.



Flange   Web

(X100, unetched)

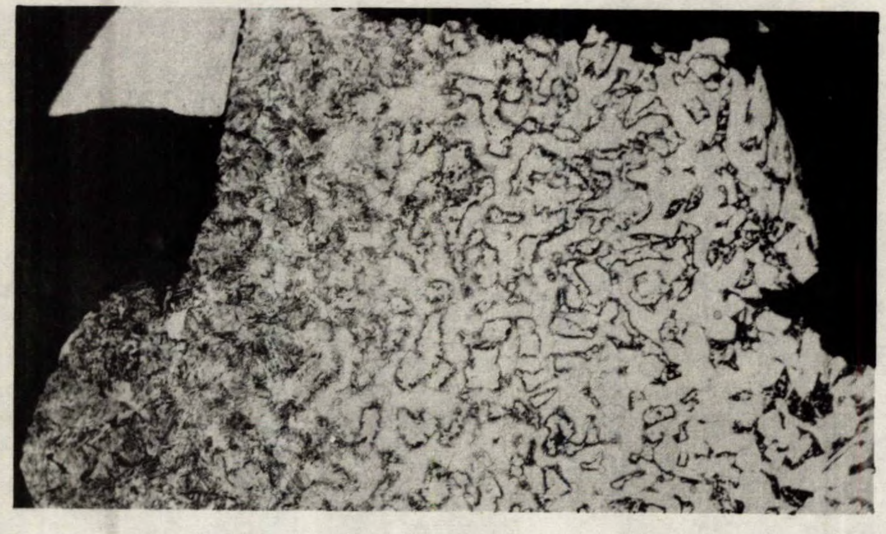
<u>Figure 8</u>. - Typical non-metallic inclusions.



Flange Web

(X100, etched in 2% nital)

<u>Figure 9</u>. - Note the marked difference in microstructure.



(X100; etched in 2% nital)

Figure 10. - Section through flame cut surface (left) and fracture (top), showing heat-affected zone.

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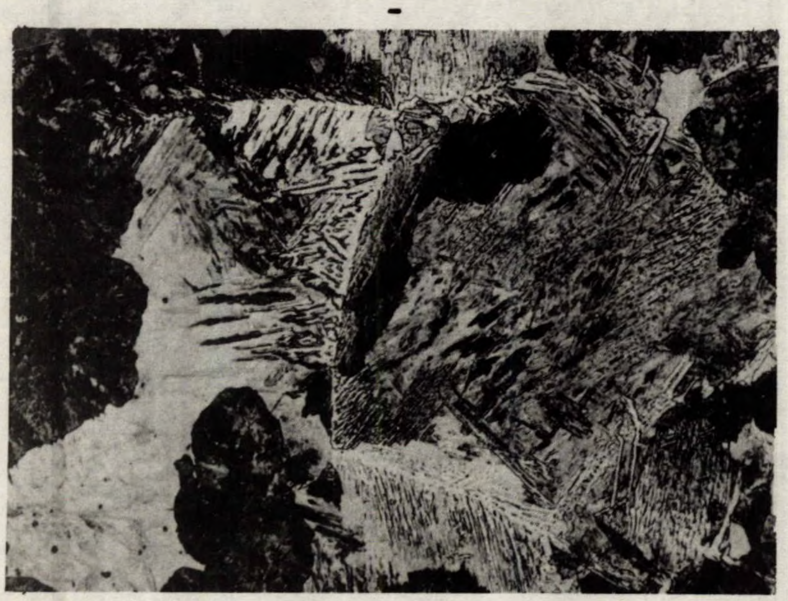

(X500; etched in 2% nital)

Figure 11. - Same section as above, near flame cut surface, showing brittle untempered martensite and bainite.

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