Return to John A. Bennett

7405 DENTON RD.
BETHESDA, MD. 20814

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NATIONAL BUREAU OF STANDARDS REPORT

9981

METALLURGICAL EXAMINATION AND MECHANICAL TESTS OF MATERIAL FROM THE POINT PLEASANT, W. VA. BRIDGE

PART I

To

Bureau of Public Roads
Federal Highway Administration
Department of Transportation

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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METALLURGICAL EXAMINATION AND MECHANICAL TESTS OF MATERIAL FROM THE POINT PLEASANT, W. VA. BRIDGE
PART I

By
John A. Bennett
Engineering Metallurgy Section
Metallurgy Division

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U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

Report on

Metallurgical Examination and Mechanical Tests of
Material from the Point Pleasant, W.Va. Bridge

Submitted by

Bureau of Public Roads

Part 1. Examination of Fractures and Adjacent Material in C13 Eye of Eyebar C11-C13 NN

Background: In January, 1968, the Bureau of Public Roads requested the National Bureau of Standards to send a representative to Point Pleasant, West Virginia, to examine the wreckage of the Ohio River bridge that had collapsed on December 15, 1967. Accordingly, Mr. John A. Bennett visited the site on January 22 and 23, 1968: his observations and conclusions were included in a report dated January 26, 1968. This report states, in part,

> " I observed only one fracture that I consider to be of primary importance in connection with the collapse of the bridge; that is the fracture through the eye of the eyebar which I believe bears the serial number 330. .....
>
> Even a cursory visual examination under difficult conditions revealed a marked difference in the fracture on the two sides of the eye. ..... I believe that this configuration of the fracture could have been produced only by a progressive cracking of the first side by loads whose maximum value did not cause appreciable plastic deformation of the eye. ..... When this first fracture was completed, the other side was subjected to an excessive load and failed rapidly, but with a fairly ductile tearing fracture. This accounts for the difference in configuration of the two sides. I have been unable to conceive of any way in which this fracture could have occurred after any other failure in the eyebar chain. I believe, therefore that it is almost unquestionably the primary fracture in the collapse."

The two pieces of eyebar C11-C13 were received at NBS in early July, 1968. (In referring to the fractured eye, the terms inboard and outboard will be used to mean directions toward and away from the shank, respectively.) In accordance with the Laboratory Specimen Plan adopted by the Structural Analysis and Tests Group on June 10, 1968, the pieces were photographed and molds were made in which plaster replicas of the fractured eye were cast.

The inboard piece was also used in connection with the reassembly of the C13 joint on September 13, 1968. At the conclusion of these operations, the eye was separated from the shank of the bar by a torch cut just inboard of the taper, and we started the examinations covered by this report. Because of the possible importance of the observations on the fracture surfaces and of the microstructure of the adjacent material, this report is being submitted as promptly as possible. A second report, covering the extensive mechanical tests and additional metallographic examinations of this and other eyes, will be submitted later.

Cleaning techniques: Three different techniques were used in removing corrosion products from the eye, depending on the need for preserving details of the surface topography. On the faces, where only the gross features were considered to be of importance, we used a power-driven wire brush. Occasionally some of the paint was removed with paint remover and a scraper before wire-brushing.

We wished to preserve somewhat finer detail on the surfaces of the hole, so here we used a commercial rust-removing preparation and stiff bristle brushes. The powdered compound was mixed with water to form a paste, applied to the surface and allowed to remain for an hour or so before the brushing was started.

It was essential, of course, to preserve as much of the surface topography as possible on the fracture surfaces, so we cleaned these with a solution of ammonium citrate and bristle brushes. We have found in the past that this procedure, while laborious, will remove the oxide with only very slight attack of the underlying steel.

Visual observations: The appearance of the fractured eye when recovered has been described in other reports but will be repeated here for completeness (figs. 1 and 2). The fracture in the lower side of the eye was very brittle in appearance; there was no evidence of plastic deformation adjacent to the fracture except for a small shear lip along a part of one side. Along much of the fracture the paint was intact to within about 1/16 in of the fracture.

The upper fracture was very different. There was evidence of extensive plastic deformation in the cracking and flaking off of the paint, in the deformation of the hole and in the thinning of the bar, particularly adjacent to the hole. (These dimensional changes can be determined from the measurements made in the Engineering Mechanics Section of NBS and reported earlier by A. F. Kirstein.) The pattern of the paint flaking indicated that the deformation was due to bending of the side of the eye with, initially, tension on the inside and compression on the outside.

The fracture surfaces also were very different. The lower fracture, figure 3, was almost exactly in a single plane and the roughness was on a fine scale. The upper fracture split into two branches after traversing about two-thirds of the distance from the inside to the outside of the eye, leaving a triangular piece, 5 to 6 inches on a side, nearly broken from the rest of the eye. This fracture surface, figure 4, was much rougher than the lower one, the irregularities being as much as 1/8 inch.

Fracture markings on both fractures indicated that they had started at the surface of the hole; those on the lower fracture seemed to point toward a location about 1/10 inch from the south face of the eye. Shortly after the cleaning of the outboard surface of this fracture was started, we noticed that a small area near this presumed origin was cleaning up more readily than the rest of the fracture. That is, the heavy red rust was more easily removed from this small area, but there was a more adherent dark grey oxide left which gave a marked contrast between this area and the rest of the fracture. This contrast was preserved by making a cellulose acetate replica of this portion of the fracture; a sufficient amount of both types of oxide were removed with the replica to show the contrast very effectively.

The surface of the lower fracture after cleaning is shown in figures 5 and 6. Figure 5 shows the extent of the shear lip adjacent to the south face of the bar in contrast to the other side, where there was very little lip. In figure 6 the fan-shaped area in the upper corner is the same area referred to earlier which had an adherent dark oxide unlike that on the rest of the fracture. This area is indicated by a solid arrow on figure 6. A similar, but smaller fan-shaped area can be seen just below the one at the corner, (Open arrow). On the inboard side of the fracture the smaller area could be seen clearly, whereas the larger one has been obliterated by battering of the corner after fracture. There appears to be little doubt that these areas represent cracks which existed for some time prior to the final fracture. The larger of these areas extended approximately 0.11 inch in from the surface of the hole.

Figure 7 shows the surface of the hole in the outboard piece adjacent to the lower fracture. The poor quality of the machining is evident in this area where the grooves and tears in the surface have not been affected by corrosion because the surface was in tight contact with the pin. There was one area of fairly severe corrosion outboard of the lower fracture; this can be seen at the upper left of the photograph, i.e. adjacent to the south face of the bar. When the corrosion products were cleaned off this area, two cracks were easily visible, figure 8.

In accordance with the Laboratory Specimen Plan, a segment (designated "0" in the Plan) approximately 1/2 inch thick was separated from the in-board piece of the eye by a saw cut parallel to the lower fracture, figure 9. A number of additional cracks were found on the hole surface in this segment, one group being close to the saw cut, i.e. nearly 1/2 inch from the fracture, (see figures 10 and 11). An attempt was made to locate the origins of these cracks and those in the outboard piece; all of them appeared to have initiated in a region lying between 0.08 and 0.48 inch from the south face. Figure 12 is a sketch, based on visual observations, of the location of the principal cracks.

Metallographic examination and hardness surveys: A piece, approximately 1/2 in. on a side, was cut from the portion of segment "0" adjacent to the south face of the eye for metallographic examination. Other, thinner specimens were cut adjacent to the first, as shown in figure 13.

Specimens A and B were mounted so that the plane of polishing was parallel to the south face, while specimen V was polished on a surface that was perpendicular to both the south face and the fracture. By successive polishing, grinding, and cutting of specimen A we examined sections of the eye at the following distances below the south face:

0.012 inch
.022
.039
.089
.110
.224
.232
.285
.394

A slice of the sample between the 0.110 and 0.224 inch sections was preserved. Representative photomicrographs showing the structure of the steel and the nature of the cracks and fractures are shown in figures 14 - 27; these photographs are all oriented with the hole surface at the left and the fracture at the top.

The microstructure of the steel changed with increasing distance from the south face, as can be seen by comparing figures 14, 15, 17, 20, 26 and 27. Near the surface the structure is tempered martensite which becomes mixed slack-quenched products with increasing depth. At greater depths the structure gradually changes to one of pearlite and ferrite. There is some evidence of spheroidization of the carbides, indicating a high tempering temperature.

The change in structure is reflected in the change in hardness shown on figure 28: these values were obtained with a Vickers hardness tester (10 kg load) on specimen V and are therefore representative of material approximately 0.6 inch from the hole. Several series of hardness tests were made on longitudinal sections of specimens A and B, and no significant variation was found as a function of distance from the hole.

The nature of the cracks that had propagated into the bar from the surface of the hole is shown in figures 18, 19, 20, 22, 23, 24, 25, and 26. They generally appeared to have initiated at corrosion pits, although many severe pits were observed that had no cracks associated with them, as in figure 14. All of the larger cracks were branched, and the branches often appeared to have propagated almost back toward the origin of the crack, figures 18, 22, and 23. Non-metallic material, presumably oxide, was present in nearly all the cracks. A number of cracks changed width abruptly, as in figure 25: also we often observed that the oxide in the wide cracks had a laminated structure which suggested that sudden changes in crack width had taken place, (figure 23).

There did not appear to be any marked change in fracture topography associated with the front of the fan-shaped areas visible at the origin on the fracture surface. The larger of these areas (figure 6), had penetrated about 0.11 inch from the hole surface, and the center of it was nearly the same distance from the south face. Figure 16 is a micrograph at low magnification, taken on a plane 0.11 inch from the south face and including the location of the front of the "fan". Although the change in direction of the crack near the middle of this figure may well be associated with the change in appearance of the fracture surface, there are no microscopic differences in the nature of the fracture that we could observe on the two sides of this region.

At some distance from the origin there were numerous secondary cracks associated with the fracture, as shown in figures 21 and 27. These were very different from the branch cracks observed near the origin, being generally straighter, narrower, and seldom showing oxidation of the crack faces. An attempt was made to determine how close to the hole there were secondary cracks on some of the sections observed, with the results shown in figure 29. Beyond the dotted line in this sketch, secondary cracking was found on all the metallographic sections examined.

<u>Electron microprobe analysis</u>: In order to determine if inclusions or other impurities were involved in the development of the cracks, an electron microprobe analysis was made on a metallographic section of specimen "A" which contained a relatively large crack. Qualitative analyses were performed at many points both in the metal and in the crack. All of the results from the crack indicated the presence of iron, and other elements of atomic number greater than 12 were not found in

significant quantity. As impurities or inclusions formed during manufacture of the steel would be composed of elements having atomic numbers greater than 12, such as manganese, silicon, and sulphur, these results indicate that the material in the crack was a form of iron oxide that formed after the cracking.

<u>Discussion</u>: The results of the examinations described above verify the conclusion of the January 26 report that the lower side of the eye fractured under loads which were not sufficient to cause appreciable plastic deformation of the steel. The fracture initiated at two preexisting cracks which appeared to be similar to numerous other cracks found within 1/2 inch of the fracture but not associated with it.

The first evidence for the existence of cracks prior to the fracture was the difference in the oxide on the small semi-eliptical area at the origin as compared with that on the remainder of the fracture. The dark grey oxide normally forms under conditions where the access of oxygen and moisture to the surface is somewhat limited. Once formed, however, it is more adherent than the loose red rust which occurs when there is free access of the reacting elements. The adherent film inhibited further oxidation of the underlying metal; this explains why there was relatively little red rust on the small area at the origin where a crack had existed for some time. When cleaning was started this rust was easily removed and the underlying grey oxide was in marked contrast to the orange-red color of the remainder of the surface.

The presence of multiple cracks in material that has not suffered gross plastic deformation is, in itself, evidence that the cracks were growing relatively slowly. As soon as rapid fracture began at the tip of one crack, complete separation would have occurred in a very short time, and there would no longer be any stress on the material near the origin. But the micrographs of the cracks in this area show that considerable oxidation had occurred on the walls of the cracks, indicating that they had been held open for some time.

All of the cracks observed had occurred in an area of the pin-hole surface where there was rather heavy corrosion damage. This observation, combined with the irregular appearance of the cracks on the metallographic sections, suggests that the mechanism of cracking was stress corrosion rather than fatigue. There may be little difference in the two mechanisms under the conditions existing at the surface of the hole, but we believe that the cracks would probably have occurred even in the absence of any fluctuation in the stress applied to the eye. Although we have not been able to locate any reference to stress corrosion cracking in material of this composition and heat treatment, the nature of the cracks is quite similar to that observed in failures of low carbon steels in gas pipe lines and of a variety of steels in anhydrous ammonia tanks. Fatigue cracks, on the other hand would probably have been less irregular and would have deviated less from a plane perpendicular to the tensile stress.

The results of the electron microprobe analysis indicate that inclusions were not an important factor in initiating the cracks.

Secondary cracks close to a fracture are generally believed to indicate that the fracture was propagating at high speed. If this is correct, then our observations of secondary cracks indicate that fast fracture initiated in the lower side of the eye when the crack depth was only about 0.6 inch. Planned measurements of fracture toughness of the eyebar steel should make it possible to estimate if this is a reasonable value of critical crack length under the loading conditions at the time of fracture.

There does not appear to be any definite evidence regarding the nature of the crack propagation from the end of the stress corrosion cracks at a depth of about 1/8 inch to the beginning of fast fracture. It may be that the crack was propagated across this region in a time period that was too short to permit the formation of much oxide, but the rate of energy release was not high enough to cause fast fracture. We did not see any microscopic evidence of a difference in fracture topography on sections through this region as compared with the stress corrosion cracks.

We had been informed that the specifications for the eyebars called for a steel having 0.6% carbon and no significant alloying element other than manganese; the heat treatment was reported to be quenching in water from the austenitizing temperature and tempering at 1150 - 1200°F. This would be expected to result in a very inhomogeneous structure across the thickness of the bar, as only the outer layers would be cooled fast enough to form martensite. This expectation was verified by the hardness tests and metallographic examination. Further inhomogeneity was caused by a marked decarburization of the outer layers of the steel. Thus, as seen in figure 28, the hardness near the surface is low because of the low carbon content; as distance from the face increases, the hardness increases to a maximum in the region where there was adequate carbon and the cooling rate was fast enough to form martensite. Further from the face the hardness decreases because the structure consists of non-martensitic constituents formed by "slack quenching". Near the center of the thickness the cooling rate was sufficiently slow so that the structure is essentially all pearlite and ferrite. The high tempering temperature has caused some spheroidization of the carbides. The hardness values indicate that the steel probably met the specification requirements for tensile strength.

It may be significant that all of the cracks originated in a band near the position of maximum hardness, i.e. 0.1 to 0.5 inches from the south face. We understand that the local stress at the origin of the fracture may have been sufficiently high to cause plastic deformation of some metal at the surface of the hole; if this were the case, the hardest zone, having the highest yield strength, would have the highest local stress.

As there is another structure virtually identical to the Point Pleasant bridge, it is of great importance to determine if there was any unique condition in the fractured eyebar that caused the cracking. If not, one must assume that cracks may be present in other bars with a similar history. In the examinations and tests covered by this report we have found nothing that we consider significant to indicate that the fractured eye was defective when installed or that it had been damaged in such a way as to make failure more likely. The only factor that could be considered in this category was the poor quality of the machining on the bore of the hole, but we do not believe that it would be surprising to find other examples of equally poor machining in a large sample of eyebars.

Conclusions:

1. The fracture on the lower side of the hole in eyebar C11-C13 NN propagated from pre-existing cracks having a depth of less than 1/8 inch. There was no gross plastic deformation of the section prior to fracture.

2. Many additional cracks had started on the surface of the hole near those involved in the fracture. All of the crack origins were in areas where severe corrosion had occurred and all were within 1/2 inch of the south face of the eyebar.

3. Almost all of the cracks not involved in the fracture were filled with oxide, indicating that they had been held open by tensile stress for a long time.

4. The nature of the cracks was similar to those caused by stress corrosion of other steels.

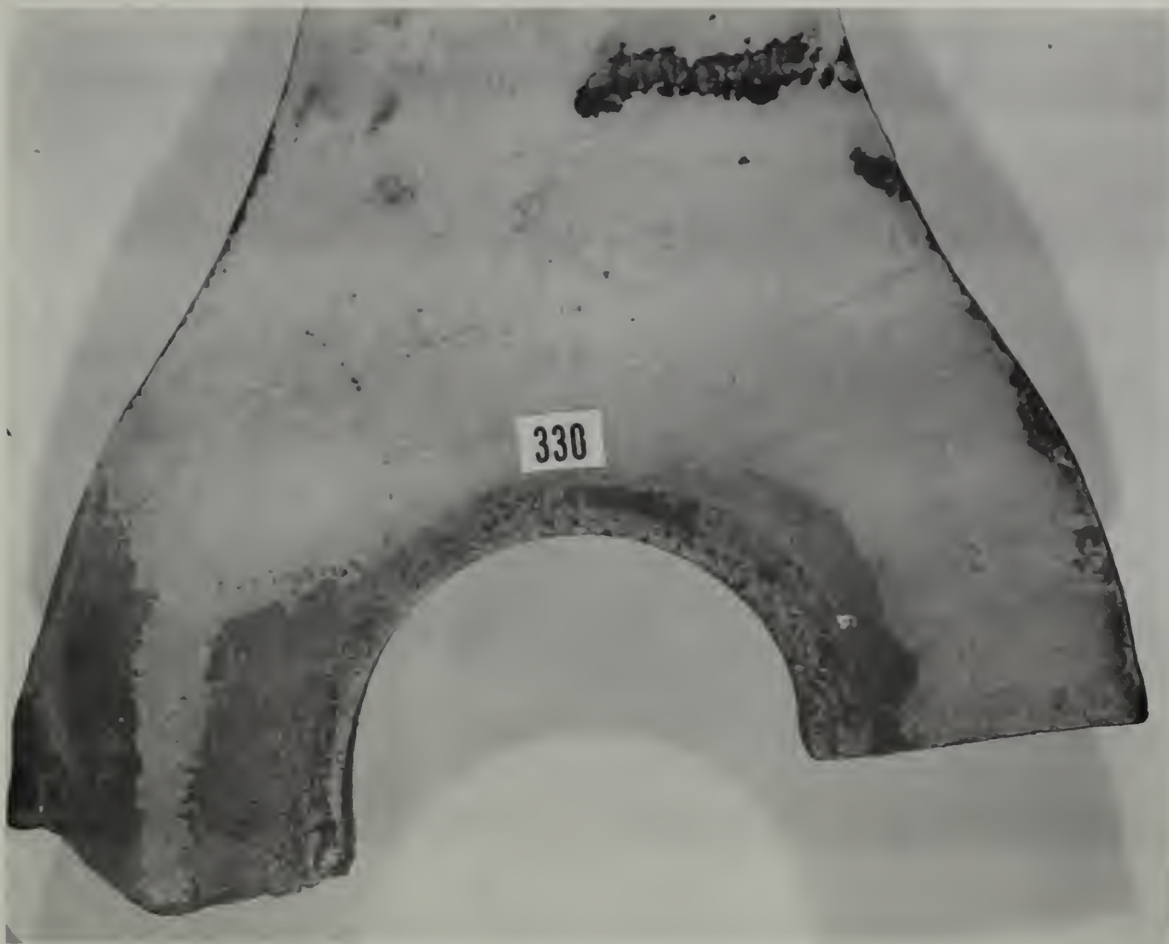
5. Based on the evidence of secondary cracks adjacent to the main fracture surface, it appears that the crack was propagating rapidly by the time it was 0.6 inch deep.

6. The crack on the upper side of the eye occurred after extensive plastic deformation in bending, and the fracture was obviously due to excessive load on the section.

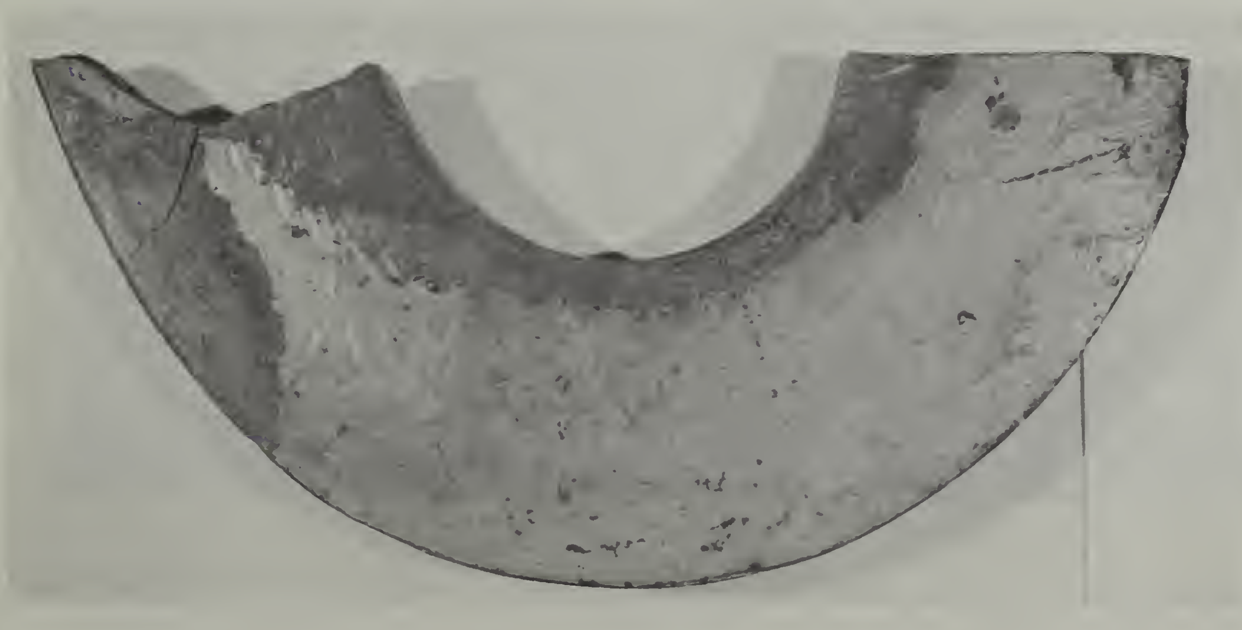
7. The microstructure and hardness of the steel varied markedly with distance from the faces of the bar, as would be expected for material of this composition, size and heat treatment. Aside from severe decarburization of the surface layer, the steel appeared to be of normal structural quality.

8. We did not observe any condition that would make this bar much more prone to failure than other bars with a similar history.

Acknowledgement: The extensive metallographic work in connection with this study was done by Charles H. Brady.

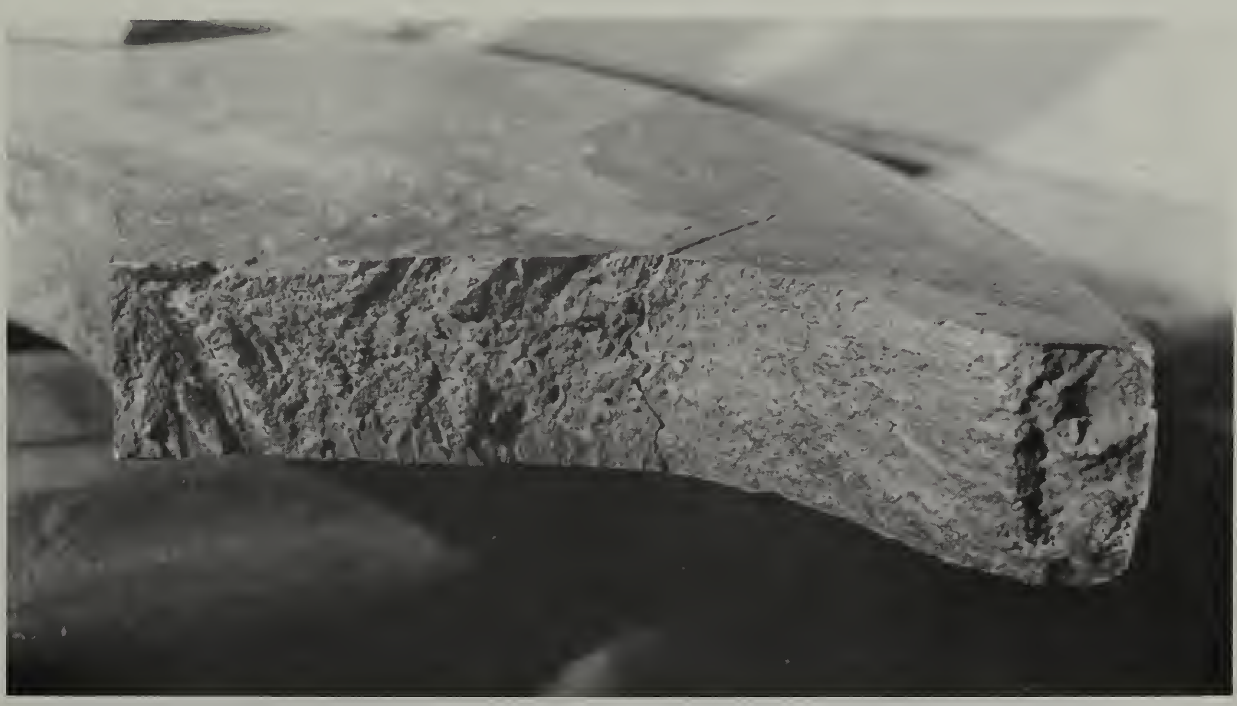


1, Inboard piece of the broken eye, as received. The north face is shown, and the lower side of the eye is at the right.



2, Outboard piece of the broken eye, as received, oriented as figure 1.

3. Fracture in the lower side of the eye before cleaning. The outboard surface of the fracture is shown, with the north face at the top.

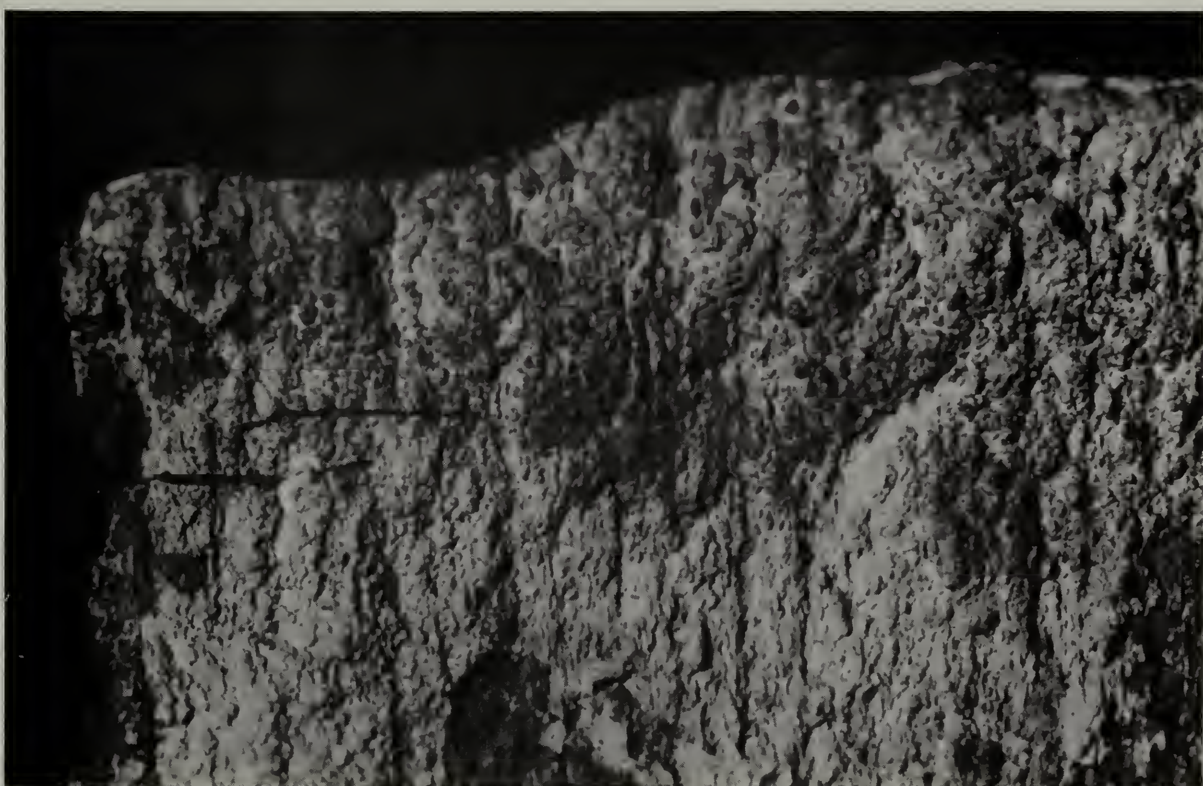


4. Fracture in the upper side of the eye before cleaning. The outboard surface of the fracture is shown, with the north face at the top.

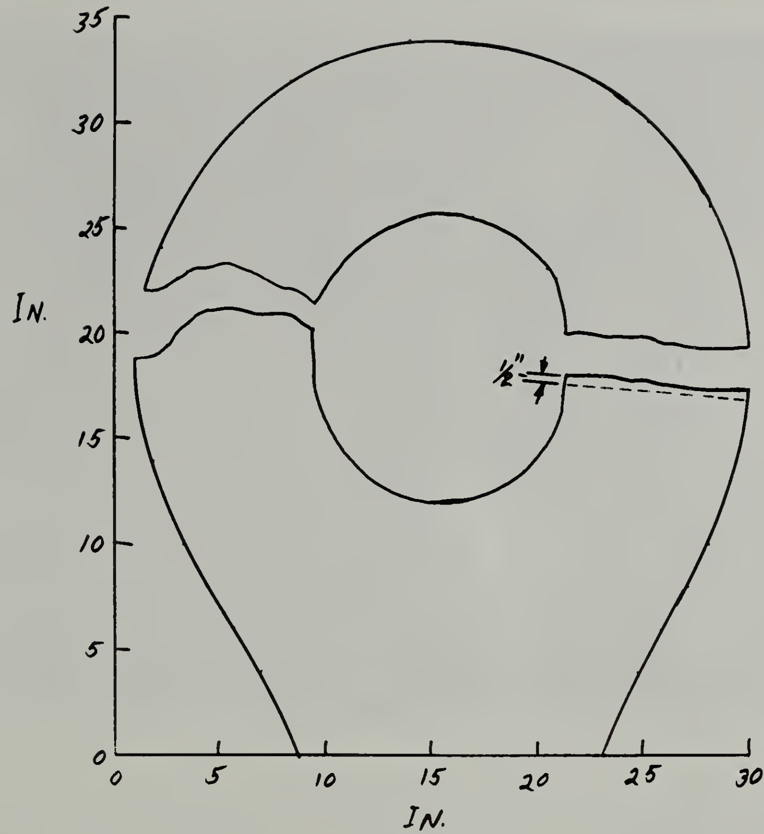
5. A portion of the outboard fracture surface after cleaning. The south face of the eye is at the upper right, the hole surface at the upper left.

6. Same as figure 5 at higher magnification. The south face is at the top. 5 X

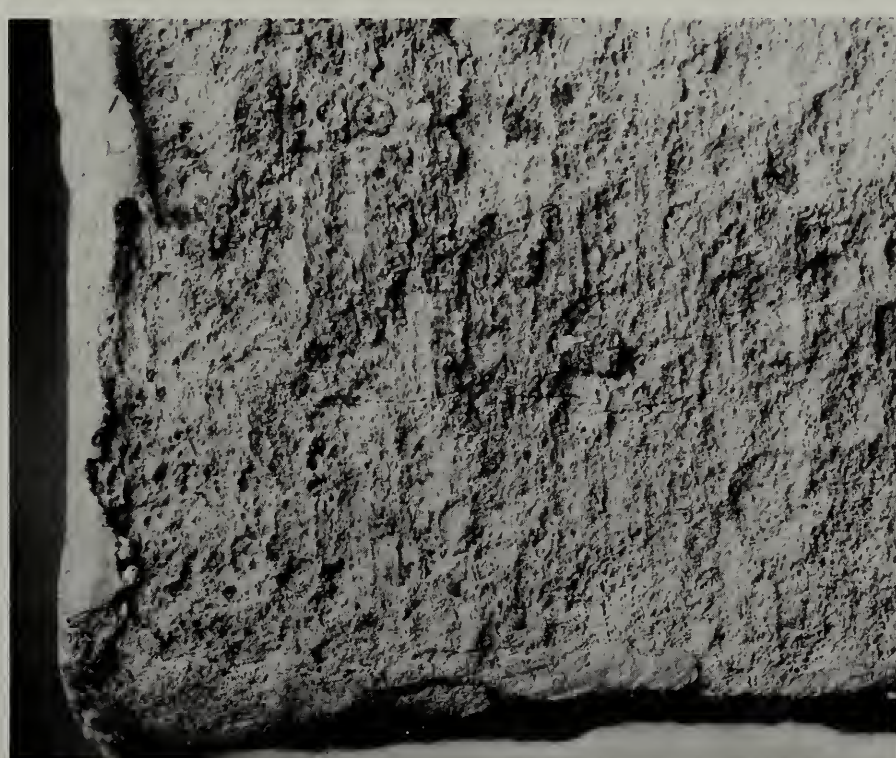
7. Surface of the hole adjacent to the fracture (top) in the outboard piece. The south face is at the left.



8. Same as figure 7 at higher magnification. 12 X

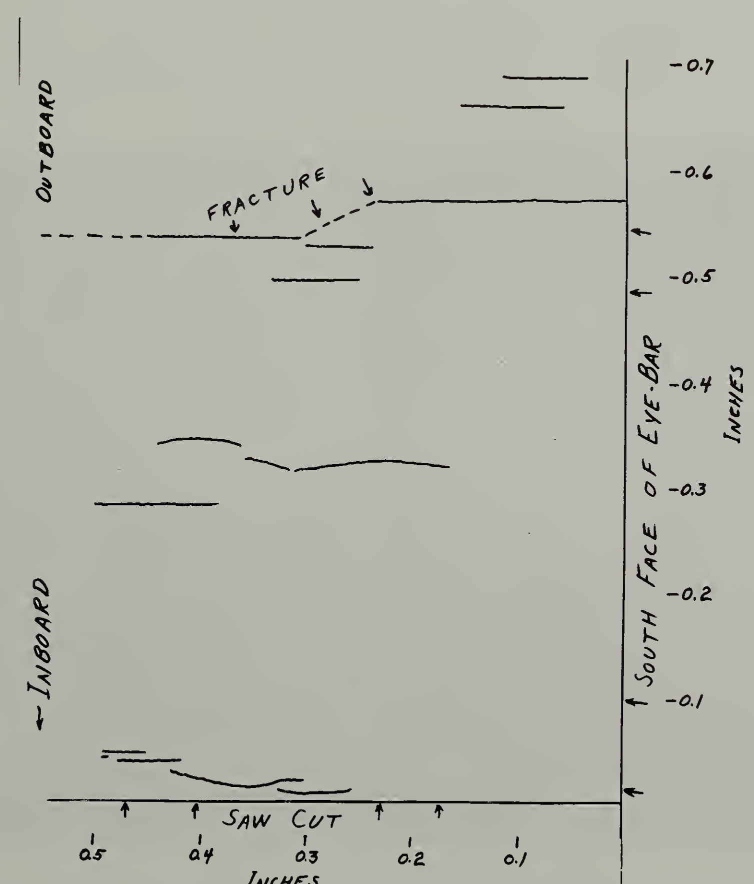


9. Sketch of the south face of the fractured eye showing the location of the segment cut from the inboard piece.

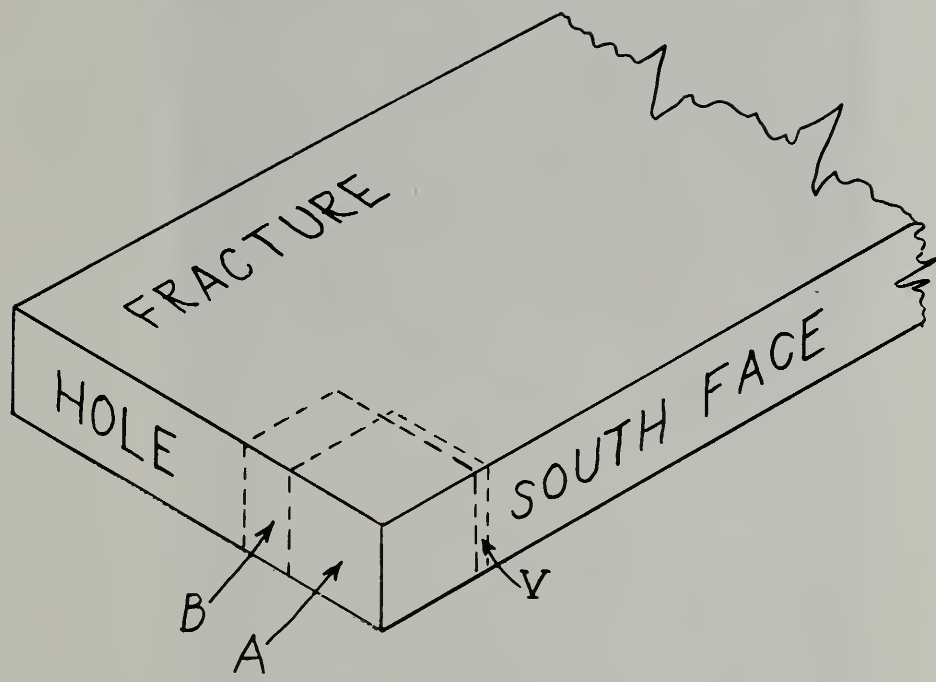


10. Surface of the hole adjacent to the fracture (bottom) in the inboard piece. The south face is at the left. 6 X

11. Surface of the hole in the inboard piece; the saw cut which separated segment "0" from the eye is at the top, the south face at the left. 12 X

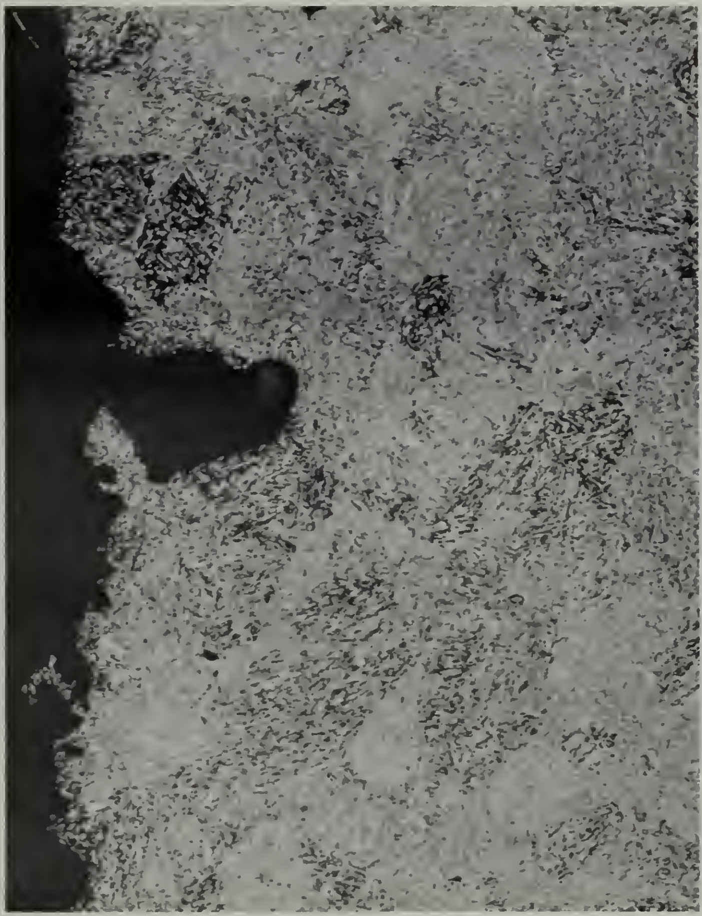


12. Sketch showing the location of cracks visible on the hole surface relative to the fracture and the south face of the eye.

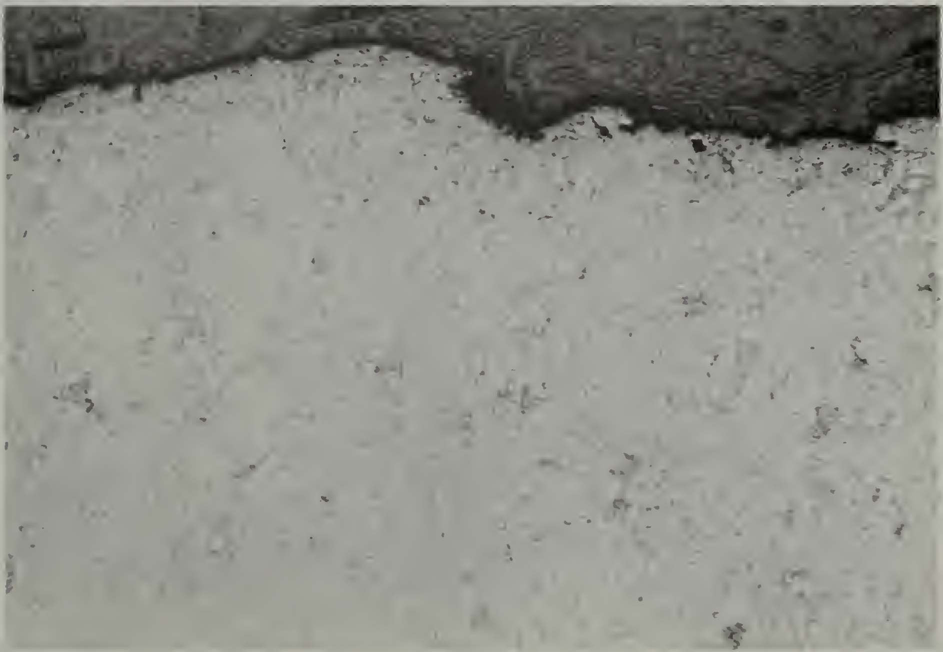


13. Sketch of segment "O" showing the location of metallographic specimens "A", "B" and "V" relative to the surfaces of the segment. The origin of the fracture was on the hole surface near the south face.

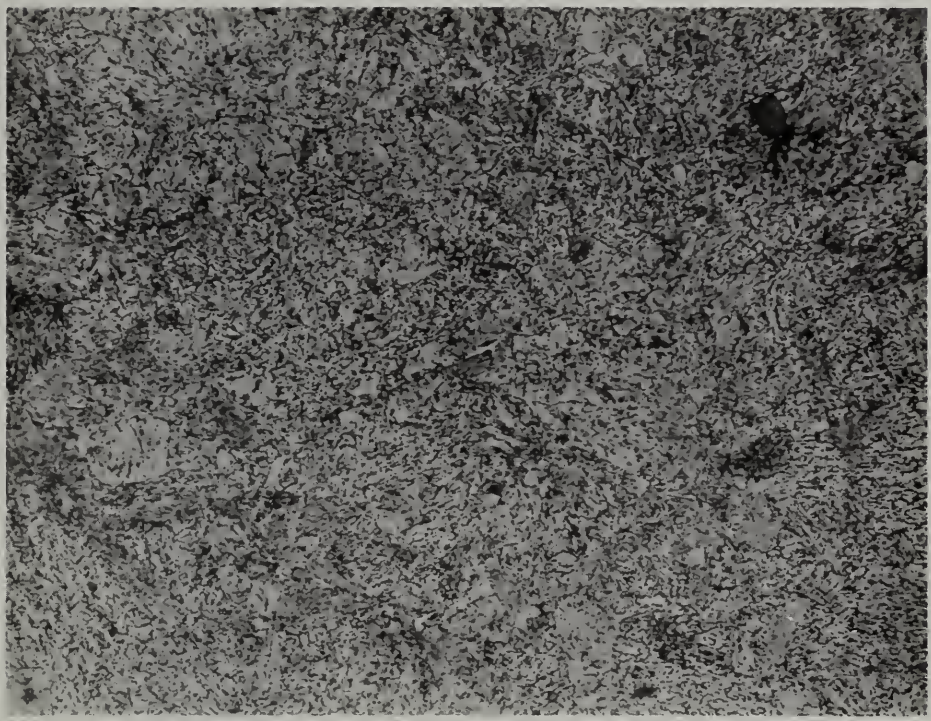
14. Typical microstructure 0.012 inch below south face. Etched, picral. 200 X



15. Corrosion on hole surface, 0.039 inch below south face. Etched, picral. 150 X
Note: all micrographs are oriented with the fracture at the top and the hole surface at the left.



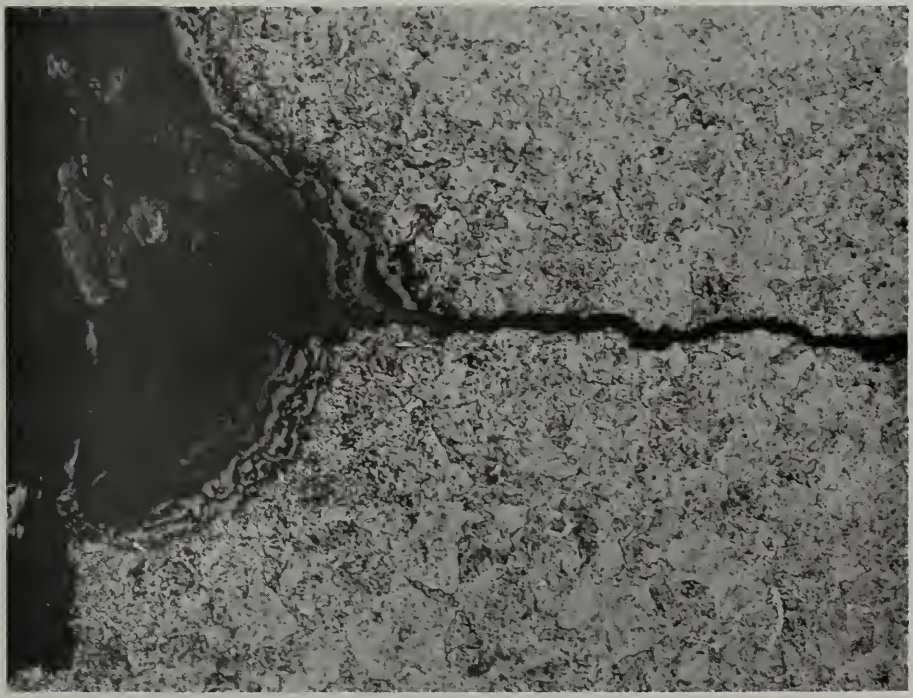
16. Fracture surface on a plane 0.11 inch below south face. Etched, picral. 60 X



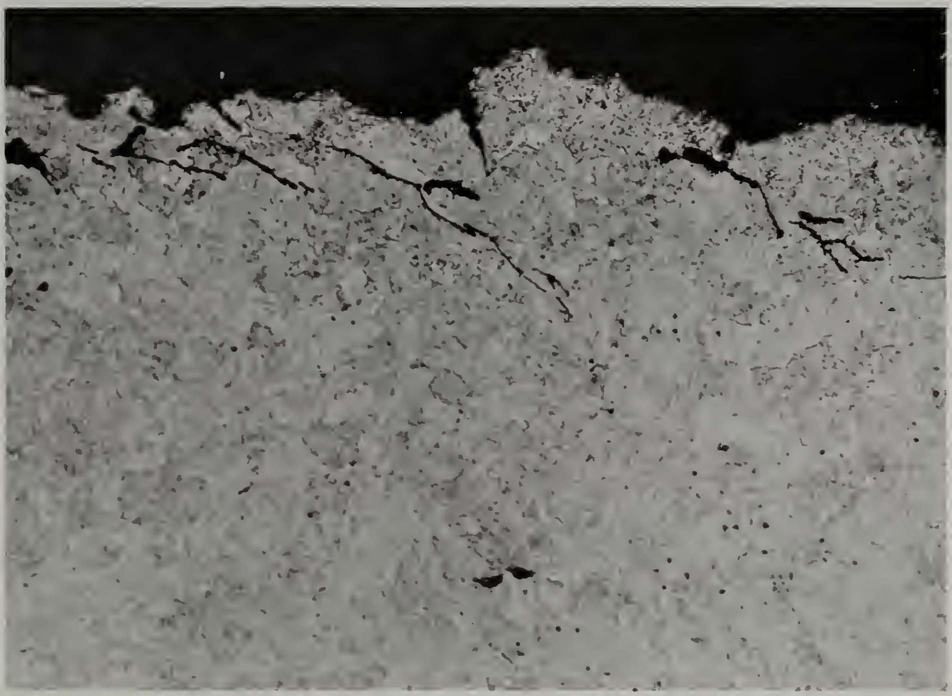
17. Microstructure 0.11 inch below south face, (approximate depth of the origin of the largest crack involved in the fracture). Etched, picral. 500 X

18 Cracks propagating from the hole surface a short distance inboard of the fracture. Depth below south face 0.232 inch. 80 X

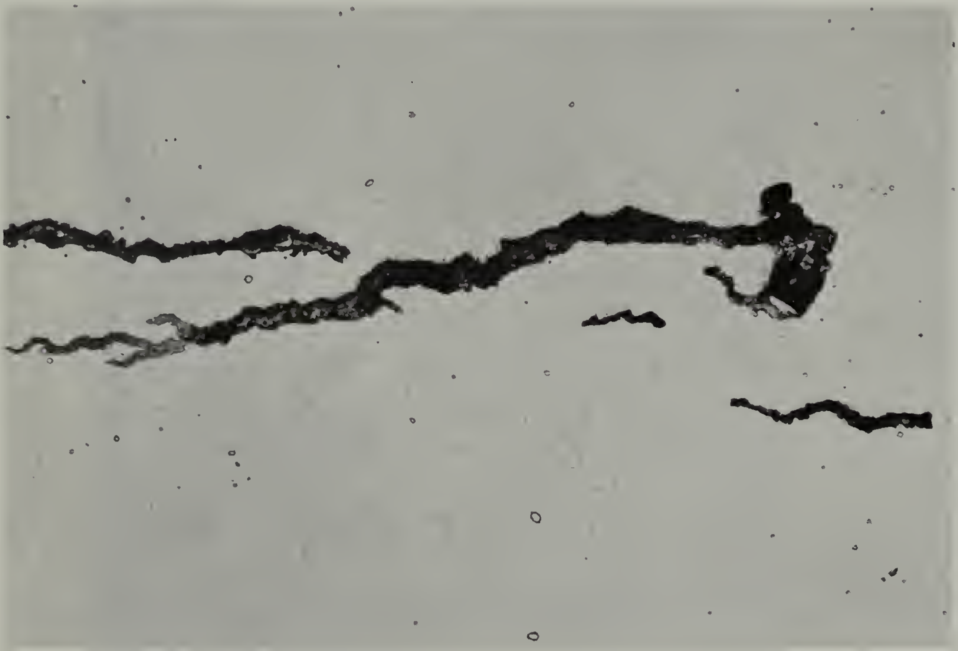
19. Corrosion and incipient cracking on hole surface, 0.285 inch below south face. 500 X



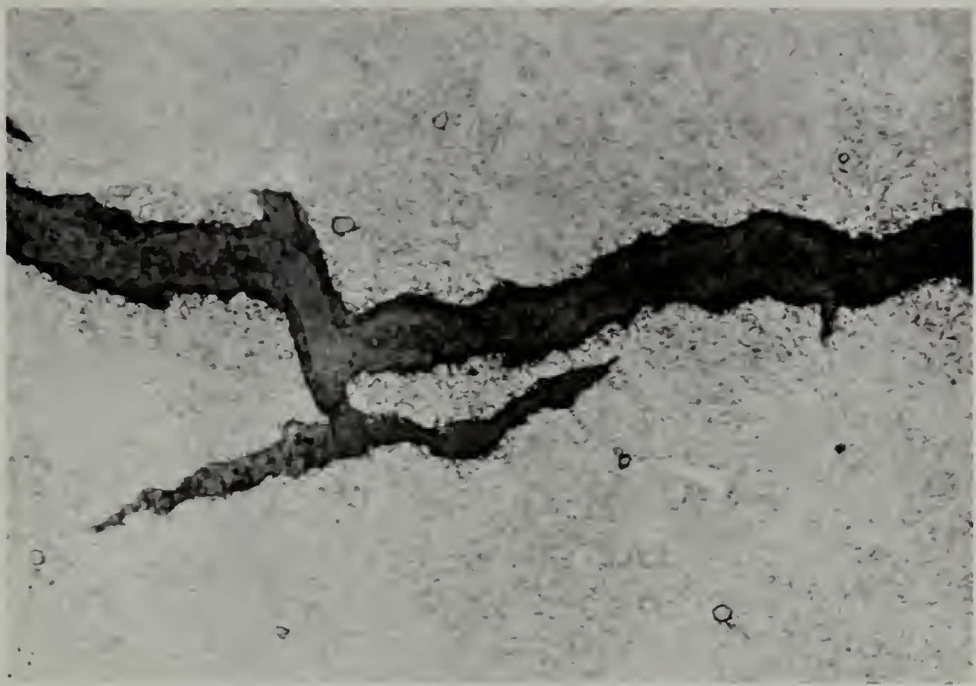
20. Crack origin at a corrosion pit, 0.285 inch below south face. Etched, picral. 200 X



21. Secondary cracks adjacent to the fracture, 0.285 inch below south face. Etched, picral. 200 X

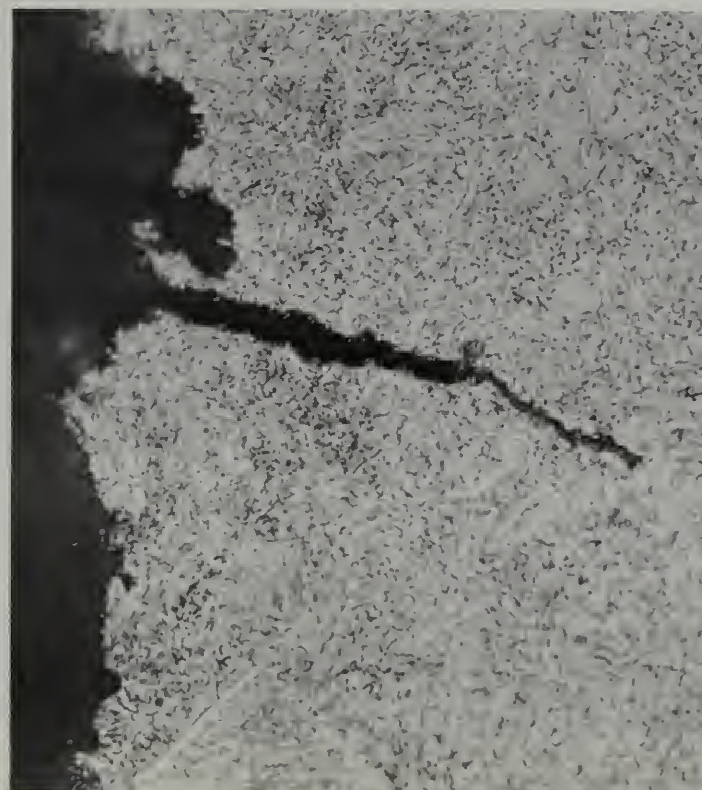


22. Typical crack appearance, 0.285 inch below south face. 200 X

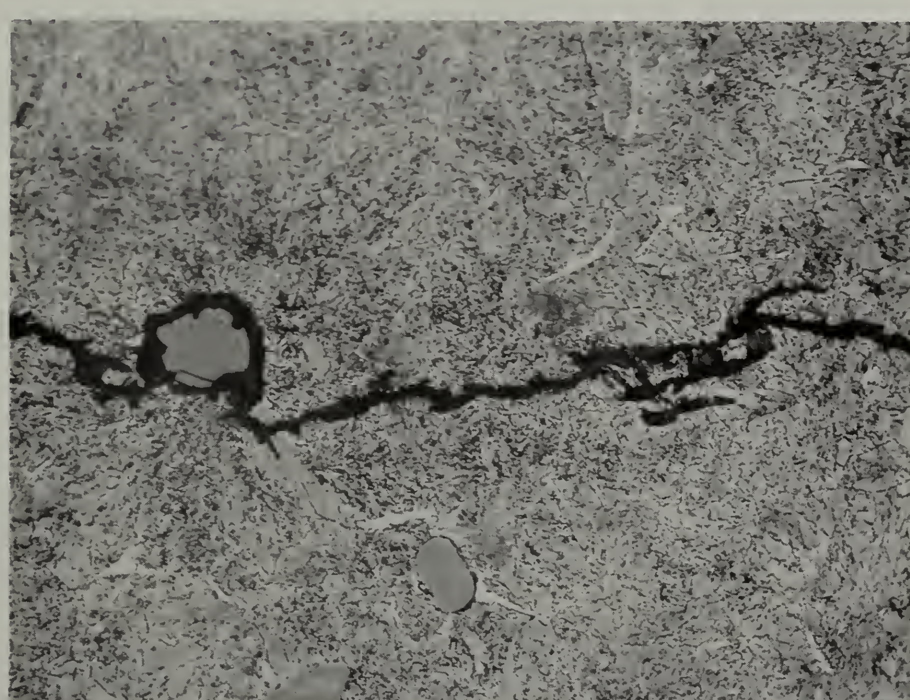


23. Lamellar nature of oxide in cracks, 0.285 inch below south face. 1000 X

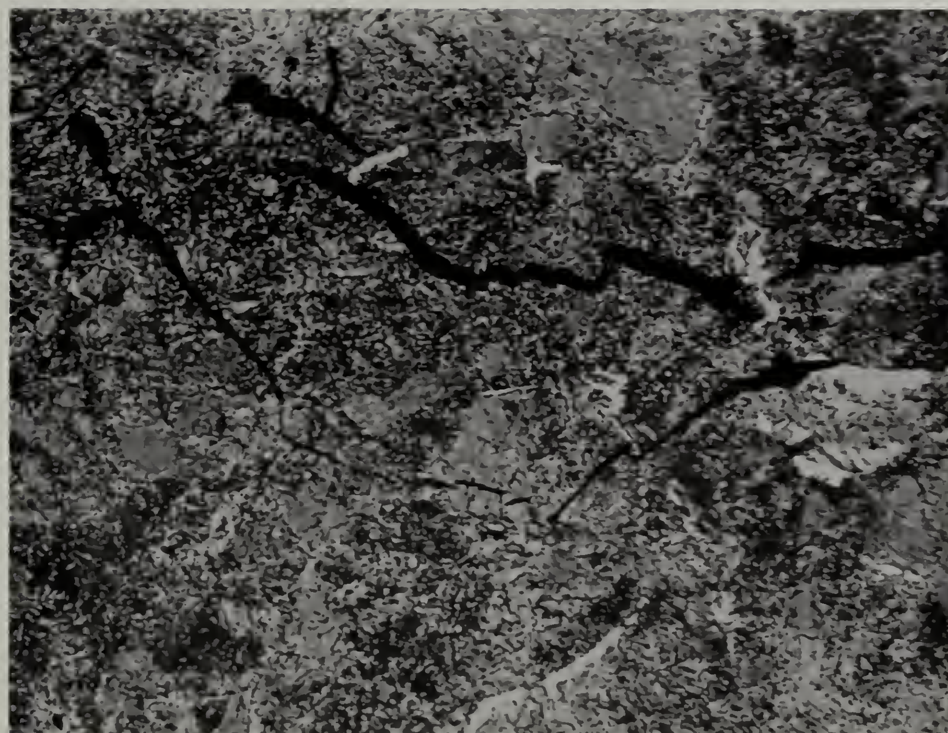
24. Incipient cracks at hole surface, 0.394 inch below south face. 1000 X



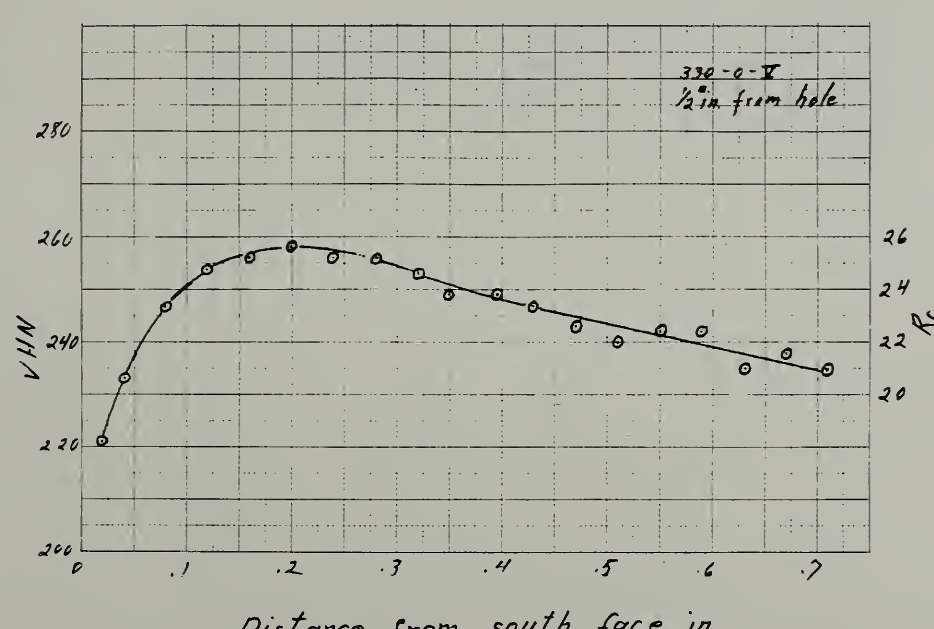
25. Crack propagating from hole surface, 0.394 inch below south face. Etched, picral. 1000 X



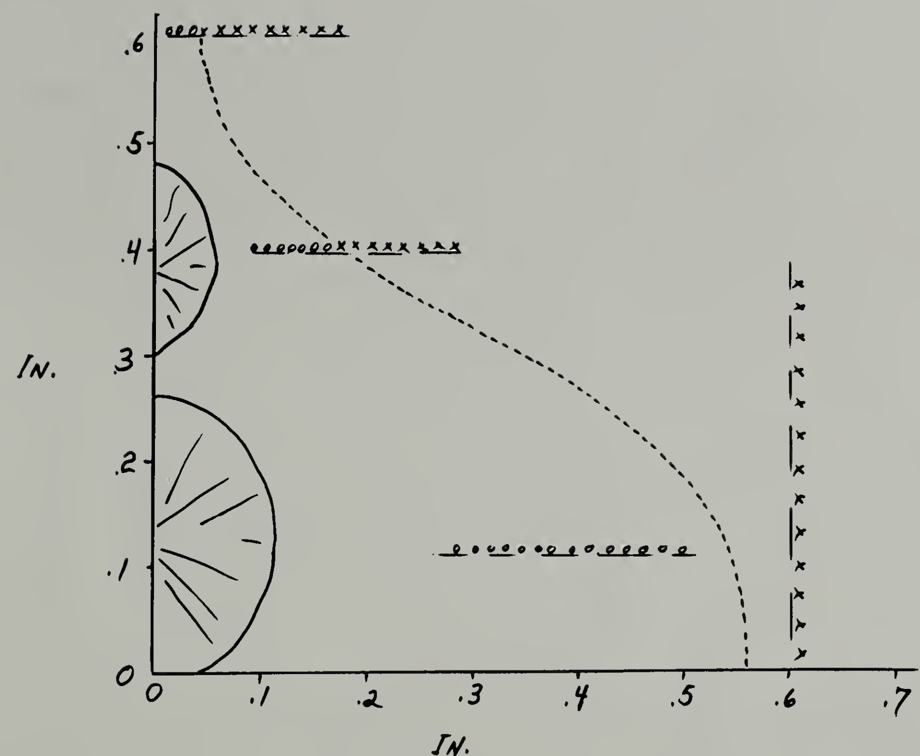
26. Typical crack appearance, 0.394 inch below south face. Etched, picral. 500 X



27. Secondary cracks adjacent to fracture, approximately 1/16 inch from hole surface. Specimen B, 0.6 inch below south face. Etched, picral. 800 X



28. Variation of hardness with distance from the face of the eyebar. Measurements were made on a transverse section of segment "0" approximately 0.6 inch from the hole.



29. Sketch of the area near the origin on the fracture surface; hole surface is at left, south face at bottom. Dashed lines represent location of metallographic sections examined. ooo - no secondary cracks found; xxx - secondary cracks observed.

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