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OHRD METALLURGICAL INVESTIGATION OF PRESSURE TUBES REMOVED FROM PICKERING 'B' UNIT 8

Report No 85-293-K

M. Léger, G.K. Shek,
A. Donner and P.G. Vesely
Metallurgy Section
Metallurgical Research Department

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ABSTRACT

A number of tubes were removed from Pickering Unit 8 due to excessive depth of fretting damage at dummy fuel bearing pad positions. Fifteen of these tubes were designated for destructive examination at three sites: AECL-CO, OHRD and CRNL. Examination of parts of six tubes from channels E08, F15, G10, J12, K18 and L14 were carried out at OHRD. The objective of the examination was to determine the extent of microcracking in the fret zones and to confirm the previously observed hydride distributions near fret marks. Results of the investigation show that there is no significant microcracking at the fret marks. However, secondary marks probably due to fretting by particles in the PHT coolant being trapped near bearing pads or under bundles, have been identified. These marks were studied in detail to determine their shapes for subsequent stress analysis. This report summarizes all these examinations.

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EXECUTIVE SUMMARY

OHRD METALLURGICAL INVESTIGATION OF PRESSURE TUBES REMOVED FROM PICKERING 'B' UNIT F

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Objective

The objective of this investigation was to establish the nature of the pressure tube damage which occurred during hot conditioning of Pickering Unit 8 and in particular to examine many cross sections for evidence of cracks.

Main Results and Conclusions

1. No sharp, radial microcracks were seen in any of the broad fretted areas of the tubes. The mechanism of material removed in these areas appears to be one of delamination wear.

2. Numerous secondary marks due to wear by debris trapped at the bundle bearing pad positions were examined in cross section; results are available for stress analysis.

3. Hydride orientations under fretted areas are less circumferential than expected.

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Generation

OHRD METALLURGICAL INVESTIGATION OF PRESSURE TUBES REMOVED FROM PICKERING 'B' UNIT 8

1.0 INTRODUCTION

Dummy fuel bundles placed in Pickering Unit 8 fuel channels to limit garter spring motion during hot conditioning caused significant fretting damage of many pressure tubes at the channel inlet ends. Mini-gauging established the distribution of wear depths at the first four dummy bundle bearing pad positions. Stress analysis indicated that a number of channels should be removed due to severity of the wear. Initial investigations of the first few channels removed showed that significant amounts of hydrogen had entered the tubes at the fretted areas. It was decided that a number of the other tubes that were to be removed be destructively examined to establish the existence and extent of any microcracking in the fretted areas. Of the channels removed, fifteen were designated for destructive examination. Nominally this examination was to include three transverse sections which would include any axial ridge and two axial sections from each of the first four fret marks in each tube. During the visual examination of these tubes, some significant secondary marks (previously reported in other tubes/1/) were seen and sections through these marks were also examined to establish the geometry of the flaws for stress analysis purposes.

2.0 INVESTIGATION TECHNIQUE

In each case, approximately 1.52 m of the inlet portion of the pressure tube from the site cut closest to the endfitting was received at OHRD. Initially three 15 cm long axial sections containing the first five fret marks were cut from the tubes and then cut in half axially. These were visually examined and photographed. Some use was made of the low power stereo microscope to judge the areas of most significant damage in order to ensure that the sections taken would include these areas. As indicated above, in addition to the 5 sections from each fret mark that were nominally indicated for examination, other sections containing secondary marks were also removed for metallurgical examination. Depths of secondary marks were also established using the metallurgical microscope by alternately focussing on the surface and then on deepest part of the mark and recording the vertical motion required to accomplish this. In some cases, there were fewer than four significant fret marks in the tubes and thus the number of sections examined was reduced. Table 1 summarizes the cross sections actually examined.

The samples cut from the tubes were cold mounted and prepared for metallurgical examination in the as-polished condition. Examination for microcracking was carried out at magnifications of 200X to 1000X. Depth of microcracking which is detectable at a magnification of 200X is about 10 μm.

Specimens were then etched to reveal hydride distributions. Following this examination, the specimens were generally ground to remove 1.25 mm of material and the process of examination was repeated. In the case of secondary marks, smaller amounts of material (0.25 mm) were removed so that the maximum depth of the defect could be more precisely established. The position of maximum depth was achieved in some cases by grinding in very small increments and examining the mark through the cold mount epoxy to determine whether the maximum depth had been reached. Scanning Electron Microscopy and X-ray analysis were used in several cases to establish the nature and composition of particles at the surfaces of several specimens.

3.0 RESULTS

3.1 Visual Examination

This examination revealed features similar to those reported for the initial examinations of marks in other channels/1/. These included:

(i) generally smooth or slightly roughened, broad areas sometimes containing axial ridges which were associated with the dummy fuel bearing pads;

(ii) smaller areas, in some cases, where the cast iron bundles had come into contact with the pressure tube: the images of the machining marks on the bundle were clearly visible on the tube surface;

(iii) secondary marks often associated with the bearing pad positions which consisted of furrowed tracks and pit-like features in the pressure tube surface; and

(iv) numerous axial fuel bundle scratches at the bottom of the tubes due to removal of real fuel bundles that had been loaded in the channels following hot conditioning.

Features (i), (ii) and (iv) are visible on low magnification photographs taken for the record. Two examples of these are shown in Figure 1(a) and (b). Others are filed at OHRD.

Additional photographs (including some stereo images) of the secondary marks were also taken. In particular, the deepest marks in the tubes from J12 and L14 are shown as stereo pairs in Figure 2. (These images require the use of a stereo viewer to produce the depth effect). Some of the secondary marks were pit-like with raised edges indicative of mechanical damage, whereas others had no significant raising of the edge since they were produced by a fretting mechanism.

3.2 Examination for Microcracks and Hydride Distributions at Broad Fret Marks

The microscopic examination of the cross sections through the broad, usually smooth areas produced by the bearing pad contacts on the pressure tube revealed a surface that was rougher than in the normal pressure tube. Features typical of those seen in many cross sections are shown in Figure 3(a-e). The apparent peak-to-peak surface roughness observed in the cross section shown in Figure 3(c) is in the range of 20-30 μm. A new pressure tube has a surface roughness more than an order of magnitude smaller. The axial-normal cross section shown in Figure 3(b) shows a fine crack parallel to the surface intersecting the surface at each end. In circumferential-normal section particles composed of alternate layers of metal and oxide, appear semicircular (Figure 3(c)). In other areas the particles are absent but the very small pit remains (Figure 3(a)). In many areas, especially in the more heavily hydrided areas, there were areas of the surface which were apparently solid hydride (Figure 3(e)) in a very thin layer (~5 μm).

None of the cross sections examined exhibited microcracking in the form of sharp radial axial cracks of any detectable depth.

The tube surface geometries associated both with the axial ridges within the broad fret marks and with the circumferential ridges associated with the ends of the fretted zones were also examined. Of all the cross sections examined, those shown in Figure 4 are the most severe in terms of the abruptness of the change in section.

In many of the figures already presented, the hydrides are visible because the micrographs were taken from etched samples. Clearly in Figure 3(a) there is a very high density of hydride immediately beneath the fretted area. Figure 5 shows another area of the first fret mark in E08. There are some large packets of hydrides intersecting the surface at about a 45° angle in this section (axial normal). The hydride distributions through the wall thickness of all tubes were studied. As noted in the examination of the first tubes removed from Unit 8/2/, the distribution of hydride depended upon the fretting wear. In sections with relatively deep marks, there was more hydride near the surface where the fretting took place than towards the outside surface of the tube. In other sections where the fretting was less severe, there was less hydride and it was more uniformly distributed through the thickness. In most tube sections, the hydrides have orientations which vary from circumferential to close to radial in parts of the pressure tube wall (Figure 6(a)). This distribution of orientations is significantly different from the predominantly circumferential orientation observed in pressure tube sections hydrided in the laboratory without stress. In one tube from channel J12 there were distinctly radial hydrides towards the outer surface of the pressure tube (Figure 6b).

3.3 Metallography of Secondary Marks

Secondary marks judged to be significant by visual examination were sectioned and closely examined. Table II summarizes the positions in the tube where these marks were observed, their axial and circumferential dimensions and the maximum depths determined by metallography. Twelve such secondary marks were examined in the six pieces of pressure tube received at OHRD.

It is apparent from the table that all the marks examined had depths equal to or greater than 0.20 mm (.008") with the deepest one being 0.80 mm (0.031"). Most were found close to the bottom of the tube although one (G10-3-1) was found at about 45° from the bottom. Marks shallower than 0.20 mm were judged to be less significant and were not recorded.

Results of the metallography through these marks are shown in Figures 7 to 12.

Figure 7 shows the cross section of the mark designated E8-3-1 at its deepest point. There is a particle embedded in the pit which was identified as ferrous material using the X-ray analysis capability of the SEM. Fine hydrides characteristic of as-received pressure tube are present in this cross section and there is some indication that the hydrides are finer close to the pit than they are at some distance away. There is no evidence for hydride orientation due to the stress field of the pit.

Several cross sections of the mark designated F15-5-1 which was seen at the beginning of the fifth fretted area in channel F15 are shown in Figure 8(a-c). There is a small lip on one side of the gouge. Again the hydride concentrations appear to be only slightly higher than as-received pressure tube. Slightly larger hydrides appear to form a halo around the gouge. This may indicate that the fretting action which produced the mark also introduced hydrogen. Very little distortion in the grain structure adjacent to the gouge was observed. After removing significant material (1.71 mm) the cross section included what had appeared as a furrowed path in the visual examination. In cross section this is shown (Figure 8(c)) to be distorted material which contains both laps formed by mechanical damage and small oxide-filled cracks which are about 0.07 mm deep.

The secondary mark in channel G10 was pit-like as most of it disappeared after removal of 1.25 mm of material from the cross section shown in Figure 9. The micrograph shows a hydride concentration slightly greater than the as-received level as well as some tendency of the hydride to be oriented due to the stress field of the pit. Hydrides beneath the pit are finer than those a distance away.

A cross section at the deepest part of the pit seen visually in channel J12 is shown in Figure 10. Again the hydrides are fine, characteristic of as-received material. There are a few finer hydrides close to the pit. The pit itself has a sharp corner at about one-half the maximum depth.

Three secondary marks were seen visually in channel K18. The cross sections through these marks (Figure 11(a-c)) exhibit characteristics which are somewhat different from those seen in marks in the other channels. Mechanical damage in these marks is more pronounced as indicated by the presence of significant upheavel of material which now is lapped over the edges of the pits. There is clear evidence of mechanical flow of material in Figure 11(a). Surrounding the mark designated K18-15 there is a large zone in which the hydrides are very fine.

The deepest mark seen in any of the channels examined at OHRD was that in channel L14 which is shown in cross section in Figure 12. Hydrides in the cross section shown in Figure 12(a) tend to exhibit orientation due to the presence of the defect. However at the deepest point (Figure 12(b)), this hydride orientation is not evident. Hydride sizes are consistent with a hydrogen level slightly above the as-received level. The cross sections of three other secondary marks in L14 are also included in Figure 12.

3.4 Other Examinations

In several of the fretted regions in these tubes other particles were noted and analyzed by SEM using the X-ray analysis facility. These included some metallic flakes identified as brass on the surface of J12 and K18 and a particle of calcium aluminum silcate in J12.

A microhardness trace through the zone of fine hydride beneath the secondary mark designated K18-15 did not indicate any alteration in microhardness associated with the hydride microstructure variation.

4.0 DISCUSSION

4.1 Mechanism of Material Removed in Pad Contact Areas

The metallographic evidence appears to indicate that material removal occurred by a mechanism involving formation of small cracks parallel to the surface (Figure 3(b)) followed by rolling up of the platelet formed by the cracking. These rolled up platelets (Figure 3(c)) were then carried away by the water. This mechanism is described in the literature as delamination wear/3,4,5/. In this case since the hydride forms platelets more or less parallel to the surface, the presence of such platelets close to the surface could accelerate the formation of the crack which produces the wear particles. Thus the wear rate and hydrogen pickup rate may be coupled in a complex way.

The operation of this mechanism of material removal does not produce sharp, radial cracking of any significant depth. Even though the surface was subject to cyclic loading due to the action of the dummy fuel bundles, no radial cracks formed.

The hydride distributions observed were consistent with a hydrogen flux into the tube at the surface being fretted.

4.2 Formation of Secondary Marks

It appears probable that the secondary marks are formed when debris particles in the PHT coolant are trapped between the bundle or pad and the tube. In some cases there is significant evidence (in the formation of laps etc) for mechanical damage, whereas in others, the material appears to have been removed with little damage to the underlying structure. The evidence for damage being due to particles is clear from the visual examination in which the tracks of the particles could be clearly seen as rippled furrows on the pressure tube surface, each ripple presumably associated with a cycle in the vibration pattern which was the cause of the fretting. The particle itself could be subject to modes of vibration different from those of the bundles due to the high velocity of water in the channel.

The zone of fine hydride immediately beneath the surface of some of the secondary marks is likely due to a local change in the stress state of the pressure tube material. One would expect that material deformed locally in compression would retain a compressive stress field near the surface (as occurs in shot peening for example) and that a counteracting tensile field would occur further from the surface. The halos of larger hydrides around the zones of fine hydride tend to support this hypothesis. This would imply that crack initiation at such defects could be impeded by the presence of this residual compressive stress. However, as noted before, there are some significantly deep marks with no fine hydrides surrounding them.

4.3 Hydride Orientations

The effects of having hydrides precipitate under operating stress are clear from a comparison of the hydride orientation distributions observed under the broad fretted areas with the distributions seen in sections of pressure tube hydrided without stress in the laboratory. The latter usually exhibit predominantly circumferential hydrides whereas in the tubes removed from P-8, the orientations varied from circumferential to radial. Since very few tube sections have been hydrided under operating stress experimentally, these P-8 tubes are a significant addition to our data base for the effects on hydride orientation of hydriding under operating stress. It is clear from the distributions seen in the P-8 tubes that our previous understanding of hydride orientation in Zr 2.5 wt% Nb pressure tube requires some revision.

The results of uniaxial tests on straightened material to determine the threshold for formation of radial hydride/6/ indicated that above a critical hoop stress of about 180 MPa (dependent upon material strength) all hydrides precipitated in the radial orientation. However, at stresses slightly lower than the threshold stress there was a mixture of circumferential and radial hydride with very few hydrides at intermediate orientations. At low stresses, hydrides were circumferential. These results were different from those obtained at CRNL/7/ in which hydride reorientation was studied by thermally cycling under stress rings of material previously hydrided without stress. In the CRNL tests a distribution of hydride orientations resulted and the threshold for formation of completely radial hydride appeared to be somewhat higher than in the OHRD tests. This distribution of orientations is similar to that observed in the P-8 tubes although in the P-8 tubes the distributions occurred at much lower stresses than in the ring tests. This difference may be due to the fact that the P-8 tubes were, in effect, hydrided under stress.

The presence of the zone of completely radial hydride under the fret mark in the J12 tube can be rationalized using the OHRD results which indicated a threshold stress of 180 MPa. Parts of J12 tube apparently retained significant residual stresses from manufacture. These were made apparent upon axial slitting of rings of material.

When a 15 cm length of tube containing the fret mark was slit axially, it was observed to open about 8 mm although no precise measurement was made. Two other rings each 5 cm long from different positions along the length of the tube approximately 20 cm and 1.15 m from the site cut at the inlet end were also slit and measured more precisely. The ring close to the inlet end opened 5.66 mm whereas the other ring closed about 0.1 mm. If a linear residual stress distribution through the wall is assumed with a compressive stress on the inside and a tensile stress on the outside, then the ring close to the inlet had a maximum tensile residual stress of 81 MPa. If the threshold stress for formation of radial hydride is exactly 180 MPa, then on a 4 mm wall thickness with an applied stress of 130 MPa and a residual stress distribution as measured, we would expect that 0.24 of the wall thickness would contain radial hydride. In fact, the observed fraction of the wall under the fret mark with radial hydride was estimated to be 0.21. Variation in both residual stress along the tube and threshold for formation of radial hydride could easily explain this discrepancy.

Current research programs are trying to resolve the roles of various factors such as internal stress, microstructure and texture in determining hydride orientation in zirconium alloys. The results from P-8, the CRNL rig tests and the OHRD uniaxial tests suggest that hydriding under stress has a significant effect on the ultimate hydride orientation distribution and that in the internal stress state in straightened material is lacking some component present in fabricated tubes which allows hydrides to assume orientations at intermediate positions between radial and circumferential. In any case, from the examination of the P-8 tubes it appears likely that non-circumferential hydrides are likely to be much more common in Zr 2.5 wt% Nb pressure tubes than previously thought.

The presence of radial hydride reduces the fracture toughness of Zr 2.5 wt% Nb material with the reduction being dependent upon the amount of radial hydride and the temperature. It is likely that the radial hydride observed in J12 would have a small effect on critical crack length at reactor operating temperatures since most of the hydride would be in solution. It could produce a noticeable reduction in the room temperature critical crack length.

Since hydride will not be present under the fret marks at operating temperature for more than a few months after start-up, any concern associated with the radial hydride will be much reduced in a short period.

5.0 SUMMARY AND CONCLUSIONS

1. No sharp radial cracks were seen in the broad fretted areas associated with the bearing pad positions.

2. Material in these areas appears to have been removed by a process of delamination wear perhaps assisted by the presence of hydride platelets parallel to the surface.

3. There are some areas of the pressure tube surface in the heavily fretted regions which are really thin layers of solid hydride.

4. The hydride distribution near the broad fretted areas previously reported was confirmed in these tubes.

5. Secondary marks greater than 0.20 mm in depth were seen in every channel examined at OHRD. These marks appear to be concentrated near the bottom of the tubes near bearing pad positions. They are not usually associated with the areas of greatest wear depth due to bearing pad contact.

6. The secondary marks are probably a result of wear due to trapping of small particles or debris in the PHT system by the fuel bundle pads.

7. The geometry of these secondary marks has been summarized for use in stress analysis.

8. The presence of radial hydride in the pressure tube removed from channel J12 can be explained on the basis of our current knowledge of the stress required to form radial hydride and the observation of significant residual stresses in parts of this tube.

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TABLE 1

CROSS SECTIONS EXAMINED

Channel	Fret* Mark	Section Designation†	Comments
E8	1 2 3	E8-1-1,2,3,4,5(A&B) E8-2-1,2,3,4,5(A&B) E8-3-1	 Secondary mark
F15	1 1	F15-1,2,3,4,5(A&B) F15-2-1(A&B)	 Designation should have been F15-1-6, mark due to bundle
	3 5	F15-3-1,2,3,4,5(A&B) F15-5-1(A&B)	 Secondary mark
G10	1 2 3	G10-1-1,2,3,4,5(A&B) G10-2-1,2,3,4,5(A&B) G10-3-1(A&B)	 Secondary mark
J12	1 2 3	J12-1-1,2,3,4,5(A&B) J12-2-1,2,3,4,5(A&B) J12-5-1	 Secondary mark
K18	1 2	K18-1,2,3,4,5,6(A&B) K18-6,15,16 K18-2-1,2,3,4,5(A&B)	 Secondary mark
L14	1	L14-3-1,2,3,4	Secondary mark

*Fret marks numbered according to number of corresponding bearing pad from inlet end.

†A corresponds to the first cross sections examined, B to the cross sections following material removal.

TABLE 2

SECONDARY MARK CHARACTERISTICS OF P-8 TUBES EXAMINED AT OHRD

Channel No	Sample ID	Distance From Inlet (Inches)	Orientation (0° at Bottom) (CW Viewed From Inlet)	Axial Length (mm)	Max Depth (mm)	Circum Width (mm)	Comments
E8	E8-3-1	24.0	0°	2.0	0.20	1.0	Contained embedded ferrous particles
F15	F15-5-1	43.5	30°	2.0	0.29	2.0	Beginning of 5th mark
G10	G10-3-1	23.5	315°	1.0	0.20	1.0	Beginning of 3rd mark
J12	J12-5-1	43.0	0°	0.8	0.24	0.8	Sharpest radius was 0.015 mm at a depth of 0.12 mm Pit at end of fretted gouge Beginning of 5th fret mark
K18	K18-1-6	7.6	0°	3.1	0.23	1.9	Under bundle
	K18-15"	15.0	0°	2.6	0.24	2.0	Under bundle
	K18-16"	16.0	0°	2.0	0.20	2.0	Under bundle
L14	L14-3-1	24.0	0°	2.4	0.80	3.5	Fretted region of 3rd mark
	L14-3-2	24.0	0°	6.0	0.24	1.1	Beginning of 3rd mark
	L14-3-3	24.7	330°	1.2	0.30	1.4	End of 3rd mark
	L14-3-4	24.0	330°	1.2	0.20	1.3	Beginning of 3rd Mark

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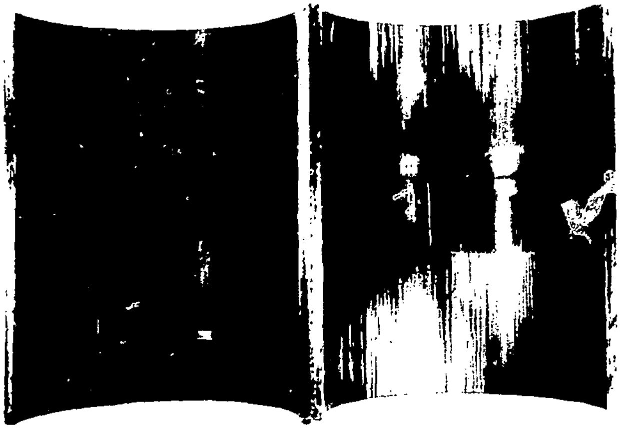
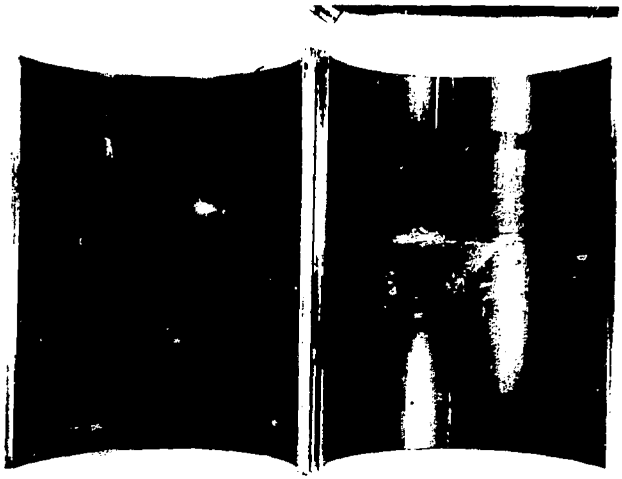


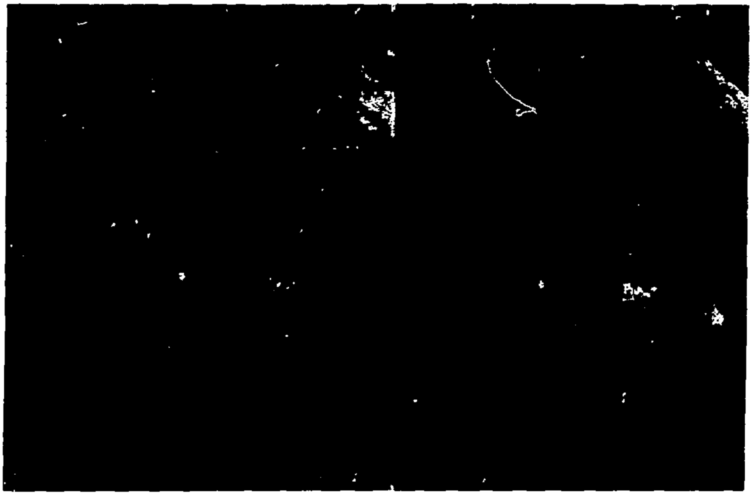
(a)



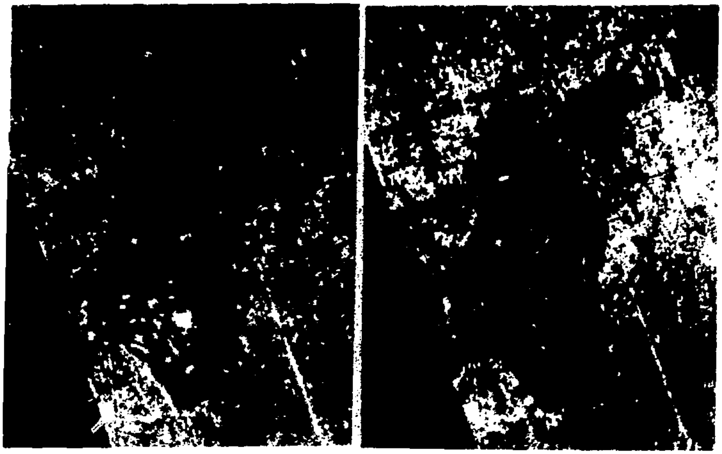
(b)

FIGURE 1(a) - Macrophotograph of inside surface of channel F15 at the first fret mark. Note fretting due to contact of the cast iron with the pressure tube (0.4 X approx).

(b) - Macrophotograph of channel J12 at the second and third fret marks (0.4 X approx).



(a)



(b)

FIGURE 2(a) - Stereo pair of secondary mark in channel J12 at fifth bearing pad position (15 X).

(b) - Stereo pair of secondary mark in channel L14 at third bearing pad position (11 X).

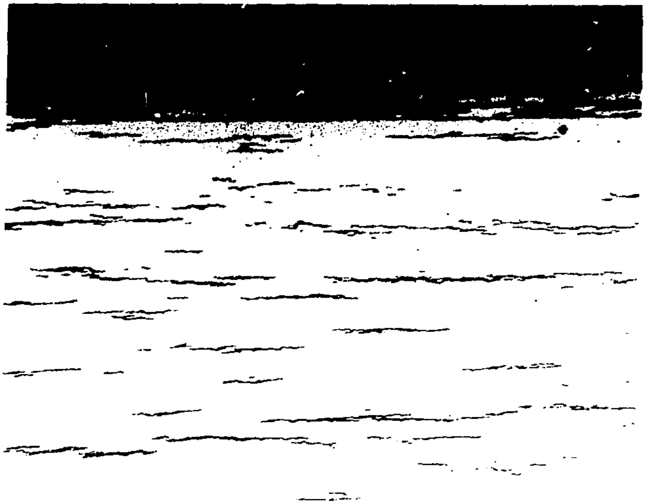


FIGURE 3(a) - Surface roughness and hydride distribution in E8-1-4; transverse normal section (100 X).

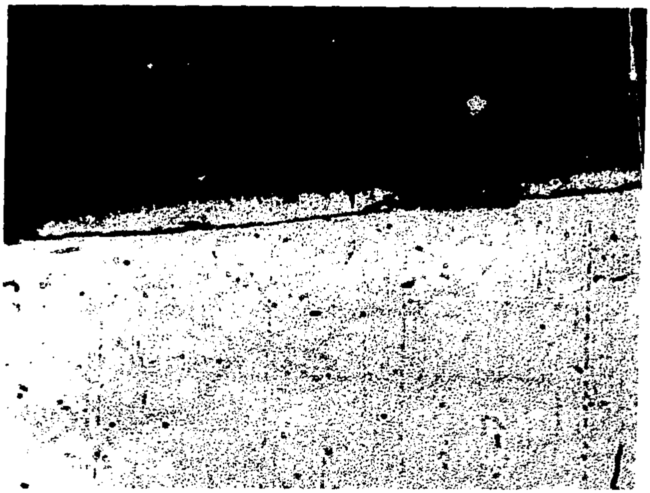


FIGURE 3(b) - Axial Normal Section showing crack parallel to surface in section E8-1-2B (1000 X).

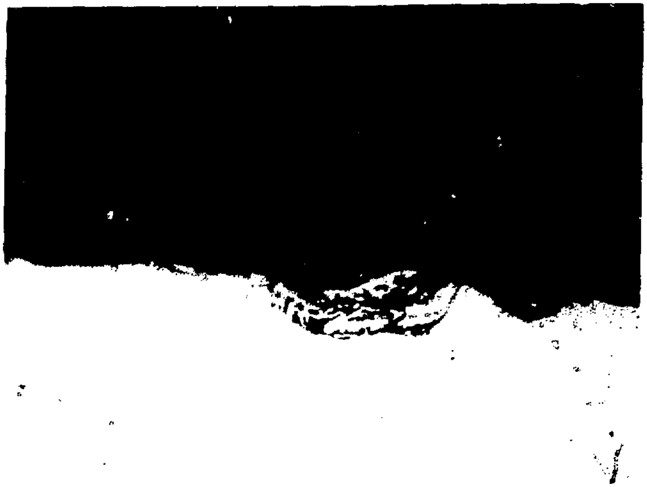


FIGURE 3(c) - Particle made up of rolled-up oxidized platelets in transverse normal section of sample E8-1-4B (1000 X).

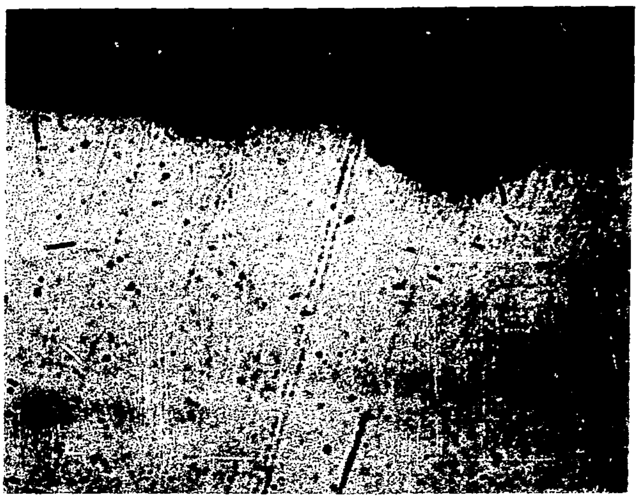


FIGURE 3(d) - Small surface pit remaining after oxidized particle has been presumably washed away (1000 X).

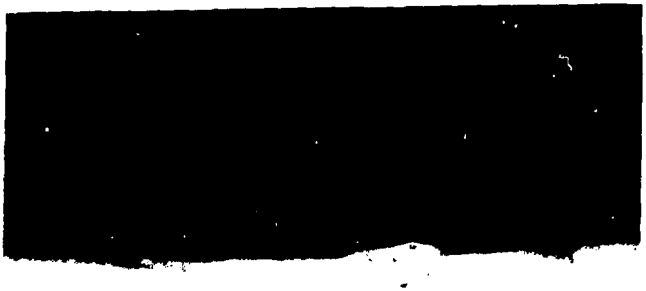


FIGURE 3(e) - Area of solid surface hydride in E8-1-4 (1000 X)

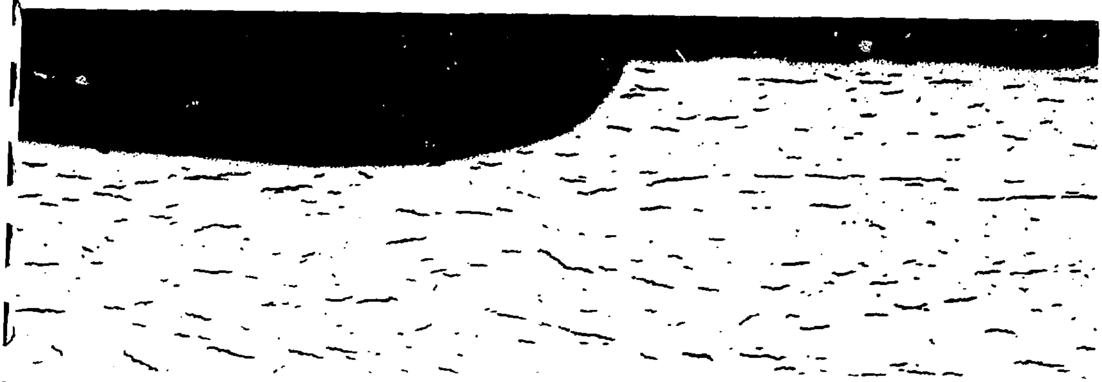


FIGURE 4(a) - Ridge geometry in axial-normal cross-section in G-10 at the first fret mark (100 X).

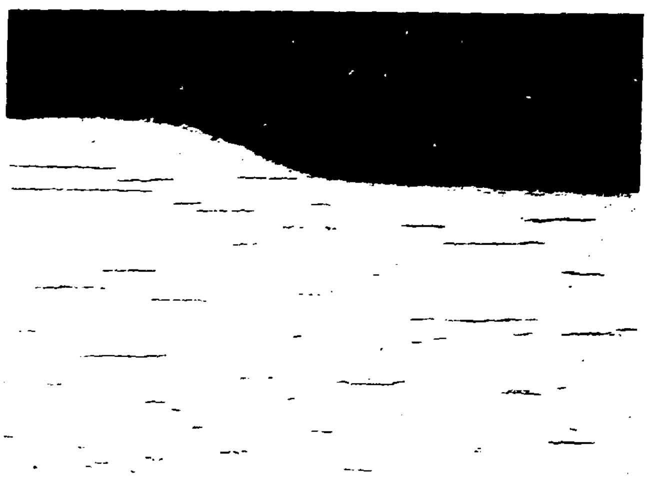
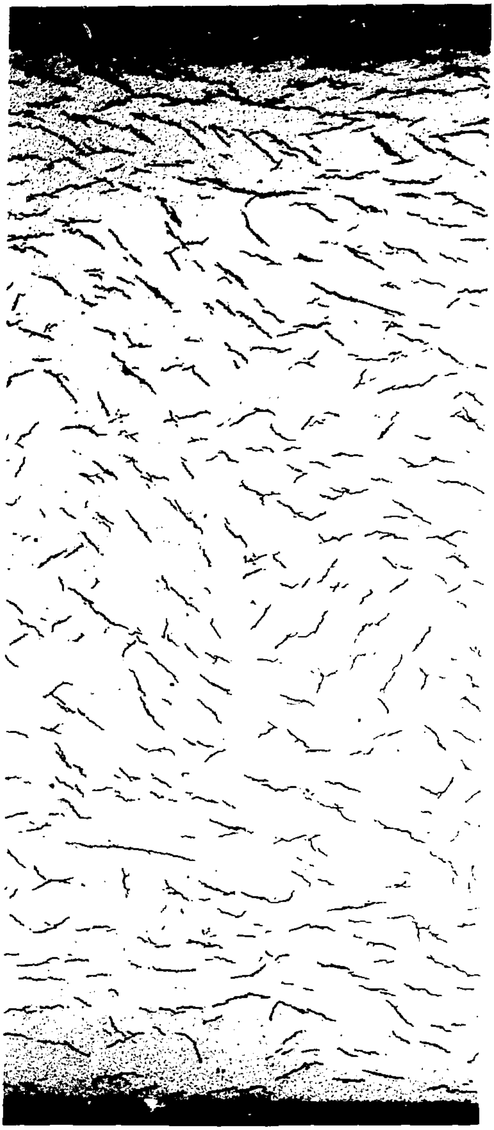
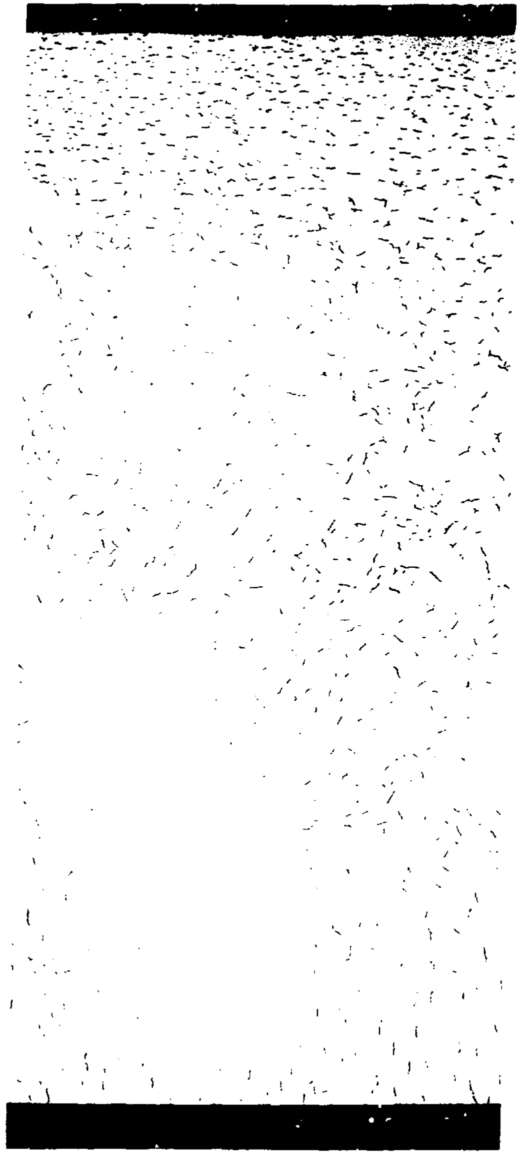


FIGURE 4(b) - Transverse ridge due to cast iron contact in F15-2-1 (100 X).

FIGURE 5 - Hydride distribution at surface of pressure tube in the first fret mark in channel E8 (100 X).



(a)



(b)

FIGURE 6 - Through-wall hydride orientation distributions under fret marks in tubes from Channels E8(*a*) and J12(*b*), (50X)

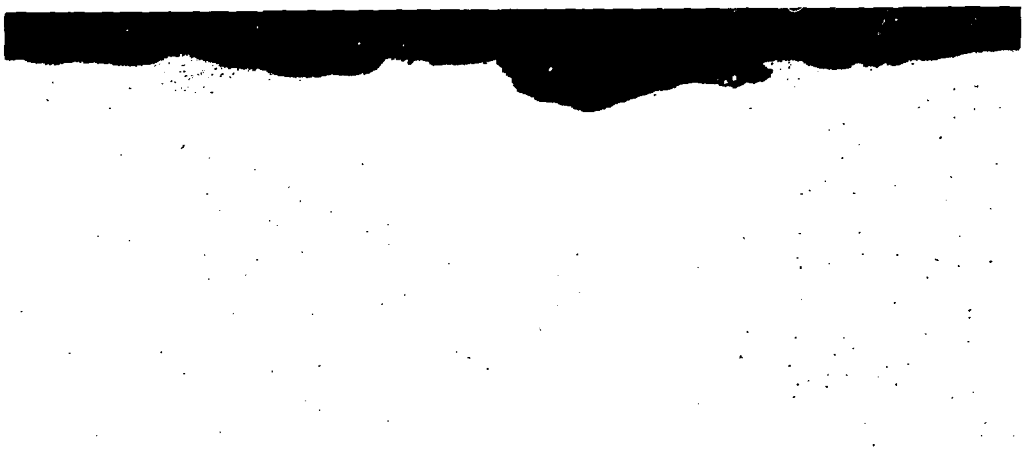


FIGURE 7 - Cross-section of secondary mark in section E8-3-1 (50 X).
Imbedded particle was ferrous.

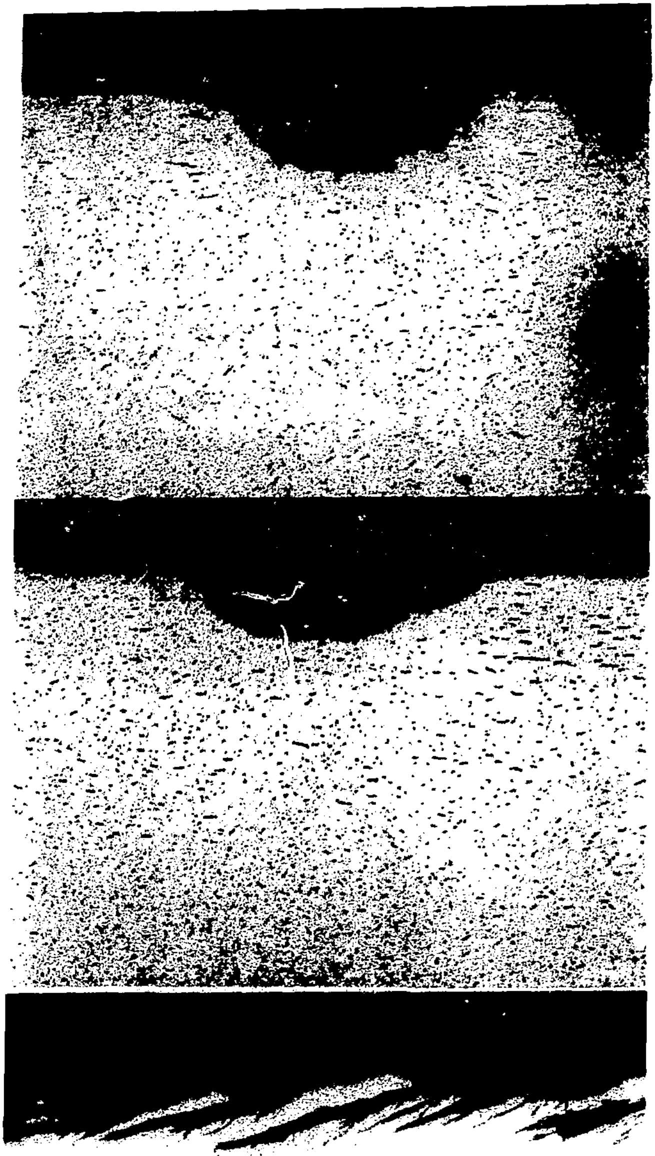


FIGURE 8(a) - Cross-section through secondary mark F15-5-1 (50 X).
(b) - After removing 1.25 mm of material (50 X).
(c) - After removing additional 0.44 mm (200 X).

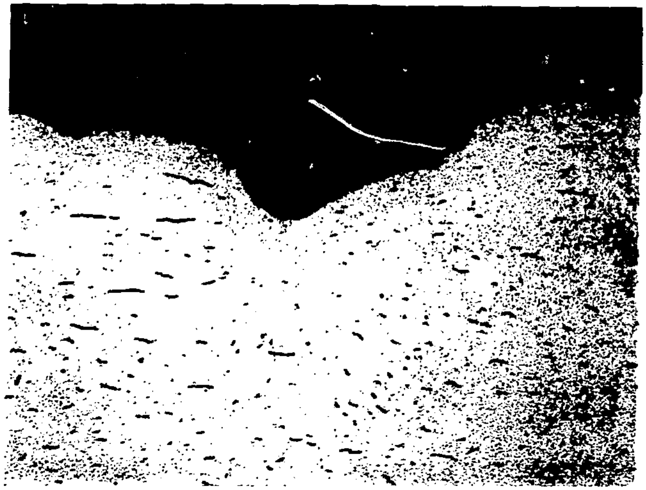


FIGURE 9 - Cross-section through secondary mark G10-3-1 (100 X

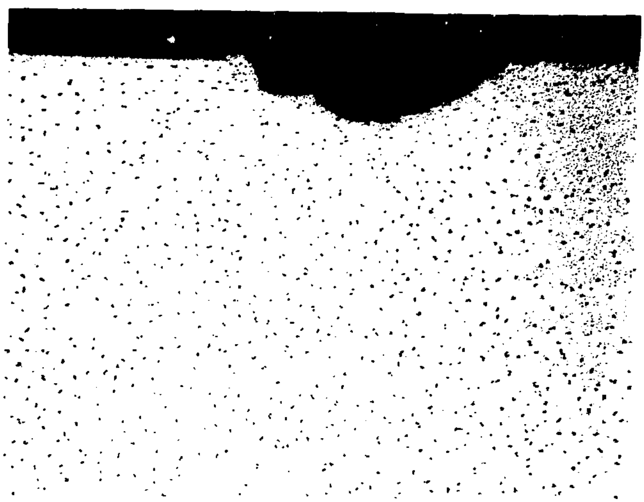


FIGURE 10 - Cross-section of secondary mark J12-5-1 at deepest point (50 X)

FIGURE 11 - (a) Montage (transvers
mark in K18-1-6. Note

SECTION 1

FIGURE 11 - (a) Montage (transverse normal) through secondary mark in K18-1-6. Note material flow (100 X)

SECTION 2

rse normal) through secondary
te material flow (100 X)

SECTION 3

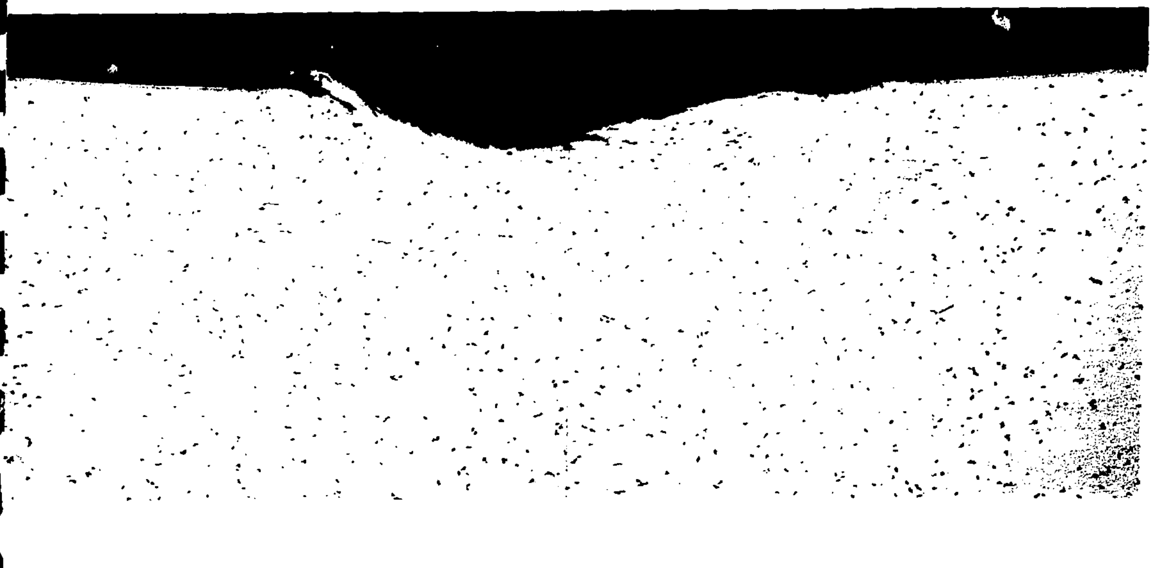
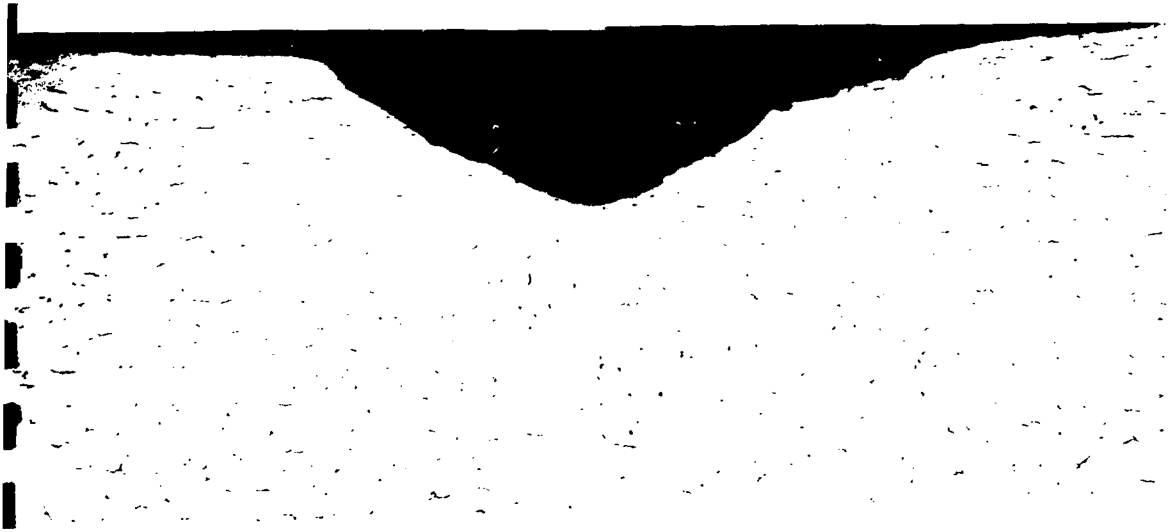


FIGURE 11 - (b) - Cross-section through K18-15 at deepest point. Note fine hydride zone (50 X).

(c) - Cross-section through K18-16 (50 X).



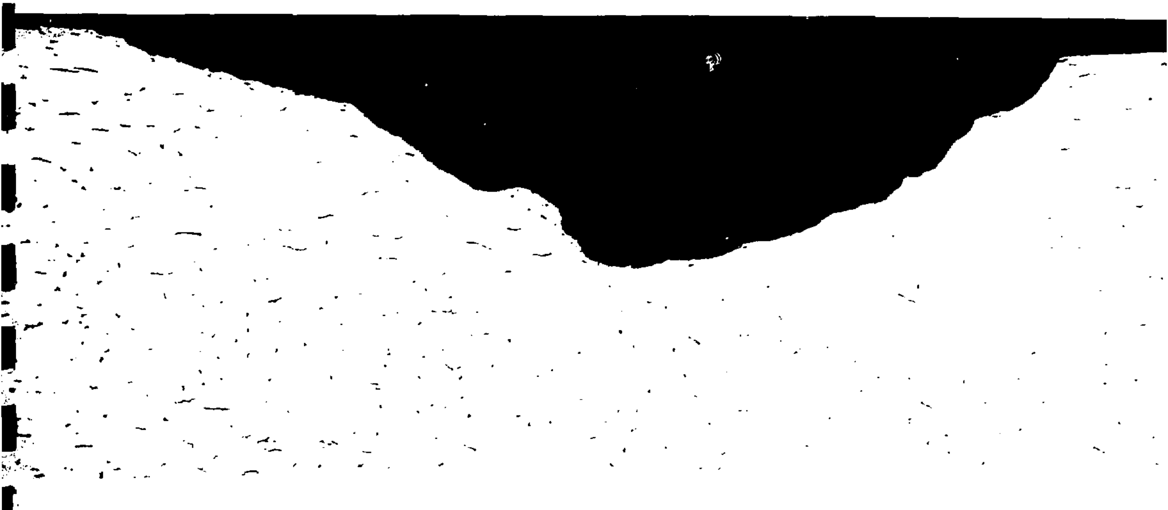


FIGURE 12(a) - Cross-section through secondary mark in L14-3-1 (50 X).

(b) - Same mark at deepest point (50 X).

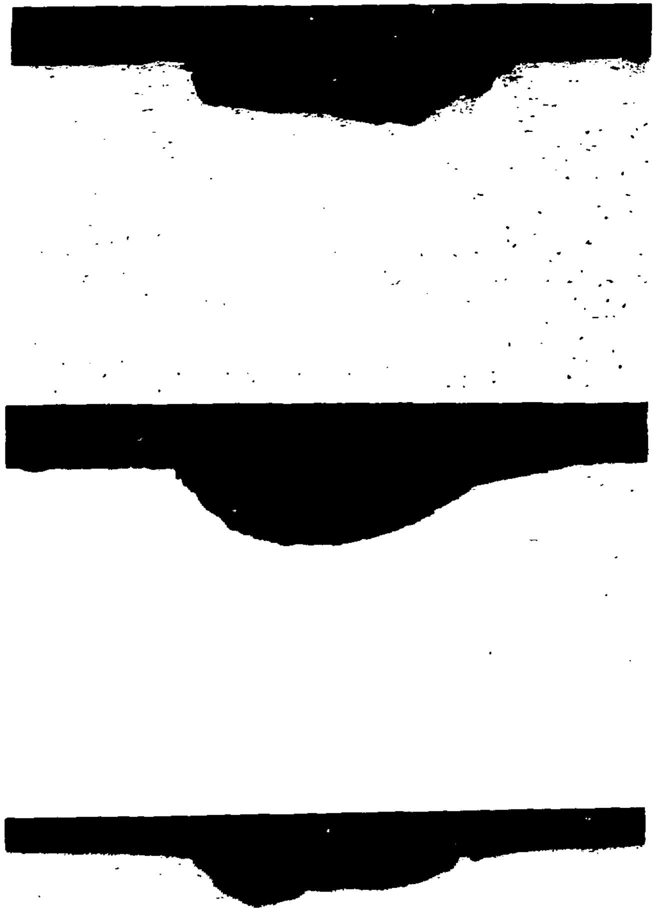


FIGURE 12(c) - Section through L14-3-2 at deepest point (50 X).
(d) - Section through L14-3-3 at deepest point (50 X).
(e) - Section through L14-3-4 at deepest point (50 X).