FAILURE ANALYSIS OF SHAFT SLEEVES IN AN AUXILIARY FEEDWATER PUMP

Report for
South Texas Project

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ABSTRACT

Two Type 420 stainless steel shaft sleeves and one Type 440A stainless steel bushing from an auxiliary feedwater pump were examined to determine the cause of failure. The sleeves split in the keyway and the bushing was completely stuck to the sleeve. The results of chemical analyses, hardness tests, metallographic examination are presented. Evidence for stress corrosion cracking/hydrogen embrittlement in the sleeves being responsible for the pump failure is discussed. Recommendations for alternative materials for the sleeves and wear rings are included.

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1.0 INTRODUCTION

An auxiliary feedwater pump for STP Unit 1 failed on February 28, 1988. This is an all-stage turbine driven 3560 rpm pump (Serial No. 1A137), built by Bingham-Willamette (B-W) in Portland, Oregon. This pump was installed in 1985. It is run intermittently (15 minutes to 2 to 3 hours at a time) mostly for testing purposes; otherwise it is on standby.

On February 28, 1988, the pump was run for about three hours when the speed dropped. It continued to drop even after the governor was adjusted. No excessive vibration was noticed. An inspection of the pump after opening the casing showed that the following parts were damaged: the shaft center bearing next to the 5th-stage impeller and the shaft throttle bearing next to the 6th-stage impeller, as follows:[1]

(1) Shaft Center Bearing

The shaft center sleeve split at the keyway. The inside and the outside surfaces showed friction marks and cracks.

The shaft center sleeve appeared to have sheared off the common key with the 5th-stage impeller. The portion of the key in the shaft center sleeve abraded the sleeve inside surface and the chamfered end of the sleeve cut into the 5th-stage impeller hub for about 5/16-inch.

(2) Shaft Throttle Bearing

- The sleeve seized (or friction welded) to the bushing.
- The sleeve split axially at the keyway (with the key still in place).
- The bushing outside surface discolored almost black with heavy abrasion marks and metal deformation.

The shaft was found to be straight (0.0015 inch maximum TIR). The impeller wear rings and hub rings showed no signs of abnormal wear or galling. Both the shaft center sleeve and the throttle sleeve were shrunk fit (0.0005/0.002 inch interference) onto the 2.640 inch diameter shaft. The radial clearance between the sleeve and the bushing was 0.004 to 0.006 inch per side in both cases. Water flows into this clearance acting as a lubricant during operation.

The fluid is steam condensate with a pH from 9.0 to 10.5. The oxygen content is 100 ppb maximum and hydrazine added to three times the dissolved oxygen content. The temperature is 120°F maximum.

The Bechtel-M&QS Laboratory received one-half of the throttle sleeve/bushing and the shaft center sleeve (Figure 1) for a failure analysis. This

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(1) Memorandum from F. J. Evans to Don Ashton, March 18, 1988.

report presents the results of our laboratory analysis on the sample parts received and the probable cause of the cracking in the sleeves based on the properties and performance of the sleeve materials in the service environment mentioned above.

2.0 CONCLUSIONS AND RECOMMENDATIONS

(1) The shaft center sleeve and the throttle sleeve are made of Type 420 stainless steel, heat treated to 51 HRC. The throttle bushing is Type 440A stainless steel, heat treated to 32 HRC.

(2) Both sleeves split axially in the keyway. The splits in these sleeves were caused by stress corrosion cracking/hydrogen embrittlement, which initiated at or near a corner of the keyway.

(3) The split in the throttle sleeve was not caused by metal particles from abraded 5th-stage impeller hub being lodged between the throttle bushing and the throttle sleeve.

(4) Wear rings and other hardened steel parts in the failed pump should be examined for signs of corrosion and cracking.

(5) Alternative materials of construction should be considered. Candidate materials include 420 stainless steel (tempered at 1100°F minimum), Type 316 stainless with Stellite hardfacing and Nitronic 60.

3.0 MATERIALS

The chemical composition of the two sleeve materials and a key were checked. The results presented in Table 1 indicate that both sleeves are Type 420 stainless steel and the key is Type 416 stainless steel. The materials of construction of the pump according to Reference (1) are as follows:

Pump casing:	CA6NM
Pump shaft:	Type 410 stainless steel (240 - 302 HB)
Pump impellers:	CA6NM
Shaft center sleeve:	Type 420 stainless steel (450 - 525 HB)
Shaft center stage piece:	Type 440A stainless steel (275 - 350 HB)
Shaft throttle sleeve:	Type 420 stainless steel (450 - 525 HB)
Shaft throttle bushing:	Type 440A stainless steel (275 - 350 HB)
Keys:	Type 416 stainless steel (96 HRB)

4.0 EVALUATION PROCEDURE

4.1 Visual Examination

The shaft center sleeve with a key and one-half the throttle bushing and its sleeve are shown in the as-received condition in Figure 1. These samples show cracks, discoloration, and friction marks. The throttle bushing and its sleeve were stuck together except for a segment that separated as shown in Figure 1(b).

The fracture faces of the throttle sleeve are shown in Figure 2. One of them occurred near a corner of the keyway. This fracture face was discolored except for a short distance (3/8 inch) from the end. The other fracture face, mating to the remainder of the throttle sleeve stuck to the bushing, was not discolored. It showed a fracture origin at the outside surface, about midpoint of its length, where the grains coarsened due to recrystallization, apparently caused by the friction heat.

The shaft center sleeve split also in the keyway (Figure 3). It appeared to have started at a corner of the keyway near the chamfered end. The split caused the sleeve to spring open by about 0.053 inch, indicating a high residual stress (about 150 ksi). The inside and outside surfaces and the chamfered end (toward the 5th-stage impeller hub) were abraded, discolored, and cracked. Only a narrow band on the outside surface near the chamfered end retained the original ground surface [Figure 3(b)]. Figure 4 shows the inside surface of the shaft center sleeve with the two mating fracture faces put together. It can be seen that the split veered off slightly from the corner of the keyway toward the rounded end of the keyway [Figure 4(a)]. The configuration of the abraded portion of the key and the shaft center sleeve inside surface seemed to fit together, as shown in Figure 4(c). In contrast, the inside surface of the throttle sleeve showed no friction marks.

The fracture faces of the two mating pieces of the shaft center sleeve are shown in Figure 5(a). A change in fracture appearance occurred toward the end opposite the keyway. This is marked by an arrow in Figure 5(b). Small areas of rust were found on the fracture faces near the corner of the keyway [Figures 5(a), (b), and (d)]. The fracture appearance of the shaft center sleeve is comparable to that of the throttle sleeve shown in Figure 6.

4.2 Scanning Electron Microscopic Examination

Scanning electron microscopic examination of the fracture faces of both sleeves showed that the principal mode of the fracture is intergranular. Figures 7 through 10 show SEM photographs of the fracture faces of the splits in the keyways of both sleeves. The other fracture face (without heat discoloration) of the throttle sleeve showed intergranular cracking in the fracture origin; the fracture mode changed to dimple away from the origin.

Figure 7(a) shows the area with rust on the fracture face of the shaft center sleeve. The area bounded by a white rectangle is shown at a higher magnification in Figure 7(b). The granular appearance is typical of intergranular cracking. Figure 7(c) is typical for the fracture face near the rounded end of the keyway. It shows no corrosion products on the fracture face. This intergranular mode of fracture persisted until the transition line indicated in Figure 5(b). The finer fracture appearance below the transition line resulted from a change in the fracture mode to a dimple fracture. This change in the fracture mode in a microscopic scale is shown in Figure 8. (A specimen cut from the shaft center sleeve and broken fresh at room temperature in the laboratory showed a dimple fracture mode.)

Typical SEM photographs of the intergranular mode of the fracture face in the keyway of the throttle sleeve are shown in Figure 9. The keyway land adjoining the fracture face (in the area marked by the arrow in Figure 6) was corroded and cracked as evidenced by intergranular attack (Figure 10). The lower halves of the SEM photographs of Figures 10(a) and (b) are a 5X magnification of the areas bounded by the white rectangles. The white arrows in Figure 10 point to the edges of the fracture face. So, the areas below the arrows are the keyway land. The corrosion in these areas delineated the grain boundaries.

The oblong area at the end of the key in Figure 4(b) revealed a characteristic shear fracture.

Figure 11 shows SEM photographs of the smeared or abraded surfaces of the sleeves. Energy dispersive X-ray spectra of the areas shown will be presented later.

4.3 Hot Acid Etch Test

Several specimens from the bushing and the sleeves were etched in dilute hydrochloric acid around 140°F. The results are shown in Figure 12. The heat affected zones from frictional heat are clearly outlined in Figures 12(a) and (b). The heat affected zone in the throttle sleeve extends through the wall thickness, except for a short distance at the end with the keyway (toward the 6th-stage impeller). This end stuck out of the bushing in the final seized condition. A thin layer at the inside surface of the bushing appeared to have melted and squeezed out to the ends. Grain growth occurred in the outside layers of the throttle bushing and the throttle sleeve. As compared with the heavy frictional heat in the throttle bushing and its sleeve, the heat affected zones in the shaft center sleeve are relatively shallow [Figure 12(b)]. The hot acid etching brought out numerous fine cracks on the inside surface and a few relatively large cracks on the outside surface of the shaft center sleeve [Figures 12(c) and (d)].

The above test also revealed that the two sleeves are a wrought product (e.g., forging), whereas the bushing is a casting.

4.4 Hardness Test

Rockwell hardness tests using the C-scale gave the following results:

- Shaft center sleeve: 51 - 52 HRC (opposite the keyway end)
  48.9 - 49 HRC near the chamfered end
- Throttle sleeve: 50.5 - 51 HRC (unscorched area)
  49 - 49.5 HRC (scorched area)
- Throttle bushing: 29.5 - 31 HRC (chamfered end)
  32 - 33 HRC (opposite end)
- Key: 96 HRB

4.5 Metallographic Examination

Figure 13(a) shows a profile of an axial-radial section of the chamfered end of the shaft center sleeve. The heat affected zones have been delineated by etching in the Villela's reagent. A straight portion on the outside surface profile near the top is without a heat affected zone as it retained the original ground surface. Figures 13(b) and (c) show profiles of the keyway corner that did not split in the shaft center sleeve. A 0.01-inch radius circle can be inscribed at the corner touching the two adjacent sides. Only a small area at the extreme end of the keyway land would be outside this circle. Thus, the keyway corner has an overall radius of 0.01 inch with a smaller radius (about 0.002 inch) at the end of the keyway land.

Figures 14(a), (b), and (c) show the heat affected zone and a typical heat crack on the outside surface layer of the shaft center sleeve. These cracks were also intergranular except for the beginning.

Smeared metal at the edge of the keyway on the inside surface of the shaft center sleeve [Figure 13(c)] contained metal particles. These particles are shown in Figure 14(d).

Figure 15(a) shows a cross section of the throttle sleeve at the location marked by the arrow in Figure 6. It can be seen that the split did not occur at the very corner of the keyway; it occurred a short distance away from it, about 1/16 inch. The corner of the keyway can be inscribed with a 0.015 inch radius circle except for a local protrusion [Figure 15(b)]. The cross section shown in Figure 15 is at the area which showed evidence of corrosion (Figure 10) in the keyway land during SEM examination. Figure 15(c) shows secondary intergranular cracks parallel to the fracture face, intergranular attack along the keyway land, and "sponge" metal (due to corrosion) near the beginning of the fracture. The two circular blobs in Figure 15(c) were produced as the etching reagent which had been absorbed by the sponge metal during etching came out later on a dried specimen surface.

4.6 Surface Chemical Analysis

The galled surface of the throttle sleeve was analyzed for nickel to see if any abraded metal particles from the 5th-stage CA6NM impeller hub were lodged on it. (CA6NM contains about 4 percent nickel, whereas 440A and 420 stainless steels about 0.4 percent nickel as residual.) Both the energy dispersive X-ray analysis (EDXA) and the wave length dispersive X-ray analysis (WDXA) were used. The latter is commonly referred to as an X-ray fluorescence analysis. No nickel in significant amounts were detected from the galled surface of the throttle sleeve. Instead, EDXA showed a large amount of silicon. Typical EDXA spectra of the throttle sleeve outside surface are shown in Figures 16 and 17. WDXA showed no differences in nickel contents between the inside and the outside surfaces of the throttle sleeve.

A small amount of nickel and some silicon were found on the chamfered end of the shaft center sleeve which cut into the 5th-stage impeller hub. Figure 18 shows EDXA spectra of the areas indicated in Figure 11(c). The metal particles found in the smeared metal at the edge of the keyway [Figures 13(b) and 14(d)] showed strong chromium peaks and weak iron peaks only and the smeared metal surrounding these particles nickel and molybdenum peaks. Therefore, the smeared metal may have come from CA6NM and the metal particles from chromium plating probably on the shaft.

5.0 Results of Evaluation

Potential cracking mechanisms for the sleeves are:

- frictional heating
- stress corrosion cracking/hydrogen embrittlement

Hardened steels are susceptible to cracking when heated rapidly in localized areas. Thus, the heat generated by friction or grinding cause what is commonly called heat checks. The higher the hardness, the more susceptible the metal is to heat checks. As shown in Figures 12(c) and (d), the numerous small cracks on the inside surface and a few large cracks on the outside surface of the shaft center sleeve are believed to have been caused by the heat generated by friction between two sliding surfaces. The abrasion marks and the heat affected zones on both the inside and the outside surfaces of the shaft center sleeve attest to the frictional heating. The frictional heating in the throttle sleeve, on the other hand, was so high that the entire cross section within the bushing was quenched and tempered. Therefore, no heat checks formed. In this case, the heat was so high that even the metals melted and grain growth occurred at the faying surfaces.

Heat checks obviously did not occur in the keyway land, including the keyway corners. Therefore, the splits in both sleeves could not have started from the inside if the frictional heating was responsible for them. It would be too much of a coincidence to blame frictional heating for the splits in the keyways of the two separate sleeves. This is because the split must have originated from the outside surface and happened to go through the keyway. Instead, metallographic evidence points to stress corrosion cracking, hydrogen embrittlement cracking, or both for the splits.

Hardened steels, including chromium stainless steels such as Type 420 stainless steel, are also subject to stress corrosion cracking and hydrogen embrittlement. Although fine differences exist between stress corrosion cracking and hydrogen embrittlement cracking, it is often not possible to distinguish which one is responsible for metal cracking in actual failures in which corrosion was a factor even slightly. Stress corrosion cracking is a result of a combined action of a static tensile stress and a corroding environment. Hydrogen embrittlement is produced by the presence of excessive amounts of hydrogen. The source of hydrogen includes corrosion as well as steelmaking, acid cleaning, and plating. For the purpose of discussion of the fractures in the sleeves, it makes little difference whether cracking can occur due to stress corrosion cracking or hydrogen embrittlement.

The evidence of corrosion and the secondary intergranular cracking (Figure 15) in the throttle sleeve keyway lands support to stress corrosion cracking. Evidence of corrosion was found also on the shaft center sleeve fracture faces, although not as strongly as in the throttle sleeve. Corrosion, resulting in acidification of localized regions, causes the hydrogen to be absorbed by the metal. Cracking caused by stress corrosion or hydrogen embrittlement in high strength steels can be either intergranular or transgranular. A mechanical overload fracture would not be intergranular, as proved by a laboratory fracture of a specimen from the shaft center sleeve. Therefore, in our opinion, the splits in the two sleeves were caused by stress corrosion cracking/hydrogen embrittlement. Both sleeves show evidence of corrosion; both sleeves were under high residual tensile stress (150 ksi) in the circumferential direction. The sleeves are in a highly hardened condition. These three conditions have been known to be conducive to stress corrosion cracking/hydrogen embrittlement.

The splits in the sleeves came first and the increase in diameter due to the splits caused the frictional heating. The 0.053 inch gap at the split of the shaft center sleeve is equivalent to an increase in diameter by 0.017 inch, which is more than the design clearance between the sleeve and the shaft center stage piece. It is reasonable, therefore, to believe that the initial friction between them was sufficiently high enough to shear the key off. Subsequently, the shaft center sleeve rotated around the shaft inside the center stage piece, cutting into the 5th-stage impeller hub. The keyway length in the throttle sleeve is much longer than that in the shaft center sleeve [See Figures 2(b) and 3(a)] Therefore, the key in the throttle sleeve remained in place, overcoming the friction force that developed as a result of the split. Instead, the friction between the throttle sleeve and the throttle bushing caused such an intense heat that the metals melted, squeezing some molten metal out, and friction welded themselves together for the most part. Since the key was stronger than the 3/8-inch diameter anti-rotation pin for the throttle bushing, the latter sheared off, causing the bushing to rotate inside the casing. This would explain the large heat affected zone and deformation around the bushing collar [Figure 12(a)].

These pumps experienced wear ring failures in another power plant in 1984. Disassembly of the pumps at B-W then showed considerable rusting inside.[2,3] Some of the wear rings (either 440A or 420 stainless steel) showed pitting corrosion. Rust streaks on the inside surfaces of the pump casings, impellers, and pitting in wear rings occurred during the standby period. It seems possible that the water remaining inside the pump became oxygenated through oxygen diffusion, causing the corrosion to occur. The faying faces between the key and the keyway in the sleeves form crevices where localized corrosion can occur preferentially. Unless the pH of the water is maintained at a high level (around 10), some corrosion may occur on 420 stainless steel under certain conditions. A sufficient quantity of hydrogen may be generated and absorbed by the metal because of the corrosion, leading to cracking after an incubation period. The time required to initiate the cracking (the incubation period) is usually much longer than the time for the crack to propagate.

Though oxygen must be maintained at low levels to avoid corrosion in the rest of the system, low oxygen is reported to markedly increase susceptibility to stress corrosion/hydrogen embrittlement vs. air saturated water.[4] This is consistent with the general observation that stress corrosion/ hydrogen embrittlement occurs when the general corrosion rate is low (low oxygen) but not when the general rate is high (high oxygen).

It appears that the two sleeves were made of the same heat of material, heat treated to the same hardness level, machined to the same inside and outside diameters, shrunk fit to the common shaft, and exposed to the same environment for the same length of time. Then, the susceptibility to cracking would have been about the same between the two sleeves, requiring about the same period of time for incubation before cracking. Since there was visible corrosion on the fracture faces on the inside of the key, it is reasonable to conclude that the shaft center sleeve had been cracked for some time before the throttle sleeve split. The corrosion on the fracture faces of the shaft center sleeve lends some support for this. It is also possible that the pump could

(2) Trip Report from S. W. Borenstein to R. A. Keidel, SWB-044-01, April 9, 1984.
(3) Trip Report from S. W. Borenstein to R. A. Keidel, SWB-044-03, April 16, 1984.
(4) H. Suss, Corrosion (October 1960) 105.

have operated with the shaft center sleeve split but not seized. It is likely that the throttle sleeve split completely during the pump operation on February 28, 1988, leading to the complete seizure between the sleeve and the bushing and the friction heat damage to the bushing and its housing.

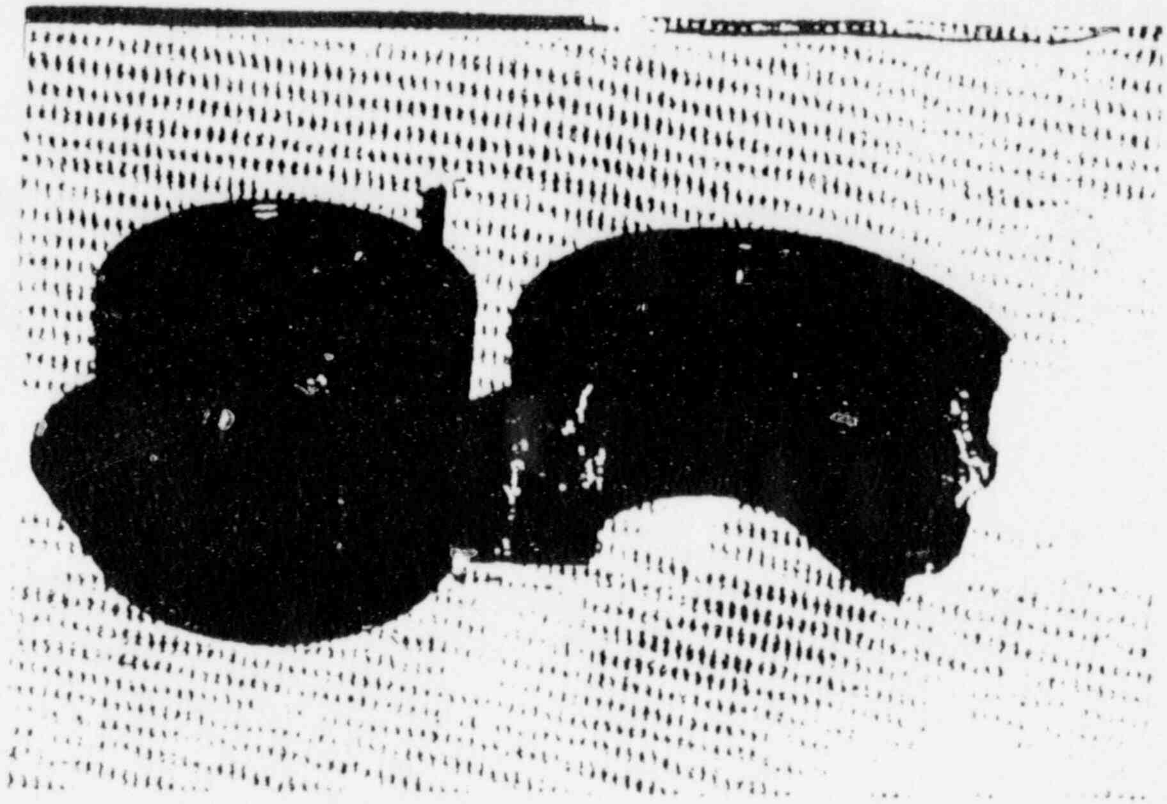
It is possible that some of the impeller wear rings in the pump that failed at STP are also a candidate for stress corrosion cracking/hydrogen embrittlement failures. B-W uses either Type 440A or 420 stainless steel (forgings or castings) for wear rings, heat treated to the same hardness level as the sleeves that failed. Therefore, during the repair of the failed pump, the wear rings should be examined for cracks and signs of pitting corrosion in other parts of the pump internals.

Protection of pump internals during the standby period by maintaining them in a dry condition or by treating the water with corrosion inhibitors may be impractical from operational requirements. Unless even the slight possibility of metal corrosion can be eliminated, Type 440A or 420 stainless steels in a high hardness condition may not be a suitable material of construction for pump internals for applications as auxiliary feedwater pumps. Then other materials such as Type 316L stainless steel with Stellite hardfacing using the plasma arc transfer process or Nitronic 60 may be considered as the shaft sleeve or wear ring materials. The former is used commonly for pump wear rings. Both have shown better wear resistance than Type 420 stainless steel. Both Stellite and Nitronic 60 are resistant to galling, friction heat cracking, and stress corrosion cracking/ hydrogen embrittlement in oxygenated or deoxygenated, condensate (with a low chloride content) over the pH ranges normally encountered. Alternatively, 420 stainless steel with an 1100°F minimum tempering temperature could be used. However, the lower hardness (needed for resistance to stress corrosion /hydrogen embrittlement) resulting from the higher temperature will have poorer wear resistance than the higher hardness material previously supplied.

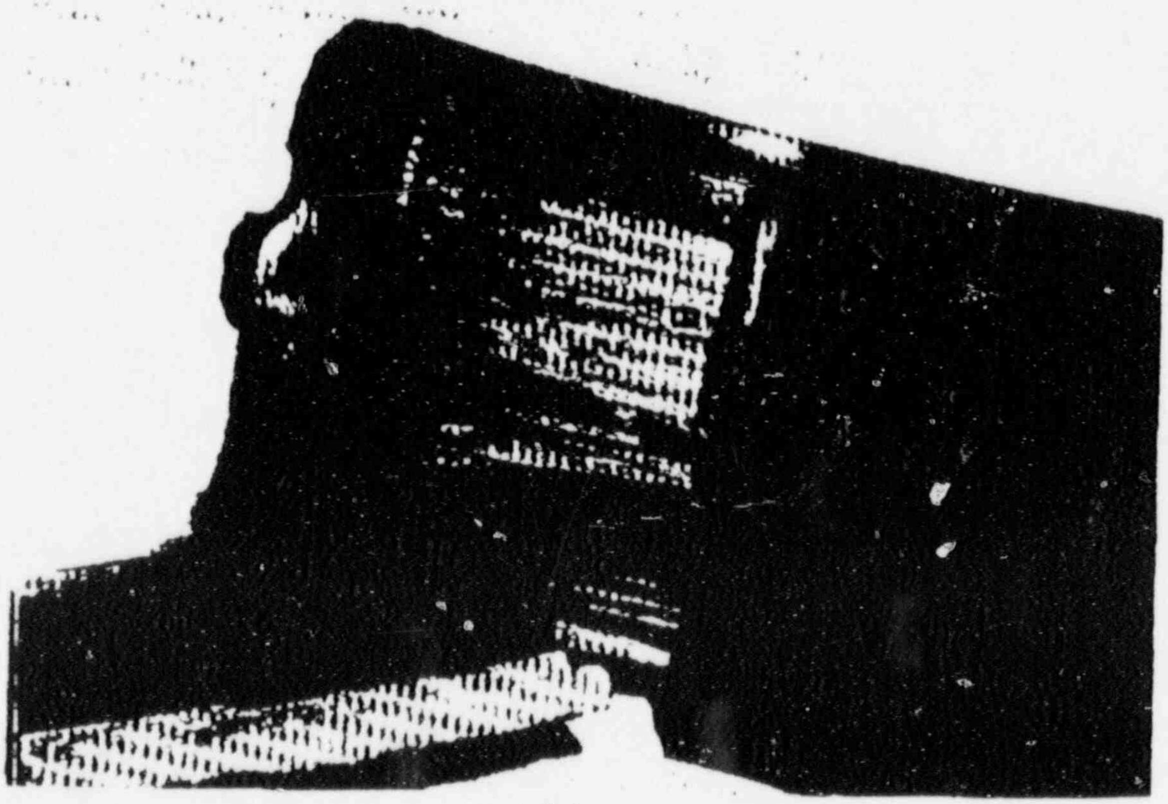
TABLE 1

THE RESULTS OF CHEMICAL ANALYSES OF SLEEVES AND THE KEY FOR THE SHAFT CENTER SLEEVE

	Weight Percent		
Elements	Shaft Center Sleeve	Throttle Sleeve Key	Key
Carbon (C)	0.31	0.34	0.092
Manganese (Mn)	0.55	0.54	0.44
Phosphorus (P)	0.019	0.020	0.016
Sulfur (S)	0.006	0.008	0.29
Silicon (Si)	0.51	0.51	0.45
Chromium (Cr)	12.67	12.68	13.24
Nickel (Ni)	0.43	0.42	
Molybdenum (Mo)	0.10	0.11	
Copper (Cu)	0.08	0.09	

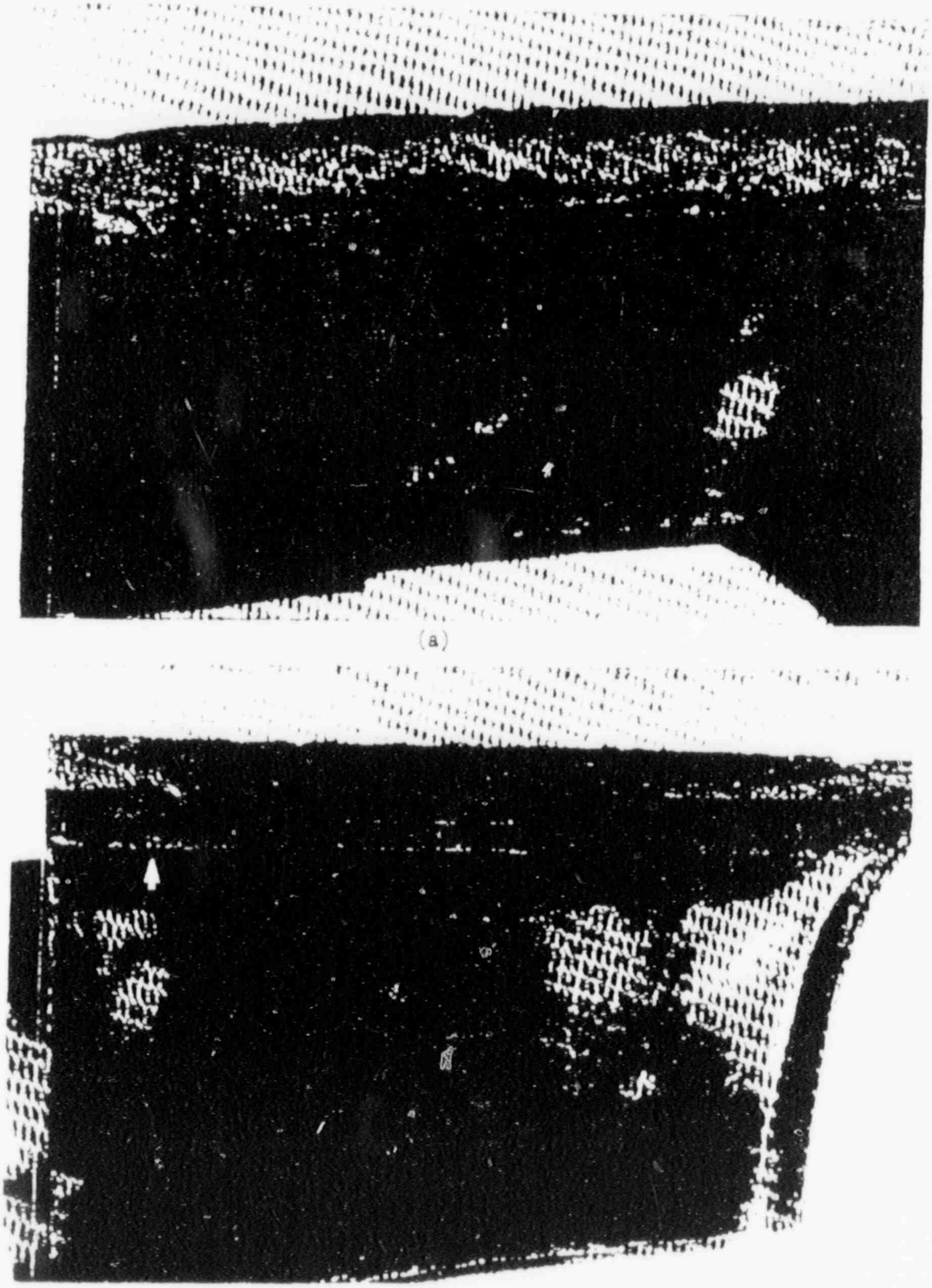


(a)



(b)

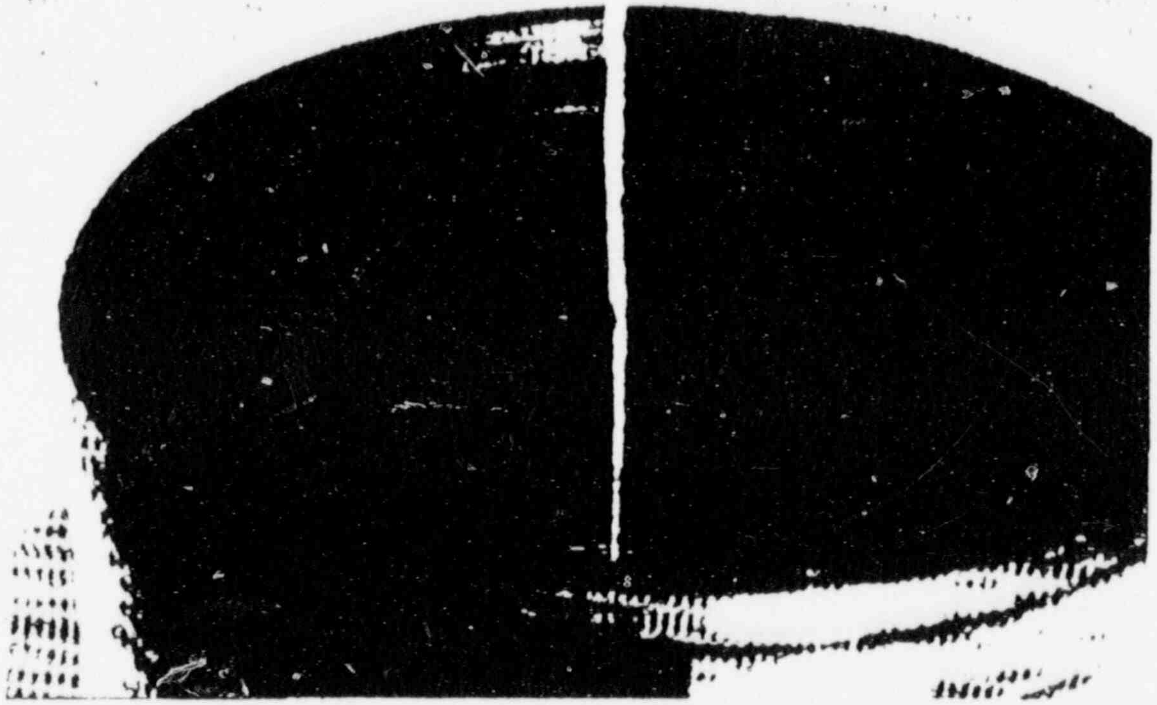
Figure 1 (a) The shaft center sleeve (left) and the throttle bushing/sleeve (right) in the as-received condition.
(b) The galled sliding surface between the throttle bushing and its sleeve.



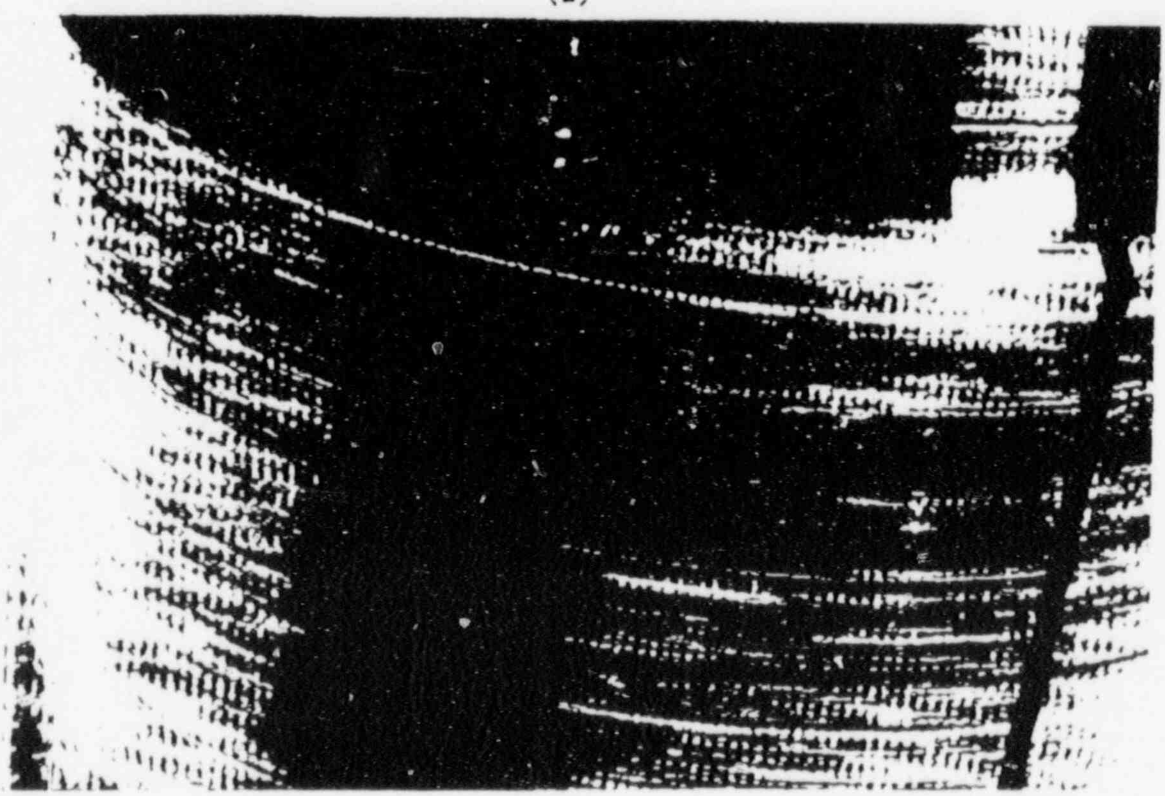
(a)

(b)

Figure 2 The two fracture faces of the throttle sleeve.

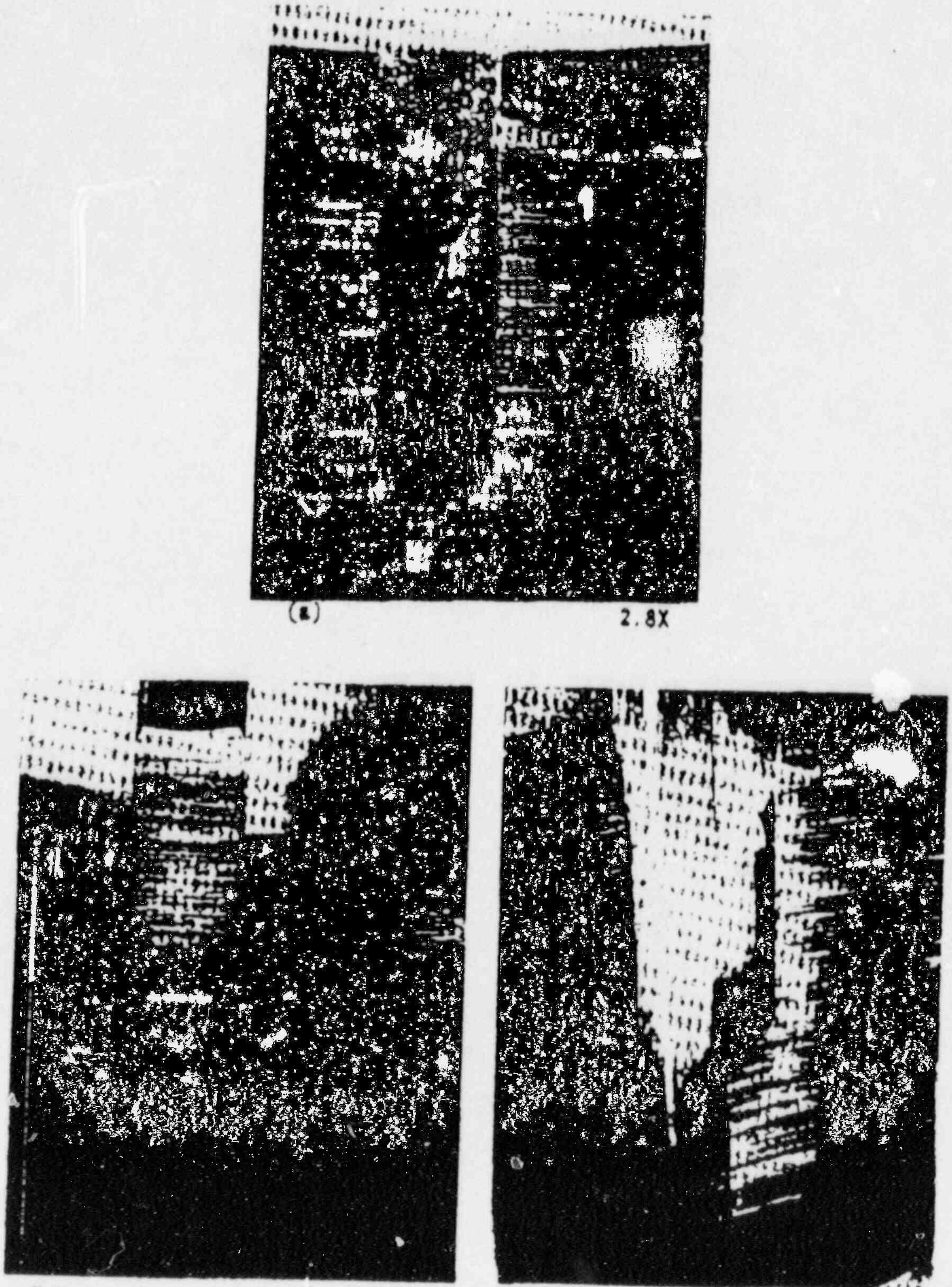


(a)



(b)

Figure 3 The crack at a corner of the keyway in the center sleeve. Heat checks on the outside surface can be seen in (b).



(a) 2.8X

(b) 2.8X (c) 2.8X

Figure 4 (a) The keyway in the shaft center sleeve viewed on the inside surface
(b) & (c) The inside surface around the keyway with the key placed in and along the keyway.

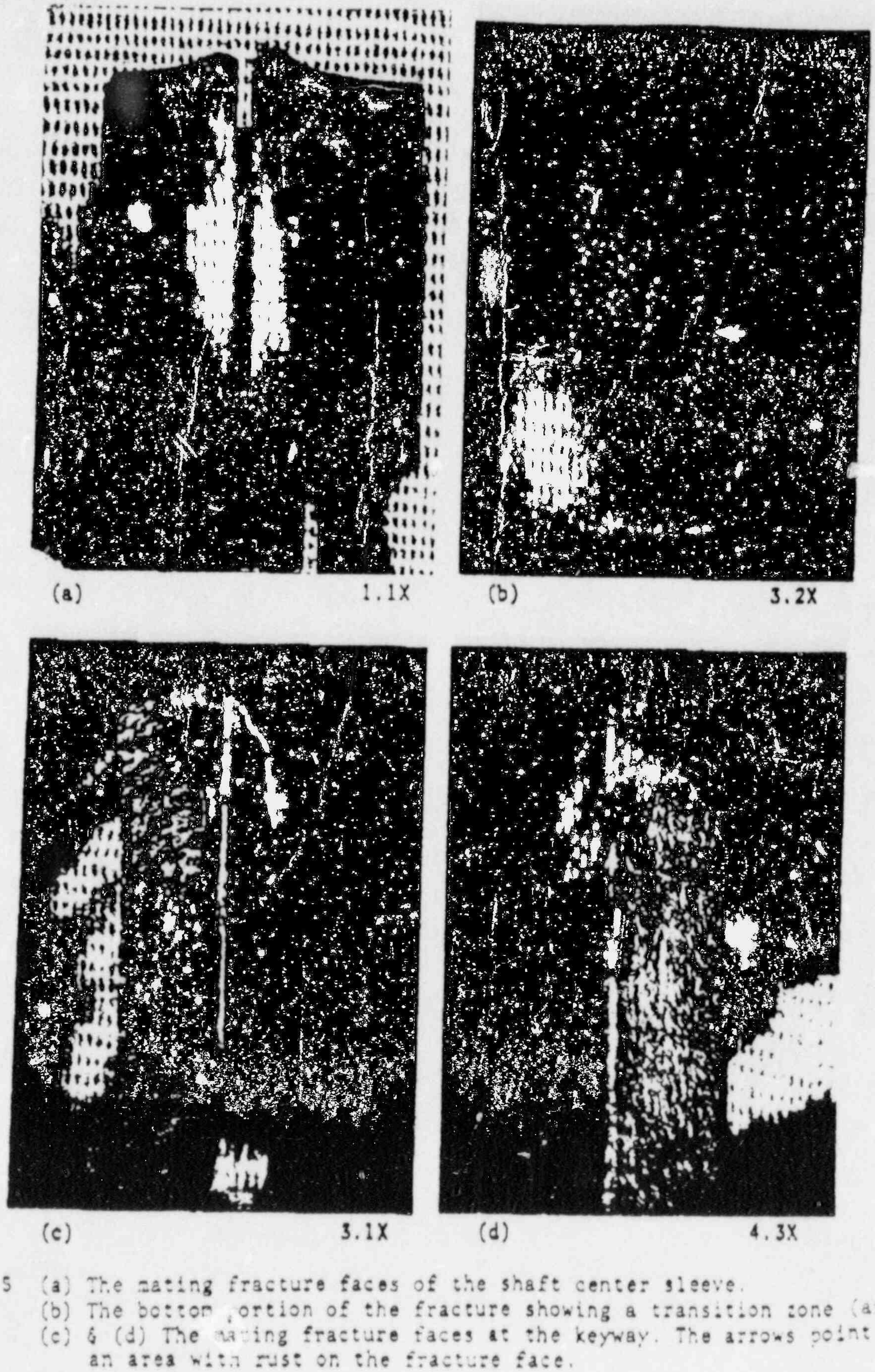
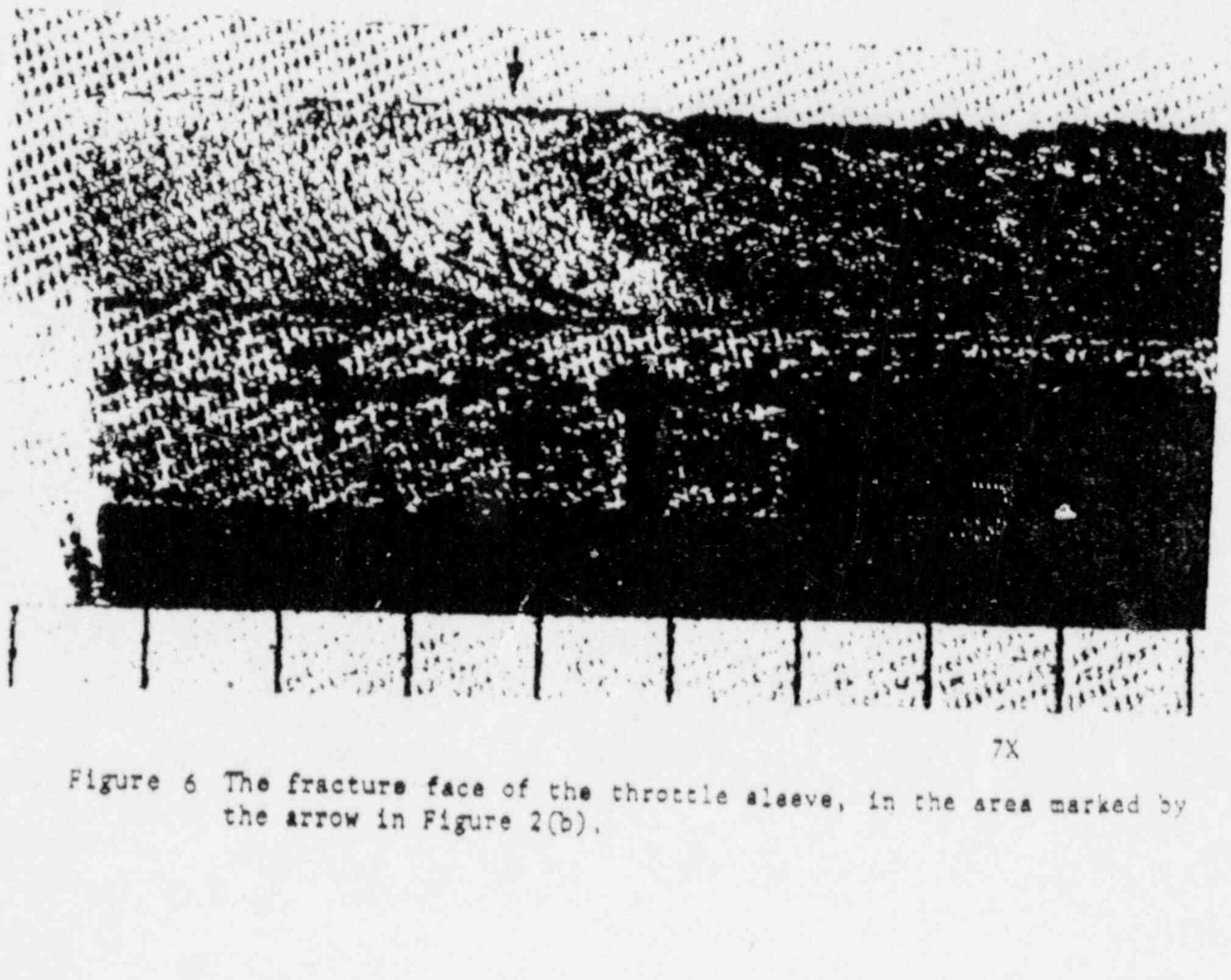
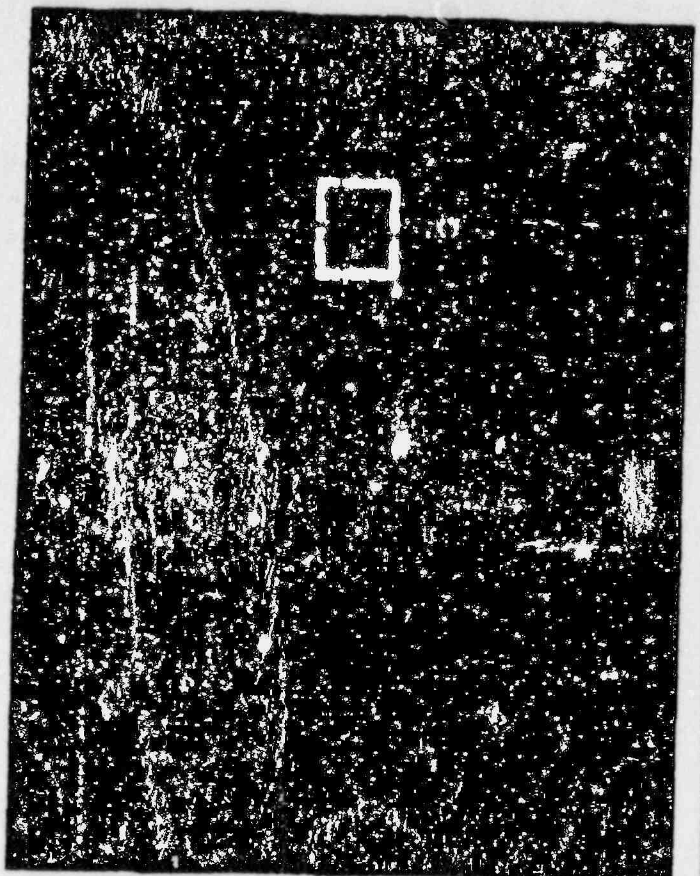


Figure 5 (a) The mating fracture faces of the shaft center sleeve.
(b) The bottom portion of the fracture showing a transition zone (arrow).
(c) & (d) The mating fracture faces at the keyway. The arrows point to an area with rust on the fracture face.

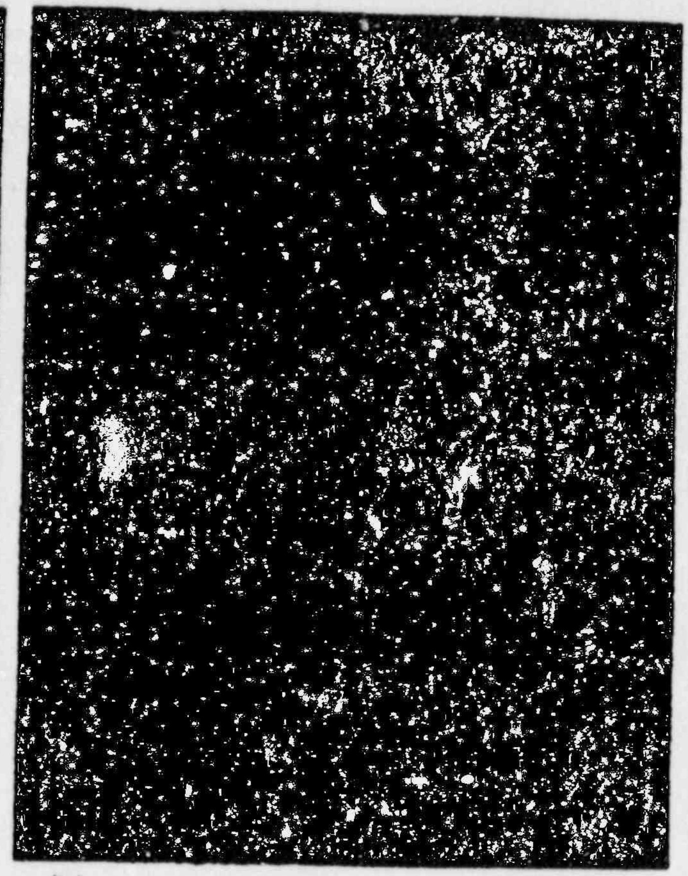


7X

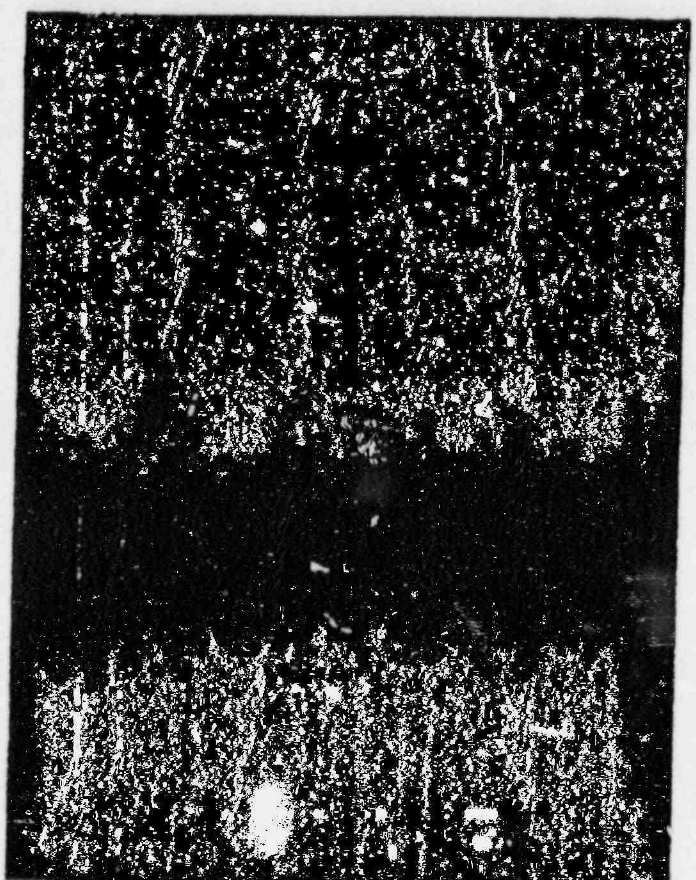
Figure 6 The fracture face of the throttle sleeve, in the area marked by the arrow in Figure 2(b).



(a) 33X



(b) 330X



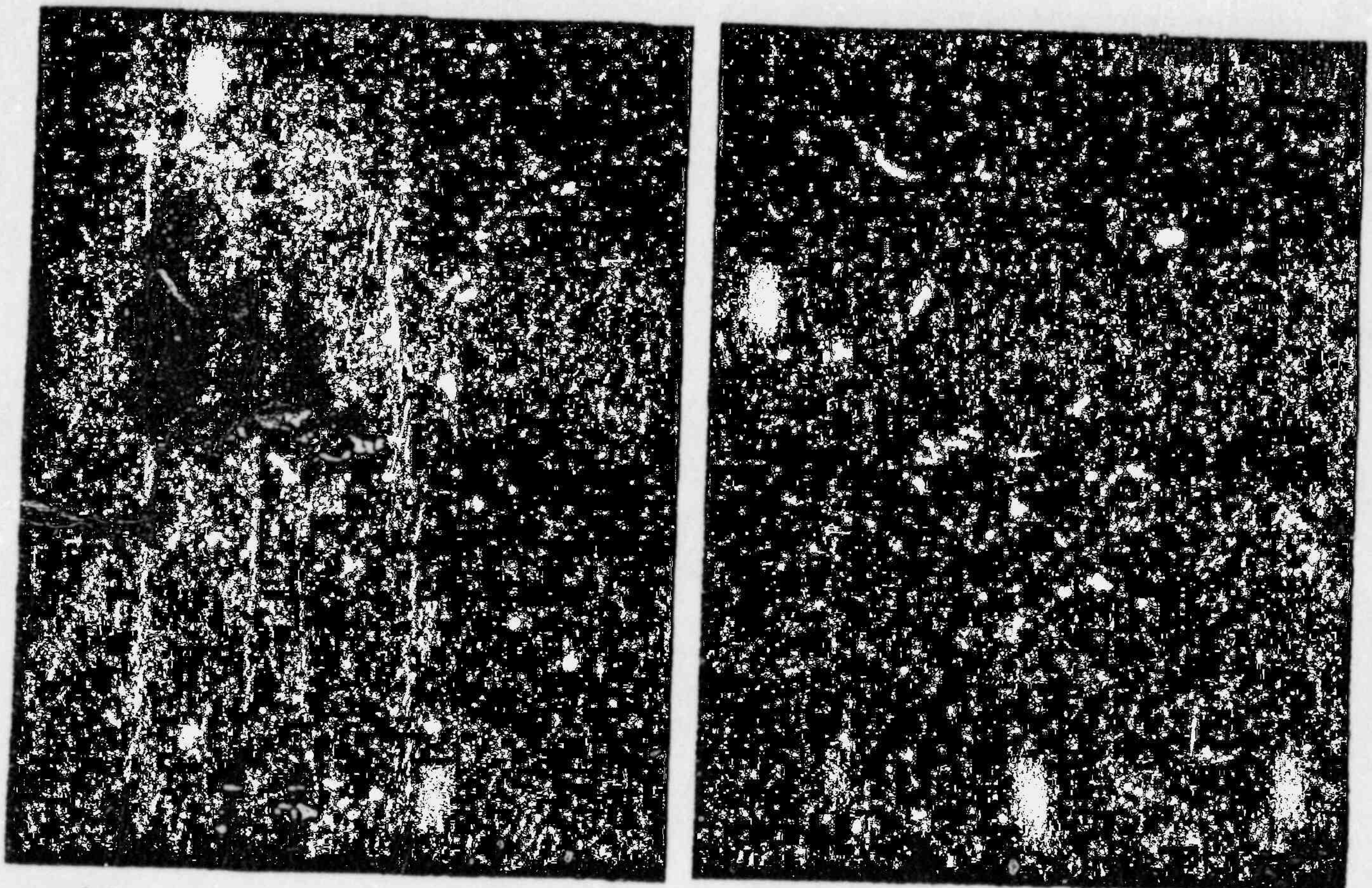
(c) 910X

Figure 7 Scanning electron micrographs of the fracture face of the shaft center sleeve

(a) The area marked by the arrow in Figure 5(d).

(b) The area bounded by the white rectangle in (a).

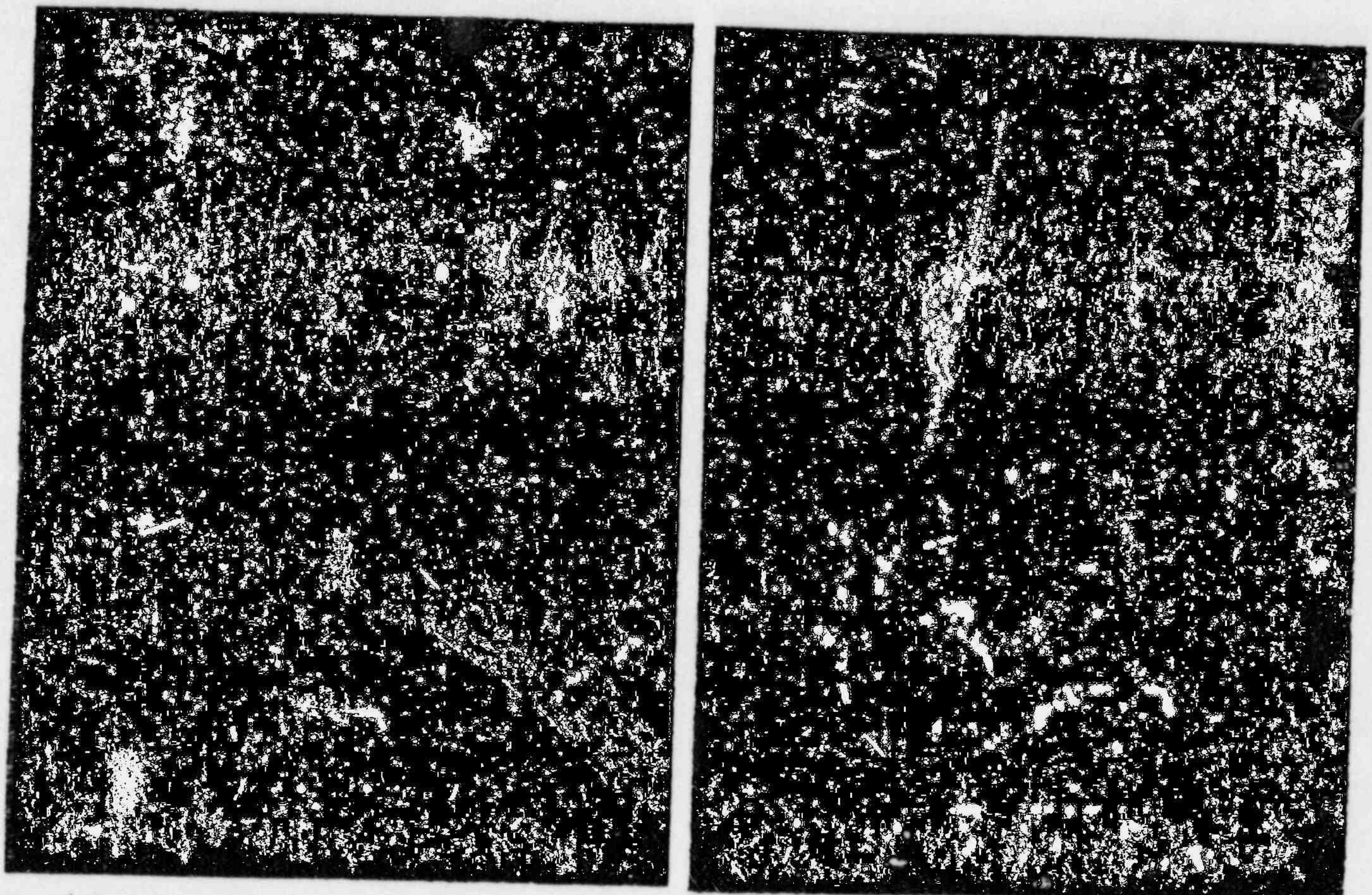
(c) An area near the end of the keyway.



(a) 980X (b) 2200X

Figure 8 (a) Scanning electron micrograph of an area just above the transition line marked by the white arrow in Figure 5(b).

(b) An area below the transition line in Figure 5(b).



(a) 72X (b) 720X

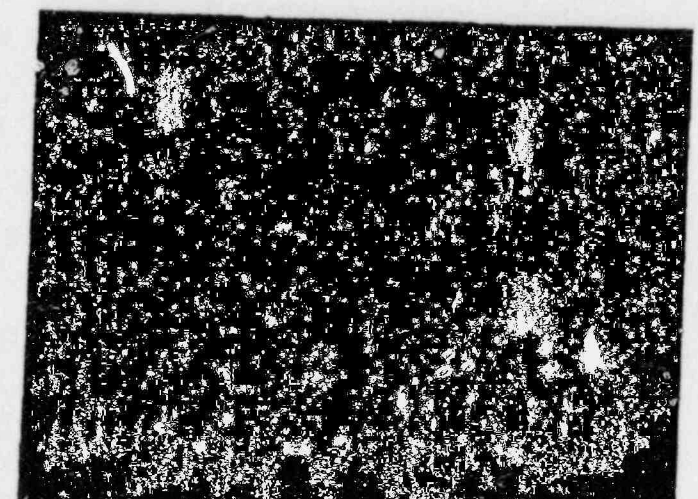
Figure 9 Scanning electron micrographs of the fracture face of the throttle sleeve.

(a) An area near the outside surface. See the area marked by the arrow in Figure 6.

(b) The area bounded by the white rectangle in (a).

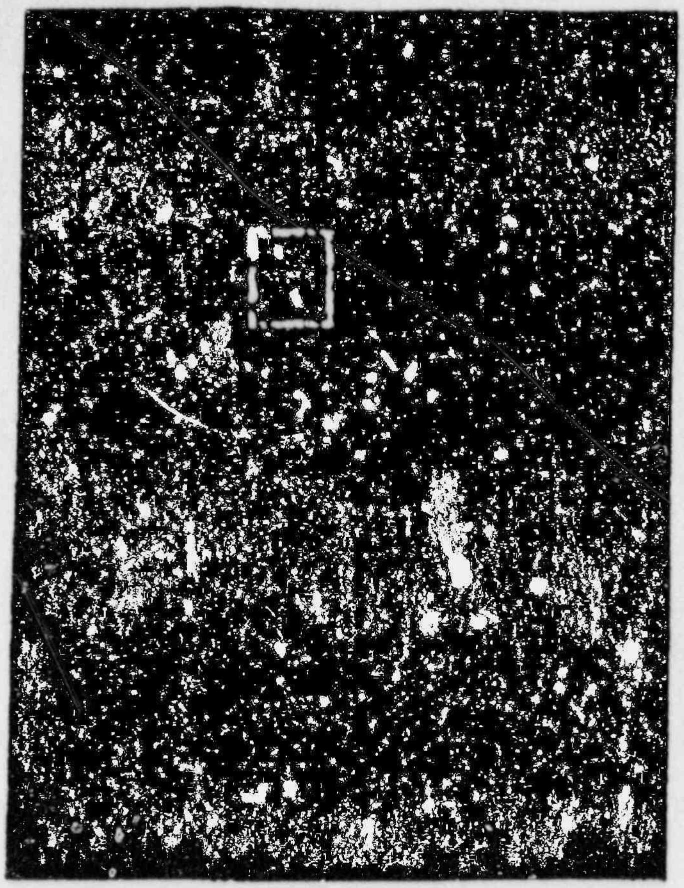
(a) 66/330X

(b) 66/330X



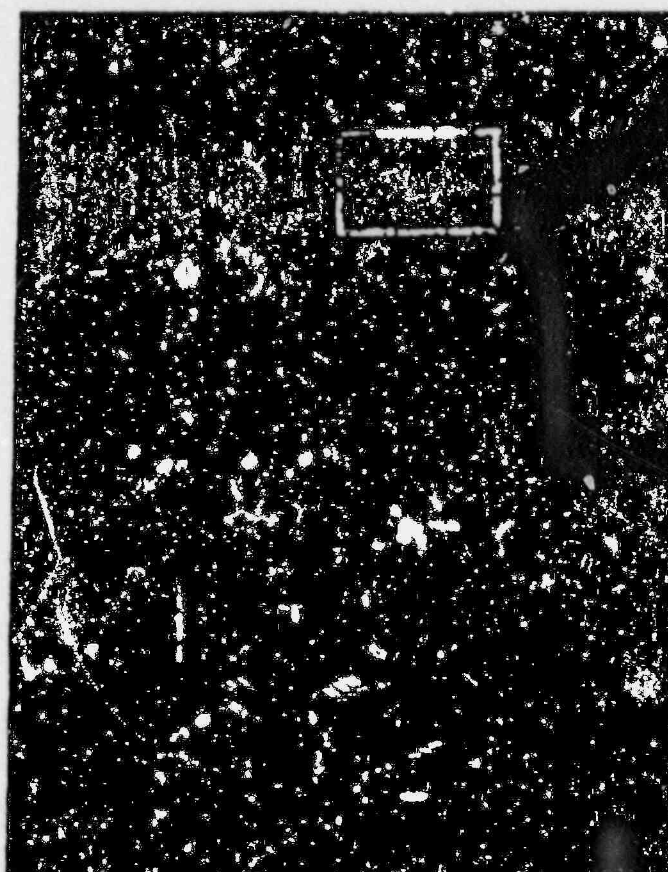
(c) 330X

Figure 10 Scanning electron micrographs of the keyway adjoining the fracture face of the throttle sleeve. The arrows mark the edge of the fracture face on the keyway.



(a) 74X

(b) 740X



(c) 40/200X

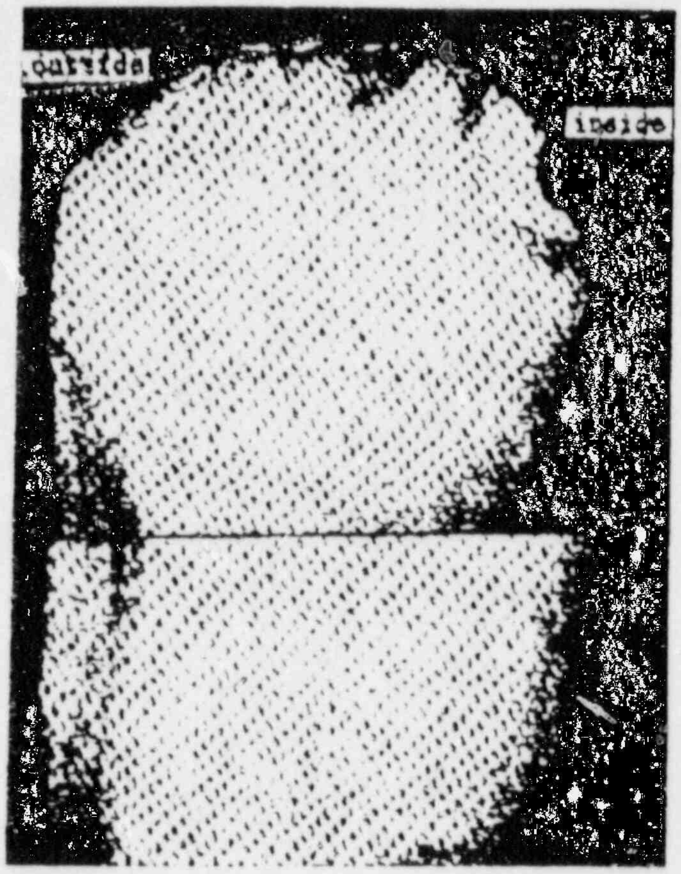
Figure 11

(a) Scanning electron micrograph of an area on the outside surface of the throttle sleeve.

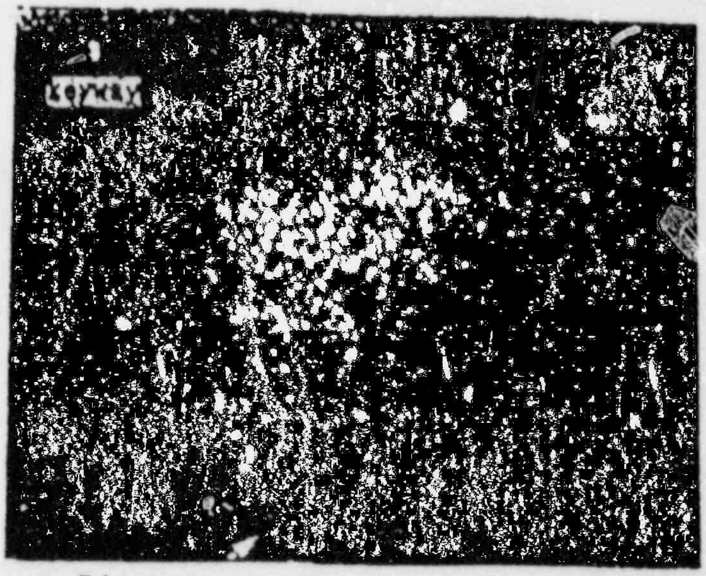
(b) The area bounded by the white rectang[l]e in (a).

(c) Scanning electron micrograph of an area at the chamfered end of the shaft center sleeve. See figures 16, 17, and 18 for EDXA spectra.

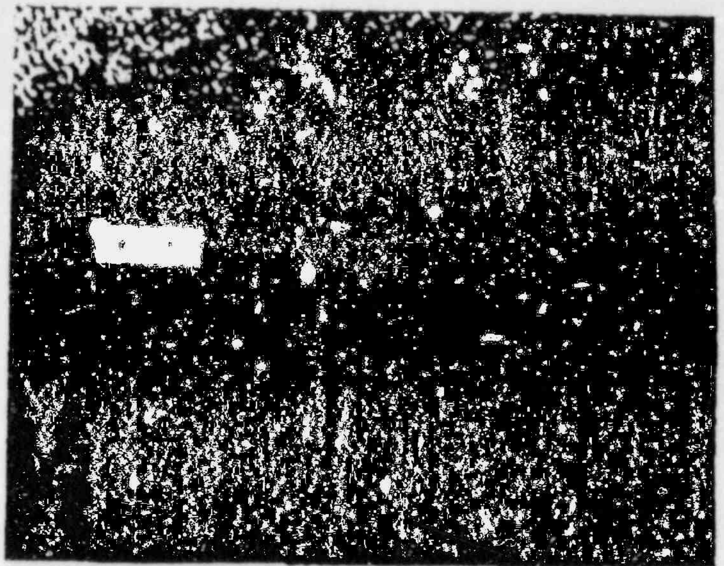
Figure 12 (a) Macrograph of the throttle bushing and its sleeve.
(b) Axial sections of the throttle sleeve and the shaft center sleeve
(c) & (d) Same as (b) showing the inside and outside surfaces
All specimens etched in dilute hydrochloric acid.



(a) 11.4X



(b) 25X



(c) 100X

Figure 13 (a) A profile of an axial section of the shaft center sleeve showing the friction heat affected zones at the chamfered end.

(b) & (c) The corner of the keyway of the shaft center sleeve at the location marked by the arrow in Figure 5(c).

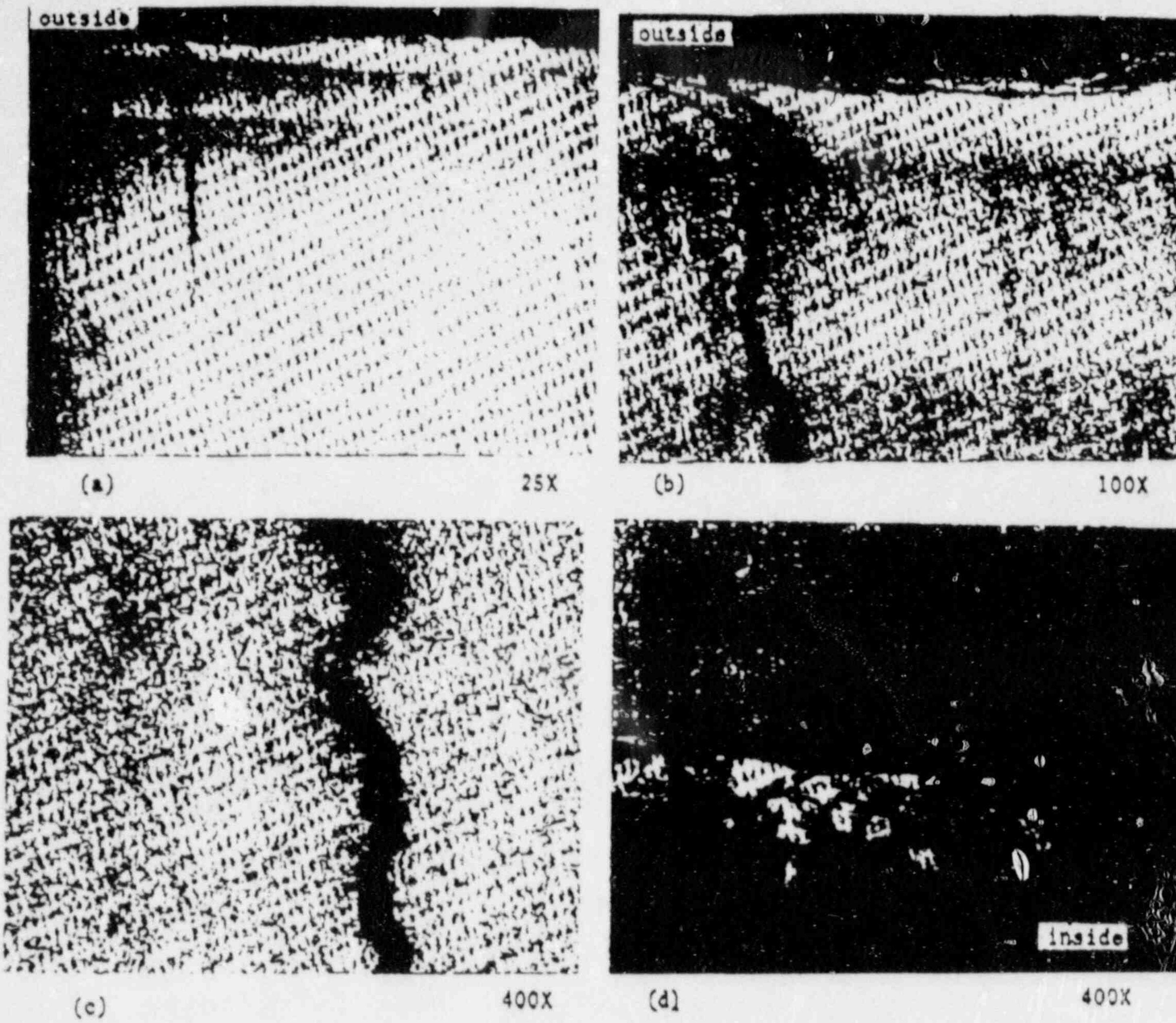


Figure 14 (a) A heat crack on the outside surface layer of the shaft center sleeve.
(b) & (c) Same as (a) except at higher magnifications
(d) Near the edge of the keyway of the shaft center sleeve showing foreign metal particles (arrows).

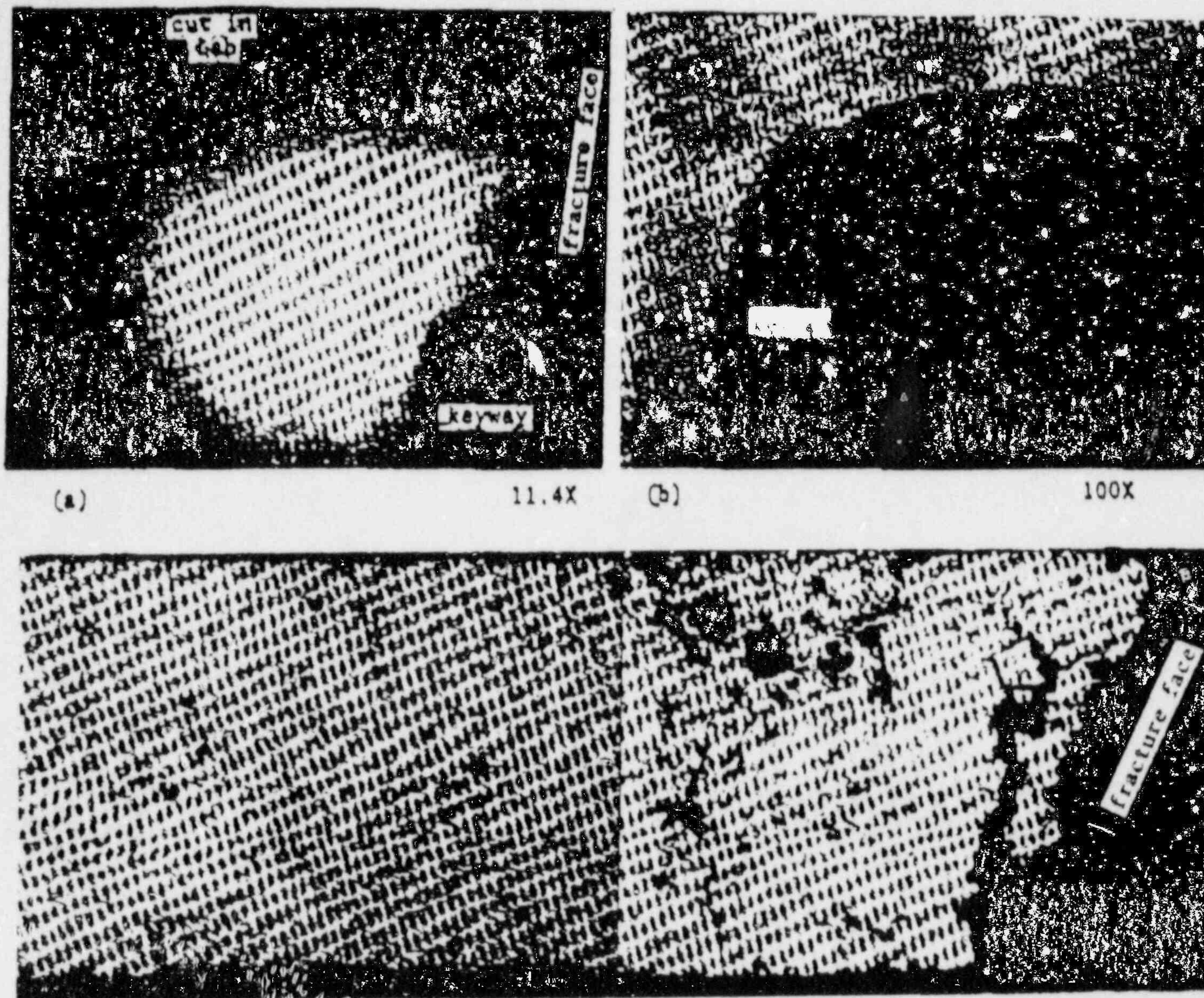


Figure 15 A cross section of the throttle sleeve at the location marked by the arrow in Figure 6. The arrow in (a) points to the fracture initiation with evidence of corrosion. (c) shows the area marked by the arrow in (a).