Attachment 3 to
AECM-84/0373

METALLURGICAL EVALUATION OF DIESEL GENERATOR CYLINDER HEAD VALVE SEAT CRACKS AT GRAND GULF NUCLEAR STATION - UNIT 1

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JUNE, 1984

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1.0 INTRODUCTION

Nuclear Plant Engineering (NPE) forwarded to Middle South Services (MSS) a ring section containing an exhaust valve seat from a cylinder head removed from the Division II standby Diesel Generator Division II. This specimen forwarded was known to have a crack in the stellite seating surface which had leaked jacket cooling water into the cylinder. This specimen had several other radial cracks on the stellite seating surface. NPE requested MSS to perform a metallurgical evaluation to:

- o determine the cause for cracks in the stellite seating surface; and
- o determine the cause for jacket water leak into the cylinder.

The Plant Quality department of Grand Gulf Nuclear Station Plant Staff had performed liquid penetrant (LP) examination of all the valve seating surfaces and determined this seating surface to be the leaking one.

2.0 LIQUID PENETRANT EXAMINATION

The specimen was examined using LP. The indications revealed are shown in Figure 1. A close up of the suspected leaker is shown in Figure 2 and Figure 3 shows multiple radial cracks on the seating surface.

The LP indications shows that the larger crack was about 90° away from the multiple cracks. A visual examination of the back side of the ring specimen, which was machined out of the cylinder head, showed a casting defect to be located behind the single large crack. Thus, it was decided to perform the following investigations:

- o fractography of fracture surface from the single crack and casting void -- determine mechanism for leak; and,
- o light and scanning electron microscopy of multiple cracks -- determine reason for cracking.

3.0 FRACTOGRAPHY

The single crack face was opened in the laboratory by cutting the ligament from the back side of the ring specimen. The fracture surface is shown in Figure 4. The following features were revealed:

- There were two casting defects (voids), one above the other on the back side of the seating surface.
- The stellite fracture surface was covered with black adherent oxide film. Also portions of the casting fracture surface was covered with this oxide film.
- There was a distinct difference in fracture surface appearance of the laboratory fracture surfaces at the bottom and top of the base material of the ring. The appearance at the top was indicative of a ductile weld material. This indicates that there was some weld repair performed in this region.
- The crack appears to have propagated from the stellite casting interface to the casting void by corrosion. The cause for corrosion is the exhaust combustion gases.

As mentioned earlier, it appeared that the cylinder head, in one area of this exhaust valve seat was repaired by welding. The need for weld repair may have been to fill the casting void such that an even surface for weld deposition of stellite was obtained. Though the weld repair achieved the objective of providing an even surface, the weld metal did not appear to have filled the entire void (See Figure 4). Furthermore, the casting void below this repaired void was untouched since it did not penetrate the exposed surface of the seat area. A section of this region was obtained using a diamond impregnated metallurgical saw. The section was used to perform metallography so as to confirm the existence of weld metal (from repair welding). The metallographic section is shown in Figure 5. Areas where microstructural evaluations were performed are also shown on this figure. No evidence of a soft butter weld between the cast steel and the stellite was observable. Figure 6 is a micrograph obtained in a area that shows the microstructure of the cast steel. The microstructure consists of a ferrite matrix with pearlite grains. Figure 7 is a micrograph obtained from an area on the top side of the stellite. The microstructure is accicular and representative of a weld material. Similarly, Figure 8, a micrograph obtained from an area below the stellite, shows a microstructure representative of a weld material. This finding confirms the existence of a weld repair, in the casting.

4.0 METALLOGRAPHIC EVALUATION

Metallographic examinations of cracks in the stellite were made in the region where multiple cracks were found. A section, parallel to the horizontal stellite surface, was made which would expose the cracks and its interface with the casting. After metallographic polishing and etching (etch to reveal casting microstructure) the specimen was examined. Figure 9 shows one such crack from the multiple set. The crack path is jagged. At the end of the crack, casting region, a pit is observed. Similar pits and crack paths were observed on all the cracks in this region. Figure 10 is a representative micrograph showing the crack in the stellite. The etchant (3% Nital) did not etch the stellite. The crack path suggests that the crack was formed due to shrinkage stresses of the stellite during cooling of the stellite weld deposit. Thus, the cracks were fabrication induced rather than service induced. Figure 11 shows a close up micrograph of the pit at the end of the crack. This pit is located in the cast material. The pit formation is due to corrosion from the hot exhaust gases (primarily oxides of nitrogen and sulphur) and not due to any fabrication practice. Also observable in Figure 11 is the intrusion of stellite (white slender lines) into the cast material. The interface between the stellite and cast steel, other than in regions where stellite cracks existed, was clean, and defect free. The bond was good.

In order to confirm the causal mechanism for the stellite cracks the specimen was re-etched[1] to reveal the microstructural features of stellite.

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[1]"Hard Surfacing Structures", WRC Publication, Welding Research Council, United Engineering Center, New York, New York 10017 (No Date).

Figure 12 shows the microstructure of the stellite. The microstructure shows that the material is a cobalt base, hard facing alloy deposited by a shielded arc process (SMAW).[2] The microstructure is austenitic with a carbide grain boundary network. Figure 13 is a micrograph showing both the crack and the microstructure. It can be seen from this micrograph that the crack runs along the grain boundary following the carbide network. From reference 2 it is observed that brittle hardfacing alloys when deposited by the SMAW process can crack and cross check during cooling to relieve the large strains in the stellite. This aspect is discussed in a later section. Thus, these cracks form in the regions where the material is still in the liquidus state. The carbide rich grain boundary is the last to solidify and hence these cracks form along the grain boundaries and are characterized as shrinkage cracks.

5.0 SCANNING ELECTRON MICROSCOPIC SEM EVALUATION

The etched stellite specimen was examined using a scanning electron microscope (SEM). The purpose of this examination was to determine the morphology of the cracks. Figure 14 shows the SEM micrographs at two magnifications. The grain boundaries are clearly visible as a raised network. At the higher magnification the cracks shows a tearing type behavior which confirms the causal mechanism to be one of shrinkage cracking. The edges of the cracks are sharp and show no sign of corrosion or errosion. The extensive cross checking of the crack is also visible.

6.0 CRACKING MECHANISM

The metallographic evidence clearly shows that the causal mechanism to be shrinkage cracking. When the coefficient of thermal expansion for the

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[2] "Welding Brazing and Soldering", Metals Handbook, Vol. 6, August, 1983, American Society of Metals, Metals Park, Ohio.

[3] "Steel Castings Handbook", 5th Edition, P. F. Wieser, Editor, Steel Founders' Society of America, Rocky River, Ohio, June, 1980.

underlying cast steel[3] and the stellite[2] are considered it can be shown that the cracks are indeed formed by shrinkage cracking.

The coefficient of thermal expansion are as follows:

Cast Steel -- 7.4×10^{-6} in/in - °F
Stellite -- 26.7×10^{-6} in/in - °F

This data shows that the ratio between cast steel and stellite is 1:4. Therefore the stellite would expand considerably more than the cast steel during welding. Conversely during cooling the stellite would shrink 4 times faster causing large strains to be developed. These shrinkage strains are accommodated by cracking along grain boundaries. The cracks may or may not expose themselves to the surface. Therefore when the stellite seat is machined some cracks may be exposed to the free surface and some still be subsurface and not detectable by LP techniques. However, it is not probable that these cracks are numerous such that a large area of grain boundary would be expected to be cracked. This is a valid supposition and is borne out by metallography which showed that a majority of the grain boundaries were not cracked.

The subsurface shrinkage cracks can open to the surface during service only during cooling. This implies, a logical extension considering the differential thermal contraction, that frequent starts and stop operation of the engine are more apt to open such cracks than is a continuous steady operation. Thus with the given mode of operation (i.e., Surveillance Testing), it is expected that pre-existing subsurface cracks would open to the seat surface and be detected in subsequent LP exams.

The adherence of stellite to the base metal (cast steel) is obtained from the austenite grains and not the carbide rich grain boundary. Reference 2 provides a good discussion on this subject and shows that the existence of such cracks are not detrimental to the intended performance. Also, it was observed that the cross sectional examination (Section 4.0) showed a good bond between the stellite and cast steel. Therefore the cracks in-it-self are not a sufficient condition for stellite failure.

7.0 JACKET WATER LEAK MECHANISM

As previously discussed, shrinkage cracks in the stellite:

- do not erode, corrode, or cause crack propagation into the cast steel; and,

- cannot cause separation of stellite from the cast steel.

However, it was also shown (Section 4.0) that corrosion pits existed at the tail end of the stellite cracks and that the fractography (Section 3.0) showed evidence of corrosion on the fracture surface of the cast steel on the leaking crack. Therefore, the mechanism that would lead to failure is by corrosion of the cast steel by the hot exhaust gases. Gases formed by combustion of the diesel fuel include; oxides of sulphur and nitrogen. These oxides and water vapor formed during combustion form respective acids which enter the stellite cracks and attack the underlying cast steel. Hence, the cracking mechanism that can cause failure is corrosion.

The observed maximum corrosion pit diameter (largest dimension) was 0.005 inches (Figure 2.0). Furthermore, NPE informed MSS that the engine had operated for about 700 hours (total) prior to removal of this head. Since the corrosion mechanism is a surface phenomenon it is reasonable to assume that the rate is proportional to the square root of the measured dimensions. Therefore it is feasible to conservatively estimate the operating time required to extend the corrosion pit to the design minimum of the cast steel wall.

The wall thickness (minimum) for this head was 0.400 inches (information obtained from NPE). Thus we have time required for leak to develop for a design minimum wall to be:

$$\text{Minimum Time to Propagate Through Wall} = 700 \times \sqrt{\frac{.400}{\text{measured diameter}}}$$

$$\text{Therefore: Minimum Operational Time} = 700 \times \sqrt{\frac{.400}{.005}} = 6,300 \text{ hours}$$

This implies that in presence of the stellite crack a conservative approach would be to devalue the design life of a cylinder head to 5000 hours of total operating life. This crude and very conservative calculation also shows that stellite cracks separated by 0.400 inches could be assumed to corrode the underlying cast steel and cause stellite failure. Hence a safe practice would be to ascertain that stellite cracks in the exhaust valve seats be at least separated by 0.5 inches. This extremely conservative approach would allow for assured uneventful operation of 5000 hours at the very minimum.

A soft butter weld layer between the stellite and cast steel would reduce the impact of differential thermal strain since this much softer material would be able to accommodate such strains. The currently manufactured heads by TDI do contain a stainless steel butter which would alleviate extensive stellite shrinkage cracking situations. However, by no means is it expected that this would enable producing a shrinkage crack free seating surface. An austenitic weld butter would, however, prevent the exhaust gases from corroding the cast steel; since the cast steel, in the crevice region of the crack, is not exposed to the corrosive exhaust gases.

8.0 CONCLUSIONS

- Cracks in the stellite are created by shrinkage stresses due to differential thermal contraction between the stellite and cast steel.

- Subsurface cracks in the stellite, which formed during the fabrication, can open to the surface due to the start-stop mode of operation required for these engines (thermal cycling).

- Shrinkage cracks in the stellite are not detrimental to the intended service of these engines.

- A very conservative approach, that would assure safe uneventful operation of the engine for up to 5000 hours (total operation), is to ascertain that shrinkage cracks in the stellite are at least separated by 0.5 inches.

- The stellite in the cracked region does neither corrode nor erode. Hence widening of these cracks is not possible. In addition, since the valves themselves spin, to some extent, during operation it is highly unlikely that the presence of such stellite cracks would do any damage to valve seating surface.

- The large number of thermal cycles experienced by the engine and its components (including cylinder head) by virtue of the required testing would tend to open up subsurface shrinkage cracks in the stellite. Thus, subsequent LP inspections following a baseline may reveal additional cracks in the stellite. The presence of such cracks during subsequent inspections should not be construed as "cracks initiated and propagated during service".

9.0 REFERENCES

1. "Hard Surfacing Structures", WRC Publication, Welding Research Council, United Engineering Center, New York, New York 10017. (No Date).

2. "Welding Brazing and Soldering", Metals Handbook, Volume 6, August, 1983, American Society of Metals, Metals Park, Ohio.

3. "Steel Castings Handbook", Fifth Edition, Wieser, P. F., Editor, Steel Founders' Society of America, Rocky River, Ohio, June, 1980.

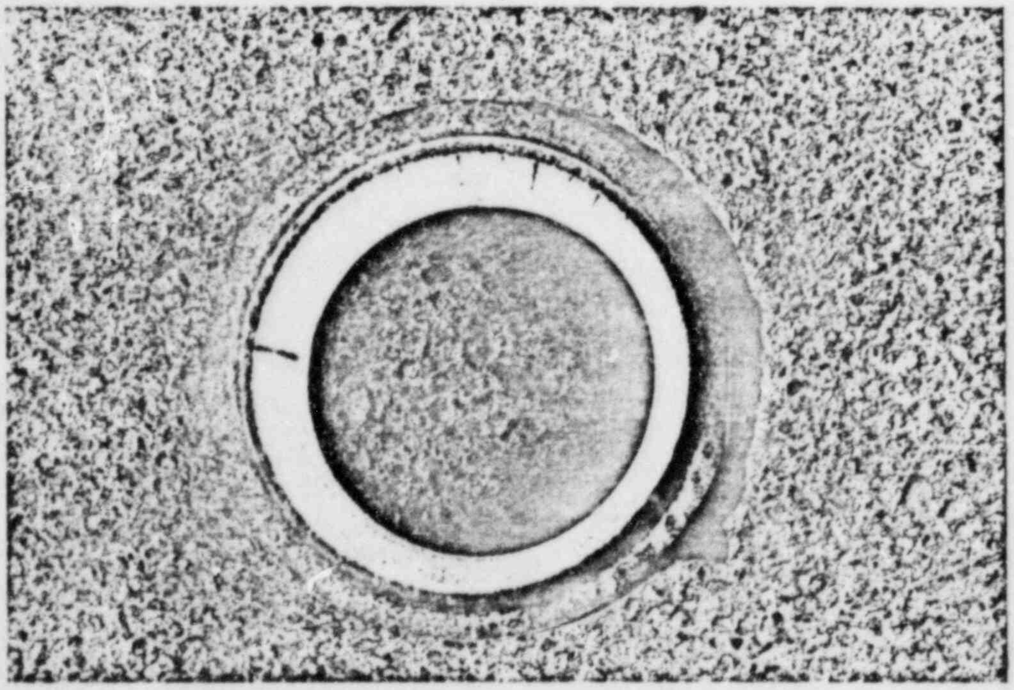


FIGURE 1: Liquid Penetrant Indications on Valve Seat

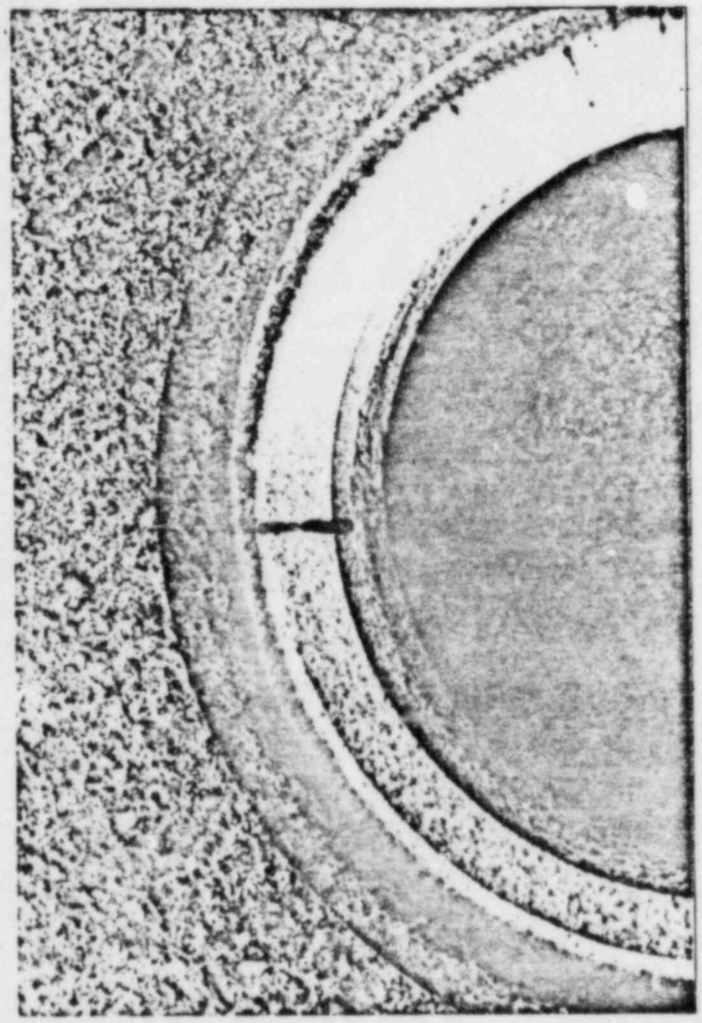


FIGURE 2: Liquid Penetrant Indication of Suspected Leaker

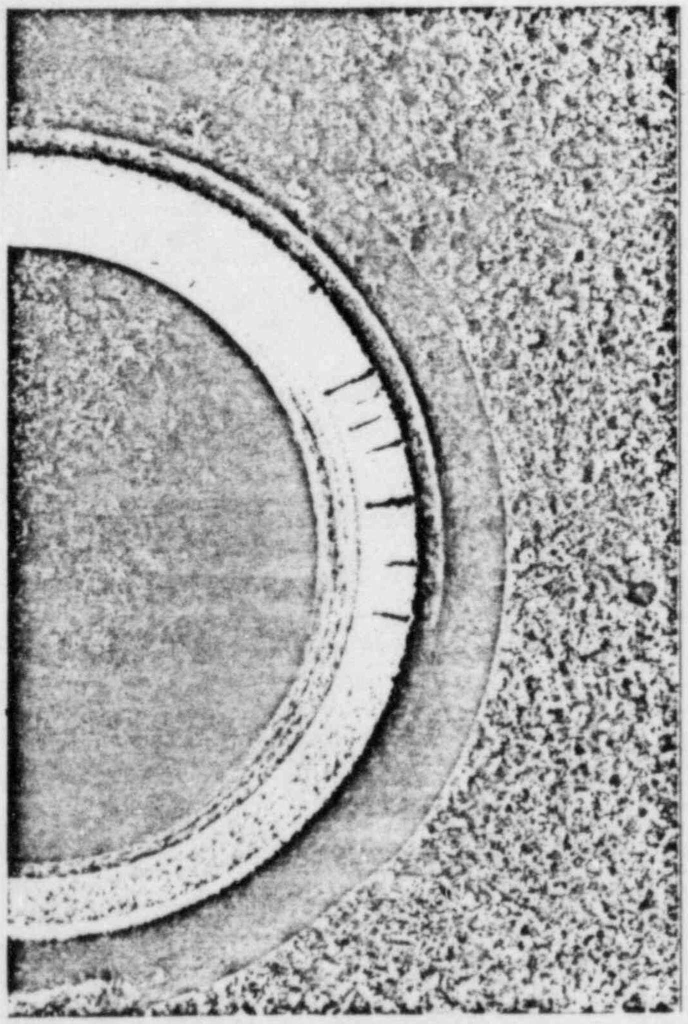


FIGURE 3: Liquid Penetrant Indications of Numerous Stellite Cracks

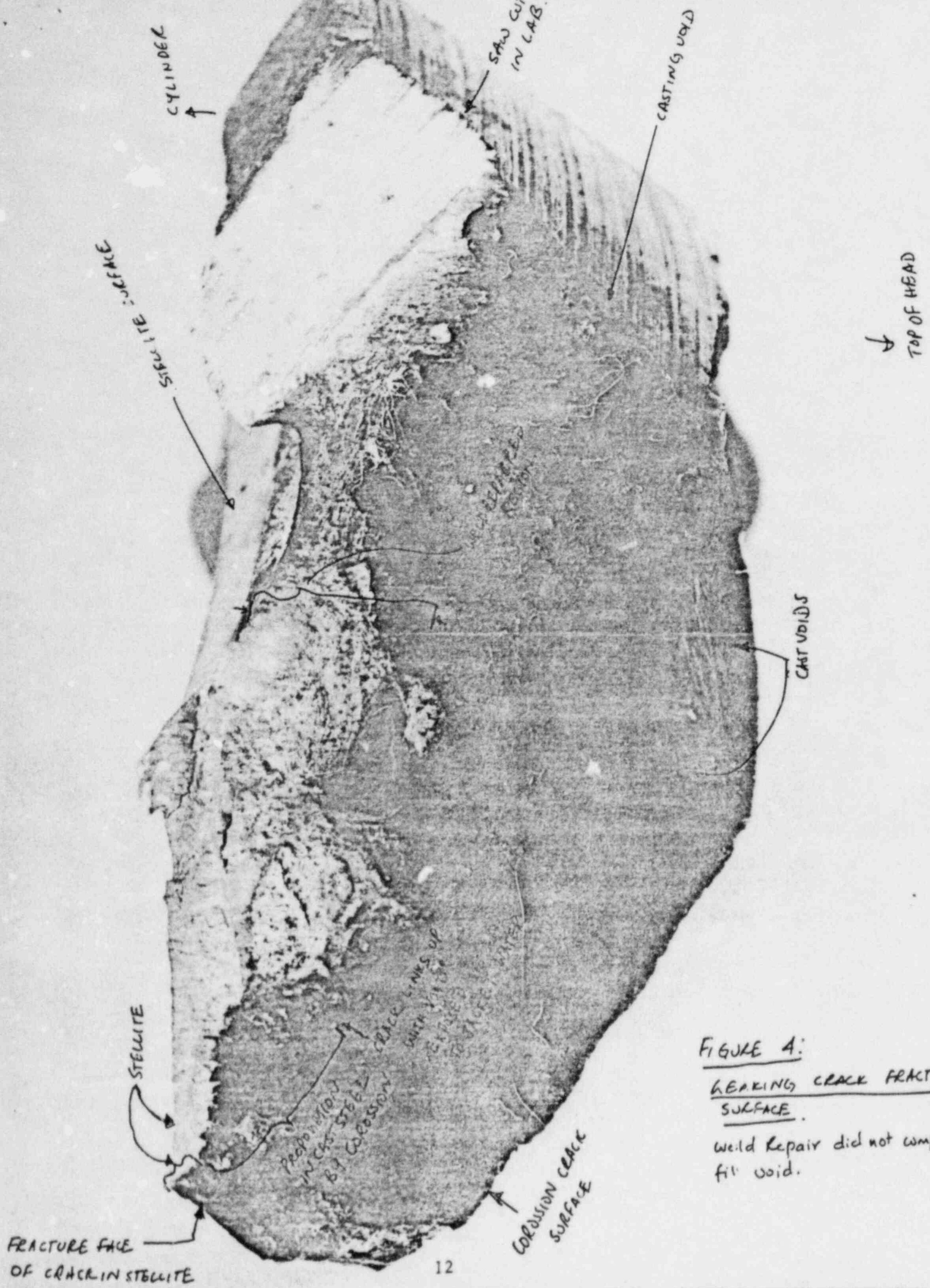


FIGURE 4: LEAKING CRACK FRACTURE SURFACE.

Weld Repair did not completely fill void.

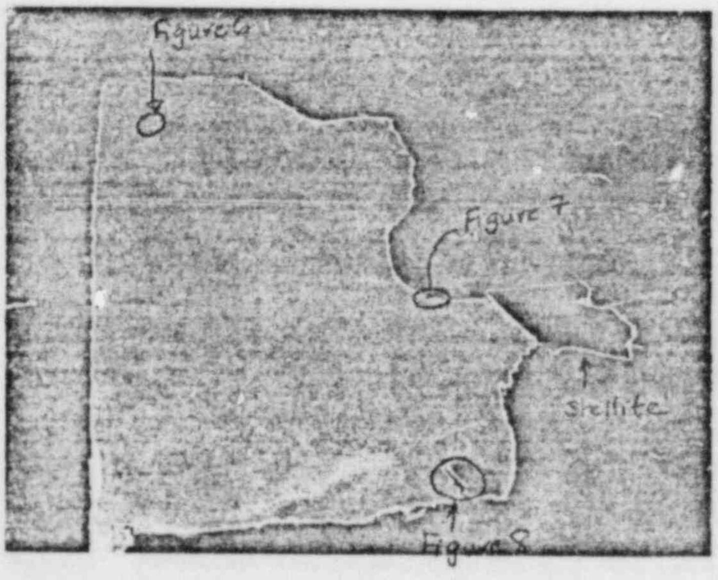


FIGURE 5: Cross Section of Valve Seat Surface

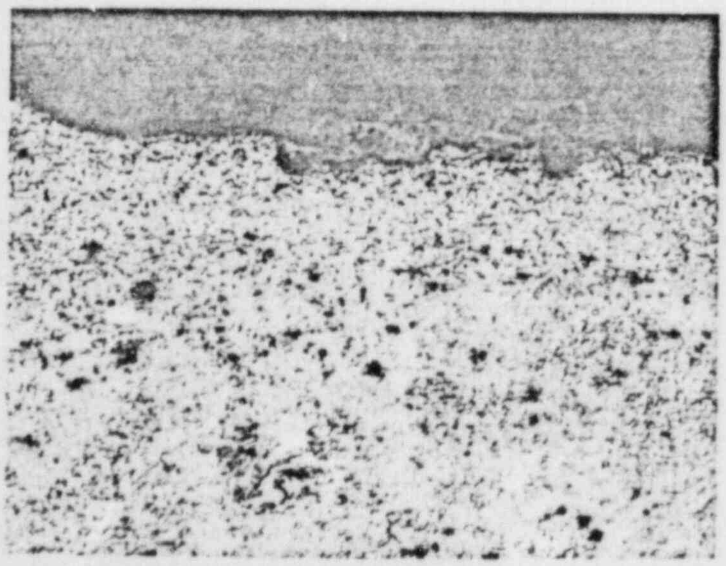
Section taken adjacent to the leaking crack.

Etchant: 3% Nital

Magnification: 100x

FIGURE 6: Microstructure of Cast Steel

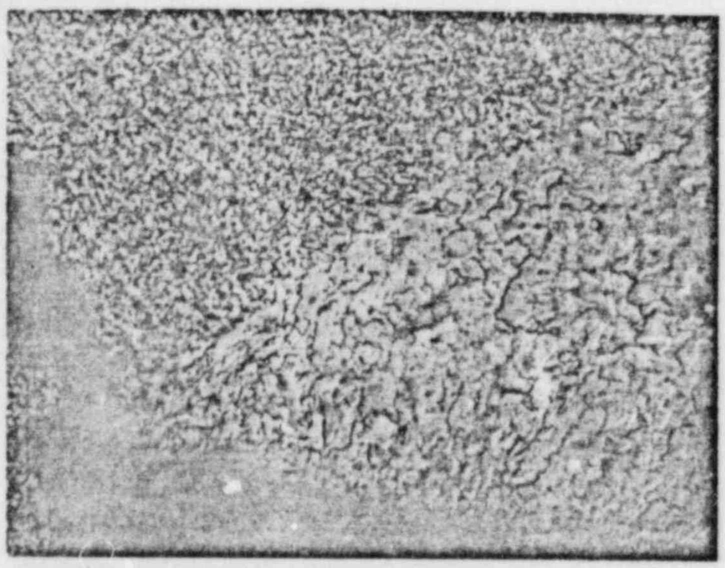
Ferrite matrix with pearlite grains. Grains at surface are coarser than the interior, as is to be expected.



Etchant: 3% Nital Magnification: 100x

FIGURE 7: Microstructure Behind Stellite Top Surface

Microstructure typical of a weld.



Etchant: 3% Nital

Magnification: 100x

FIGURE 8: Microstructure Behi i Stellite Bottom Surface

Microstructure typical of weld metal.

Magnification: 100x

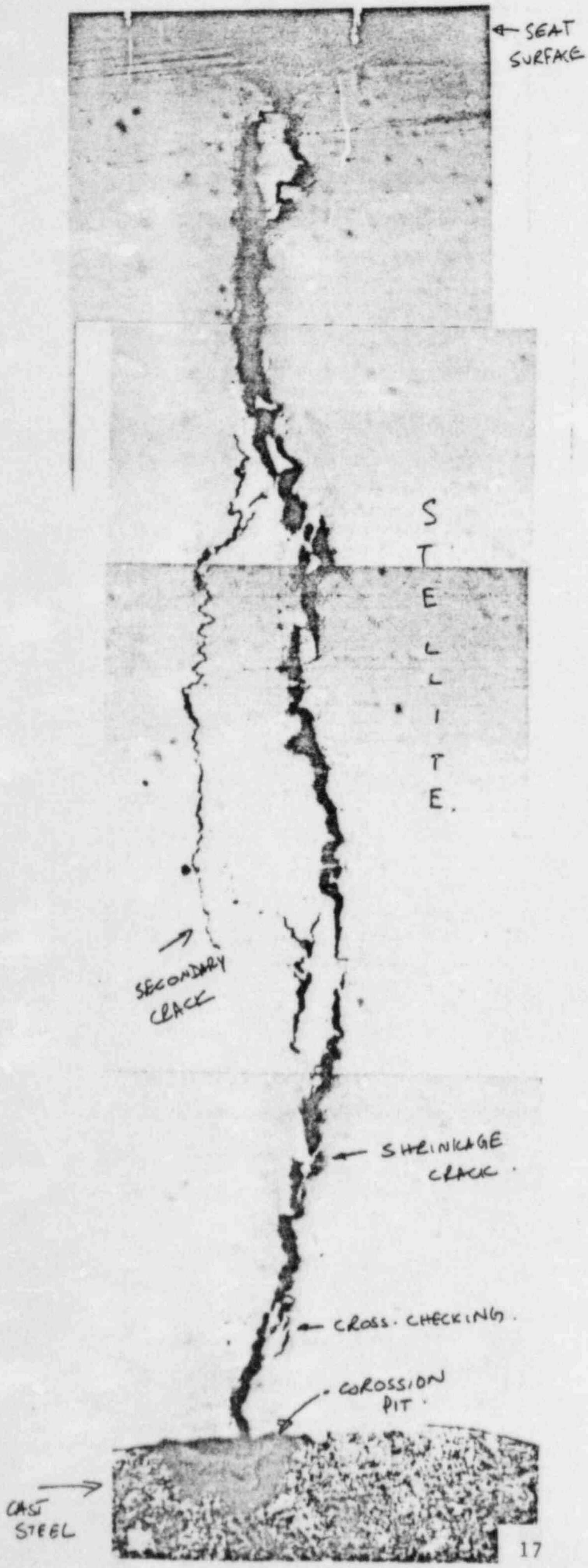
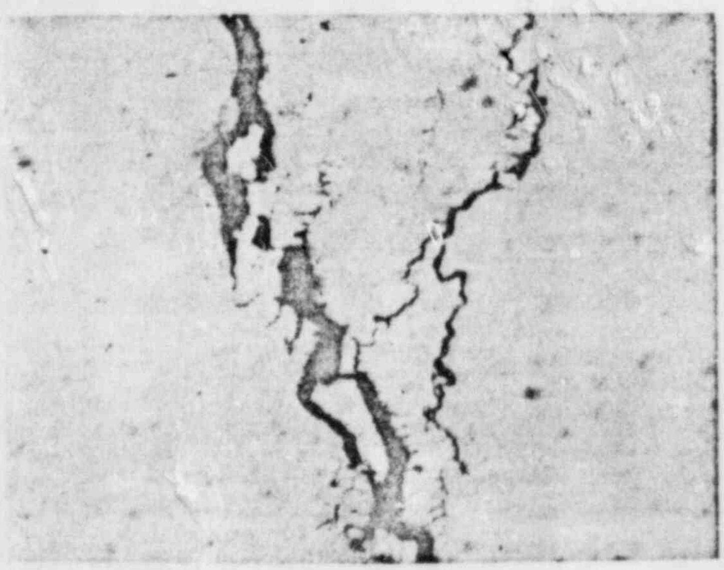


FIGURE 9: Montage - Shrinkage Crack in Stellite

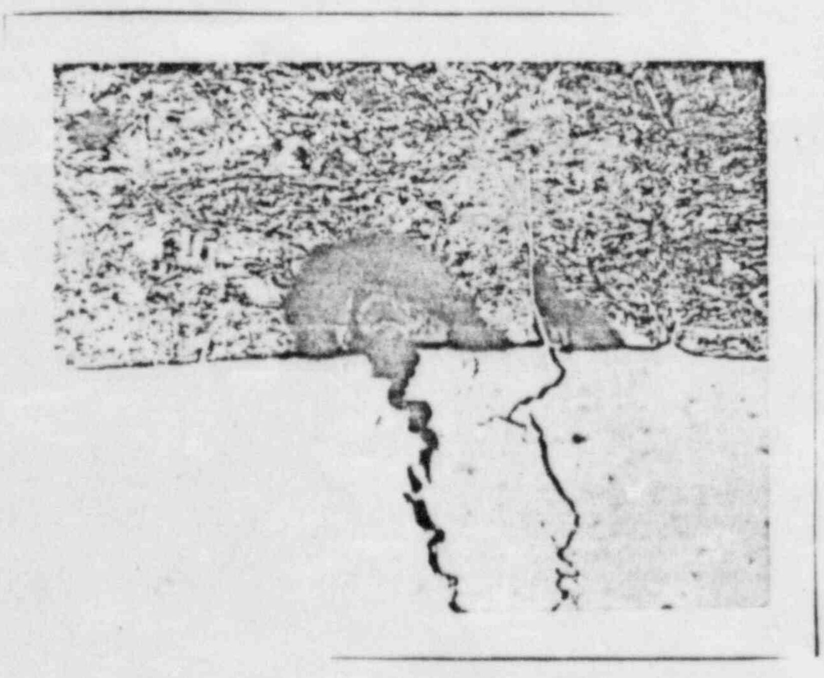
A typical crack in stellite. Jagged path and secondary cracks.



Etchant: 3% Nital

Magnification: 200x

FIGURE 10: Details of Shrinkage Crack

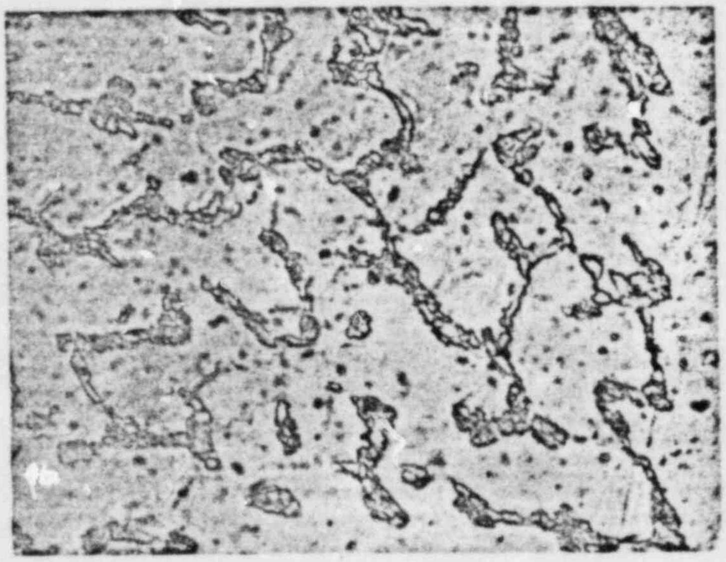


Etchant: 3% Nital

Magnification: 200x

FIGURE 11: Micrograph Near Stellite Cast Steel Interface

Corrosion pit at the end of shrinkage crack.
Evidence of stellite intrusion into cast steel.
Fusion line between stellite and cast steel
in regions other than cracks and pits is good.



Magnification: 400x

Magnification: 800x

Etchant
Per reference 1

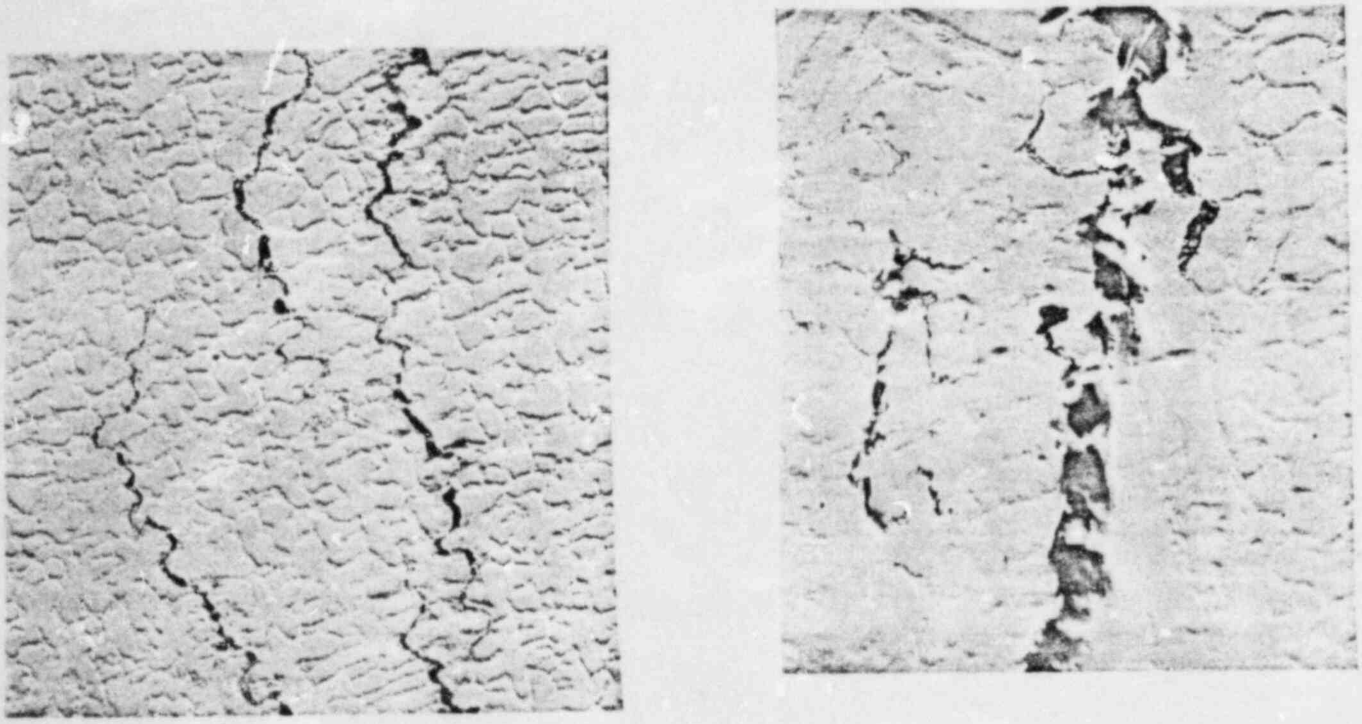
FIGURE 12: Microstructure of Stellite

Shows carbide network at grain boundaries.

Etchant: Per Reference 1 Magnification: 200x

FIGURE 13: Crack in Stellite and Microstructure

Crack is clearly in carbide network at Grain Boundaries.



Magnification: 400x

Magnification: 600x

FIGURE 14: SEM Metallograph of Stellite Crack

Metallograph taken after etching per reference 1. Grain boundary cracks and extensive cross-checking in cracks are evident.