SUMMARY REPORT

on

A METALLOGRAPHIC INVESTIGATION OF A TYPE 304 STAINLESS STEEL SCHEDULE 80 PIPE

to

POWER AUTHORITY OF THE STATE OF NEW YORK
JAMES A. FITZPATRICK NUCLEAR POWER PLANT

March 25, 1982

by

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March 25, 1982

Mr. A. V. Sorentino
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Dear Mr. Sorentino:

Enclosed are ten copies of our summary report entitled "A Metallographic Investigation of a Type 304 Stainless Steel Schedule 80 Pipe". This report describes the details of our investigation as proposed in our letters of December 18 and December 30, 1981, and the results obtained.

Briefly, the results of the investigation indicated that one of numerous linear defects observed on the inside surface of the subject pipe was the site of a fabrication-induced surface flaw. Although this defect apparently was not the indication believed to have been detected by the Power Authority of the State of New York using an ultrasonic nondestructive-detection technique, it was adjacent to it. The surface flaw appeared to be a lap or fold that probably occurred during the piercing or other operation in the process of producing the seamless pipe. However, the surface flaw apparently was a major contributor to the initiation of an intergranular stress-corrosion crack that propagated from the base of the flaw through about 77 percent of the thickness of the pipe wall.

During our meeting with the Messers. John Boardman and David Sancic on February 18, we discussed the need for additional investigative work concerning the linear defects and cracking. In particular, other linear defects located away from the weld should be examined.

We have enjoyed performing the subject metallographic investigation, and we look forward to a continuation of the investigation. If you have any questions concerning our work or the results obtained, please feel free to contact me.

Very truly yours,

R. D. Buchheit

R. D. Buchheit

RDB:rw

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A METALLOGRAPHIC INVESTIGATION OF A TYPE 304 STAINLESS STEEL SCHEDULE 80 PIPE

by

R. D. Buchheit

INTRODUCTION

A part of the core-spray system for a boiling-water reactor at the James A. Fitzpatrick Nuclear Power Plant of the Power Authority of the State of New York (PASNY) was constructed of 12-inch-diameter Type 304 stainless steel Schedule 80 seamless pipe. The core-spray system, which contained stagnant water at a temperature of about 545 F and a pressure of 1005 psig, was placed in service in July, 1975.

After approximately 6 years of service that included intermittent pipe inspections, an inspection of the pipe by nondestructive ultrasonic-inspection techniques detected the presence of a linear defect of unknown type. The linear ultrasonic indication was located on the inside surface of a straight section of the pipe adjacent to a circumferential weld that joined the straight pipe section to an elbow section. The indication was reported to be about 1-3/8 inches long, in close proximity and oriented perpendicular to the weld (i.e., parallel to the longitudinal axis of the pipe). From the nature of the indication, the defect probably had not penetrated the weld metal.

The PASNY was concerned about the nature of the defect that was detected ultrasonically. In particular, if the defect were a crack, it was important to know whether or not the crack exhibited characteristics common to stress-corrosion cracking (SCC). Consequently, PASNY requested that Battelle's Columbus Laboratories (BCL) conduct a metallographic investigation to identify, insofar as possible within the limits of the study, the nature of the linear surface defect that had been detected ultrasonically. The procedure used and results of the investigation conducted by BCL are described in this report.

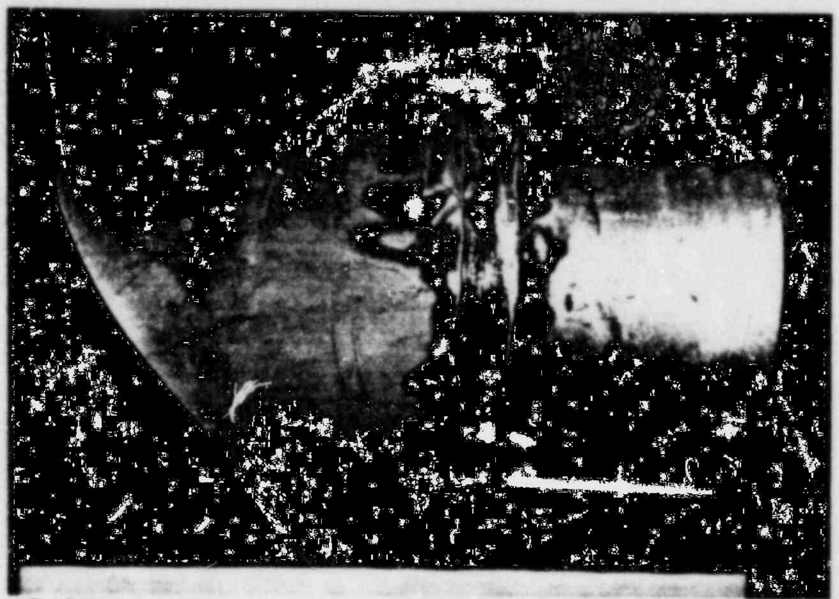
SUMMARY

Macroscopic examination of the inside surface of a 12-inch-diameter Type 304 stainless steel seamless pipe revealed the presence of numerous linear defects in addition to one that was detected by PASNY using nondestructive ultrasonic-inspection techniques. A cross section through one of the linear defects that was located close to a weld was examined metallographically. The results of the examination indicated that the linear defect was most likely a fabrication-induced surface flaw that resembled a lap or seam. The surface flaw apparently acted as a stress raiser and in the presence of a corrosive environment (the water contained in the pipe), and under the influences of hoop stresses induced by the internal pressure and possibly residual stresses in the hoop direction, it led to the initiation and propagation of an intergranular stress corrosion crack through a sensitized region in the weld heat-affected zone.

PROCEDURE

The photograph in Figure 1 shows a portion of the Type 304 stainless steel pipe that contained the linear indication detected by PASNY, that was submitted to BCL for the investigation. That portion of the pipe was approximately 15 inches long; it included about 7 inches of the straight-pipe section and about 7 inches of the elbow section that were joined together by the circumferential weld.

Figure 1 shows the welded pipe sections after decontamination treatments were performed at BCL. Due to the high level of radiation from the surfaces of the welded pipe section upon receipt at BCL, the pipe section was decontaminated by immersion for 1 to 2 hours at 200 F in a solution that consisted of 100 g of sodium hydroxide and 30 g of potassium permanganate dissolved in 1000 cc of water, followed by immersion for 1 to 2 hours at 200 F in a solution that consisted of 100 g of ammonium citrate dissolved in 100 cc of water. After the two immersion treatments, the pipe section was rinsed in water and dried in air. This entire procedure was repeated several times until the radiation level was reduced to about 4 mR/hr on



~1/4X C9643

FIGURE 1. PORTION OF THE TYPE 304 STAINLESS STEEL PIPE FROM THE REACTOR CORE-SPRAY SYSTEM THAT CONTAINED THE LINEAR INDICATION DETECTED ULTRASONICALLY

contact. That level of radiation permitted the entire metallographic investigation to be performed using "cold" metallographic-laboratory facilities.

Subsequent to decontamination , three different regions that contained defects were visible to the unaided eye on the inside surface of the straight-pipe section. A dye-penetrant inspection of the inside surface did not produce any indications of linear defects that were not observed visually. One of the regions of the inside surface that contained the linear defects and the linear indication obtained ultrasonically by PASNY was removed from the welded pipe section by sectioning and was examined metallographically.

EXAMINATIONS AND RESULTS

Macroscopic Examinations

The photograph in Figure 2 reveals two regions on the inside surface of the pipe that contained linear surface defects. The defects are only faintly visible in Figure 2; a few of the defects are denoted by small arrows. Note that the two regions were essentially aligned parallel to each other, but were oriented at a small angle to the axial direction.

FIGURE 2. TWO REGIONS THAT CONTAINED LINEAR DEFECTS ON THE INSIDE SURFACE OF THE PIPE

The region of the inside pipe surface that was subjected to metallographic examinations was located about 180 degrees from the portion of the surface shown in Figure 2. A photograph of that surface is shown in Figure 3. Linear defects were observed at the locations of the unlabeled

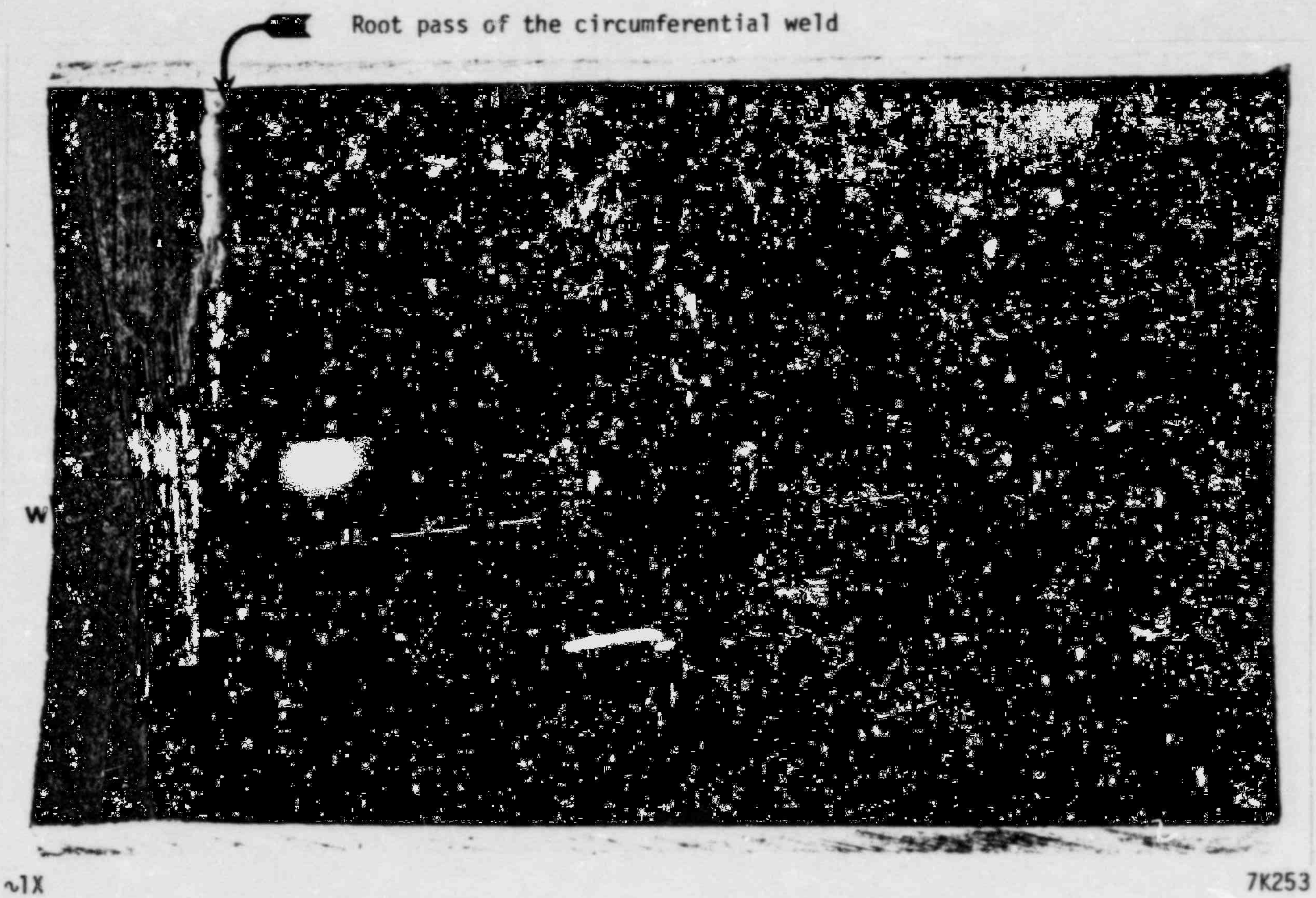


FIGURE 3. LINEAR DEFECTS OBSERVED ON THE INSIDE SURFACE OF THE STRAIGHT-PIPE SECTION

The arrows identify the linear defects.

arrows and, also at the locations of Arrows 1 and 2 in Figure 3. Approximately 20 separate surface defects were visible at magnifications up to 30X. Three of those linear surface defects were very close to the root pass of the weld. The general orientations of the defects were not axial; they were oriented at an angle of about 10 degrees to the axial direction. This orientation was essentially parallel to the defects in the two regions in Figure 2. Associated with the linear defects, other surface imperfections that appeared to be evidence of thin slivers of surface metal that had been removed or lost were observed at the three locations denoted H in Figure 3. At the location of Arrow E, there appeared to be a thin sliver of surface metal that had been lifted, but not removed, from the surface, The slivers appeared to have resulted from mechanical deformation of surface metal in the direction from the bottom toward the top in Figure 3. At a magnification of 30X the more prominent linear defects also appeared to have been formed by deformation of surface metal in the same direction, i.e., those linear defects had the appearance of surface folds or laps. A minority of the linear defects were tight, hairline indications; macroscopic examination suggested that they were cracks.

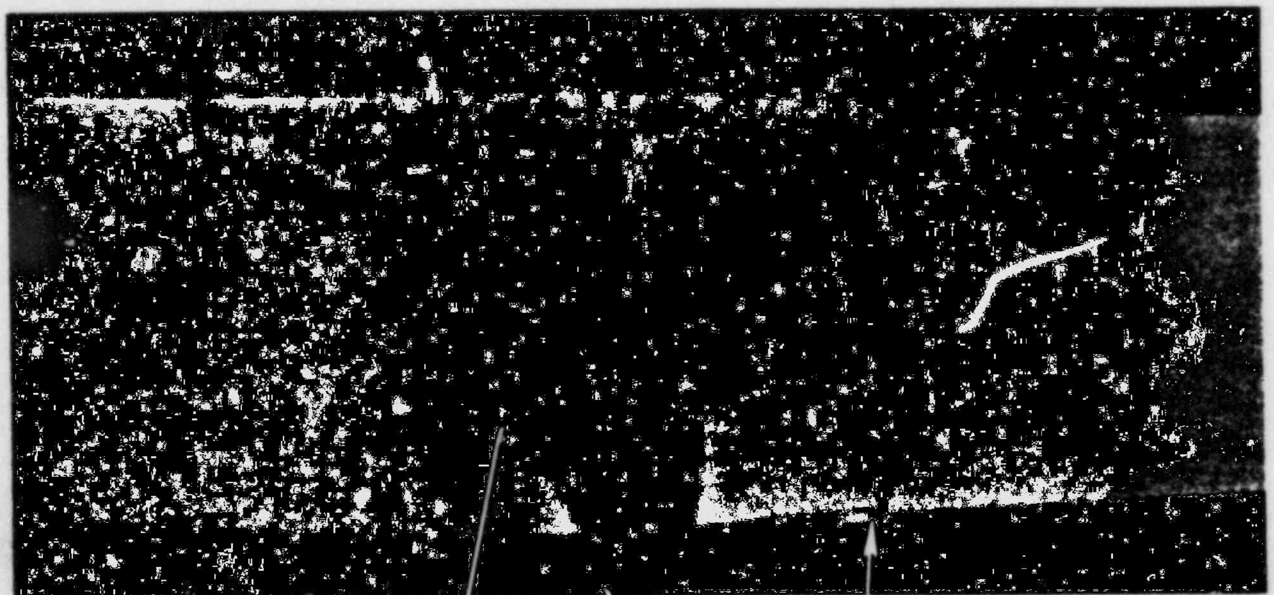
The length of the linear defects that were observed varied from about 0.06 to about 1.56 inches. The linear defect at the location of Arrow 2 in Figure 3 was about 1.37 inches long. That defect apparently corresponded in location and length to the indication that was obtained during the ultrasonic, nondestructive inspection by PASNY.

Figure 3 also reveals evidence that the region of the inside surface of the pipe that contained the linear defects had been ground mechanically or abraded. The abraded area covered part of the root pass of the weld and extended for about 4 inches from the weld. With proper illumination on the abraded surface, the surface appeared to have been abraded slightly deeper along the linear defect located at Arrow 2 than over the remainder of the surface in the abraded region. That appearance is barely discernible in Figure 3 because of problems in illuminating the specimen so as to reveal all of the features in one photograph. This observation suggests that a purposeful attempt was made at some time after welding to remove observed surface imperfections, particularly the linear defect that probably was detected later ultrasonically and marked by Arrow 2 in Figure 3.

Examination of the Weld

A metallographic cross section of the weld, Section W-W in Figure 3, was prepared for microscopic examination to determine if the weld heat-affected zone in the straight-pipe section had been sensitized. The cross section was located about 1/4 inch from the linear defect identified by Arrow 1 in Figure 3. The specific objective in examining the weld cross section was to determine the approximate location of a sensitized zone, if one were present, so that the location of the zone could be translated to the linear defect of Arrow 1 and a cross section of that defect could be made within the sensitized zone.

A photomacrograph of the cross section of the weld is presented in Figure 4. The root pass of the weld identifies the inside surface of the pipe. Microscopic examination revealed that sensitized material was present principally in the straight section in the heat-affected zone that was adjacent to the root pass. The degree of sensitization appeared to be



4X Etched 7K252

FIGURE 4. CIRCUMFERENTIAL WELD BETWEEN THE ELBOW SECTION (LEFT) AND THE STRAIGHT SECTION (RIGHT) OF THE TYPE 304 STAINLESS STEEL SCHEDULE 80 PIPE

The cross section is identified as Section W-W in Figure 3.

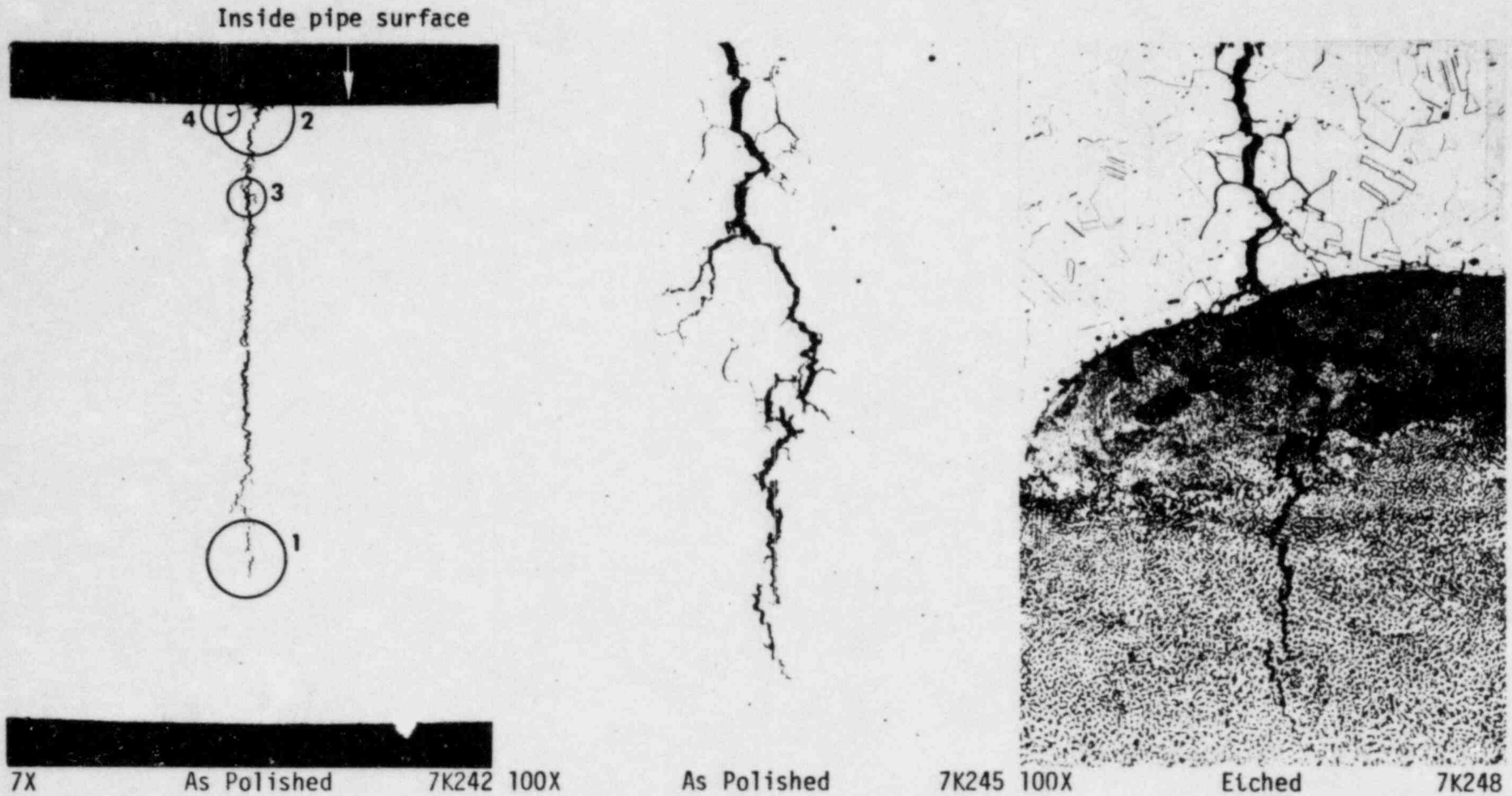
mild based on the apparent size and concentration of the carbide precipitates in the austenite grain boundaries. The sensitization appeared to become considerably less severe towards the outside pipe surface. At the inside surface, the midregion of the sensitized zone was at the approximate location of the arrow in Figure 4. That location was translated to Section S-S (shown in Figure 3) across the linear defect marked by Arrow 1.

Examination of a Linear Defect

A cross section at Section S-S of the linear defect marked by Arrow 1 in Figure 3 was prepared metallographically for microscopic examinations. Section S-S was located about 0.19 inch from the visible end of the defect closest to the weld. As was noted above, that cross section with respect to the weld corresponded to the approximate location of the arrow in Figure 4. At that location, the cross section intersected the top passes of the weld in the outside surface of the pipe.

The metallographic cross section of the linear defect is shown in the as-polished condition in Figure 5a. The cross section revealed the presence of a crack that was perpendicular to the surface of the pipe. The crack extended from a location about 0.010 inch below the inside pipe surface for a distance through the pipe wall of about 0.41 inch. The wall thickness of the pipe at that cross section was about 0.53 inch; thus, the crack extended through approximately 77 percent of the pipe wall. As is shown in Figure 5c, the crack propagated into weld metal for a distance of about 0.027 inch and then terminated. In the weld heat-affected zone, crack propagation occurred entirely along the boundaries of equiaxed austenite grains; in the fusion zone, the crack continued to propagate along the austenite grain boundaries of the weld metal. Intergranular branching cracks were numerous along the entire length of the crack, although fewer branching cracks were observed within the weld metal. It appeared as though crack propagation may have been arrested by the weld metal.

The as-polished appearance of the linear defect in the inside surface of the pipe in this cross section is shown in Figure 6, which is Circled Area 2 in Figure 5a at a higher magnification. The surface defect

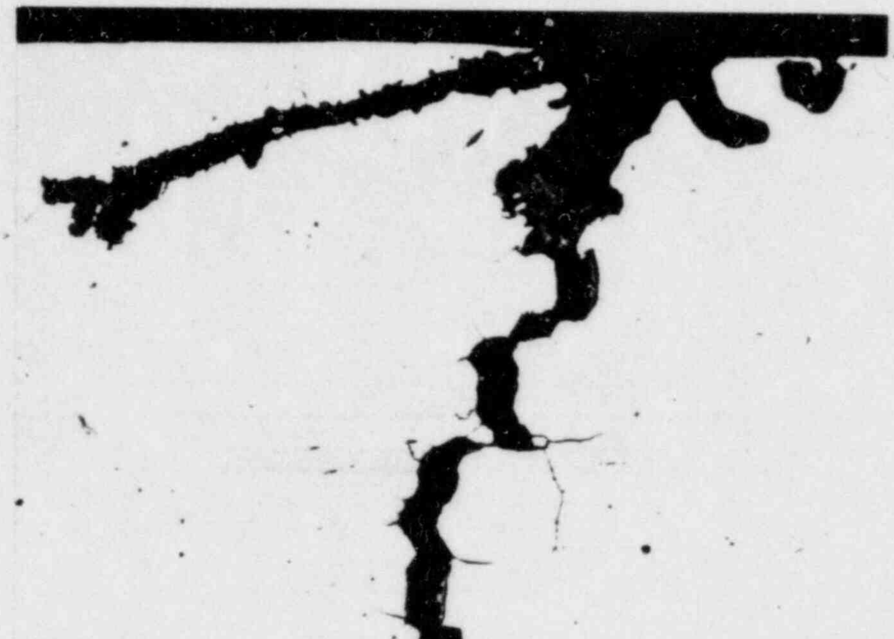


a. Crack in the Pipe Wall

b. Circled Area 1 in (a) at a Higher Magnification

c. Same Field as (b) After Etching Electrolytically in 10% Oxalic Acid

FIGURE 5. CRACK OBSERVED IN THE CROSS SECTION THROUGH THE LINEAR SURFACE DEFECT MARKED BY ARROW 1 IN FIGURE 3



100X As Polished 7K243

FIGURE 6. CROSS SECTION OF THE LINEAR DEFECT WITHIN CIRCLED AREA 2 IN FIGURE 5a

at which the crack initiated seemed to extend to a depth of about 0.010 inch below the surface and did not appear to be an intergranular crack. Rather than exhibiting characteristics of an intergranular crack, the defect exhibited characteristics similar to those generally observed for seams or laps in billet surfaces. For example, an apparent overlap, or fold, of surface metal that contained what appears to be oxide at the interface is evident in Figure 6 to the left of the part that showed on the pipe surface. The start of intergranular cracking was apparent only at a depth of about 0.010 inch (the depth of the lap and associated pit) below the surface.

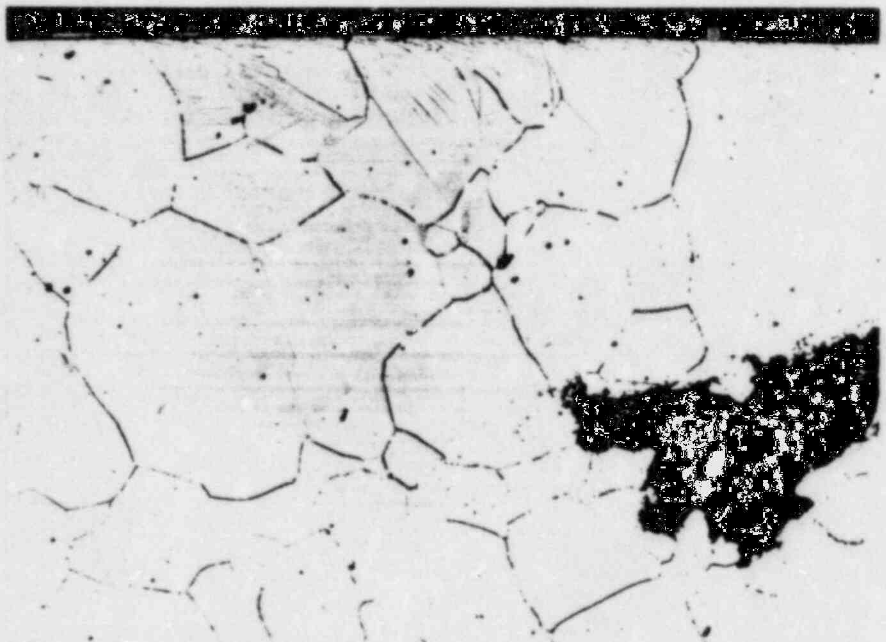
A typical region of the intergranular crack is shown in Figure 7. That region is within Circled Area 3 in Figure 5a. A dense nonmetallic corrosion product that can be seen in Figure 7 was observed on the principal crack surfaces and in adjacent grain boundaries where crack branching

250X As Polished 7K246

FIGURE 7. TYPICAL REGION OF THE INTERGRANULAR CRACK THAT WAS LOCATED WITHIN CIRCLED AREA 3 IN FIGURE 5a

occurred. The crack was nearly filled with the corrosion product near, and at the tip (see Figure 5b).

Sensitization was revealed in the cross section through the defect by electrolytic etching using an electrolyte that consisted of 10 percent by weight of oxalic acid in water. (This is an etch commonly used to reveal a sensitized microstructure in stainless steels.) Evidence of sensitization, the presence of fine carbide precipitates in the austenite grain boundaries, is presented in Figure 8. The area shown in Figure 8 was located within Circled Area 4 in Figure 5a. The presence of sensitized material was



250X Electrolytic Oxalic Acid Etch 7K247

FIGURE 8. SENSITIZATION (CARBIDE PRECIPITATE IN THE GRAIN BOUNDARIES) OBSERVED IN THE REGION OF THE LINEAR SURFACE DEFECT

Circled Area 4 in Figure 5a.

revealed clearly by the etch to a depth of about 0.20 inch below the inside surface of the pipe. Beyond that depth, evidence of sensitization was observed in random grain boundaries.

Figure 8 also shows evidence of some cold working of the metal at the inside pipe surface. Strain lines and deformation that indicated cold working can be seen faintly in Figure 8 in grains at the pipe surface. The cold-worked surface metal was most likely a result of the mechanical surface grinding or abrasion that was evident.

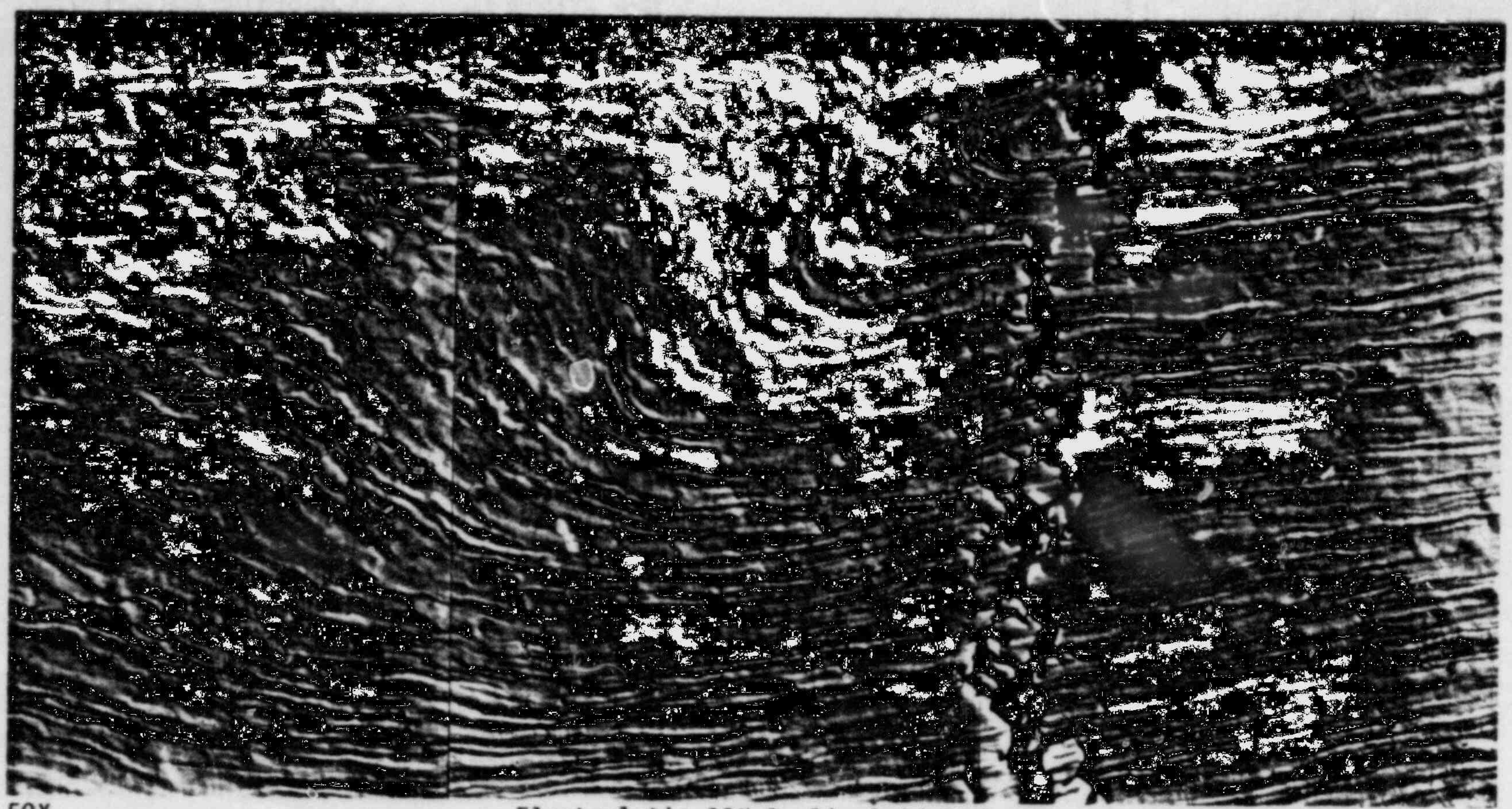
In addition to the sensitizied region, the cold-worked surface metal, and the intergranular cracking that was revealed in the micro-structure by etching, the etched microstructure also revealed a flow pattern of the metal that developed during the fabrication of the pipe. The flow pattern was manifested by coring in the microstructure that had persisted through all of the fabrication steps during the production of the seamless pipe from the ingot. Coring is interdendritic solid-solution alloy segregation that originates during the solidification of the ingot. In essence, coring is chemical inhomogenity in the material that affects the rate of attack by etching reagents. The rate of attack of some reagents might be affected more than that of other reagents. The coring in the subject pipe had a significant effect on the rate of attack of the electrolytic oxalic acid etchant that was used to reveal sensitized material. The coring that was revealed by the etchant in the cross section of the linear surface defect is exhibited in Figure 9 as wavy striations or bands. The striations, which were actually alternate ridges and grooves in the etched surface, were enhanced for photography by the use of Nomarski interference-contrast microscopy.

The coring pattern in Figure 9 shows that an interruption of the normal flow of metal occurred around the linear defect in the surface of the pipe during fabrication. The flow pattern around the linear defect was similar to that sometimes observed around seams or laps in billet surfaces. However, inasmuch as the linear defect was on the inside surface of seamless pipe, the origin of the linear defect must have been associated with the piercing or other operation in the process of producing the seamless pipe.

Note in Figure 9 that the cored regions were independent of the grains and the grain boundaries and that the coring had no noticeable effect on the initiation or propagation of the crack.

DISCUSSION

The metallographic investigation revealed the presence of a significant number of linear defects on the inside surface of the pipe, in addition to the linear defect that was detected by PASNY using a nondestructive ultrasonic inspection technique. The linear defect chosen for metallographic examination in cross section was probably not the exact indication that was obtained ultrasonically, but was adjacent to it. The results of the examination of the selected defect indicated that, at the inside pipe



50X Electrolytic 10% Oxalic Acid Etch 7K254

FIGURE 9. CORING THAT REVEALS THE FLOW PATTERN OF METAL AROUND THE LINEAR SURFACE DEFECT

The photomicrograph was taken using Nomarski interference-contrast microscopy to enhance the cored structure.

surface, there was a surface flaw probably introduced during the piercing or other operation in the production of the seamless pipe. The presence of slivers associated with other linear surface defects and the macroscopic appearance of most of the linear defects observed suggest that all of the linear defects were fabrication-induced surface flaws that were similar to laps or seams.

The crack that was associated with the surface flaw that was examined possessed characteristics usually associated with intergranular stress-corrosion cracking (IGSCC). The factors that led to the initiation and propagation of IGSCC apparently were (1) the presence of the surface flaw that acted as a stress raiser, (2) the presence of a sensitized microstructure in the weld heat-affected zone, (3) the corrosive environment, that is, the water contained in the core-spray system of the reactor, (4) the hoop tensile stress in the pipe wall as a result of the internal pressure, and (5) possibly residual stresses in the hoop direction. In the absence of either the surface flaw or the sensitized microstructure that increases the susceptibility of stainless steel to IGSCC and to localized corrosion, it is possible that IGSCC may not have occurred. The microstructure of the pipe in regions outside the weld heat affet zone probably was not sensitized*, and IGSCC therefore, may not have occurred at the linear defects located in those regions. Thus, it is advisable to examine metallographically other defects to (1) determine the nature of the linear defects, (2) detect the presence or absence of cracks that might be associated with the linear defects, and (3) identify the mode of crack propagation, if cracks are found to be present.

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* No evidence of sensitization was found in the unaffected parent metal in the section shown in Figure 4.