Report Number 87-1

INVESTIGATION OF BRIDGE PIN FAILURES

for

MISSOURI
HIGHWAY AND TRANSPORTATION COMMISSION

FINAL REPORT

to

Missouri Highway and Transportation Commission

on

INVESTIGATION OF BRIDGE PIN FAILURES

submitted by

Donald R. Askeland

Fred Kisslinger

Robert V. Wolf

Department of Metallurgical Engineering

University of Missouri-Rolla

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Severe corrosion, cracking, and even failure of the pins used in bridges having the pin and hanger strap connections have occurred in a number of bridges throughout Missouri. Fracture of four of the twelve pins in the connections on a bridge on Interstate 55 in St. Louis launched an inspection and correction procedure by the Missouri Highway and Transportation Department and led to the discovery of cracked and fractured pins in others of the approximately 90 such bridges in the state.

In this report, the results of a metallurgical examination to determine the mechanism of cracking and fracture of these pins are presented. This research suggests that the failure mechanism occurs by a combination of corrosion and corrosion-originated overload. The corrosion on the pin is particularly severe at the interface between the hanger strap and web section where corrosion is accelerated by the accumulation and retention of salt-laden moisture. This corrosion in the pin is also accelerated by the presence of high stresses in the pin. The stresses are caused by a torque applied to the pin by the hanger strap and web section after corrosion inside the holes in these bridge components causes the pin to become "frozen" in the joint. Relative motion between pin, hanger strap, and web section ceases as a result of this corrosion, and expansion and contraction of the bridge results in a torque on the pin.

Eventually the combination of stress and corrosion of the pin at the interface between the hanger and web causes a crack to nucleate and grow. Once the crack nucleates, growth accelerates due to additional corrosion and reduction of the cross-section until failure finally occurs. Severe pitting corrosion is not essential for the fracture to occur -- at least one sample that was studied contained a deep crack with virtually no surface corrosion pitting. However it is necessary that sufficient corrosion occur to prevent the rotation of the pin in the web and hanger strap.

Overall Inspection of pin-strap connection

Two visits to bridges utilizing the pin and hanger strap method of support were conducted. An early attempt by the Highway and Transportation Department to remove a pin from the Thayer bridge was witnessed; in addition the bridge on Highway B south of Jefferson City was inspected. Photographs were taken at these two times to provide a better understanding of the relationship between the pins, straps, and girders of typical bridges. Figure 1 shows this type of connection in the Thayer bridge; Figure 2 shows the same type of connection on the Highway B bridge. Figure 2 also illustrates that the support connection is located directly beneath the opening of the road-bed, permitting easy access of moisture to the connection.

Examples Studied

Several pieces from the I-55 bridge in St. Louis and the bridge near Clinton were received. These pieces include the following:

1. a full pin containing cracks and corrosion. A hole had been previously burned longitudinally through the center of this pin to assist in its removal from the bridge.

2. half of a pin also containing cracks and corrosion. This pin had been cut in half longitudinally by the Highway and Transportation Department. A hole had also been burned through the center to assist in the removal of this pin from the bridge.

3. a section of a hanger strap containing a broken pin with the bronze washer still attached (the washer was on the web side of the strap).

4. a section of a hanger strap containing a broken pin but no washer (the bronze washer was apparently on the nut side in this case).

5. two pins from the Clinton bridge; both contained deep cracks and corrosion pits.

With the exception of item 4, samples were removed from each piece and were subjected to metallographic examination as well as inspection using a scanning electron microscope (SEM), as described below:

Item #1: The full pin from the I-55 bridge contained two circumferential regions of damage -- one area consisted of a shallow corrosion pit or groove with no visible indication of crack nucleation while the second area consisted of a deeper corrosion pit or groove from whose base a crack had formed. Sections were removed from this pin using a band saw. Figure 3 illustrates some of the cuts that were made. Samples were prepared for metallographic and SEM examination from locations that were only corroded and locations that were both corroded and cracked. In addition, a section was removed in such a manner that the section still contained the crack, Figure 4. This section was trimmed to a suitable size, then fractured; the final surface contained both the crack surface as well as a fresh fracture surface. The surface of the fractured specimen was examined with the SEM.

Item #2: The pin from the I-55 bridge that had previously been cut in half also contained two regions of damage, just as in the full pin. Sections were removed from the I-55 half pin, using a band saw to do the cutting. Several samples were prepared for metallographic and SEM examination. These samples included sections through the corroded and cracked region as well as from an area of the pin not subjected to concentrated corrosion.

Item #3: This item included a hanger strap-pin-washer junction from the I-55 bridge. This particular pin had actually fractured completely while in place in the bridge; the hanger strap had previously been cut by the Highway Department during their repair. The bronze washer, which was on the opposite side of the strap from the nut, was about flush with the fracture surface of the pin and was still firmly attached to the strap and pin. Initial attempts to cut the strap section containing the bronze washer with a band saw were unsuccessful because of the hardness of the bronze washer. Instead, a power saw with an abrasive wheel was used to cut through the washer. As this was being done, a layer of corrosion product (about 1/16 inch thick) popped off the fracture surface of the pin. Figures 5a and 5b show the section after the cut with the abrasive wheel -- the two fragments on the pin surface are a portion of the remains of the oxide that popped off during cutting; originally the entire fracture surface of the pin was covered with this material. In addition, at this time the washer separated from the strap.

The cut through the strap and pin was then completed with a band saw and, in addition, another section was removed to include the pin-strap interface, Figure 6. This interface was later examined metallographically. The pin fell loose from half of the strap during this cutting process. There was some very thin loose corrosion product between the strap and pin; this product was responsible for freezing of the joint but was not strong enough to firmly hold the pin in the strap after the junction was sectioned. There was a layer of corrosion product (about 1/8 inch thick) between the strap and the prior location of the bronze washer, as can be seen in both Figures 5b and 6. A portion of this layer popped off during cutting and was also saved. Both the corrosion product on the fractured surface of the pin and the product between the strap and washer were examined using the SEM.

Item #5: As in the I-55 bridge pins, both of the Clinton pins contained two areas of circumferential corrosion. One area contained corrosion only while the second area contained both corrosion and deep cracks. Using the band saw, both the top and bottom pins were cut longitudinally. Figure 7 shows the outside surface as well as the cross-sections of these pins. Two samples were removed from the top pin -- one from the corroded area and one from the corroded and cracked area. These samples were also examined microscopically and with the SEM. Although the bottom pin was also cut longitudinally, no additional samples were removed.

Low Power Inspection

Samples from the deeply cracked regions from both of the I-55 pins were mounted in Bakelite. The samples were then sanded through 600 grit papers to reveal the corrosion pits and cracks. Photographs were taken of the mounted samples, then each sample was photographed at a low magnification using a metallograph; photographs were overlapped so that a composite of each crack could be composed. Examples of a sample and crack are shown in Figure 8 (for the full I-55 pin) and Figure 9 (for the half I-55 pin). In Figure 8, a corrosion pit and a relatively straight crack, each about 3/16 inch deep, are observed. In Figure 9, no significant corrosion pit is observed but a branched crack about 3/8 inch deep is found.

Sections were also cut from the strap-pin-washer piece. The actual crack is located at the junction between the washer and where the web would have been. The fracture surface of the pin was covered with a thick layer of corrosion product. The washer itself had corroded; the thickness of the washer near the hole was somewhat greater than 0.25 inch while the thickness at the outer edge was as small as 0.175 inch. The metal loss from the washer was concentrated at the web-washer interface rather than at the strap-washer interface. The strap, however, had corroded beneath the washer to a great extent, Figure 6b, and shows an exceptionally thick corrosion product present between the web and the washer.

Scanning Electron Microscope Examination

Several samples were examined using the scanning electron microscope. The results of the SEM examination are as follows.

Sample 1: This sample was removed from the full pin from the I-55 bridge. It contained a large rounded corrosion pit with a short crack at its base. This pit with crack was located on the pin adjacent to the interface between the strap and web. The sample was polished through 600 grit polishing paper before the examination and is Sample 1 shown in Figure 10.

Figure 11a shows the corrosion pit in this sample, while Figure 11b reveals that the crack beyond the pit contains a residue of corrosion products. A slight contrast between the residue and the surrounding steel was observed and is revealed in Figure 11b.

The scanning electron microscope was used to identify the elements present in the residue as well as in the steel. This is accomplished by bombarding tiny segments of the sample with a beam of electrons; the highly energetic electrons excite X rays from atoms in that segment of the sample. The energies of X rays excited from the sample are then displayed as a spectrum, which includes the intensity, or number, of X rays being excited. The energies of the X rays are related to the type of atom from which the X rays are emitted. In the SEM used in this work, X rays from all atoms having an atomic number greater than 12 (magnesium) can be detected.

Figure 12 shows the X-ray energy spectrum excited from the residue in the crack. The energy peaks indicate the presence of iron and chlorine. Semi-quantitative analysis using the intensity of the energy peaks suggests that the residue contains 17 wt% (25 at%) chlorine, balance iron in the residue. Accuracy is on the order of plus or minus 5%.

Figure 13 shows that no chlorine is present in the steel; the steel contains iron and a trace of manganese, as would be expected. No carbon is indicated due to the low atomic number of carbon.

Sample 2: This sample was obtained from the I-55 half pin and has a smaller corrosion pit but a deeper, branched crack than the previous specimen, as shown in Figure 10. This sample was also polished through 600 grit polishing paper. Figure 14 shows the specimen in the SEM. Two areas of the crack residue were examined.

In an area near the surface, Figure 15a, small crystals were present which had apparently oozed out between the residue and the steel on both sides of the crack during the vacuum desiccation that preceded insertion of the specimen into the SEM. The residue itself contained only iron and manganese. Figure 16 shows the typical energy spectrum from the crystals. The crystals contained about 40 wt% (52 at%) chlorine. During preparation of the samples, moisture used to lubricate the sample during polishing apparently dissolved the salt in the residue. The salt solution was then drawn from the residue prior to examination, allowing the crystals to form.

Only chlorine is present in the energy spectrum; sodium, which almost surely is present in the crystals, does not have a high enough atomic number to be detected.

Figure 15b shows an area of the crack lying deeper into the pin, somewhat to the upper left of Figure 15a, where the crack had branched. This area also contains a residue plus small crystals. Figure 17 is the energy spectrum from the residue, which contained 14 wt% (20 at%) chlorine.

Sample 3: Figure 10 and Figure 18 show the crack-fracture surface that was obtained from the I-55 full pin; the crack began from a rounded corrosion pit in the foreground. Several areas are visible on this surface.

Point A is located on the corrosion crack surface at the deepest part of the crack; Figure 19 shows that chlorine in the amount of 23 wt% (32.5 at%) is present.

Point B lies on the corrosion crack surface just below the rounded portion of the pit; Figure 20 shows that a smaller amount of chlorine, about 16 wt% (24 at%), is present.

The surface of the rounded pit, point C, contains relatively little chlorine, as shown in Figure 21. Analysis indicates 9.5 wt% (14 at%) chlorine at this point; perhaps most of the chlorine in this area had been washed away by rainfall.

Sample 4: A deep crack from the top pin from the Clinton bridge was examined. Figure 22 shows the sample in the SEM. There is a rounded corrosion pit, followed by a deep open crack, and finally a thin crack still filled with corrosion product. The open portion of the crack may be due to the sand blasting process used by the Highway Department for clean-up. Figure 23 shows the X-ray spectrum observed in parts of the residue; the analysis is 11 wt% (16.5 at%) chlorine. Some locations in the residue showed no chlorine.

Sample 5: The corrosion product that had flaked off of the fractured pin and also the residue between the strap and washer were examined. The very thick residue between the strap and washer was primarily iron, presumable an iron oxide or hydride. The source of the iron was primarily the strap, which was deeply corroded where the bronze washer had been located.

The thinner residue that flaked off the fracture surface contained a significant amount of copper, silicon, and calcium, Figure 24. The source of the copper and silicon was the bronze washer. The calcium might be from calcium chloride since calcium chloride had been used to salt this particular bridge; little chlorine was observed, however. Eight different elements were detected in this residue and the SEM was not able to give a reasonable semi-quantitative analysis of the material.

Summary and comments: The results of the SEM analysis prove that chlorine is present in the crack residue. However the exact amount of chlorine cannot be accurately determined because indications of iron and other elements may be detected from the sides or beneath the areas that were examined. The SEM also cannot indicate how the chlorine is held --whether as NaCl, $FeCl_2$, or other compound -- particularly since sodium cannot be detected with the instrument. Also no indication of oxygen, nitrogen, or other light-weight element, which might be expected, can be obtained, again because of the sensitivity of the instrument. No copper was found anywhere in the matrix or residue on any of the samples except in the corrosion product removed from the fracture surface of one of the pins. With this one exception, it is apparent that the bronze washer is not a factor in the corrosion and failure process.

Metallographic Inspection

Several samples removed from the two I-55 pins and from one of the Clinton pins were polished and examined. In particular, the structure of the steel was noted, with special reference to the ferrite grains. The structure of the steel is consistent with that of a 1010 steel; the bulk of the structure is ferrite, with small patches of pearlite. The photomicrographs in Figure 25 are representative of the matrix structure in each of the pins that were examined. The light appearing portion of the structure is ferrite (almost pure iron) while the darker portion is pearlite. Pearlite is a mixture of ferrite and cementite (Fe_3C) in a platelike arrangement; the platelets are often too thin to be resolved at normal magnifications.

The ferrite grains contained strain markings adjacent to deep cracks; however no strain markings were observed when only corrosion had occurred and no strain markings were observed in the bulk of the pins. This held true for all of the pins that were inspected in this manner. Figure 26 includes two examples of strain markings in the ferrite near cracks. The presence of these strain markings, plus some indication of distortion of the ferrite grains, indicates that these areas were subjected to a localized overload. It appears that considerable plastic deformation of the steel pin occurs, either after the crack has formed or perhaps helping to initiate the crack.

Evidence of plastic deformation was only found in the steel very close to crack surfaces. Figure 27 shows an example of ferrite, without strain markings, adjacent to a corrosion pit from which no crack has yet begun. The pin-strap-web junction at this area had not yet frozen, a torsional overload had not yet developed, and therefore corrosion without cracking was the only noticeable damage. Similar structures were found in all of the areas in which a corrosion groove but no cracking was observed.

Conclusions

Based on the results of the metallographic and SEM examinations of the bridge pins, plus other observations and discussions, it is clear that the pin failures are caused by a combination of corrosion and overload. The pin - hanger strap connection used in these bridges is intended to permit movement of the bridge sections by rotation about the pins in the holes through the straps and girders. As long as this rotation is permitted, no substantial amount of torsional, or twisting, forces are exerted on the pins. Some degree of wear and corrosion might be expected, but all evidence from the I-55 and Clinton bridge pins suggests that general wear and corrosion are not significant and that, if these were the only problems, the pin - hanger strap connection would function successfully for much longer periods of time. Furthermore, the bronze washer does not appear to be an important factor; pins freeze and fail whether the washer is on the outside of the hanger strap, inside the strap, or even if it is not present.

The circumferential corrosion pits or grooves observed on most of the pins are also, in and of themselves, not the limiting problem. These grooves, some of which are nearly 1/4 inch deep after approximately 20 years exposure, are a result of general corrosion probably accelerated by the easy access of salt-laden moisture from the deck of the bridge. However even this corrosion is sufficiently slow that the pins could probably survive more than another 20 years before the safety of the connection would be jeopardized.

The real problem is that a sufficient amount of corrosion occurs between the pins and the bearing surfaces of the straps or webs that causes the bridge pins to become "frozen" in the holes through the hanger straps and girder webs. After this happens, relative motion between hanger straps or girder webs cannot occur and any expansion or contraction of the bridge components resulting from load or temperature change causes a torque on the pin. This torque produces high stresses in the pin that appear to encourage general corrosion, stress corrosion, or even corrosion fatigue. When the circumferential corrosion grooves are deep, these stresses are even magnified. At some point, cracks will nucleate and grow until there is insufficient pin material left to maintain even the static load. Note that the freezing of the pins is the critical factor; deep circumferential corrosion grooves were observed without crack formation while cracks were observed in at least one case with virtually no circumferential corrosion groove.

As a consequence of this investigation, it is apparent that keeping the pins free to move is of paramount importance. This might be done by a variety of techniques, which are discussed in the next section.

Recommendations

The pin - hanger strap connection must be made in such a way that the pin remains free to rotate during the lifetime of the bridge. Several approaches could be taken to help assure that this is the case.

1. The holes in the straps or girder could be made somewhat oversized to minimize the likelihood that the pin will freeze up in the connection. There is some danger, however, that there may be better access of moisture to the pin-strap or pin-girder interface and the problem may eventually reoccur.

2. Some type of grease fitting might be incorporated into the connection to assure that lubrication is maintained and, at the same time, assure that moisture is kept out of the bearing surfaces. This has the disadvantage of requiring additional maintenance.

3. A polymer or rubber material, in the form of a gasket, might be placed between the girder and strap interfaces to help keep moisture from the pin. The gasket material should be designed so that it would remain compressed between the sections to provide a water-tight seal.

4. To help keep moisture from the pin, some type of shield might be placed over the connection to divert the bulk of the water from the joint. This would perhaps reduce the rate of corrosion and freezing of the connection but probably would not prevent its eventual occurrence.

If pins are to be replaced in all of the bridges, then the pins might be redesigned so that the threaded ends are closer to the same diameter as the bulk of the pins. This would improve the ability to detect corrosion grooves and cracks at an earlier stage by ultrasonic inspection by minimizing the beam spreading that now must be accomplished.

Changing the pin material to a more corrosion resistant material such as stainless steel might introduce other problems. While the pin, which is admittedly the most critical member of the connection, might have a longer life, accelerated corrosion of the girder or hanger strap might occur; it is more difficult to detect the corrosion in these areas than in the pin. It is also possible that corrosion products from the hanger or girder might accumulate in the holes and still cause even the stainless steel pins to freeze in the holes, even if the pin itself does not corrode.

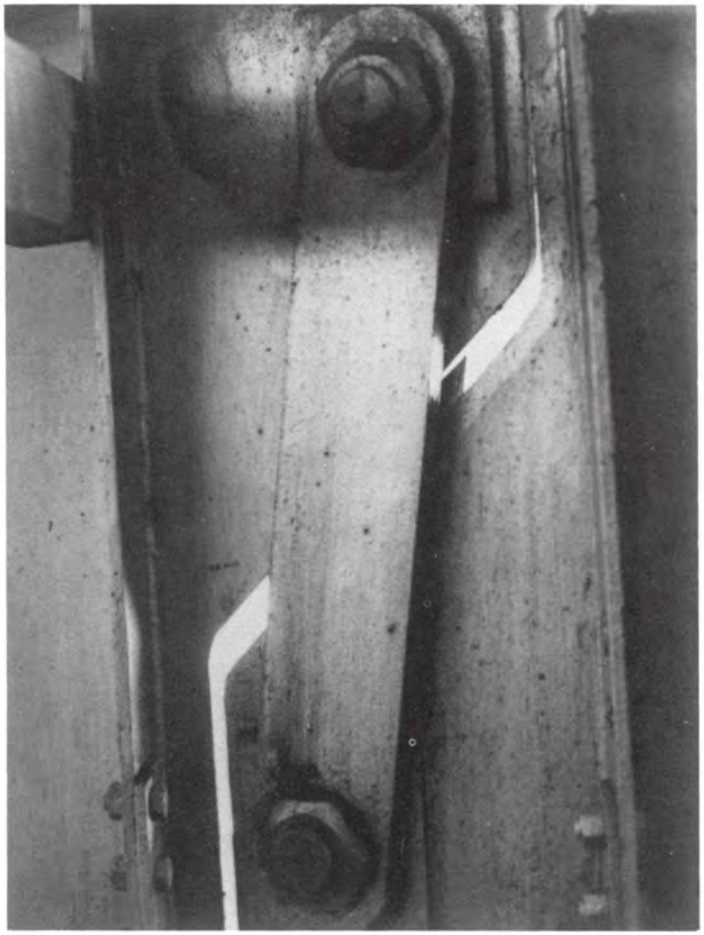

Figure 1: The pin and hanger strap system of support from the Thayer bridge, illustrating the nature of the connection.

Figure 2: The pin and hanger strap system of support from the Highway B bridge south of Jefferson City. Note that the connection is situated directly below the opening in the road-way.

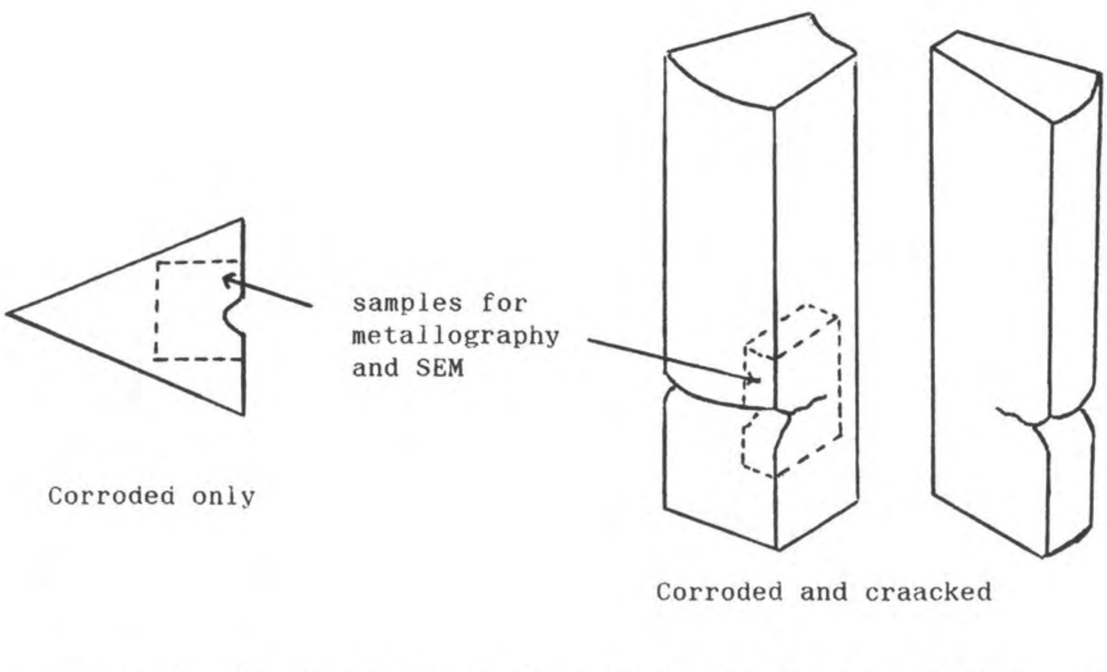

Figure 3: The full pin from the I-55 bridge after sectioning. The pin was first cut into two halves. Additional slices were then obtained from the two halves to provide samples for metallographic and SEM inspection. One of the longitudinal slices was fractured so that the actual crack surface could be observed, shown in greater detail in Figure 4.

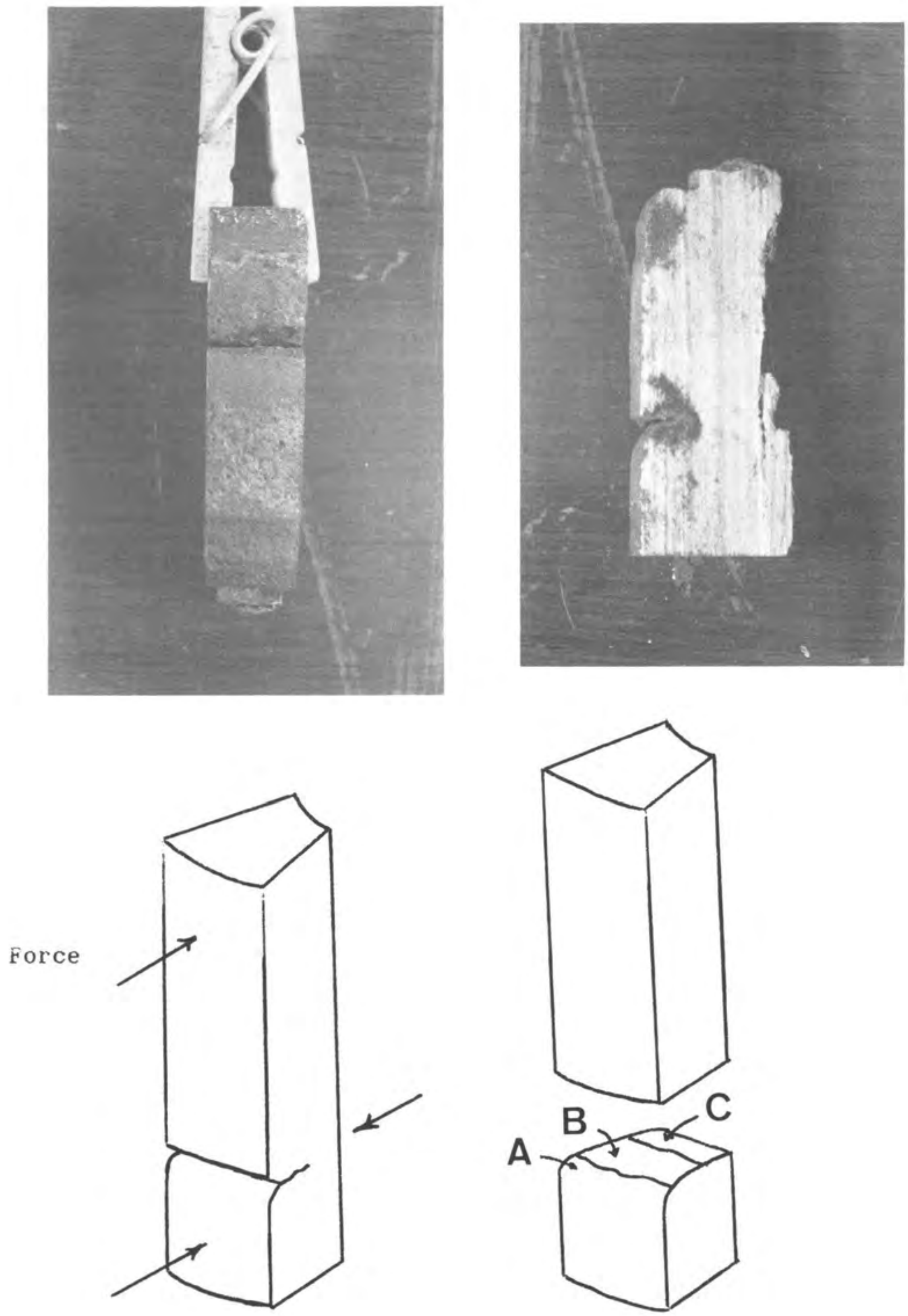

Figure 4: One of the wedge shaped samples cut from the full pin was fractured, revealing a surface composed of part corrosion pit (a), part corrosion surface that was a part of the crack (b), and a fresh fracture surface (c).

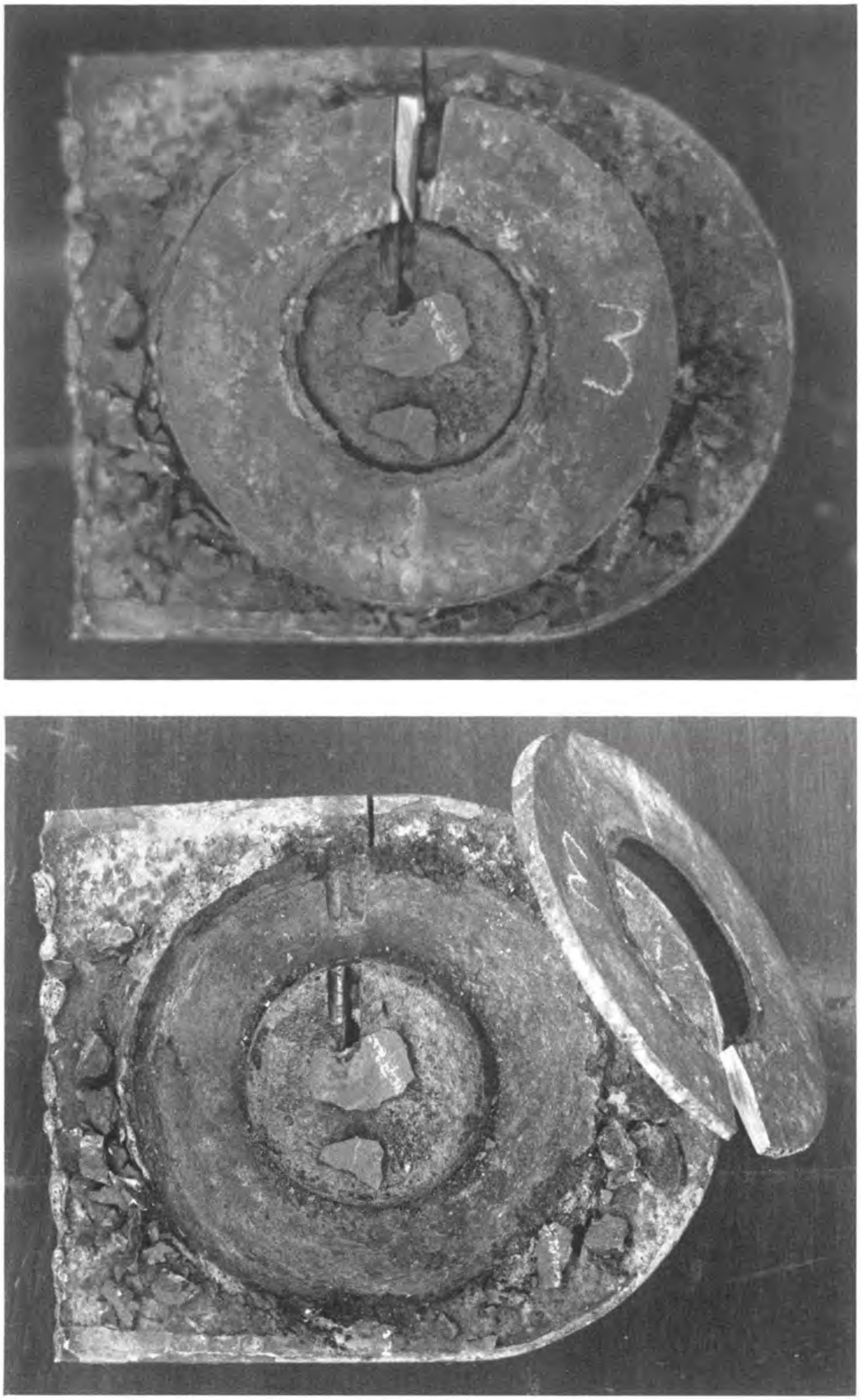

Figure 5: Photographs of the pin-strap piece containing the bronze washer.
(a) The piece after the bronze washer was cut with an abrasive wheel.
(b) The piece with the washer removed, showing the thick layer of corrosion product between the washer and the strap, two pieces of corrosion product originally on the pin fracture surface, and the start of the band saw cut.

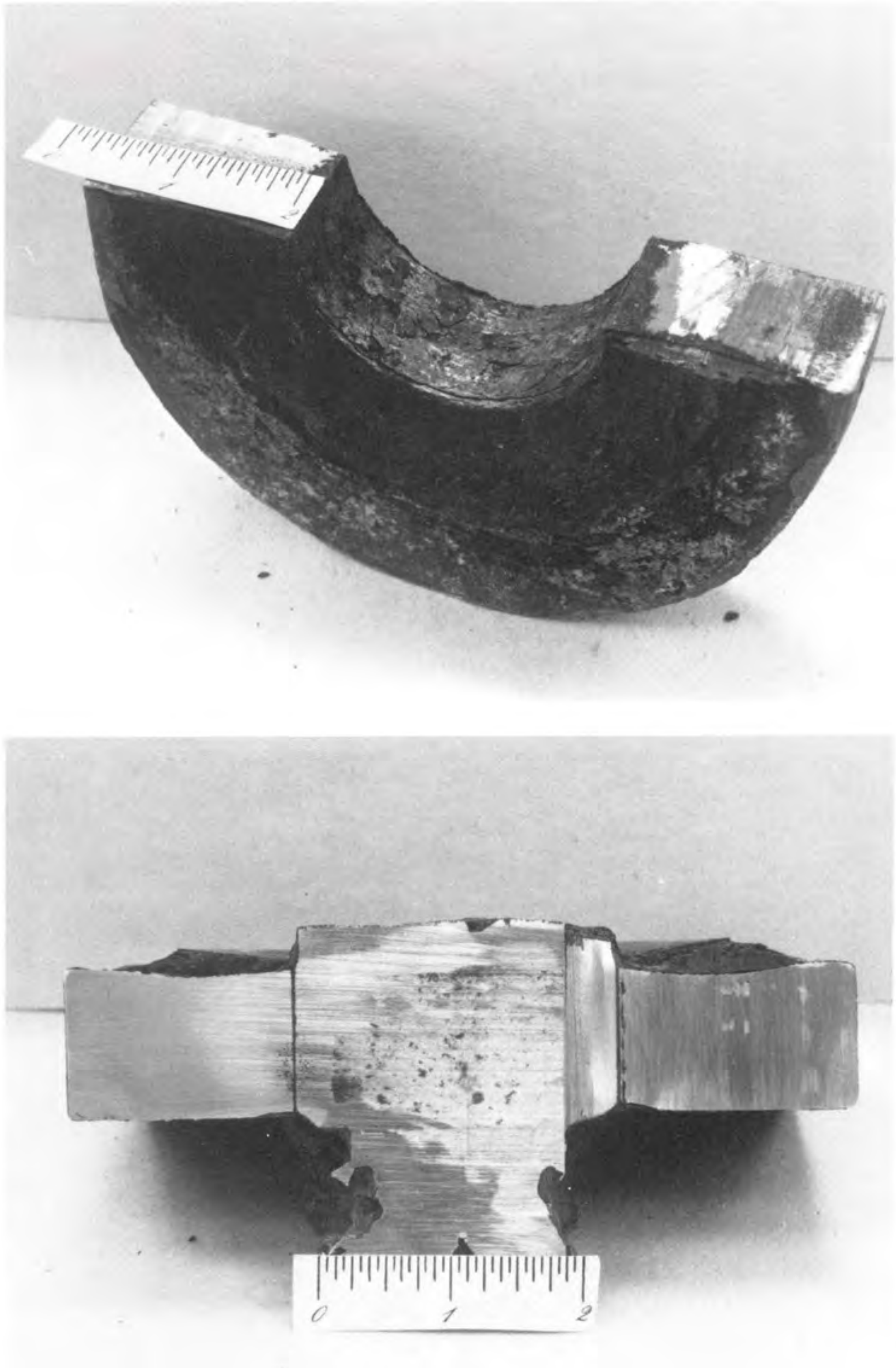

Figure 6: Photograph of the pin-strap piece after the band-saw sectioning was completed. (a) Half of the pin fell out of the strap after sectioning was done; (b) the other half remains fixed in the remainder of the strap. In (b), an extra cut was made on the right side so that the interface between the pin and strap could be examined. Note the thick layer of corrosion on the strap at the top of the photograph, with significant metal removal from the strap material.

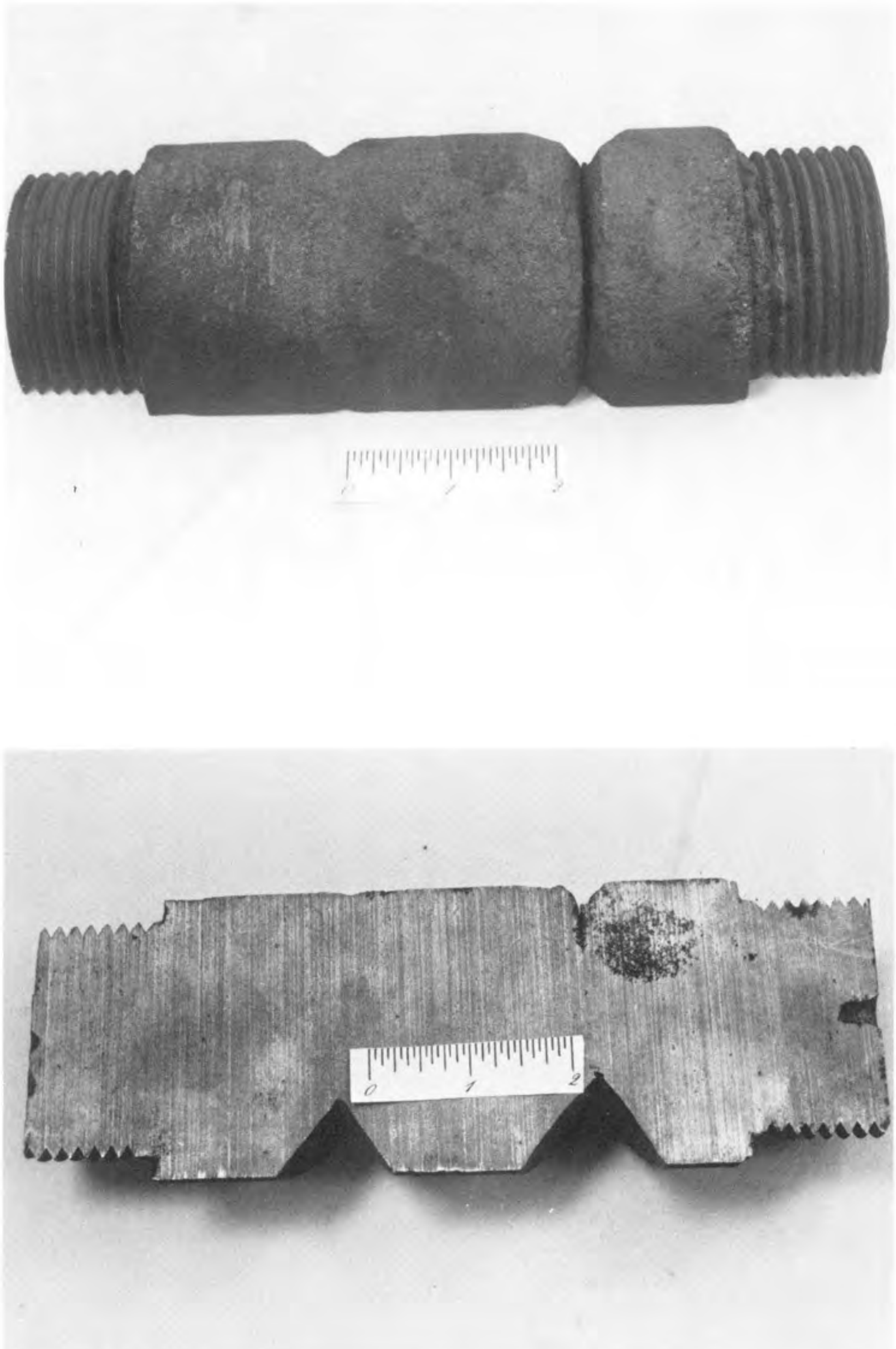

Figure 7: Photographs of the Clinton pins. Note that only mild corrosion occurred at one pin-strap-web junction but deep corrosion and cracking occurred at the second junction on each of the pins. Cracks were about 1/2 inch deep, with combined corrosion plus crack extending about 3/4 inch beneath the original pin surface.

Figure 7 (continued)

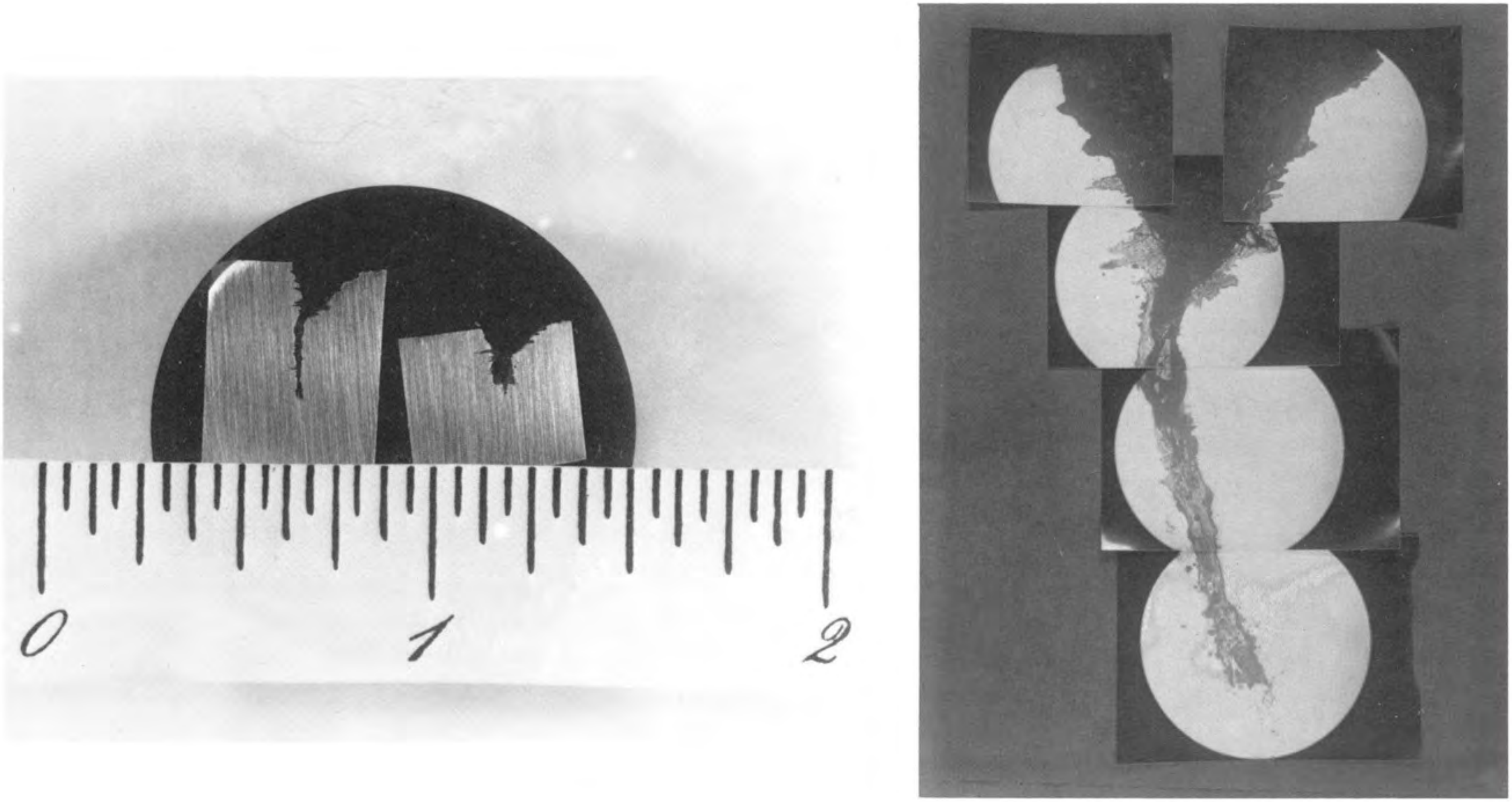

Figure 8: Mounted samples and composite crack photograph in the I-55 full pin. The crack begins at the base of a deep corrosion pit and, in this case, propagates about 3/16 inch further into the pin. The total corrosion and crack is nearly 3/8 inch.

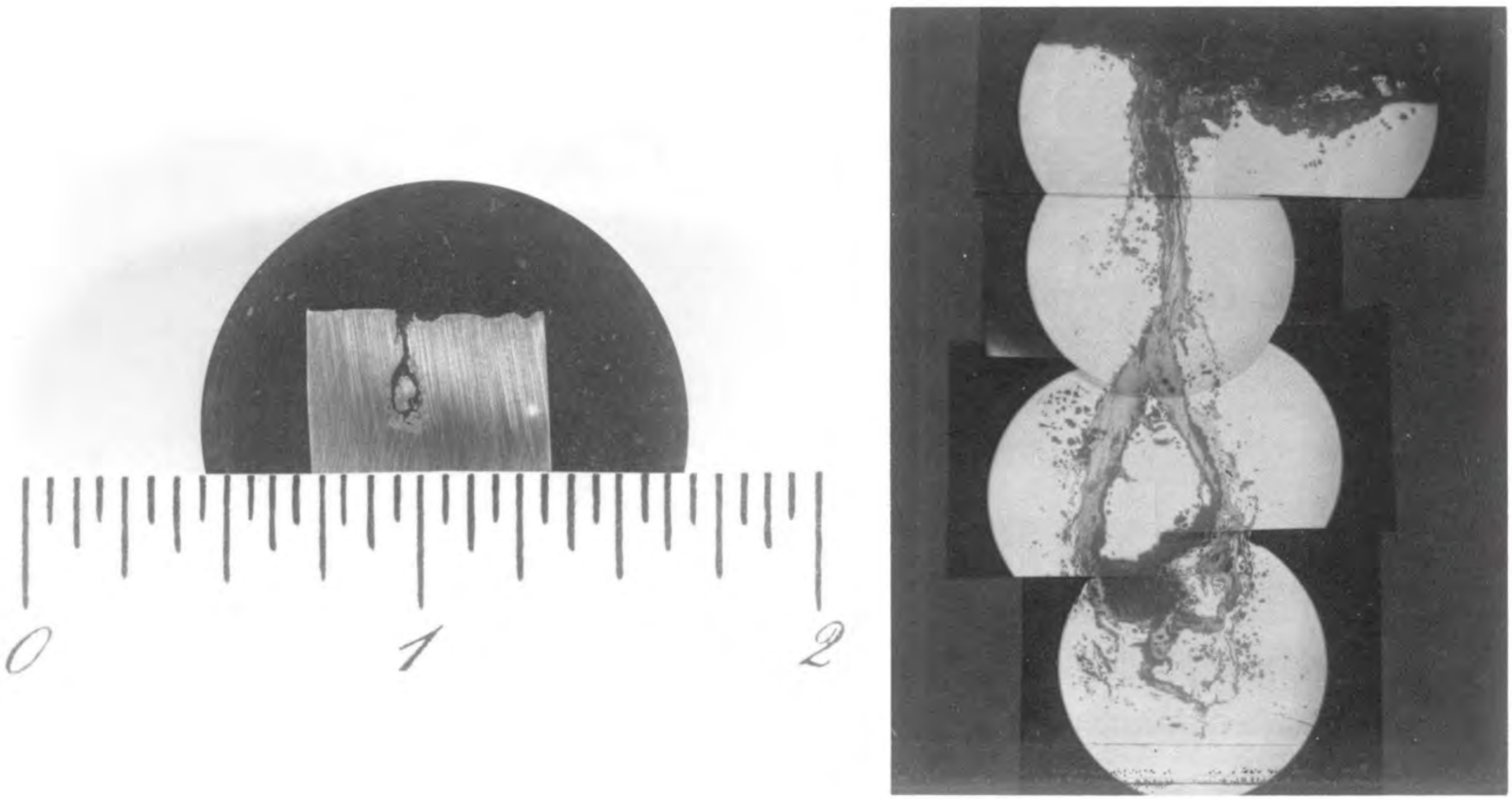

Figure 9: Mounted sample and composite crack photograph from the I-55 half pin. In this case, there is virtually no corrosion pit but the crack extends over 1/4 inch beneath the pin surface. Particularly in this example, extensive branching of the crack and corrosion near the crack is evident.

Figure 10: Photographs of samples from the I-55 bridge that were examined using the scanning electron microscope. Sample 1 was obtained from the full pin and has both a corrosion pit and a crack; sample 2 was obtained from the half pin and contains a branched crack with little corrosion pit; and sample 3 is the actual crack surface obtained from the full pin. The interface between the bright and dark region denotes the end of the crack -- the bright surface was fractured during preparation of the specimen.

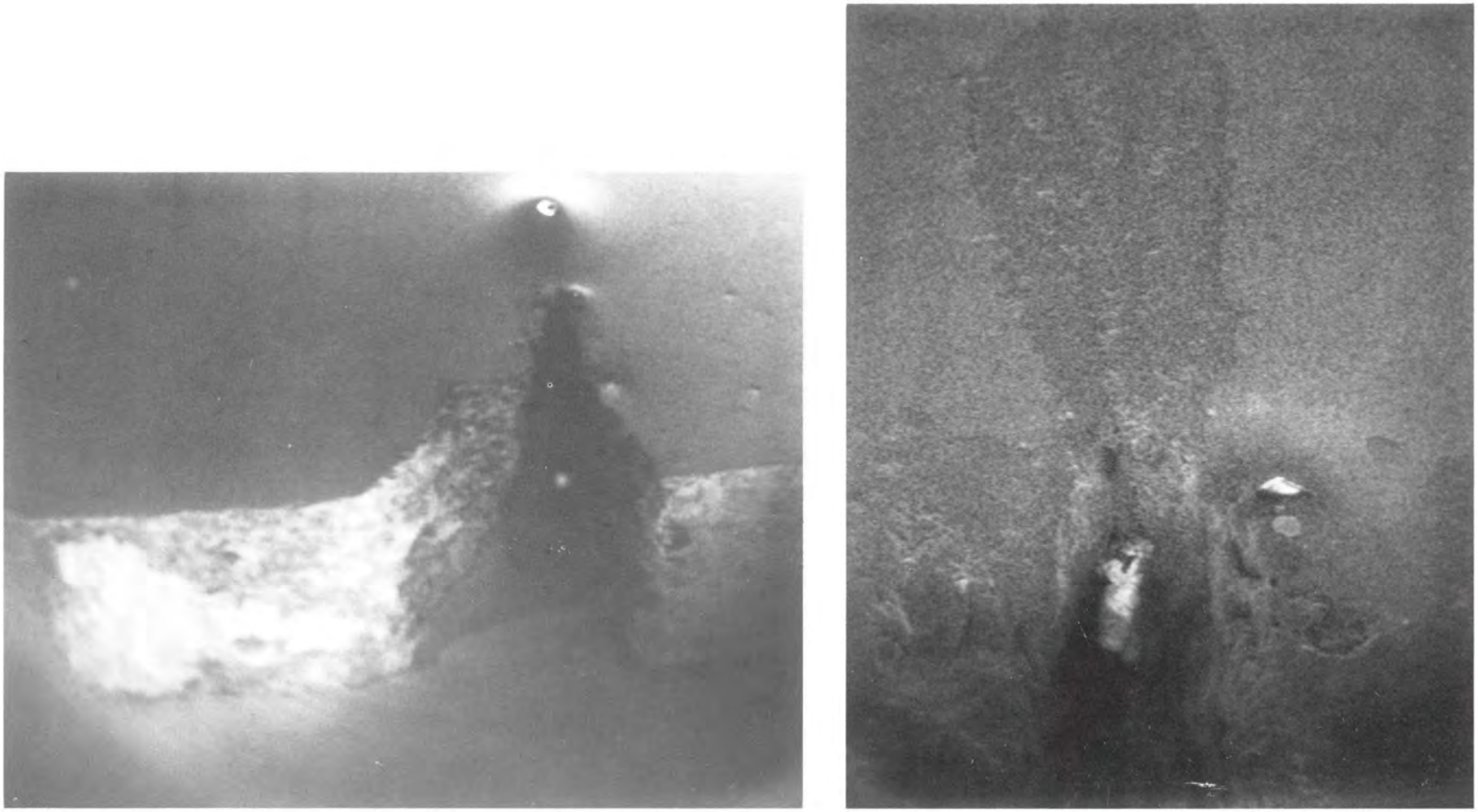

Figure 11: Scanning electron microscope photographs from sample 1 in Figure 10. (a) The corrosion pit and crack (the bright spot near the base of the crack is due to the SEM) x5 and (b) the crack at the base of the corrosion pit, showing some degree of contrast between the matrix material and the crack residue x72.

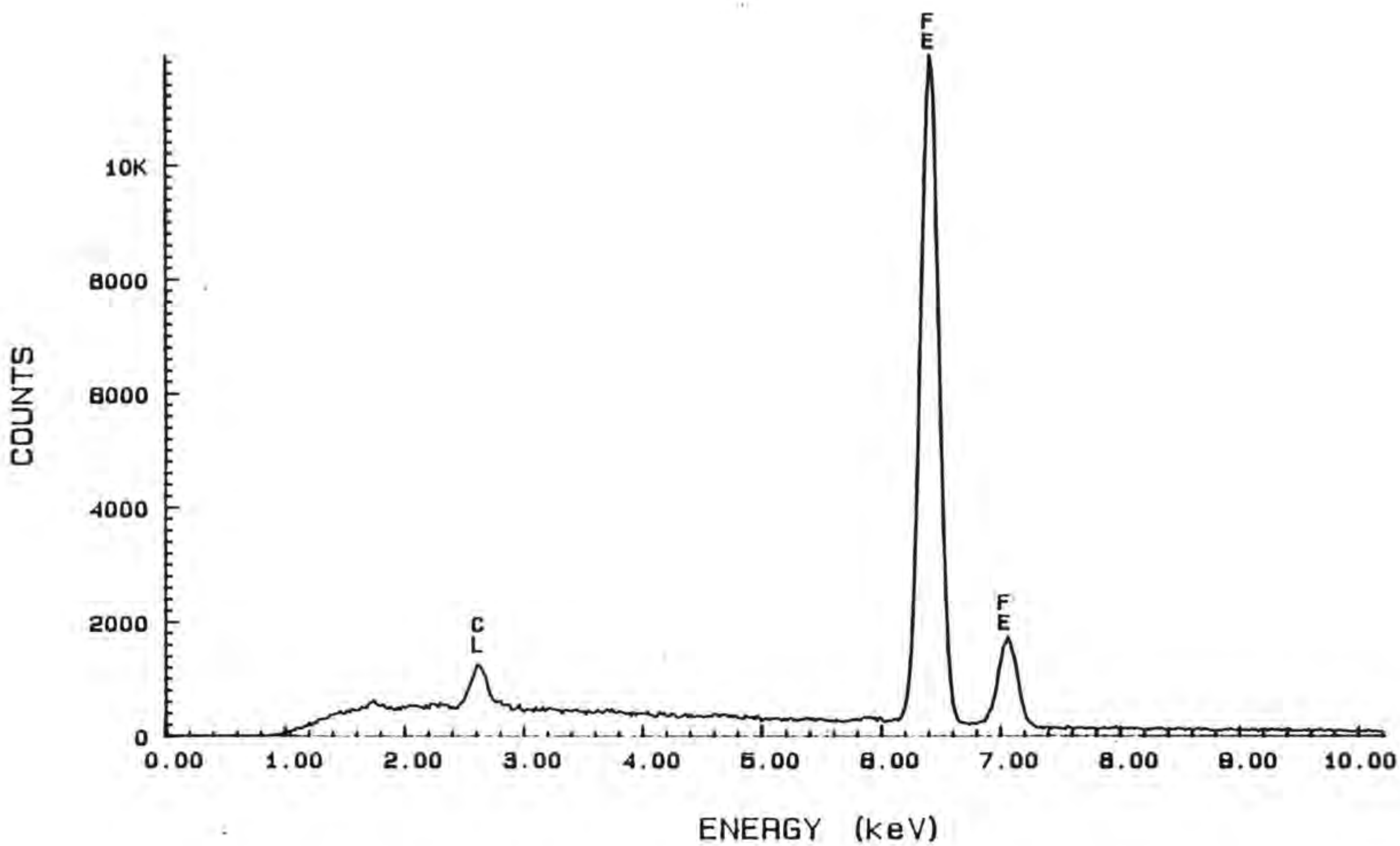

Figure 12: Energy spectrum of X rays emitted from the corrosion product in the crack shown in Figure 11. Note the presence of a significant quantity of chlorine in the residue.

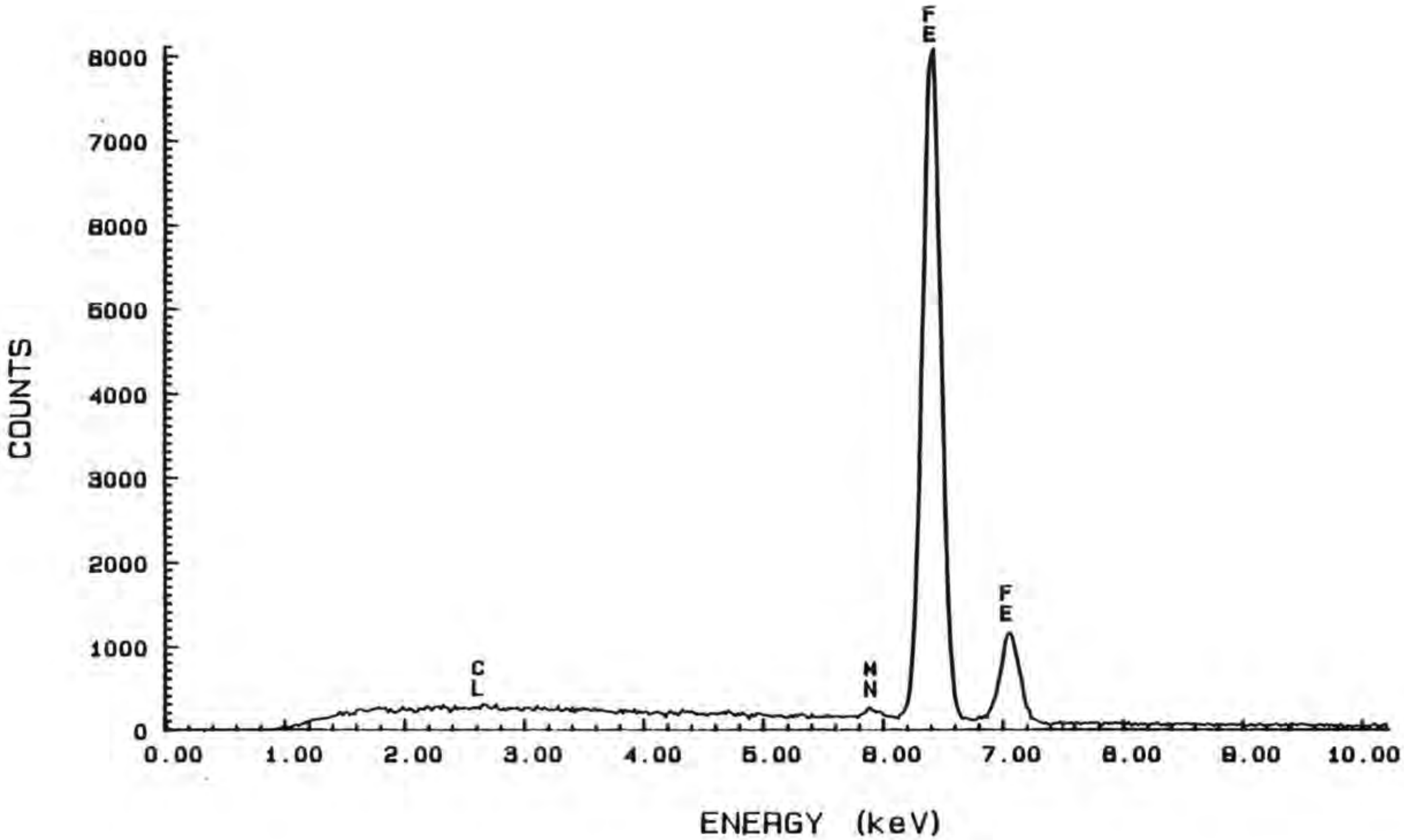

Figure 13: Energy spectrum of X rays emitted from the steel matrix near the crack shown in Figure 11. Note the absence of any chlorine in the matrix.

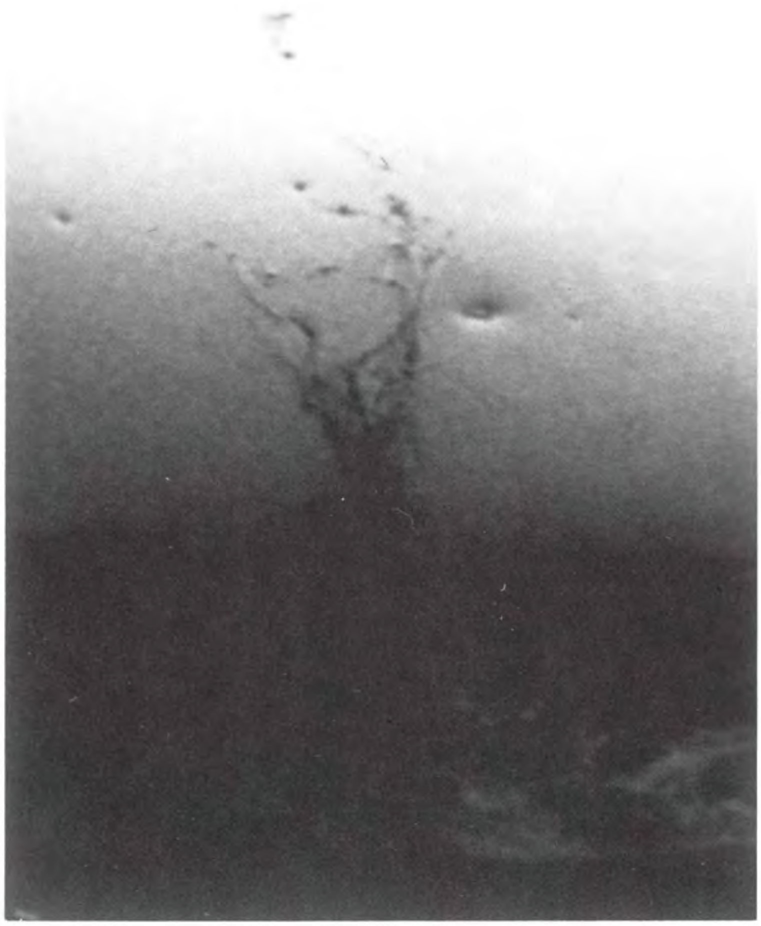

Figure 14: Scanning electron microscope photograph of a crack from the half pin (sample 2 in Figure 10), showing the branched crack that was studied x5.

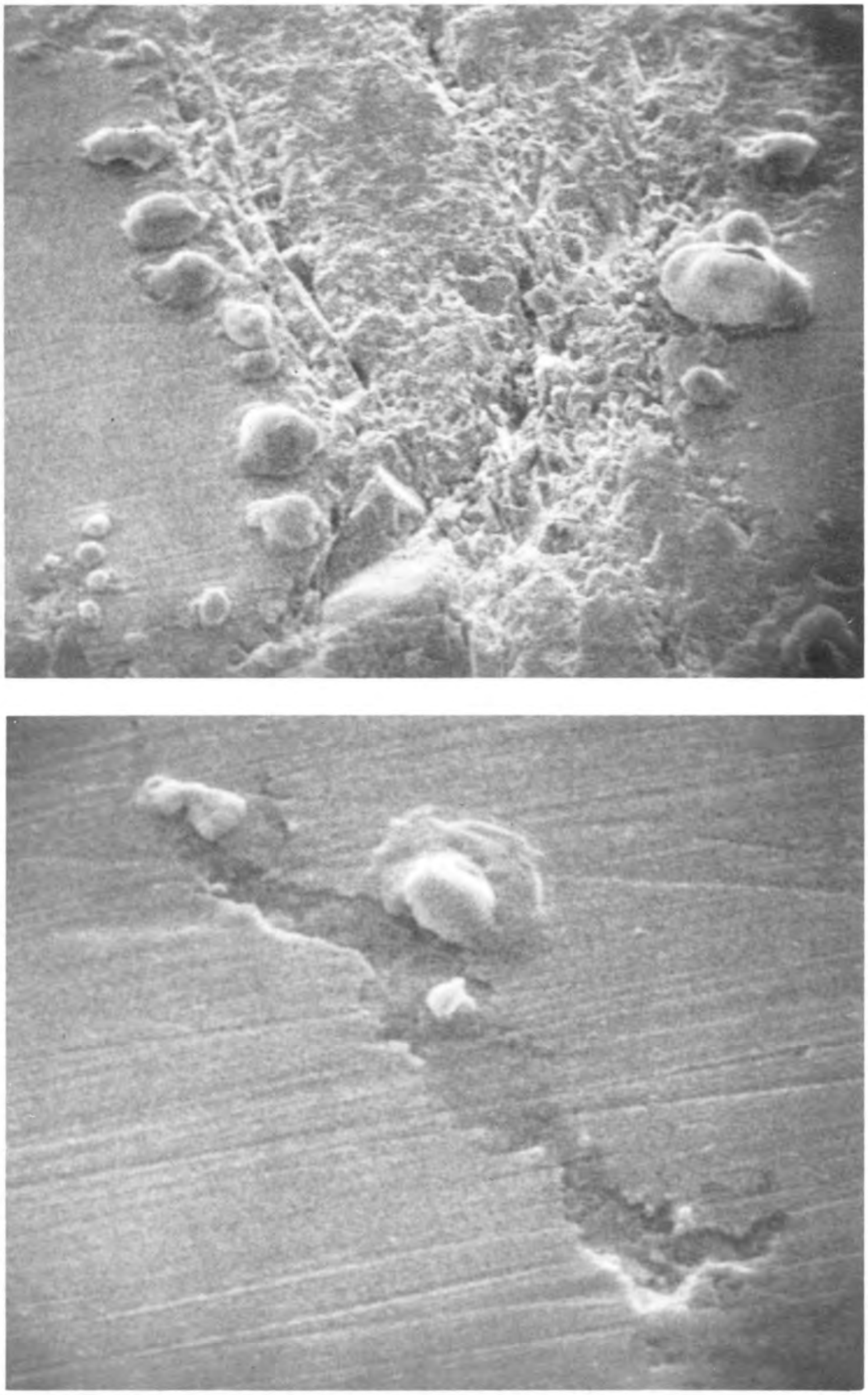

Figure 15: Scanning electron microscope photographs of the crack shown in Figure 14. Note the small globules or crystals at the edges of the crack residue. (a) Near the start of the crack. (b) Near the end of the crack. x720.

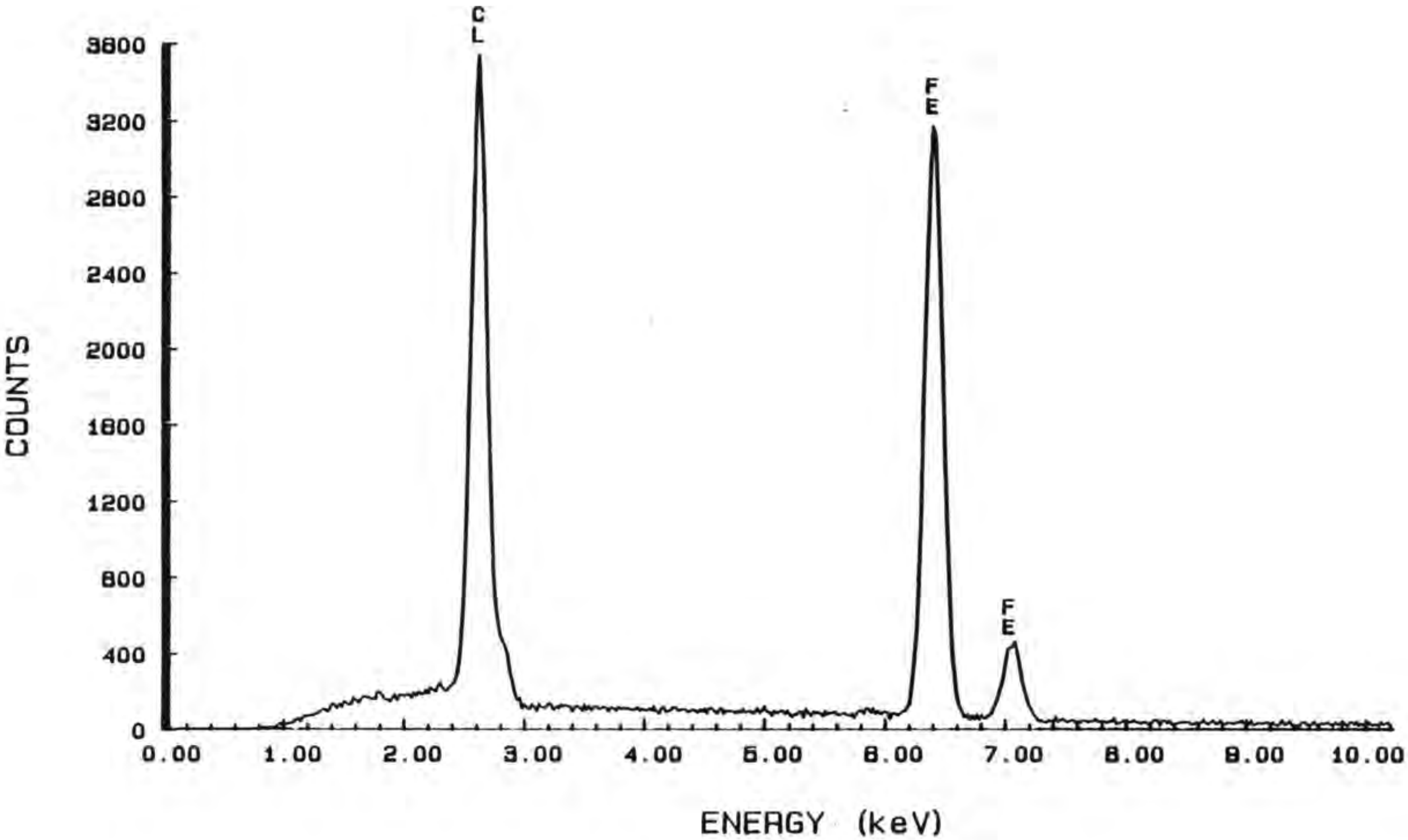

Figure 16: Energy spectrum of X rays emitted from a crystal at the crack residue boundary in Figure 15a. Note the large quantity of chlorine present in the crystal.

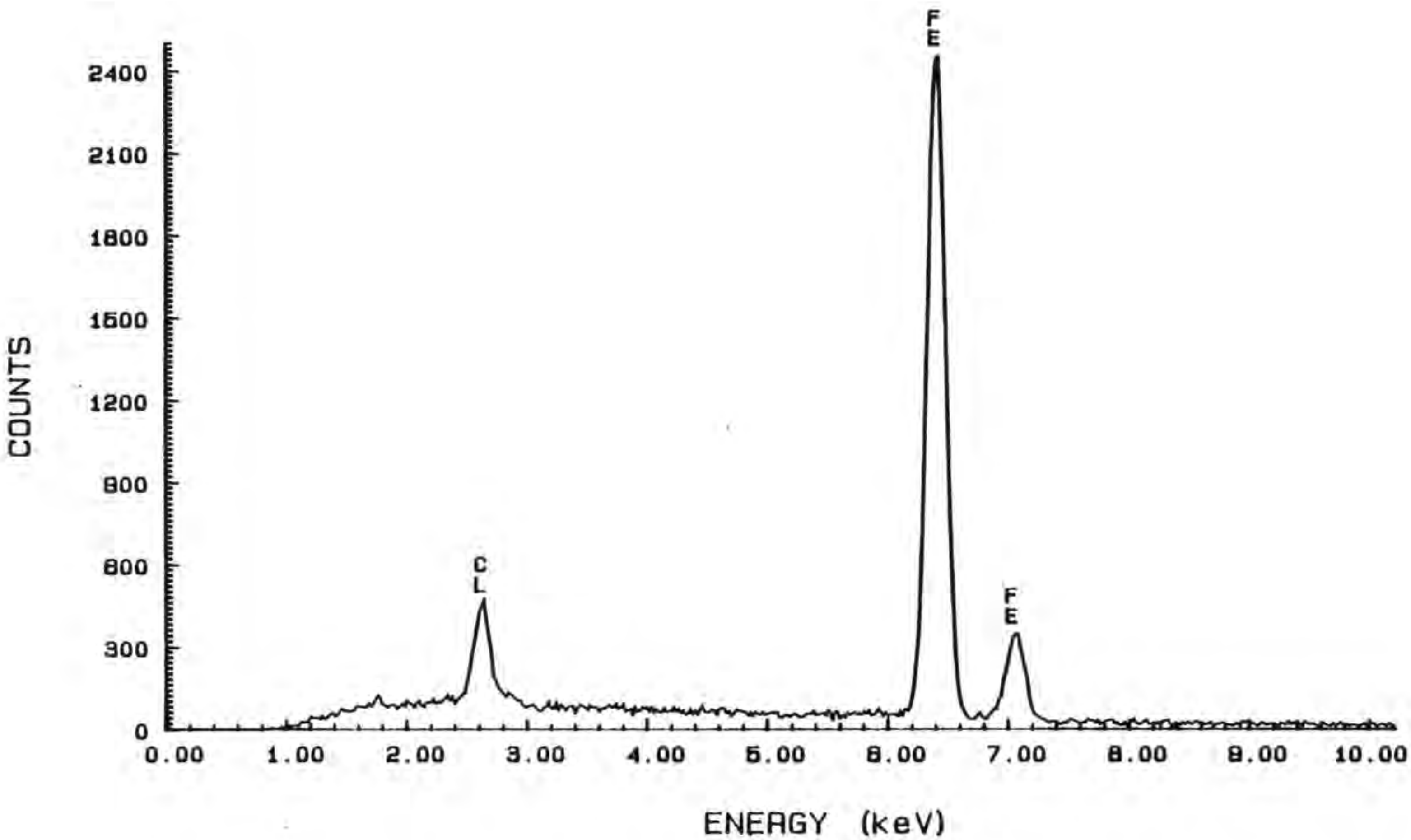

Figure 17: Energy spectrum of X rays emitted from the crack residue in Figure 15b. Chlorine is present in the residue. Note that small crystals are also found at this location in the crack.

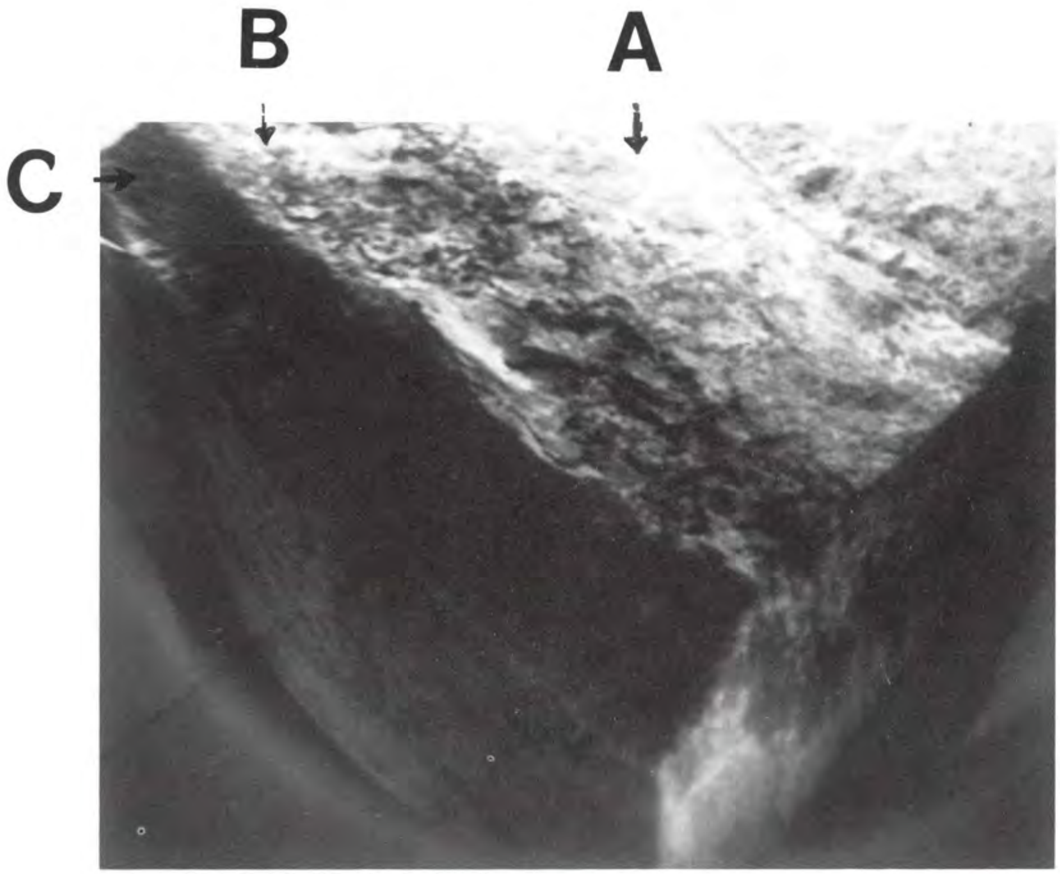

Figure 18: Scanning electron microscope photograph showing the crack surface from the full pin. The rounded area , in the foreground and toward the left sidde of the photograph, is corrosion pit; the next area is a fracture surface caused by the corrosion crack; and the final area, toward the upper right-hand corner of the photograph, is a fresh fracture caused during the preparation of the sample. x5.

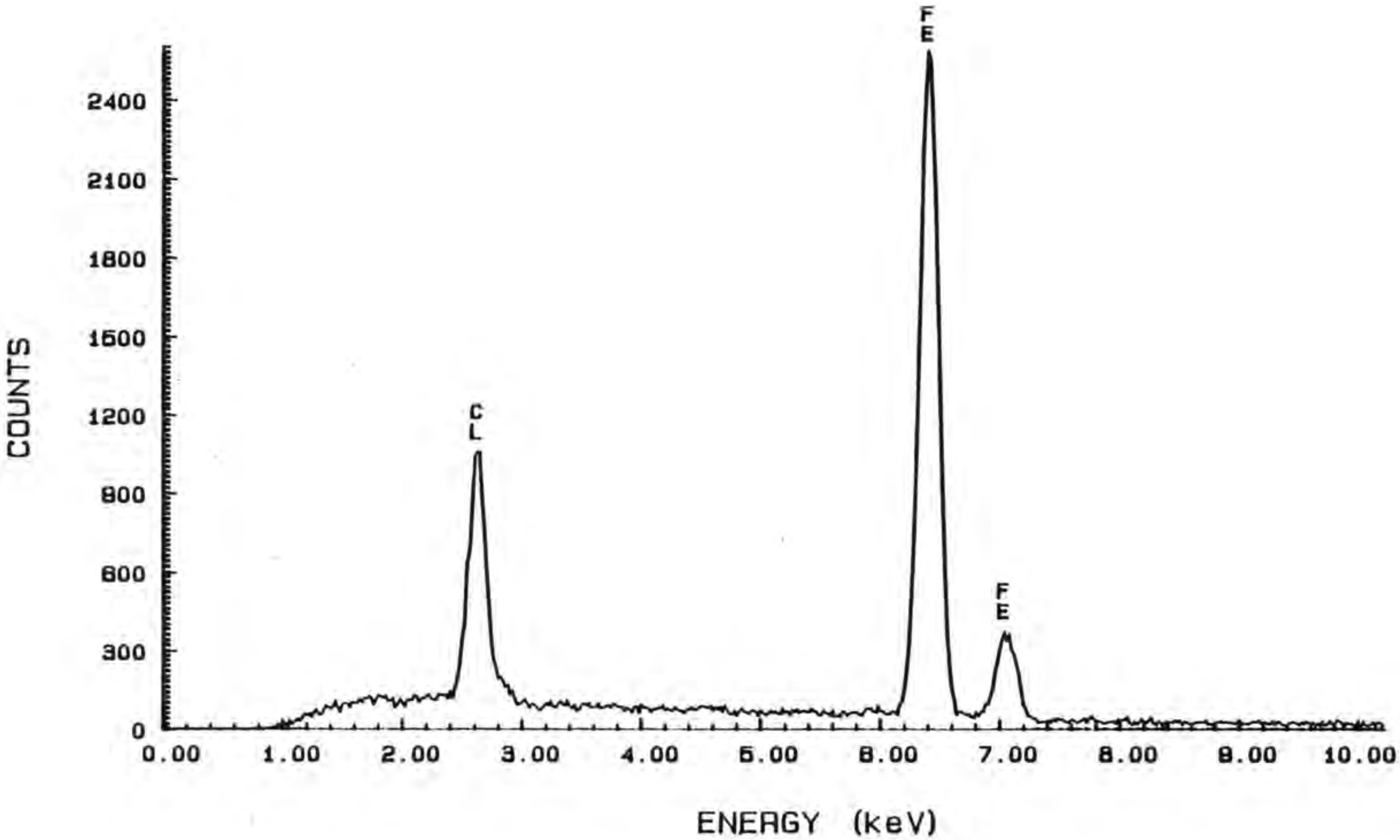

Figure 19: Energy spectrum of X rays emitted from the crack surface near the bottom of the crack. Note the large quantity of chlorine indicated by the SEM.

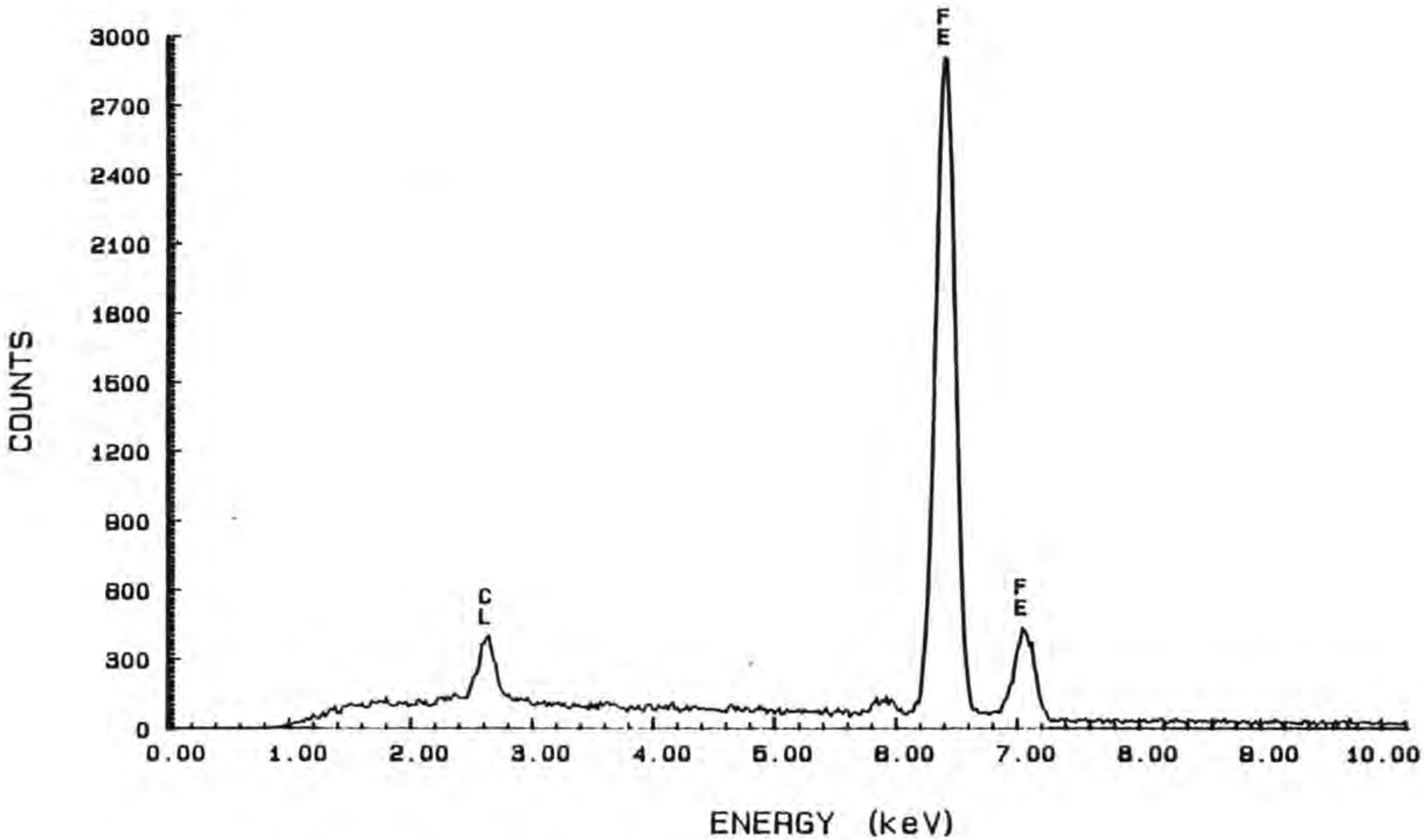

Figure 20: Energy spectrum of X rays emitted from the crack surface just beneath the curved corrosion pit. A smaller amount of chlorine is located here than deeper in the crack.

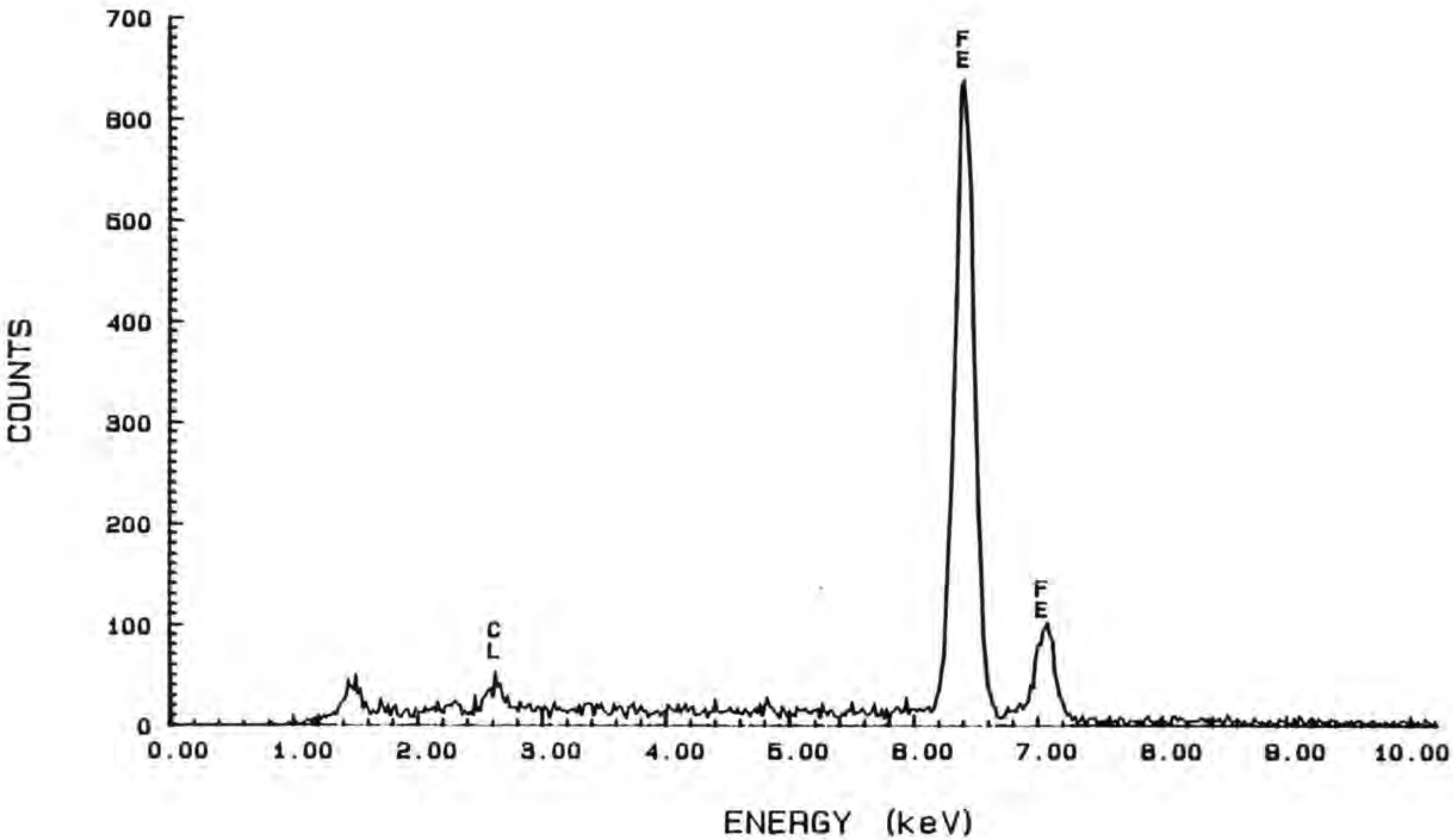

Figure 21: Energy spectrum of X rays emitted from the surface of the curved corrosion pit. Note that the chlorine level is quite small compared to that observed in the actual crack.

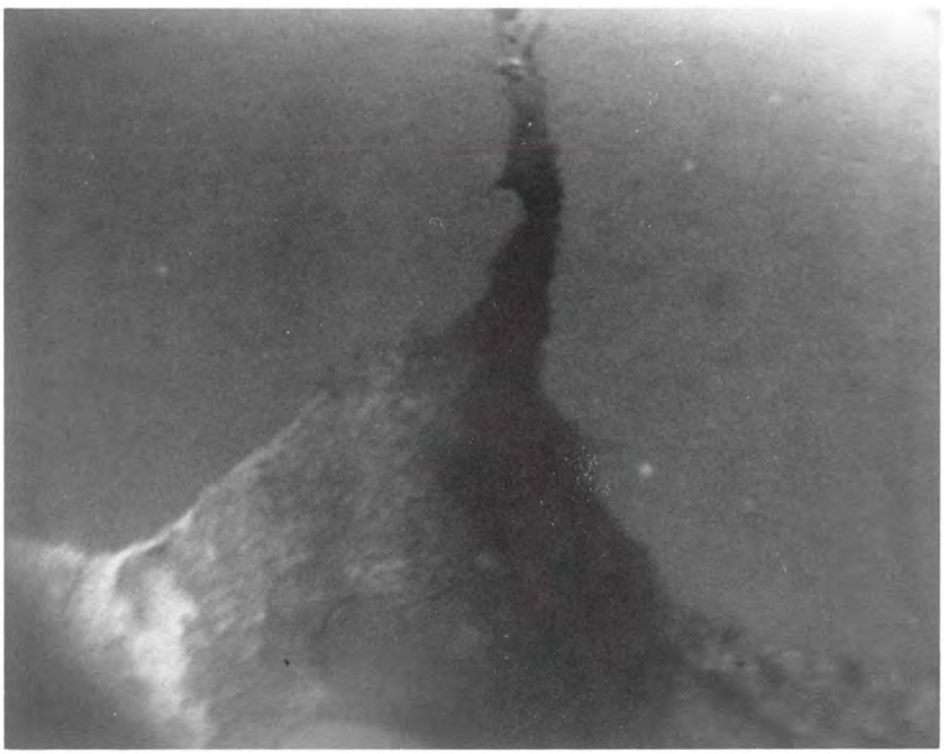

Figure 22: Scanning electron microscope photograph of a corrosion pit and crack obtained from the Clinton pin. Note that the crack does not appear to be filled with any corrosion product, probably because the pin had been sand blasted prior to inspection. x5.

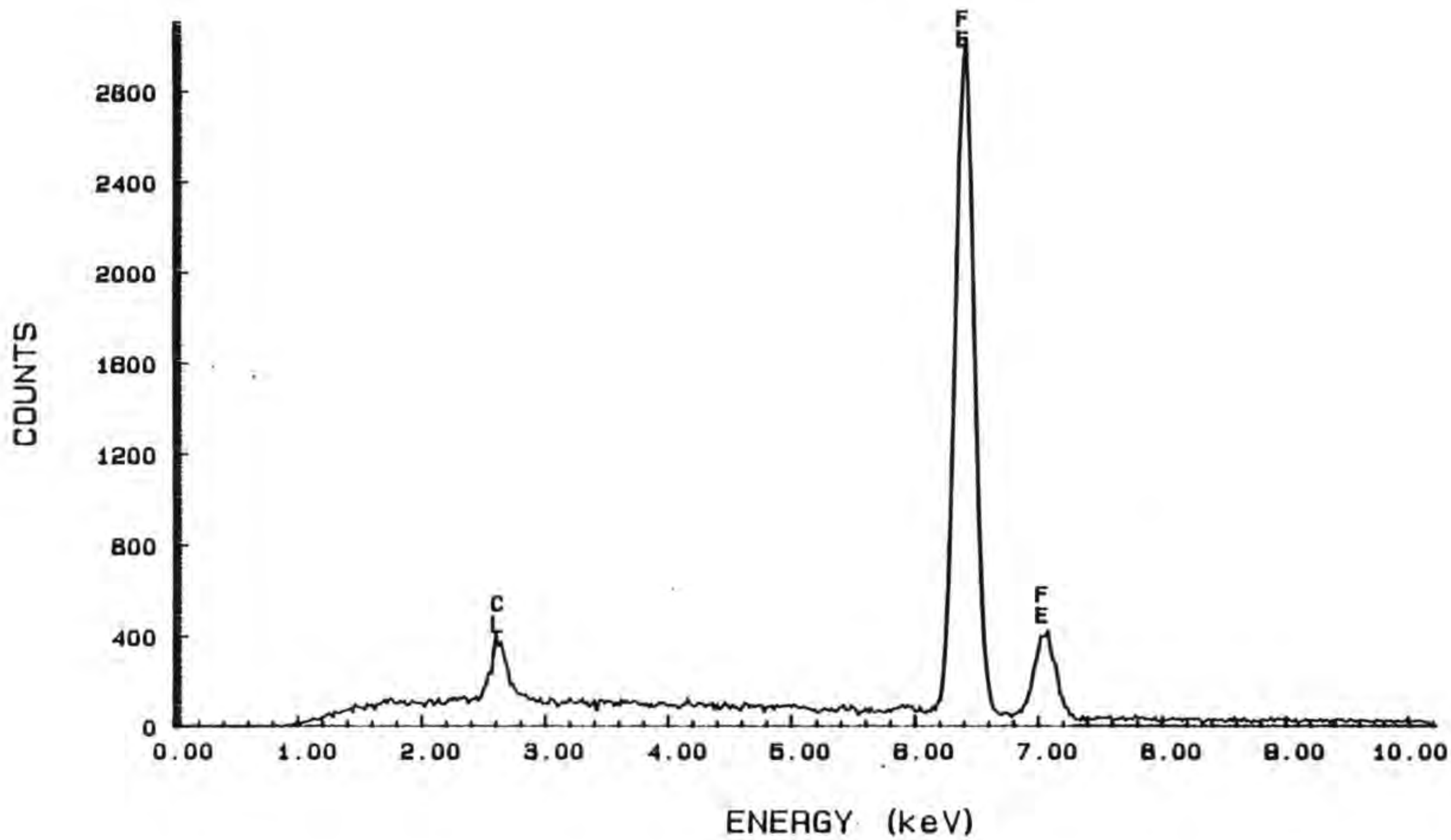

Figure 23: Energy spectrum of X rays emitted from the corrosion product in the Clinton pin, showing the presence of chlorine.

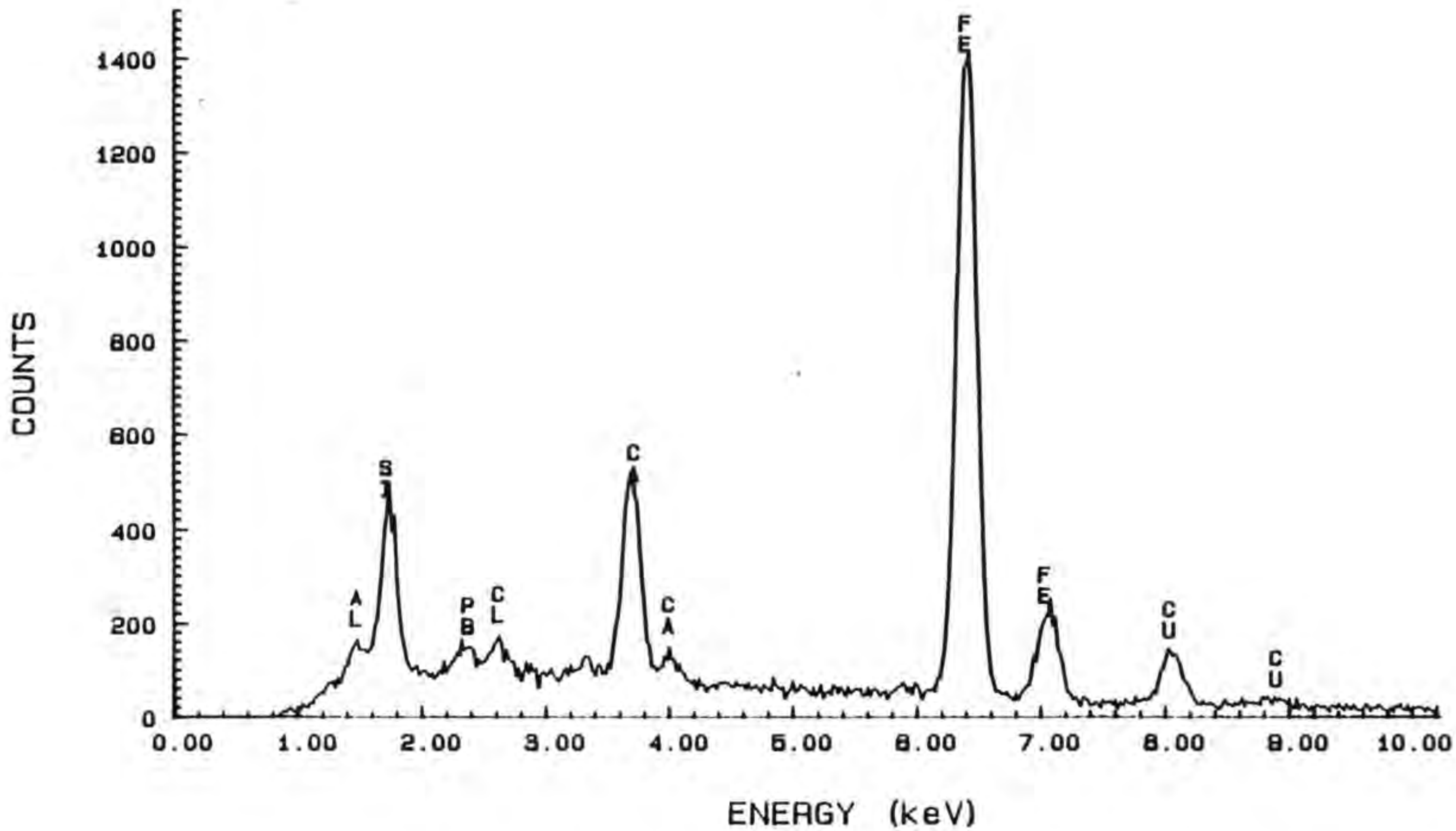

Figure 24: Energy spectrum of X rays emitted from the corrosion product on the fractured pin of the pin-strap piece. Note the variety of elements present in the deposit, including copper and calcium.

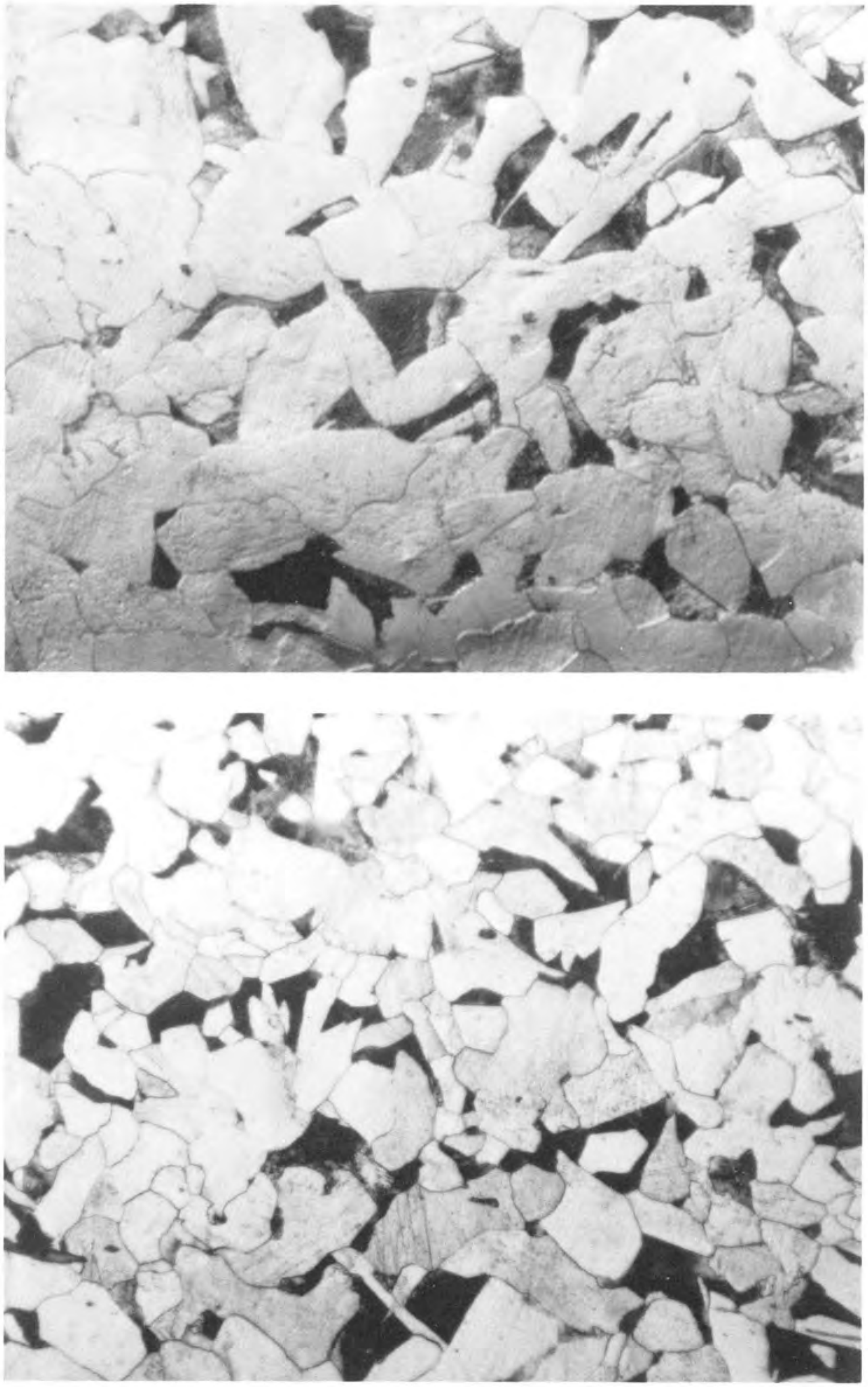

Figure 25: Photomicrographs of the matrix of the pins, showing a typical structure for a 1010 steel. The dark patches are pearlite, while the white areas are ferrite. The ferrite grains are equiaxed and contain no strain lines. x250.

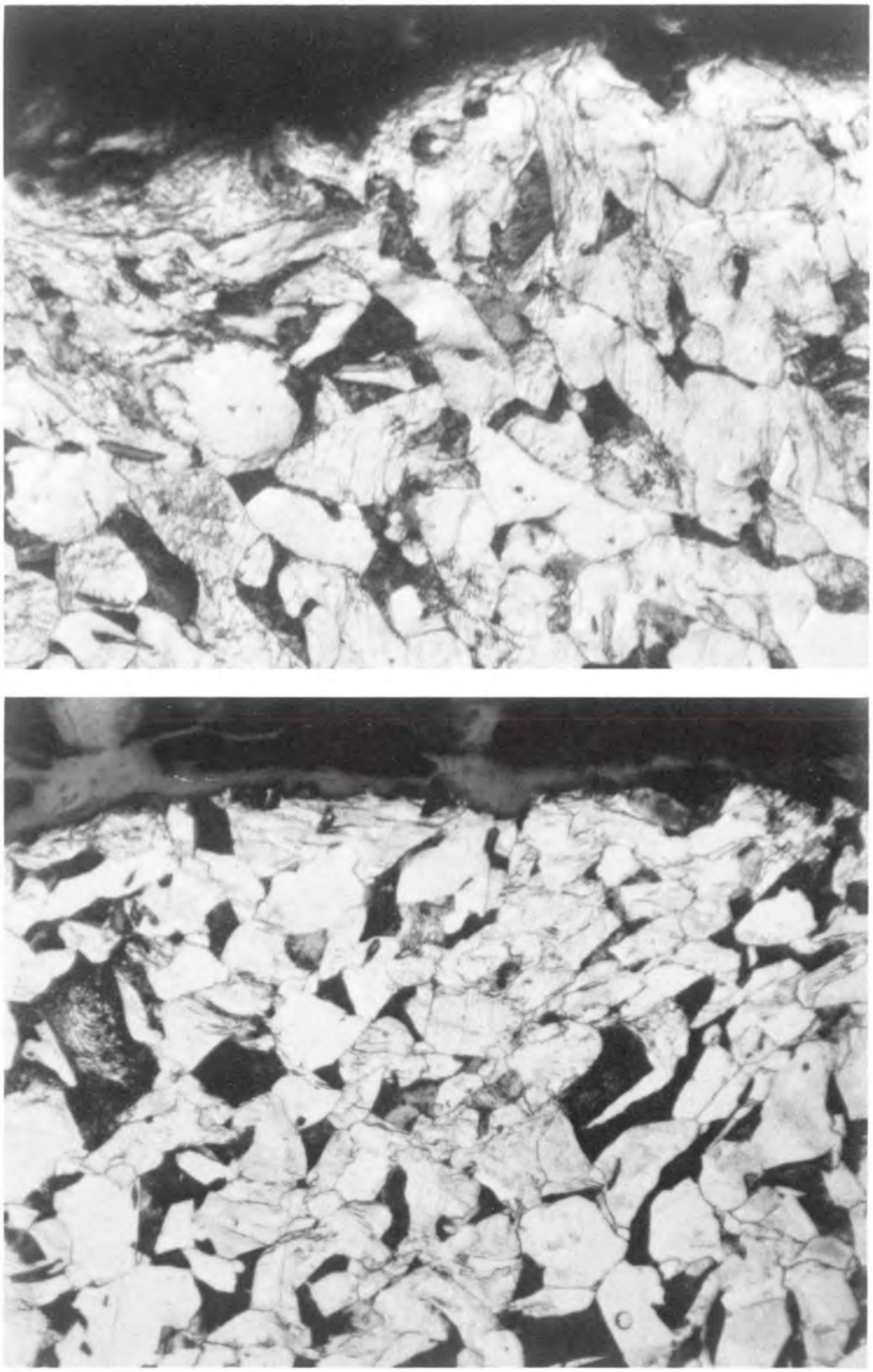

Figure 26: Photomicrographs of the steel pin adjacent to cracks and corrosion pits. (a) The matrix next to the crack in a Clinton pin and (b) the matrix next to the crack in an I-55 pin. Note the dark strain marks in the ferrite grains next to the crack. x250.

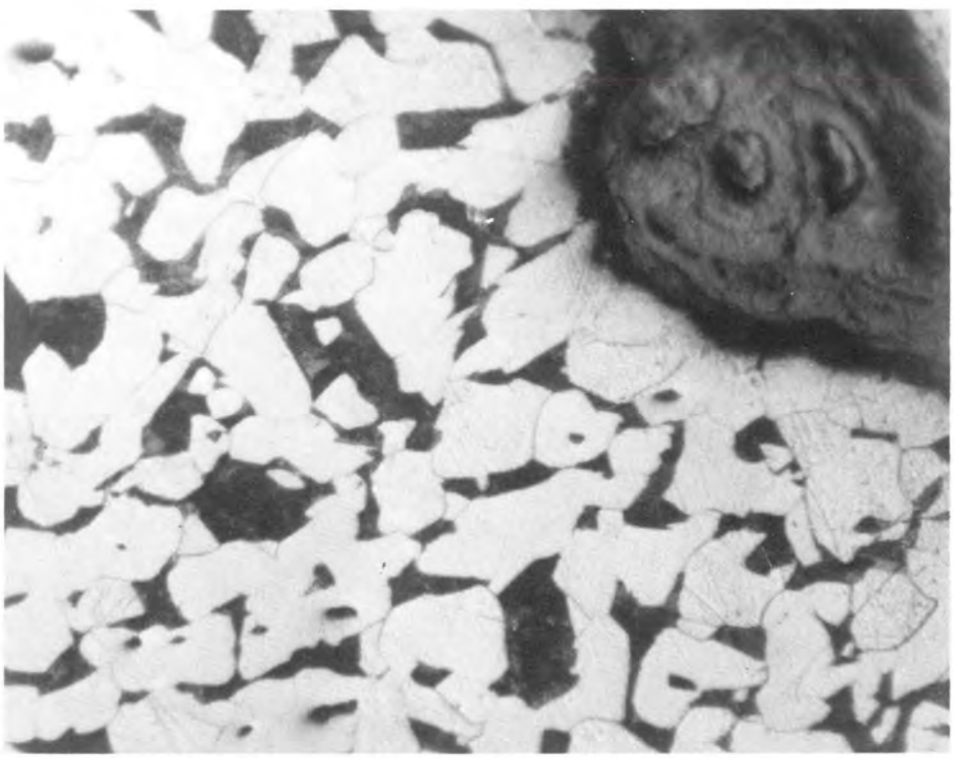

Figure 27: The matrix next to a corrosion pit from which no crack devel-oped. No strain marks are observed in the ferrite next to the corrosion pit. x250.