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DEFINITION OF MUTUALLY OPTIMUM NDI AND PROOF TEST CRITERIA FOR 2219 ALUMINUM PRESSURE VESSELS

VOLUME III APPLICATIONS TO RAIL DEFECT EVALUATION

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16. Abstract The success of ultrasonic nondestructive inspection methods and equipment in quantifying the location and size of buried defects in 2219 aluminum weldments for Space Shuttle lead to evaluation of the technique for inspection of railroad rails containing transverse fissure defects.

Both pulse-echo and pitch-catch inspection techniques were used. The pulse-echo technique results suggest that a multiple-scan approach using varying angles of inclination, three-surface scanning, and dual-direction traversing may offer promise of characterization of transverse defects. Because each scan is likely to produce a reflection indicating only a portion of the defect, summing of the individual reflections must be used to obtain a reasonably complete characterization of the defect.

Collimated pitch-catch technique results were also encouraging. Preliminary results show the ability of this technique to detect relatively small amounts of flaw growth. The method appears to have a problem in characterizing the portions of the defect near the top surface or web intersection.

The work performed was intended to be a preliminary evaluation of the prospects for automated mapping of rail flaws. Additional work should be performed to further study the multiple pulse-echo and collimated pitch-catch techniques as potentially practical systems for evaluation of railroad rails in the field.

17. Key Words NDI, Ultrasonic, Collimated, Pitch-Catch, Pulse-Echo, Defect, Railroad rails, Flaw Mapping

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FOREWORD

This report presents the results of the third phase of the program and deals with the application of the collimated ultrasonic pitch-catch technique to quantifying the location and size of buried defects in railroad rails. The Department of Transportation, Transportation System Center, Cambridge, Massachusetts funded this phase.

The work was performed under the management of NASA Project Manager Mr. Gordon T. Smith.

The Martin Marietta Program Manager for the activity was Fred R. Schwartzberg. Principal Investigator was Mr. Charles Toth, Jr. Messrs. Richard G. King and Paul H. Todd, Jr. assisted.

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SUMMARY

The success of ultrasonic nondestructive inspection methods and equipment in quantifying the location and size of buried defects in 2219 aluminum weldments for Space Shuttle lead to evaluation of the technique for inspection of railroad rails containing transverse fissure defects.

Two groups of rails were obtained--one from the Department of Transportation Center, another from the Denver and Rio Grande Western Railroad Company. In both cases, the rails had been in service and removed because of defects found during routine maintenance inspections.

Both pulse-echo and pitch-catch inspection techniques were used. Pulse-echo technique results suggest that a multiple-scan approach using varying angles of inclination, three-surface scanning, and dual-direction traversing may offer promise of characterization of transverse defects. Because each scan is likely to produce a reflection indicating only a portion of the defect, summing of the individual reflections must be used to obtain a reasonably complete characterization of the defect. This technique could be readily automated and computerized so that a computer graphics presentation of the defect would be presented.

Collimated pitch-catch technique results were also encouraging. Preliminary results show the ability of this technique to detect relatively small amounts of flaw growth. The method appears to have a problem in characterizing the portions of the defect near the top surface or web intersection. However, further evaluation may be able to correct this problem. The work performed to date has used machined side surfaces. Whether this is necessary for defect characterization was not studied. If necessary, this operation, although simple, would be a handicap to implementation of the pitch-catch method.

The work performed was intended to be a preliminary evaluation of the prospects for automated mapping of rail flaws. Additional work should be performed to further study the multiple pulse-echo and collimated pitch-catch techniques as potentially practical systems for evaluation of railroad rails in the field.

INTRODUCTION

NASA contract NAS3-17790, "Definition of Mutually Optimum NDI and Proof Test Criteria for 2219 Aluminum Pressure Vessels," was initiated to provide a rational basis for selection of proof-test and nondestructive inspection (NDI) acceptance criteria for Space Shuttle 2219 aluminum weldments. Volume I of this report describes the ultrasonic apparatus and illustrates how it was used to generate data applicable to Space Shuttle hardware.

An additional program was conducted to study specific aspects of the fracturing process using the ultrasonic methods and equipment already developed. This work is described in Volume II.

The success of the technique in quantifying the location and size of buried defects lead to an evaluation of the practicality of using this method for inspection of railroad rails containing transverse fissure defects. Funding for this activity came from the Department of Transportation (DOT), Transportation System Center. This volume describes the evaluation of railroad-rail defects.

EXPERIMENTAL APPROACH

The first series of rails (received from the DOT) was initially evaluated using conventional pulse-echo C-scan ultrasonic inspection techniques at a frequency of 2.5 MHz. Inspection was performed both normal and at an inclination of 70° to both the top and side surfaces. Because the emphasis was on head defects, no attempts were made to evaluate the web or flange sections.

After preliminary inspection, the rails were cut into 0.7-meter (2-ft) lengths and the heads parted from the web. The sides of the head were machined to remove only enough material to provide flat, parallel surfaces.

Rails were then reexamined using the pulse-echo C-scan technique from the side surfaces only, with normal and 70° inclination of the transducer.

The system was then modified for collimated pitch-catch inspection. Although detailed descriptions of the technique are given in Volumes I and II, highlights of the method are summarized in this volume.

Figure 1 is a schematic of the concept. The transmitted signal was reflected from the back surface of the material being evaluated. The receiving transducer was positioned for angle and appropriate distance to maximize reception of the reflected signal. Because the collimators reduced the beam to a small diameter, precision adjustment of the transducer combination was essential. Defects were precisely located by traversing the transducer array until the presence of a defect blocked the signal. As shown in Figure 1, defect growth could be characterized in terms of the location where the defect blocked the signal.

The short rail sections were then inspected using the collimated technique, and two pieces (sections from rails 64 and 65) were selected for cyclic loading and study of defect growth.

Initially, specimens were flexurally loaded in a Sonntag fatigue machine. Flexure did not promote the desired type of uniform growth. The remainder of the growth was created in tension and provided satisfactory simulation of service growth. To grip specimens in a 690-kN (100-kip) closed-loop servohydraulic testing machine, the head surface was machined flat at each end to permit insertion in friction grips.

Specimens were alternately cycled and inspected until adequate growth was detected. No attempt was made to inspect during loading.

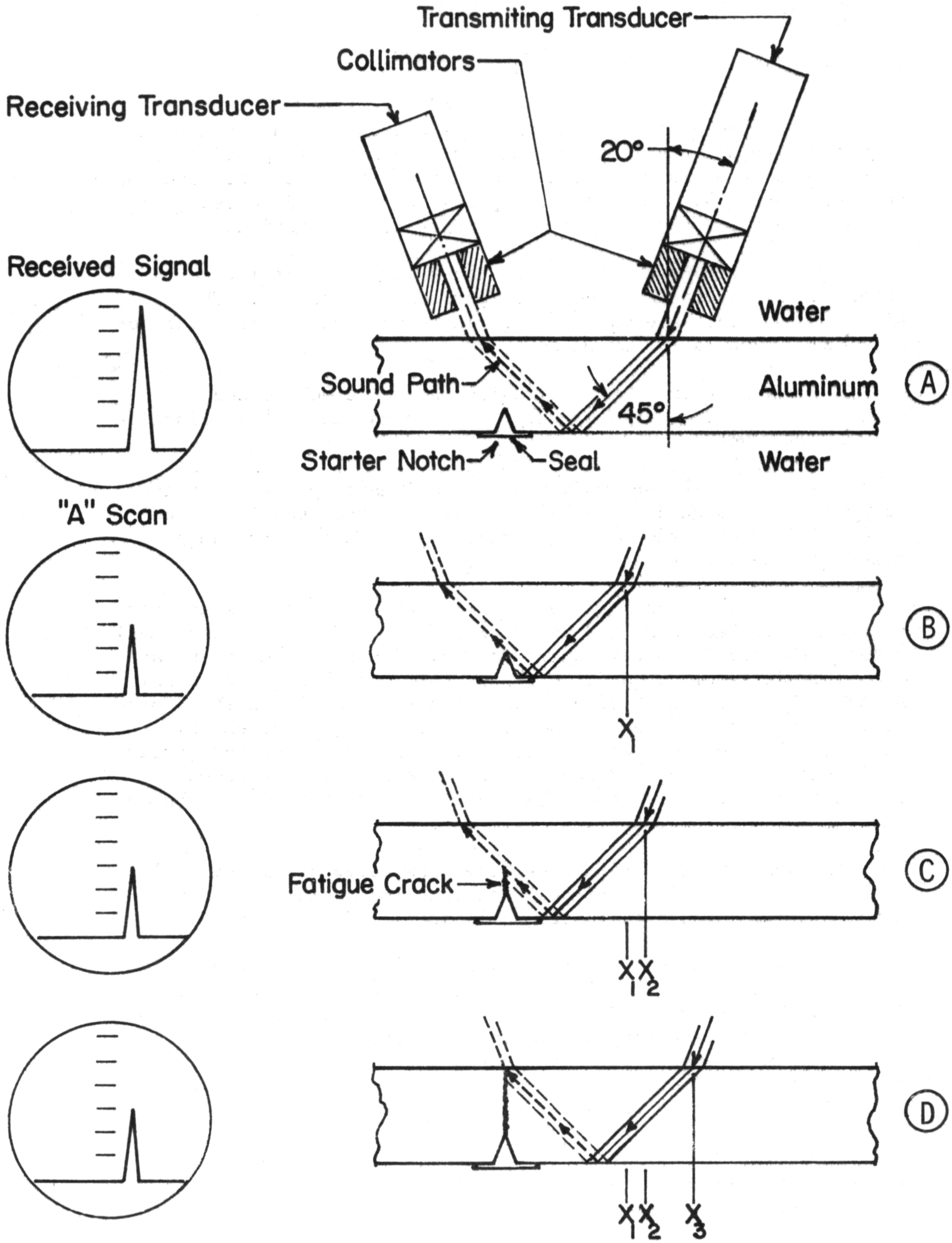


Figure 1. - Schematic of collimated pitch-catch technique.

The second series of rails (obtained from the Denver and Rio Grande Western Railroad Company) was received in lengths of approximately 0.7 m (2 ft) and were cut to remove the web and flange and machined to give flat, parallel side faces. Pulse-echo C-scan measurements were made with the transducer inclined at an angle of 70°. The top and side surfaces were evaluated.

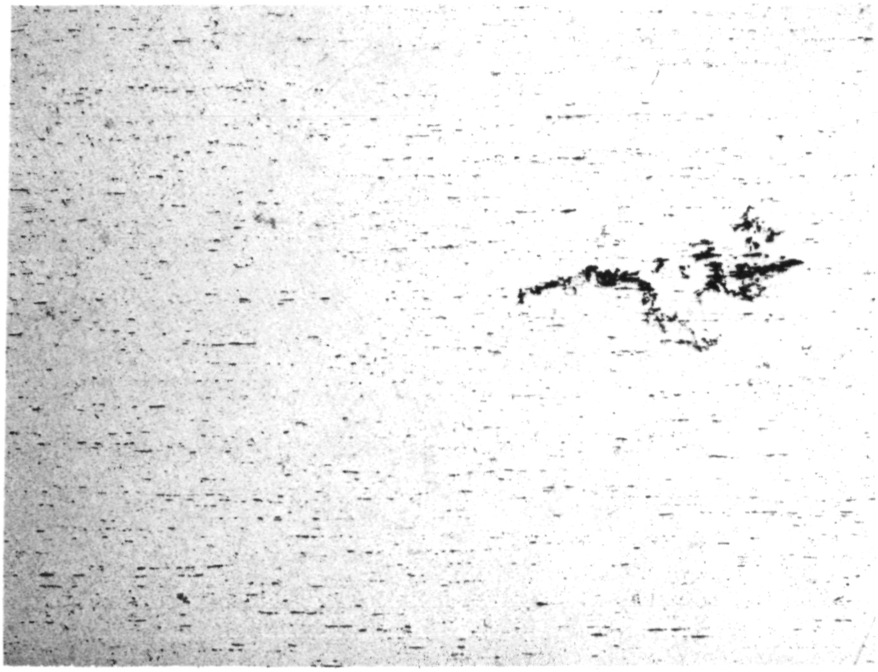
Specimens were then evaluated using the collimated pitch-catch ultrasonic technique from the side surfaces only. Specimens were then cyclically loaded to provide flaw growth and periodically reexamined.

MATERIALS

Rails for evaluation in this program were obtained from two sources. The first group of rails was obtained from the Department of Transportation Transportation Center and had been subjected to various investigations. A second group of rails was procured from the Denver and Rio Grande Western Railroad Company. In both cases, rails had been in service and were removed because of defects found during routine track maintenance inspections.

EXPERIMENTAL RESULTS

Ultrasonic C-scanning using conventional pulse-echo techniques was performed on the as-received first series of rails to locate the defects that required removal from service and to determine the detectability of transverse fissures. The high level of inclusions in the steel produced so many defect indications that operators, unaccustomed to evaluating this type of material, had difficulty establishing the locations of the transverse fissures. The ultrasonic inspection was repeated several times to verify that the indications were due to inclusions. Sectioning and macroetching confirmed the high level of inclusions. Figure 2 shows such a section.



As-polished 10X

Figure 2. - Longitudinal section through rail obtained from DOT.

Rails containing defect location markings were cut into 0.7-m (2-ft) lengths and the heads parted from the web section. Side faces were inspected using the pulse-echo technique with the transducer oriented 90° and 70° from the surface. Data for the normal (90°) scans failed to identify transverse fissures, but did show the numerous inclusions in the rail steel. Figure 3 shows part of the scans for the various sections. Scans made at 70° inclination using two different gain levels indicated defects in three sections. It was unclear whether there were defects in the other rail sections. Note the difference between the number and relative size of the indications as a function of gain. Although defects were apparent, characterization could not be made directly from the C-scans illustrated.

The rails were ultrasonically inspected using the collimated pitch-catch technique. The same ultrasonic monitoring and traversing apparatus was used except for the substitution of the dual transducer head. These collimated beam scans clearly showed large indications in two rail sections. The scans in figure 4 show these defects. Note that each defect indication appears twice because the defect blocked the ultrasonic signal reflected from the back surface; then, as the transducer was moved, the defect blocked the direct signal. Figure 5 illustrates this sequence. The distance between the two defect indications was a function of the thickness of the material, defect magnitude, and defect location.

Rails 64 and 65 contained two defect indications and were selected for more extensive ultrasonic evaluation and cyclic loading. Subsequent work used the Sonnatest UFD-1 ultrasonic generator and a X-Y recorder. A Budd SR-150 ultrasonic bridge scanning system was used to drive the transducer assembly. Using this system, another series of pulse-echo measurements was made of rails 64 and 65.

Rail 65 was inspected in six directions, representing traverses from left to right and right to left (two directions) for each of the three surfaces (head and each side). Figure 6 shows the scans obtained by traversing the head in each direction. Note the significant difference in size and shape of the defect indications. Similarly, figures 7 and 8 show the scans for each side face. One trace was duplicated on the next day and was found to agree quite well with the previous result. Such scans had to be adjusted for the angle of transmission of the signal through the metal. By doing so and making a composite of the seven scans (six directions plus one repeat), the representation of the defect shown in figure 9 was obtained. Experience has shown that a better correlation with actual defect size was obtained by incorporating a correction for beam width. Figure 10 illustrates the reduction in size of the indicated defect by half- and full-beam-width correction and compares actual defect size and shape.

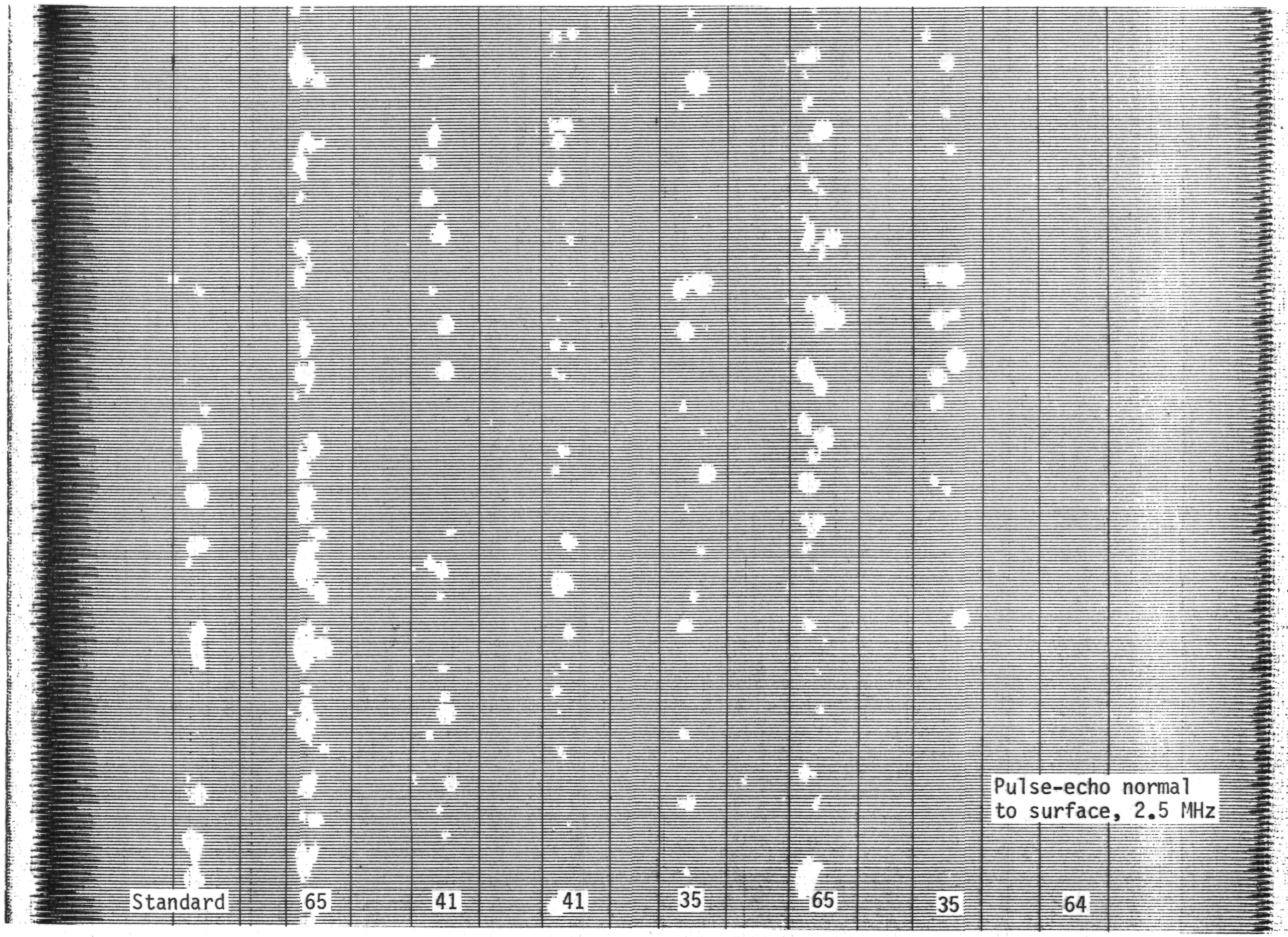


Figure 3. - Pulse-echo scan of DOT rails (side of head).

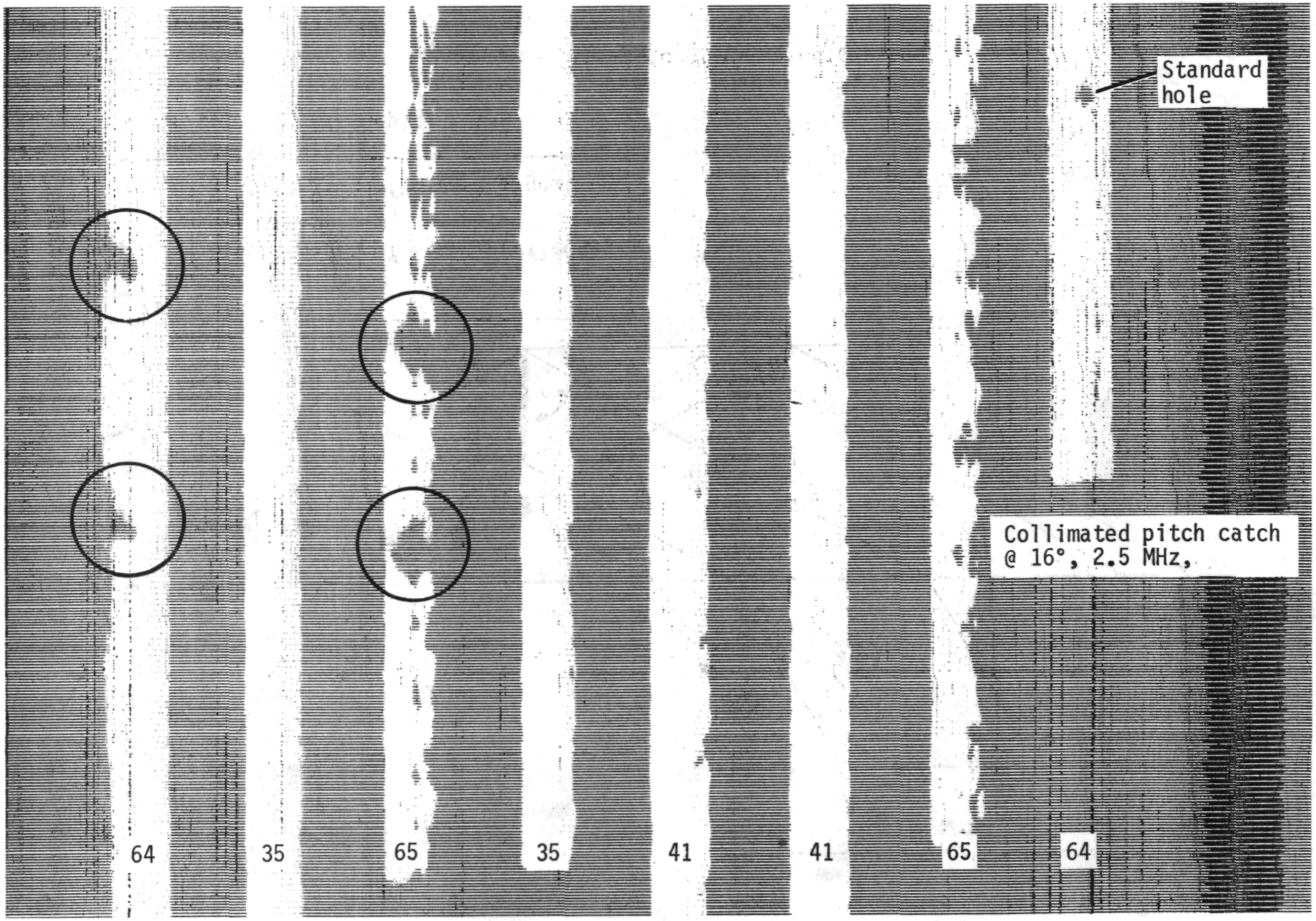
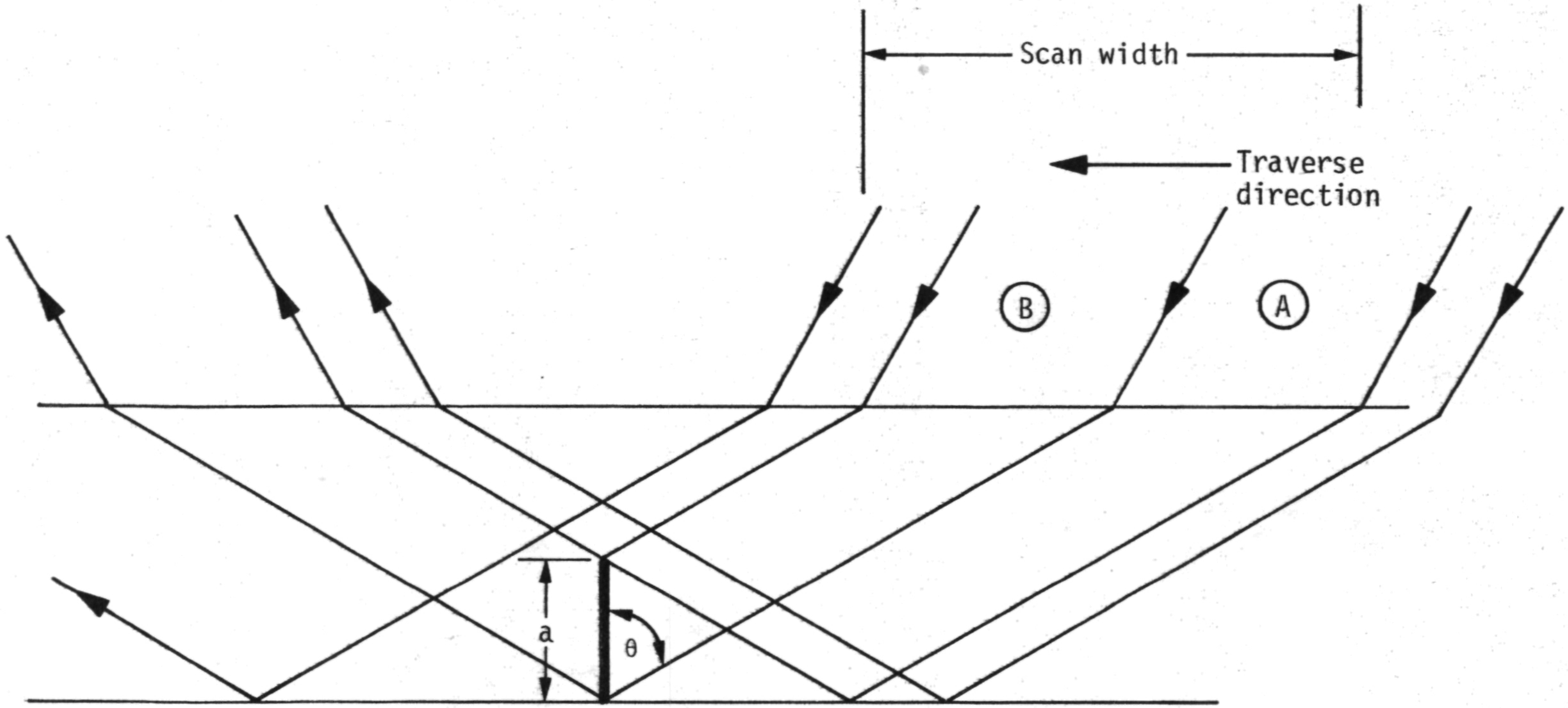


Figure 4. - Collimated pitch-catch scan of DOT rails (side of head).



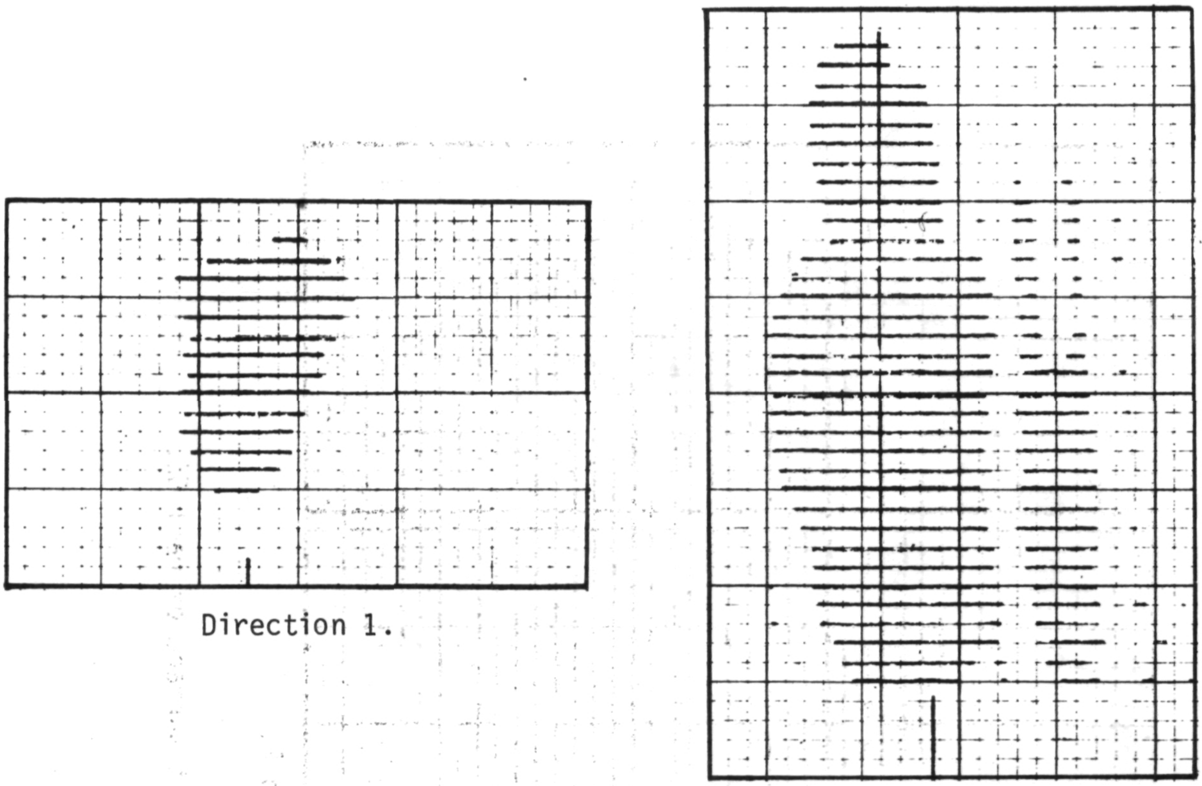
Legend:

Ⓐ No transmission of signal reflected from back surface

Ⓑ No transmission of direct signal

Scan width/2 = a (crack depth) x tan θ

Figure 5. - Schematic of ultrasonic path.



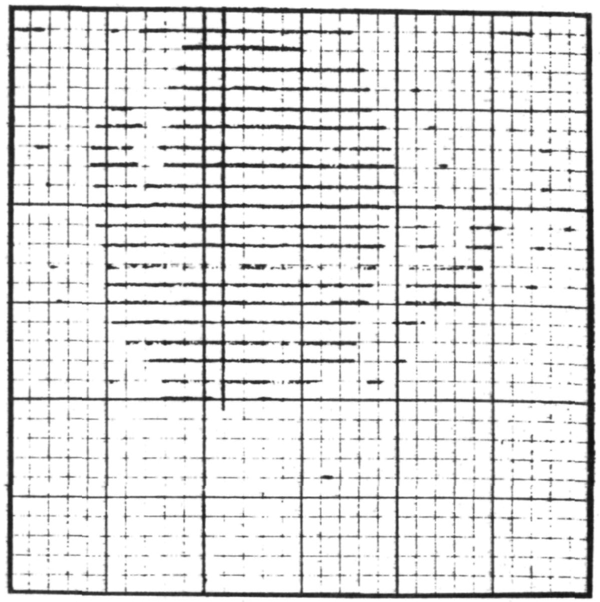
Direction 1.

Direction 2.

Figure 6. - Pulse-echo scans of top surface of rail 65.

Rail 64 was similarly evaluated. Two scans failed to show evidence of a defect. Three scans revealed small defect indications and one revealed a large indication. Figure 11 shows the composite of the various scans. Note the significant difference in the size and location of individual indications. The large dotted image was obtained from a top-surface traverse. The top-surface traverse in the opposite direction did not produce any reflection. Traverses from the side surfaces produced small indications grouped together, which suggested that defect characterization might be influenced by detail fracture.* Side-surface

*Detail fracture - A fracture starting from a longitudinal separation close to the running surface on the gage side of the rail head that rotates to progress transversely. This is a service defect and one of the more serious unsolved rail-failure problems.


Direction 1.

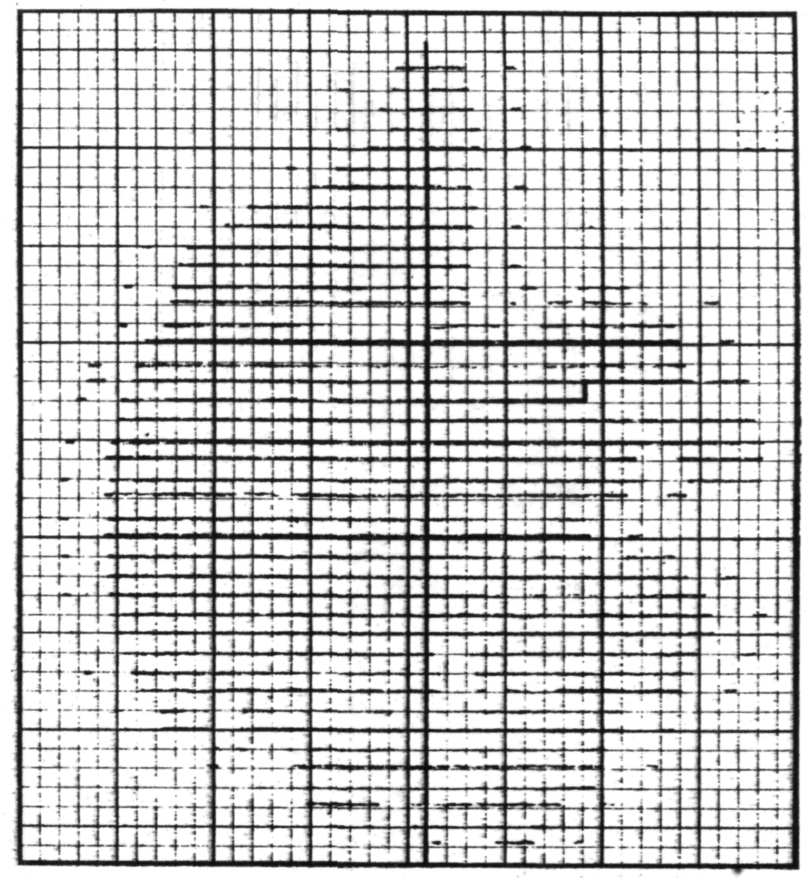
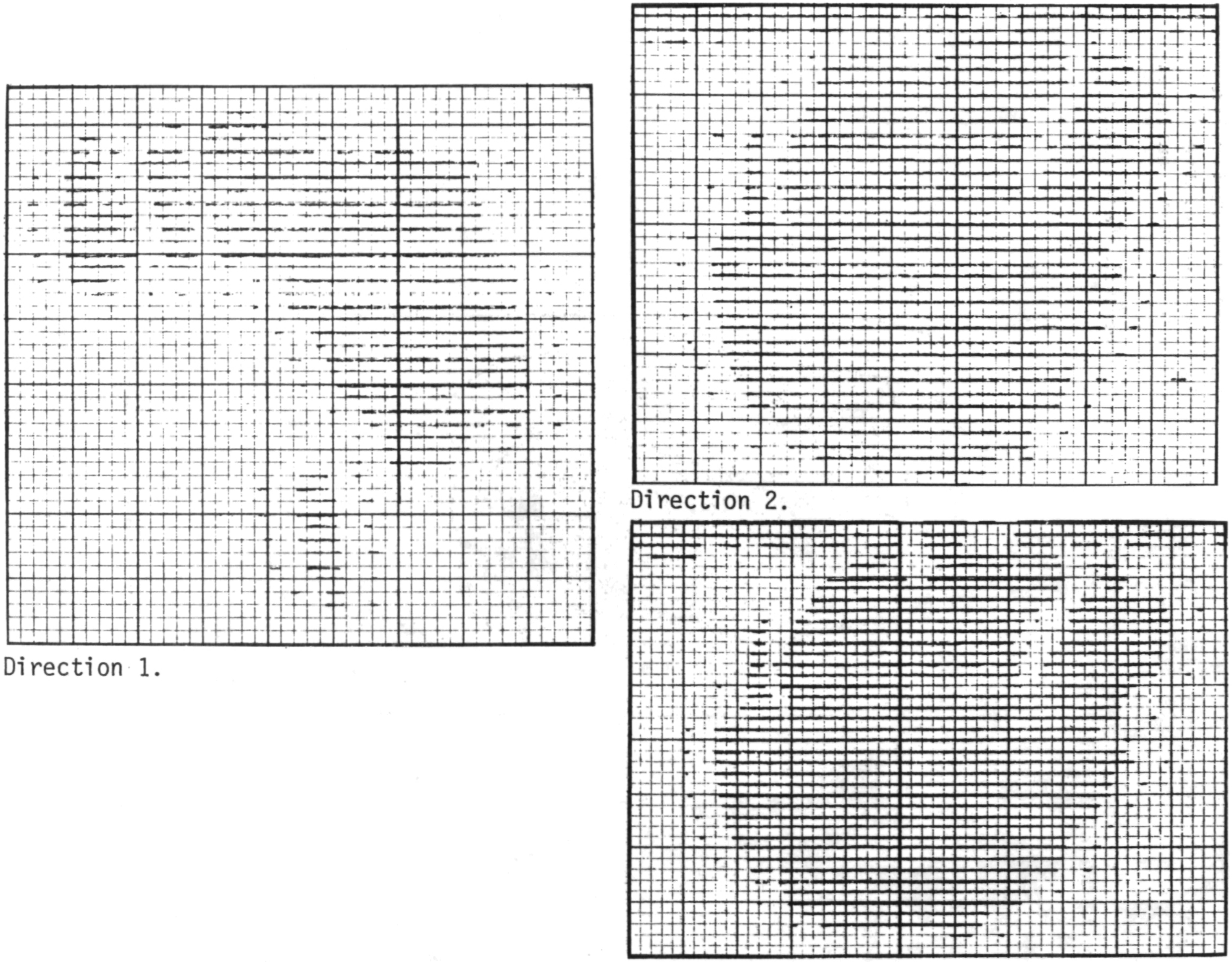

Direction 2.

Figure 7. - Pulse-echo scans of front surface of rail 65.



Direction 1.

Direction 2.

Direction 2 repeated.

Figure 8. - Pulse-echo scans of back surface of rail 65.

traverses characterized the transverse portion of the defect. Figure 12 illustrates the envelope suggested by the transverse portion.

Opening the defect confirmed that initiation was in the longitudinal direction and that, during propagation, it rotated to the transverse orientation. Figure 13 shows the fracture surface.

Collimated pitch-catch measurements on the side faces only were made of rails 64 and 65.

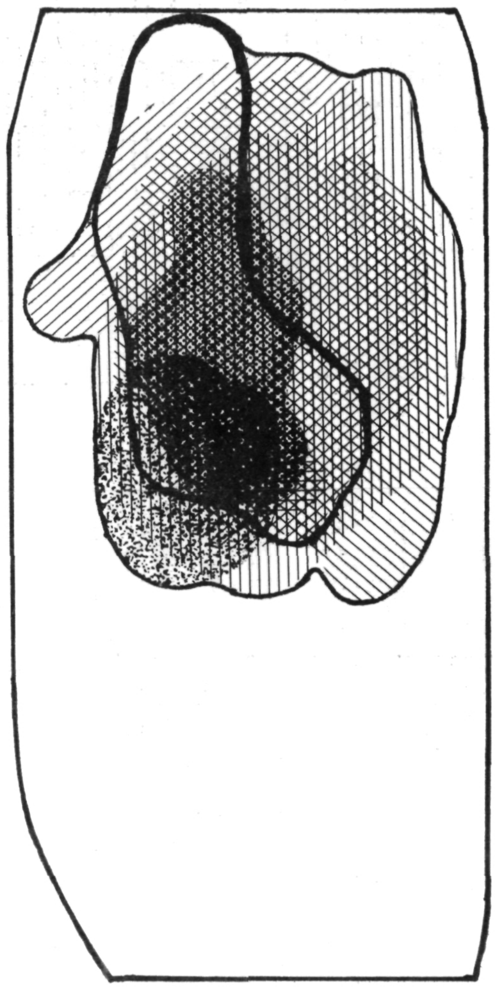
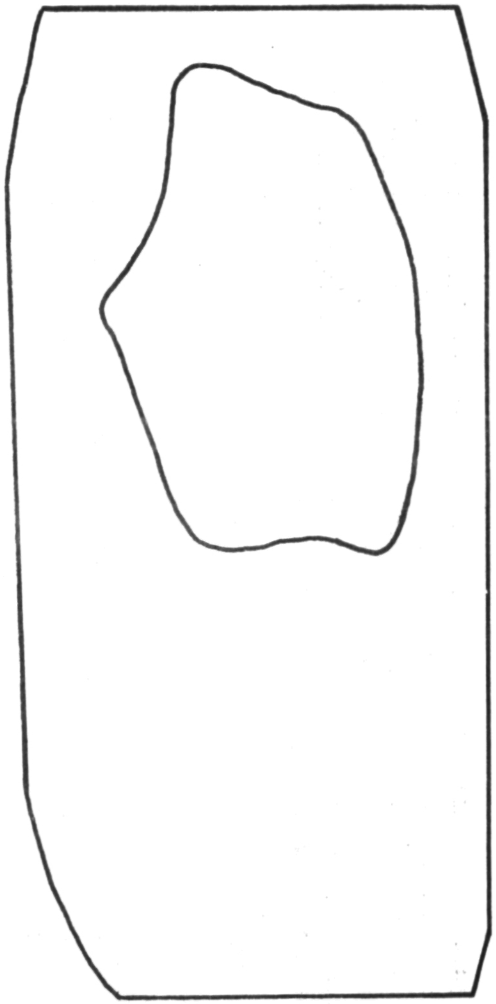
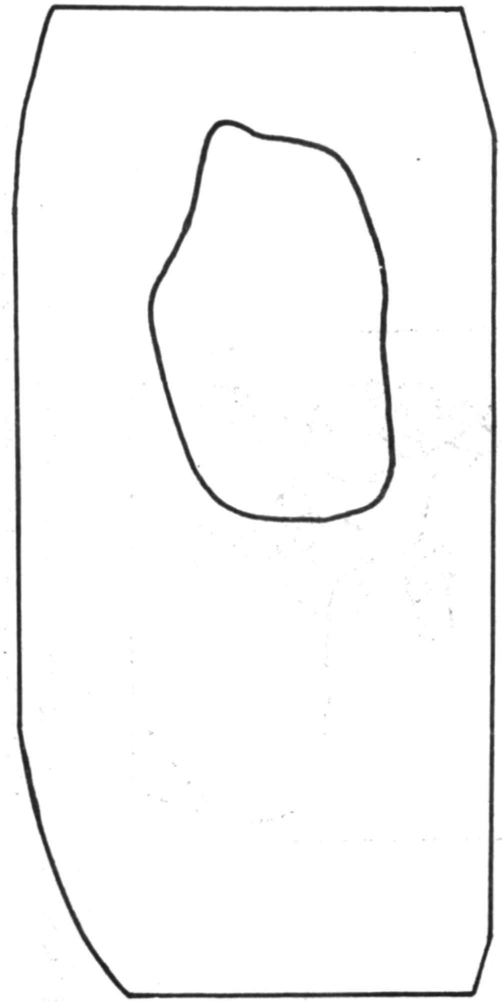


Figure 9. - Characterization of defect in rail 65 obtained by multiple pulse-echo scans.



50% beam-width correction.



100% beam-width correction.

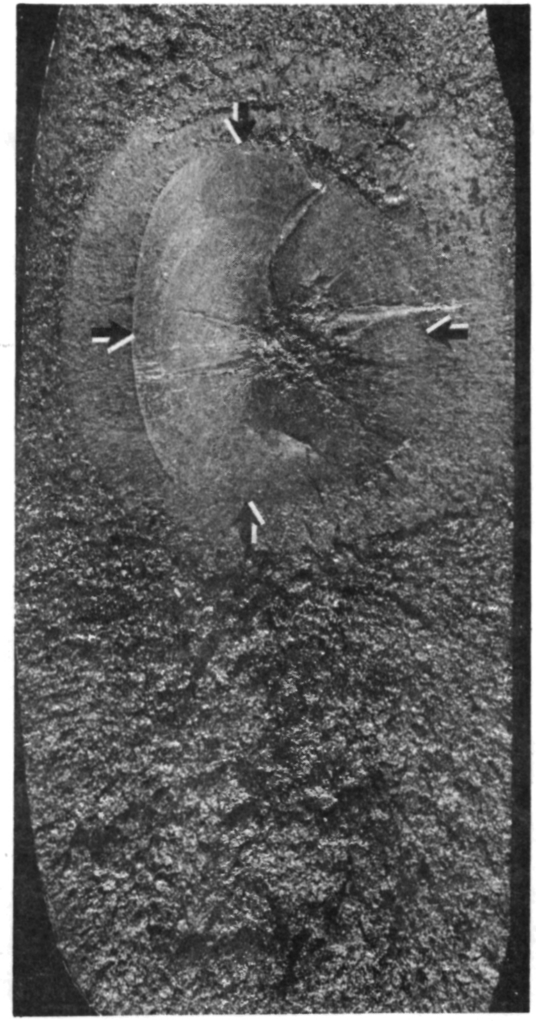


Figure 10. - Comparison of fracture with corrected pulse-echo scans of rail 65.

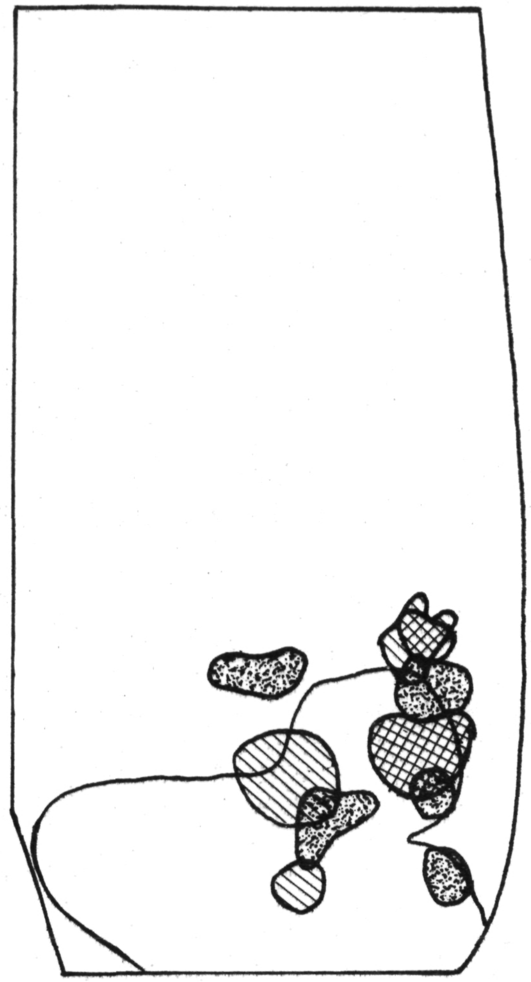


Figure 11. - Characterization of defect in rail 64 obtained by multiple pulse-echo scans.

Figure 14 illustrates actual rail 64 data evaluated from each side. The trace from one side shows two indications of the defect widely spaced; the trace from the other side shows the indications to be overlapping.* This observation indicated that the defect was quite close to one side. Further study of the figure showed that the defect was near the head. The dissimilarity in size of the two indications suggested an orientation that is not normal to the surface.

*The short lines adjacent to the defect indication are ink blots caused by the rapid raising or lowering of the pen, and should be disregarded.

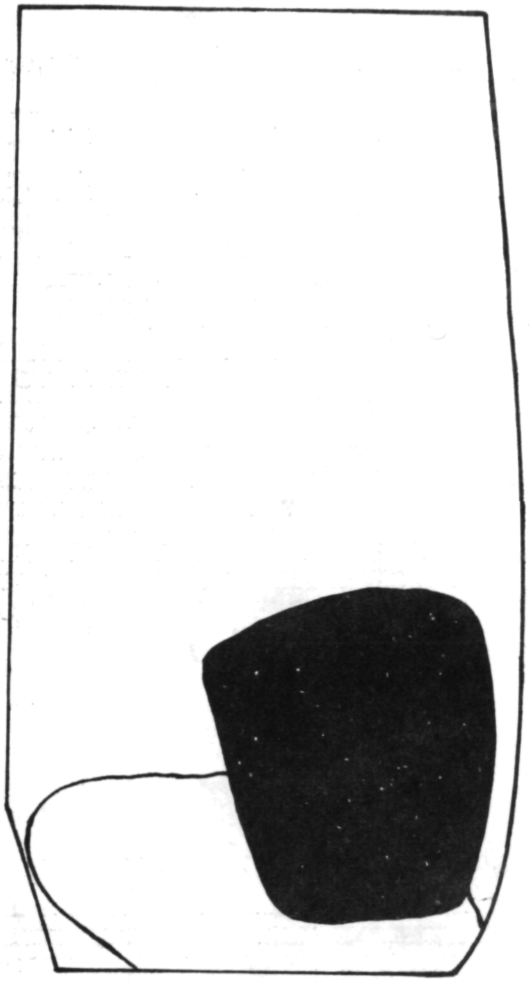


Figure 12.- Characterization of transverse portion of defect in rail 64.

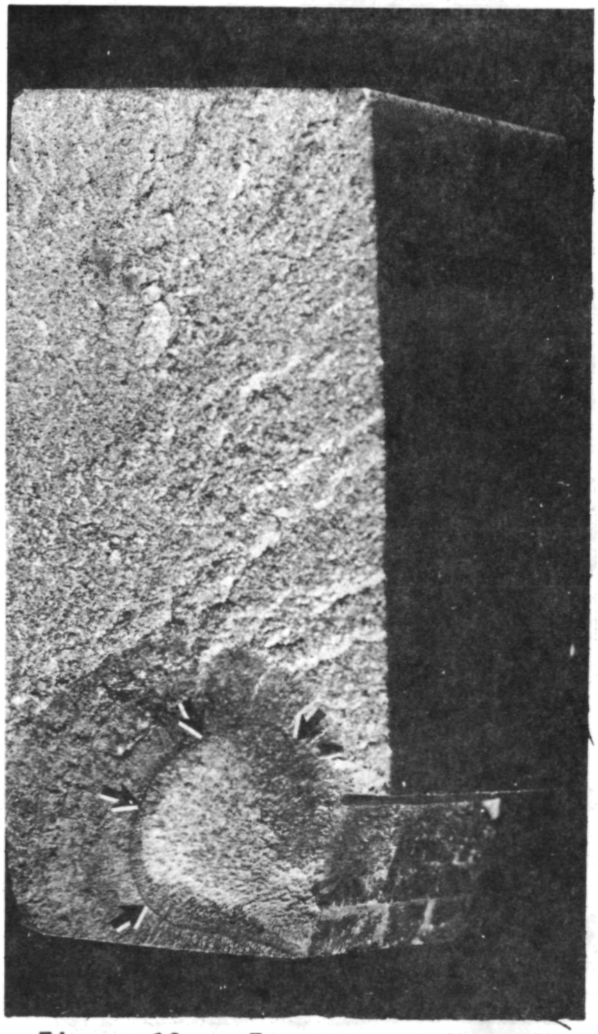


Figure 13. - Fracture surface of rail 64.

To enlarge the defect, the specimen was then subjected to a series of cyclic loadings at 172 MN/m^2 (20 ksi). After each cyclic loading, the rail section was reinspected. The growth band was marked by cycling at a lower stress to produce a small growth band of different appearance. The marking cycle was 5000 reversals at a stress of 138 MN/m^2 (20 ksi). Five growth and inspection sequences were performed. Figure 15 is an ultrasonic record after cycling in which depth growth was apparent. For additional clarity, ink blots have been removed, and a flaw map of these data transformed to true shape. Figure 16 shows a fracture-face photograph.

Rail 65 was similarly inspected, cycled, and reinspected using the collimated pitch-catch ultrasonic technique. Actual data traces are combined in figure 17 to illustrate growth resulting from cycling. The data traces suggest that the defect extends

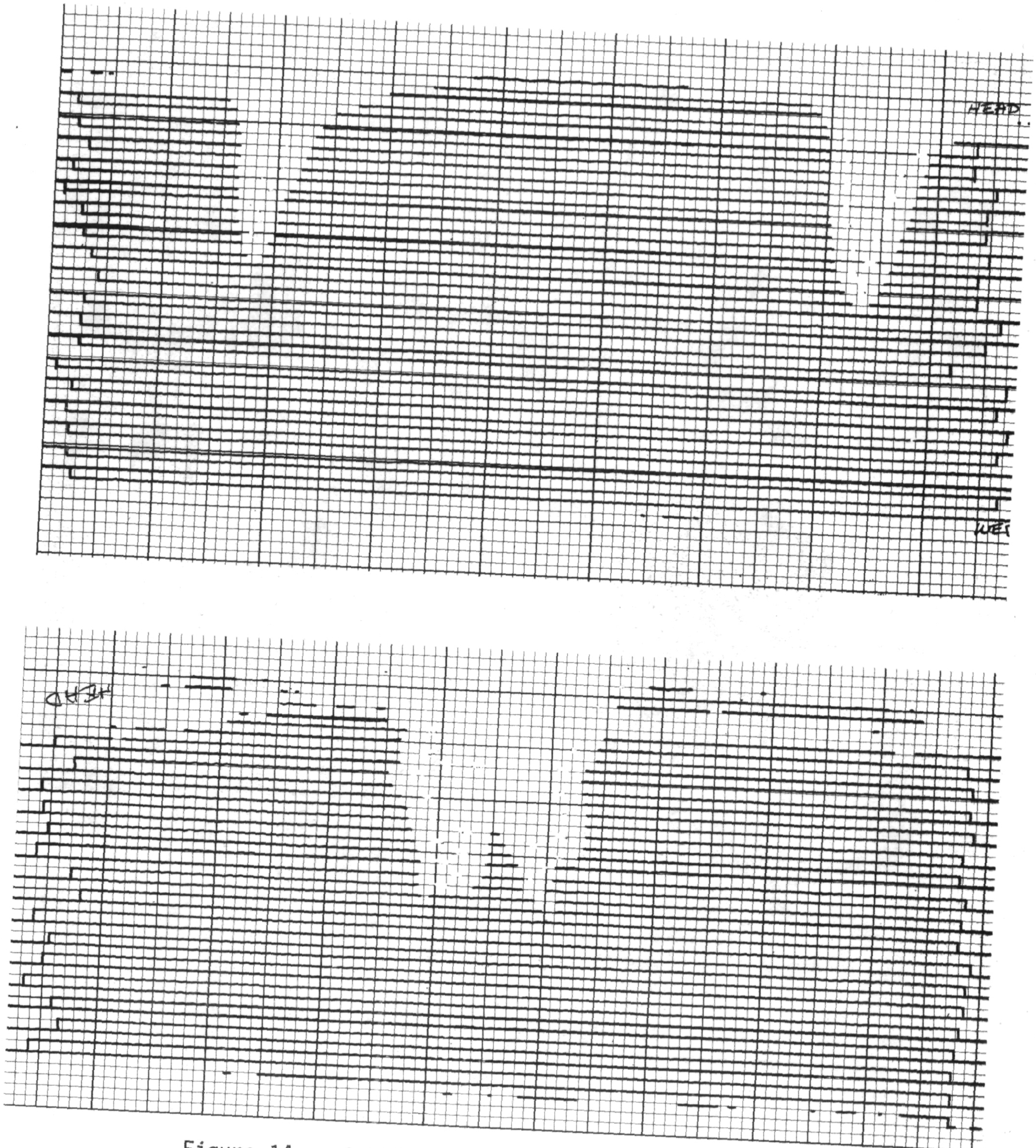


Figure 14. - Collimated pitch-catch data for rail 64
in as-received condition.

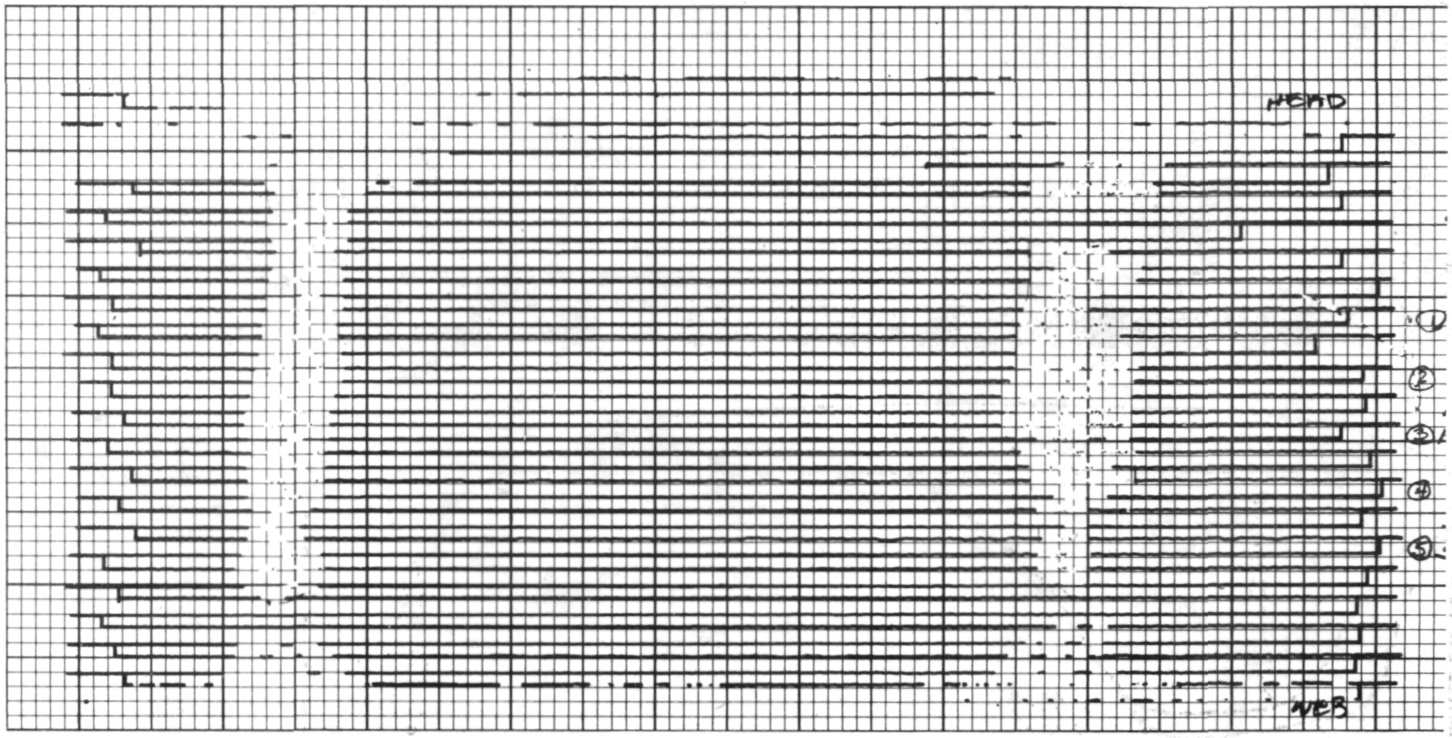


Figure 15. - Collimated pitch-catch data for rail 64 after cyclic loading.

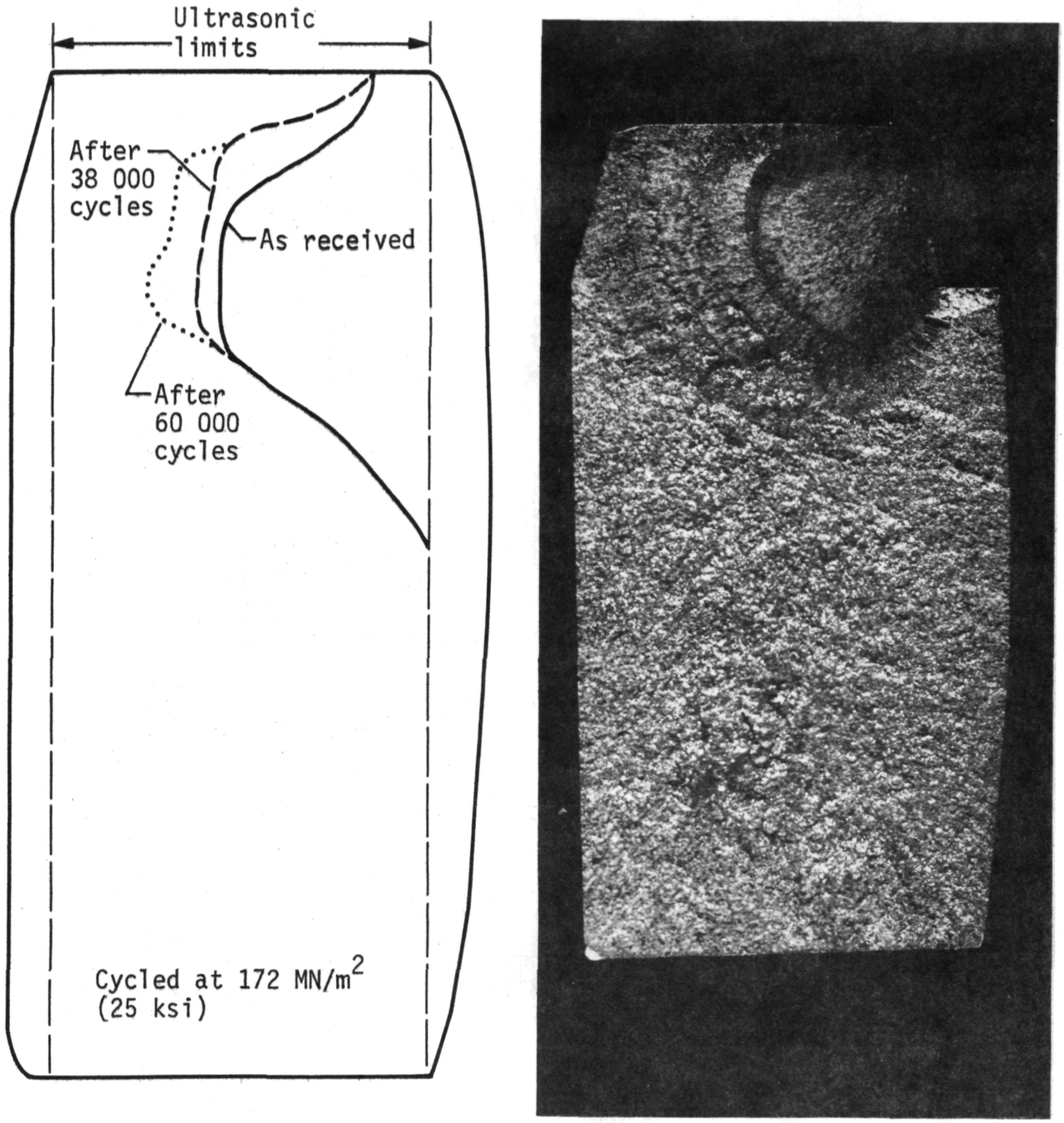
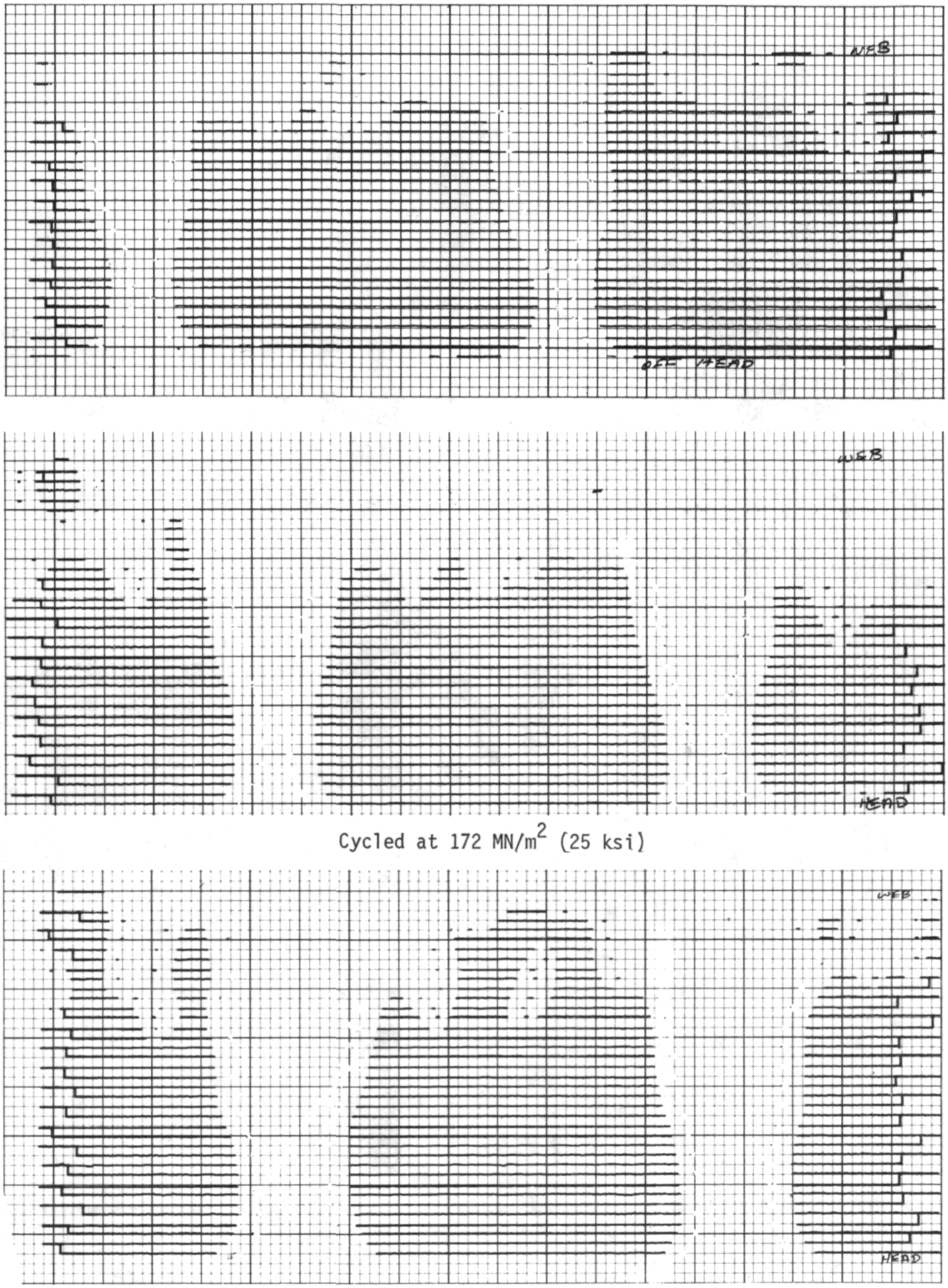


Figure 16. - Pitch-catch flaw map and fractograph of rail 64.



As received

After 20 000 cycles

Cycled at 172 MN/m^2 (25 ksi)

After 31 000 cycles

Cycled at 172 MN/m^2 (25 ksi)

Figure 17. - Collimated pitch-catch data for rail 65 in as-received condition and after cycling.

through the entire section from head to web. The traces also suggest an hourglass shape for the defect. The fractograph in figure 18 shows the defect to be totally embedded; a flaw map constructed from the data is also shown.

The results of this part of the evaluation show that, although crack growth could be tracked, the ability to map the entire cross section was limited. It appeared that only the central portion could be adequately monitored. As the head and web surfaces were approached, the ultrasonic signal did not validly represent the defect shape.

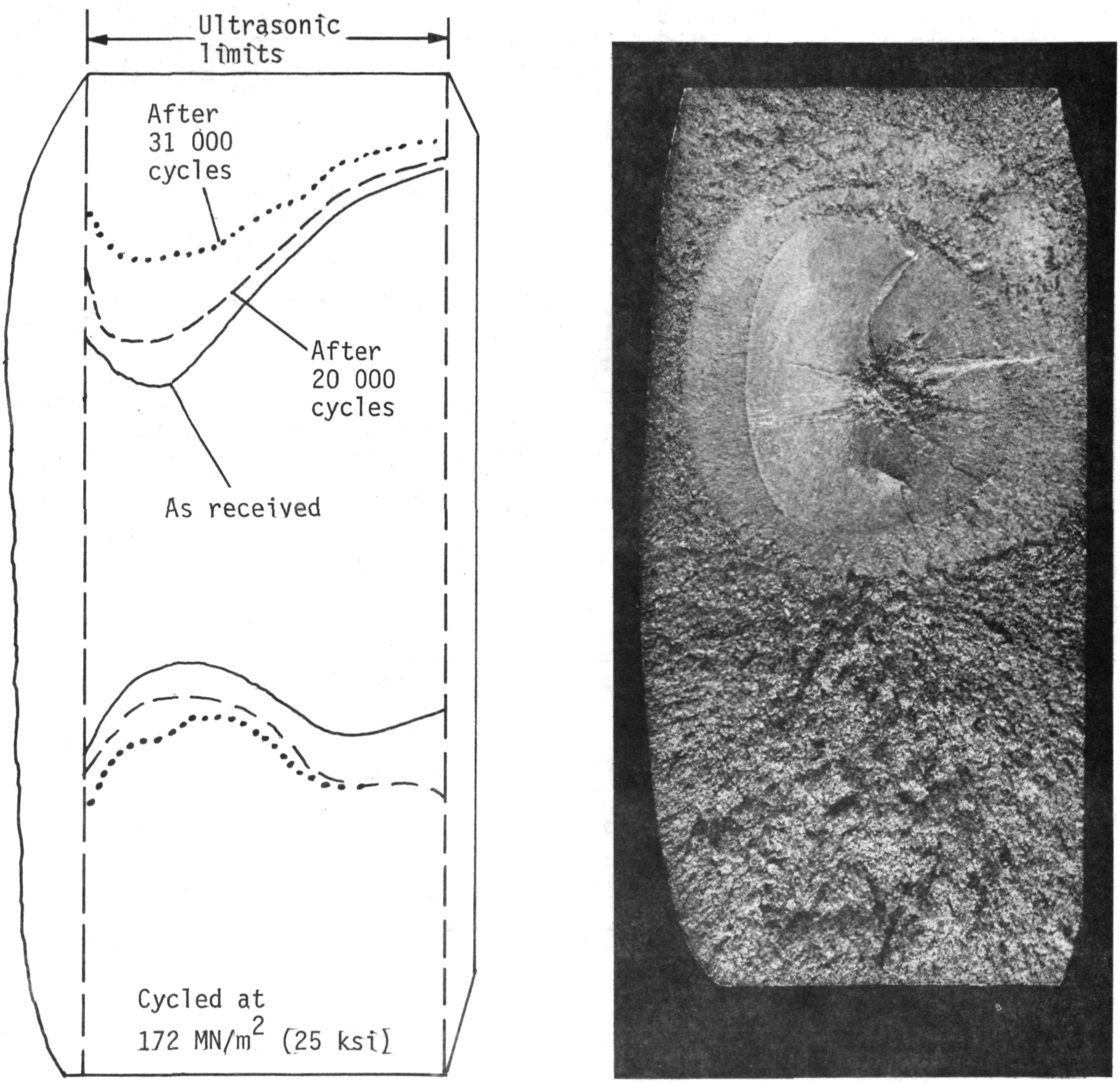
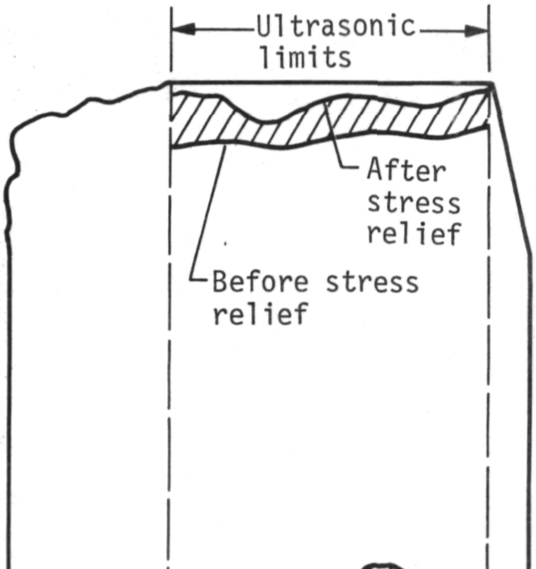


Figure 18. - Pitch-catch flaw map and fractograph of rail 65.

The second series of rails (1 through 6) was evaluated using the ultrasonic pitch-catch technique. Rail 1 was ultrasonically inspected, then stress relieved at 538 C (1000°F) for 2 hours and reinspected. Ultrasonic inspection indicated that the defect extended from close to one surface to approximately halfway across the width; the defect was shown to be at least 2 cm (0.8 in.) high. Figure 19 shows a fractograph of the defect and the flaw map drawn before opening. Stress relieving had little effect on the appearance of the defect.



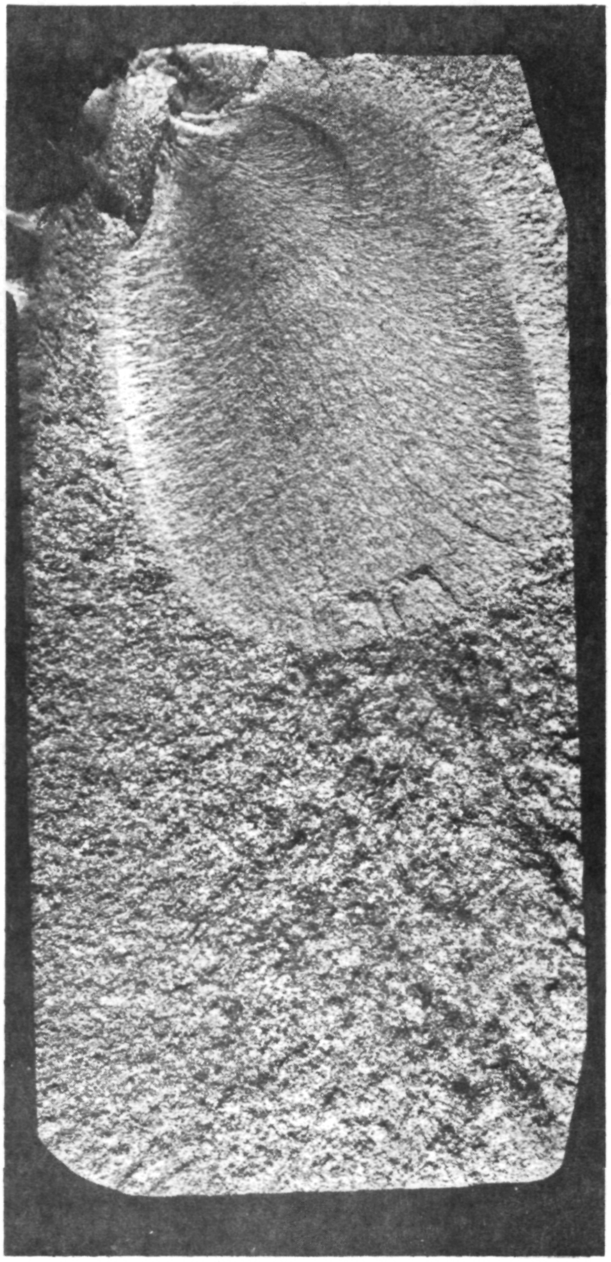


Figure 19. - Pitch-catch flaw map and fractograph of rail 1.

Rail 2 was inspected, cycled, and reinspected. Agreement between the flaw map and fractograph was relatively good, as shown in figure 20.

Rail 3 showed a large defect indication. Actually, two defects in close proximity were noted. The flaw maps indicated large defects of irregular shape. We surmised that part of the indication resulted from a detail fracture oriented so that it partially

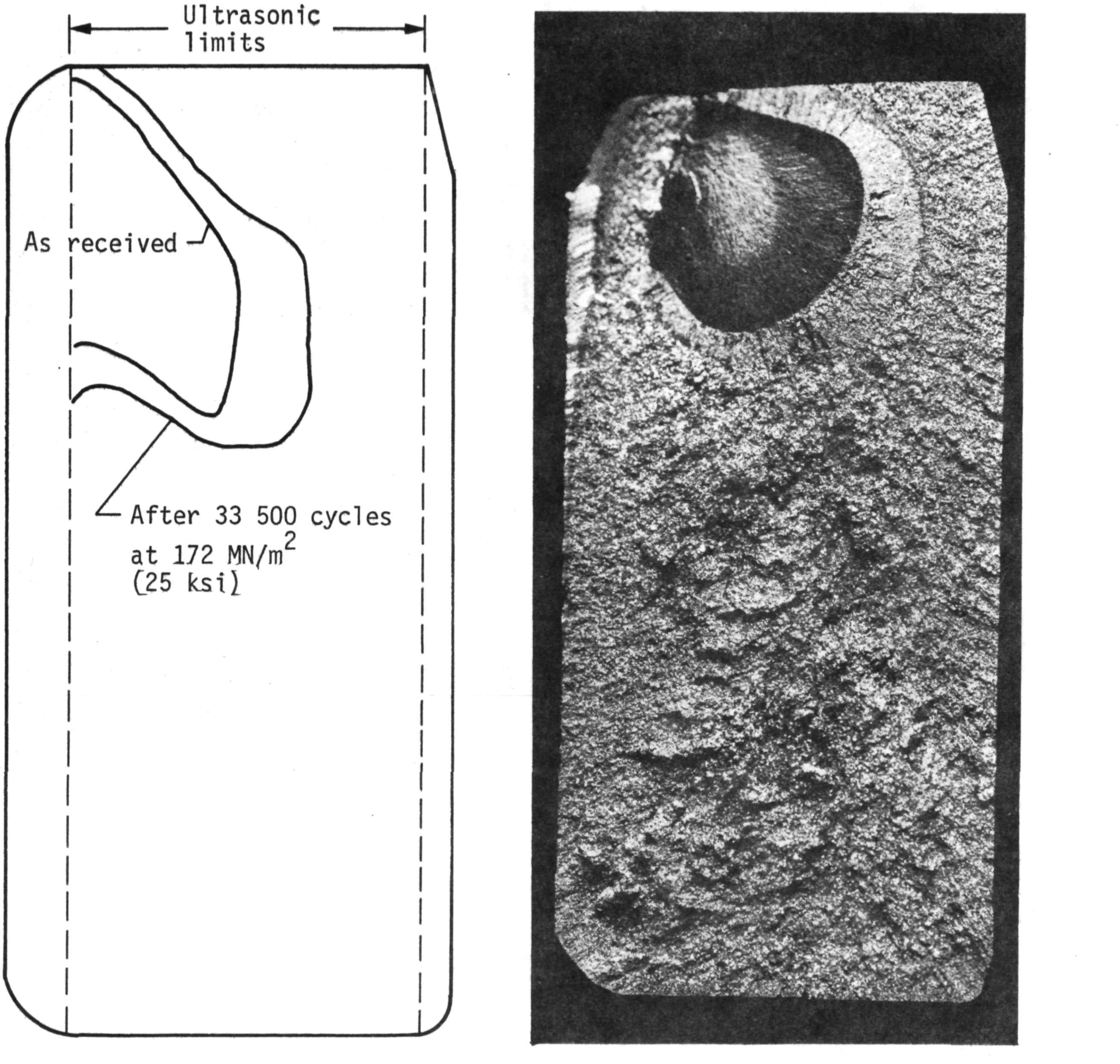
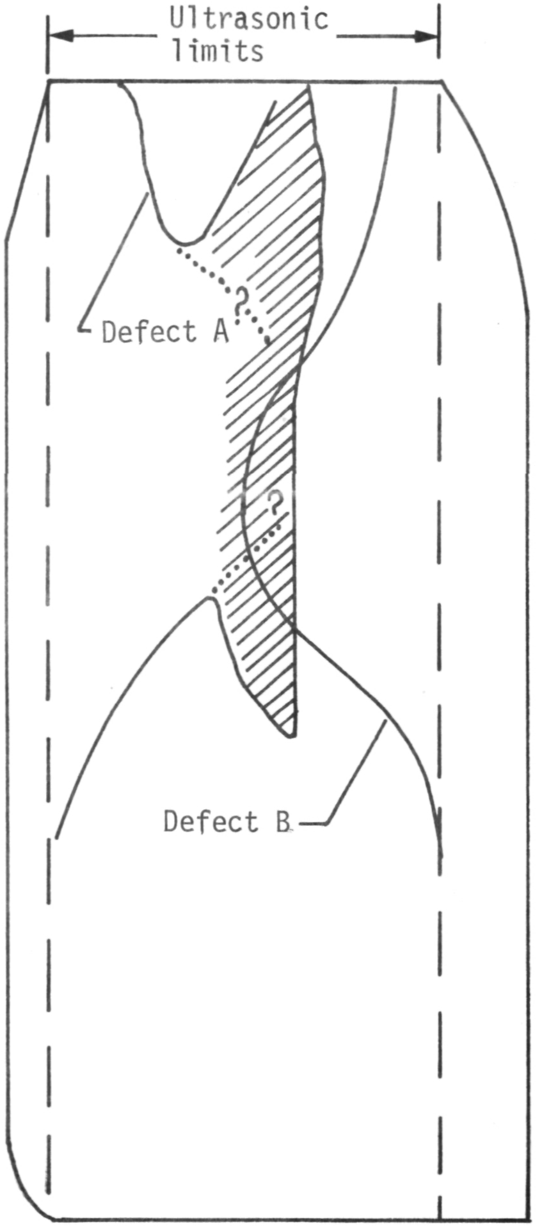


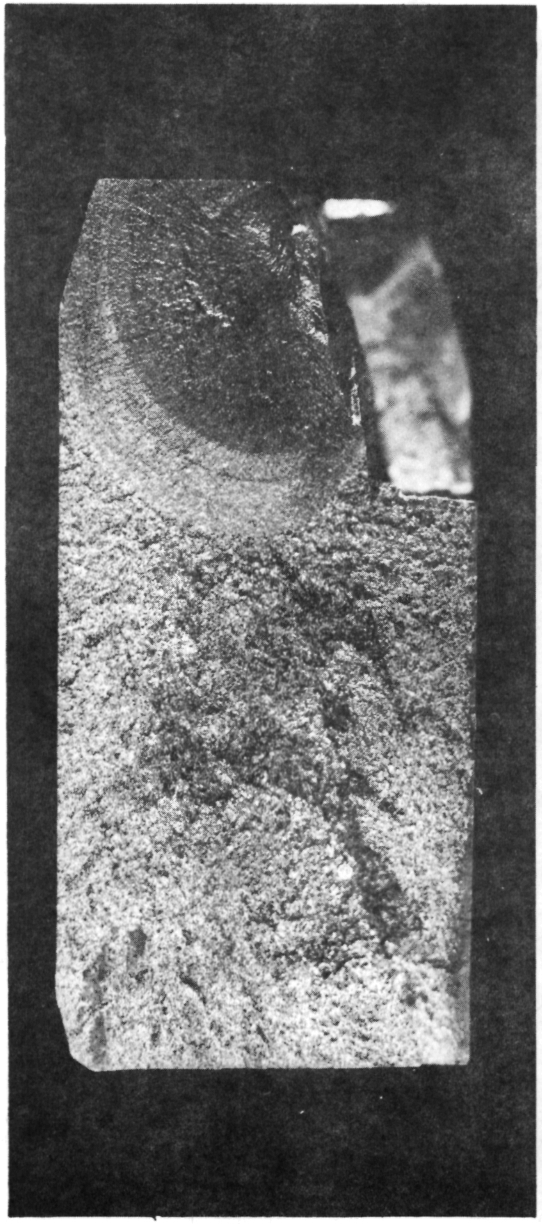
Figure 20. - Pitch-catch flaw map and fractograph of rail 2.

blocked the ultrasonic signal. Figure 21 shows the flaw map and views of the two transverse fracture faces. The flaw map identifies defects A and B. Defect A narrowed as it extended into the center of the rail, then suddenly widened. The widening was probably caused by detection of the detail portion of the fracture and is shaded in the flaw map. As anticipated, the detail portion of the defect was skewed and would mask the ultrasonic signal. Figure 22 is a photo of the two defects in rail 3 showing their relative proximity.

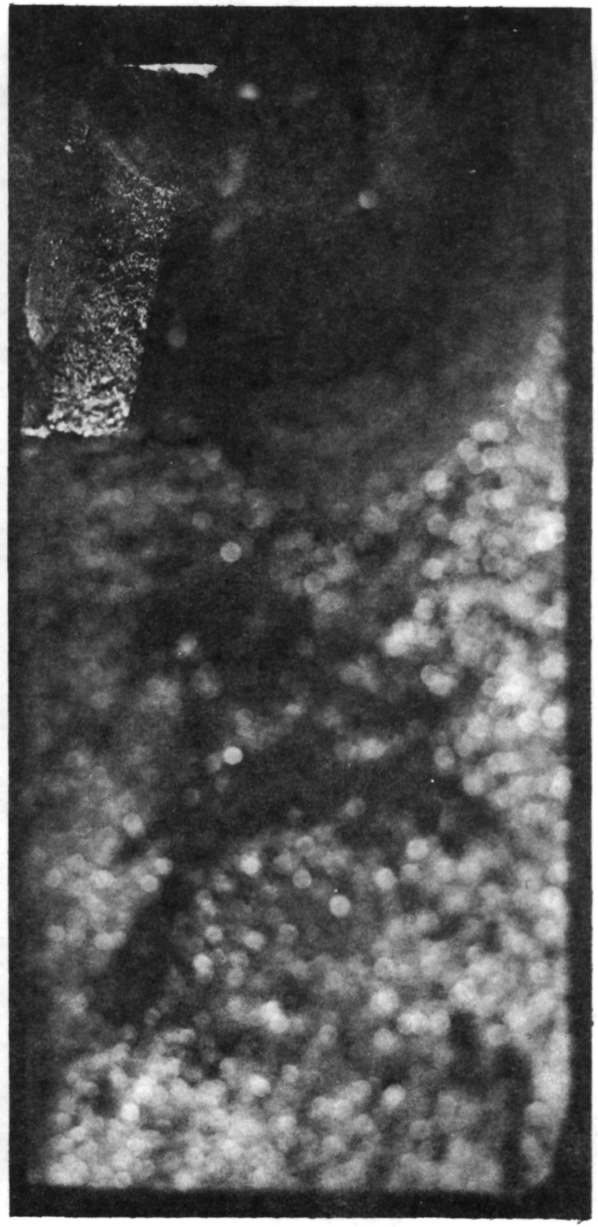
Rail 4 was inspected, stress relieved, inspected, then cycled and reinspected. Stress relieving did not produce significant changes in flaw character. Figure 23 shows the flaw map and fractograph.

Rails 5 and 6 were inspected, cycled, and reinspected. As shown in figures 24 and 25, agreement between the flaw map and fractograph was reasonably good.





Defect A.



Defect B.

Figure 21. - Pitch-catch flaw map and fractographs of rail 3.

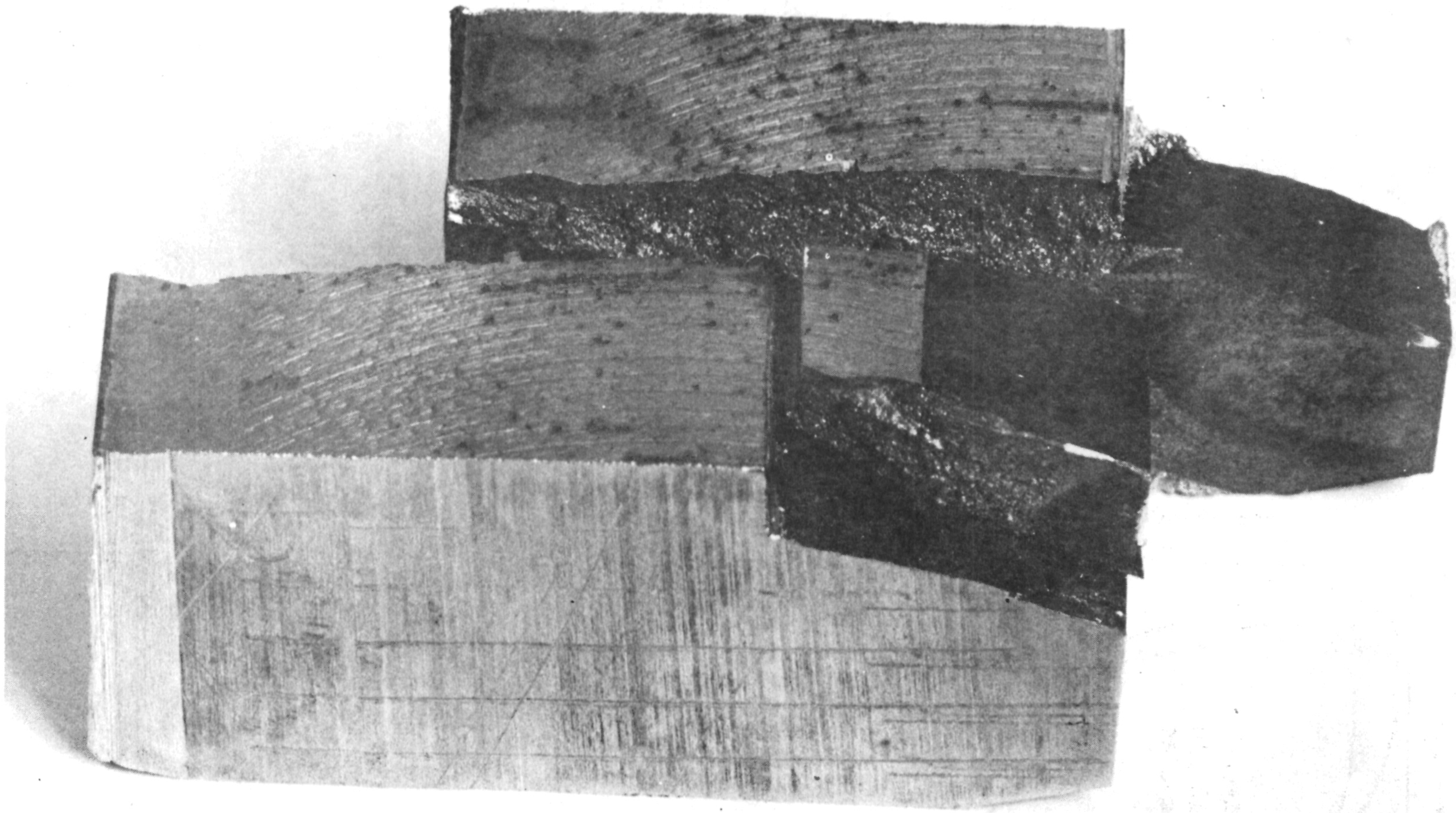


Figure 22. - Photograph of multiple defects in rail 3.

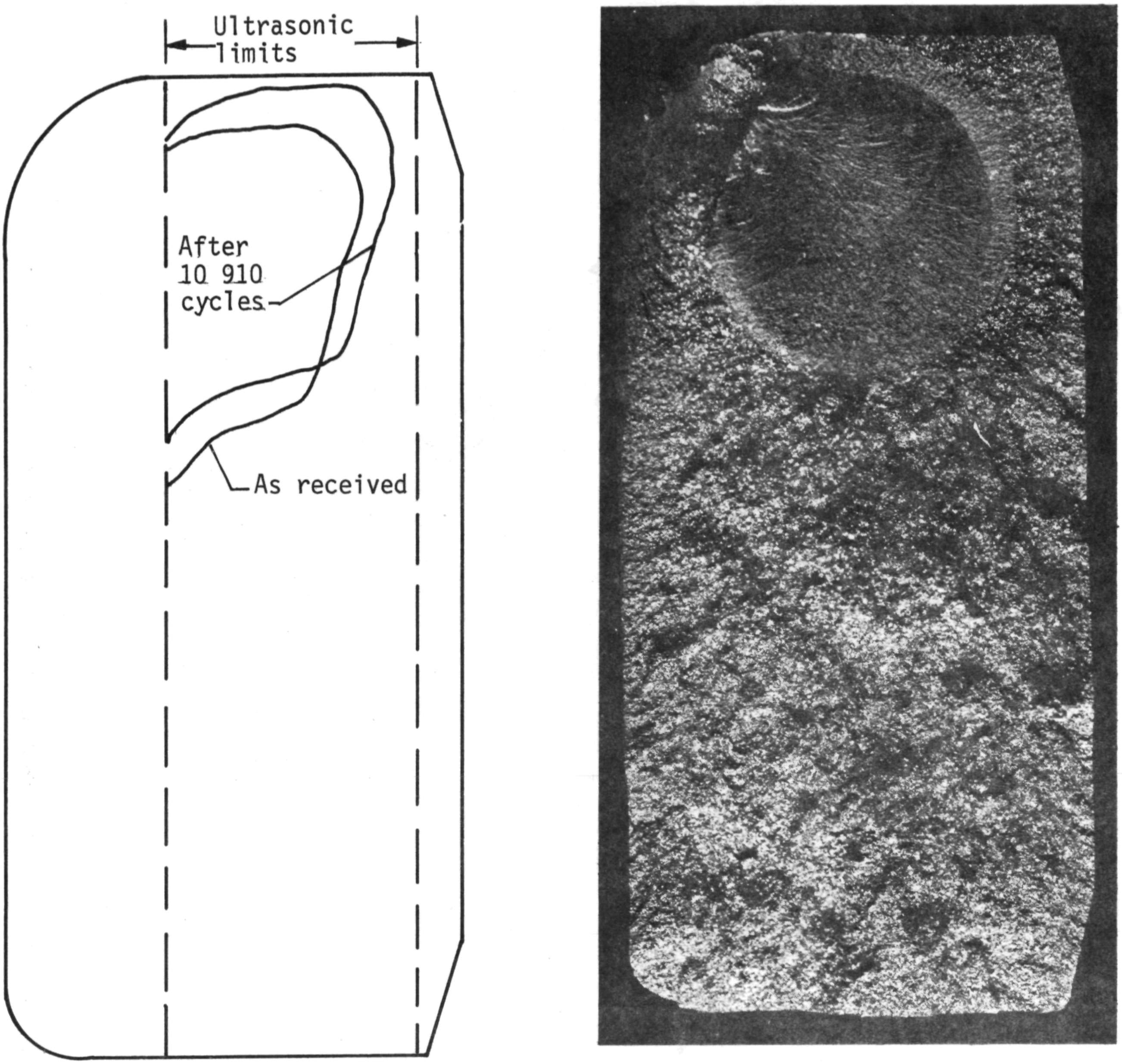
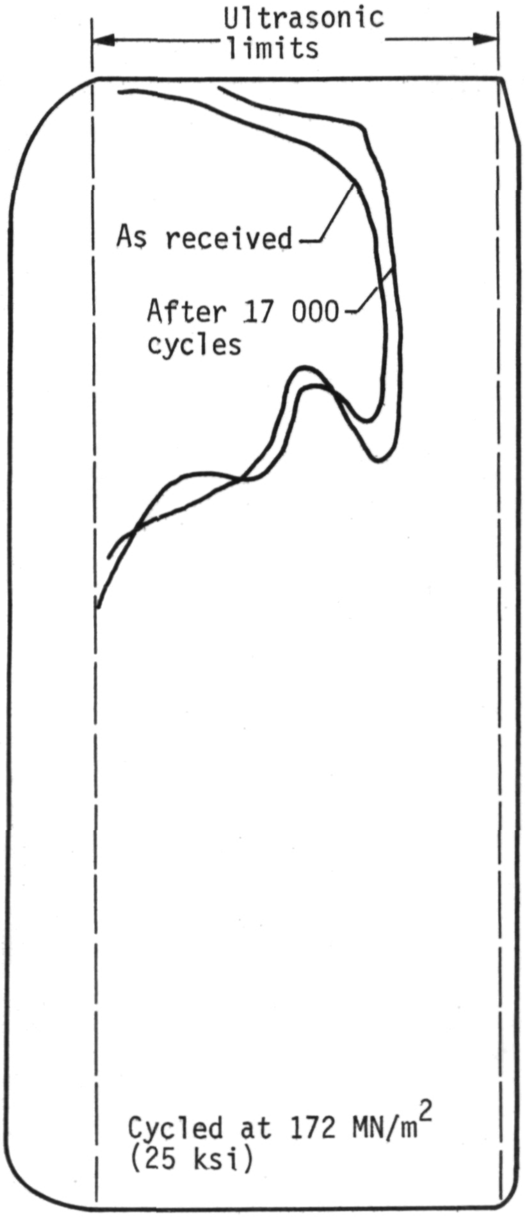


Figure 23. - Pitch-catch flaw map and fractograph of rail 4.



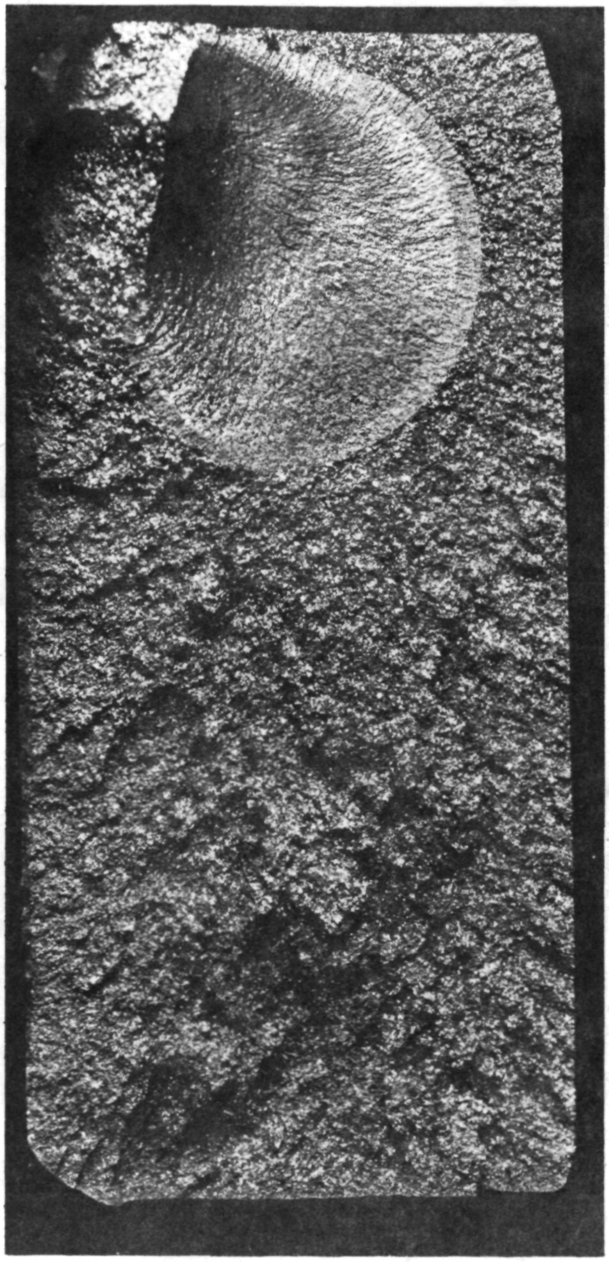
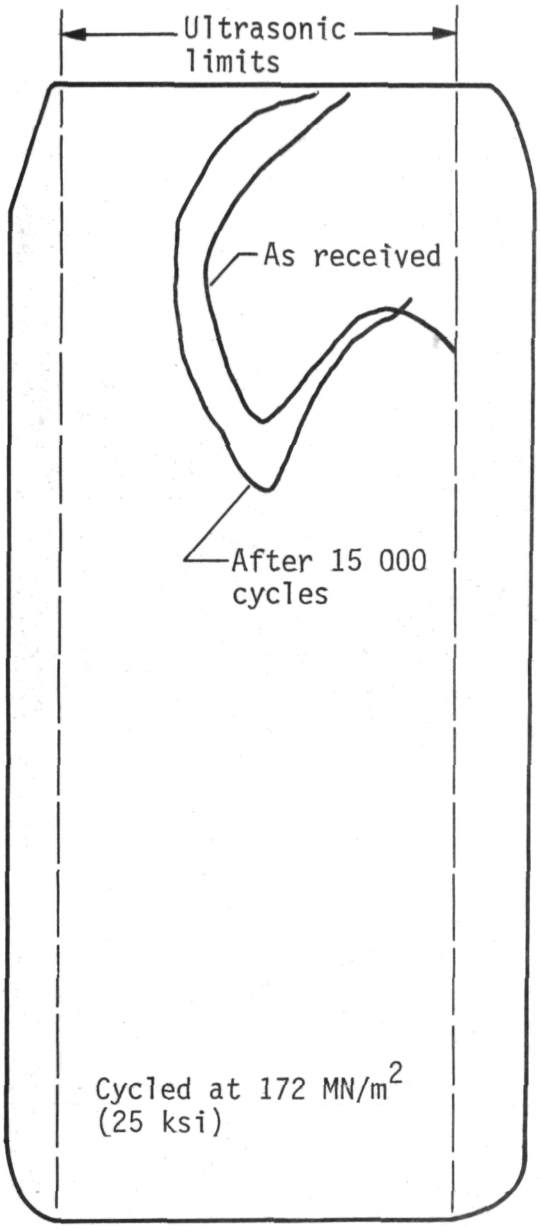


Figure 24. - Pitch-catch flaw map and fractograph of rail 5.



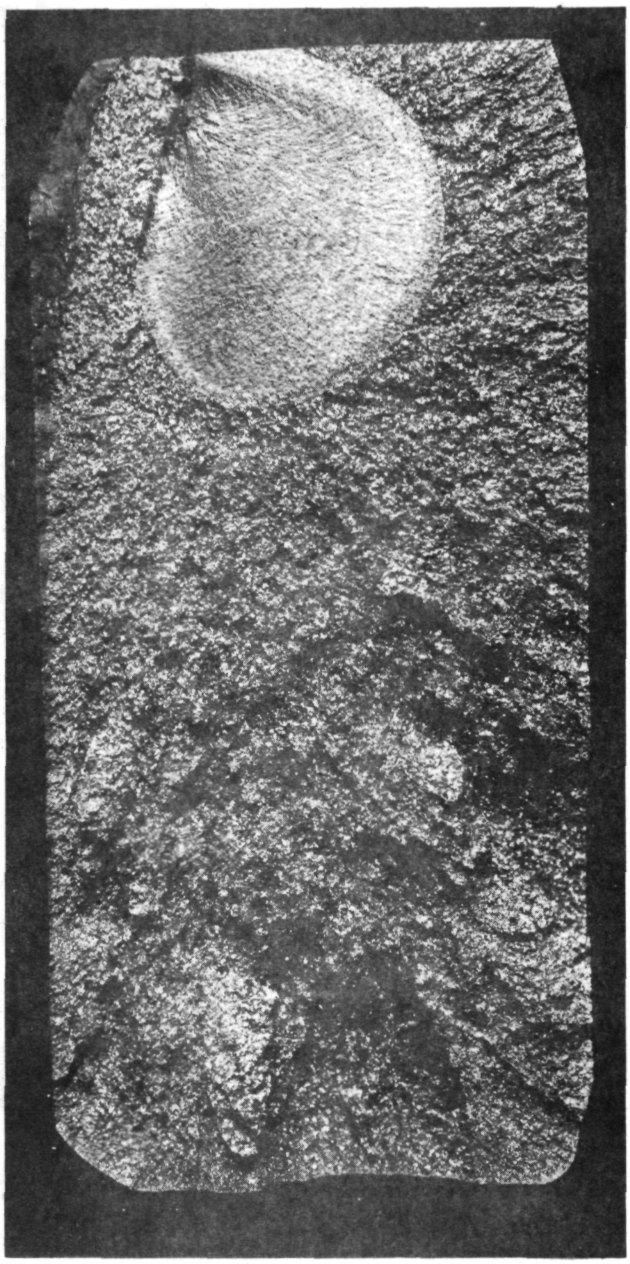


Figure 25. - Pitch-catch flaw map and fractograph of rail 6.

CONCLUSIONS

The results of the rail evaluation indicate that the prospects for ultrasonic characterization of buried transverse defects are relatively good.

The pulse-echo technique results suggest that a multiple-scan approach using varying angles of inclination, three-surface scanning, and dual-direction traversing may offer promise of characterization of transverse defects. Because each scan is likely to produce a reflection indicative of only a portion of the defect, a summing of the individual reflections must be used to obtain a reasonably complete characterization of the defect. This technique could be readily automated and computerized so that a computer graphics presentation of the defect would be presented. Additional work to further develop this scheme is desirable. Although the transducer array would be more elaborate than the pitch-catch method, the advantage of being able to scan the rail without the need to machine the side faces on the rail head is most attractive.

Collimated pitch-catch technique results were also encouraging. Preliminary results reported here show the ability of this technique to detect relatively small amounts of flaw growth. The method appears to have a problem in characterizing the portions of the defect near the top surface or web intersection. However, further evaluation may be able to correct this problem. The work performed to date has used machined side surfaces. Whether this is necessary for defect characterization was not studied. If necessary, this operation, although simple, would be a handicap to implementation of the pitch-catch method.

The work performed was intended to be a preliminary evaluation of the prospects for automated mapping of rail flaws. Additional work should be performed to further study the multiple pulse-echo and collimated pitch-catch techniques as potentially practical systems for evaluation of railroad rails in the field.

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