PROGRESS REPORT

on

FATIGUE TESTS OF SHIP WELDS

by

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CORNELL UNIVERSITY
Under Navy Contract NObs-31218

COMMITTEE ON SHIP CONSTRUCTION
DIVISION OF ENGINEERING & INDUSTRIAL RESEARCH
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Serial No. SSC-7

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December 13, 1946

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2101 Constitution Avenue
Washington, D. C.

December 13, 1946

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Navy Department
Washington 25, D. C.

Dear Sir:

Attached is Report Serial No. SSC-7, entitled "Fatigue Tests of Ship Welds". This report has been submitted by the contractor as a progress report on the work done on Research Project SR-89 under Contract NObs-31218 between the Bureau of Ships, Navy Department and Cornell University.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

Frederick M. Feiker

Frederick M. Feiker
Chairman, Division of Engineering
and Industrial Research

Enclosure

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals that were actively associated with this research program. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels".

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Progress Report

Bureau of Ships, Navy Department
Contract NObs-31218

FATIGUE TESTS OF SHIP WELDS

31 August 1945 to 31 July 1946

by

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Abstract

The fatigue studies described in this report were initiated under NDRC Research Project NRC-89 and are now carried on under contract with the Bureau of Ships, U. S. Navy Department. Previous results[1] are included.

The results of fatigue tests of twenty-eight specimens representing typical ship welding problems are described. Stress range of zero-to-30,000 psi tension was applied to 11½" wide plates having a longitudinal weld in the direction of tension and to 17" plates with central holes whose boundary was flame cut, flame cut and ground, flame cut and machined, and which had welded reinforcing inserts.

Variation in number of weld passes in the longitudinal weld from 1 to 3, each side, is not believed to affect the fatigue behavior significantly, but irregularities such as folds or pits in the weld surface are shown to act as stress raisers and to initiate failure. Tests were made on welds whose surfaces were ground smooth and flush with those of the plate. Two specimens of 50% greater width, and two of another steel, showed no difference in fatigue behavior from the balance of specimens of similar nature. The backstep method of laying weld passes is shown to be superior to the continuous technique.

The results of tests of eight specimens with central holes emphasizes the fact that discontinuities of form and stiffness require special treatment to provide paths free of stress raisers.

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[1] OSRD Report No. 6544, Serial No. M-606, January 17, 1946, "Fatigue Tests of Ship Welds", S. C. Hollister and J. Garcia.

I Introduction and Purposes.

The work reported herein is a continuation, under Contract NObs-31218 with Bureau of Ships, U. S. Navy Department, of the investigation initiated under NDRC Research Project NRC-89, Contract OEMsr-1382. The testing machines constructed for this project, and the test results obtained prior to the termination of Contract OEMsr-1382 are described in OSRD Report No. 6544, Serial No. M-606. However the results of the previous work are included* in the present report in order that the endurance characteristics of various specimens may be more easily compared.

The primary objective of the investigation is to determine relative fatigue behavior of typical ship welds and flame cut surfaces when subjected to zero-to-tension loads. A nominal stress range of zero-to-30,000 psi tension was chosen for all specimens. The type of electrode and the nominal stress range were held constant throughout this investigation. The specimens were made from 3/4" ship plate of ABS quality and were either 12 inches or 17 inches nominal width.

The investigation may be divided into two parts as follows:

(a) Plates with longitudinal welds subjected to repeated tensile stress in the direction of the weld. The following factors were varied:

1. Weld surface (as-welded vs. ground smooth)
2. Number of weld passes (2 to 6)
3. Backstep vs. continuous method of welding
4. Width of specimen ($11\frac{1}{2}$" vs. $16\frac{1}{2}$")
5. Type of steel

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*Except for endurance studies of tensile coupons with flame cut edges.

(b) Plates with central openings having various treatments such as flame cut, flame cut and ground, flame cut and machined, and with welded reinforcing insert.

II Description of Specimens

Three general types of specimens were tested as follows. All steel used was from the same batch of ABS steel on hand at termination of previous work. The physical properties are given in previous report.[1] see page 2 and Fig. 1 of that report.

A. Longitudinal weld at center of plates 3/4" x 7'11" and of two widths, 11½" and 16½" respectively. See Fig. 2 of previous report[1], and Fig. 1 herein. These specimens are identified as: AA, AB, AC, AD, AE, EE series, all 11½" wide; DE series, 16½" wide.

The weld surfaces were ground smooth on the specimens of the AB and AD series; the remainder were in the as-welded condition.

The EE series were constructed from another steel.*

B. Plates 17" wide with central hole with various edge preparations. The diameter of the hole (4¼") was chosen to be approximately one-fourth the width of the plate. The dimensions are shown in Fig. 2, and are identified as: FA, untreated manually flame cut hole; FB, flame cut hole with ground surface; FC, flame cut and machined to 1/2" greater radius.

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*This series of specimens was constructed from a semi-killed shipbuilding steel as used on Bureau of Ships Contract NObs-31222 and there identified as Steel "A". See Reports "Causes of Cleavage Fracture in Ship Plate: Flat Plate" Series, OSRD No. 6452, Serial No. M-608, January 10, 1946; SR-92, Serial No. SSC-2, August 23, 1946 and SR-92, Serial No. SSC-8 (to be published).

The procedure followed in cutting the holes is described in Appendix 3. Evidence of high "locked-in" stress is discussed.

C. A plate 17" wide with central opening reinforced by fillet welded ring or collar. This specimen, B-2, was identical with B-1 previously tested, see Fig. 3 of previous report.[1] The procedure described previously for the construction of B-1 was followed as closely as possible.

III Welding Specifications and Procedure

General Discussion: All welding was done using E-6010 electrodes with DC current on reverse polarity as described in a previous report.[1] The edges of the plates to be welded were beveled, by machine flame cutting equipment, as shown in Fig. 1. The "back-step" method of laying weld beads was employed for all specimens except AA-1 and 2. In general, each pass on a given specimen started at the same end. - this end is subsequently referred to as the top of the specimen.

Moderately good fusion at the root of the weld, as seen by sectioning, e.g. Figs. 37, 39 and 40, and by radiographs, Fig. 3 and 4, obtained for the first six or seven specimens constructed. The next group of six had rather poor fusion and many slag inclusions, see Figs. 5 and 6, resulting probably from the tendency during welding for the gap to close and for one plate to climb upon the other, as discussed more fully below. The subsequent group of six specimens were prepared on a "hold-down" table*, and extensive chipping of first passes was done. This resulted in nearly perfect fusion at the root, as seen in Fig. 7, 8, and 9.

Radiographs of all welds were made, but are not included in this report. The seven presented here, Figs. 3-9, inc. were chosen to represent both

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*See Appendix 1, Section B "Restraint III" and Fig. 85.

the extreme of poor and good fusion, smoothness of weld surface, etc., from all the specimens constructed. Additional photographs are shown in the previous report.[1]

Some discussion concerning welding difficulties for individual specimens is given in Appendix 1.

Distortion of the Plates: Unlike the case for large ship plates, the laying of many weld beads to join the edges of two, six-inch wide, plates nearly 8 feet long causes severe bowing, climbing of one beveled edge over the other, and similar distortion. Such deviations from a plane surface with a longitudinal weld are very unsatisfactory since they make uncertain the actual stress which may exist in the specimen when placed under tension by the fatigue testing machine, as well as leading to poor root fusion, slag inclusion, etc. Serious tendency of the plates to distort, experienced in the construction of the initial four or five specimens, was minimized by turning the specimen between passes so as to place successive passes on alternate sides of the specimen. No jigs or other device was used to provide a mechanical restraint except at the ends of the plates. Subsequently this technique was extended to placing but a few beads at a time on alternate sides, and to hold the two plates in the central region by means of three simple clamping bars with rollers.

Since specimens of not entirely satisfactory geometry were made by the alternate bead method described above, it was decided, after discussion with representatives of the Bureau of Ships and the War Metallurgy Committee, to follow the conventional practice of employing a "hold-down" table to prevent distortion of the specimen. This device, which permitted free motion of the plates only in the plane parallel to their surfaces is described later in this section. A further objective was to return to the method, in accord with industrial practice, of placing one or more complete passes on one side at one time.

Study of the OSRD Reports* on investigations of the effect of various welding procedures on residual stresses in ship welds lead to the conclusion that specimens constructed under the type of restraint described above would have residual stresses very little if any different from those of the first two groups constructed by alternating the passes. The reference reports state that for 6' x 8' panels "considerable restraint caused practically no change in the magnitudes of the stresses ...." ---"considerable variation in welding sequence did not produce any great difference in residual welding stresses ...."

To recapitulate, in an attempt to minimize distortion specimens reported herein were constructed by one of three methods, superficially different but believed sufficiently identical basically to permit adequate comparison of fatigue behavior. A brief description of each method, and enumeration of the specimens so constructed, is presented in Appendix 1.

IV. Test Procedure and Stress Determination

Test Procedure: The fatigue testing machines have been described previously.[1]

Each specimen was subjected to a stress range as close to zero-to-30,000 psi tension as it was possible to adjust the equipment. The actual stress ranges are given in Table 1, "Summary of Test Results".

To adjust the load to the desired stress range was a moderately laborious

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* "Residual Stresses in Ship Welding", E. DeGarmo, J. L. Meriam, F. Jonassen; OSRD Nos. 3176, 3698, 4388 and 4867, Serial Nos. M-190, M-266, M-370 and M-463 respectively, 1944-45.

procedure requiring four to eight hours time and resulting in a total of 600 to 1700 cycles of operation for each of the specimens reported herein. However, the stress was usually 90 to 98% of its final value within the first 200 cycles of load. Strain measurements were taken repeatedly in order to insure that no part of the specimen was overstressed during load adjustments. After the load adjustment was satisfactory the testing machine was operated continuously until 300,000 cycles of stress was attained*, or fatigue fracture developed to such an extent that the stress in the plate distant from the crack (as determined from the strain readings, see next section) dropped rapidly to less than 90% of its initial value. In most of these cases the crack had become 1-1/2 to 2 inches wide and plastic flow was evident at its ends. A visual examination for cracks, employing a strong light and thin oil, was made about every 2000 cycles, or oftener as necessary. Strain readings and computation of stress range were made about every 45,000 cycles until a crack became visible, at which time strain readings were taken immediately. Radiography was done after the specimen was removed from the testing machine.

Enforced rest periods occurred for certain specimens as described in the results of tests and in Table 1.

Each specimen was oriented so that any curvature present was convex as viewed from in front of the testing machine; this side was subsequently identified as the "front" of the specimen.

Stress Determination: The stress range was determined as described in the previous report.[1] A brief resume is given here for the convenience

*One specimen, AB-3, was carried to 397,000 to test a modification in design of the end connection. Premature halting of the test had been necessary in two cases, AA-4, AC-3, because failure in the grip section made it impossible to maintain the desired load.

of the reader.

Strain measurements were made with a 10-inch Whittemore Strain Gage equipped with a ten-thousandth dial. Strain could be measured corresponding to a stress of 150 psi. Gage holes were laid out on both front and back with a 10-inch punch bar and then drilled with a No. 55 twist drill at the locations shown in Figs. 13 and 14. The location of gage holes on specimen B-2 are shown in Fig. 7 of the previous report.[1]

In the case of specimens with longitudinal weld it was possible to compute the particular stress range at the gage location adjacent to the fatigue crack. This condition, however, does not hold for specimens of the B and F series, i. e., with holes. For the specimens in these two series the load was adjusted, based on the average stress computed from the strains determined at the 20 positions shown in Fig. 14, so that the stress (load divided by net area) on the test section, i.e., at the hole, varied nominally from zero to 30,000 psi.

V Description of Test Results

A summary of information concerning each specimen having a longitudinal weld is given in Table 1, and for those with a central opening is given in Table 2. An explanation of the symbols will be found adjacent to Table 1.

The stress range, as measured during the test, is shown for each specimen. The three ranges given are defined as follows:

Average Stress Range:	Average of stress values computed from strain measurements at all gage points.
Critical Stress Range:	The stress computed from strain measurement at that gage length of the specimen for which the strain was greatest.

Local Average Stress Range: Average of stress values computed from strain measurements at those gage points nearest fatigue crack, and on the same face of the specimen on which the crack occurs.

No "cycles to failure" value can be assigned to the cracks discovered from examination of radiographs taken after the test was completed. All specimens were radiographed to search for internal cracks.

Sectioning was accomplished by cutting out a small "coupon" of material containing the crack, notching it near the crack, and pulling the coupon to fracture in an ordinary testing machine. During this process, a few surface cracks (identified by the suffix "T") opened up which were too small to detect by the oil-strong technique during the fatigue test. Photographs of each fatigue fracture are shown in Figs. 34 - 78, inc., and a description of each is given in Appendix 4.

It should be noted that three specimens were permitted to rest a period of the order of 29 to 52 days during test, because of failure of equipment.

VI. Analysis of Test Results

1. Specimens Containing Longitudinal Welds

A. Origin of Cracks: The following data do not include 7 cracks which occurred beyond the test length.

Table 3

Number of Cracks vs. Origin, All specimens

Inside	22	Front	24	Upper	20
On Surface	15	Back	17	Middle	11
Unclassified	10	Unclassified	6	Lower	16

The distribution of cracks appears to be entirely random.

A. Origin of Cracks (cont'd)

Table 4

Number of Cracks vs. Origin; As Welded Surfaces Only.

Identity	AA	AC	AE, DE, EE	Total
Inside	2	5	7	14
Surface	6	6	2	14
Unclassified	2	0	3	5

For those with ground surfaces, similar figures are:

Surface	1
Inside	8
Unclassified	5

Examination of the above listed surface crack shows that pinpoints or high porosity in the crater was present and doubtless responsible for the fracture, see Fig. 65.

B. Variation in Weld Passes:

Table 5

Relative Fatigue Behavior vs. Number of Passes

Number of Passes	Total Number of Cracks	Cycles to First Crack Each Specimen
1 pass Group (AC) 2 specimens	14	(1) 191,500 (2) 199,000
(plus one specimen to 146,000 without any crack developing)		
2 pass Group (AA) 4 specimens	8	(1) 82,500 (2) 57,000 (3) 34,000 (4) ? (5) 57,900
(Plus one specimen to 124,000 with 2 faint, non-visible cracks)		
3 pass group (AE, DE, EE) 6 specimens	13	(1) 152,000 (2)189,000 (1) 181,000 (2)152,000 (1) 189,500 (2)204,000

As seen in Tables 1 and 5, the results for the three-pass group are remarkably consistant. Since only two specimens of the one-pass type were tested, the moderately good agreement may be accidental. More observations are required to determine if the low values shown for the two pass group are truly related to the number of passes. At present it is believed that the increased experience in using the E-6010 rod resulted in smoother weld surfaces on the one and three pass groups than obtained for those first made - the two pass group.

In the two pass group, (AA), the majority of cracks started at ripples in the weld surface and at craters as, for instance in specimen AA-1, see Figs. 34 and 36. This specimen was welded by the continuous method. It is evident that the "back-step" method of welding prevents the formation of cleavage planes where one bead overlaps another, and is therefore less likely to result in weld regions susceptible to early fatigue fracture.

Poor root fusion did not always result in a fatigue fracture, or in rapid failure. Although rather poor root fusion existed in specimens of the AB and AD groups, AB-3, Fig. 5, passed 397,000 cycles without any sign of cracks either by visual or radiographic examination, and after 300,000 cycles AB-2 developed only 2 very faint cracks detected by radiography. Although one of these, see Fig. 45, was at the root, it was very small at the end of the test. The other crack, Fig. 46, was near the surface. Specimens AC-1, see Figs. 47, 51 and 52; AC-2, see Fig. 54, AD-1 also developed cracks at the surface adjacent to slag inclusions or unfused root areas. It is believed that the geometry of the unfused area, rather than its absolute size, governs.

2. Specimens Containing Openings

A. Unreinforced Openings. The fatigue behavior of the individual two specimens of each group was satisfyingly consistant. The difference between the behavior of those with ground and with unground surface of the flame-cut hole illustrates the harmful effect of the as-cut surface. The third member of this series, FC-1, was designed to eliminate geometrical irregularities and heat-affected material as a cause of early fatigue. However, in order to save machining time the hole in specimen FC-1 was flame-cut to a one-inch smaller diameter than necessary and then machined to size. It is known that removal of less than 1/2 inch of metal along a flame cut free boundry removes the residual thermal stresses resulting from the flame cutting process. Hence it was at first believed that the removal of 1/2 inch on specimen FC-1 might be adequate to leave the hole stress-free and its fatigue behavior would represent an upper limit for comparison of other types of finish of openings. The extent to which thermal stresses were set up in the plate, as discussed in Appendix 3, throws some doubt on the above conclusion.

While the partly-machined hole, FC-1, offers considerable improvement over the unfinished hole, FA, nevertheless fatigue fracture occurred in these specimens at values many times less than for parent plate metal. It is believed that the rather large heat input suffered by these specimens is a significant factor in their poor fatigue behavior.

B. Reinforced Openings. As can be inferred from the data in Table 2, the fatigue strength of the three specimens with reinforced openings is very greatly reduced from that for the parent plate metal; and compares unfavorably with that of the unreinforced hole with a ground or machined surface. It is believed that the difference between B-1 and B-2 is characteristic of the statistical spread to be expected in specimens in which the characteristics of the fillet weld play so significant a part.

The location and the direction of propagation of the fatigue fractures in specimen B-2, Fig. 28, were practically of the same nature as those found in B-1 and described previously.[1] It is apparent that considerable stress concentration occurs at the rounded corners of the reinforcement where its excessive stiffness does not permit sufficient deformation to distribute the stress over a large region. Furthermore, a fillet weld of the character of that employed in the B series will always result in a notch in its underside.

Conclusions

The conclusions set forth below must be considered tentative in view of the relatively few number of specimens that have been studied.

1. Fatigue cracks started after approximately one-third the number of cycles in specimens containing longitudinal welds as compared to homogeneous plate specimens[1] of the same steel. Both types of specimens were subjected a nominal tensile stress varying from zero to 30,000 psi.

2. In 20 specimens containing longitudinal welds and having flame cut edges, all fatigue cracks started in the welds.

3. The results presented herein strengthen the conclusion made previously; for the high stress range employed in these studies, stress raisers in the form of surface folds or pits in the weld metal are incipient points of fatigue failure.

4. The back-step method of welding, by insuring good fusion when the one bead joins the one previously placed, reduces the possibility of fatigue failure at these points.

5. In specimens containing longitudinal welds, poor root fusion will not always result in fatigue failure. In several cases cracks

started at the surface adjacent to unfused root areas. See, for example, Figs. 47, 51, 52 and 54. Two specimens with poor fusion as seen by radiographs, e.g., Fig. 5, and by sectioning, Fig. 45 and 46, but with ground weld surfaces, underwent a much greater number of cycles of stress than the majority of those tested.

6. In certain cases small (1/4" to 1/2" length) fractures occur within the weld in such a manner or in a location such that the cracks become arrested before they extend into the parent metal. The reason for this is not clear. A crack which has extended into the original plate metal has in no case become arrested.

7. The increase in width of plate from 11½ to 17½" makes no difference in the fatigue behavior of longitudinal welds in tension.

8. Based on two tests the fatigue behavior of specimens containing longitudinal welds made from another steel of shipbuilding quality (semi-killed) did not differ from that obtained using project steel.

9. The results of tests of longitudinal welds having one, two and three weld passes on each side of the plate are not believed to show any significant relation between number of weld passes and fatigue behavior.

10. The results of the test of one additional specimen with a discontinuity in cross-section, i.e., welded reinforcing ring at edge of hole, confirms previous conclusions; that such forms of reinforcement as constructed in this study need special treatment to prevent early fatigue failure.

11. If the surface of flame cut holes is not ground smooth, the fatigue strength of the plate is greatly reduced. By removing (grinding)

the irregularities left by the torch, the fatigue behavior is improved markedly relative to that of specimens in the "as-flame-cut" condition. An additional improvement beyond that of the ground hole is obtained when the hole is machined to size after flame cutting.

12. Premature fatigue failures in the end connections of specimens, for that type employing "cover plates" or increased thickness of metal, may be eliminated by the combination of the following factors:

(a) The boundary of the cover plate, where the stress flows into the main plate, approximates one and one-half periods of a sine wave.

(b) The fillet weld between the cover plate boundary and the main plate is ground to a smooth contour to eliminate the stress raisers in this region where stress concentrations occur.

Appendix 1

Comments Concerning Construction of Specimens

A. Introduction

The general welding procedures for the construction of specimens with longitudinal welds is described in the main body of this report, see Section III. Certain details encountered in the construction of each specimen that may be of interest are described in the following.

B. Method of Restraining Specimens During Welding

a. Restraint I: (Thermal) Specimens AA-1, -2, -3, AC-1 and -2.

No mechanical restraining jig was employed. The ends of the plates generally were clamped to steel horses, and a weld pass placed on the side of the specimen on which it was believed the thermal forces would be effective in either maintaining the plates flush, or reducing the angle between their surfaces.

Weld beads were placed in a continuous fashion on specimen AA-1, and the first two passes on AA-2. Subsequent passes were made in the back-step fashion. Evidence of the superiority of the back-step method is shown in the summary of results.

Complete passes were made on alternate sides of AA-3 and AA-4 without satisfactory control of distortion. The placing on alternate sides an arbitrary number of beads (the number was chosen to minimize distortion) rather than completing the whole pass at one time was started on specimen AC-2, and was carried out for a number of subsequent specimens.

b. Restraint II: (Thermal plus simple clamp) Specimens AA-4, -5, AC-3, AB and AD series.

In order to control the distortion of the plates in the

B. Method of Restraining Specimens During Welding (cont'd)

b. Restraint II: (cont'd)

central region of the specimens, three C-shaped clamps bearing on channels separated from the specimen by rollers, were applied. The placing of one or more beads on alternate sides were continued for this group of specimens. No chipping was done.

c. Restraint III: ("Hold-down" table, see Fig. 85) Specimens AE, DE, EE series.

A rigid table was made to which the two, six-inch wide, plates could be clamped while they were being welded. Clamps and rollers were so arranged that the plates were free to move in the plane of their surfaces, but their motion was restricted in a direction perpendicular to their surfaces. It was hoped that this would prevent the distortion which previously had been experienced in the construction of specimens.

The table consisted of a steel plate 1" x 24" x 8'0" welded to two 6" H beams 7'6" long. To increase the stiffness in the 24" direction steel straps were welded across the lower flanges of the beams. Three clamps were made in such a manner that they could be shifted longitudinally on the specimen as the welding progressed. Two rows of cold rolled steel rollers, 1/2 inch diameter by 3 inches long, were placed between the table and each of two plates forming the specimen; the rollers were suitably placed between each of the three clamps and the specimen. By judicious spacing and tightening the clamps it was possible to prevent all but a slight amount of distortion of the specimens during the welding process.

C. Detail Description of Specimens

a. Specimens Constructed Using Restraint I

Specimen AC-2

(Specimens AA-1, 2, 3, and AC-1 were described previously[1].)

To reduce the large gap that existed at the center of the specimen the beveled ends were ground until a uniform 5/32" gap was obtained. The ends were welded in the manner described for specimen AA-5. After eight beads were placed on alternate sides (four on each face), the gap at the center was reduced to 1/8". Two beads were made on the side required to draw the plates and two more were made on the opposite side - the order followed to complete the welding of the specimen. The root of all welds were chipped in this case with a diamond-point drill whose point was rounded to approximately 1/16" radius. In this particular specimen the beveled edges did not always draw tightly together just ahead of the torch as was the case in certain other specimens.

b. Specimens Constructed Using Restraint II

Specimen AA-4

Welding procedure for this specimen is not given since the test is not considered completed. Fracture in the grip section resulted in early failure of the specimen, see Table 1.

Specimen AA-5

When the two beveled edges were placed so as to touch at their ends, a 3/16" gap remained at the center. In preparation for welding the ends, two clamping jigs described elsewhere were placed at the ends of the test length and the ends of the plates themselves were clamped to steel horses by C clamps. For about 15" in from each end (beyond the test length) and on both sides of the specimen, the groove was filled with one pass of 3/16" Murex Type F electrode with the Amperage = 240 and Voltage = 30. The welding reduced the gap at the center to 1/16".

Pass 1.* The root beads were placed on alternate sides of the specimen. When four beads had been made on each side, the beveled edges started to climb over each other because the clamp jigs were not strong enough to maintain the surfaces of the two plates flat. The gap at the center was now entirely closed. The welder attempted to prevent this distortion of the two plates by directing the arc slightly toward the beveled edge of one plate instead of directly in the root with the hope that the extra heat would cause that plate to expand more than the other plate and thus lessen the tendency to climb. After one bead was made, no apparent improvement was noticed. Therefore it was decided to start Pass 1 from the other end of the specimen. First, however, a short light bead was placed at the ends of the last two beads laid so that when the last bead of Pass 1 was started at this point the weld metal would be shallow.

Later, when the second pass would be made over this particular point, the shallow cleavage plane would be well fused. Pass 1 was then completed from the opposite end and the resultant distortion was slight. The placing of each bead was controlled by the side of the specimen which required drawing in order to maintain the specimen flat.

* In the case where each successive bead was placed on alternate sides of the specimen, Pass 1 denoted the root pass for both faces of the test piece.

Pass 2** was then made, but the beads on each side of the specimen were not placed alternately. Instead all the beads were laid on one side in hopes of drawing the plates flat. This did not prove to be completely successful. The remainder of Pass 2 was made on the opposite side to complete the specimen.

Specimen AB-1

The plates were clamped and the ends welded as described for specimen AA-5. After the ends had been welded, 1/16" gap remained at the center of the specimen. Pass 1 was made on alternate sides of the specimen; more than one bead at a time was laid on the side requiring the more drawing to produce a flat specimen. Pass 2 was made over Pass 1 and on alternate sides. However, at certain points more than one bead would be placed in order to control the distortion of the plates.

Specimen AB-2

The ends were welded in the same manner as for AA-5 with 1/16" gap remaining in the center of the specimen. Pass 1 was started by placing beads on alternate sides of the specimen, but after two beads had been made on each side it was found that the plates were not remaining flat. Two subsequent beads were placed on the side requiring drawing and the next bead was laid on the opposite side. Two more beads were made on alternate sides but the plates were still distorted. It was then decided to go back and start Pass 2 over Pass 1 on the side that required the drawing. The five beads made in this length flattened the plates. Now, Pass 1 was completed by placing beads on

**Also same pass number for each side.

alternate sides. For Pass 2, five beads were made opposite the original five beads, and from this point on the remainder of the beads of Pass 2 were made on alternate sides.

Specimen AB-3

In this specimen a 1/4" gap between the two plates was left at one end and none at the other. The closed end was clamped to a steel horse and a clamping jig was applied to the other end so that only lateral motion was permitted. In this case the beads in grip section were to be similar to those in the test length.

Pass 1 was started at the closed and top end of the specimen by placing beads on the alternate sides and five had been placed on each side before the plates commenced to deviate from the desired plane. After two beads were laid on the side that required drawing, the alternate scheme was re-introduced, but the one side had two beads ahead of the other. As the welding progressed the gap at the open end kept closing just ahead of the bead being placed. After the completion of the root pass, the plates were not flat with respect to each other.

After placing five beads of Pass 2 on one side in order to straighten the plate, the alternate laying of beads was carried on two at a time, i.e., two on one side and two on the other, until Pass 2 was completed.

Specimen AC-3

Welding procedure for this specimen is not given since the test is not considered completed. Fracture in the grip section resulted in early failure of the specimen, see Table 1.

Specimen AD-1

When the two plates were clamped as described for AA-5 a gap of 5/32" remained in the center of the specimen. The length of weld at the ends was changed from 15" for AA-5 to 8".

Pass 1 was made by placing each successive bead on alternate sides for the full length of the specimen. In this specimen difficulty was encountered in the breaking of the weld arc and still filling the craters. The beveled edges were drawn tightly together ahead of each pass being placed. No chipping was done.

Specimen AD-2

The two plates were clamped in the manner described for specimen AA-5, but in this case a 1/16" gap was left at each end which resulted in a gap of 3/16" at the center. The ends were welded on both faces for a length of 6" with 3/16" Vertex E-6010 in order to hold the plates for the welding of the test length.

Pass 1 constituted one bead on each face of the specimen and made successively on alternate sides to complete the specimen in one continuous operation. As the welding progressed, the gap ahead of each bead was entirely closed so that no tears of weld metal resulted. No chipping was done.

Specimen AD-3

The two plates were clamped in the manner employed for specimen AA-5, and the ends were welded as described for specimen AD-2.

Pass 1 was made as in specimen AD-2 as with the same results.

C. Detail Description of Specimens (cont'd)

c. Specimens Constructed Using Restraint III

The following general description of the welding procedure applies to all specimens in this category:

It was found desirable to grind the beveled edges lightly so that they would be straight for the full length of the specimen. The root face varied from 0 to 1/16" for the full length of the plates. The neck portion of each plate was also ground to reduce the stress concentration that might result from the irregularities of the flame cut edge.

Since a 5/32" gap was required between the plates when they were tacked together, strips of 5/32" cold-rolled flat strip were inserted every 6" between the beveled edges in order to maintain the gap while the specimen was being tacked.

The two edges of the specimen were tack-welded together using 1" tacks placed on 6" centers. One tack was always located at the transverse center line of the specimen. 5/32" E-6010 electrodes were used for tacking and for the root passes. The tack-welds were cleaned and chipped before the root pass was laid. The root pass was made using a back-stepping procedure, chipping the starting point of each bead to insure good fusion. Craters and porosity in the weld were chipped out using the round nose chisel. Particular attention was paid to minimize under cutting. Areas that might contain slag inclusions were also chipped out.

Upon the completion of the root pass on the first side, a second pass was made using 3/16" Vertex E-6010 electrodes.

The specimen was allowed to cool and was then turned over and back-chipped. The root pass (third pass) and a fourth pass were then welded. The specimen was then turned over and the final pass (fifth) completed on the first side, after which the specimen was turned again and the last pass (sixth) completed on the second side.

The back-stepping procedure was used throughout. The electrode sizes, current and voltage are given on pages 24 and 25 of this appendix.

Specimen AE-1

After Pass 4 was made, the surface of the two plates formed an angle since the clamps of the table were not able to hold them perfectly flat. Pass 5 was made on the opposite side so that the shrinkage of the weld would tend to straighten the plates but without complete success.

Specimen DE-2

In the Pass 3, one of the beads had a very porous crater. To repair this condition, the entire bead was chipped out and rewelded. This locality was marked on the specimen, but when tested, no fatigue failure occurred at this point.

Specimen EE-1

In this specimen in Passes 5 and 6 several beads had to be chipped out and rewelded because of poor craters. These beads were marked but no fatigue failure took place at such points.

D. Welding

a. Specimens with Reinforced Hole

At no rounded corner of the ring was there a crater which might cause fatigue cracks.

The details of the weld passes are:

Face of Specimen	Pass	Voltage	E-6010 Electrode
Back	1	150	5/32"
Front	2	200	5/16"
Back	3	100	5/32"
Front	4	200	3/16"

b. Specimens Containing Longitudinal Welds

The amperage, voltage and electrode size employed in the construction of each specimen are given in the table below.

Specimen	Pass Number	Amperage	Voltage	Electrode Size
AA-4	1	160	26	5/32"
	2	220	28	3/16"
AA-5	1	165	28	5/32"
AB-1,2,3	1	160	28	5/32"
	2	220	28	3/16"
AC-1	1	280	30	1/4"
AC-2	1	230	28	3/16"
AC-3	1	245	29	1/4"
AD-1	1	255	30	1/4"
AD-2	1	245	30	1/4"
AE-1	1	150	28	5/32"
	2	190	28	3/16"
	3	170	28	3/16"
	4,5,6	220	28	3/16"
AE-2	1	130	28	5/32"
	2	190	28	3/16"
	3	140	28	5/32"
	4,5,6	200	28	3/16"
DE-1	1	140	28	5/32"
	2	200	28	3/16"
	3	140	28	5/32"
	4,5,6	200	28	3/16"
DE-2	1	130	28	5/32"
	2	200	28	3/16"
	3	140	28	5/32"
	4,5,6	200	28	3/16"

D. Welding (cont'd)

b. Specimens Containing Longitudinal Welds (cont'd)

Specimen	Pass Number	Amperage	Voltage	Electrode Size
EE-1	1	130	28	5/32"
	2	200	28	3/16"
	3	140	28	5/32"
	4,5,6	200	28	3/16"
EE-2	1	130	28	5/32"
	2	200	28	3/16"
	3	150	28	5/32"
	4,5,6	200	28	3/16"

Appendix 2

Procedure for Grinding the Longitudinal Weld Surfaces

In the AB and AD group of specimens, the weld surface on both sides was ground flush with the two plates that constituted the specimen. Since scratches transverse to the longitudinal direction of the specimen might institute early fatigue fractures, the finish grinding was done so that any very faint scratches remaining were in the direction of load application. Care was exercised to remove any folds from the finished surface, principally because their presence would make it difficult to detect fatigue cracks.

The choice of wheels and technique for grinding the weld surfaces smooth was determined as a result of experiments on specimen AB-1. A Gaston 1 H.P. Disc Grinder Style No. 4110 with a Resinold Bonded Wheel A16 PHS C42 used for the rapid removal of the greater portion of the welds had the disadvantage of creating deep scratches transverse to the line of pull on the specimen - undesirable stress raisers. A Black & Decker Portable 5" Grinder with a Norton A16 - P4B5 wheel removed the transverse scratches and created grooves in the longitudinal direction. Initial polishing was done by a finer grit wheel (Norton A30-P4B5), and final polish by a Rubber Bonded Grit wheel (Norton A46-D2RR).

The remaining scratches were very fine and in the direction of load application, and the surface finish, see Figs. 5 and 6, was such that a fatigue failure could easily be detected.

Appendix 3

Description of Specimens with Flame Cut Holes

The general dimensions of these specimens are shown in Fig. 2. The holes were cut by hand as follows:

Circles of the proper diameter were scribed (FA group - 4 1/8" dia., FB group - 4" dia., FC group - 3 1/4" dia.) at the intersection of the center lines of the specimen and punch marked in order that the burner could direct the torch along the desired path.

The cut was started from a hole pierced with the flame torch at the center of the circle.

Except for specimen FA-1, the cutting proceeded continuously in the direction of the longitudinal axis or line of tension to the upper edge of the circle and then along the marked circle clock-wise to the lower point resulting in a cut for one-half of the hole. The flame cut was started again at the upper point and taken counter-clockwise to complete the hole. This order of cutting offered an uninterrupted flame pass at the sides of the hole where the stress concentration is greatest.

All flame cutting was done with the plane of the specimens horizontal, the flame vertical. The side of the plate that was up is subsequently referred to as "front". Care was used to hold the torch as perpendicular as possible to the surface of the plate.

However, in the first specimen of this group (FA-1) the flame cut was started at the pierced hole and carried to the right, continued along the circle so that three-quarters of the circle was cut. The flame cut was once again started at the right side of the circle and taken clock-wise for the last quarter of the bottom point which completed the hole. Because of the order taken in cutting the circle, a notch was left on the inside face of the hole on the right side where the second flame cut was started. However, it was not much more severe than some of the other grooves.

The following equipment was used:

Specimen:	All except FB-2	FB-2
Torch:	Airco Combination Style 9900	Presto-Weld C-101
Tip Size:	#1	#2
Acetylene Pressure:	3-4 Lbs.	4 Lbs.
Oxygen Pressure:	35 Lbs.	40 Lbs.

Coarse grinding of the inner surface of the hole on specimens FB-1 and 2 was done with a Norton A16 - P4B5 wheel driven by a Black and Decker, portable 5" grinder. Finish grinding was done with a Norton A36-QB wheel on an Aro-Grinder (air). The finished surface was quite smooth, see Figs. 82 and 83. In this process all the burned metal but not over 1/16" depth of metal was removed.

In the fifth specimen, FC, the hole was bored to 4 1/4" diameter, in a vertical boring mill, removing the metal to a radial depth of 1/2" at the surface of the hole, (cut to 3 1/4" diameter, machined to 4 1/4" diameter). Special attention was given to the tool so as to leave a very smooth surface after the last cut, as shown in Fig. 84.

<u>Flame Stress</u>: In the photograph of the plate, Fig. 80, radial "lines" are seen where the scale has been chipped away; evidence that plastic flow of the metal has extended some three to four inches from the edge of the hole. These shear lines occurred during the flame cutting of the hole, and indicate that considerable residual stress may exist in the region adjacent to the surface of the hole. No annealing or other heat treatment was given the

plate subsequent to the cutting of the hole.

Appendix 4

Description of Fatigue Fractures

A brief comment is made in this section concerning the characteristics of the fatigue fractures. Each specimen has been sectioned and each fatigue crack opened up so that its surface could be examined. Photographs of the fractured area are shown in Figs. 34 - 78, inclusive.

The cracks discovered in a given specimen were assigned consecutive numbers; the letter following the number indicates the method of discovery. (See explanation of symbols, page 49).

In all photographs the lower edge of the fractured area is the front face of the specimen.

The words "top and bottom" refer respectively to the upper and lower faces of the transverse fractured area of the specimen as it underwent test in the fatigue machine.

A photograph of the weld surface is shown only for those as-welded surfaces in which the fatigue crack was visible at the surface. The photograph is also oriented so that its top is toward the top of the specimen.

Specimen AA-1

Location of Cracks, see Fig. 9, previous report.[1]

Crack No. 1-V, 82,500 cycles, back face, in upper third of test length. The crack appeared on the surface of the weld at a re-entrant angle where the common end of two successive beads formed a cleavage plane. The fracture (Fig. 34) shows that the fatigue crack started at the surface and traveled inward.

Crack No. 2-V, 92,000 cycles, back face, lower third of test length. The first evidence of the crack was at the juncture of two successive beads. From the general appearance of the fracture (Fig. 35) it was difficult to determine the origin of the fatigue crack. With reservation it might be stated that it started at the surface of the weld.

Crack No. 3-V, 95,000 cycles, front face, upper third of the test length. The fracture (Fig. 36) showed that the crack originated at the surface of the weld and propagated inward. This crack can be seen at the re-entrant angle created where a short bead overlapped a shallow bead.

Crack No. 4-V, 95,000 cycles, front face, middle third of test length. The crack appeared at a re-entrant angle formed at the start of a short bead made to bring that part of the weld surface flush with the plate. From the fracture (Fig. 37) it is seen that the crack started at the weld surface.

Specimen AA-2 and AA-3

Specimen AA-2

Location of Cracks, see Fig. 10, previous report.[1]

Crack No. 1-V, 57,000 cycles, front face, upper third of the test length. The crack appeared at a deep ripple in the weld. The fracture of the weld (Fig. 38) does not indicate clearly the origin of the fatigue crack. A comparison of the crystalline appearance of the metal near the weld surface with that of the metal near the root, leads one to assume that the crack started at a point of poor root fusion.

Specimen AA-3

Location of Cracks, see Fig. 11, previous report.[1]

Crack No. 1-V, 34,100 cycles, front face, upper third of test length. The crack appeared in a deep ripple of the weld surface. The fracture (Fig. 39) shows that the fatigue crack propagated inward from its origin at the surface of the weld. In careful examination of the fracture, a small smooth surface could be discerned close to the front face, (arrow). The weld metal on the opposite side of the fracture had a rough appearance which would indicate a shear failure. In this case good fusion existed at the root of the weld.

Crack No. 2-V, 36,000 cycles, front face, middle third of the test length. The crack appeared in a deep ripple at one end of a short bead placed to bring a shallow weld even with the surface of the plate. From the fracture it is seen that the crack started at the surface. There was good fusion at the root of the weld.

Specimen AA-4 and AA-5

Specimen AA-4

Fatigue failure of the specimen in the region where reinforcing plates are applied for purpose of clamping in the testing machine necessitated the premature halting of the test at 124,000 cycles of stress. Up to this point no visible fatigue cracks were detected in the test portion of the specimen. However, from examination of the X-Rays of the weld taken after the test it is suspected that two fatigue cracks exist - $19\frac{1}{2}$" and 5-5/16" above the transverse center line of the specimen, respectively. This specimen was not sectioned because it is planned to repair the damaged end, continue the fatigue test, and observe the number of cycles required for the suspected fractures to appear on the surface of the weld.

Specimen AA-5

Location of Cracks, Fig. 15.

Crack No. 1-V, 57,900 cycles, back face, upper third of the test length. The crack appeared along a ripple and at 82,500 cycles of stress it extended the full width of the weld. At 146,000 cycles the crack appeared on the front face of the specimen. At the end of the test (147,300 cycles) the fracture extended about 1/2" into the plates at either side of the weld. The fracture (Fig. 41) revealed poor fusion at the root. Since the outer parts of the weld metal showed large granular structure and the center portion had a smooth appearance, it is believed the crack started at or near the root.

Specimen AB-1 and AB-2

Specimen AB-1

Location of Cracks, Fig. 16.

Crack 1-V, 289,000 cycles, front face, upper third of test length. The fracture (Fig. 42) showed poor fusinn at the base of the root pass; this is believed responsible for the fracture which appeared on the front face.

Crack 2-X, front face, bottom third of test length. This crack also started at the root and progressed toward the front face of the specimen. See Fig. 43.

Crack 3-X, front face, middle third of test length. Likewise started in the region of poor fusinn at the root and progressed toward, but did not reach, the surface. See Fig. 44.

Crack 4-X, suspected from Radiograph, but not sectioned because it was within an inch of crack 3-X.

Specimen AB-2

Location of Cracks, Fig. 17.

No fatigue cracks visible to the eye developed on the surfaces of this specimen during 300,000 cycles of stress. However, two fractures were suspected from examination of Radiographs. Subsequent sectioning revealed the cracks described below.

Crack 1-X, The upper third of test length. Figure 45 showed that the crack started at the point of poor fusion in the root of the weld and propagated toward the back face of the specimen. However, the fatigue fracture was so small that it could barely be detected.

Crack 2-X, The lower third of test length. Figure 46 shows the same general characteristics as obtained for Crack No. 1-X above.

Specimen AB-3 and AC-1

Specimen AB-3

No fatigue cracks visible to the eye developed in this specimen during 397,000 cycles of stress. Radiographs do not show any indication of internal minute cracks.

Specimen AC-1

Location of Cracks, see Fig. 12, previous report.[1]

Crack No. 1-V, 191,500 cycles, back face, middle third of test length. The crack appeared at a deep ripple on the surface of the weld. It propagated slowly; at the end of the test (275,000 cycles) it was about equal to the width of the weld. The fracture (Fig. 47) shows definitely that the fatigue crack originated on the surface of the weld. When the 1-V crack was sectioned another crack (which had not been previously detected) was found just opposite (see arrow) the first. This fatigue crack started on the surface of the front weld at a deep ripple in the weld metal, and traveled inward.

The poor fusion at the base of the root passes obviously was not the cause of these failures since neither crack reached the root of the weld.

Crack No. 2-V, 193,000 cycles, front face, upper third of test length. The crack appeared at a pin-hole in one of the weld craters. The fracture (Fig. 48) indicated very poor fusion and distortion of the plates at the root. During the laying of the longitudinal weld beads, distortion of the plates occurred so that one bevel edge climbed over the other edge. From a study of the fracture it was concluded that the crack started near the root.

Crack No. 3-V, 193,000 cycles, front face, beyond the test length. The crack appeared in a small pin-hole at a crater. At the end of the test, the crack was slightly wider than the weld. From the fracture (Fig. 49) it was difficult to determine at which point the crack started and in which direction it traveled. It is thought the crack started at the root.

Crack No. 4-V, 263,000 cycles, front face, lower third of test length. The crack formed at a ripple in the weld surface but did not grow as the test continued. After 300,000 cycles of stress it was not much larger in size than when first detected. This failure was so close to the 6-V crack that it could not be sectioned. However, when the weld length was pulled in the testing machine, the crack opened sufficiently (see Fig. 50) to reveal that it had originated at the surface of the weld.

Crack No. 5-V, 264,000 cycles, back face, upper third of the test length. The crack appeared in a ripple that was very close to a crater. Apparently the propagation of this crack was arrested, for when the test ended it was not much larger than when discovered. The fracture (Fig. 51) definitely showed that a small crack (arrows) started at the surface, although the root was not well fused.

Crack No. 6-V, 264,000 cycles, back face, lower third of the test length. The crack appeared in a ripple of the weld surface but remained constant in size. From the fracture (see arrows,

Fig. 52) it is clear that the crack originated on the weld surface.

Crack No. 7-T, Directly opposite Crack No. 1-V. Refer to the description of Crack No. 1-V.

Crack No. 8-T, Approximately 1/2" below the 6-V crack. The weld length which was pulled in a testing machine exposed another fissure on the front face at a deep ripple in the weld metal. This was too close to the 6-V crack to section. From examination of the small fracture which was opened by the tensile force applied to the weld, it could be seen that the crack started at the surface. See Fig. 53.

Specimen AC-2

Location of Cracks, Fig. 18.

Crack No. 1-V, 199,000 cycles, top front face, beyond the test length. The crack appeared at the edge of a crater. At the end of the test (300,000 cycles) it was still small. The fracture (Fig. 54) showed that the crack definitely started at the surface, and was not caused by the poor fusion at the root of the weld. Also, the cross-section of the crater at this point does not show pit-holes or porosity.

Crack No. 2-V, 242,000 cycles, bottom front face, beyond the test length. The crack started at a point in the weld surface where two beads joined one another At this point the direction of laying the last weld pass had been changed so that it did not involve the back-step sequence of welding but instead was of the continuous type. The fracture (Fig. 55) shows that good fusion was achieved at the root and that the fatigue crack commenced at the surface of the weld.

Crack No. 3-V, 255,000 cycles, front face, lower third of the test length. The crack appeared on the surface of the weld at a pin-hole in a crater. At the end of the test (300,000 cycles) the crack remained small. The fracture (Fig. 56) indicates that the fatigue crack started at the root of the weld because of poor fusion there and that it traveled outward toward the front face of the specimen.

Crack No. 4-X, The fracture (Fig. 57) indicated poor fusion at the root and also that a small fatigue crack started in the weld on the back face.

Crack No. 5-X, The fracture (Fig. 58) revealed the same characteristics as the failure described above.

Crack No. 6-X, The fatigue crack (Fig. 59) evidently started because of a slag inclusion at the root. By the end of the test it had nearly reached the surface of the front weld.

Specimen AC-3

This specimen was subjected to 146,000 cycles of stress before the test was discontinued because of failure in the grip portion of the test piece.

Repair and continuation of the test are under consideration, hence no sectioning has been done. Radiographs of the weld do not show any indication of internal cracks.

Specimen AD-1

Location of Cracks, Fig. 19.

Crack No. 1-V, 83,500 cycles, bottom front face, beyond the test length. The crack appeared at a pin-hole where a crater was formed by the back-step sequence of welding. At the end of the test (381,800 cycles) the fissure had become arrested as verified by the fracture (Fig. 60). Only a small pin-point fatigue crack (arrows #1) is seen.

Crack No. 2-V, 114,000 cycles, top back face, beyond the test length. The crack started at a pin-hole in a crater. At the completion of the test the crack was 1-1/2" wide. The fracture (Fig. 61) revealed a large amount of porosity in the crater - probably the cause of the failure.

Crack No. 3-V, 307,000 cycles, front face, upper third of test length. The crack appeared at a pin-hole in a crater, and when the test was halted was approximately 5/16" wide. The fracture (Fig. 62) is difficult to analyze for not only was there poor fusion at the root but porosity and a definite air pocket (arrow) existed in the weld metal close to the surface.

Crack No. 4-V, 329,000 cycles, back face, upper third of test length. After the crack appeared at a pin-hole in a crater, it did not propagate noticeably. The fracture shows a slag inclusion at the root of the weld; it appears that the crack started there and traveled toward the surface. See Fig. 63.

Crack No. 5-V, 334,000 cycles, back face, upper third of test length. This crack appeared at some pin-holes in a crater, (see Fig. 64) but remained small. This crack was too close to the 4-V crack to permit sectioning.

Crack No. 6-V, 334,000 cycles, back face, and just at the end of the lower third of the test length. The crack, visible at a pin-hole in a crater, was approximately 1/4" wide at the end of the test. The fracture shows that the pin-hole (see arrow, Fig. 65) was deep and that the crack started at the surface. The poor fusion at the root evidently did not institute the failure.

Specimen AD-2

Location of Cracks, Fig. 20.

Crack No. 1-V, 240,500 cycles, back face, lower third of test length. The crack appeared at a pin-hole in a crater and at the end of the test (332,000 cycles) it had become approximately 1/2" long. The fracture (Fig. 66) exposed a crater with porosity and poor fusion at the root of the weld. It is questionable where the fatigue crack started.

Crack No. 2-V, 310,500 cycles, bottom front face and beyond the test length. After the crack appeared on the front face it traveled through to the back face, and finally became so large that the test had to be discontinued. Examination of the fracture showed that an air pocket in the weld was the cause of the failure.

Crack No. 3-T, When the weld was sectioned for crack 1-V, a second fatigue crack was exposed (see arrows, Fig. 66) about 1/2" lower, and which had nearly reached the surface. The poor fusion at the root was the cause of the crack.

Specimen AD-3 and AE-1

Specimen AD-3

Location of Cracks, Fig. 21.

Crack No. 1-V, 167,000 cycles, front face, lower third of test length. The crack appeared at a pin-hole in a crater. At the end of the test (300,000 cycles) the crack was 3/4" long but was not visible on the back face of the specimen. The fracture (Fig. 67) showed that the fatigue crack started at a point of poor fusion in the root and propagated to the front surface of the weld.

Crack No. 2-X, Radiograph of the weld indicates a possible fracture which could not be sectioned because it was too close to the 1-V crack.

Specimen AE-1

Location of Cracks, Fig. 22.

Crack No. 1-V, 152,000 cycles, back face, upper third of test length. The crack appeared in a region where apparently there were no flaws in the weld surface. At 153,000 cycles the failure was across the weld, and at 159,000 cycles it broke through to the back face. At the end of the test (188,000 cycles) the fracture was 2" to either side of the center line of the weld. The fracture (see Fig. 68) showed poor fusion at the root of the weld. From the appearance of the section it is believed that the crack started at this point and traveled outward toward the faces of the weld.

Crack No. 2-V, 168,000 cycles, top back face, beyond the test length, at a point where the weld had been ground flush. At 169,000 cycles the crack was almost the width of the weld, and at the termination of the test the crack had broken through to the front face. The fracture (Fig. 69) exposed, at the root of the weld, a slag inclusion which created this fatigue crack.

Specimen AE-2

Location of Crack, Fig. 23.

Crack No. 1-V, 189,500 cycles, front face, upper third of the test length. The crack appeared at a pin-hole in a crater. At 207,000 cycles the crack broke through to the back face, and at the end of the test (234,000 cycles) was approximately 2" wide on the front and back faces of the specimen. The fracture (Fig. 70) indicates that the crack started at the root of the weld where poor fusion existed.

Crack No. 2-V, 190,500 cycles, front face, middle third of test length.

The crack became visible at the surface of the weld where there was a small pin-hole created by under-cutting, and traveled across the ripples of the weld and not along the ripple itself. It broke through to the back face at 218,000 cycles; at the completion of the test (234,000 cycles) the crack was 3" wide on the front face. The fracture (Fig. 71) shows that the fatigue crack started at the root.

Specimen DE-1

Location of Cracks, Fig. 24.

Crack No. 1-V, 181,000 cycles, front face, middle third of test length. A very small crack was first detected in a ripple of the weld, and traveled across the ripples as the test progressed. At 198,500 the crack was slightly wider than the weld, at 202,500 cycles it broke through to the weld surface on the back face, and finally at the end of the test (254,000 cycles) the crack was 7" wide. From the fracture (Fig. 72) it is concluded that the fatigue crack originated at the root of the weld, where poor fusion existed, and traveled outward toward the surfaces of the weld.

Crack No. 2-X, Approximately 240,000 cycles, back face, upper third of the test length. The cycles to failure for this fatigue crack was estimated from the data taken during the test. This crack, although it had reached the surface, was not detected until radiographs of the specimen were examined.

The fracture (Fig. 73) indicated poor fusion at the root of the weld; it is believed that the fracture traveled from the root toward the back face of the specimen.

Crack No. 3-X, Approximately 230,000 cycles; back face, lower third of the test length. This crack was detected in the same manner as the 2-X crack, and the cycles to failure was estimated from the data taken during the test. The fracture (Fig. 74) revealed poor fusion at the root where the fracture started.

Crack No. 4-X, Radiographs show a fine crack but sectioning was not possible.

Crack No. 5-X, Same conditions as number 4-X above.

Specimen DE-2

Location of Cracks, Fig. 25.

Crack No. 1-V, 152,000 cycles, front face, upper third of the test length. When first seen the crack was in a deep ripple of the weld surface. At 167,000 cycles the crack was the full width of the weld; at 195,000 cycles the crack broke through to the back face; at 209,000 cycles the crack was approximately 3-1/2" wide, and at the end of the test (234,000 cycles) the crack had become 7" wide. The fracture (Fig. 75) showed that the crack had started on the front surface of the weld.

Specimen EE-1 and EE-2

Specimen EE-1

Location of Cracks, Fig. 26.

Crack No. 1-V, 189,000 cycles, front face, middle third of test length. The crack also was first seen in a deep ripple of the weld metal. The crack propagated rapidly; at 192,000 cycles it was the full width of the weld surface; at 208,000 cycles it was seen on the back face, and at the end of the test (219,000 cycles) the crack was 2" wide on the front and back faces. It was not possible to determine definitely from the fracture (Fig. 76) the point of the weld at which the crack originated.

Specimen EE-2

Location of Cracks, Fig. 27.

Crack No. 1-V, 204,000 cycles, back face, upper third of test length. The crack appeared across the ripples of the weld surface. The crack was seen on the front face at 223,000 cycles and became 2-1/2" wide at the end of the test (246,300 cycles). The fracture (Fig. 77) shows a slag inclusion at the root of the weld where the fatigue crack originated.

Crack No. 2-X, Radiographs of the weld indicated a fracture which was verified by a sectioning of the weld (Fig. 78). The crack definitely started at the front surface in a ripple of the weld and propagated inward.

Specimen B-2

Location of Cracks, Fig. 28.

The position of all the fatigue cracks with respect to the welds are shown in the diagram of the ring (Fig. 28). Almost all of these cracks appeared on the surfaces of the weld and then spread either to the edge of the weld or to the edge of the ring. The propagation of all the fatigue cracks was very rapid for by the end of the test (30,900 cycles) most of them were of the order of 1" in length. Radiographs of the specimen do not show the fractures clearly. Sectioning has not been carried out.

Note: The results of previous tests on two specimens are abstracted below from description given in previous report.[1]

Specimen B-1. Construction was identical to that of specimen B-2 above. Four fatigue cracks became visible at 10,500 cycles to 15,000 cycles and the test had to be stopped at 20,000 cycles. In all four cases the cracks started in the weld surface and traveled along the weld before breaking out into the plate.

Specimen C-1. Construction was identical with B series except that edges of the hole were beveled, see Fig. 3 of previous report[1]. Eight cracks appeared between 11,500 and 30,000 cycles of stress. The cracks started in discontinuities in the weld surface.

Specimen FA-1 and FA-2

Specimen FA-1

Fatigue Crack: 10,500 cycles, on the front left edge about 1/2" above the transverse center line of the hole, see Fig. 79. The crack did not start in a small notch on the inside surface of the hole resulting from the flame cutting process. The crack traveled along a ripple in the flame cut surface and was visible on the back face of the specimen at 13,300 cycles. At nearly the same number of cycles a second crack appeared on the front right edge of the front face exactly on the transverse center line. This crack also traveled along a flame ripple (Fig. 80) to the back face of the specimen. The test had to be discontinued at 23,900 cycles because the cracks had spread about 2-1/2" to either side of the hole. The reduction in the cross-section caused plastic flow at the ends of the crack (see Fig. 80 and Fig. 29).

Specimen FA-2

Fatigue Crack: 14,500 cycles, on the front left edge at the transverse center line of the hole. The crack followed a flame groove on the inside of the hole and appeared on the back face at 23,000 cycles. On the front right edge of the hole a crack developed 3/8" above the transverse center line at 21,500 cycles and at 23,500 cycles appeared on the back face. The test was stopped at 26,000 cycles because the cracks then extended approximately 5/8" into the metal at the sides of the hole (see Fig. 30).

Note: Fig. 81 illustrates the quality of surface flame cut by hand for these two specimens.

Specimens FB-1 and FB-2

Specimen FB-1

62,500 cycles, on the back left edge of the hole (Fig. 82) about 5/16" above transverse center line. At 75,000 cycles the fracture had traveled along the inside of the hole and became visible on the front face. At the end of the test (76,600 cycles) this crack was approximately 1-1/4" long on the back face and 1/4" long on the front face. The crack on the opposite side of the hole appeared at 71,500 cycles on the back right edge of the opening about 1/16" below the outer line. It traveled through to the front face, appeared there at 74,000 cycles. The test was stopped when Lueders' Lines formed on all faces of the specimen at the ends of the cracks. Location of Cracks, see Fig. 31.

Specimen FB-2

77,500 cycles on the back right edge of the hole about 3/16" above the transverse center line, this fracture appeared on the front face at 106,500 cycles (see Fig. 83). The crack continued to grow until at the end of the test (115,000 cycles) it was 1-1/2" long. On the opposite side of the hole, a very small crack appeared on the back edge at 109,000 cycles. In this specimen, more cycles of stress were required for the cracks to result in failure to carry load than seemed to be the case for specimens FA-1, 2 and FB-1. Location of Cracks, see Fig. 32.

Specimen FC-1

91,000 cycles, on the front right edge of the hole about 3/16" above transverse center line (see Fig. 84). At 100,000 cycles it reached the back face and by the end of the test (120,800 cycles) the fracture had become 1-1/2" long. On the opposite side of the hole the crack first appeared on the inside of the hole at 104,500 cycles, spread rapidly to the back face and finally appeared on the front face at 112,000 cycles. The cracks had so reduced the net-section that plastic flow occurred at the ends of the crack. Figure 33 shows location of cracks.

Explanation of Symbols used in Table 1 and 2

WH - Width of specimen in inches

P - Number of weld passes each side

AW - Weld surfaces in the as-welded condition
G - Weld surfaces ground smooth and flush with surfaces of specimen

Restraint I - No clamps, weld passes on alternate sides
Restraint II - Beads placed on alternate sides
Restraint III - Clamped to "hold-down" table, see Text, Section III

S - Crack started at surface
I - Crack started inside metal

V - Crack detected visually
X - First seen in radiograph
T - Appeared when section subjected to tension

F - Front side of specimen, see Text
B - Back side of specimen
U - Upper third of test length
M - Middle third of test length
L - Lower third of test length

E_1 - Beyond test length, top
E_2 - Beyond test length, bottom

* - These results were reported previously.[1]

NOTE: All specimens were subjected to 300,000 cycles of stress unless noted otherwise under "Remarks" in Table 1.

TABLE 1

SUMMARY OF TEST RESULTS

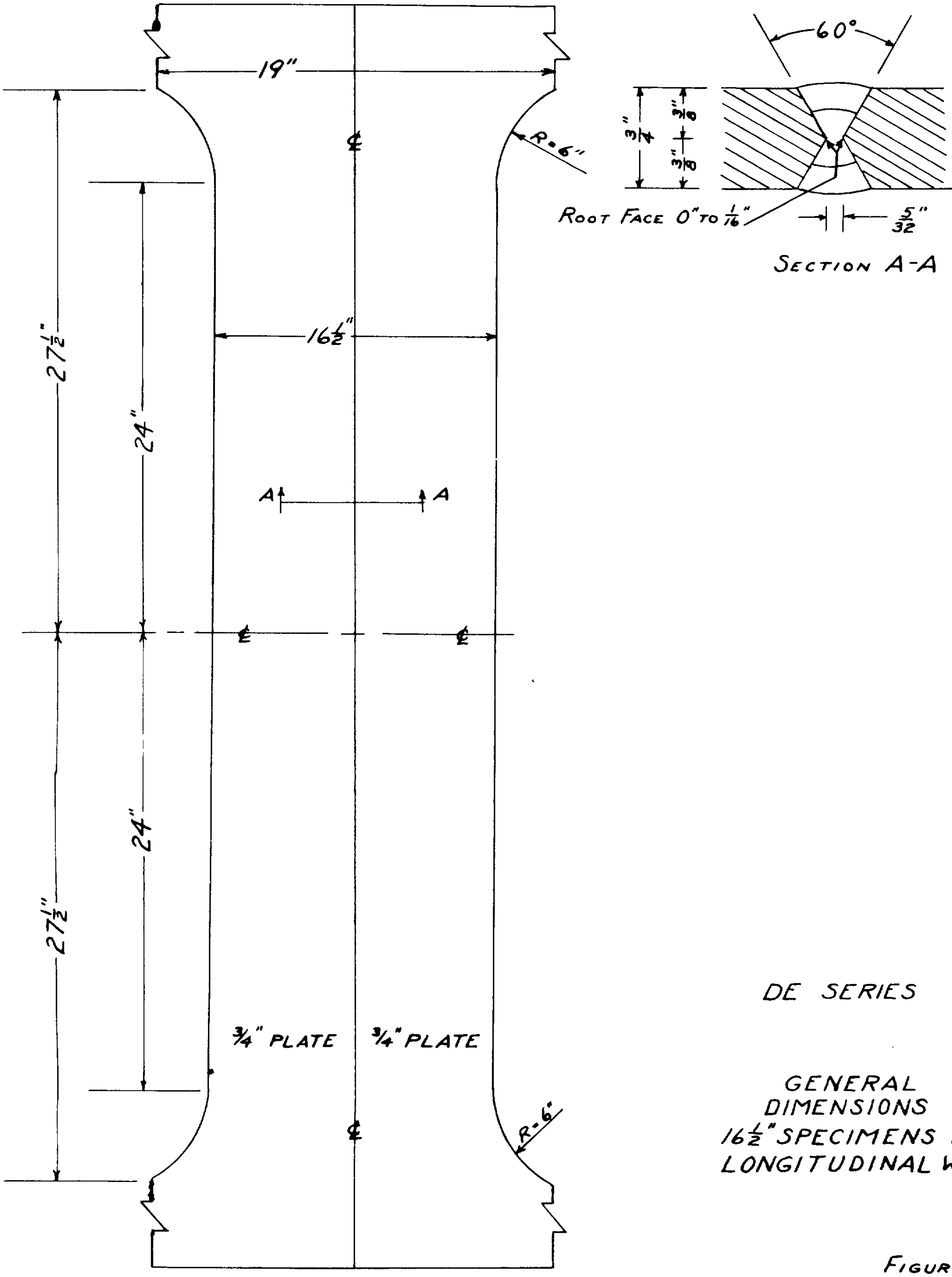
Specimen	Description	Restraint	Average Stress Range Lower Limit psi	Average Stress Range Upper Limit psi	Critical Stress Range Lower Limit psi	Critical Stress Range Upper Limit psi	Local Average Stress Range Lower Limit psi	Local Average Stress Range Upper Limit psi	Cycles to Failure	Crack No.	Origin	Location	Remarks
*AA-1 11½WH	Long. Weld 3P-AW	I	+350	+26800	+400	+30400	+1600	+30600	82500	1-V	S	BU	WELD BEADS PLACED IN "CONTINUOUS" SEQUENCE – ALL SUBSEQUENT SPECIMENS WERE "BACK-STEP" WELDED.
							+450	+28900	92000	2-V	S	BL	
							+450	+25100	95000	3-V	S	FU	
							+2300	+29000	95000	4-V	S	FM	STOPPED AT 95300 – GRIP FAILURE
*AA-2 11½WH	Long. Weld 2P-AW	I	+350	+26200	+350	+30000	+350	+27500	57000	1-V	I	FU	STOPPED AT 76700 CYCLES
*AA-3 11½WH	Long. Weld 2P-AW	I	+250	+27600	0	+30000	+400	+27600	34100	1-V	S	FU	STOPPED AT 55000 CYCLES
							+300	+29000	36000	2-V	S	FM	
AA-4 11½WH	Long. Weld 2P-AW	II	-500	+28200	+1350	+30900						U	FAILURE IN GRIP SECTION STOPPED TEST AT 124000 CYCLES – 2 CRACKS INDICATED BY RADIOGRAPHY.
												M	
AA-5 11½WH	Long. Weld 2P-AW	II	0	+26500	+1650	+31500	+900	+31300	57900	1-V	I	BU	STOPPED 147300 CYCLES
AB-1 11½WH	Long. Weld 2P-G	II	-50	+28300	+300	+30800	+225	+30100	289000	1-V	I	FU	DIFFICULTY WITH DISTORTION IN PLATES DURING WELDING OF THIS SERIES.
							-150	+28300	—	2-X	I	BL	
							-50	+29600	—	3-X	I	FM	
							—	—	—	4-X		M	
AB-2 11½WH	Long. Weld 2P-G	II	+700	+27800	+450	+30900	-500	+25000	—	1-X	I	BU	
							+900	+26500	—	2-X	I	FL	UNDERWENT 397000 CYCLES TO TEST GRIP DESIGN – NO FAILURES IN SPITE OF POOR ROOT FUSION.
AB-3 11½WH	Long. Weld 2P-G	II	-500	+26900	-1450	+30100	—	—	—	none			
*AC-1 11½WH	Long. Weld 1P-AW	I	+1100	+27200	+3100	+30900	+2000	+27800	191500	1-V	S	BM	STOPPED AT 275500 CYCLES – 4" CRACK 1-V, 3-V PROPAGATED SLOWLY 2-V " RAPIDLY 4-V, 5-V, 6-V " VERY SLOWLY
							+450	+26400	—	7-T	S	FM	
							+400	+26000	193000	2-V	I	FU	
							—	—	193000	3-V		FE$_1$	
							—	—	263000	4-V	S	FL	
							+1800	+28400	264000	5-V	S	BU	
							+2600	+28350	264000	6-V	S	BL	
							—	—	—	8-T	S	BL	
AC-2 11½WH	Long. Weld 1P-AW	I	+750	+29200	+1050	+31300	—	—	199000	1-V	S	FE$_1$	THE PLACING OF INDIVIDUAL BEADS ON ALTERNATE SIDES WAS STARTED ON THIS SPECIMEN.
							—	—	242000	2-V	S	FE$_2$	PROPAGATION "ARRESTED"
							+650	+27950	255000	3-V	I	FL	
							+450	+29000	—	4-X	I	FU	
							-300	+30100	—	5-X	I	BU	
							+650	+28000	—	6-X	I	FL	
AC-3 11½WH	Long. Weld 1P-AW	II	-850	+26150	-900	+29300	—	—	—	none			FAILURE IN GRIP SECTION STOPPED TEST AT 93700 CYCLES – AFTER 29 DAYS REST, TEST EXTENDED TO 146000 CYCLES – GRIP SECTION FAILED AGAIN.
			-100	+28600	-600	+30800	—	—	—	none			
AD-1 11½WH	Long. Weld 1P-G	II	+100	+27700	+1050	+30400	—	—	83500	1-V	S	FE$_2$	FAILURE OF TESTING MACHINE STOPPED TEST AT 80950 CYCLES – AFTER 37 DAYS REST, THE TEST WAS CONTINUED TO 382000 CYCLES. — LOCAL AVERAGE STRESS RANGE FIGURES ARE AVERAGE OF READINGS FOR BOTH TEST PERIODS.
			-500	+26900	+1500	+29300	—	—	114000	2-V	S	BE$_1$	
							-550	+27650	307000	3-V		FU	
							+1300	+27150	329000	4-V	I	BU	1-V, 4-V, 5-V, 6-V PROPAGATION "ARRESTED" 2-V, 3-V PROPAGATED SLOWLY.
							—	—	334000	5-V		BU	
							+1400	+29400	334000	6-V	S	BL	
AD-2 11½WH	Long. Weld 1P-G	II	+100	+28500	+800	+30100	—	—	—	—	—	—	FAILURE OF TESTING MACHINE STOPPED TEST AT 73400 CYCLES – AFTER 52 DAYS REST, THE TEST WAS CONTINUED TO 330500 CYCLES.
							+700	+27100	240500	1-V		BL	1-V PROPAGATED SLOWLY 2-V PROPAGATED VERY RAPIDLY
							+300	+29600	—	3-T	I	FL	
							—	—	310500	2-V	S	FE$_2$	
AD-3 11½WH	Long. Weld 1P-G	II	+500	+27500	+350	+29900	+350	+27250	167000	1-V	I	FL	1-V PROPAGATED SLOWLY
							—	—	—	2-X		L	
AE-1 11½WH	Long. Weld 3P-AW	III	+850	+27900	+2400	+29950	+2600	+28750	152000	1-V	I	BU	THIS AND FOLLOWING SPECIMENS HAD GOOD ROOT FUSION. 1-V PROPAGATED RAPIDLY
							—	—	168000	2-V	I	BE$_1$	STOPPED AT 188000 CYCLES
AE-2 11½WH	Long. Weld 3P-AW	III	+400	+27000	+900	+30100	+100	+27800	189500	1-V	I	FU	STOPPED AT 234000 CYCLES 1-V, 2-V PROPAGATED RAPIDLY
							+550	+29600	190500	2-V	I	FM	
DE-1 16½WH	Long. Weld 3P-AW	III	+1250	+27300	+3800	+30000	-1300	+25750	181000	1-V	I	FM	STOPPED AT 254000 CYCLES 1-V PROPAGATED RAPIDLY
							+3800	+29200	240000	2-X	I	BU	
							+600	+29800	230000	3-X	I	BL	
							—	—	—	4-X		M	
							—	—	—	5-X		L	
DE-2 16½WH	Long. Weld 3P-AW	III	+100	+27050	+50	+30150	-250	+28300	152000	1-V	S	FU	1-V PROPAGATED RAPIDLY STOPPED AT 234000 CYCLES
EE-1 11½WH	Long. Weld 3P-AW	III	+550	+28100	+1050	+30050	+550	+29300	189500	1-V		FM	MADE FROM "CHATTANOOGA" STEEL STOPPED AT 219000 CYCLES
EE-2 11½WH	Long. Weld 3P-AW	III	+325	+27500	-850	+31750	-1700	+27000	204000	1-V	I	FU	MADE FROM "CHATTANOOGA" STEEL STOPPED AT 246300 CYCLES – BOTH 1-V CRACKS PROPAGATED RAPIDLY.
							-1200	+29300	—	2-X	S	FL	

TABLE 2

SUMMARY OF TEST RESULTS
(continued)

SPECIMEN	DESCRIPTION	AVG. STRESS RANGE AT NET CROSS-SECTION AREA AT HOLE		AVG. STRESS RANGE ON FACE OF FAILURE AT NET CROSS-SECTION AREA AT HOLE		CYCLES TO FAILURE	LOCATION FIG. NO.
		PLATES WITH FLAME-CUT HOLES, WITHOUT REINFORCEMENTS					
FA-1	As cut	-300	+30300	-1350	+30500	10,500	29
FA-2	As cut	+250	+29700	-1100	+33600	14,500	30
FB-1	Surface ground	+300	+32200	- 400	+30350	62,500	31
FB-2	after cutting	+800	+29900	+1850	+29050	77,500	32
FC-1	Machined after cutting	-300	+29700	-1275	+28900	91,000	33
		PLATES WITH CENTRAL OPENINGS, WITH REINFORCEMENTS					
B-2	See Figs. 10, 11.	+800	+26750	- 550 0 +1700 +2100	+28900 +26500 +25000 +27600	23,000 23,000 26,000 26,500	28
*B-1	Same as B-2	See previous report				10,500	Location similar to B-2
*C-1	Similar to B-2	See previous report				11,500	See previous report

* These results were given in OSRD Report No. 6544, Serial M-606



DE SERIES

GENERAL
DIMENSIONS
16 1/2" SPECIMENS WITH
LONGITUDINAL WELD

Figure 1

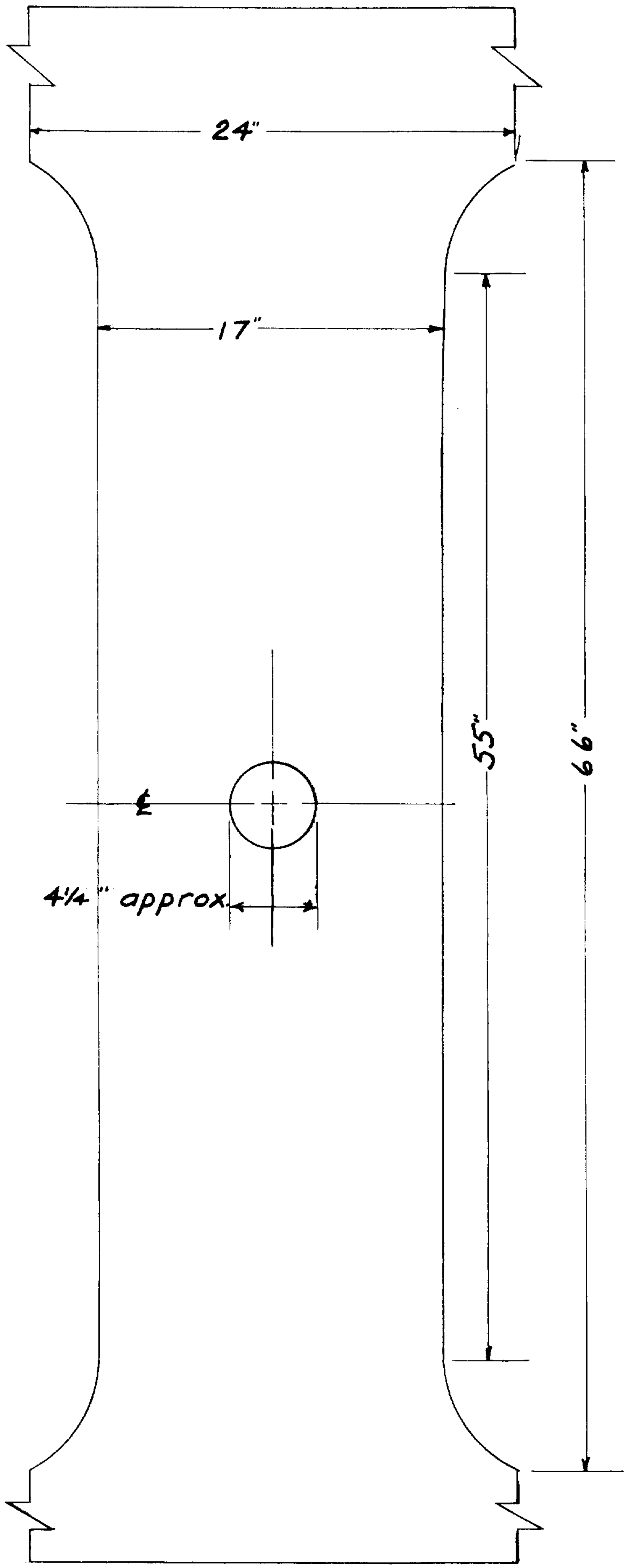
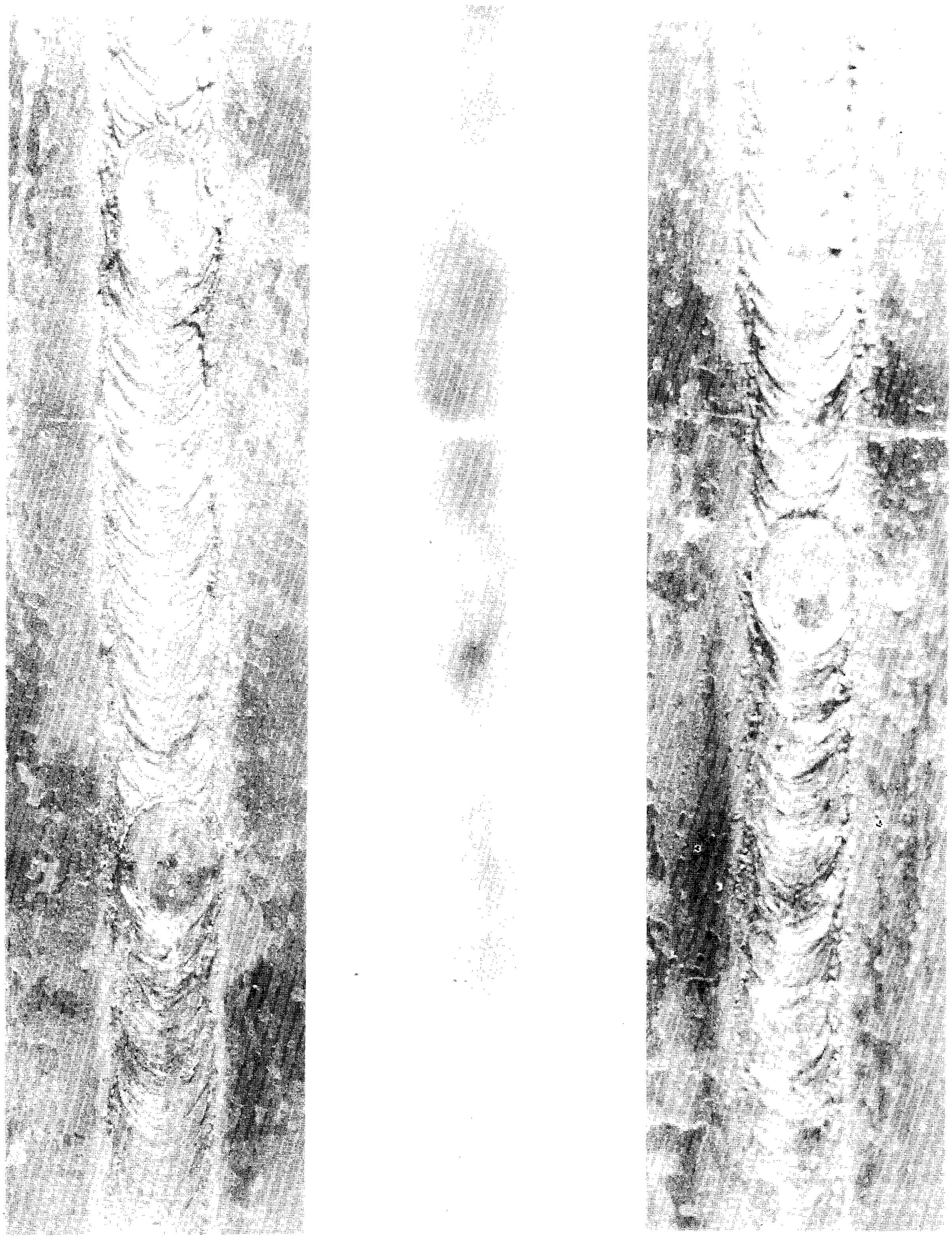


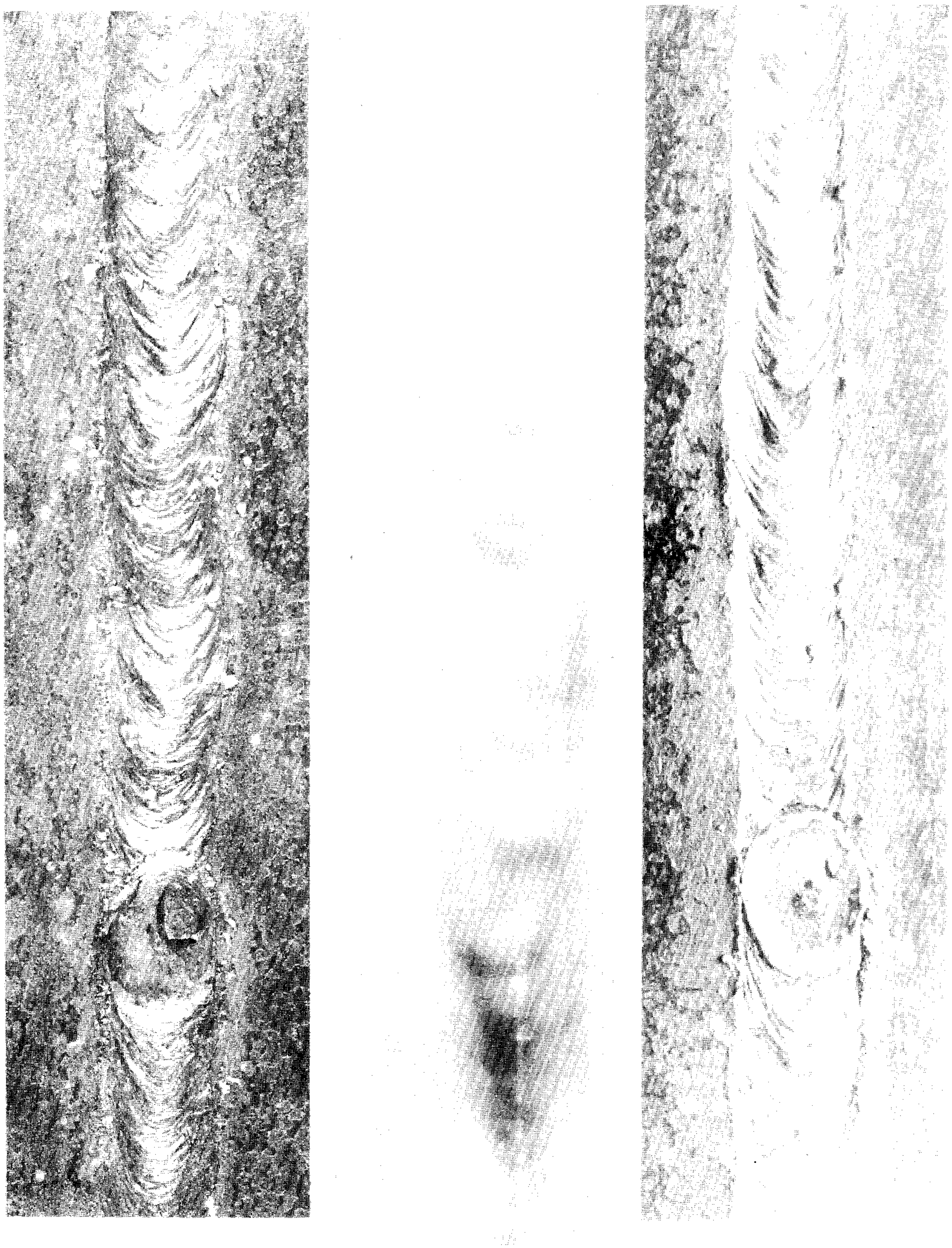
FIGURE 2

GENERAL DIMENSIONS OF SPECIMENS IN "F" GROUP



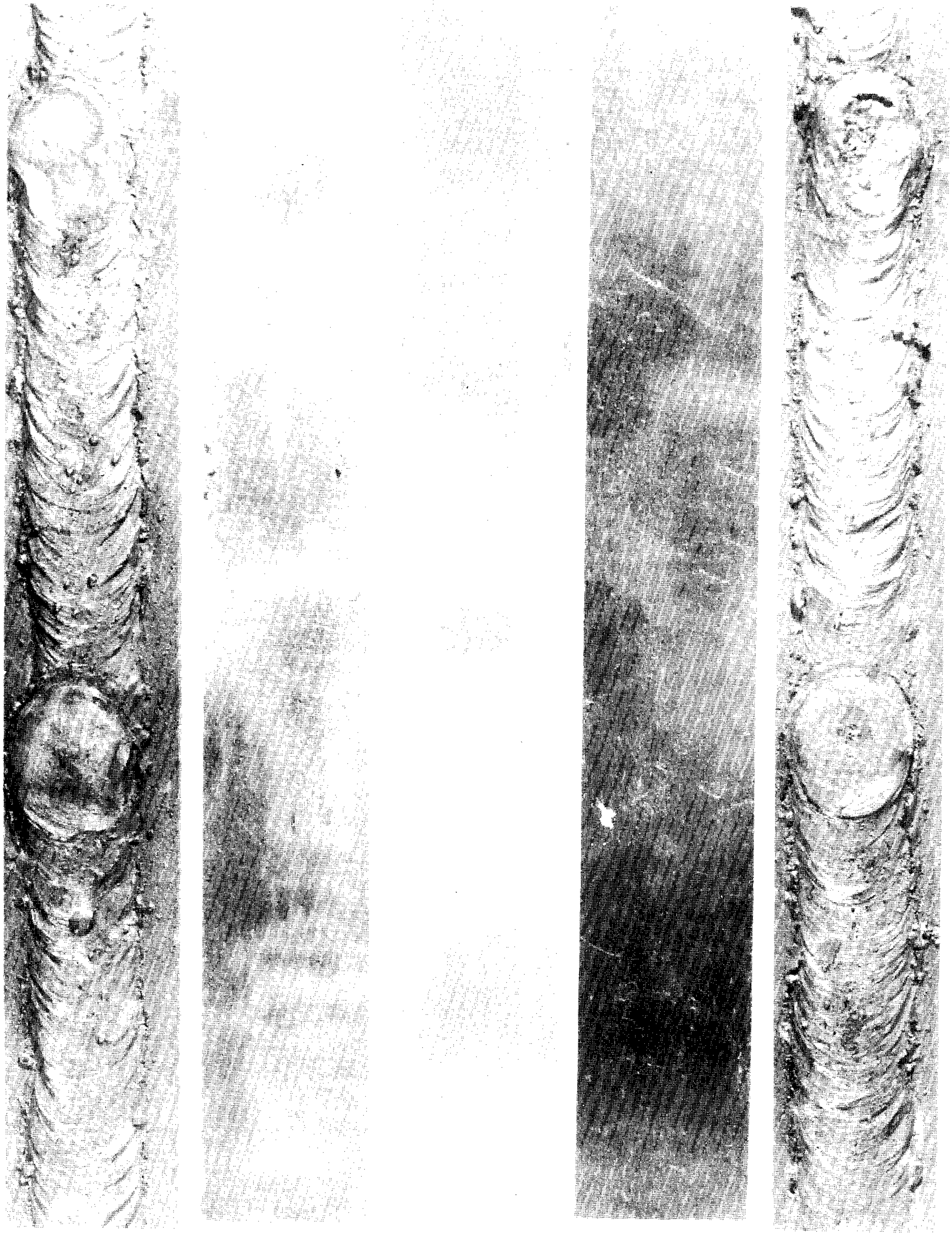
Front Face X-Ray Back Face

Figure 3 Specimen AA-5 8-16 in. From Top



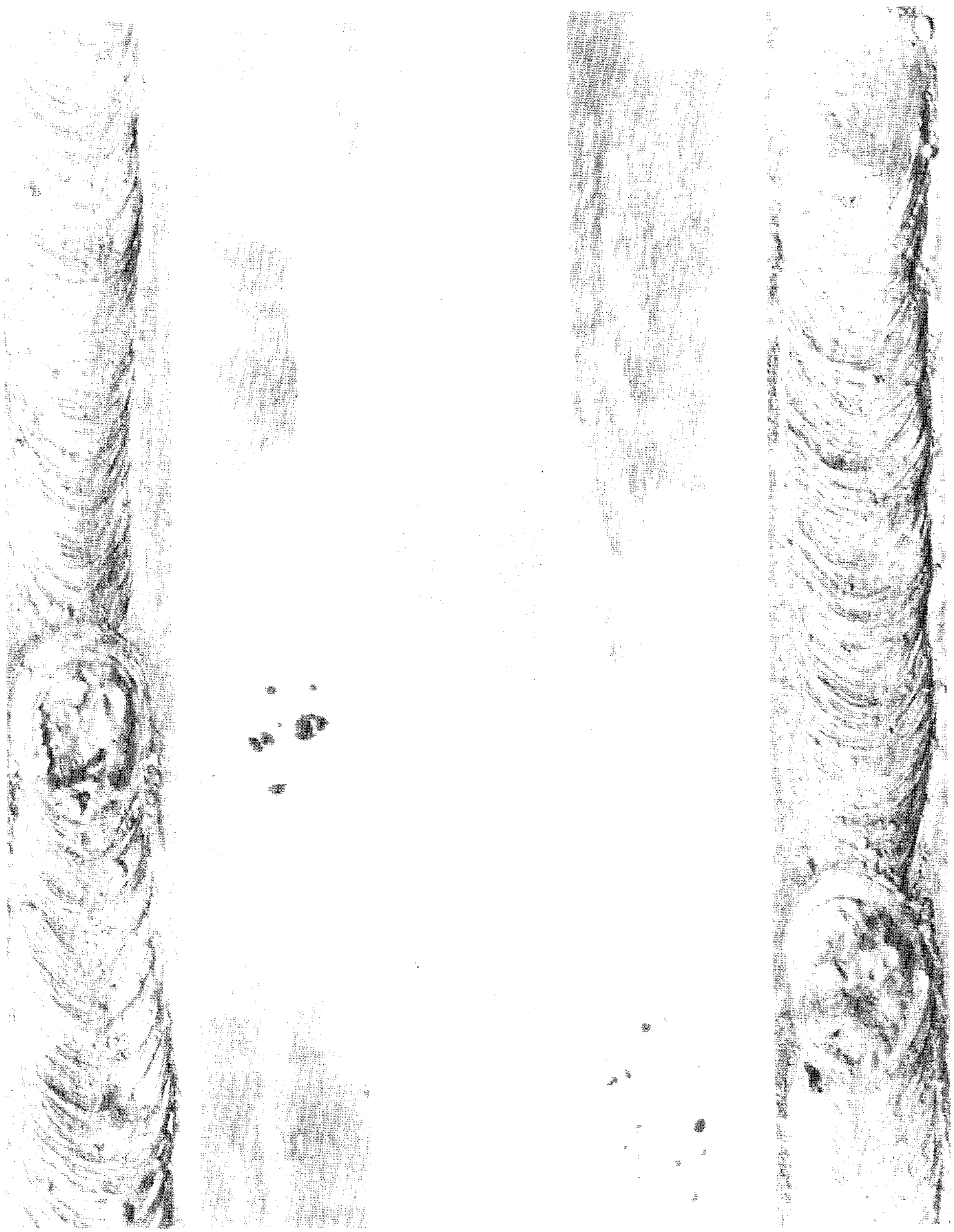
Front Face X-Ray Back Face

Figure 4 Specimen AC-2 8 - 16 in. From Top



Front Face Front Face Ground X-Ray Back Face Ground Back Face

Figure 5 Specimen AB-3 32-40 in. From Top



Front Face　Front Face Ground　X-Ray　Back Face Ground　Back Face

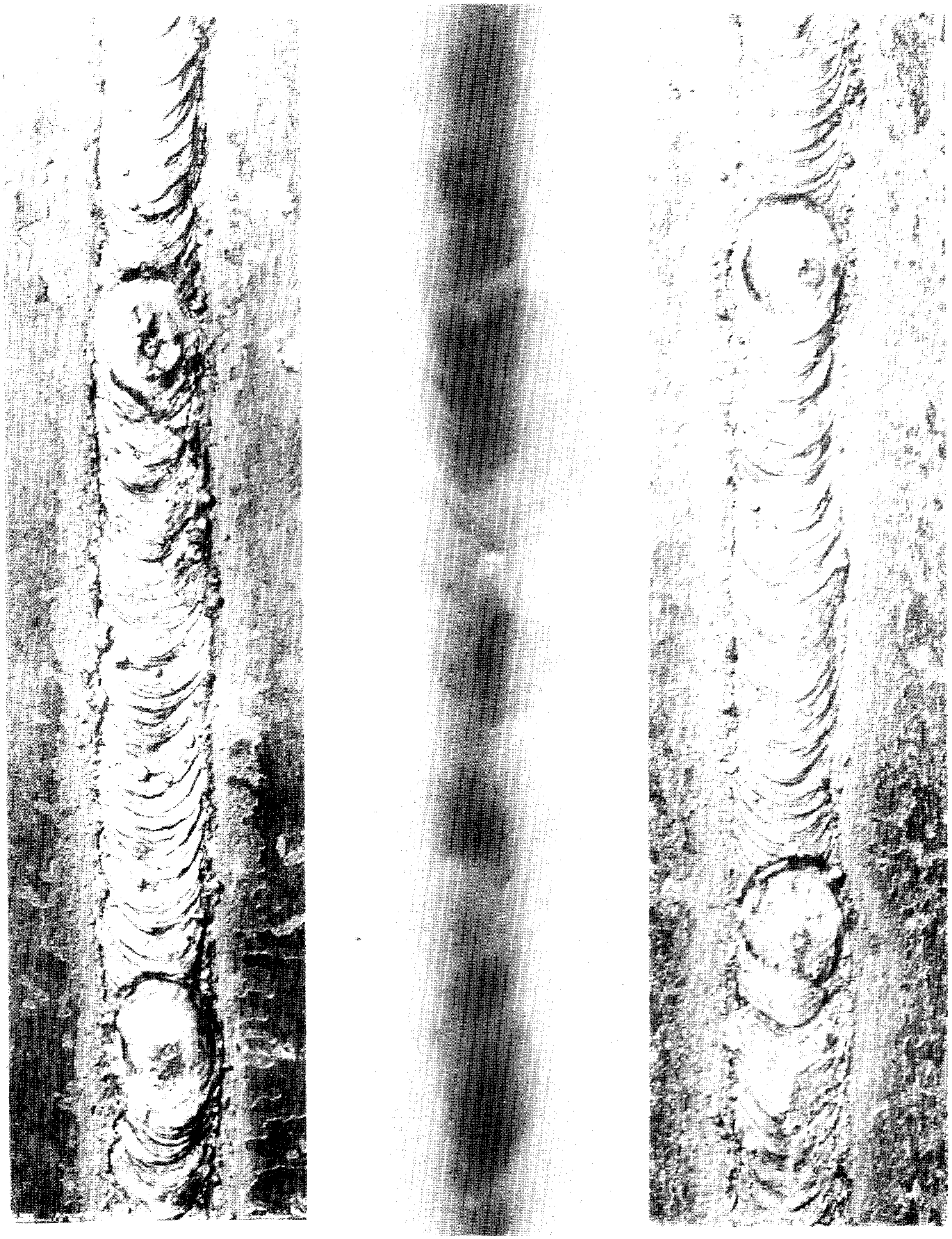
Figure 6 Specimen AD-1 0- 8 in. From Top

Front Face X-Ray Back Face

Figure 7 Specimen AE-2 40-48 in. From Top

Front Face X-Ray Back Face

Figure 8 Specimen EE-1 24-32 in. From Top



Front Face X-Ray Back Face

Figure 9 Speciman DE-1 16-24 in. From Top

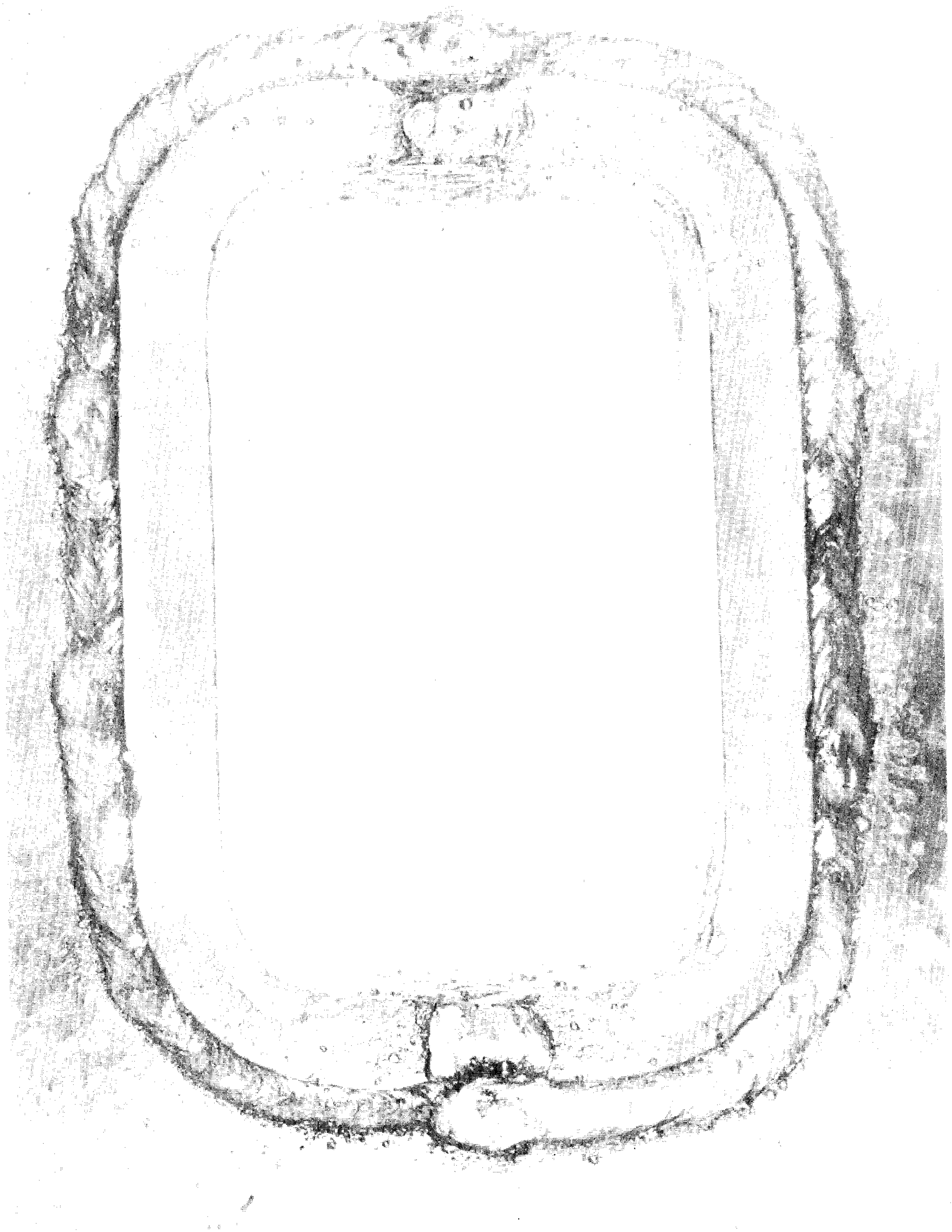


Figure 10 Specimen B-2 Front Bottom

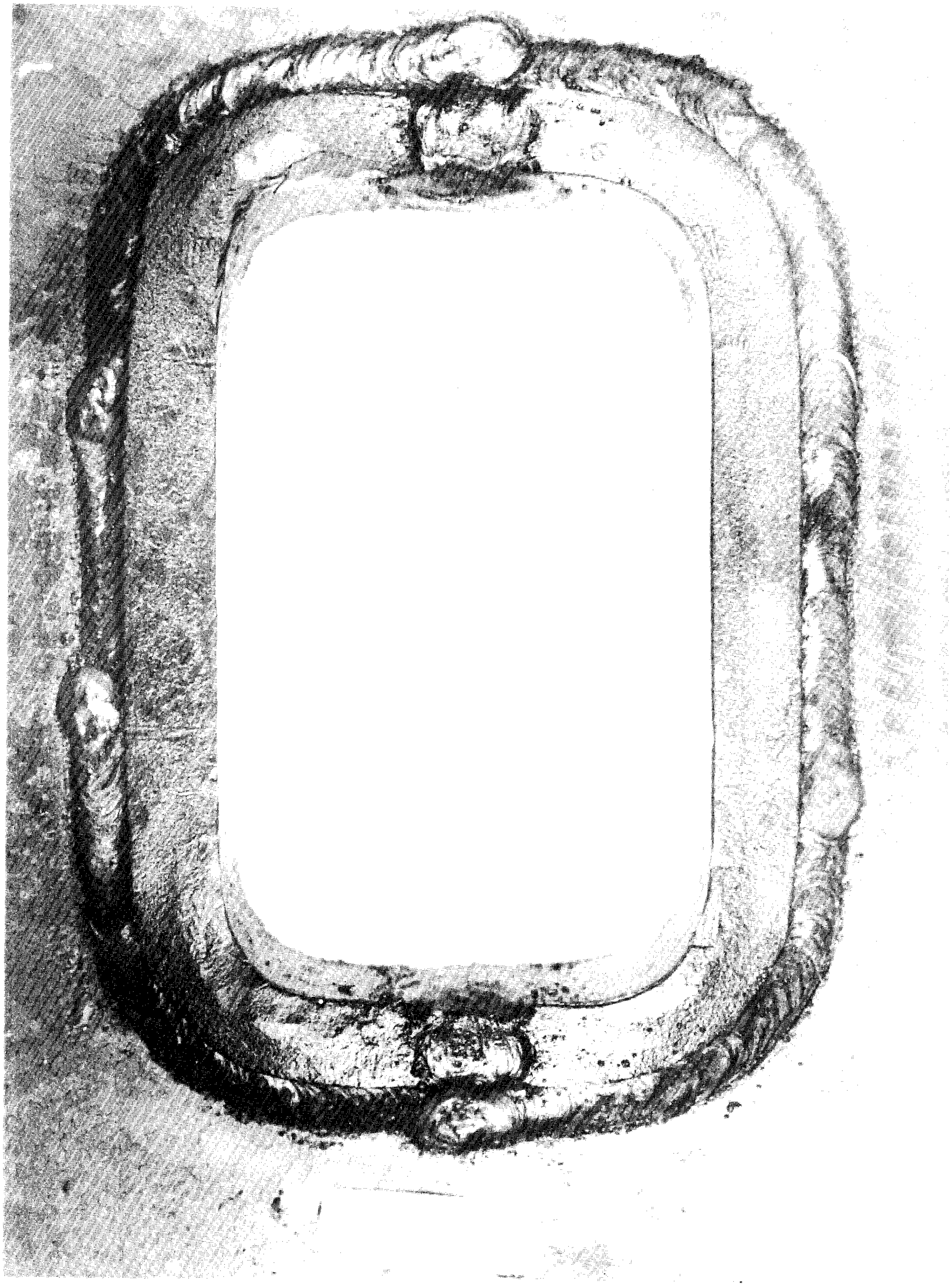


Figure 11 Specimen B-2 Back Bottom

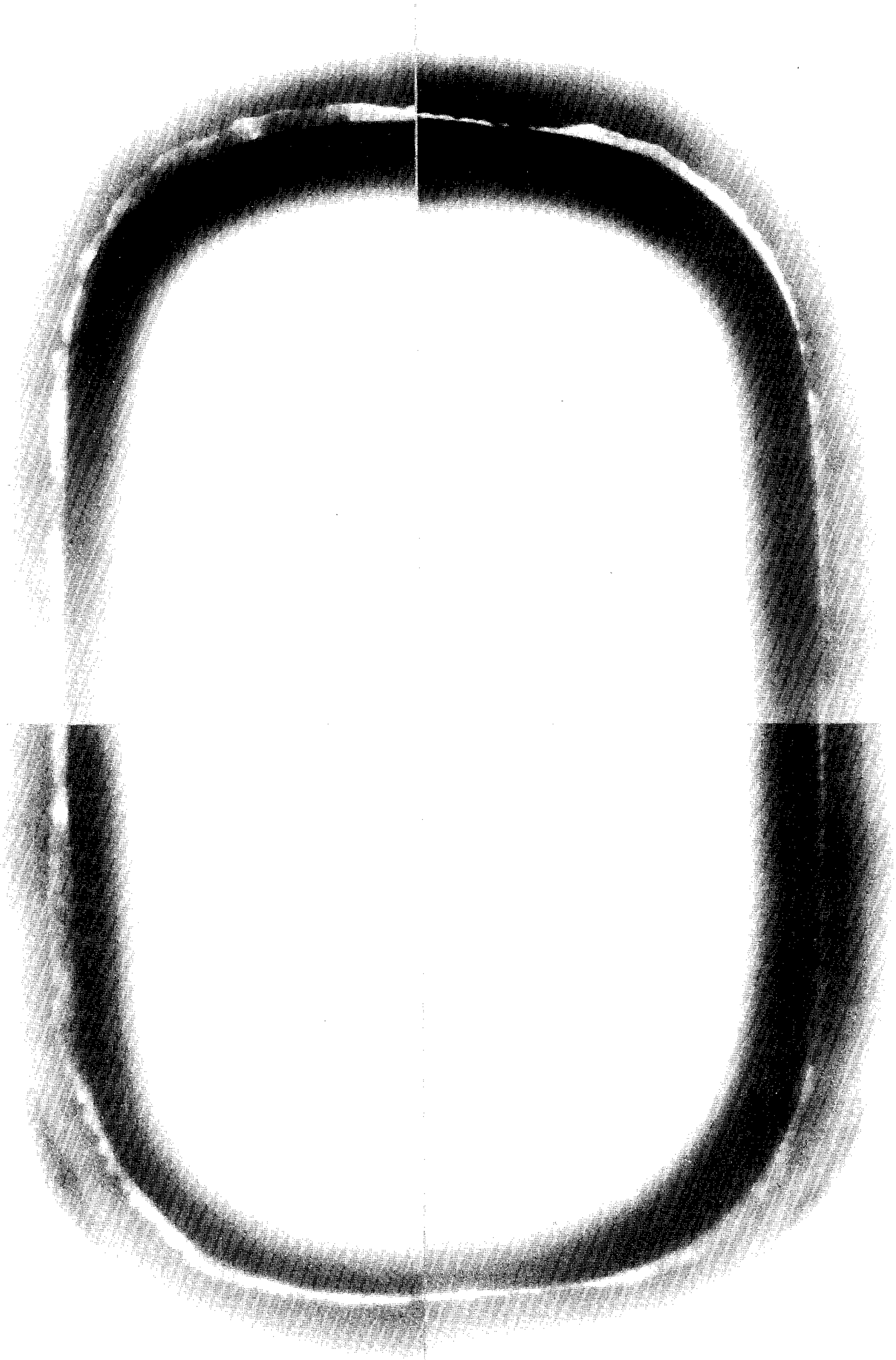


Figure 12 Specimen B-2 Back X-Ray

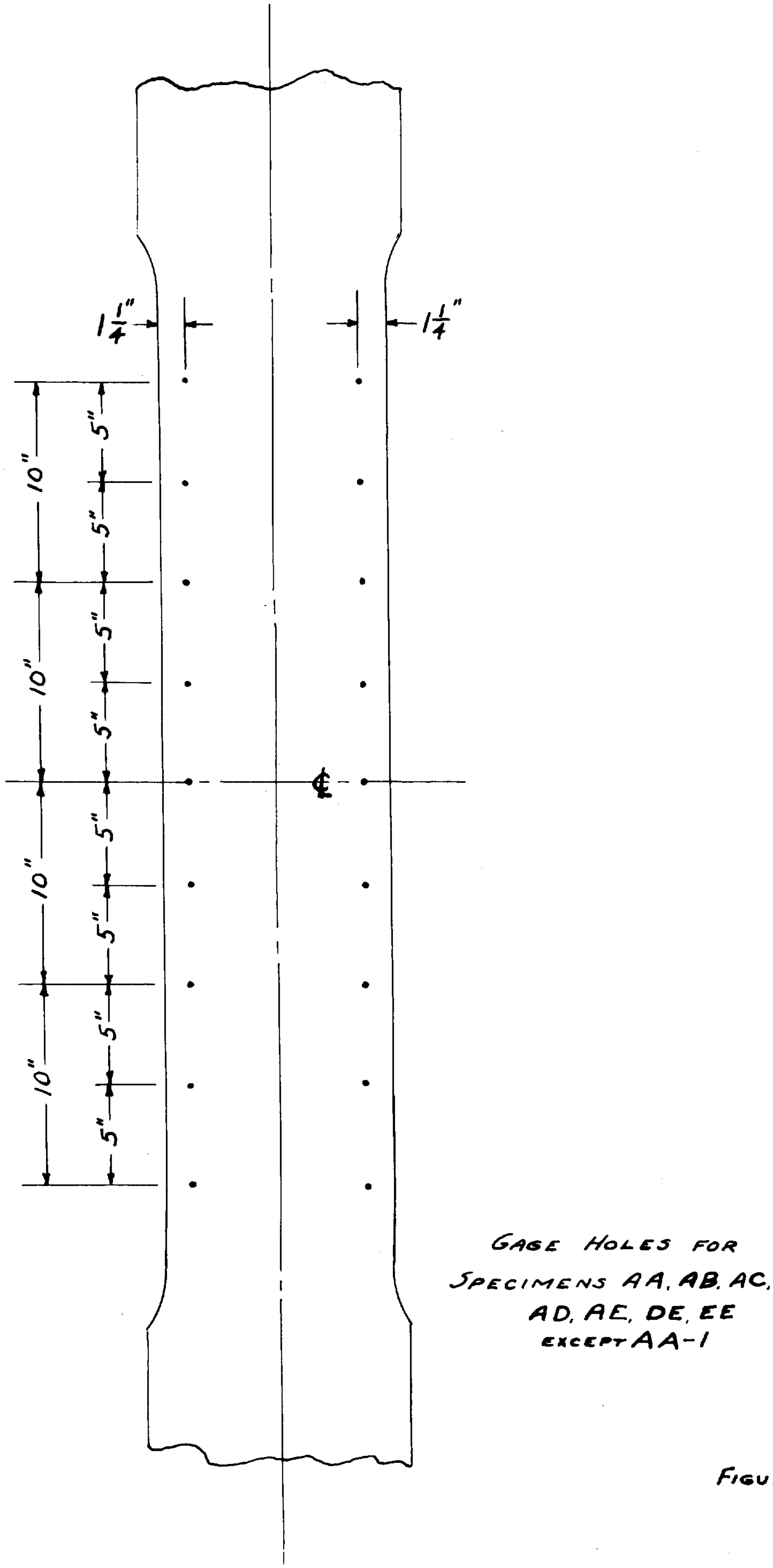
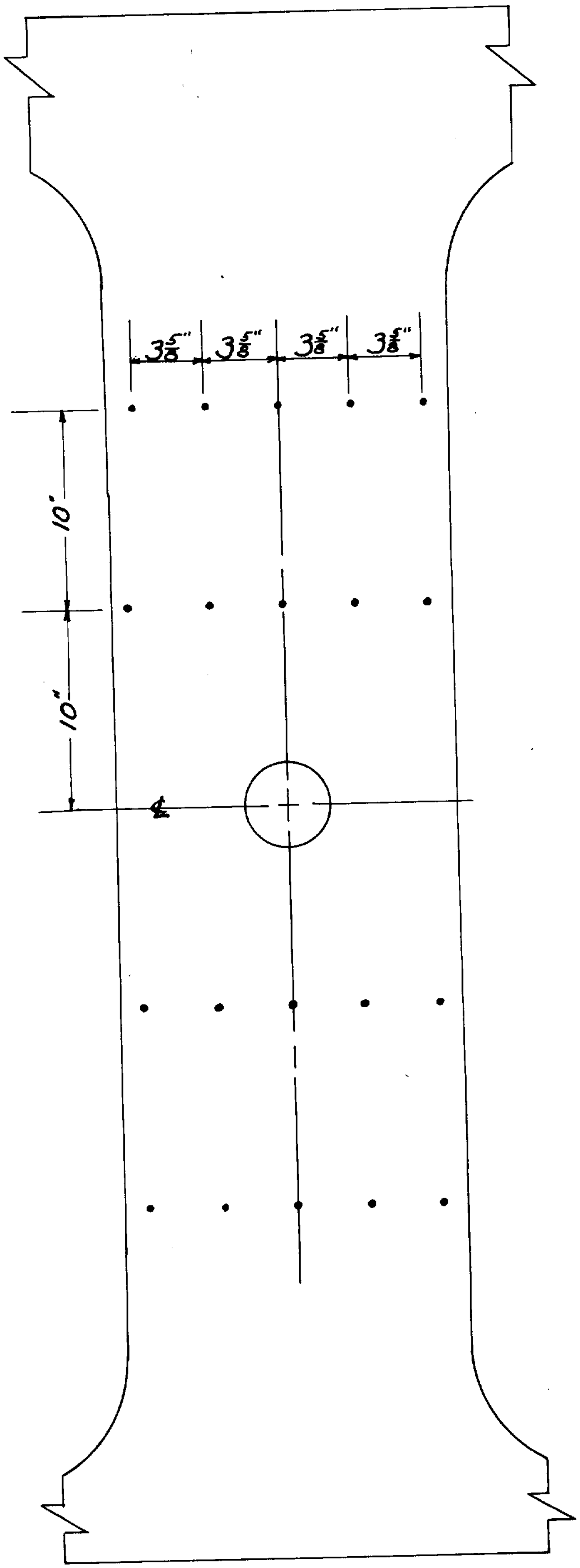
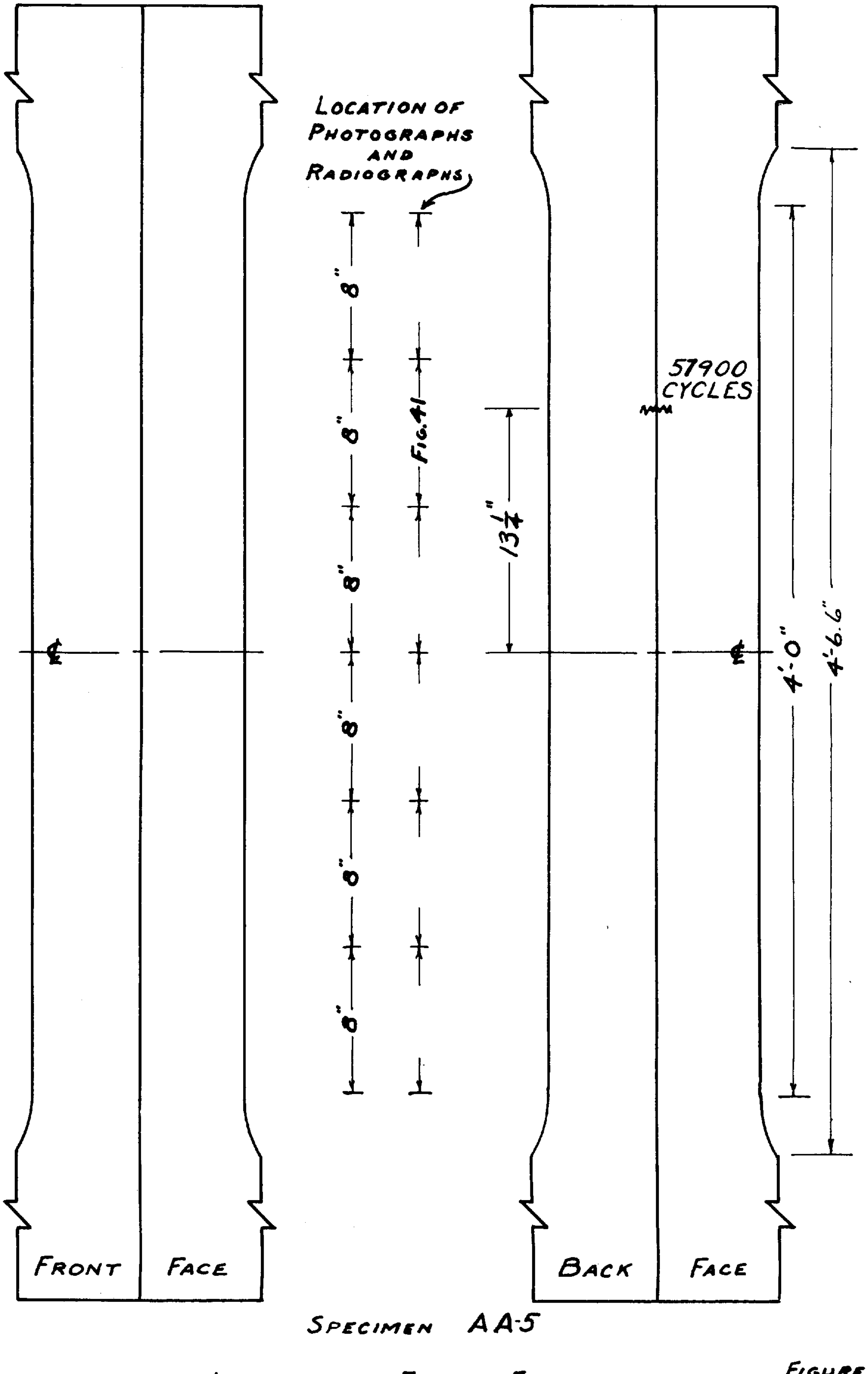

1 1/4"
1 1/4"
10"
10"
10"
10"
5"
5"
5"
5"
5"
5"
5"
5"
℄
Gage Holes for
Specimens AA, AB, AC,
AD, AE, DE, EE
except AA-1

Figure 13



GAGE HOLES FOR
"F" SPECIMENS

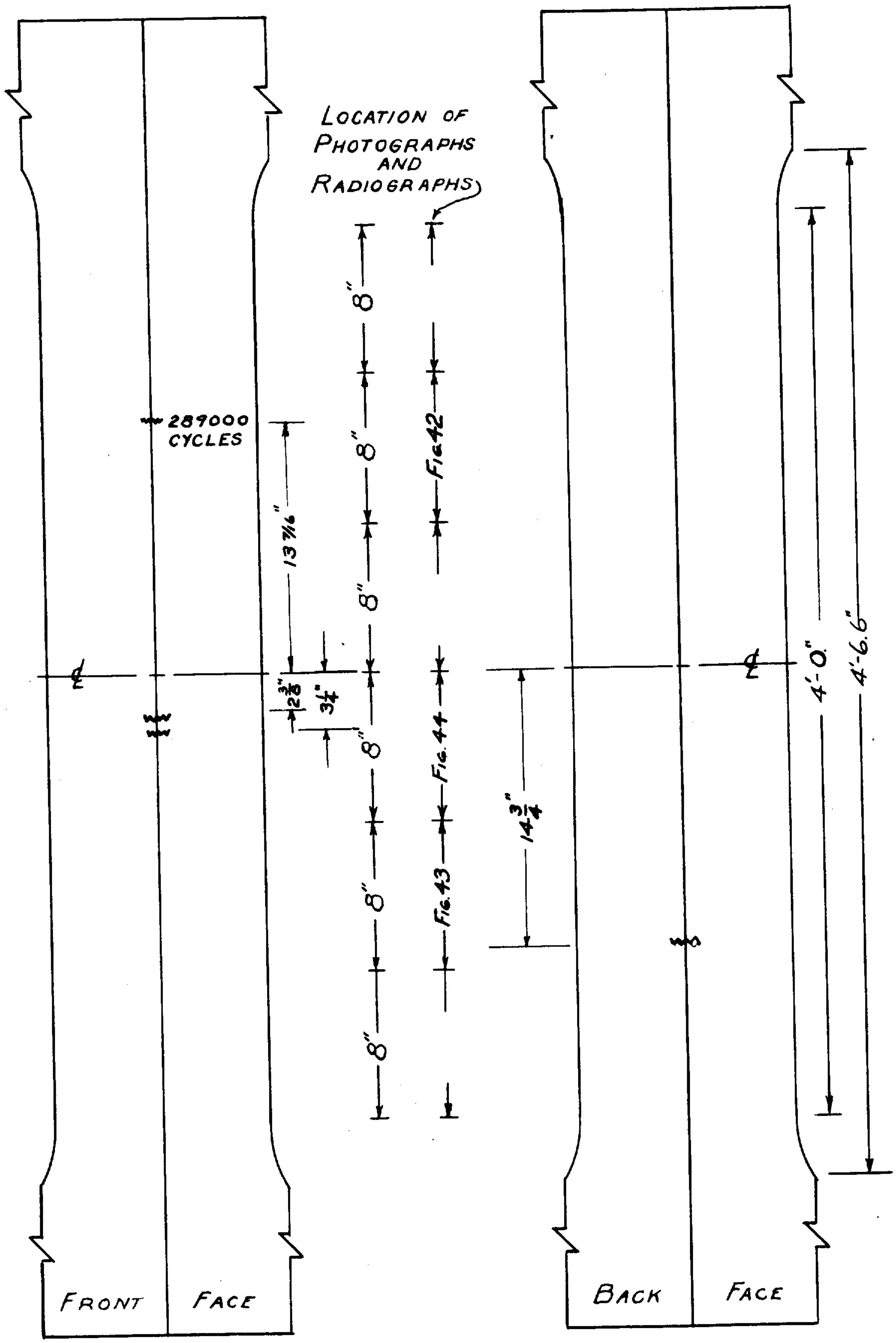
FIGURE 14



SPECIMEN AA-5

LOCATION OF FATIGUE FAILURES

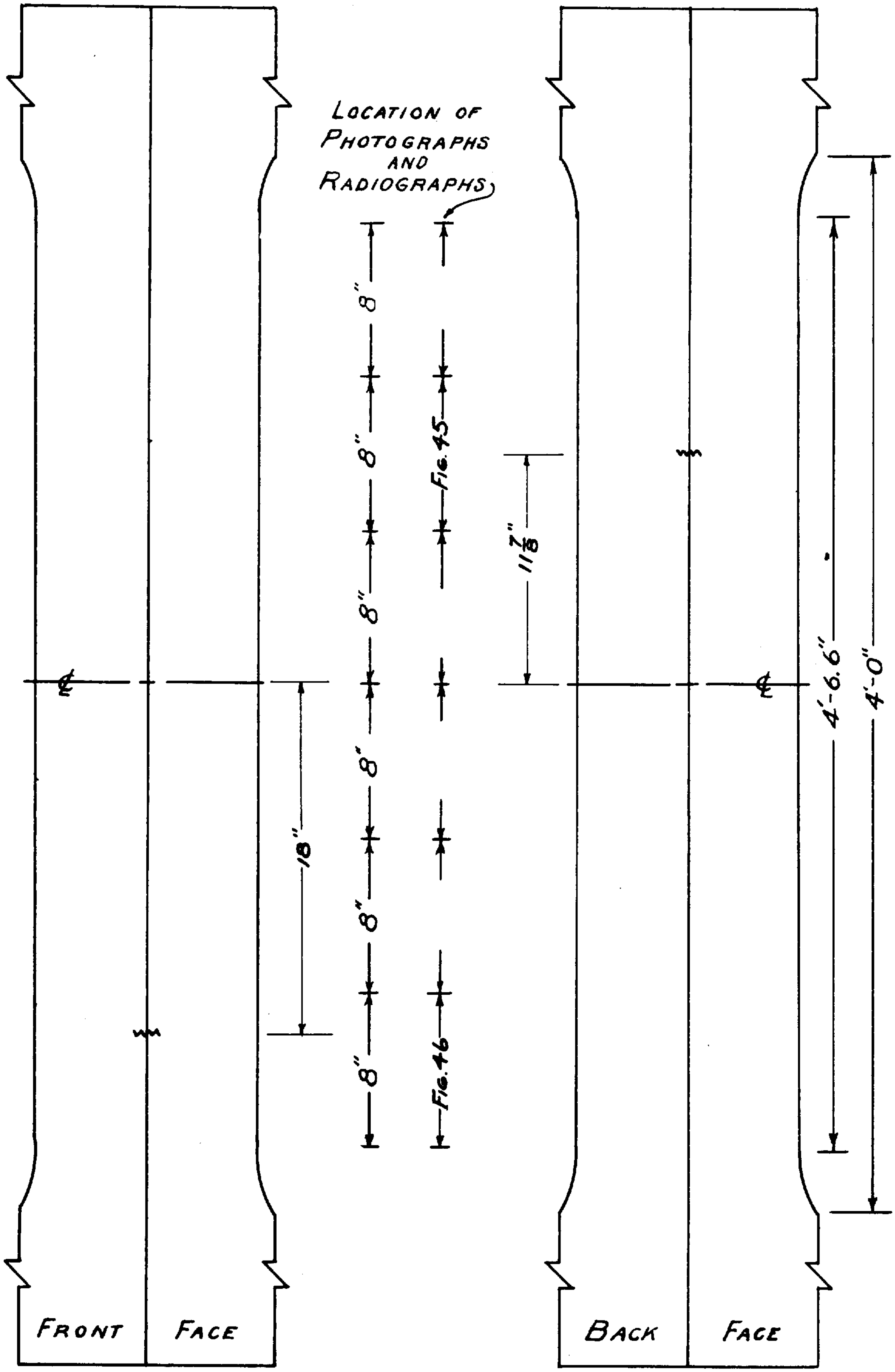
FIGURE 15



Specimen AB-1

Location of Fatigue Failures

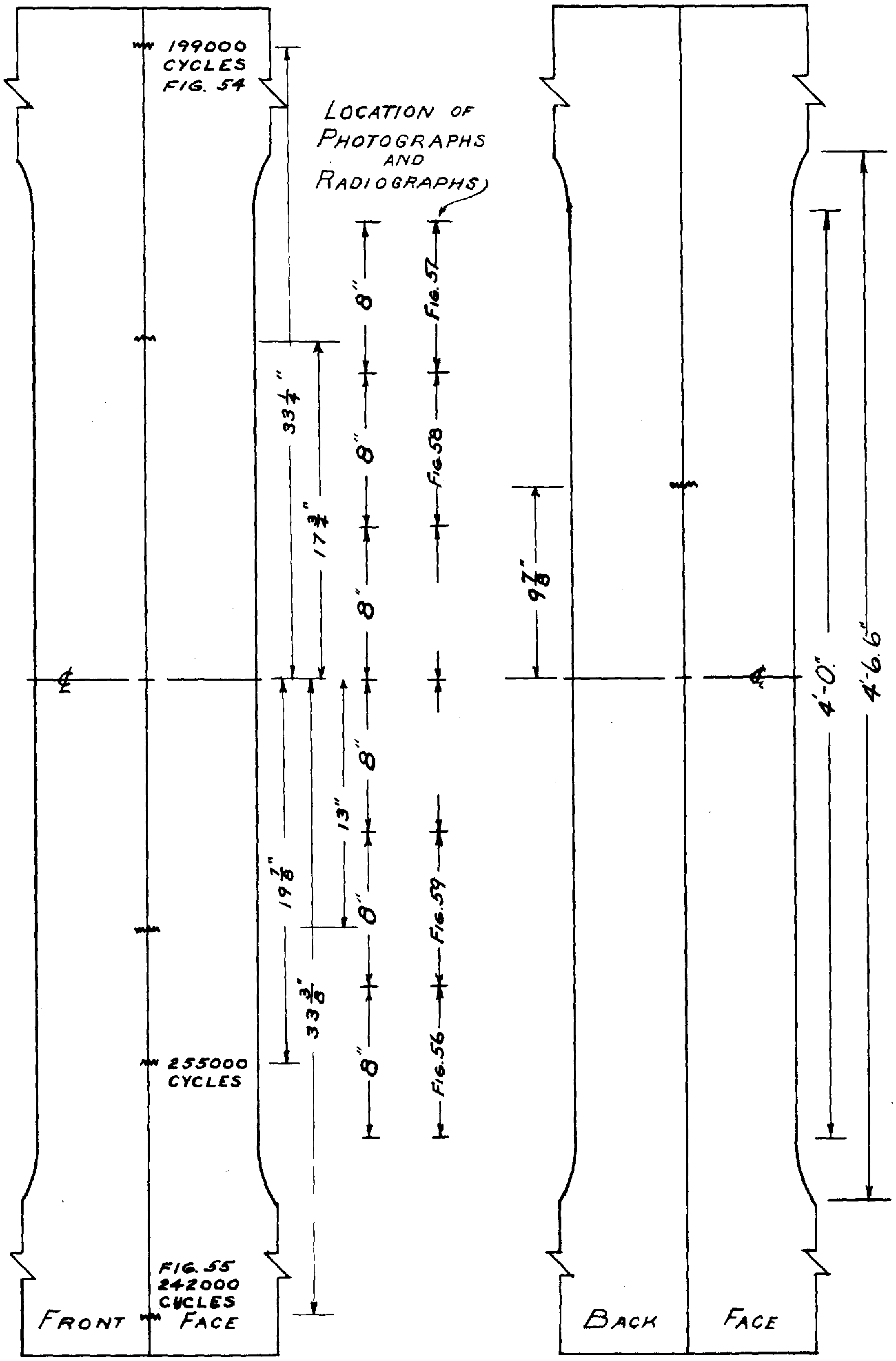
Figure 16



SPECIMEN AB-2

LOCATION OF FATIGUE FAILURES

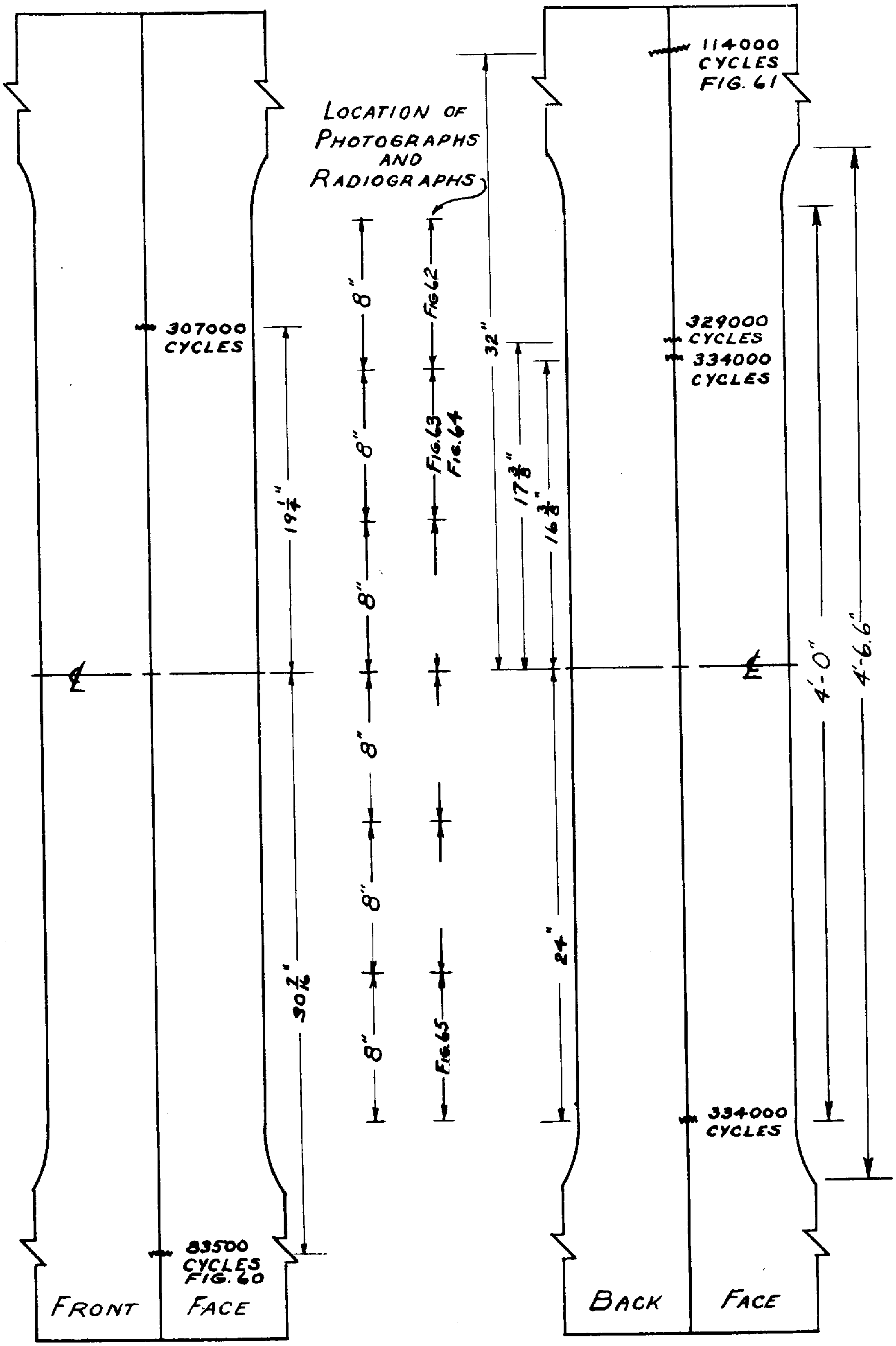
FIGURE 17



SPECIMEN AC-2

LOCATION OF FATIGUE FAILURES

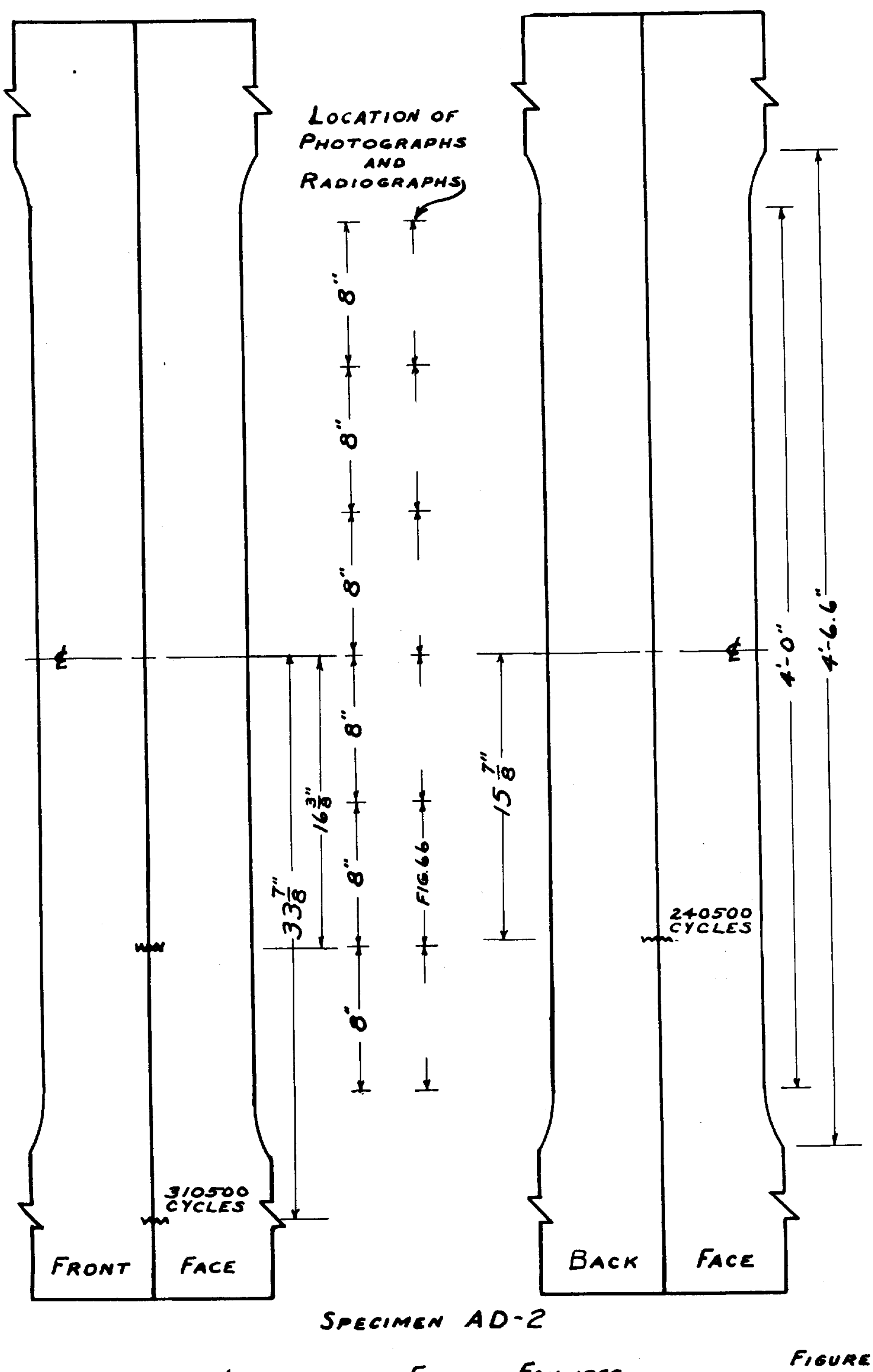
FIGURE 18



SPECIMEN AD-1

LOCATION OF FATIGUE FAILURES

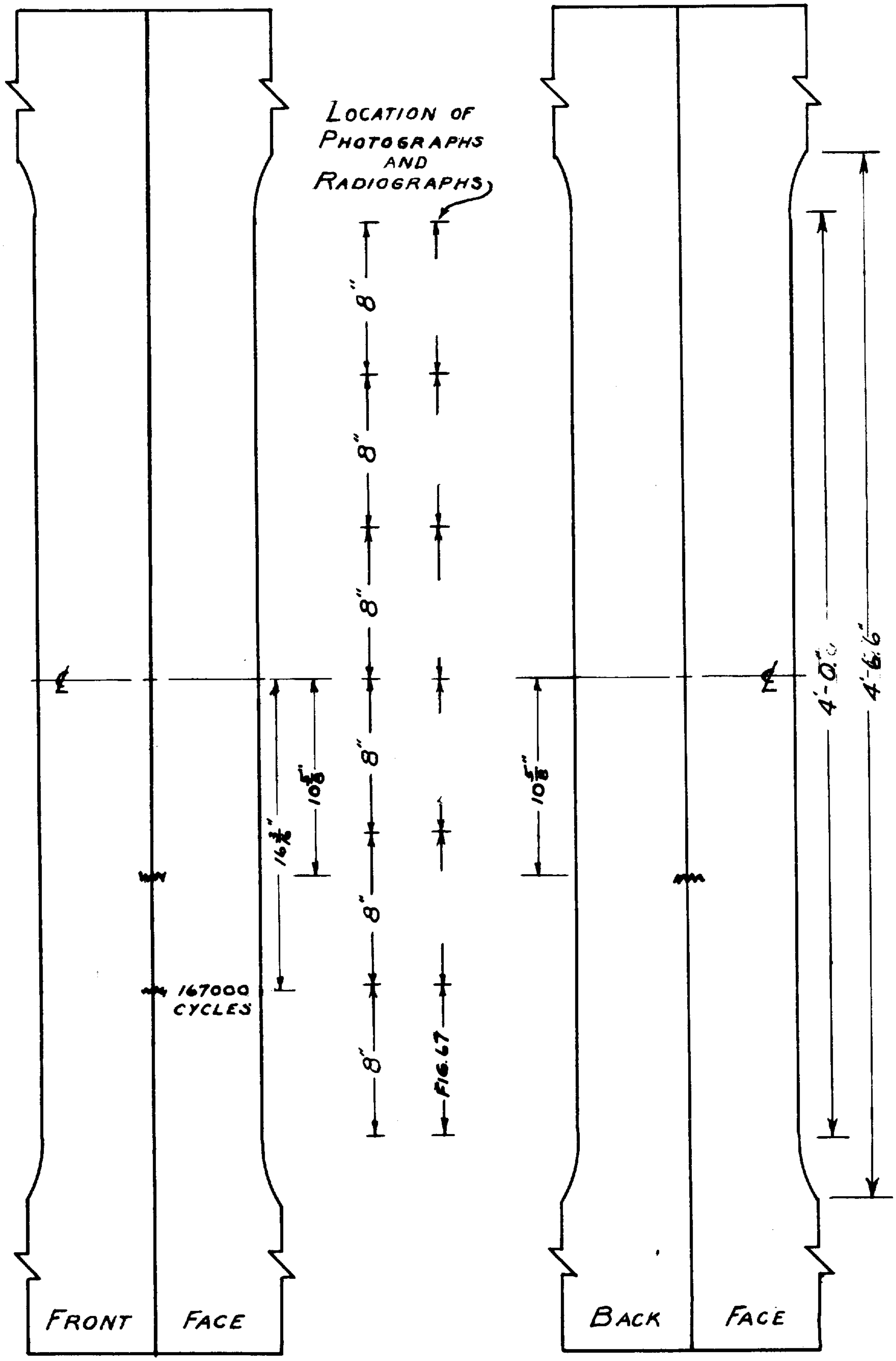
FIGURE 19



Specimen AD-2

Location of Fatigue Failures

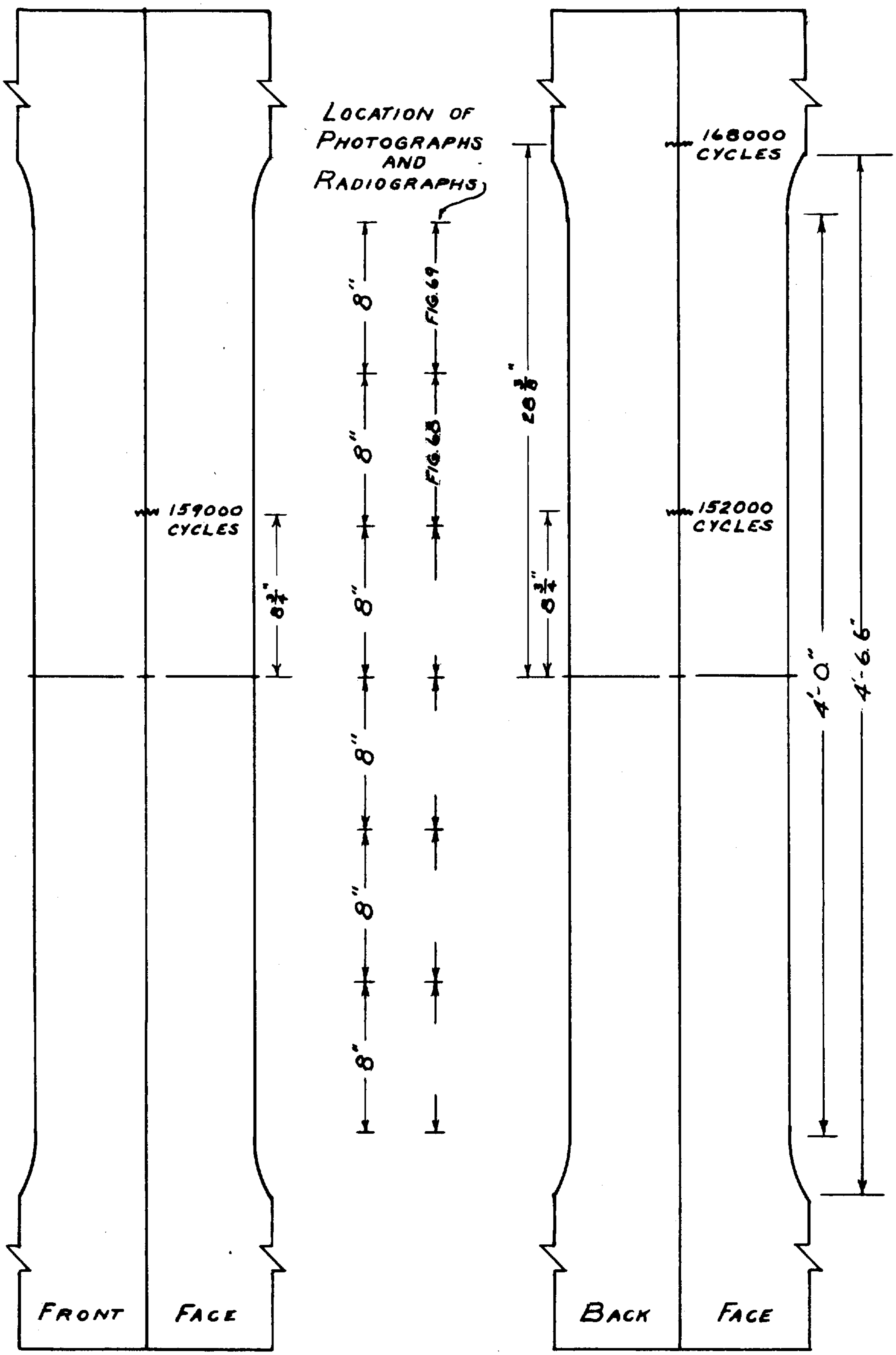
Figure 20



SPECIMEN AD-3

LOCATION OF FATIGUE FAILURES

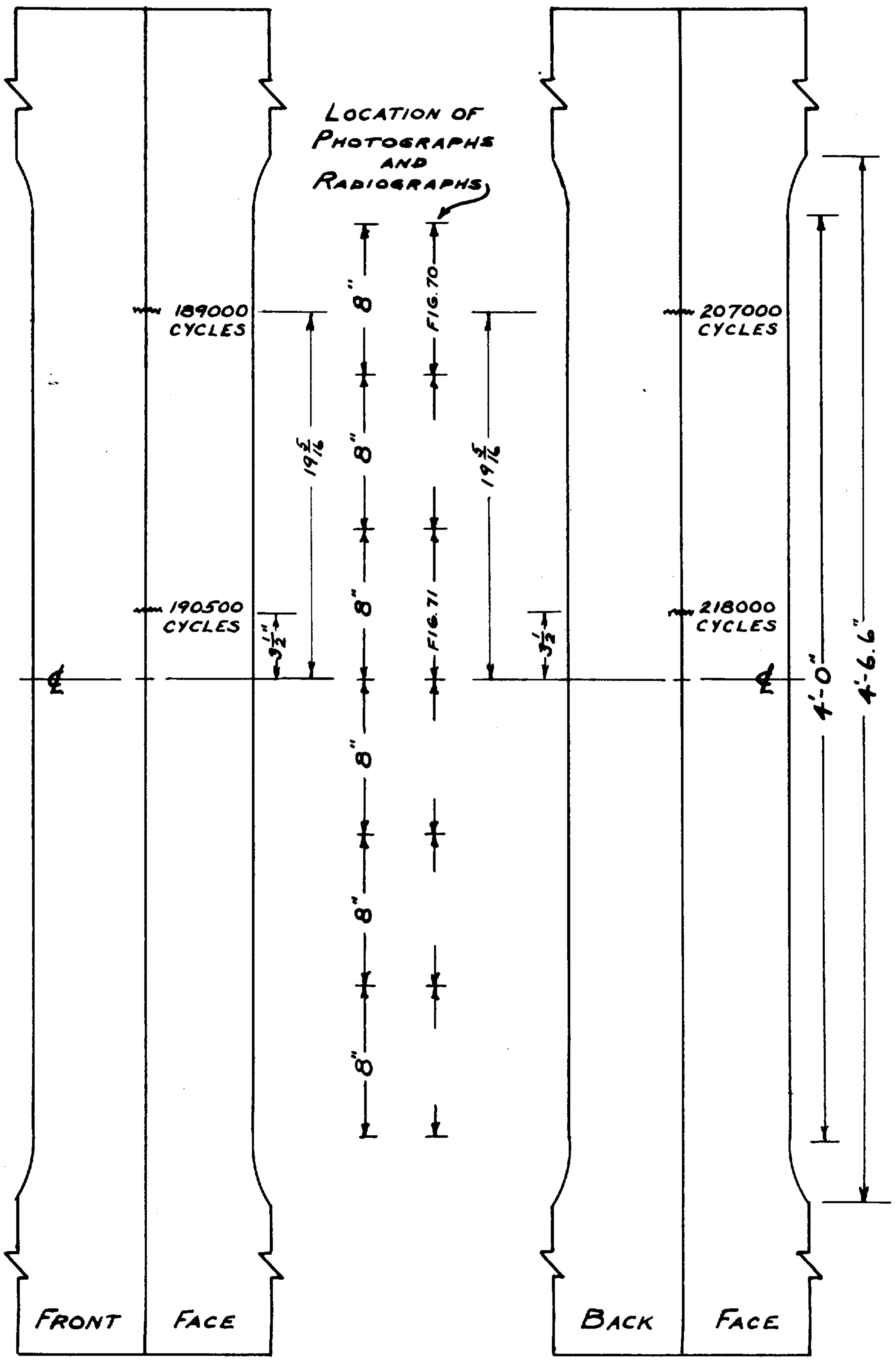
FIGURE 21



SPECIMEN AE-1

LOCATION OF FATIGUE FAILURES

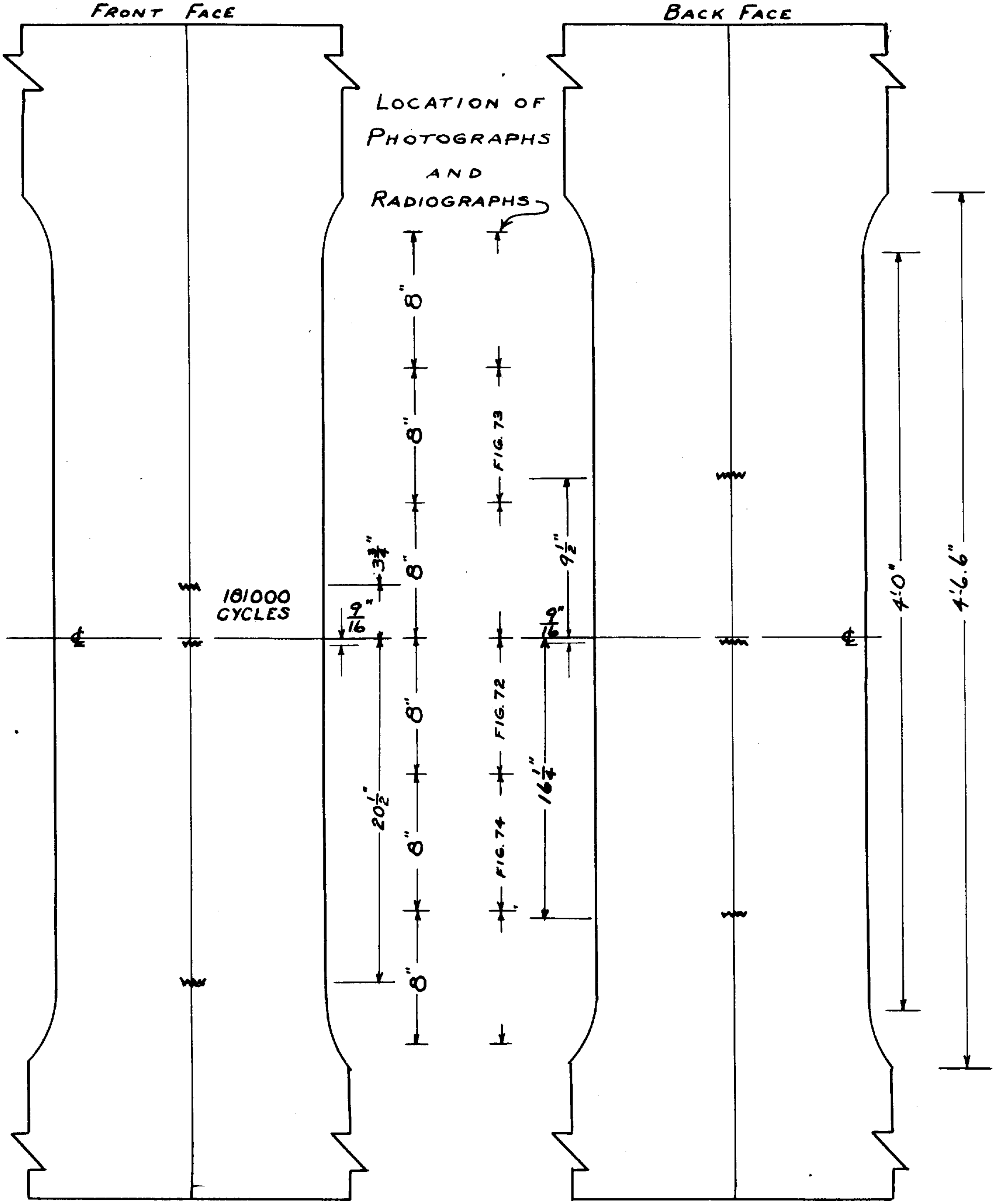
FIGURE 22



SPECIMEN AE-2

LOCATION OF FATIGUE FAILURES

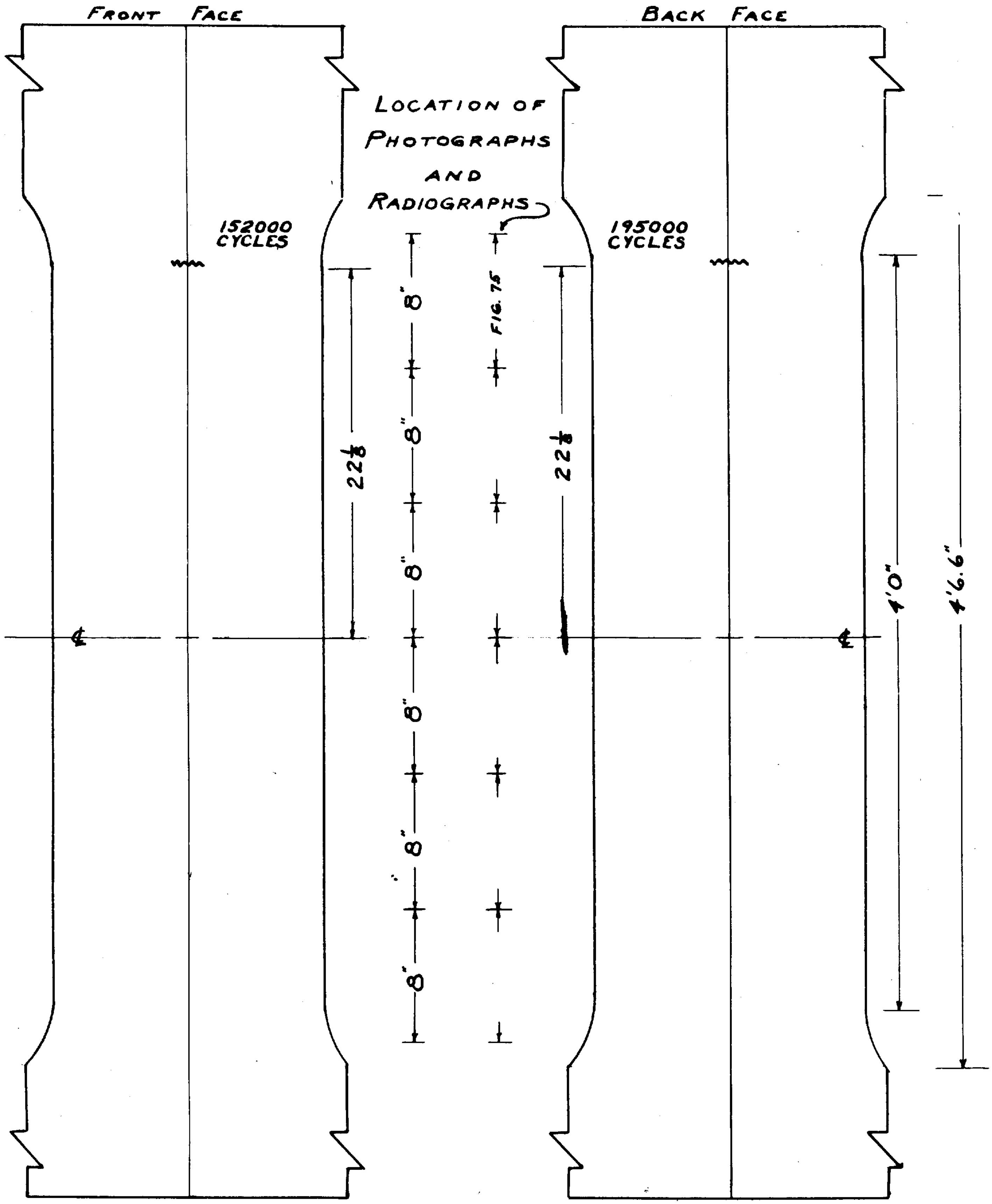
FIGURE 23



SPECIMEN DE-1

FIGURE 24

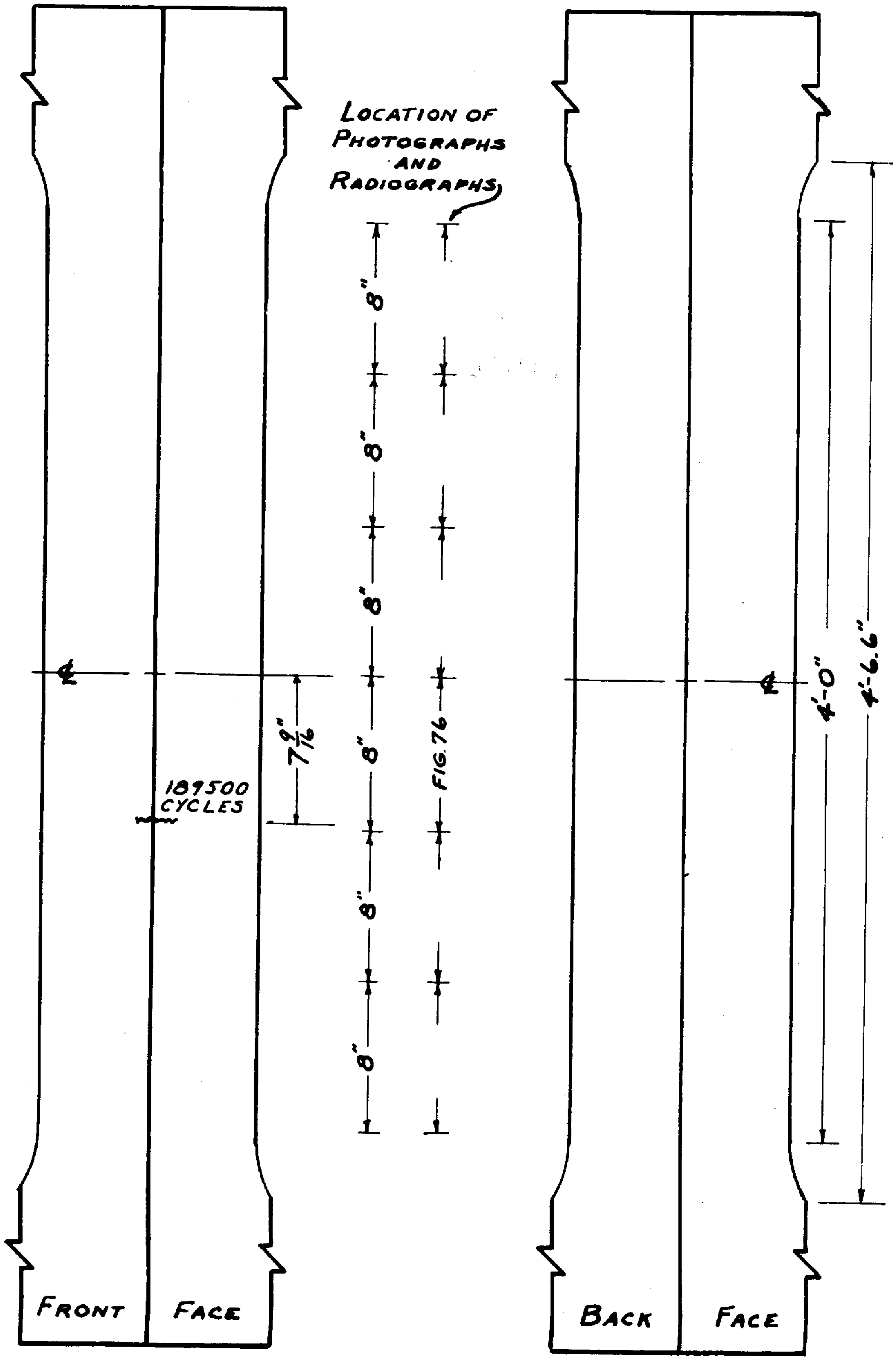
LOCATION OF FATIGUE FAILURES



SPECIMEN DE-2

FIGURE 25

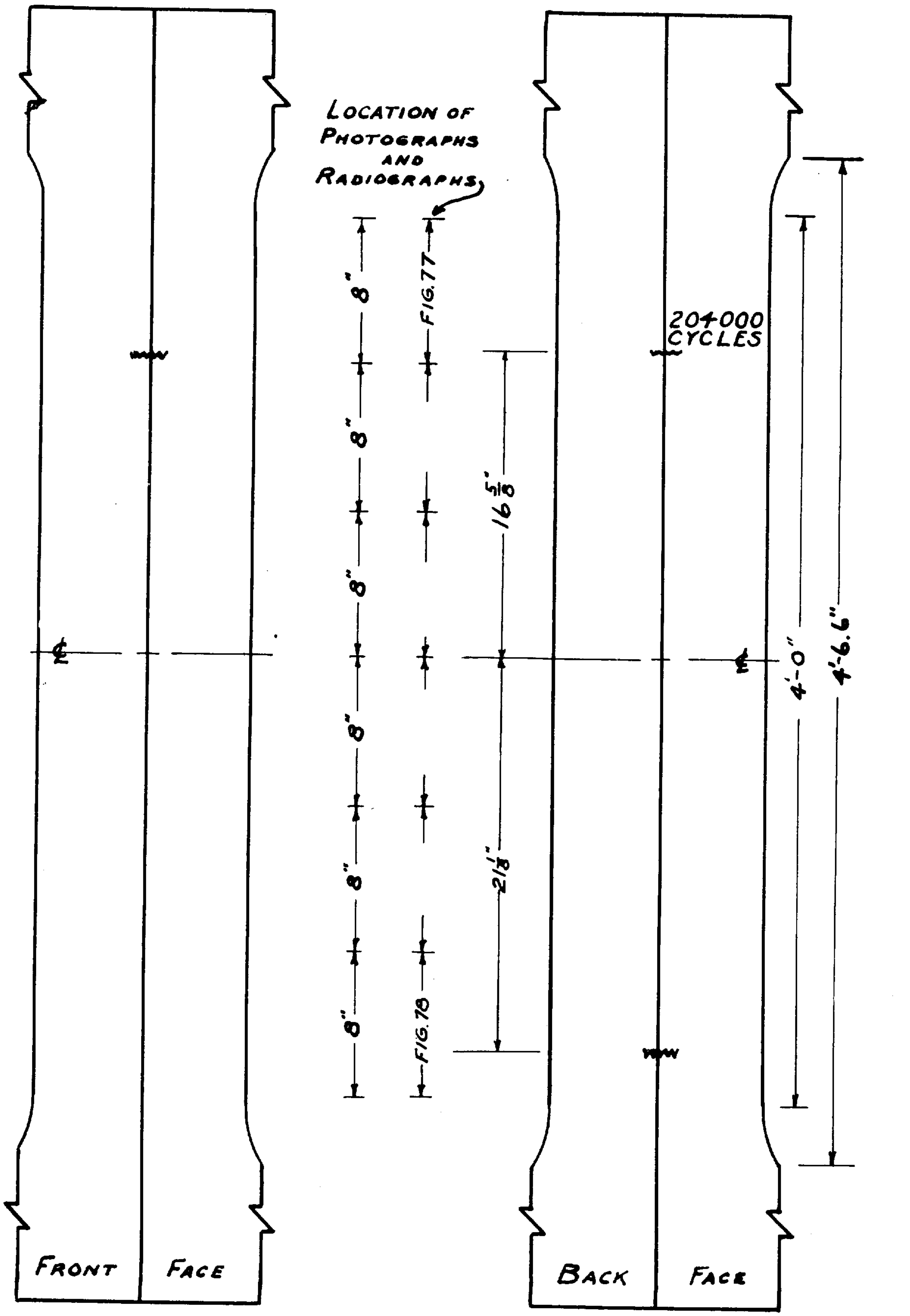
LOCATION OF FATIGUE FAILURES



SPECIMEN EE-1

LOCATION OF FATIGUE FAILURES

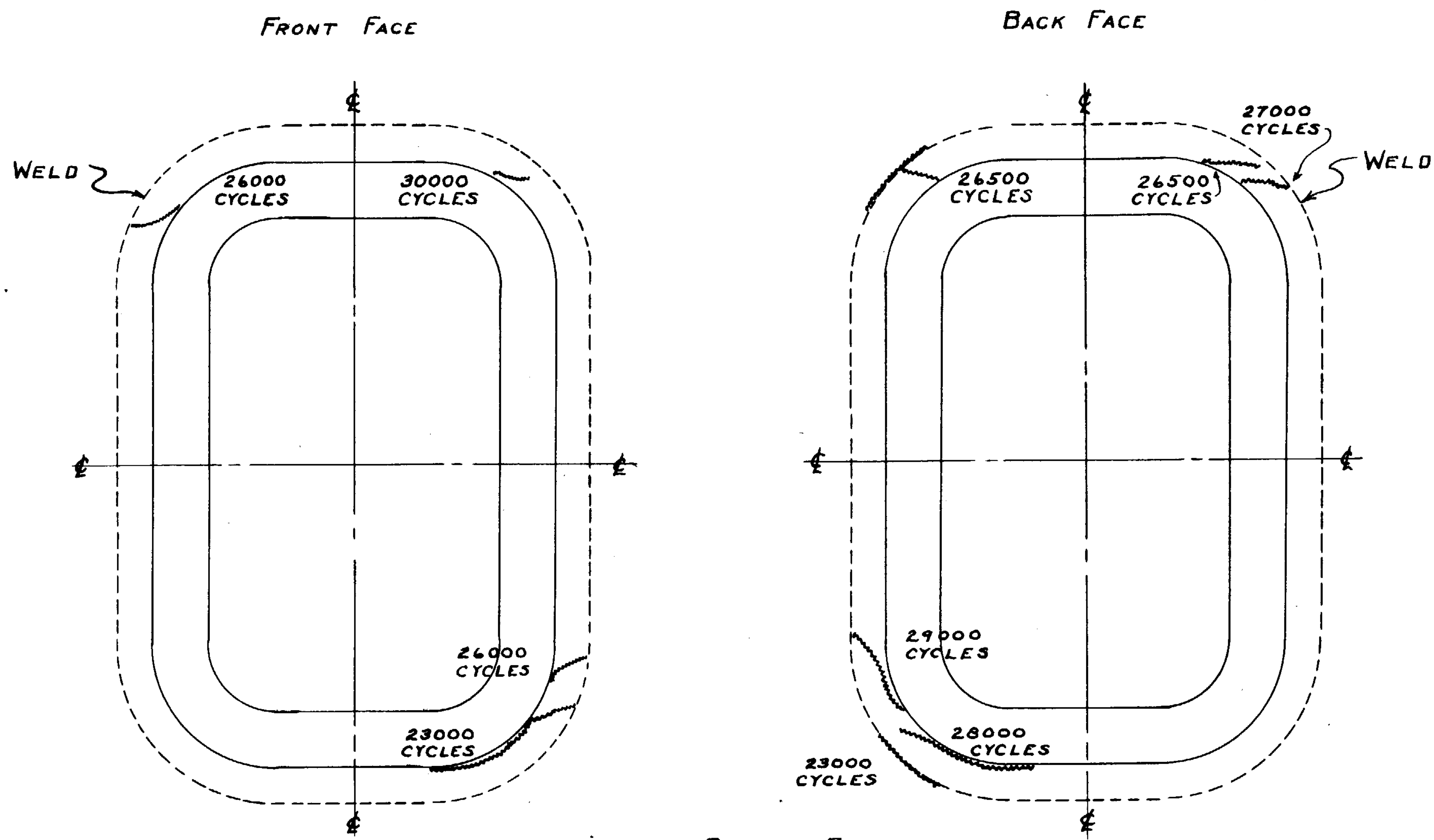
FIGURE 26



SPECIMEN EE-2

LOCATION OF FATIGUE FAILURES

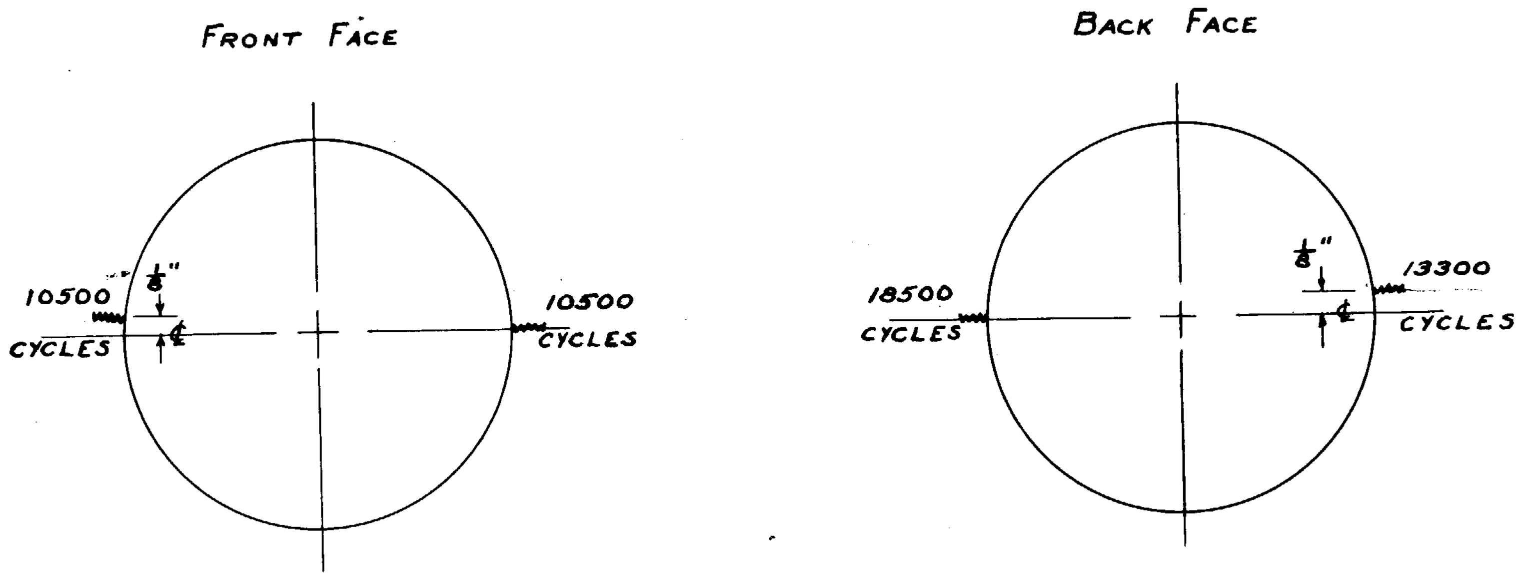
FIGURE 27



LOCATION OF FATIGUE FAILURES

SPECIMEN B-2

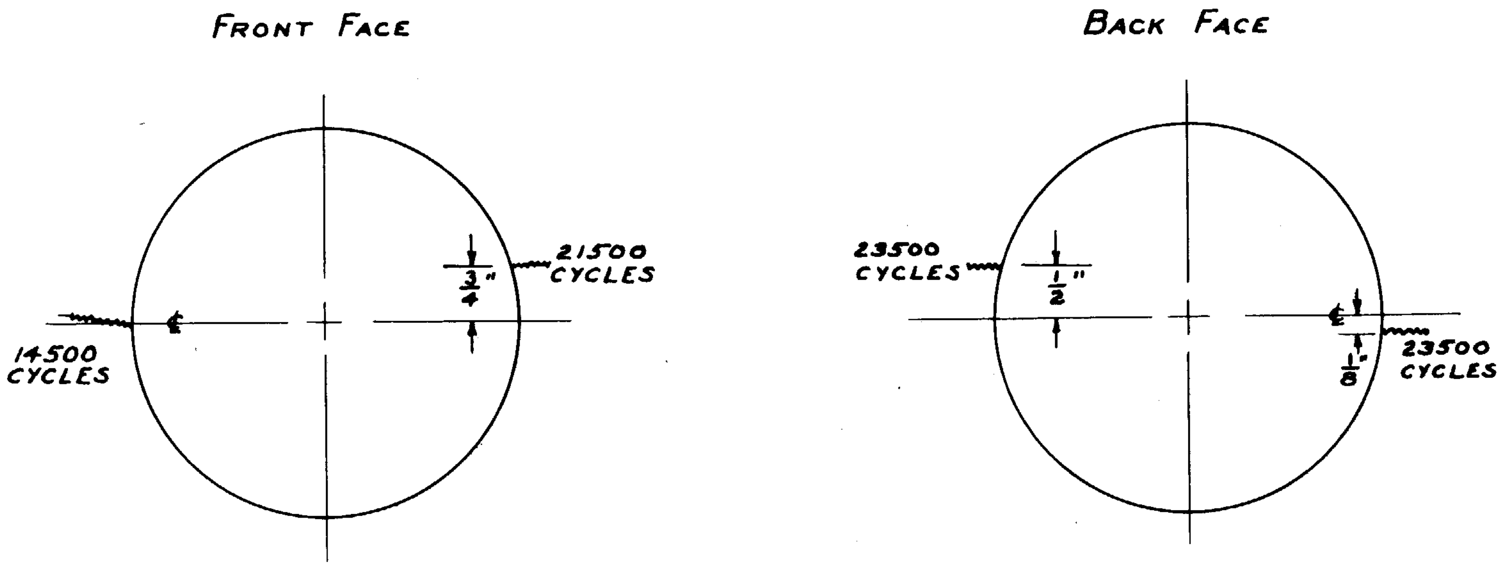
FIGURE 28



SPECIMEN FA-1

LOCATION OF FATIGUE FAILURES

FIGURE 29



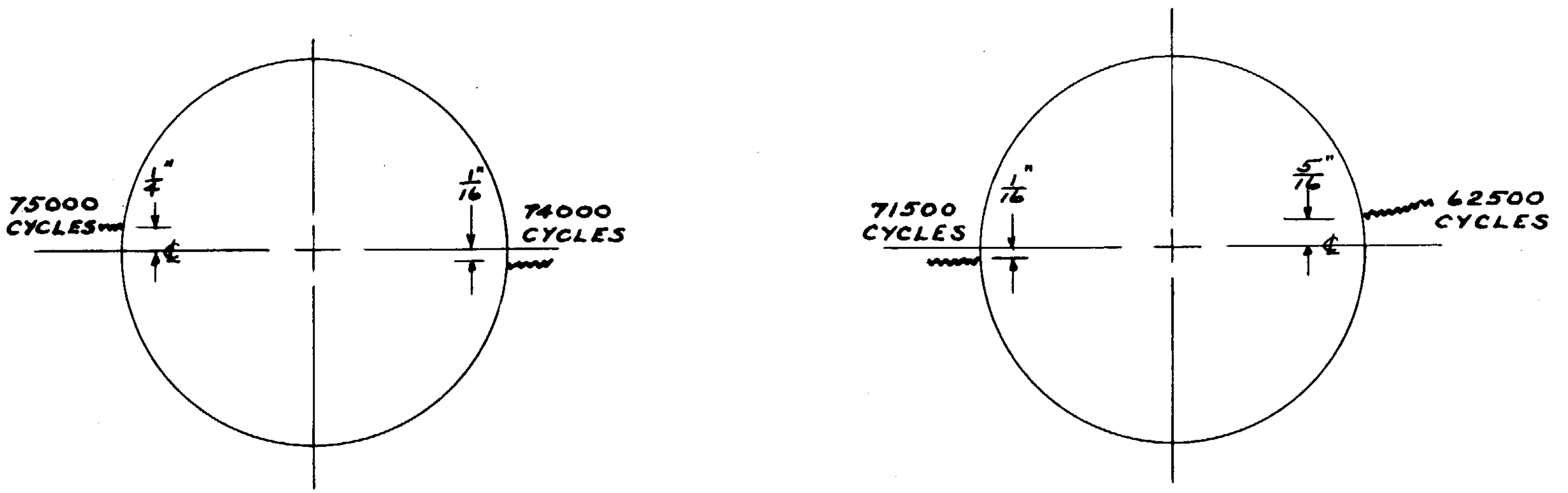
SPECIMEN FA-2

LOCATION OF FATIGUE FAILURES

FIGURE 30

Front Face

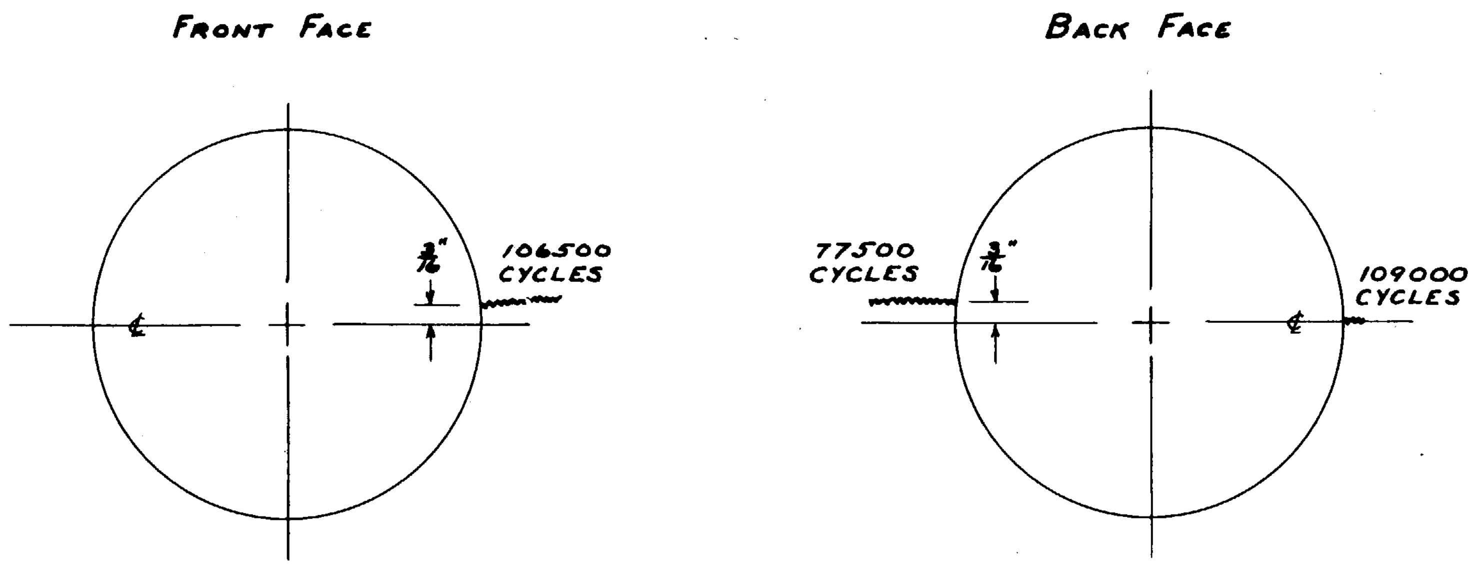
Back Face



Specimen FB-1

Location of Fatigue Failures

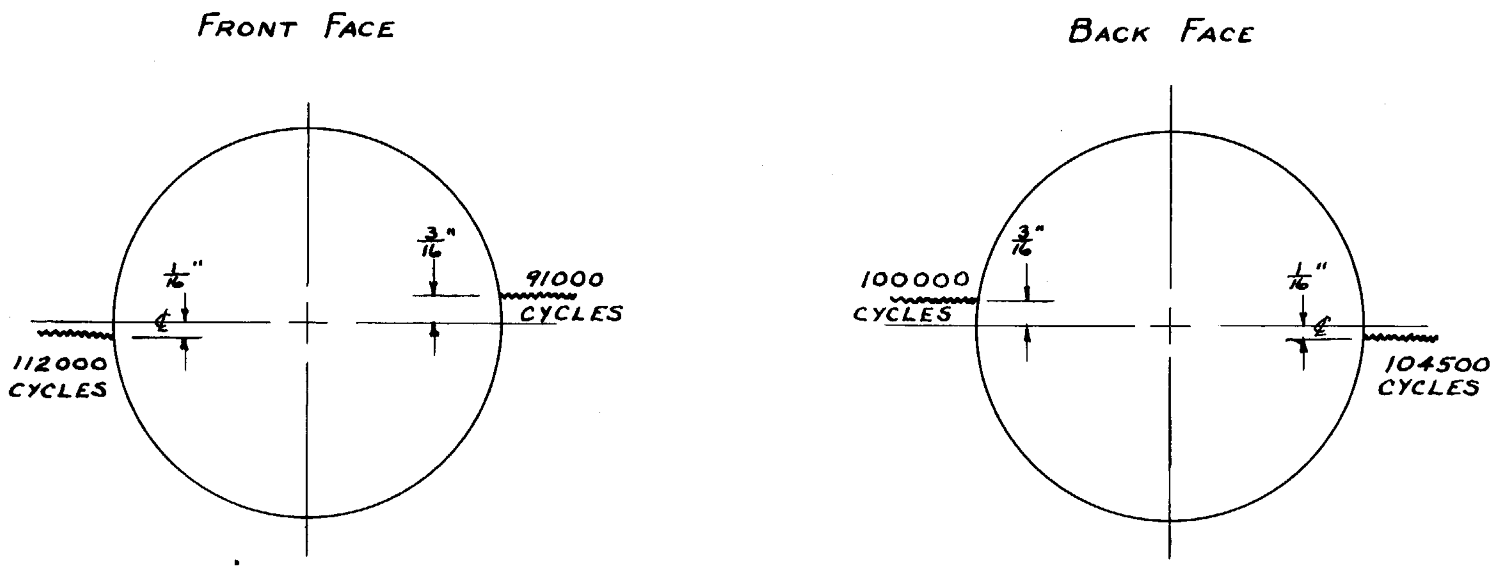
Figure 31



SPECIMEN FB-2

LOCATION OF FATIGUE FAILURES

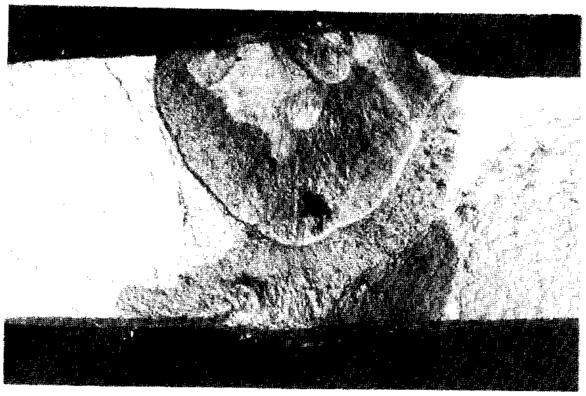
FIGURE 32



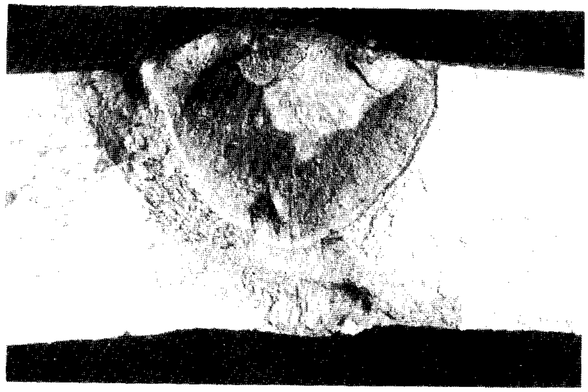
SPECIMEN FC-1

LOCATION OF FATIGUE FAILURES

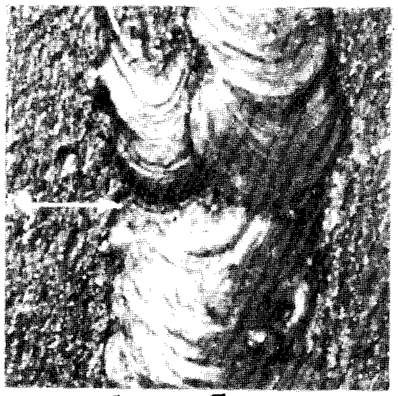
FIGURE 33



Top



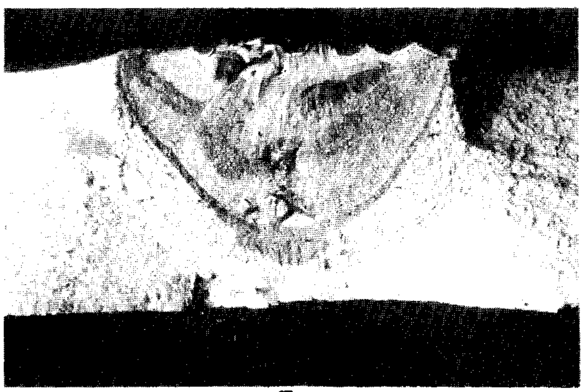
Bottom



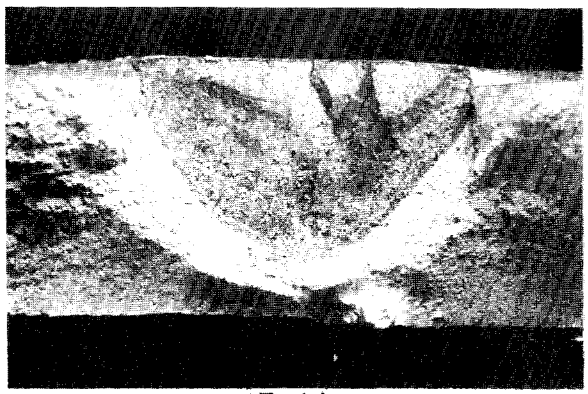
Back Face

Fatigue Crack 1-V

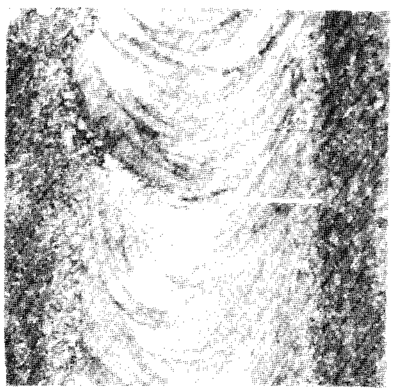
Specimen AA-1 Figure 34



Top



Bottom

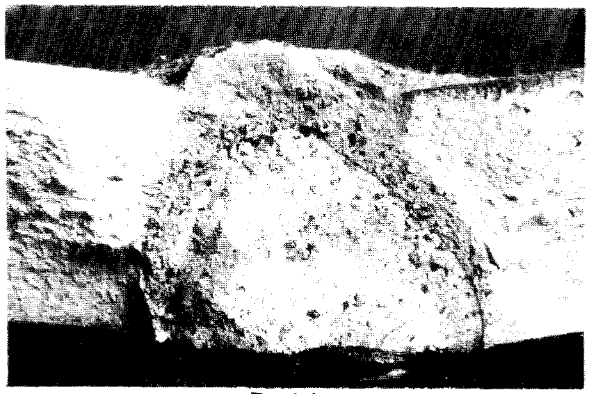


Back Face

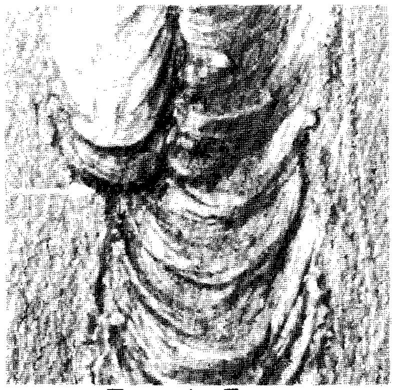
Fatigue Crack 2-V

Specimen AA-1 Figure 35

Top



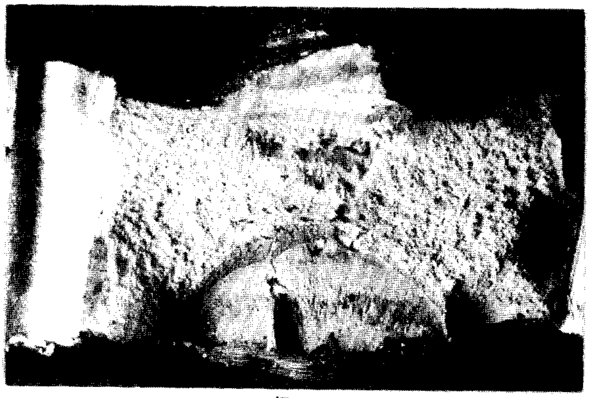
Bottom



Front Face

Fatigue Crack 3-V

Specimen AA-1 Figure 36



Top

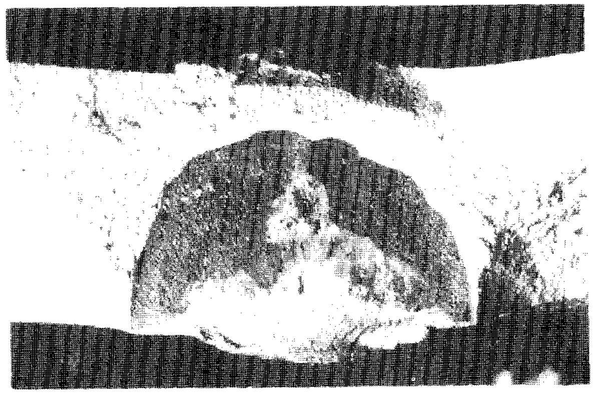
Bottom

Front Face

Fatigue Crack 4-V

Specimen AA-1 Figure 37

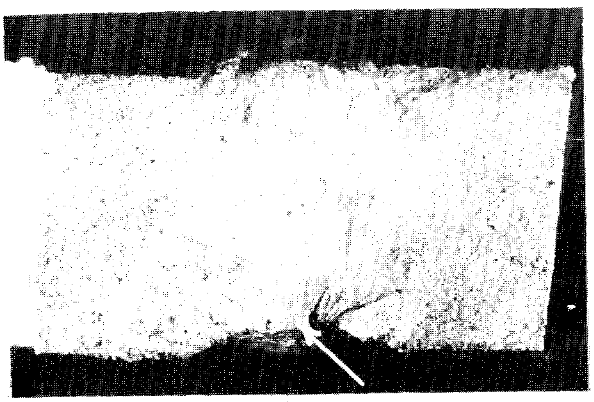
Top



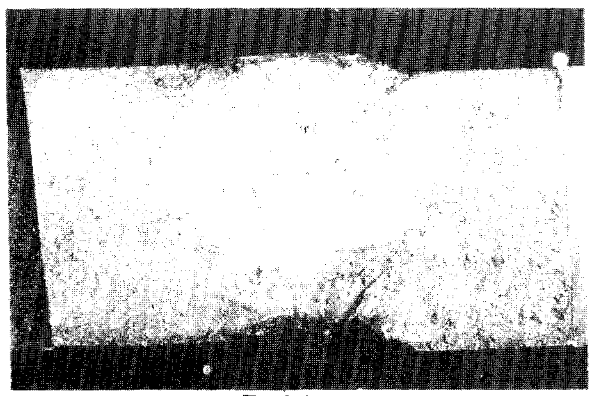
Bottom

Fatigue Crack 1-V

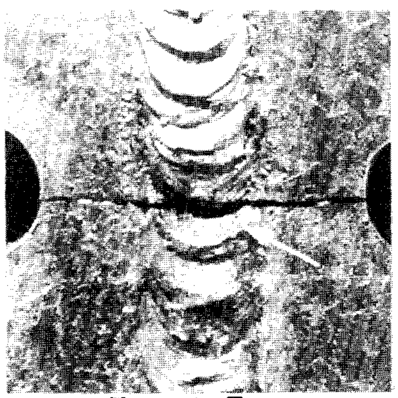
Specimen AA-2 Figure 38



Top



Bottom



Front Face

Fatigue Crack 1-V

Specimen AA-3 Figure 39


Top


Bottom


Front Face

Fatigue Crack 2-V

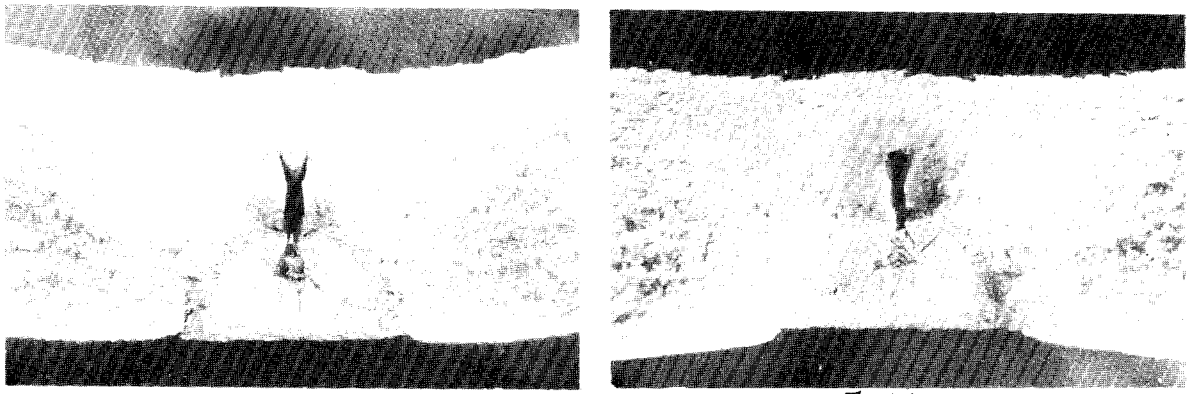
Specimen AA-3 Figure 40


Top


Bottom

Fatigue Crack 1-V

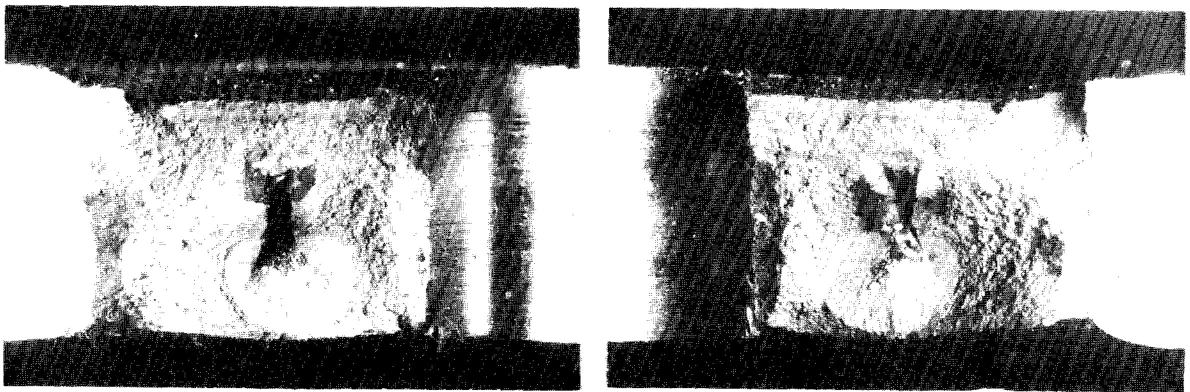
Specimen AA-5 Figure 41



Top Bottom

Fatigue Crack 1-V

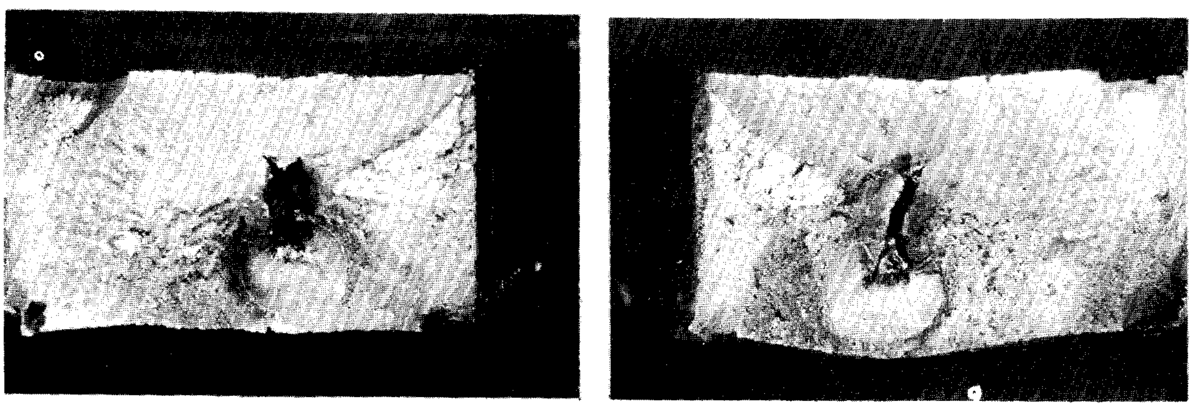
Specimen AB-1 Figure 42



Top Bottom

Fatigue Crack 2-X

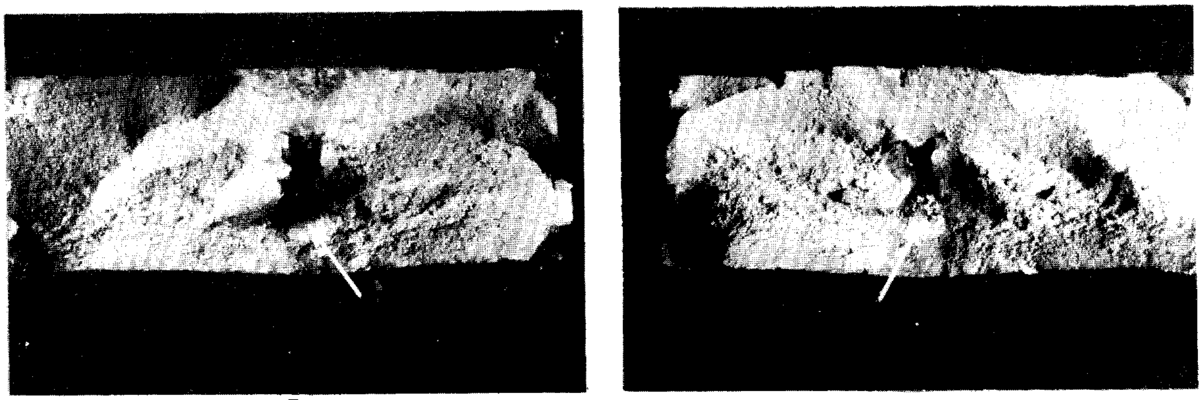
Specimen AB-1 Figure 43



Top Bottom

Fatigue Crack 3-X

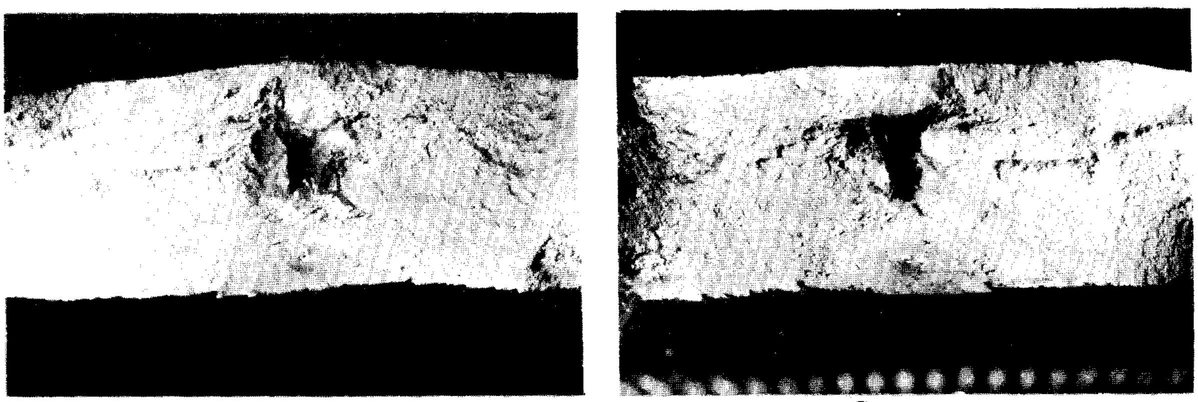
Specimen AB-1 Figure 44



Top Bottom

Fatigue Crack 1-X

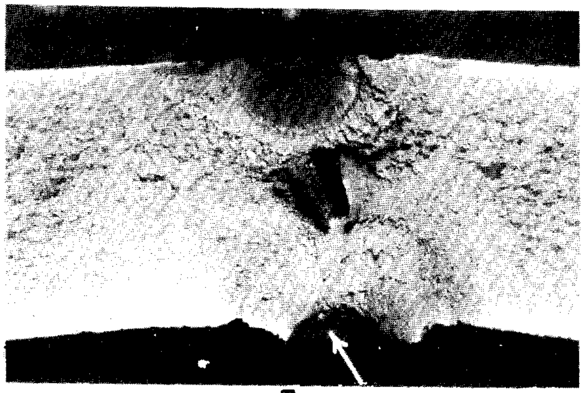
Specimen AB-2 Figure 45



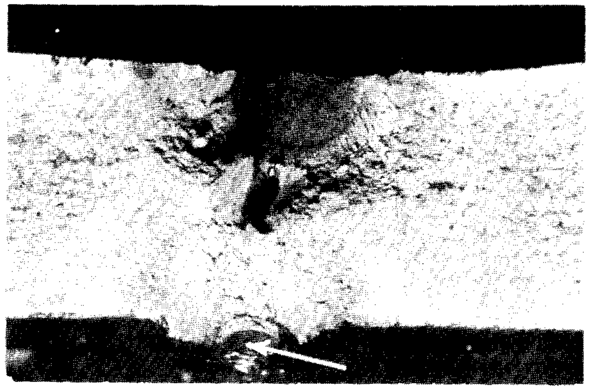
Top Bottom

Fatigue Crack 2-X

Specimen AB-2 Figure 46

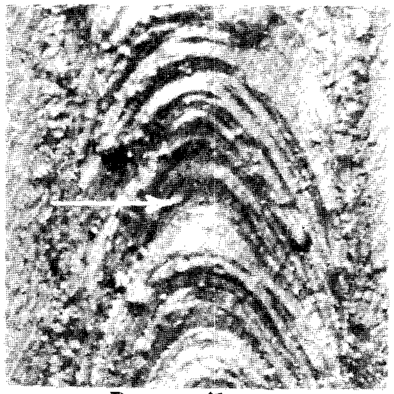


Top



Bottom

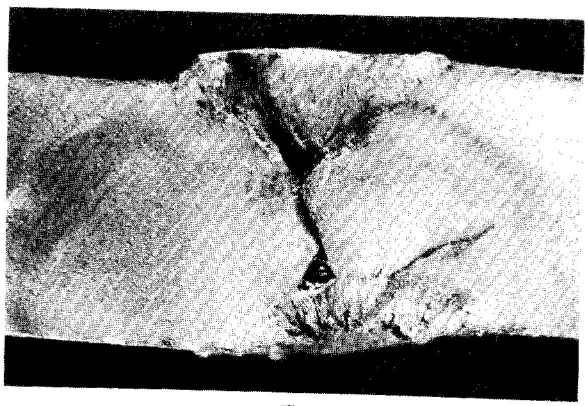
Front Face



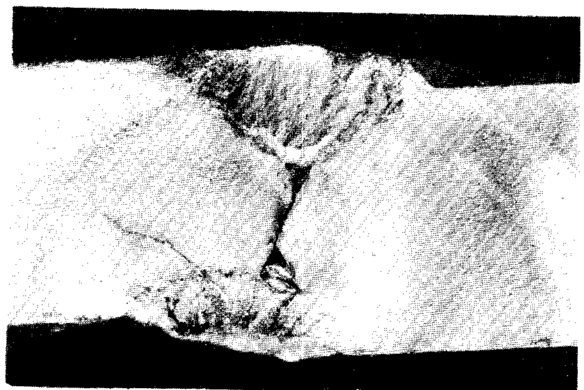
Back Face

Fatigue Crack 1-V

Specimen AC-1 Figure 47



Top



Bottom

Fatigue Crack 2-V

Specimen AC-1 Fighre 48

Top Fatigue Crack 3-V Bottom

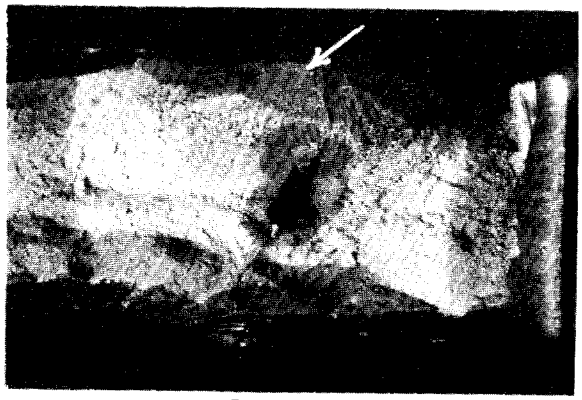
Specimen AC-1 Figure 49

Front Face

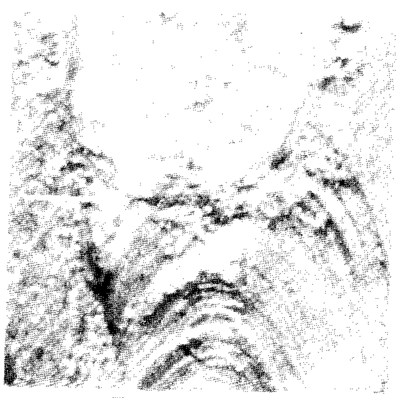
Fatigue Crack 4-V

Specimen AC-1 Figure 50

Top



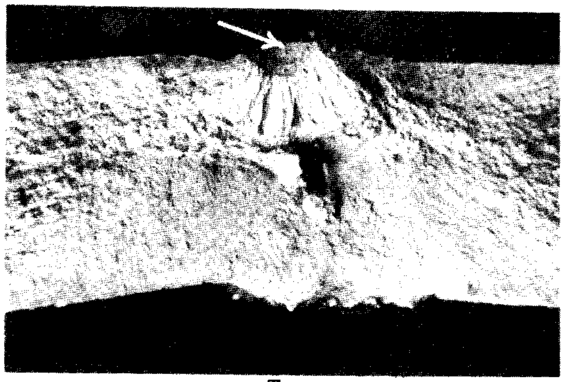
Bottom



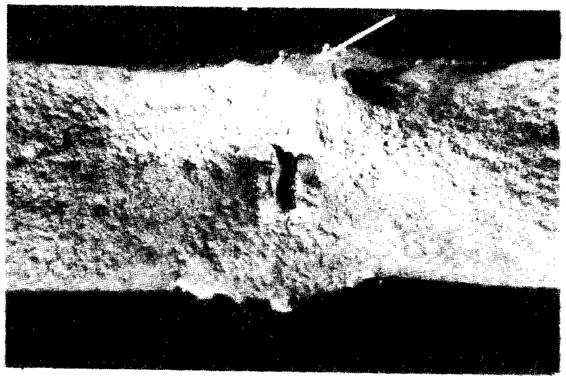
Back Face

Fatigue Crack 5-V

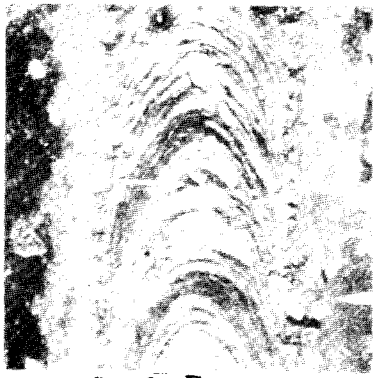
Specimen AC-1 Figure 51



Top



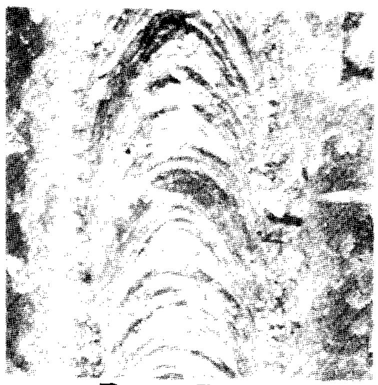
Bottom



Back Face

Fatigue Crack 6-V

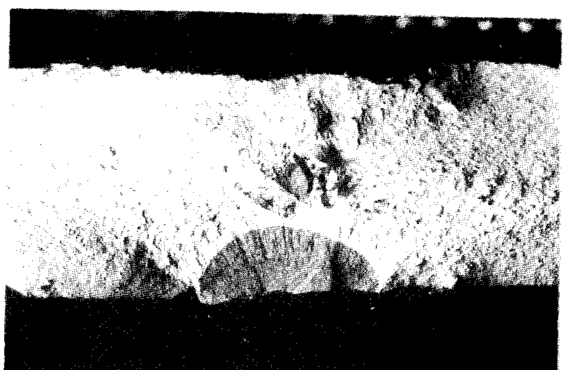
Specimen AC-1 Figure 52



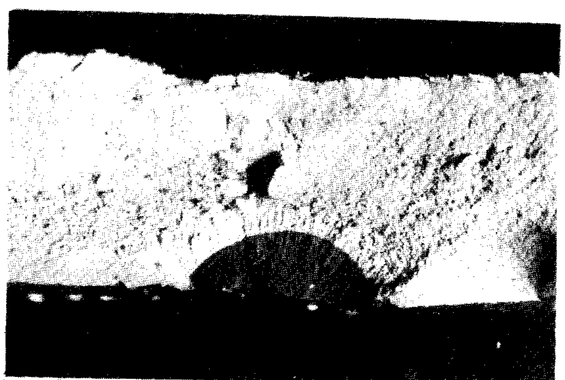
Back Face

Fatigue Crack 8-T

Specimen AC-1 Figure 53



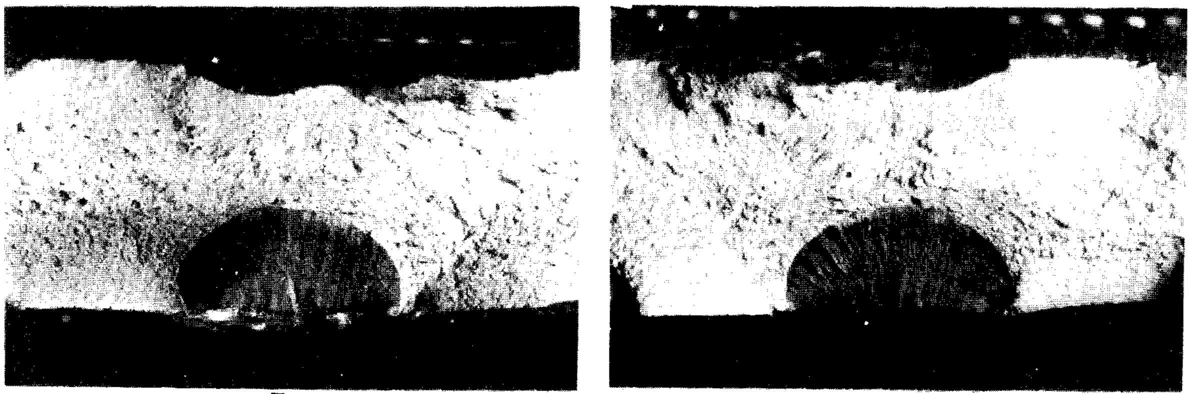
Top



Bottom

Fatigue Crack 1-V

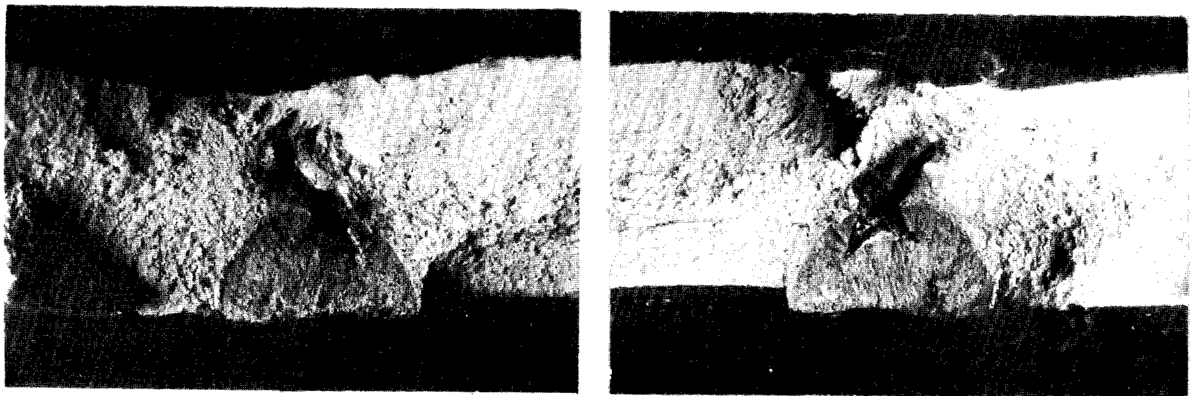
Specimen AC-2 Figure 54



Top Bottom

Fatigue Crack 2-V

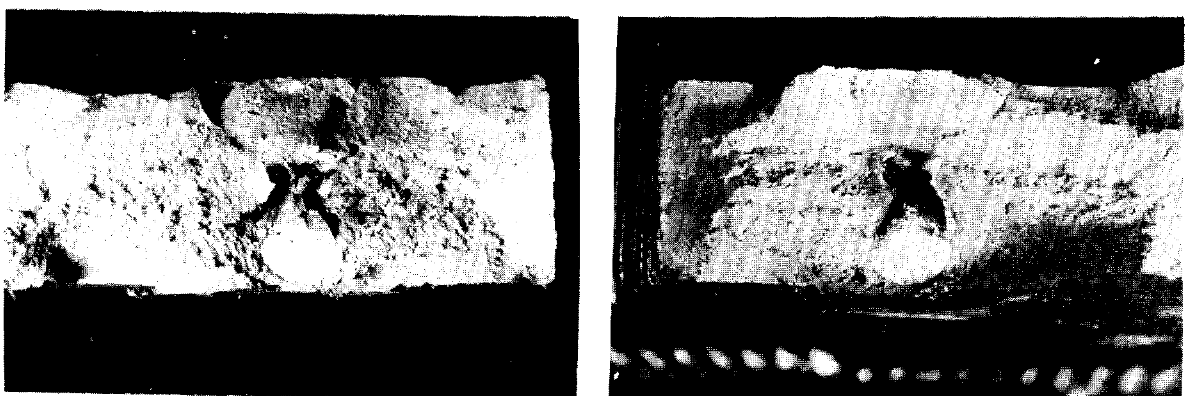
Specimen AC-2 Figure 55



Top Bottom

Fatigue Crack 3-V

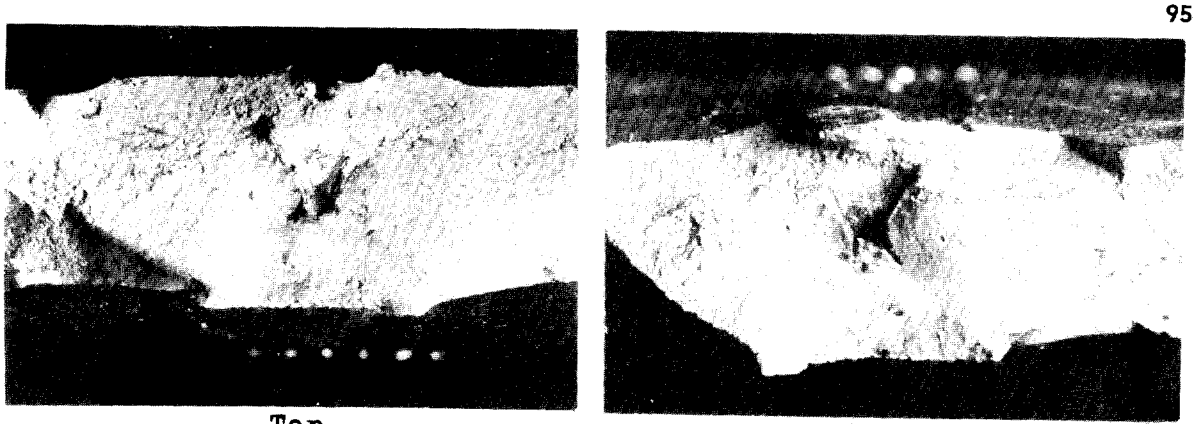
Specimen AC-2 Figure 56



Top Bottom

Fatigue Crack 4-X

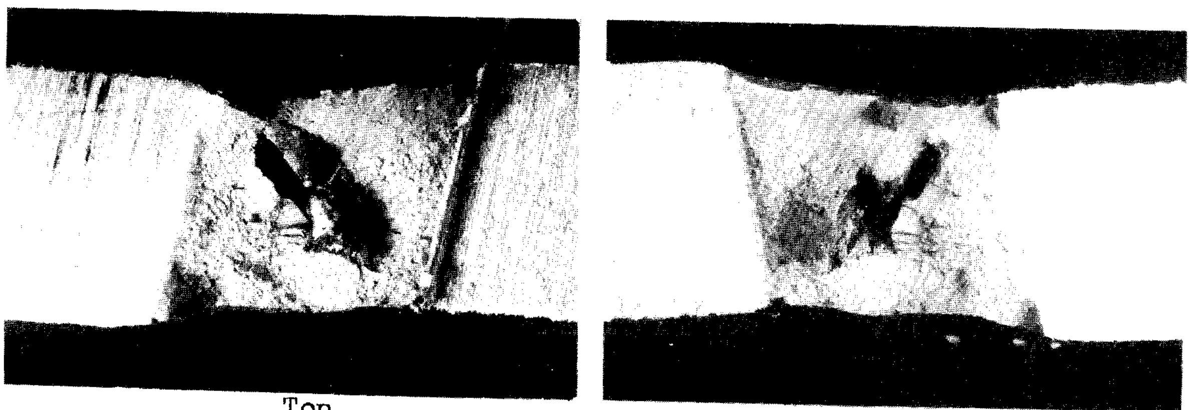
Specimen AC-2 Figure 57



Top Bottom

Fatigue Crack 5-X

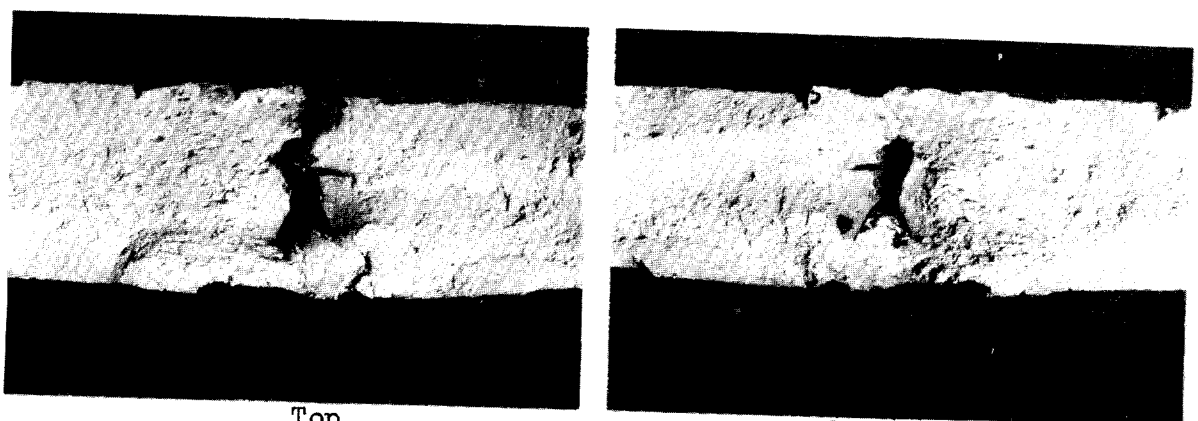
Specimen AC-2 Figure 58



Top Bottom

Fatigue Crack 6-X

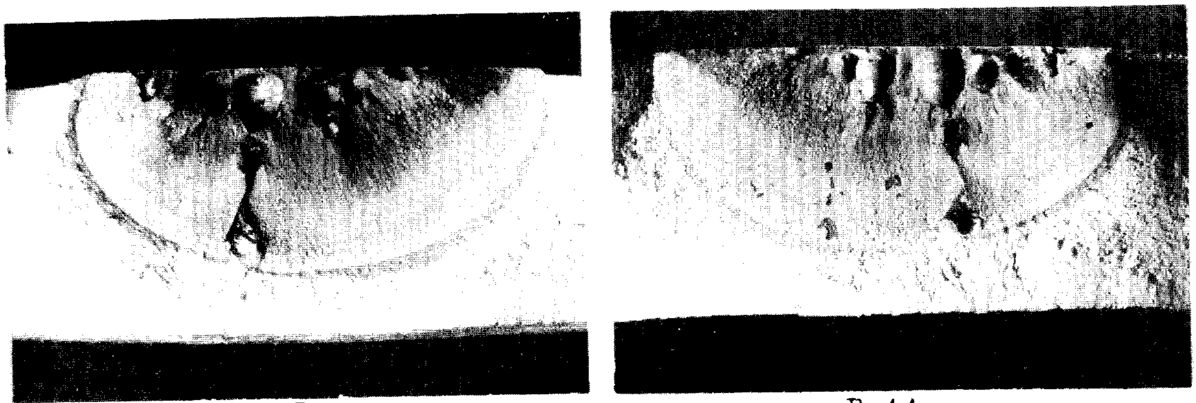
Specimen AC-2 Figure 59



Top Bottom

Fatigue Crack 1-V

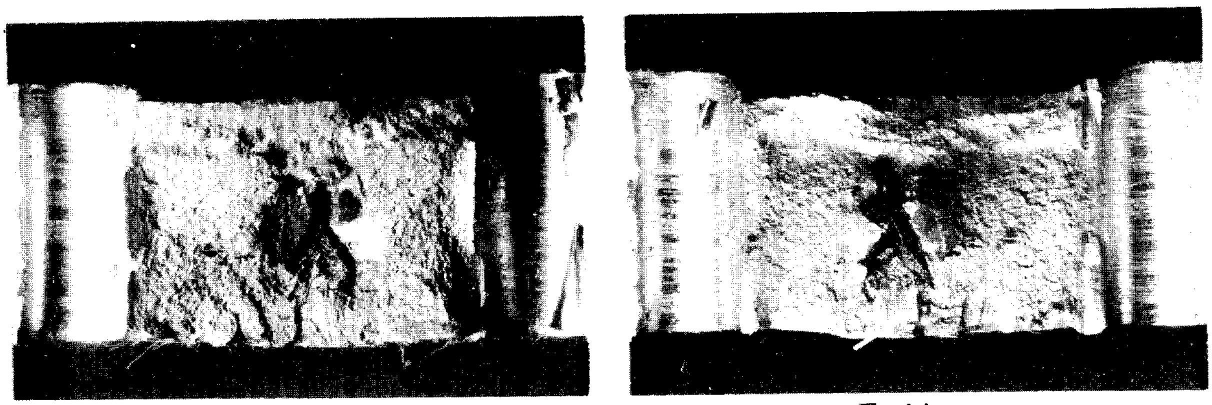
Specimen AD-1 Figure 60



Top Bottom

Fatigue Crack 2-V

Specimen AD-1 Figure 61

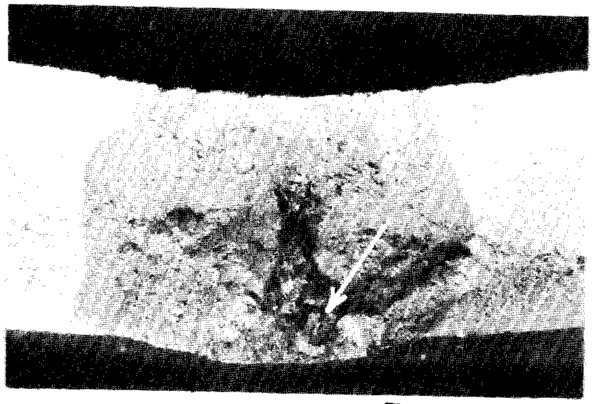


Top Bottom

Front Face

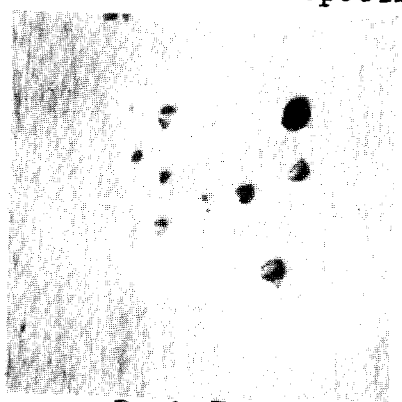
Fatigue Crack 3-V

Specimen AD-1 Figure 62




Top Fatigue Crack 4-V Bottom

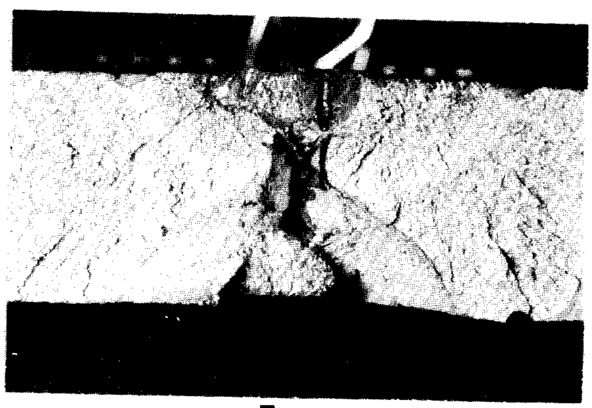
Specimen AD-1 Figure 63



Fatigue Crack 5-V

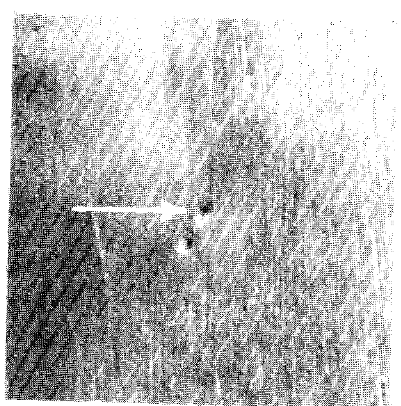
Specimen AD-1 Figure 64

Back Face




Top

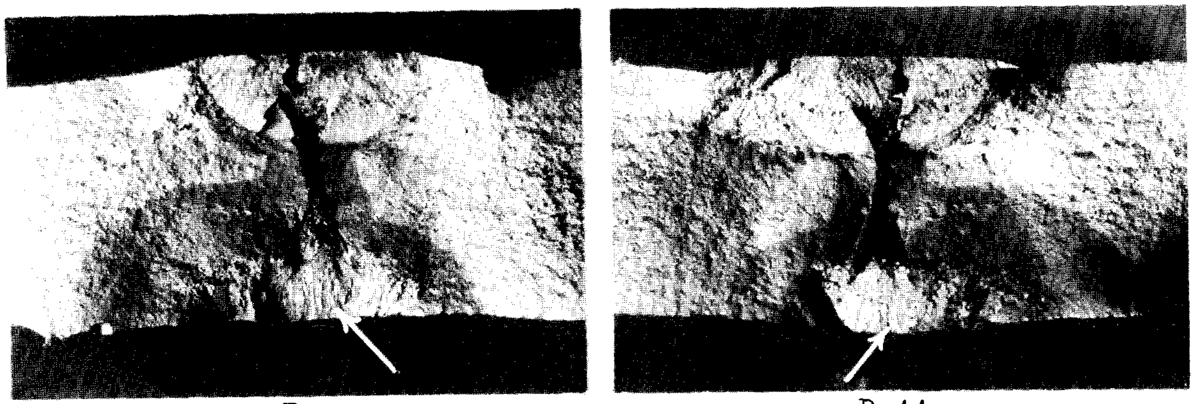
Bottom



Fatigue Crack 6-V

Specimen AD-1 Figure 65

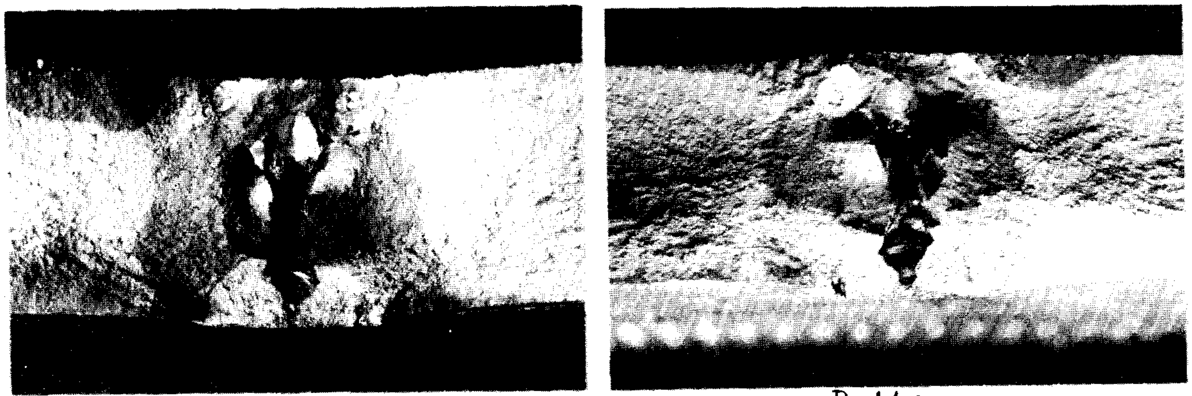
Back Face



Top Bottom

Fatigue Crack 1-V

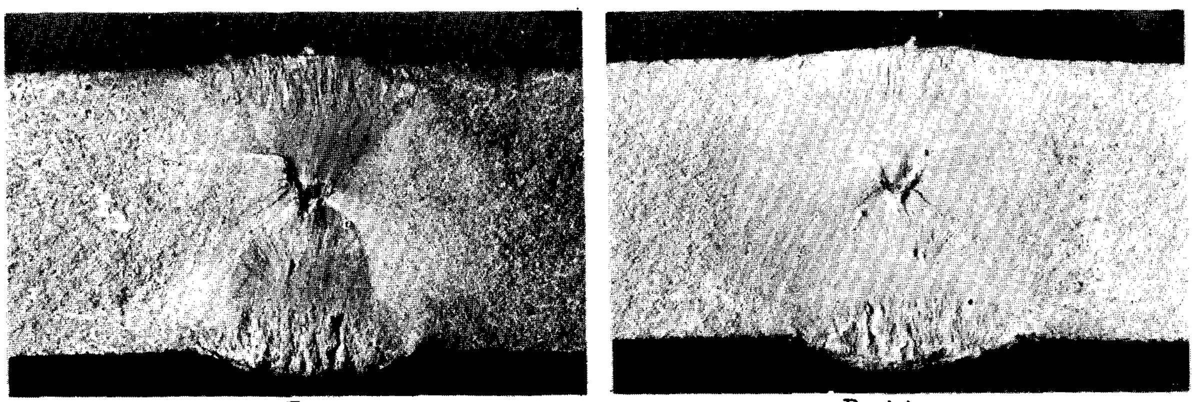
Specimen AD-2 Figure 66



Top Bottom

Fatigue Crack 1-V

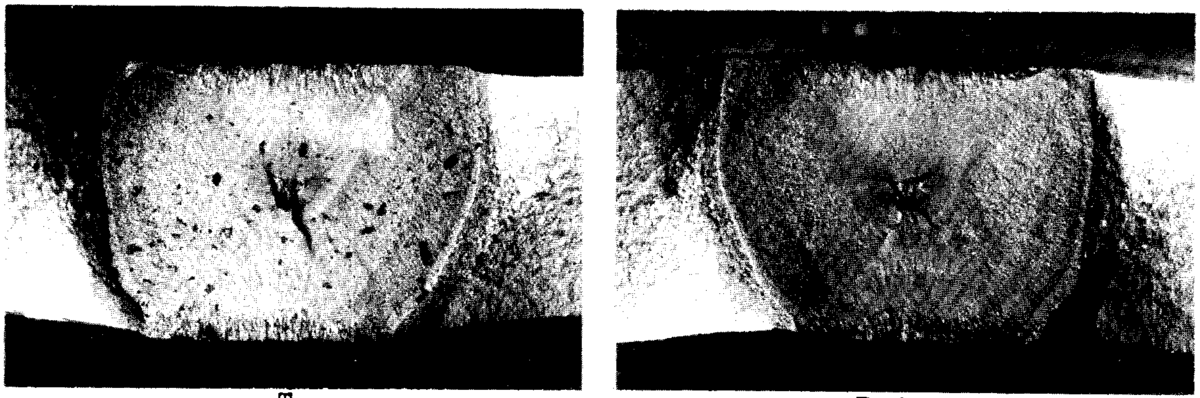
Specimen AD-3 Figure 67



Top Bottom

Fatigue Crack 1-V

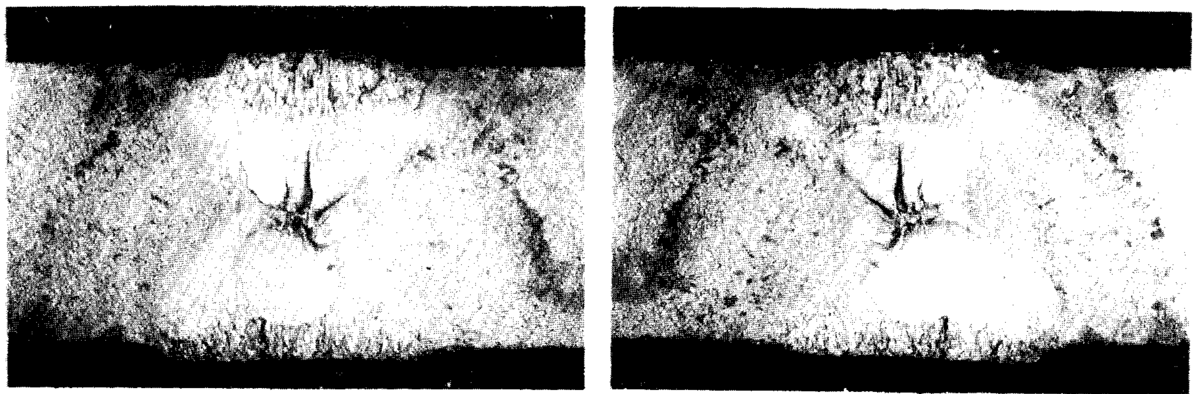
Specimen AE-1 Figure 68



Top Bottom

Fatigue Crack 2-V

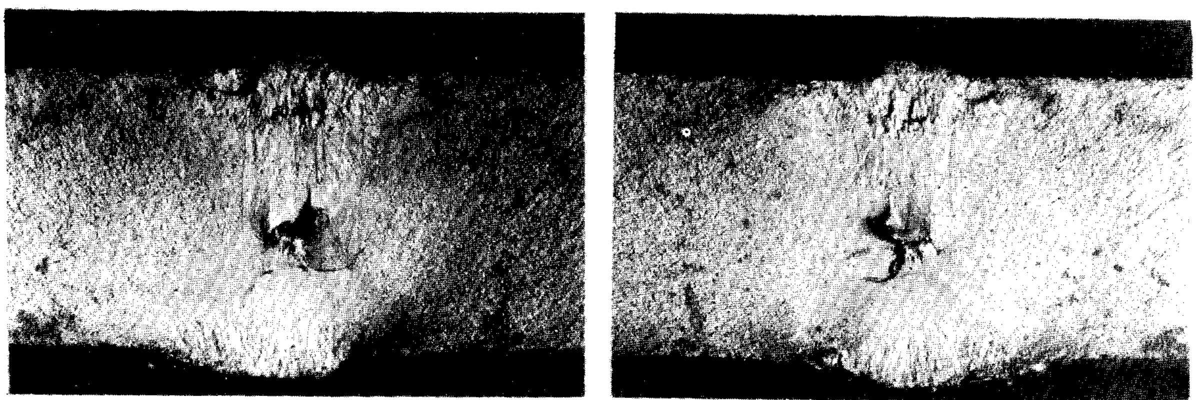
Specimen AE-1 Figure 69



Top Bottom

Fatigue Crack 1-V

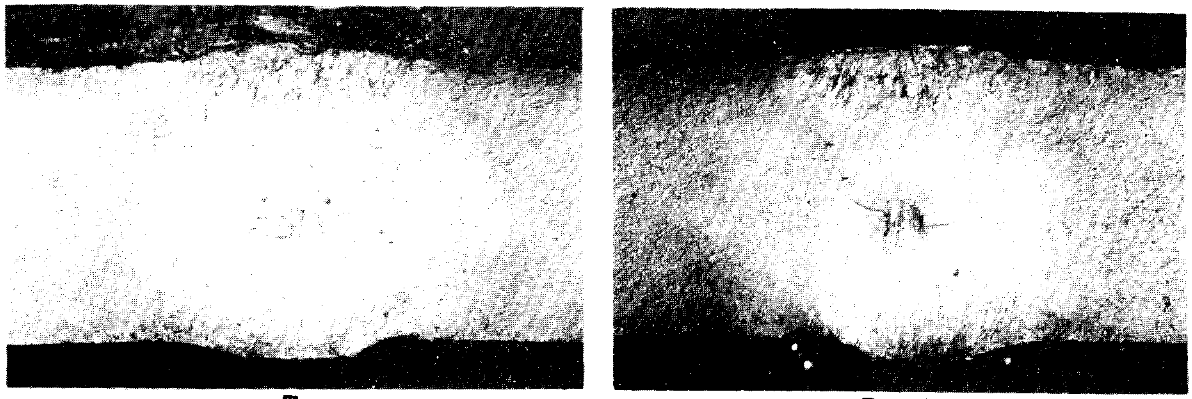
Specimen AE-2 Figure 70



Top Bottom

Fatigue Crack 2-V

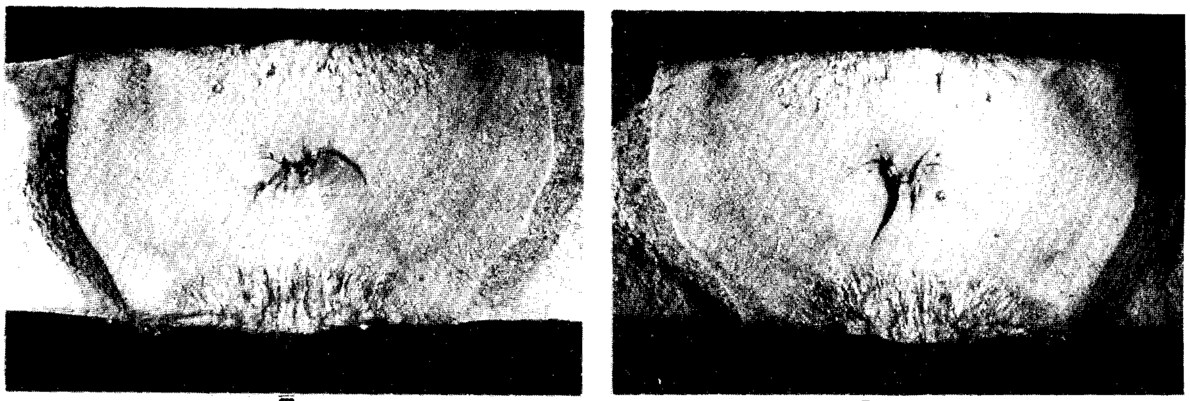
Specimen AE-2 Figure 71



Top Bottom

Fatigue Crack 1-V

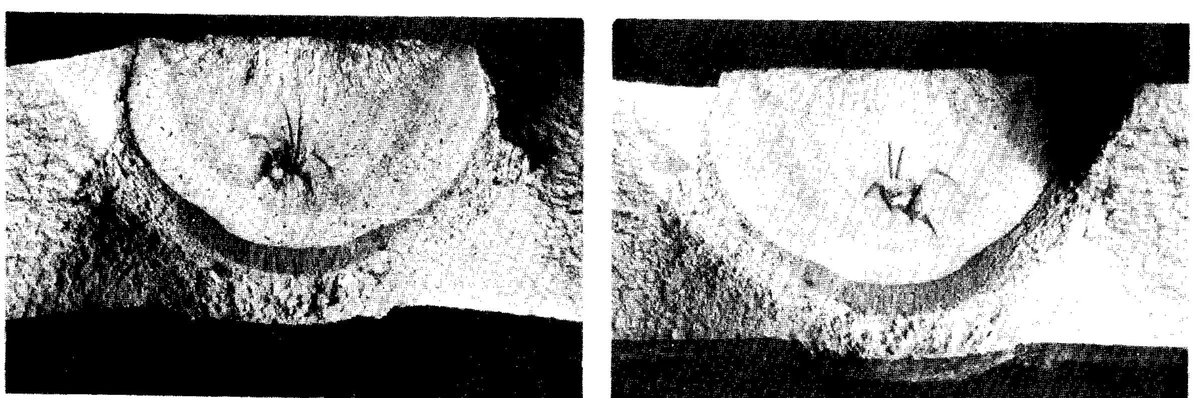
Specimen DE-1 Figure 72



Top Bottom

Fatigue Crack 2-X

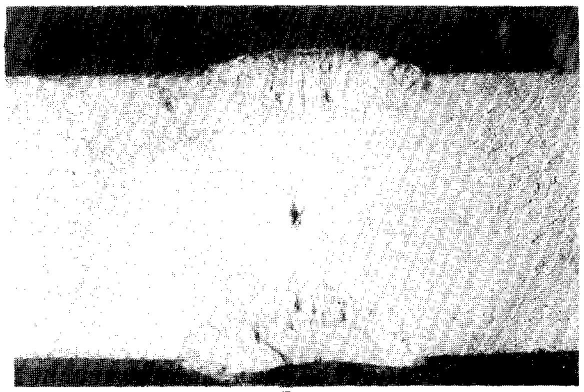
Specimen DE-1 Figure 73

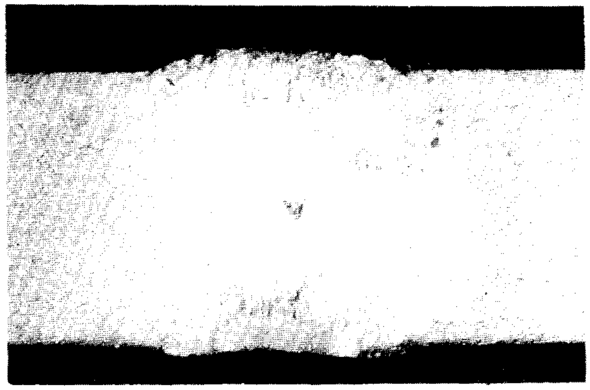


Top Bottom

Fatigue Crack 3-X

Specimen DE-1 Figure 74


Top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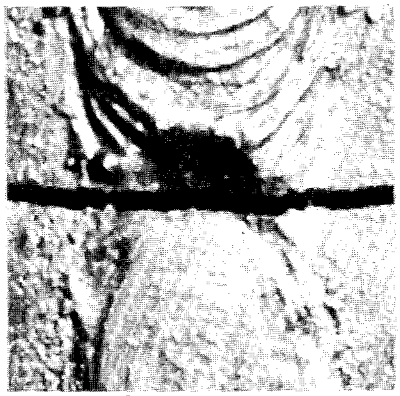
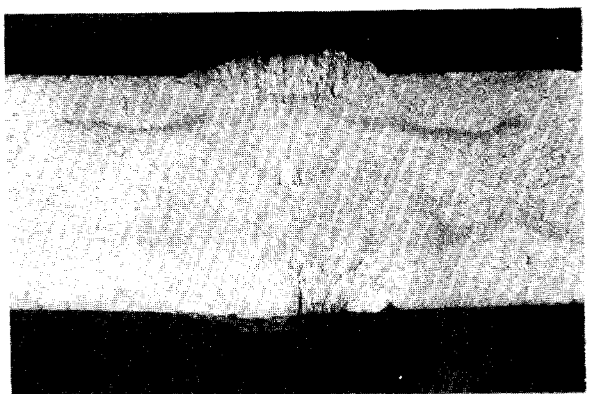

Front Face

Fatigue Crack 1-V

Specimen DE-2 Figure 75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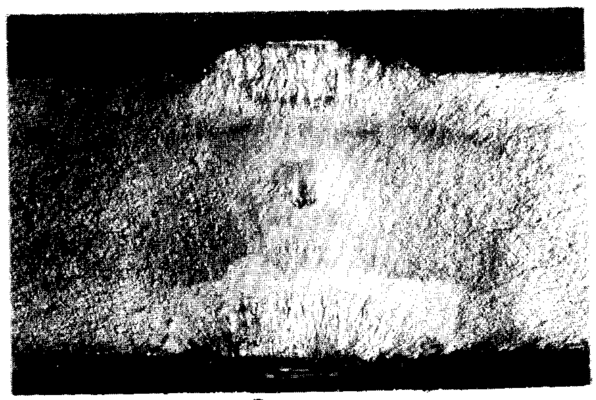
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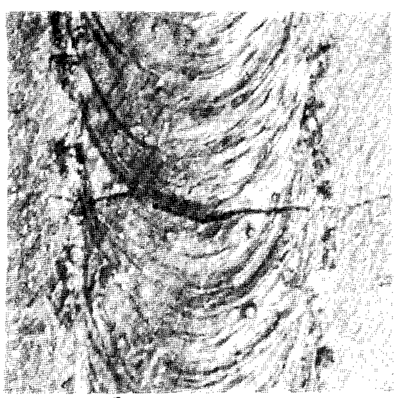
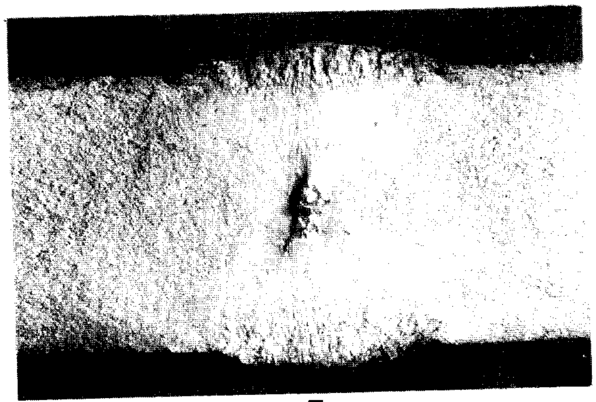
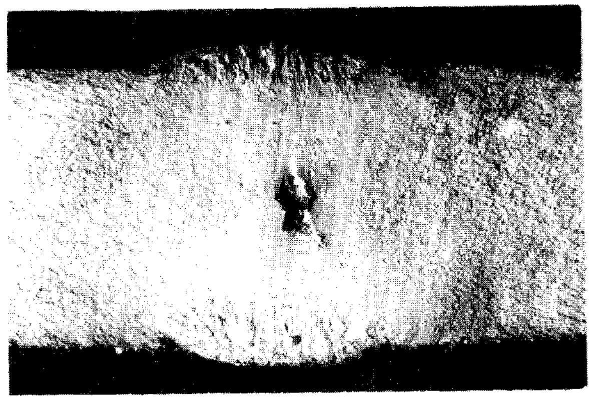

Front Face

Fatigue Crack 1-V

Specimen EE-1 Figure 76



Top

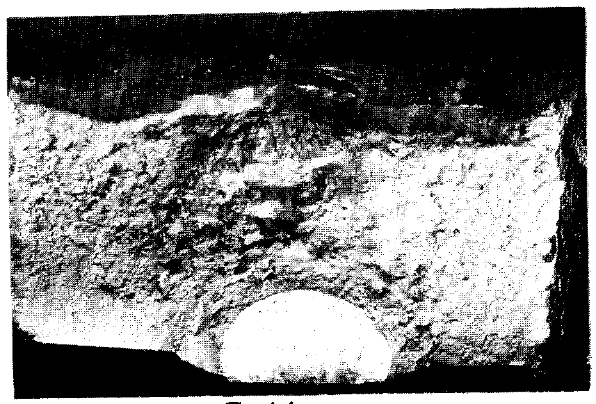


Bottom

Fatigue Crack 1-V

Specimen EE-1 Figure 77

Top



Bottom

Front Face

Fatigue Crack 2-X

Specimen EE-2 Figure 78

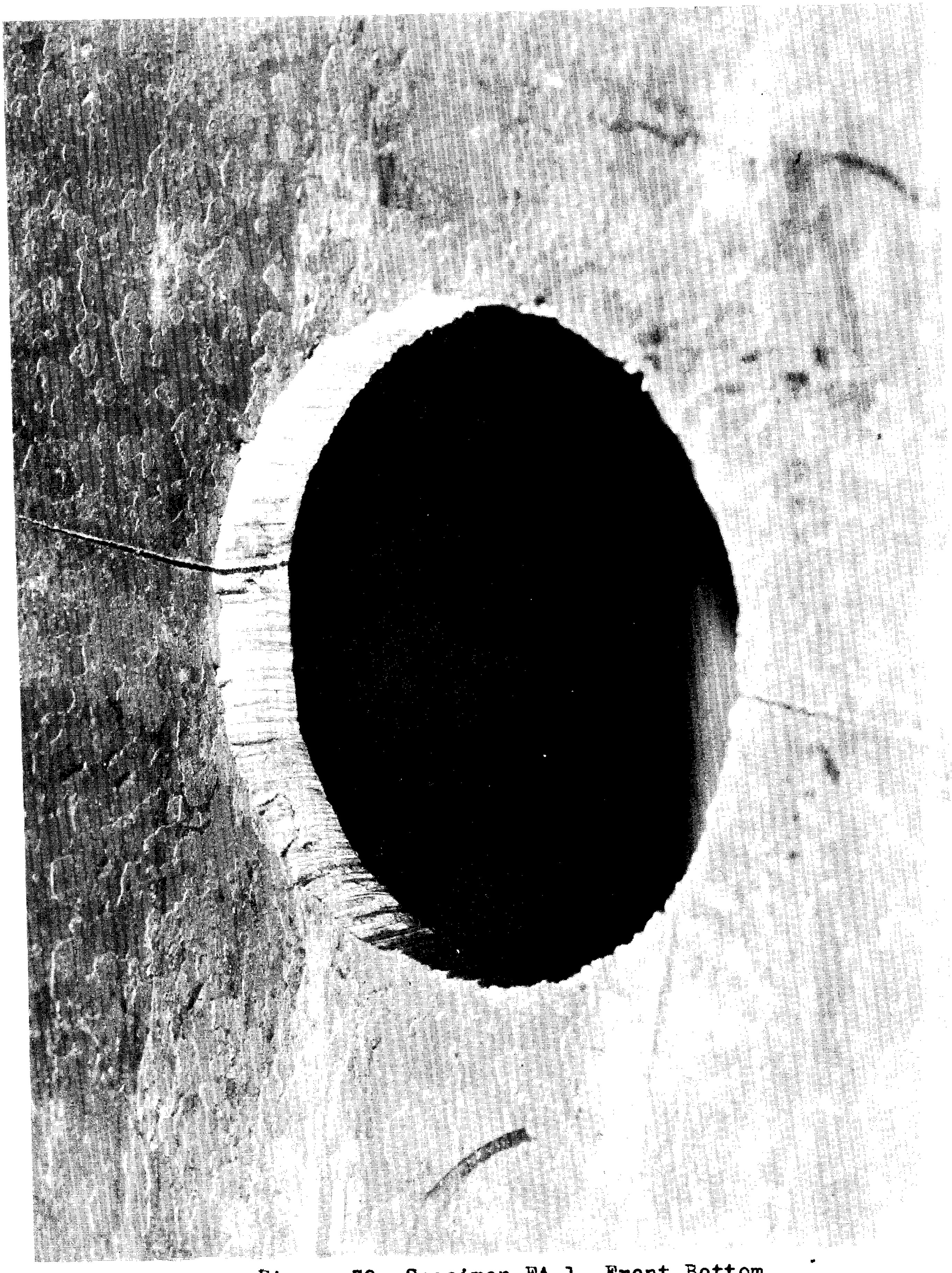


Figure 79 Specimen FA-1 Front Bottom

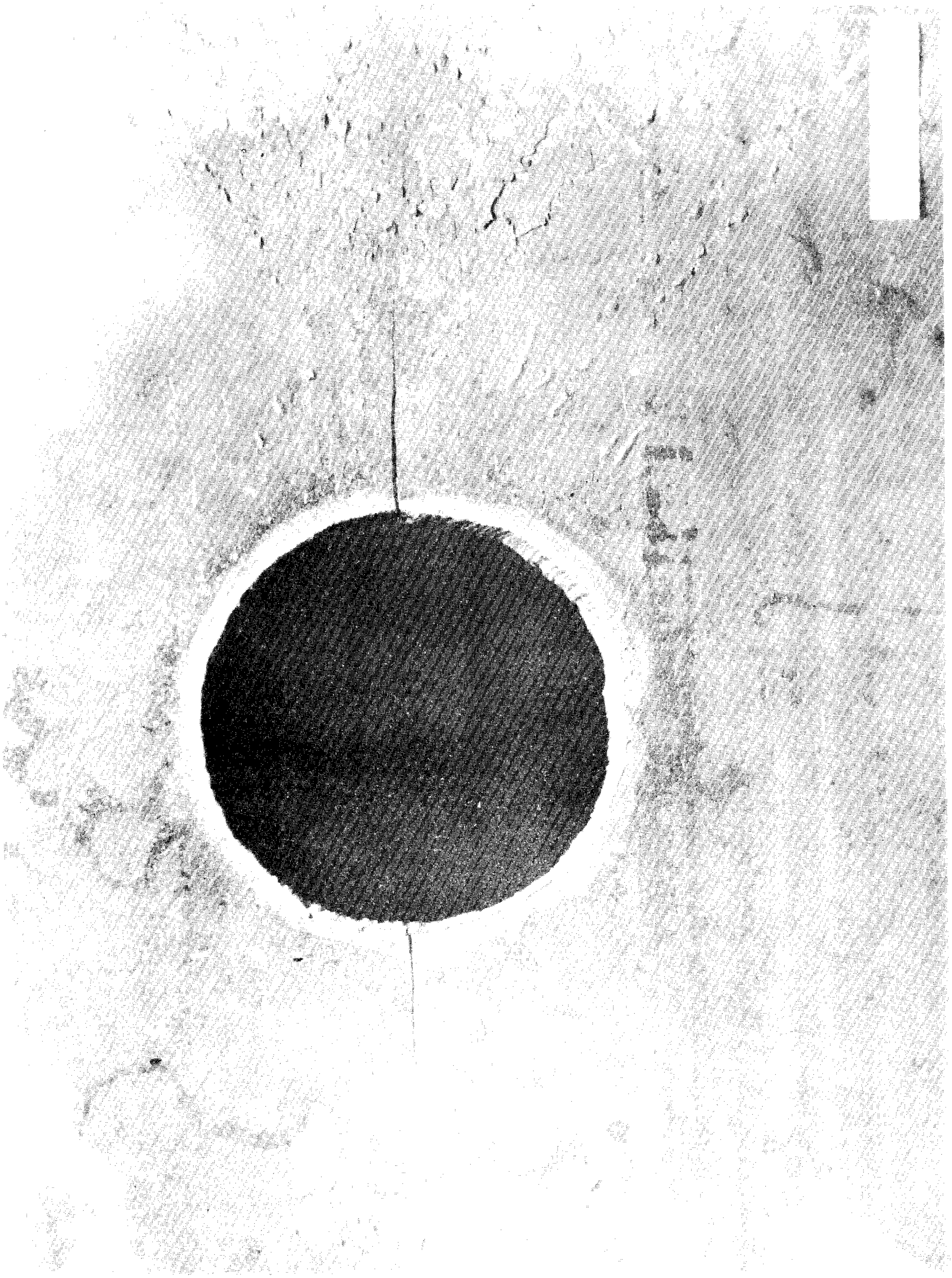


Figure 80 Specimen FA-1 Back Bottom

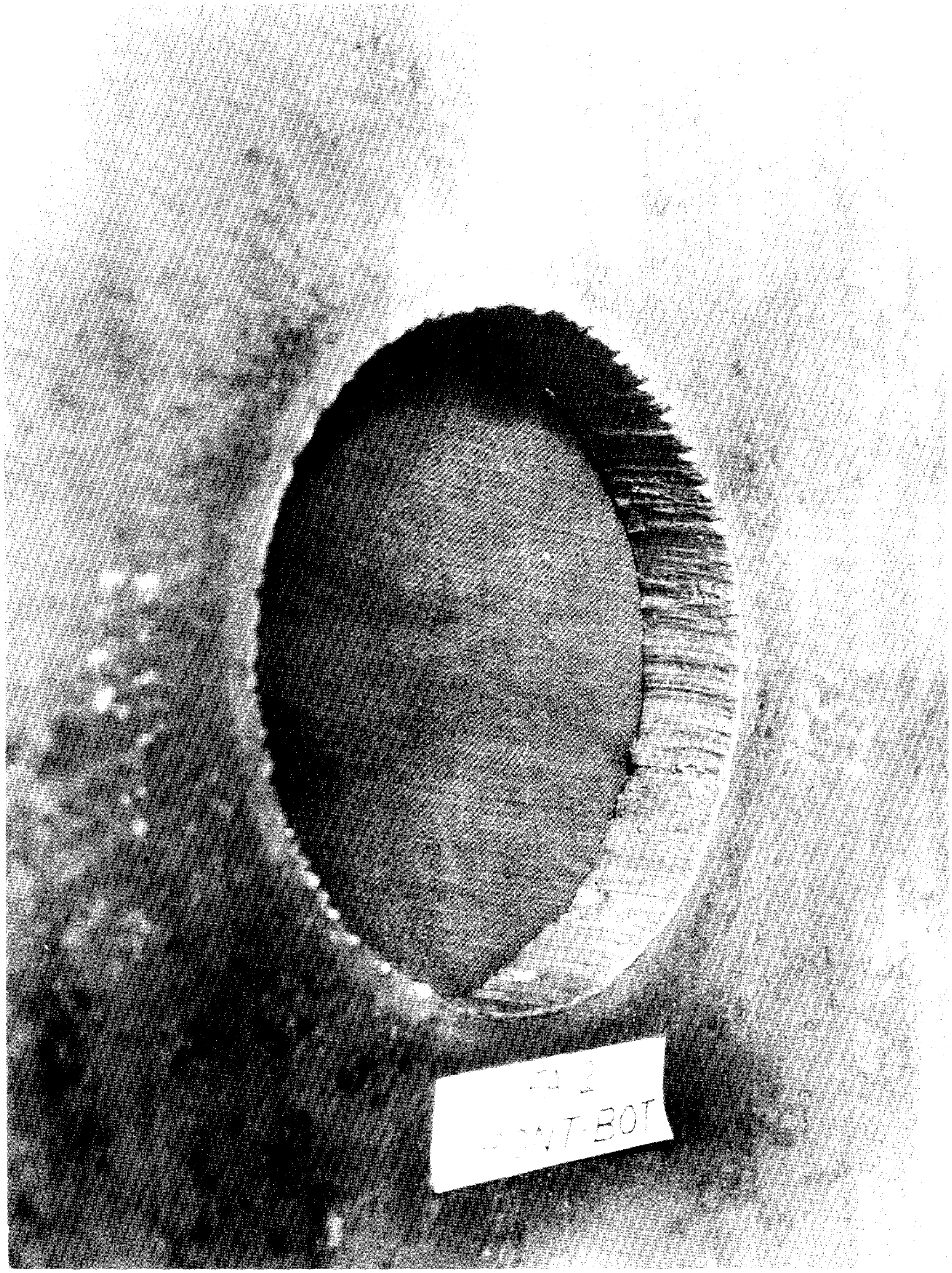


Figure 81 Specimen FA-2 Front Bottom

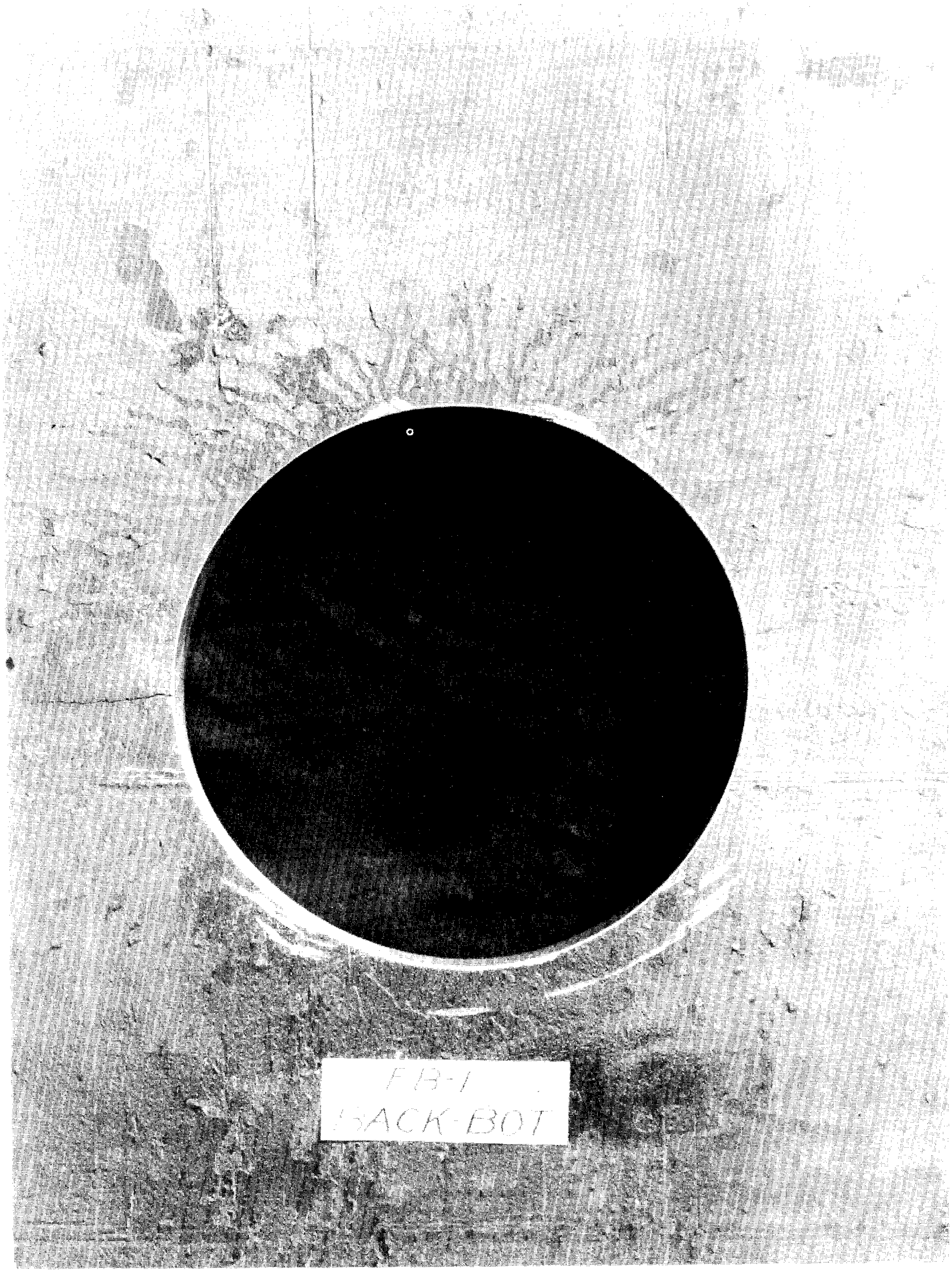


Figure 82 Specimen FB-1 Back Bottom

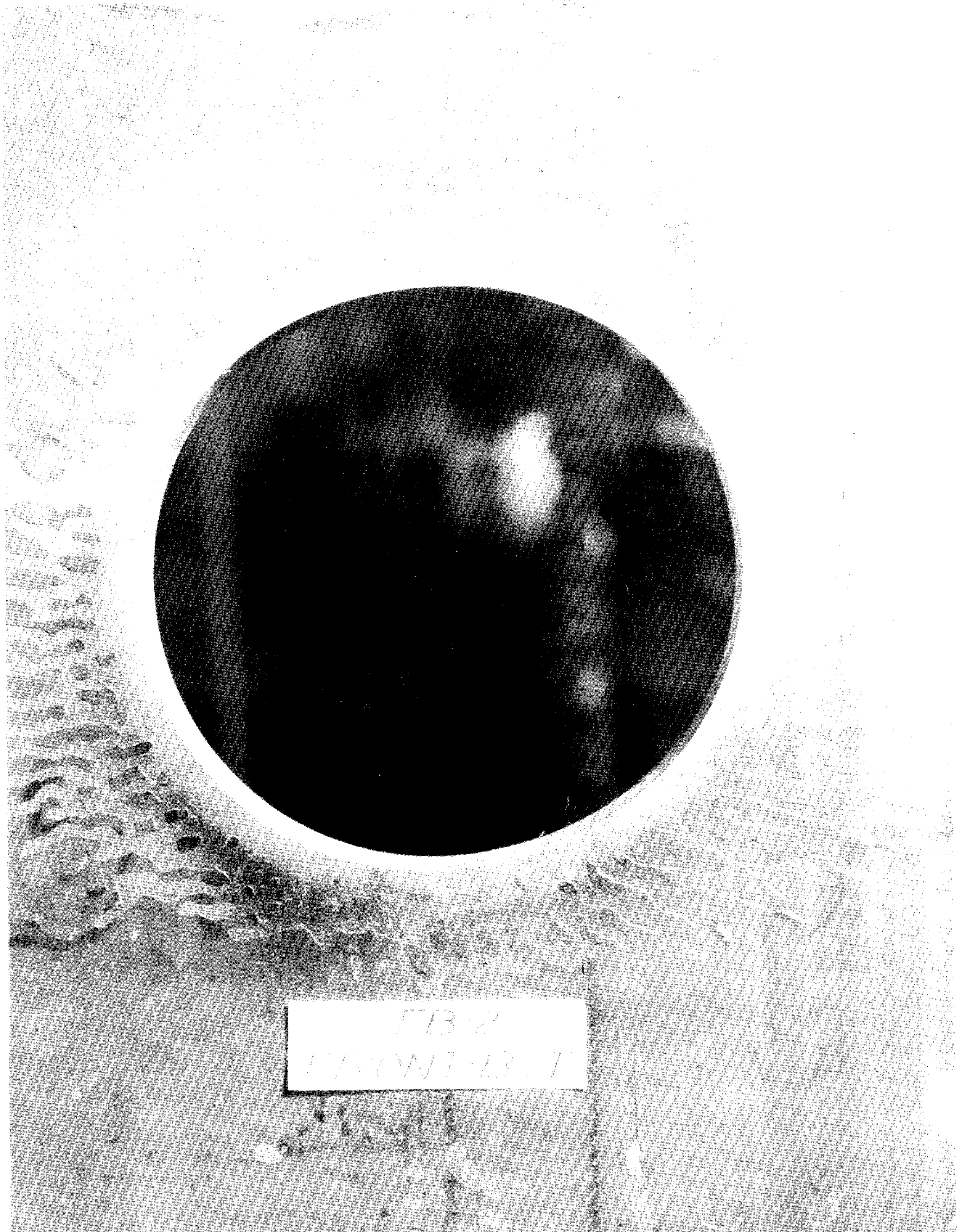


Figure 83 Specimen FB-2 Front Bottom

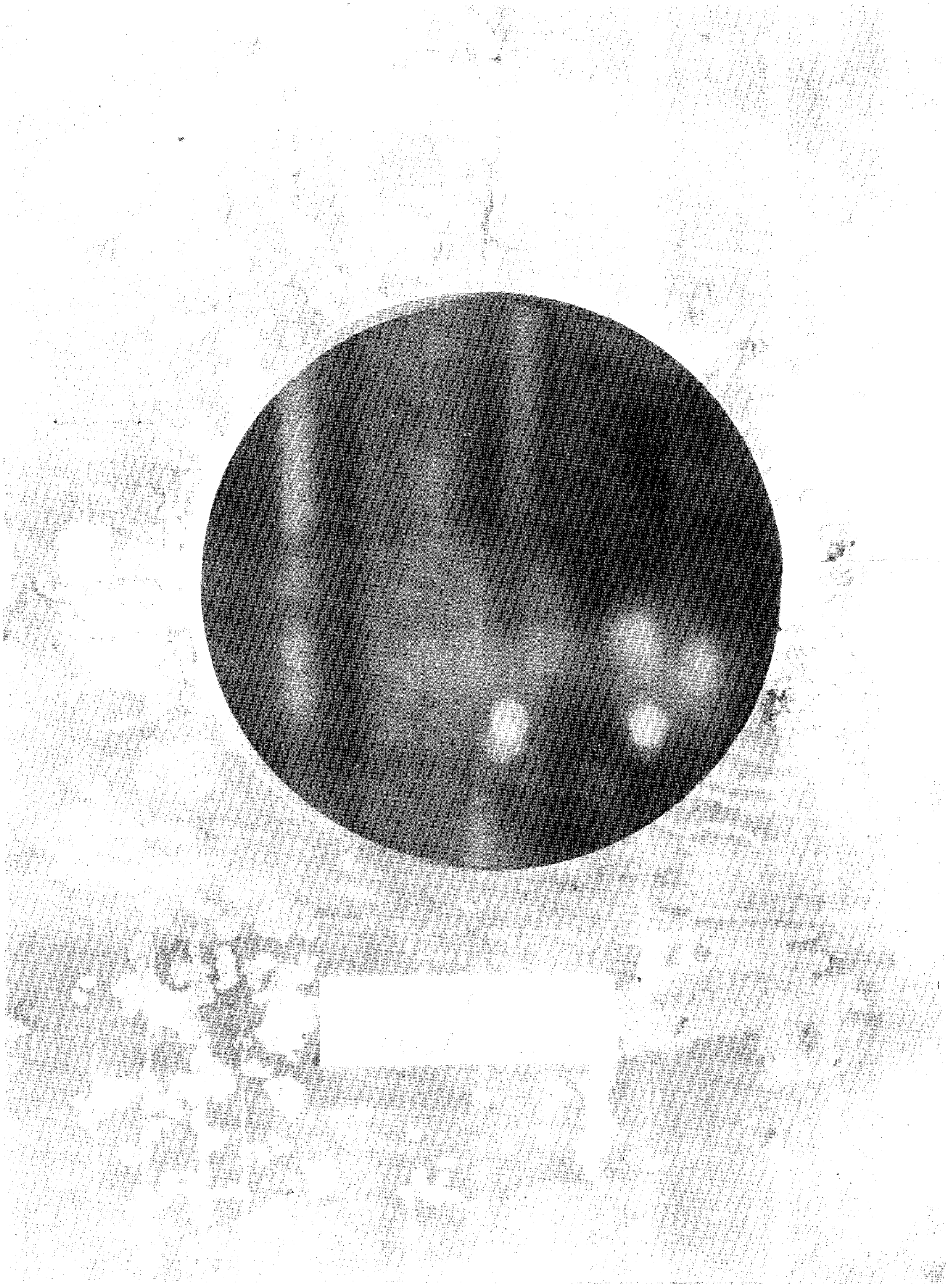


Figure 84 Specimen FC-1 Front Bottom

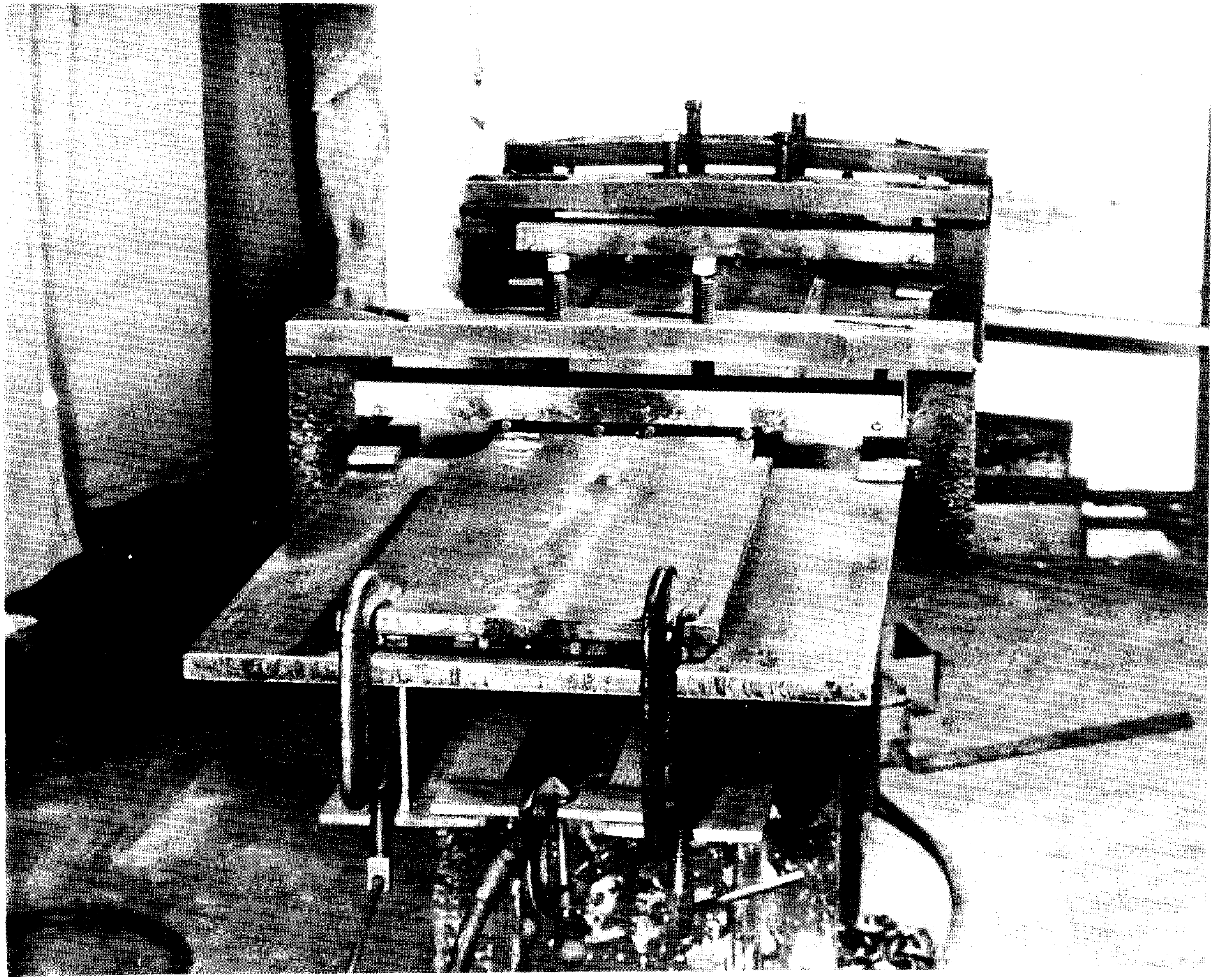


Figure 85. The "Hold-down" Table Employed to Minimize Distortion in the Specimen Caused by Welding. The Rollers Permit Free Lateral Motion