FINAL REPORT

ON

FATIGUE TESTS OF SHIP WELDS

BY

S. C. HOLLISTER, J. GARCIA AND T. R. CUYKENDALL

Cornell University

Under Navy Contract NObs-31218

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

NATIONAL RESEARCH COUNCIL

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SHIP STRUCTURE COMMITTEE

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Washington, D. C.

February 4, 1948

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Dear Sir:

Attached is Report Serial No. SSC-14 entitled "Fatigue Tests of Ship Welds." This report has been submitted by the contractor as the final 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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Final Report

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FATIGUE TEST OF SHIP WELDS

31 August 1945 to 31 August 1947

by

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List of Illustrations and Tables

ABSTRACT

This report summarizes the results of an investigation of the relative fatigue behavior of plates with (a) longitudinal ship welds, (b) reinforced and unreinforced flame cut openings, and (c) flame cut edges. The specimens, of the order of 12 to 17 inches wide and 7 feet long, were constructed from 3/4" plate of semi-killed shipbuilding steel and were subjected to zero-to-tension loading in especially built fatigue testing machines. The stress range generally was 0 - 30,000 psi tension.

Specimens with longitudinal welds (total =25) were made with either one, two or three passes on each side, and the weld surface was either as welded, or ground flush with the plate.

Reinforced holes (total of 4), had a collar insert of dimensions such that the net cross-sectional area across the test piece was equivalent to that of the plate before cutting the opening. The inserts had either (a) a fillet weld on each face, or (b) a full penetration weld.

Unreinforced, circular (4 1/4" dia.) holes (total of 19) were (a) flame cut either by hand or by machine, or (b) bored on a vertical mill. The surfaces of the holes were (a) as cut, (b) ground smooth, or (c) heat treated.

Fatigue control specimens were flat plates of tensile-coupon shape with flame cut edges. It is concluded that for a stress range of approximately zero-to-30,000 psi tension the characteristics of the flame cut edge were not significant in determining fatigue life within 500,000 cycles of stress.

In comparison to the control specimens, longitudinal welds showed a greatly reduced fatigue life. All fatigue fractures started in the weld metal itself, usually in regions of porosity, deep surface ripples, poor root fusion, etc. Improved fatigue life for specimens with ground weld surfaces indicates

that surface ripples, folds, or pits are incipient points of fatigue failure. The change in width from 12" to 16" is not believed to be significant.

All specimens with reinforced openings had a very short fatigue life (less than 30,000 cycles).

Unreinforced, as cut, openings had a greater fatigue life than the reinforced openings. Treatment of the surface by grinding or by heat treatment markedly increased the fatigue life.

I. INTRODUCTION

This report describes an investigation of the relative fatigue behavior, under zero-to-tension loads, of certain welded structures having residual stresses of the nature found in welded ships. The limited knowledge of the effect of these factors in producing early fatigue fracture, and the occurrence in many ships of structural fractures after short periods of service, led to the establishment of a subcommittee of the War Metallurgy Committee to formulate a program for this study of fatigue characteristics of ship welds.

Under OSRD Contract OEMsr-1382, Cornell University was authorized to undertake the investigation of "Fatigue Tests of Ship Welds" known as Project NRC-89. Subsequently, the work was carried on under the auspices of the U. S. Navy under Contract NObs-31218. Technical advice and assistance was given by a Project Advisory Committee, at first under the War Metallurgy Committee and later under the Committee on Ship Construction of the National Research Council.

This report contains, in addition to the results of recent studies, a comprehensive review of all the studies on fatigue behavior made at Cornell under the above contracts. For specific details, appropriate reference is made to earlier reports.

Specimens with significant geometrical variations were fatigue tested generally under a nominal stress range of 0 - 30,000 psi tension; a few specimens were tested at 0 - 20,000 psi tension. It would have been desirable to employ a reversed range of ± 20,000 psi. Since the specimens were full scale models, the application of a compressive force was out of question for reasons of bending or buckling. The "2/3 rule," which states that a stress range of either 0 - 30,000 psi tension or ± 20,000 psi produces equivalent results, was suggested as a justification of the stress range employed. It was recognized that at stress raiser points the large upper limit stress would produce plastic flow affecting the established elastic relationship upon which the rule is based. However, it was finally agreed that "fatigue tests on a cycle of 0 to tension would produce the same segregation of desirable and undesirable designs as obtained when testing specimens under loads alternating from tension to compression."

The type of electrode for all specimens and the stress range selected for the repsective test groups were held constant throughout the entire investigation. All specimens were made of 3/4" steel plates - semi-killed shipbuilding steel of ABS quality.

The investigation was divided into the following three major phases with all specimens subjected to a cyclic tensile stress.

1. Small control specimens with machine flame cut edges.
2. Plates with longitudinal welds (stressed in the direction of the weld) to study comparative fatigue behavior for such variables as: ground and unground welds, various number of weld passes (1 to 3)* variation in width of the specimens (11 1/2" vs. 16 1/2"), two heats of the same type of steel.
3. Plates with central openings having two main geometrical conditions in order to note their relative efficiency in fatigue.
   a - Reinforced rectangular holes - collar insert (welded) to produce a net cross-sectional area (across the test piece) equivalent to the original net section before the introduction of the opening. The inserts were secured either with (1) fillet weld, symmetrically placed on each side of the plate, and (2) a full penetration weld.
   b - Unreinforced circular holes - in which further sub-divisions of hole preparation were studied such as: bored, flame cut by machine or by hand, and the removal (grinding) of the flame cut surface in the

*Throughout this report the number given as "number of weld passes" is the number of passes made on <u>each</u> side of the symmetrical V-butt weld.

flame cut holes.

II. DESCRIPTION OF SPECIMENS INVESTIGATED

The specimens investigated were of three general types with various subdivisions as to geometric conditions and physical preparations as described below. All test pieces were constructed from 3/4" thick semi-killed steel of ABS quality[3] of two heats - identified as "A" steel and Project Steel (SR-89), respectively. The methods employed in the construction of the various specimens is given in previous reports and in Appendices B and C.

1. Longitudinal Weld

Each specimen was formed from two plates (length = 7'11") of equal width joined by a symmetrical "Double-V butt" weld for their entire length. The use of two different widths of individual plates produced specimens with 11 1/2" or 16 1/2" widths in the test length. The procedure for holding the plates during welding, type of welding electrode, current, etc., are all described in Appendix B, "Construction of Specimens with Weldment".

a. Specimens with 11 1/2" Widths (Fig. 1)

These specimens, twenty - two in number, had either one, two or three weld passes on each side of the plates. Six of them with either one or with two weld passes on each side, had the weldment ground flush with the surface of the plates.

b. Specimens with 16 1/2" Widths (Fig. 1)

Three specimens of this width, with three weld passes on each side of the plates were made. No treatment was applied to

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3 - Appendix A, Characteristics of Steels

the weld surface of this group.

2. Center Openings of Various Geometries

These specimens were made from 24" x 7'11" x 3/4" plates. The central geometries were symmetrically located at the intersection of the transverse and longitudinal center lines of the specimen, (17" wide in test length).

a. Unreinforced Holes (Fig. 2)

The 4 1/4" dia. holes in the nineteen specimens studied were constructed by several methods (bored, manually flame cut, and machine flame cut). Similar openings were given different edge preparations (hand flame cut and ground, machine flame cut and ground, and machine flame cut and heat treated). The procedure for the construction of these holes is given in Appendix C "Fabrication of Specimens with Holes."

b. Reinforced Holes (Fig. 3)

Four specimens of this type possessed a rectangular collar or ring with rounded corners symmetrically welded at the intersection of the plate's center lines. A description of the method of construction of these specimens has been given previously.*

3. Straight Specimens with Flame Cut Edges (Fig. 4)

The side edges of the four small specimens (2" width) were machine flame cut. No other treatment was given to the edges.

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* Reference 1, pages 11 - 13

III. ANALYSIS OF TEST RESULTS

The test results for each class of specimens are summarized in five appropriate Tables, numbers I - V inc. An explanation of symbols will be found adjacent to Table I. Pertinent information concerning location of cracks, etc. are given in the tables.

The stress ranges employed, where applicable, 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 measurements at that gage length of the specimen for which the strain was greatest.

Local 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 appears.

All specimens were radiographed after testing; cracks so detected cannot be assigned a value for "cycles-to-fracture".

The surfaces of fatigue cracks were made available for examination by cutting out a small "coupon" of material containing 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-light technique during the fatigue test, and were not visible in the radiograph.

Photographs of the surfaces of the cracks, radiographs, and other graphic information for the majority of the specimens are given in previous reports.[1,2] Illustrations shown in this report are for specimens recently tested.

[1,2] See References.

1. Fatigue Control Specimens (Table III)

No significant fractures occurred in that portion of the metal surface which was typical of machine flame cutting. The two cracks, which did appear, formed at geometrical discontinuities--one in a deep flame cut notch, the other at a "dimple" on the surface of the plate. Thus, for both the high and low stress ranges employed, the metal appears to withstand satisfactorily cyclic loading of the nature investigated. Unfortunately, time did not permit subjecting the last two specimens to a longer cyclic test until fracture did develop, and thus to note the relative fatigue behaviour.

2. Specimens with Longitudinal Welds

The location and illustration of fractures not shown previously are shown in Figs. 5-7 inc., Figs. 23-27 inc., Figs. 35-39 inc.

a. Stress Range of 0 -30,000 psi. tension (Table 1)

The following deductions were arrived at principally from previous study, since only one additional specimen (EE-3) was added to this group since the last report.

(1) Origin of Cracks

A study of the number of cracks vs. geometric origin (inside or surface of weld, face of specimen--front or back, and in which general region or the test length--upper, middle or lower third) does not indicate any one outstanding source of weakness in fatigue. Fractures started at regions of porosity in the weld, of poor root fusion, and at deep ripples in the weld surface. This is as one would expect since these local weld flaws accentuate the stress state.

With the exception of one specimen, those with ground weld surfaces, (types AB and AD) had a greater fatigue life than those of the untreated groups (AE, DE, and EE). Additional studies would be desirable to determine the extent of the improvement to be expected by the removal of one source of incipient failure, i.e. deep weld ripples.

(2) Variation in Weld Passes

A comparison of the fatigue life for specimens constructed with one, two and three weld passes cannot be made satisfactorily because of the several other variables which were unavoidably present. In the two pass group, AA series, the plates warped and tended to close the gap during welding, making it difficult to secure a good weld. A different method of restraint was employed for the three pass group, see Appendix B. The AB and AD series had poor root fusion. Increased experience with the E6010 electrode resulted in smoother weld surfaces for the one and three pass groups than for the two pass groups (the first type constructed). Accordingly, although the two pass group is found to show considerably lower fatigue life (see Table I) than either the one or the three pass groups, the lower fatigue life is not believed to be related principally to the number of passes.

The results given in Table II for specimens AA-6, AE-4 and DE-3, could be interpreted to indicate a relationship between fatigue life and number of weld passes. These specimens were constructed in identical fashion except for the number of weld passes. However, the fact that the two pass specimen, AA-6, fractured at the lowest number of cycles for any of the three specimens may well be quite accidental; many more tests would be required to establish the effect of a variation in number of weld passes.

b. Stress Range of 0 - 20,000 psi. tension (Table II)

Three specimens were tested at the above stress range; the fourth one at a stress-range of 0-17,300 psi. tension after it had experienced a certain amount of over-load.

For comparative purposes, the 3 - pass specimens AE-4 ($11\frac{1}{2}$") and DE-3 ($16\frac{1}{2}$") may be grouped, since the fatigue behaviour of the longitudinal weld was found in earlier tests to be independent of specimen width for the two widths tested ($11\frac{1}{2}$" vs. $16\frac{1}{2}$"). The third specimen of the 3-pass type, AE-3 was initially overstressed,* and then cyclically loaded below the nominal stress range of 0 - 20,000 psi. Since under such loading conditions the residual stress pattern would be different and less severe than the existing stress state in the two corresponding specimens, a true comparison with the former two specimens cannot be made.

Of all the longitudinal welded specimens investigated, the three specimens AE-3, AE-4 and DE-3, experienced the longest cyclic service without significant fractures--DE-3 had a small arrested crack. Therefore, the endurance limit for this particular 3-pass type of weld lies in the approximate region of the stress ranges employed.

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* Appendix F

It is interesting to note that the only visible crack among the lower stressed test pieces formed in the 2-pass specimen (AA-6). It seems advisable to investigate further the 2-pass type at a stress range of 0 - 20,000 psi tension in order to determine if this indication of less satisfactory service would become a definite trend.

3. Specimens with Openings

(a) Un-reinforced holes

The fatigue results of all specimens with unreinforced openings of $4\frac{1}{4}$ inch diameter are listed in Table V. Obviously, all fractures occurred on or close to the transverse center line of the specimen; the exact location and details of the fractures for specimens not previously reported are shown in Figs. 9 to 20, inc., and certain pertinent and typical fractures are shown by photographs Figs. 28 to 34, inc.

With the exception of the FM group, the fatigue life of the specimens in the respective groups are satisfyingly consistent.

A relative study of the FA (hand flame cut) and FD (machine flame cut) groups proves the superiority of the latter; evidently the more irregular surface geometry of the hand flame cut hole, as compared to the machine flame cut surface, markedly lowers the fatigue life of such openings. The reader may gain some idea of the characteristics of these surfaces by comparing Figs. 28 and 29 with Figs. 31 and 32.

A comparison of the fatigue behaviour of the specimens with ground surfaces with those having unground surfaces of the flame cut hole illustrates the harmful effect of the as-cut surface for both the machine and hand flame cut groups. It is interesting to note that removal by shallow grinding of the rough metal surface in both the hand and machine flame cut groups (FB and FE respectively) appears to produce for all practical purposes equivalent life in the two cases. Although only one specimen of the ground, machine flame cut hole (FE) was tested, this above result is in general agreement with the results of studies of flame cut surfaces made elsewhere.[5] The greater depth of heat affected metal (because of longer cutting time, ref. 5) in the hand flame cut group would appear, from the results herein, to be of much less significance than the change in surface geometry.

However, there are factors other than surface geometry which appear to be of considerable significance in relation to the fatigue life under the present test conditions. The hardness of the metal increases very rapidly as the flame cut surface is approached; (Appendix E and reference 5); grinding, by removing a portion of the heat affected metal, results in lower hardness values for the surface of the hole. It is known (see Page 228-s, reference 5) that the flame cut edge is subjected to residual stress; perhaps this stress may be of the order of the yield point of the material. With these factors in mind it is interesting to examine the following results. The heat treatment applied to the flame cut holes (FF specimens, Appendix C) definitely decreased the hardness* of the metal adjacent to the hole, and significantly increased their fatigue life as compared to the untreated FD group. Furthermore, these heat treated holes produce results which compare favorably to the FB group (hand flame cut and ground).

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[5] See Reference

* Appendix E

Since groups FD and FF were prepared in identical manner, (machine flame cut), the surface characteristics of the holes were similar, see Fig. 31-33, and hence the results obtained are independent of this factor. Unfortunately, neither the magnitude of the initial residual stresses nor the extent to which they are reduced by the heat treatment is known. Microscopic examination (see Figure 22, Appendix H) shows that some decarburization has taken place in the heat treated specimen, but that otherwise the structure of metal is very similar to that in the other groups. Hence it may possibly be that the change in fatigue life observed may be caused to a considerable extent by a relief of high residual stress and thus modification of end points of the stress range. Some knowledge of the fatigue characteristics for stress ranges with upper limit at yield point, for specimens of different hardness, would be of value in this connection.

The FM specimens (machine bored with no heat input) were selected as the group to possess the best fatigue behavior, and thus represents the extreme case for comparison with the other types of hole preparation; it was presumed that these specimens would produce the most consistent fatigue values. However, the spread of fatigue life for the FM group is both unsatisfactory and puzzling. The results for the FA and FB specimens appear to eliminate differences in the inherent properties of the two steels as a cause for large spread between FM-1 and FM-3. Extensive analysis was unsuccessful in establishing a major cause for the wide discrepancies among the fatigue values of the FM specimens.

Therefore, additional specimens of the FM type must be tested to establish definitely the fatigue life for this type of edge preparation.

In the majority of cases the initial fatigue crack, after forming at one edge of the hole, propagated across the inside surface of the opening to the opposite face of the specimen. However, the different preparations of the openings affected the rate at which this inside fracture spread. For all holes in the as-cut state (heat treated and untreated) the rate of propogation was rapid. While the removal of the flame cut surface decreased the speed with which the fracture spread, the slowest propogation was experienced by the machine bored holes (no heat input). Since the surface finishes of the ground and bored openings were identical for all practical purposes, the difference in propogation can only be explained by the possible existence of residual thermal stresses, and/or metallurgical changes in the metal, immediately adjacent to inside surface in the group with the ground hole.

The geometrical location of the initial stage of the first fracture formation at the edges of the hole (see Table V) indicates a random origin with respect to the position assumed by the specimen in the fatigue machine. However, the initial formation of the first fatigue crack in each specimen reveals that the majority of the fractures (9 vs. 3) started at one of the two edges of the hole located opposite to the face of the plate from which the flame cutting was conducted.

To determine if any characteristic difference existed along the treated surface of the hole from one face to the other of the plate, a section of metal adjacent to the crack was removed from six specimens, and a hardness survey was conducted across that face of the sectioned surface immediately adjacent to the crack. See Appendix E. The hardness traverse, which especially explored that area near and immediately adjoining the flame cut surface, indicated that a relatively greater metal hardness existed in that region adjacent to that surface from which the hole was cut as compared to the corresponding local region removed from the torch. Specimen FD-1 (machine flame cut) was the only exception, since in this case the hardness was approximately equivalent across the depth of the plate. Specimens FE-1 (machine flame cut and ground) and FF-1 (machine flame cut and heat treated) also possessed this difference in hardness along the treated inside edge from one face of the plate to the other. Therefore, it is apparent that the initial crack for the flame cut holes generally started on the softer edge of the flame cut surface, - i.e. that face removed from the flame cutting torch. No visible difference in roughness could be detected in the surface of the hole adjacent to either face of the plate.

b) Reinforced Holes

As can be inferred from the data in Table IV, the fatigue strength of the four specimens with reinforced openings is very greatly reduced from that of the parent plate, and compares unfavorably to the unreinforced hole with a ground or machined surface. Specimen B-3 (Fig. 8) verified the former results[2]. It is believed that the difference between the three specimens of B group is characteristic of the statistical spread to be expected for specimens in which the fillet geometry significantly affects fatigue behavior.

The one specimen of C group, different as to the type of fillet (full penetration) but similar to the B group with respect to the geometry of the reinforcement, tends to verify the fatigue results of the B specimens. However, further study with this full penetration fillet for the collar insert would be of value, because this type eliminates the gap, and the dangerous stress-raiser associated therewith at the underside of the weld, as always created by the fillets of the B type specimen. Such critical notch-like effects tend to cloud a study of the geometrical effects as formed by this particular reinforcement.

Because of the similar location of the cracks, and the direction and rapid rate of the fatigue fracture propagation in these four specimens, it is apparent that a severe stress concentration occurs at the rounded corners of the reinforcement where the local geometrical character of the ring forms a detrimental, three-dimensional state of stress. Since the excessive stiffness of the ring does not permit a deformation sufficient to distribute the stress over a large region, the study of special treatments is required to arrive at that design of reinforcement which does not offer large local restraining forces.

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2 See Reference

IV. CONCLUSIONS

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

The investigators have taken into consideration various factors in the construction and test of the specimens which it is believed have a significant effect on the fatigue life; these considerations are reflected in certain of the conclusions.

Fatigue Control Specimens

1. The presence of notches or other forms of stress-raiser appears, for the high range of stress cycle applied, to be the chief factor in determining fatigue behavior within a life of 500,000 cycles. It is interesting that the characteristics of the "good" machine flame cut edge seem not to be significant in determining the fatigue life within approximately 500,000 cycles.

Longitudinal Welds

2. In comparison to the control specimens subjected to high stress ranges, high quality longitudinal welds (comparable with the AE, DE, EE series; and ignoring the AA series) at a nominal stress range of 0-30,000 psi. had a greatly reduced fatigue life, probably not over one-third as long; and at 0-20,000 psi. had an equivalent or better cyclic service. This conclusion applies especially to specimens in which the flame cut edges are lightly ground.
3. For stress-ranges of zero to tension, a decrease of the upper limit increases fatigue life.
4. In specimens with longitudinal welds, all fatigue fractures start in the weld metal itself and not in the parent material adjacent to the weld.

Starting points are regions of high porosity, deep ripples, poor root fusion, etc. In some cases, fracture does not start at points of poor root fusion, as one might expect, (See Fig. 46-54 of reference #2).

5. For the high and low stress ranges employed in these studies, stress-raisers in the form of surface folds or pin-holes in the weld metal are incipient points of fatigue failures.

6. The back-step method of welding, by insuring good fusion when the one bead joins the one previously placed, reduces the possibility of fatigue fracture at these points. This conclusion is based on the results obtained for only one "continuously" welded specimen; the first one constructed.

7. It has been previously concluded that the number of weld passes (one, two or three each side) has no significant effect upon endurance life. Although the result of the test on one specimen, AA-6, recently tested, see Table II, is inconsistent with the above conclusion, it is believed many more tests would be necessary to determine if a relationship between weld passes and endurance life truly exists.

8. The increase in width of specimen from $11\frac{1}{2}$" to $16\frac{1}{2}$" makes no difference in the fatigue behavior of longitudinal welds in tension.

9. In certain cases, small ($\frac{1}{4}$" to $\frac{1}{2}$") 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.

Openings - Reinforced

10. For members with discontinuity in cross-section, i.e. welded reinforcing ring at edge of hole, it appears that such forms of reinforcement need special treatment to prevent early fatigue failure.

11. Reinforcements of the type employed in this study, in which the net cross-sectional area is made equivalent to the main plate, prove to be detrimental rather than beneficial because of the relatively rigid insert.

12. The insertion of a "rigid" reinforcement in a flame cut hole is not as efficient as grinding or heat treating the inside surface of the hole as a means of increasing fatigue life.

<u>Openings - Un-reinforced</u>

13. Early fatigue fracture occurs in the flame cut surface of the hand and machine f"ame cut holes--machine flame cutting is slightly better.

14. The degree of surface roughness of the cut edge, such as the inside surface of a hole, is one significant factor in creating early fatigue failure. (See #15, 16, below).

15. Removal (grinding) of the irregular flame cut surface in both the machine and hand flame cut holes greatly increases their fatigue life--grinding creates almost equal fatigue life for both cases.

16. Heat treatment, i.e. flame softening, of a machine flame cut hole reduces, but not to that of the parent plate, the hardness of the flame cut surface and increases its fatigue life to nearly that of the ground surface.

17. For all practical purposes, the fatigue life of the heat treated machine flame cut openings and the ground flame cut holes are equivalent.

18. Rapid propagation of fatigue fractures occurs in the hardened metal surface of the hole in both the heat treated and untreated states; slower propagation occurs in ground or bored surfaces.

19. Flame cutting through a steel plate causes a gradient of hardness across the flame cut surface, with the harder metal adjacent to the face from which the cutting was done.

General

20. From the results of the tests on specimens with un-reinforced holes, it is concluded that for practical purposes the fatigue behavior is independent of the two steels used (Type A and Project Steel SR-89). These steels were both semi-killed shipbuilding steel of ABS quality, but were rolled in two separate heats.

21. Premature fatigue failure in the end connections of longitudinal weld specimens, where "cover plates" or "doublers" are employed to increase the thickness of the metal, may be eliminated by the combination of the following factors:

See Figure 41

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 minimize the stress raisers present in this region.

V. RECOMMENDATIONS FOR FUTURE STUDIES

Inasmuch as the investigation reported herein has of necessity been of a limited scope, it seems appropriate to set forth, from a broader point of view, studies of fatigue behavior of additional types of structures, the results of which may not only be of value to the design engineer, but may add to our basic knowledge of fatigue phenomena.

A. Fatigue Control Specimens

In order to segregate the effects of different residual stress states caused by various edge preparations from the effects of detrimental stress-raisers caused by geometrical factors, it is believed desirable to investigate additional tensile control specimens (Fig. 4; probably wider than 2") under the several conditions noted below.

1. Flame cut by hand
2. Machine Flame Cut
   (a)* as cut.
   (b) flame cut edges lightly ground.
   (c) flame cut edges heat treated.
   (d) flame cut edges peened.
3. Sheared edges.
4. Variation in width for certain of above.

These specimens may be tested at the following stress ranges:

1. 0-30,000 psi. tension as done in the present study.
2. From the results of (1) above, certain types may be tested under stress ranges in which the upper limit is decreased in magnitude (0-25,000 psi. tension, 0-20,000 psi. tension, etc.).

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*Conditions which have been studied in this investigation but which require further verification.

3. Likewise, the lower limit may be varied while the upper limit is held at 30,000 psi.

B. Longitudinal Welded Specimens

A pertinent consideration in studies of fatigue life of a weldment is the nagnitude assumed by the residual stress in the weld once cyclic loading is applied. Different initial loads will definitely produce different magnitudes of stress relief in the welds and correspondingly affect cyclic performance.

Since a state of tensile residual stress of yield point magnitude exists in the longitudinal direction of a weld pass, the first application of external tensile force to the member produces a certain amount of local yielding of the weld metal and adjacent heat affected metal. As a result of this plastic flow, the internal stress state is reduced by the amount of applied stress upon the total release of the external load. Yet, upon the second cycle of load, the internal stress once again assumes a value of yield point magnitude. Thus, for an external load of zero to tension, the weld and associate metal is stressed from a tension to yield point stress.

This situation where the upper limit of the stress range is always at yield point stress is an interesting one to explore. From an elementary point of view, it should be possible to apply to the specimen load ranges of different end points but which produce exactly the same stress range in the weld metal. For example, if a residual stress of 50,000 psi. tension is assumed in the weld, an applied stress range of 0-20,000 psi. tension will create a stress range of 30,000 psi. to 50,000 psi. tension in the weld. However, the same stress limits in the weld may result from an applied stress range of 10,000 psi to 30,000 psi tension. The results of a few such tests may give more information on the effect of weld stress on fatigue life.

It is expected that the stress ranges proposed below would be modified by the results of the initial results.

1. O-Tension

Increase the upper limit of the stress range from 10,000 psi in 5,000 psi steps until a final stress range of 0-30,000 psi is reached.

2. Tension - Maximum

Maintain the upper limit at a maximum value of 30,000 psi and set the lower limit at various magnitudes (5,000, 10,000 psi., etc.) for each of several stress ranges.

In addition to studies of longitudinal welds in the as-welded condition, other variables may be introduced, such as

(a) weld surface shot-peened

(b) specimen given low temperature stress-relief

(c) maintain elevated interpass temperatures

(d) weld surface ground smooth

It may be that grinding the weld surface produces greater increase in fatigue life than is demonstrated by the studies reported herein, since certain of the specimens tested had abnormal weld flaws which likely contributed to early fracture. Hence it is considered desirable to test a few additional specimens of type "d", above.

C. Backstep Welding

In one specimen constructed by the "continuous" method of laying down weld beads, all fractures started in ripples where consecutive beads joined one another. It is not clear if such regions are necessarily places of inherent weakness in fatigue. Hence it may be desirable to test additional 3-pass specimens constructed by each of the two techniques.

D. Specimens with Openings

When structural members in which openings have been cut are subjected to cyclic stress, an important consideration involves means of preventing or minimizing early fatigue fractures which are initiated in the weakened region of the structural member. In consideration of the magnification of stress created by the geometrical form of the opening, common design practice has dictated the use of one of several types of reinforcement. On the other hand, it is entirely possible that only an application of a simple edge preparation to the inside surface of a flame cut opening may be sufficient to produce satisfactory fatigue life. Therefore, the fatigue performance of the reinforcements versus the edge treated hole would be of interest.

1. Reinforced

In order to compare the efficiency of various types of reinforcing inserts, it is desirable that fatigue tests be carried out at 0-30,000 psi tension, since a stress range of this magnitude explores regions of major geometrical weakness with their various inherent residual stress states, and thus provides a basis for further studies.

(a) Ring Insert - A type of reinforcement identified as Group C in this investigation. In this case the fillet around the ring and on both sides of the specimen was designed to have full penetration through the plate in order to avoid the notch-like effect inherent in the fillet weld of Specimens B of this report.

Since only one specimen with full penetration welds was tested it may be desirable to test additional specimens in order to determine if the fatigue life of this type is relatively short compared to other methods of reinforcement.

(b) Doublers - Secondary plates are symmetrically mounted on both faces of the plate with the hole in order to reinforce the opening. A heavy weld bead is required on the periphery of the doubler to transmit stress; a light weld on the inside of the hole is adequate to seal the contact surfaces of the doublers and the main plate.

(1) Round

(2) Diamond - "Rhombus" with the major diagonal coinciding with the direction of loading or a "Square" in which one diagonal is in the direction of pull. Rounded points on the diamond form an interesting variation.

Doublers may be studied in which the outer, heavy weld has been treated as follows: (1) in the as-welded condition, (2) ground smooth, (3) shot peened, (4) annealed.

The grinding forms a smooth surface transition from plate to doubler; the latter two treatments reduce the residual stress and thereby provide means for investigating its importance in fatigue life. Although it is believed that the doubler reinforcement will minimize or even prevent fatigue failure at the hole, the rigidity of the ring doubler plus the abrupt change of section which introduces a severe 3-dimensional stress state may well create a fatigue fracture in the region where the periphery of the ring intersects the axis of pull. A solution to this may be the diamond shaped doubler which is known to possess an efficient stress transfer distribution—here the absorption of stress from the parent plate to the doubler is more uniform. Although an abrupt change of section exists at the peaks of the doubler, the local stress-raiser may be sufficiently low to reduce the tendency for failure at this point. Under such stress conditions it is exceedingly doubtful as to whether the initial crack will form at the peaks of the periphery or at the hole—and certainly so for the diamond in which the peaks are rounded and the weld is ground.

2. Un-reinforced

The spread of fatigue life observed for the machined bored circular openings was too great to be satisfactory. More tests of this type are desirable.

It is not believed essential to conduct more tests of unreinforced flame cut holes since the information at hand will serve for a comparison with various types of reinforcements.

Explanation of Symbols used in Table I and II

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 inisde 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

* Symbol employed in Tables I - V to denote specimens tested since the last progress report.

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

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TABLE I

SUMMARY OF TEST RESULTS

SPECIMENS TESTED AT AVERAGE STRESS RANGE • 0-30,000 PSI.

Specimen	Description	Restraint	Average Stress Range		Critical Stress Range		Local Average Stress Range		Cycles to Failure	Crack No.	Origin	Location	Remarks
			Lower Limit psi	Upper Limit psi	Lower Limit psi	Upper Limit psi	Lower Limit psi	Upper Limit psi					
AA-1 1½WH	Long. Weld 3P-AW	I	+350	+26800	+400	+30400	+1600	+30600	82500	1-V	S	BU	WELD BEADS PLACED IN "CONTINUOUS"
							+450	+28900	92000	2-V	S	BL	SEQUENCE - ALL SUBSEQUENT
							+450	+25100	95000	3-V	S	FU	SPECIMENS WERE "BACK-STEP" WELDED.
							+2300	+29000	95000	4-V	S	FM	STOPPED AT 95300 - GRIP FAILURE
AA-2 1½WH	Long. Weld 2P-AW	I	+350	+26200	+350	+30000	+350	+27500	57000	1-V	I	FU	STOPPED AT 76700 CYCLES
AA-3 1½WH	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 1½WH	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 1½WH	Long. Weld 2P-AW	II	0	+26500	+1650	+31500	+900	+31300	57900	1-V	I	BU	STOPPED 147300 CYCLES
AB-1 1½WH	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 1½WH	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 1½WH	Long. Weld 2P-G	II	-500	+26900	-1450	+30100	—	—	—	none			
AC-1 1½WH	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		FE₁	
							—	—	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 1½WH	Long. Weld 1P-AW	I	+750	+29200	+1050	+31300	—	—	199000	1-V	S	FE₁	THE PLACING OF INDIVIDUAL BEADS ON ALTERNATE SIDES WAS STARTED ON THIS SPECIMEN
							—	—	242000	2-V	S	FE₂	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 1½WH	Long. Weld 1P-AW	II	-850	+26150	-900	+29300	—	—	—	none			FAILURE IN GRIP SECTION STOPPED TEST AT 98700 CYCLES - AFTER 29 DAYS REST, TEST EXTENDED TO 146000 CYCLES - GRIP SECTION FAILED AGAIN.
			-100	+28600	-600	+30600	—	—	—	none			
AD-1 1½WH	Long. Weld 1P-G	II	+100	+27700	+1050	+30400	—	—	83500	1-V	S	FE₂	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. 1-V, 4-V, 5-V, 6-V PROPAGATION "ARRESTED" 2-V, 3-V PROPAGATED SLOWLY.
			-500	+26900	+1500	+29300	—	—	114000	2-V	S	BE₁	
							-550	+27650	307000	3-V		FU	
							+1300	+27150	329000	4-V	I	BU	
							—	—	334000	5-V		BU	
							+1400	+29400	334000	6-V	S	BL	
AD-2 1½WH	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. 1-V PROPAGATED SLOWLY 2-V PROPAGATED VERY RAPIDLY
							+700	+27100	240500	1-V		BL	
							+300	+29600	—	3-T	I	FL	
							—	—	310500	2-V	S	FE₂	
AD-3 1½WH	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 1½WH	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	BE₁	STOPPED AT 188000 CYCLES
AE-2 1½WH	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 1½WH	Long. Weld 3P-AW	III	+550	+28100	+1050	+30050	+550	+29300	189500	1-V		FM	MADE FROM "TYPE A" STEEL STOPPED AT 219000 CYCLES
EE-2 1½WH	Long. Weld 3P-AW	III	+325	+27500	-850	+31750	-1700	+27000	204000	1-V	I	FU	MADE FROM "TYPE A" STEEL STOPPED AT 246300 CYCLES — BOTH 1-V CRACKS PROPAGATED RAPIDLY.
							-1200	+29300	—	2-X	S	FL	
EE-3 1½WH	Long. Weld 3P-AW	III	+400	+28300	+200	+30000	+300	+30700	151000	1-V	S	FM	AT 66000 CYCLES RESTED 63 DAYS (FAILURE OF TESTING MACHINE) AT 215000 CYCLES RESTED 13 DAYS. TEST COMPLETED AT 234000 CYCLES. 1-V, 2-V PROPAGATED SLOWLY MADE FROM "TYPE A" STEEL
ALL SPECIMENS EXCEPT EE GROUP WERE MADE FROM PROJECT STEEL SA-49							-1000	+28000	180000	2-V	S	FL	
							—	—	—	3-X	I	M	

TABLE II

SUMMARY OF TEST RESULTS

SPECIMENS TESTED AT AVERAGE STRESS RANGE = 0-20,000 PSI.

SPECIMEN	DESCRIPTION	RESTRAINT	AVERAGE STRESS RANGE LOWER LIMIT PSI.	AVERAGE 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-6, 11½ WH	LONG WELD 2P-AW	III	+150	+20,200	+700	+19,850	583,000	I-V	S	BM	RAN 666,000 CYCLES CRACK PROPATED SLOWLY
*AE-3, 11½ WH	LONG WELD 3P-AW	III	+450	+17,300	—	—	—	—	—	—	RAN 500,000 CYCLES - NO FAILURES
*AE-4, 11½ WH	LONG WELD 3P-AW	III	+500	+20,150	—	—	—	—	—	—	RAN 778,000 CYCLES - NO FAILURES
*DE-3, 16½ WH	LONG WELD 3P-AW	III	-250	+20,050	+350	+20,450	—	I-X	S	BL	RAN 840,000 CYCLES CRACK PROPAGATION "ARRESTED"

TABLE III

SUMMARY OF TEST RESULTS

CONTROL FATIGUE SPECIMENS

SPECIMEN	STRESS RANGE LOWER LIMIT PSI.	STRESS RANGE UPPER LIMIT PSI.	CYCLES TO FAILURE	REMARKS
MB-1	+7,900	+37,900	312,000	FAILED AT DEEP NOTCH FORMED BY FLAME CUTTING
MB-2	+7,000	+37,000	802,000	FAILED AT WORK HARDENED SURFACE "DIMPLE"
MB-3	0	+35,000	—	RAN FOR 304,000 CYCLES NO FAILURES
MB-4	0	+15,000	—	RAN FOR 560,000 CYCLES NO FAILURES

TABLE IV

SUMMARY OF TEST RESULTS

SPECIMENS WITH REINFORCED OPENINGS

SPECIMEN	AVG. STRESS RANGE AT NET CROSS-SECTIONAL AREA AT HOLE LOWER LIMIT PSI	AVG. STRESS RANGE AT NET CROSS-SECTIONAL AREA AT HOLE UPPER LIMIT PSI.	AVG. STRESS RANGE ON FACE OF FAILURE AT NET CROSS-SECTION OF HOLE LOWER LIMIT PSI.	AVG. STRESS RANGE ON FACE OF FAILURE AT NET CROSS-SECTION OF HOLE UPPER LIMIT PSI.	CYCLES TO FAILURE	LOCATION OF FIRST FAILURE
B-1	+450	+26,900	+50	+30,700	10,500	FRONT FACE-UPPER RIGHT HAND CORNER OF RING
B-2	+850	+28,500	-550	+28,900	23,000	FRONT FACE-LOWER RIGHT HAND CORNER OF RING
* B-3	+1,100	+28,200	-600	+27,800	29,000	FRONT FACE-LOWER LEFT & UPPER RIGHT HAND CORNERS
C-1	+450	+26,900	-300	+25,500	11,500	BACK FACE - LOWER LEFT HAND CORNER OF RING

ALL SPECIMENS LISTED IN TABLE II, III, AND IV MADE FROM PROJECT STEEL SR-89

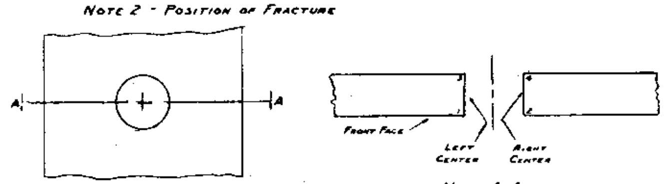
TABLE V
SUMMARY OF TEST RESULTS
PLATES WITH UN-REENFORCED OPENINGS

Specimen	Edge[1] Preparation	Type of Steel	Avg. Stress Range at Net Cross-Section Area at Hole - psi Lower Limit	Upper Limit	Avg. Stress Range on Face of Failure at Net Cross-Sectional Area at Hole - psi Lower Limit	Upper Limit	Cycles to First Fracture	Position of Fracture[2]	Face from Which Burned	Location Fig. No.	Rate of Propagation	Cycles to End of Test	Remarks
FA-1	-1- Hand Cut	Proj[3]	-300	+30300	-1350	+30500	10,500	1 and 2	Back		Intermediate	23900	Crack Started in Small Notch and Spread Along Ripple
-2		Proj	+250	+29700	-1100	+33600	14,500	1	Front		Intermediate	26000	Crack Followed Ripple
* -3		A	+750	+30050	-450	+30100	15,500	1 and 2	Back	9	Fast	27700	Initial Crack Became Arrested As Second Crack (Same Side) Developed
* -4		A	-400	+30700	-600	+31150	12,000	2	Back	10	Fast	19200	Cracks On Both Sides Of Hole Propagated In Erratic Path Crossing Ripples
FB-1	-2- Hand Cut Ground	Proj	+300	+32200	-400	+30350	62,500	3	Front		Intermediate	76600	Crack Followed Ripple
-2		Proj	+800	+29900	+1850	+29050	77,500	4	Front		Slow	115000	Crack Followed Ripple
* -3		A	0	+29950	-550	+30550	54,000	1	Back	11	Intermediate	86700	Crack Did Not Propagate Directly Across Depth Of Plate - See Fig. No.
* -4		A	-200	+30000	+500	+29100	76,000	3	Front	12	Intermediate	100500	One Crack Propagated In Erratic Path Across Depth of Plate
FC-1	-3- Hand Cut Bored	Proj	-1300	+28950	-1275	+28900	91,000	2			Intermediate	120800	
*FD-1	-4- Machine Cut	A	+800	+31650	+1150	+30550	10,500	3	Back	13	Fast	27100	Similar Crack Propagation To FA-4 Initial Crack Started at Deep Notch
* -2		A	-250	+29950	+200	+28400	29,000	Rt. Center	Back	14	Fast	47300	Initial Crack Formed on Inside Surface, Not Edges, Of Hole - On Opposite Side of Hole, 3 Cracks Appeared Simultaneously
* -3		A	0	+30300	0	+30300	21,500	2	Back	15a	Fast	33200	Two Cracks Appeared on Same Side
*FE-1	-5- Machine Cut Ground	A	-100	+30150	-700	+31250	50,500	2	Back	15b	Slow	94650	
*FF-1	-6- Machine Cut Heat Treated	A	+250	+29900	+250	+29900	58,400	Rt. Center	Back	16	Fast	86700	Initial Crack-Similar To FD-2 - On Opposite Side Of Hole, 2 Cracks Appeared Simultaneously
* -2		A	-150	+29600	-400	+29700	51,000	2	Front	17	Intermediate	76650	Similar Crack Propagation To FA-4
*FM-1	-7- Bored No Heat	Proj	-200	+30400	+300	+29200	133,000	3		18a	Slow	171000	
* -2		A	+ 50	+30000	+200	+30450	75,000	1		18b	Intermediate	89000	
* -3		A	-350	+30100	-1100	+30650	41,800	2		19	Slow	68900	
* -4		A	-150	+30200	-550	+30400	84,000	2		20	Slow	106800	Similar Crack Propagation To FB-3

Note 1 - Edge Preparation of Holes
1 - Flame Cut By Hand
2 - Flame Cut By Hand, and Then Ground
3 - Hand Flame Cut To 3" Dia., and Then Machined To $4\frac{1}{4}$" Dia.
4 - Flame Cut By Pantograph Machine
5 - Flame Cut By Pantograph Machine, and Then Ground
6 - Flame Cut By Pantograph Machine, and Then Heat Treated The Edge
7 - Machined - No Heat Input

Note 3 - Special Steel for Project SR-89

Note 2 - Position of Fracture



View A-A

TABLE - VI

SUMMARY OF ALL DETAILS FOR THE FABRICATION AND FINISH OF HOLES

SPECIMEN	FABRICATION OF HOLE: MEANS OF CUTTING HOLE	FABRICATION OF HOLE: APPARATUS	FABRICATION OF HOLE: TIP SIZE	FABRICATION OF HOLE: ACET. PRESS. PSI.	FABRICATION OF HOLE: OXY. PRESS. PSI.	FABRICATION OF HOLE: PREHEAT OXY. PRESS. PSI.	FACE FROM WHICH BURNED	PREHEAT TIME[1]	CUTTING TIME[2]	INITIAL GRINDING: EQUIPMENT	INITIAL GRINDING: TYPE OF WHEEL	FINAL GRINDING: EQUIPMENT	FINAL GRINDING: TYPE OF WHEEL	REMARKS SEE TEXT FOR FURTHER DETAILS
FA-1	TORCH CUT MANUAL	AIRCO COMBINATION STYLE #9900	1	3	35		BACK							RIPPLES CREATED BY FLAME CUTTING ARE VERY IRREGULAR
-2	"	"	3	3	35		FRONT							"
-3	"	"	3	4	40		BACK	1-MIN. 45-SEC.	2-MIN. 2-SEC.					"
-4	"	"	3	4	35		"	50-SEC.	2-MIN. 20-SEC.					"
FB-1	"	"	1	4	35		FRONT			HAND GRINDER BLACK & DECKER 5" DIA	NORTON A16 P4 B5	MANUAL ARO - GRINDER (AIR)	NORTON A36-QB	GRINDING PRODUCED A SMOOTH SURFACE. HONED EDGES TO REMOVE BURRS.
-2	"	PRESTO-WELD C-101	2	4	40		"			"	"	"	"	"
-3	"	AIRCO COMBINATION STYLE #9900	3	4	40		BACK	1-MIN. 22-SEC.	1-MIN. 24-SEC.	"	"	MANUAL KIPP-MADISON MODEL-VT (AIR)	KIPP-MADISON TYPE "HASN"	"
-4	"	"	3	4	40		FRONT	1-MIN. 28-SEC.	1-MIN. 17-SEC.	"	"	"	"	"
FE-1	TORCH CUT AUTOMATIC	AIRCO PLANOGRAPH #10	AIRCO 124 #2	4	40	20	BACK	1-MIN. 15-SEC.	58-SEC.	"	"	"	"	"
FC-1	TORCH CUT MANUAL TO 3¼" DIA.	AIRCO COMBINATION STYLE #9900	1	3	35									
	BORED TO 4¼" DIA.	VERTICAL BORING MILL												VERY SMOOTH FINISH. EDGES HONED TO REMOVE BURRS.
FD-1	TORCH CUT AUTOMATIC	AIRCO PLANOGRAPH #10	AIRCO 124 #2	4	40	20	BACK	1-MIN. 15-SEC.	56-SEC.					THESE RIPPLES (MACHINE FLAME CUT) ARE SMALL AND REGULAR AS COMPARED TO THOSE IN GROUP FA
-2	"	"	"	4	40	20	"	1-MIN. 15-SEC.	56-SEC.					"
-3	"	"	"	4	40	20	"	1-MIN. 15-SEC.	58-SEC.					"
FF-1	"	"	"	3	40	30	BACK	35-SEC.	40-SEC.					
-2	"	"	"	3	40	30	FRONT	1-MIN. 15-SEC.	55-SEC.					

HEAT TREATMENT OF HOLE

SPECIMEN	APPARATUS	TIP	ACET. PRESS. PSI.	OXY. PRESS. PSI.	INITIAL HEAT TIME[3]	SWEEP HOLE TIME[4]	REMARKS
FF-1	AIRCO RADIAGRAPH #10	HEATNG TORCH 9802 MIXER 0913 TIP 1033 AIRCO	11	15	15-SEC.	2-MIN. 15-SEC.	RIPPLES SIMILAR TO FD GROUP. HEAT TREATMENT DID NOT DESTROY RIPPLES' SURFACE GEOMETRY
-2	"		11	15	20-SEC.	2-MIN. 15-SEC.	"

SPECIMEN	MEANS OF CUTTING HOLE	APPARATUS
FM-1	BORED	VERTICAL BORING MILL
-2	"	"
-3	"	"
-4	"	"

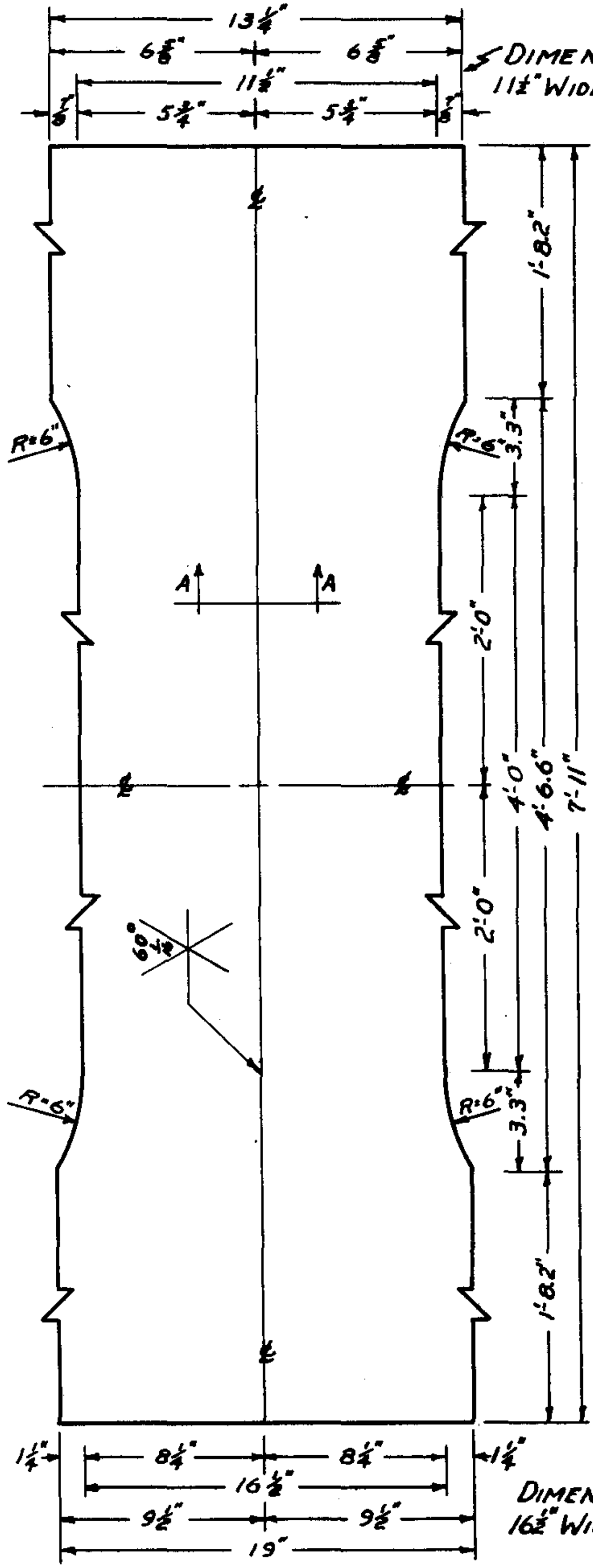
SURFACE FINISH OF THE HOLES WERE VERY SMOOTH. THE EDGES WERE HONED TO REMOVE THE BURRS. SEE TEXT.

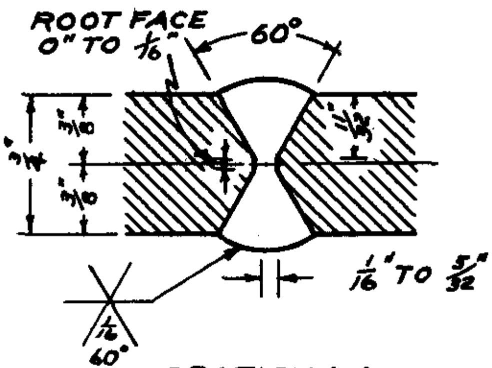
1- PREHEAT TIME
  a. SPECIMENS FA AND FB - TIME TO BURN A HOLE THROUGH THE CENTER OF PLATE AND TO MAKE A CUT TO THE EDGE OF THE HOLE IN THE LONGITUDINAL DIRECTION (EXCEPTION FA-1 - CUT TAKEN TO EDGE OF HOLE IN TRANSVERSE DIRECTION.
  b. SPECIMENS FD, FE, FF - TIME TO START CUT AT 7/16" DIA. HOLE AT CENTER OF 4¼" DIA. HOLE AND TO MAKE CUT TO EDGE OF HOLE IN LONGITUDINAL DIRECTION.

2- CUTTING TIME - TIME TO CUT THE HOLE ITSELF.
  a. SPECIMENS FA, FB, FC - DONE IN TWO OPERATIONS, ONE CUT ON EACH SIDE OF THE HOLE.
  b. SPECIMENS FD, FE, FF - ENTIRE HOLE DONE IN ONE OPERATION.

3- INITIAL HEAT TIME - TIME TO OBTAIN CHERRY RED HEAT OF LOCAL METAL. ONCE ACHIEVED, RADIAGRAPH OPERATED.

4- SWEEP HOLE TIME - TIME REQUIRED TO ROTATE THE TORCH OVER THE ENTIRE HOLE FOR THE HEAT TREATMENT.





SECTION A-A

a- SPECIMENS HAVE 1, 2, OR 3 WELD PASSES ON EACH SIDE

b- CERTAIN SPECIMENS HAVE WELDS GROUND FLUSH WITH PLATES

GROUPS TESTED

1-	GROUP	AA	-11½WH,	2P-AW,	PROJ. STEEL
2-	"	AB	"	2P-G	"
3-	"	AC	"	1P-AW	"
4-	"	AD	"	1P-G	"
5-	"	AE	"	3P-AW	"
6-	"	EE	"	3P-AW	TYPE-A-STEEL
7-	"	DE	"	3P-AW	PROJ. STEEL

SYMBOLS
- WH - WIDTH OF SPECIMENS IN INCHES
- P - NUMBER OF PASSES ON EACH SIDE
- AW - WELD SURFACE IN THE AS-WELDED CONDITION
- G - WELD SURFACES GROUND SMOOTH AND FLUSH WITH SURFACES OF SPECIMEN

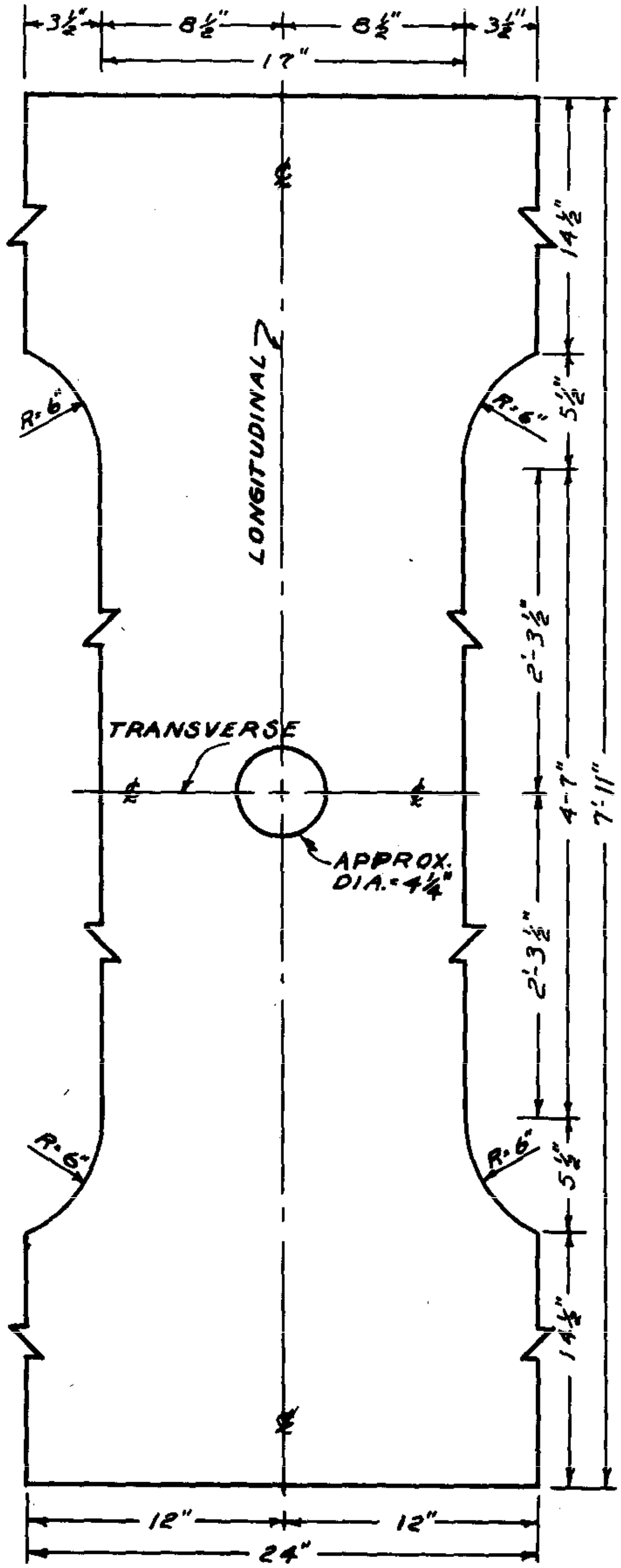
WELDING SPECIFICATION
ELECTRODES - E 6010
a- 1, 2, OR 3 WELD PASSES
ROOT PASS - 5/32" ϕ
OTHER PASSES 3/16" ϕ
b- 1 PASS - ¼" ϕ

BEVELED EDGES AND NECKED PORTION OF SPECIMENS WERE FLAME CUT BY MACHINE

ALL SPECIMENS ¾" THICK

LONGITUDINAL WELD SPECIMENS
11½" AND 16½" WIDTH
FATIGUE TESTS OF SHIP WELDS

FIGURE 1



PREPARATION OF HOLES

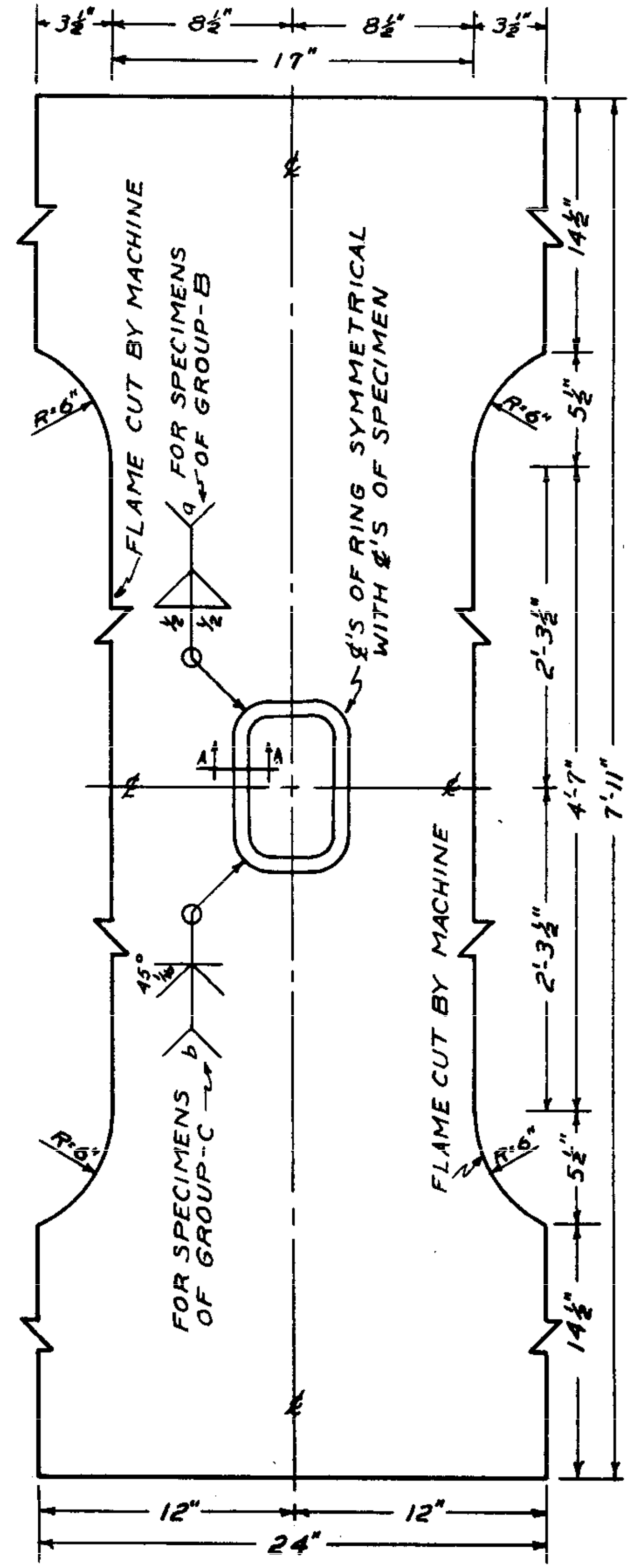
1- GROUP FA
FLAME CUT BY HAND
2- GROUP FB
FLAME CUT BY HAND, AND THEN GROUND
3- GROUP FC
HAND FLAME CUT TO 3" DIA AND THEN MACHINED TO 4¼" DIA.
4- GROUP FD
FLAME CUT BY PANTOGRAPH MACHINE
5- GROUP FE
FLAME CUT BY PANTOGRAPH MACHINE, AND THEN GROUND
6- GROUP FF
FLAME CUT BY PANTOGRAPH MACHINE, AND THEN HEAT TREATED THE INSIDE SURFACE OF THE HOLE
7 GROUP FM
MACHINED - NO HEAT INPUT

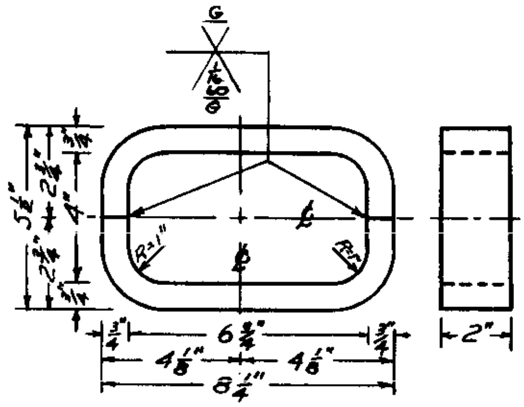
NECKED PORTION OF SPECIMEN FLAME CUT BY MACHINE

ALL SPECIMENS MADE FROM ¾" THICK PLATES

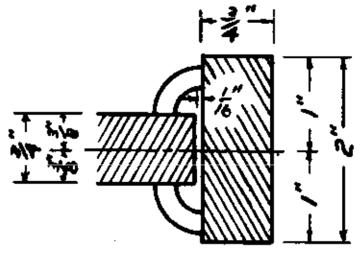
SERIES F
SPECIMENS WITH UN-REINFORCED HOLES
FATIGUE TESTS OF SHIP WELDS

FIGURE 2

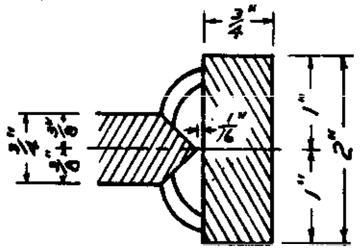




-RING FOR REINFORCED HOLE-
EACH HALF OF BAR HEATED
AND BENT TO RADIUS SHOWN



SECTION A-A
GROUP-B



SECTION A-A
GROUP-C

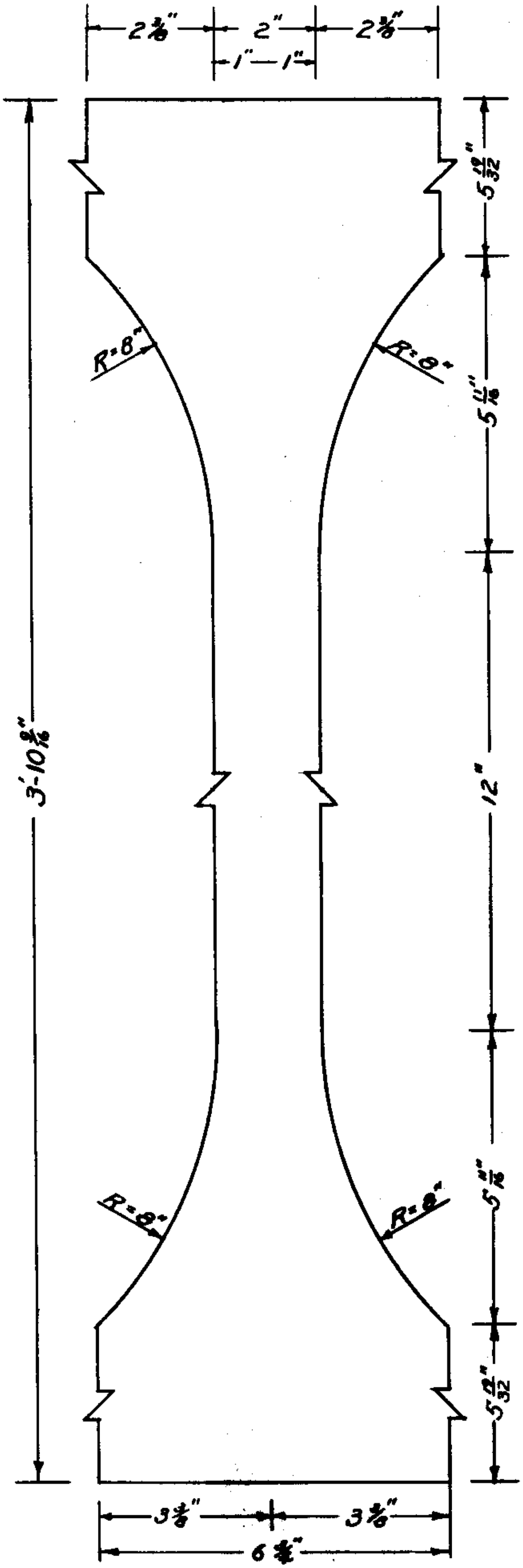
HOLES IN PLATES WERE
MANUALLY FLAME CUT

ALL SPECIMENS ¾" THICK

WELDING SPECIFICATION REFERENCE
ALL ELECTRODES - E6010
a- ROOT PASS 5/32" φ
2ND PASS 3/16" φ
b- ROOT PASS 5/32" φ
2ND PASS 3/16" φ

SPECIMENS WITH REINFORCED HOLES
GROUPS B AND C
FATIGUE TESTS OF SHIP WELDS

FIGURE 3



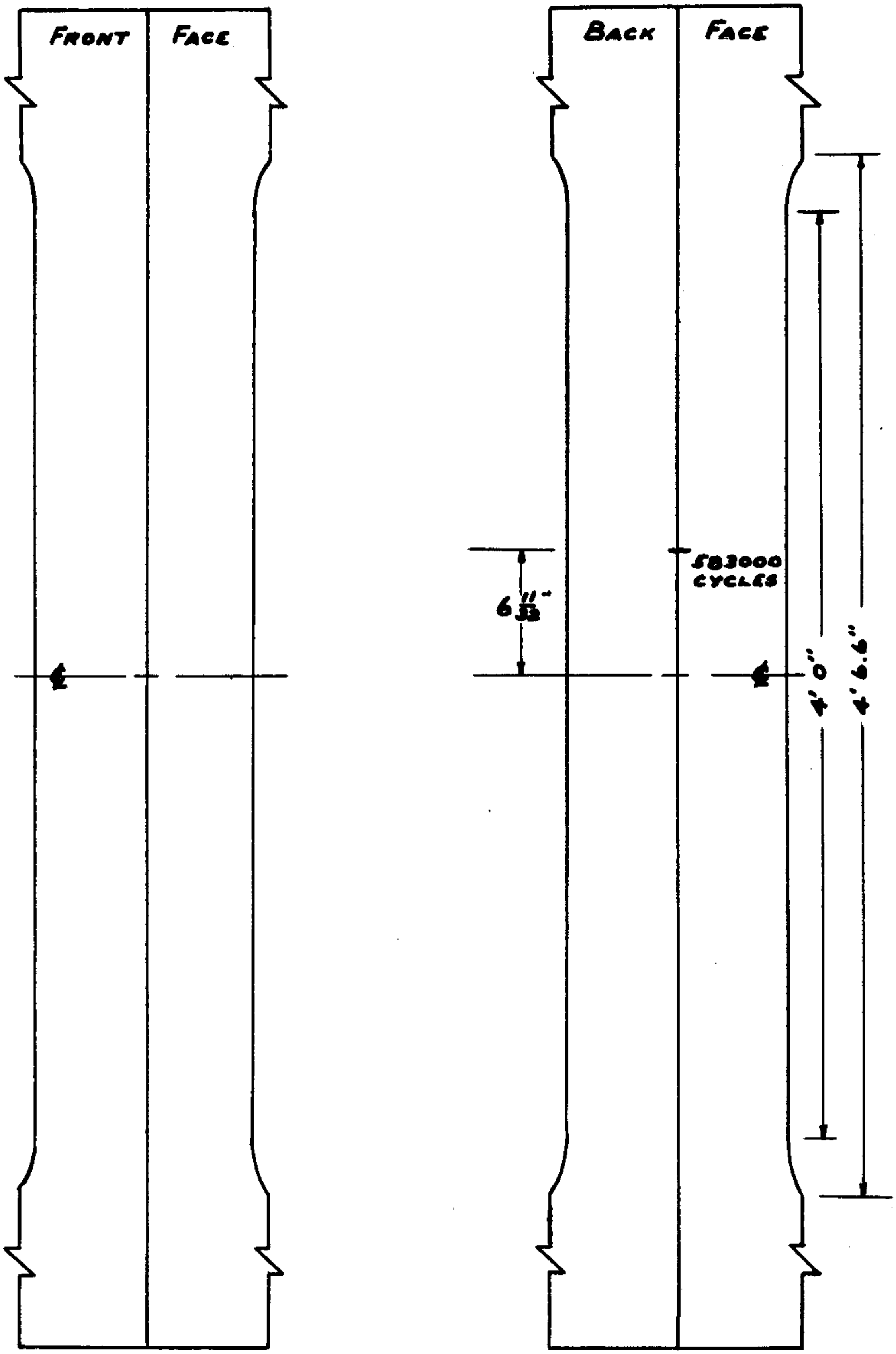
NECKED PORTION OF SPECIMEN FLAME CUT BY MACHINE

ALL SPECIMENS MADE FROM 3/4" THICK PLATES

SPECIMENS FOR GROUP MB

FATIGUE
CONTROL SPECIMENS
FATIGUE TESTS OF SHIP WELDS

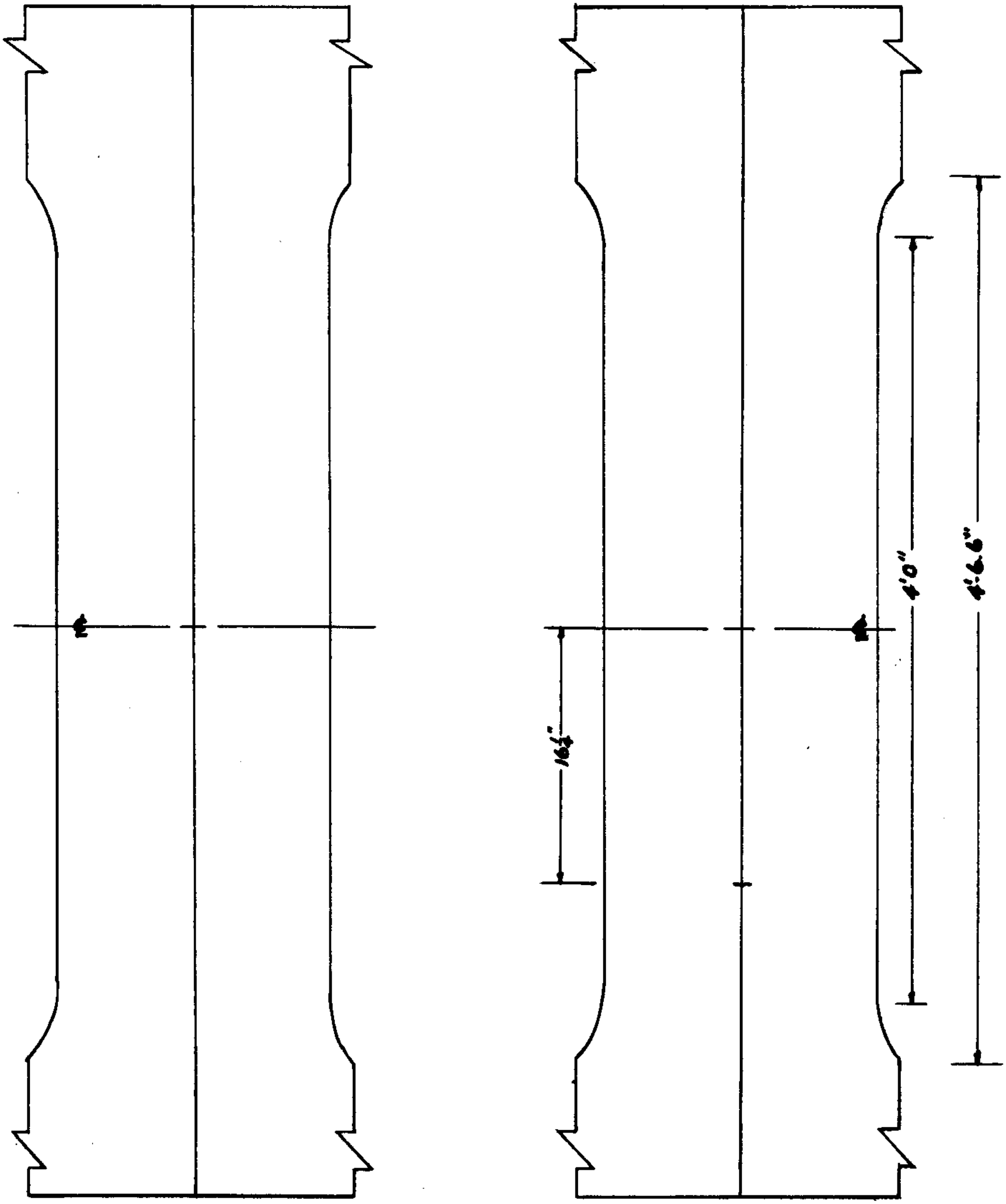
FIGURE 4



SPECIMEN AA-6

LOCATION OF FATIGUE FAILURES

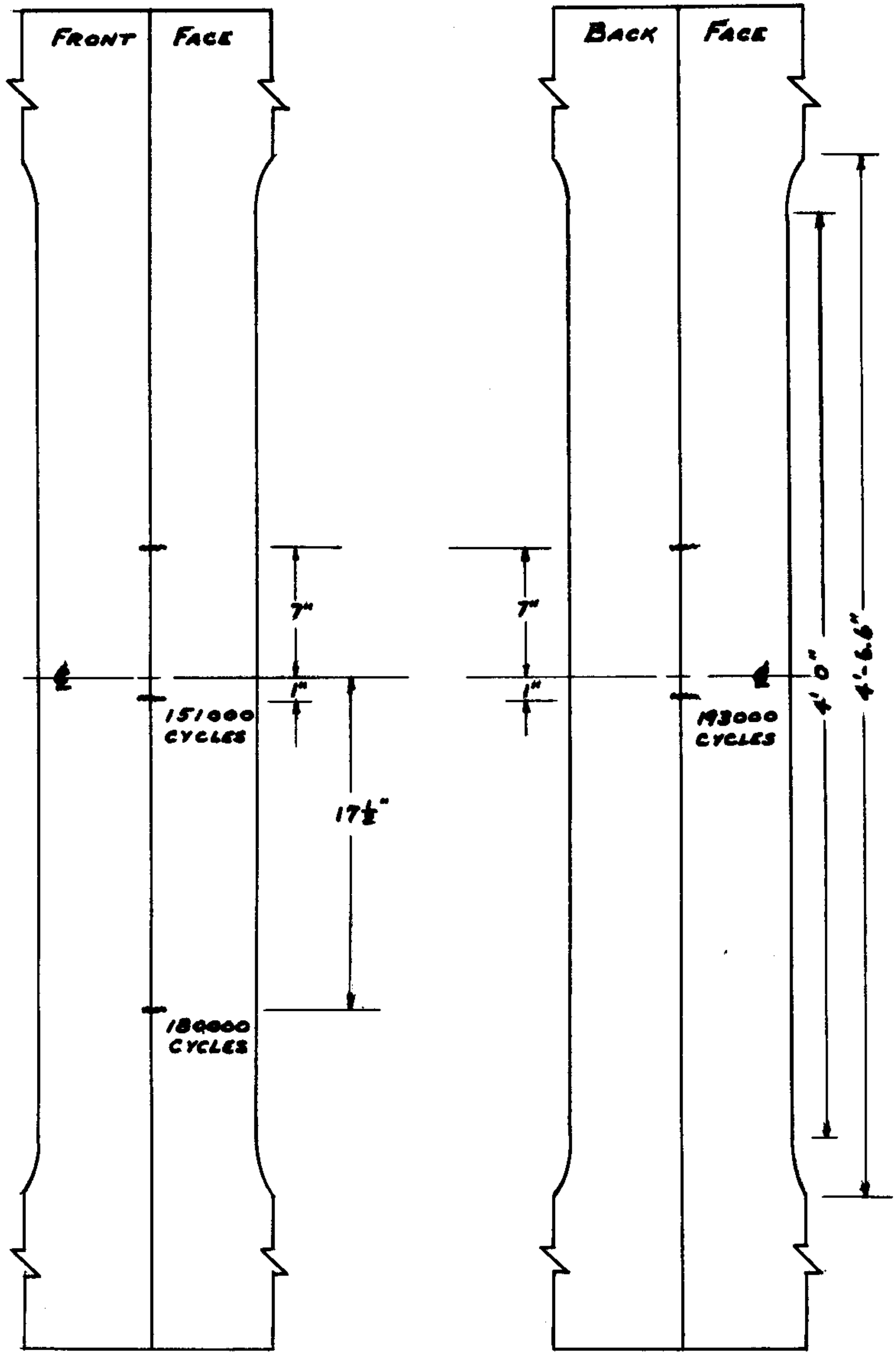
FIGURE 5



Specimen DE-3

Figure 6

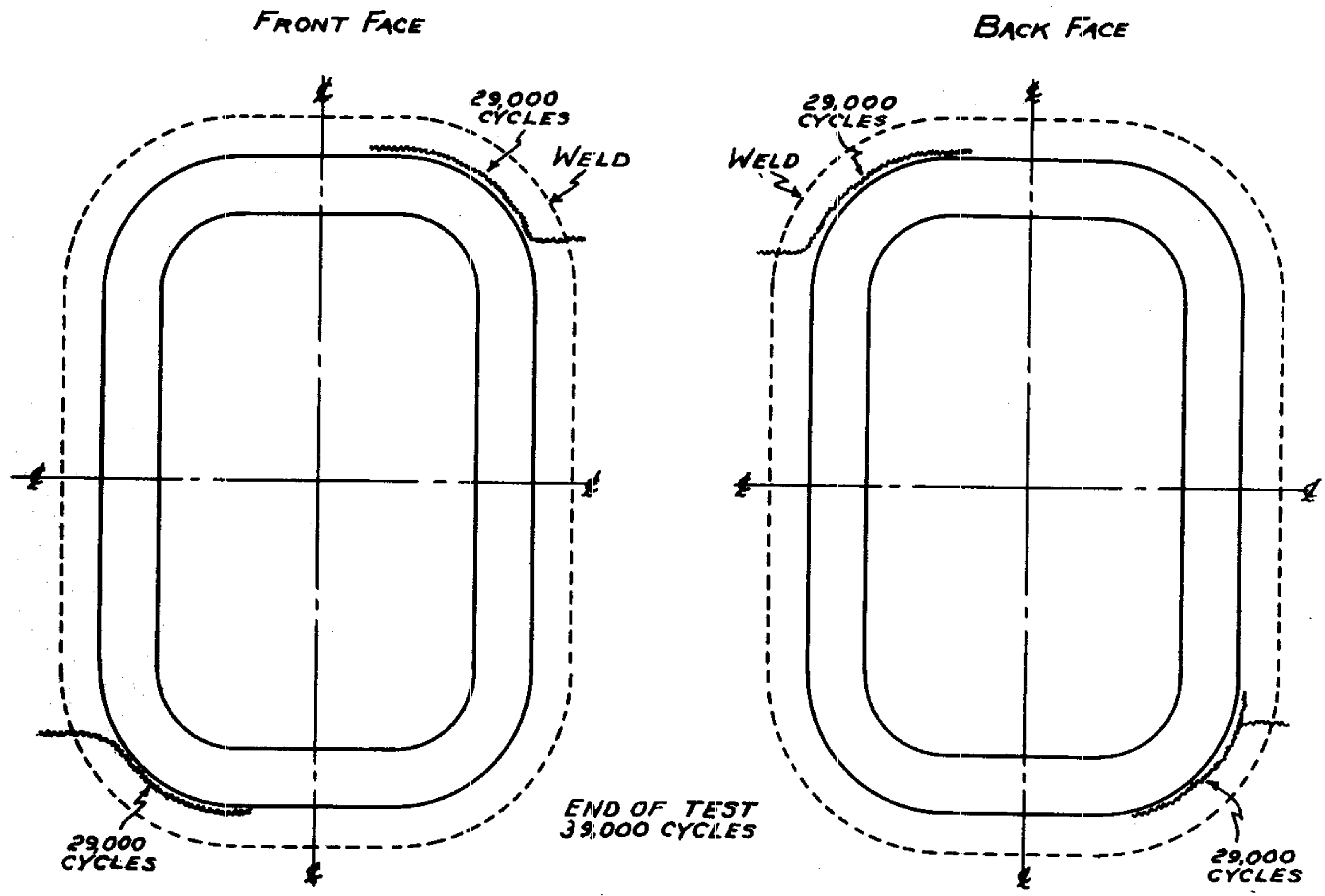
Location of Fatigue Failures



SPECIMEN EE-3

LOCATION OF FATIGUE FAILURES

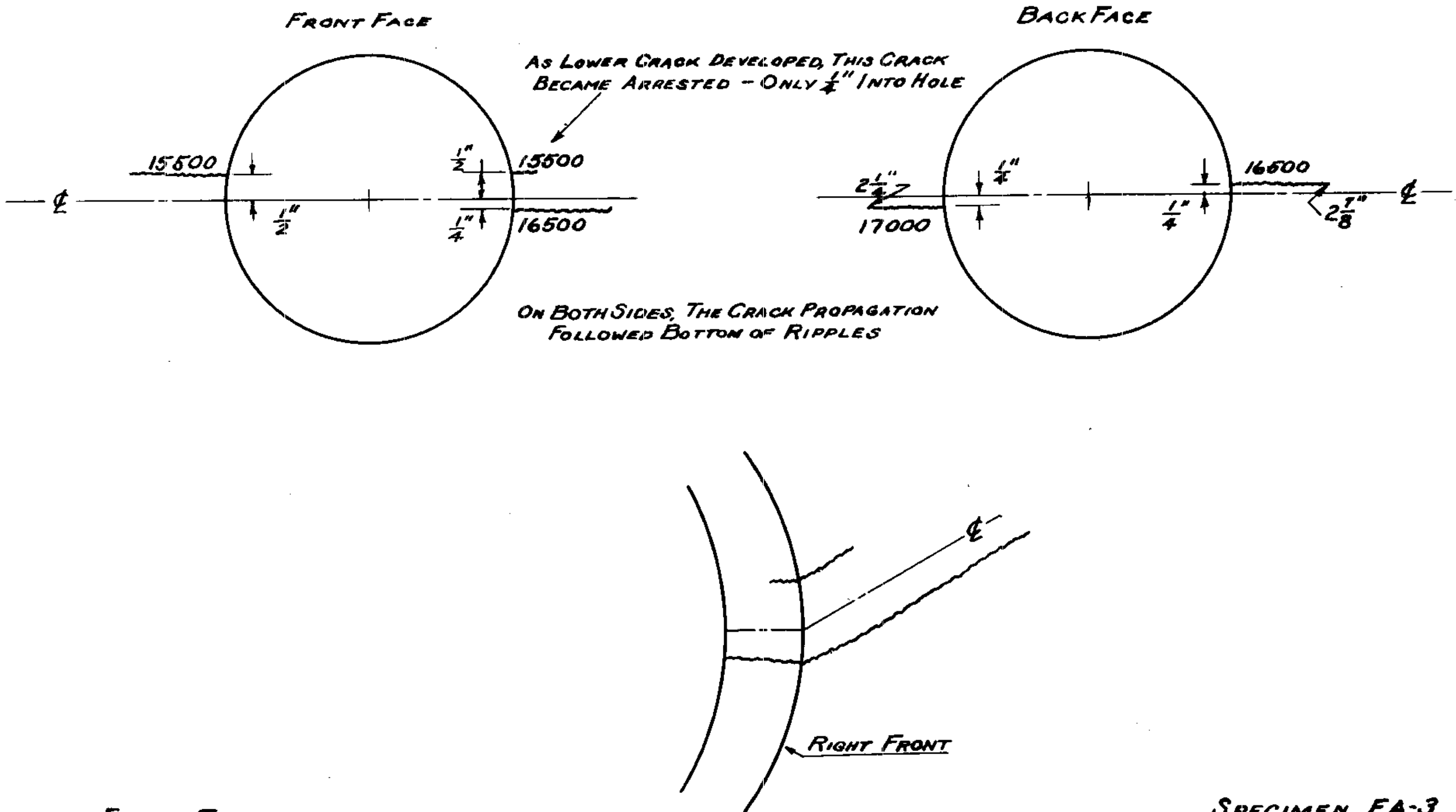
FIGURE 7



LOCATION OF FATIGUE FAILURES

SPECIMEN B-3

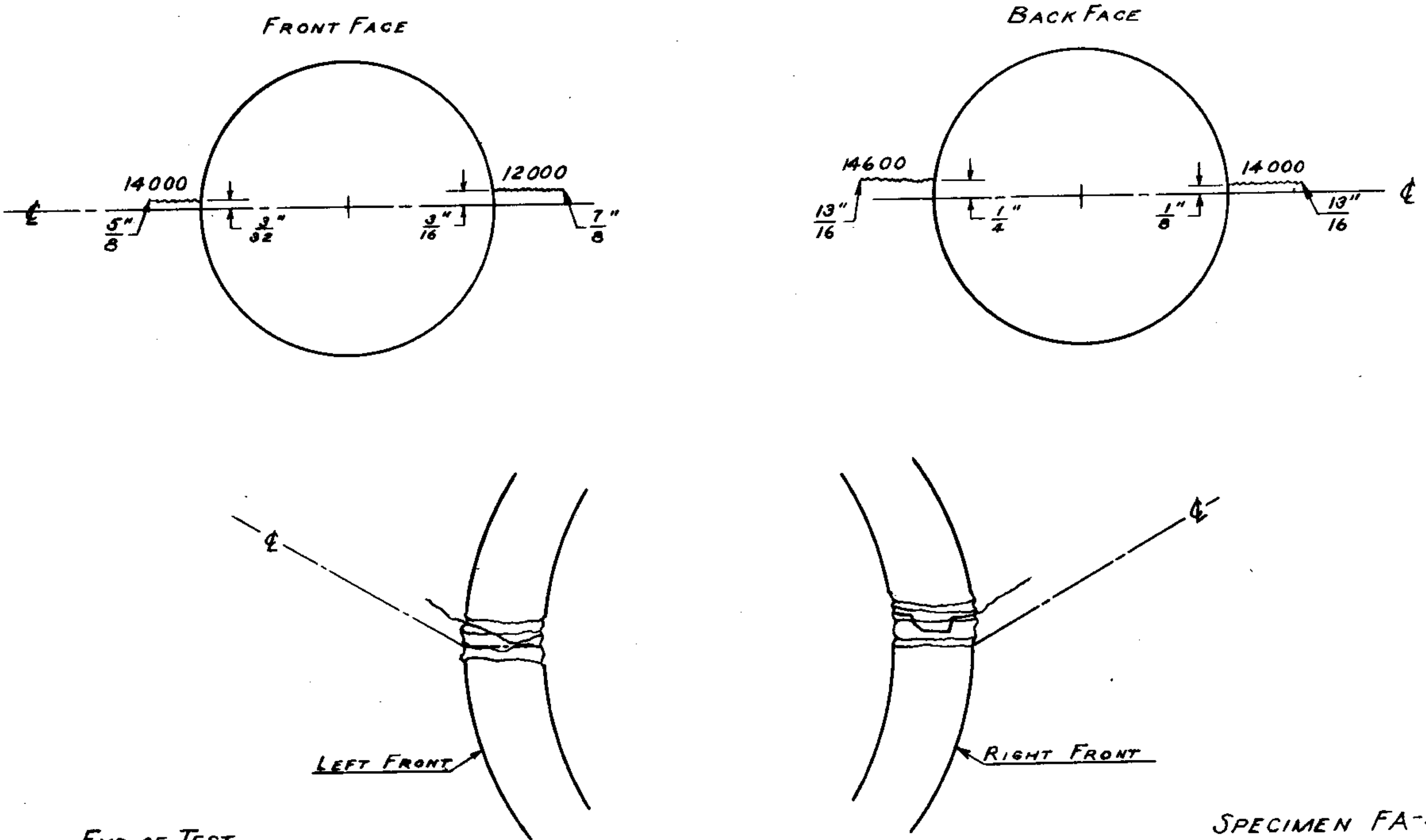
FIGURE 8



END OF TEST -
27700 CYCLES

SPECIMEN FA-3
FIGURE 9

LOCATION OF FATIGUE FAILURES



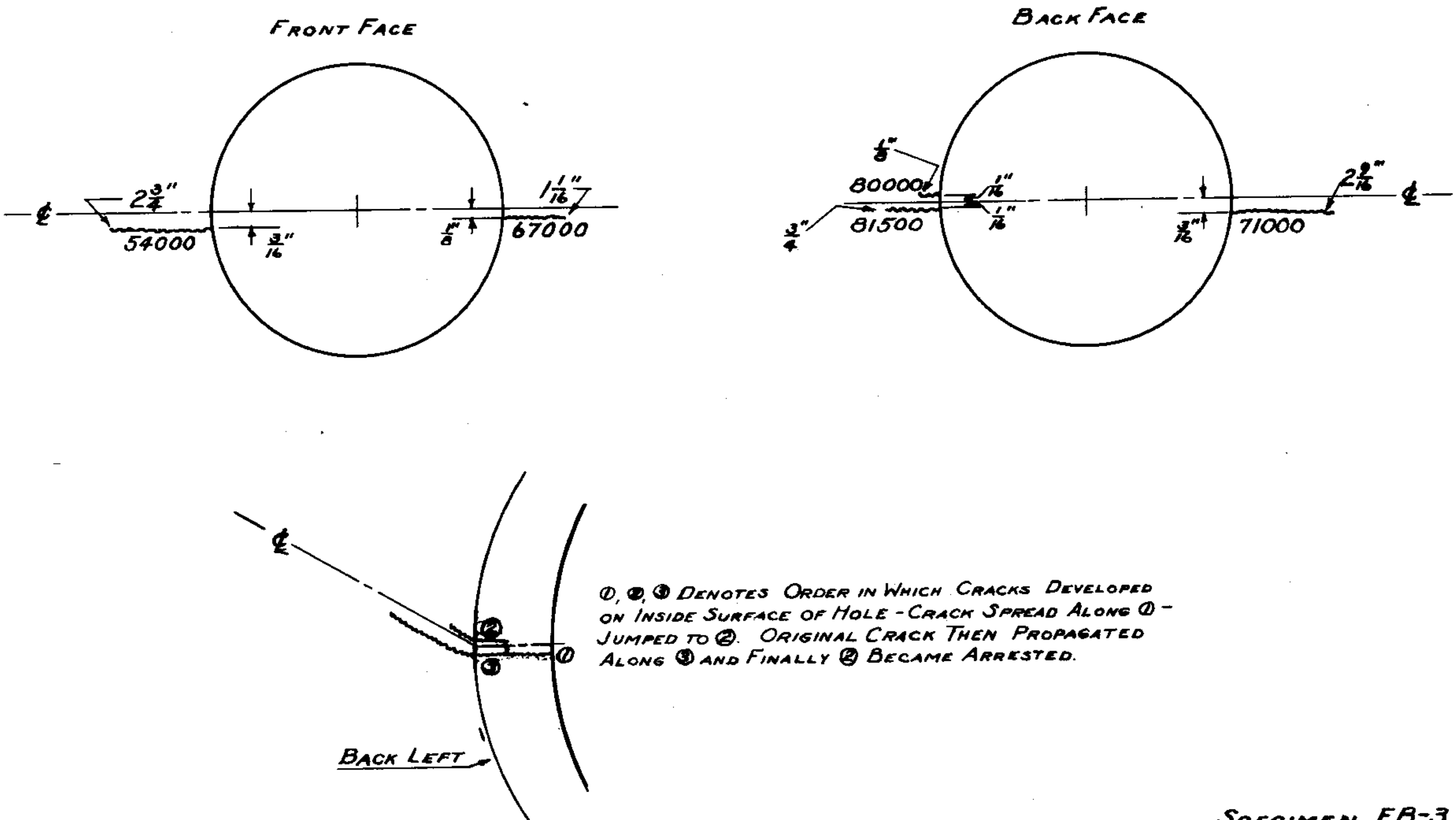
END OF TEST

19200 CYCLES

SPECIMEN FA-4

FIGURE 10

LOCATION OF FATIGUE FAILURES



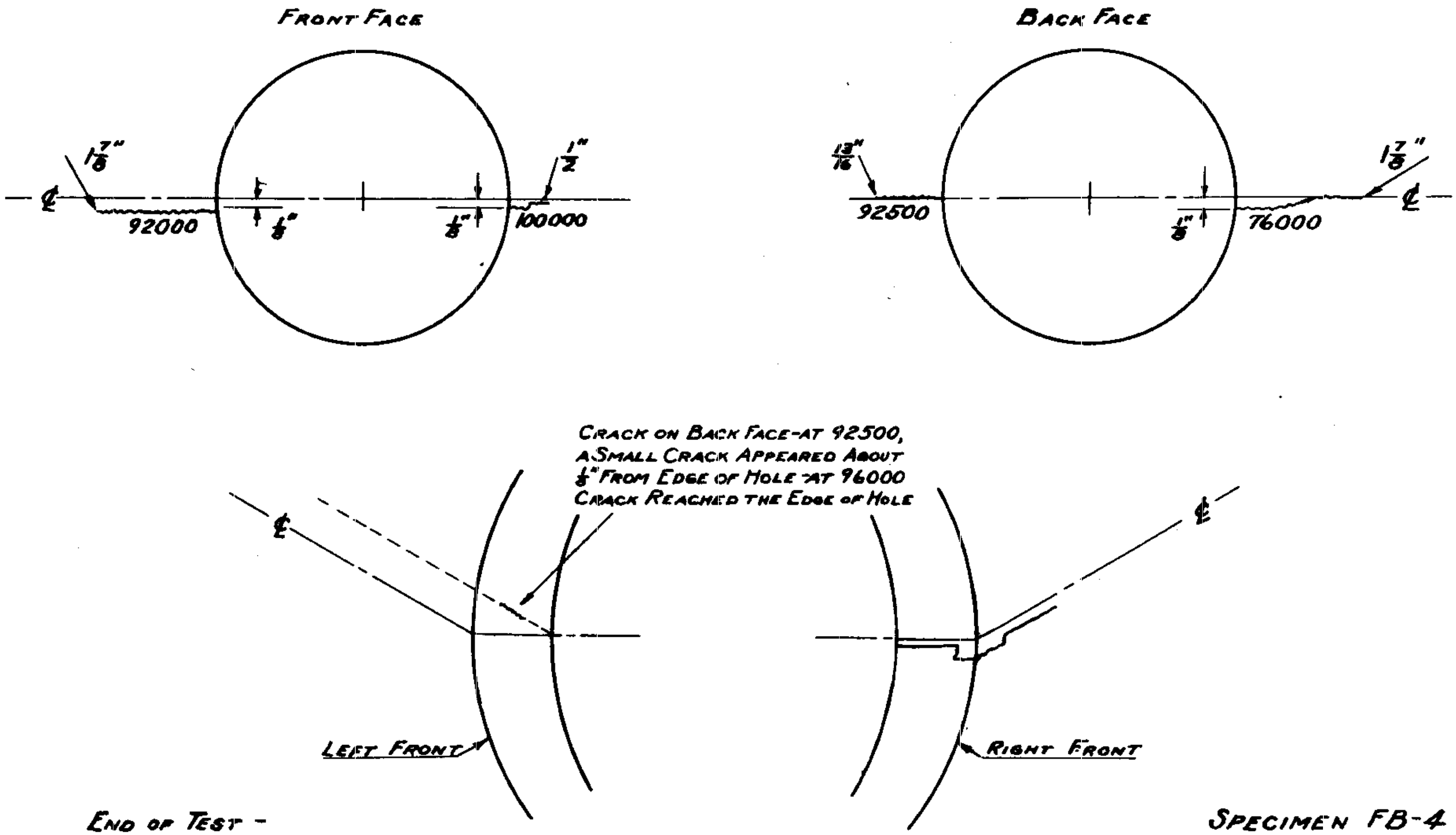
END OF TEST -

86700 CYCLES

SPECIMEN FB-3

FIGURE 11

LOCATION OF FATIGUE FAILURES

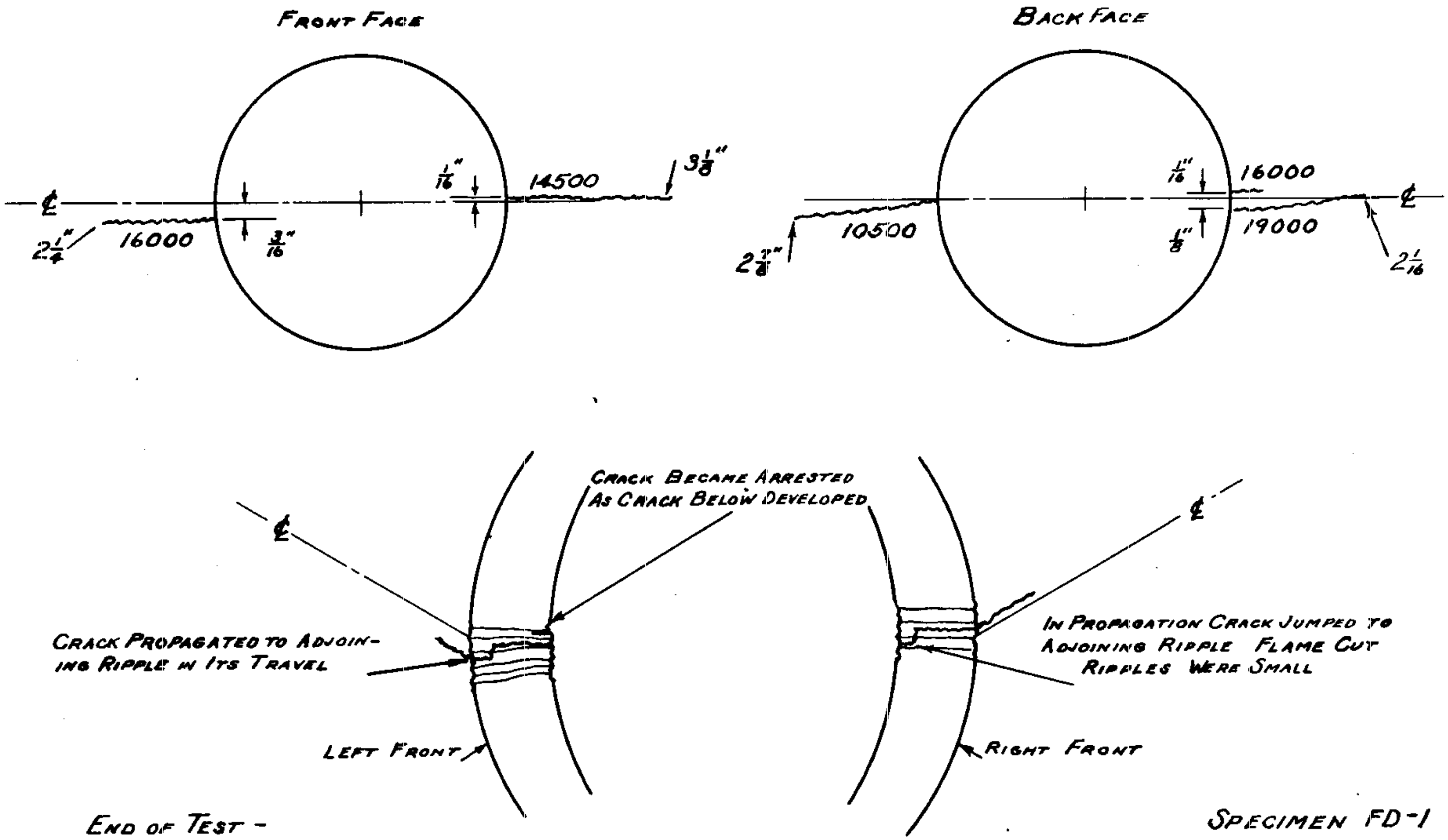


END OF TEST -
100500 CYCLES

SPECIMEN FB-4

FIGURE 12

LOCATION OF FATIGUE FAILURES

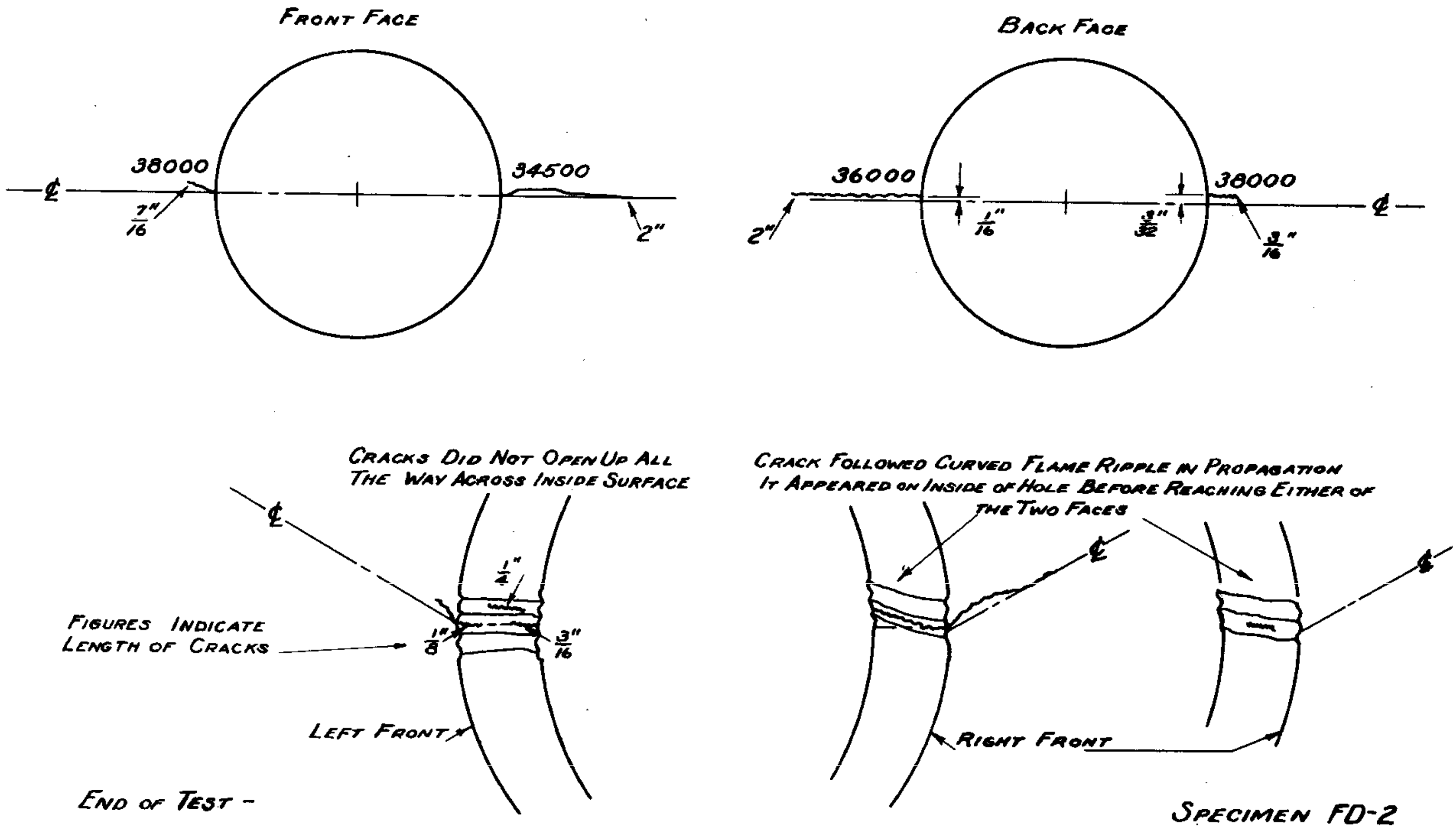


END OF TEST - 27100 CYCLES

SPECIMEN FD-1

FIGURE 13

LOCATION OF FATIGUE FAILURES

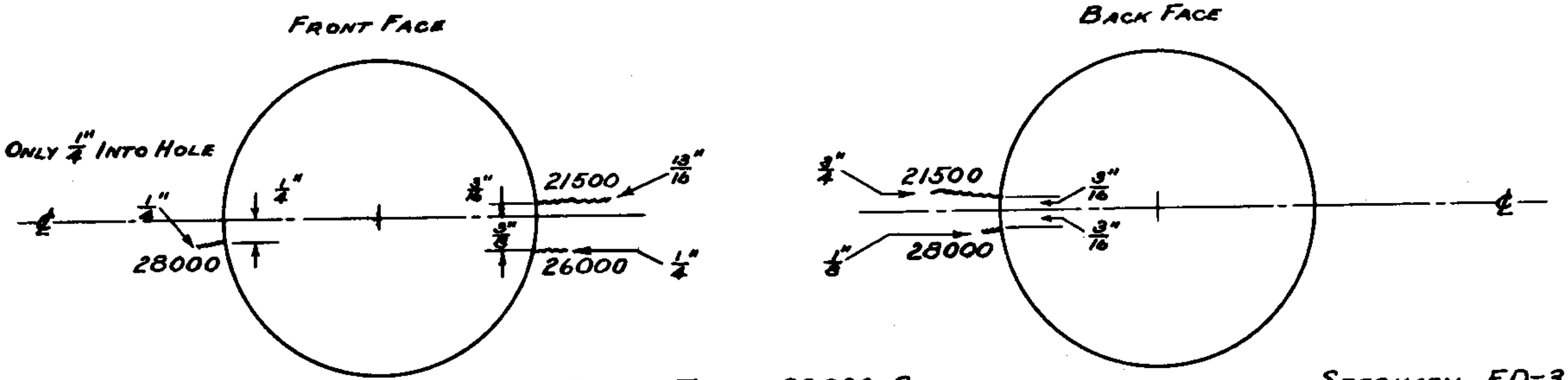


End of Test -
47300 Cycles

Specimen FD-2

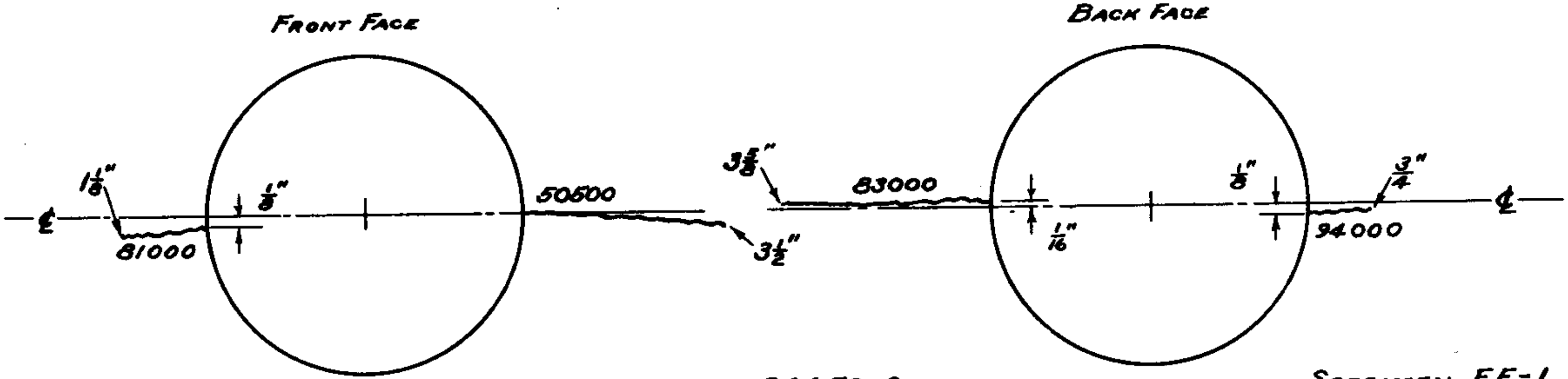
Figure 14

Location of Fatigue Failures



END OF TEST - 33200 CYCLES

SPECIMEN FD-3
FIGURE 16a

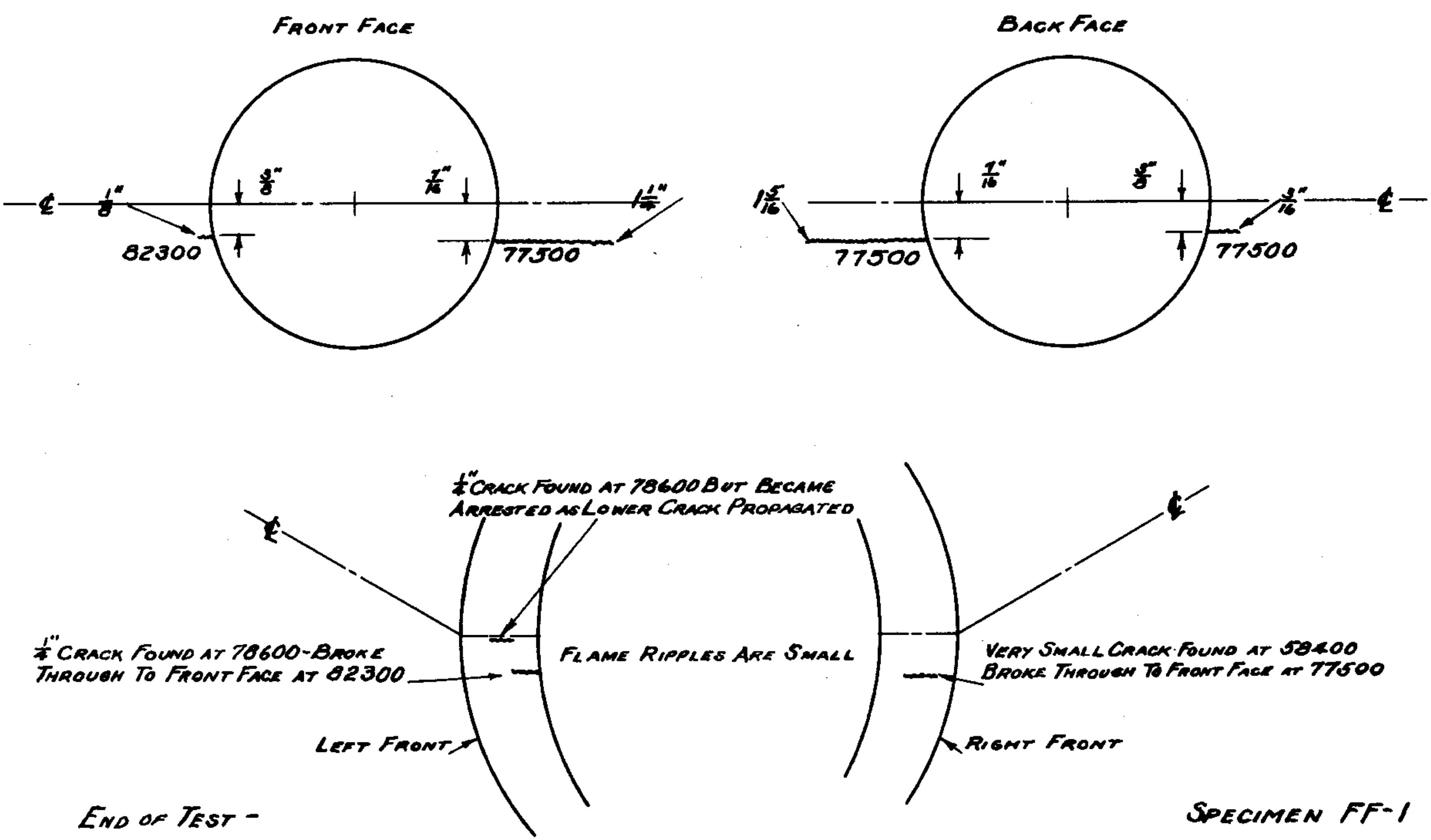


END OF TEST - 94650 CYCLES

SPECIMEN FE-1

FIGURE 15b

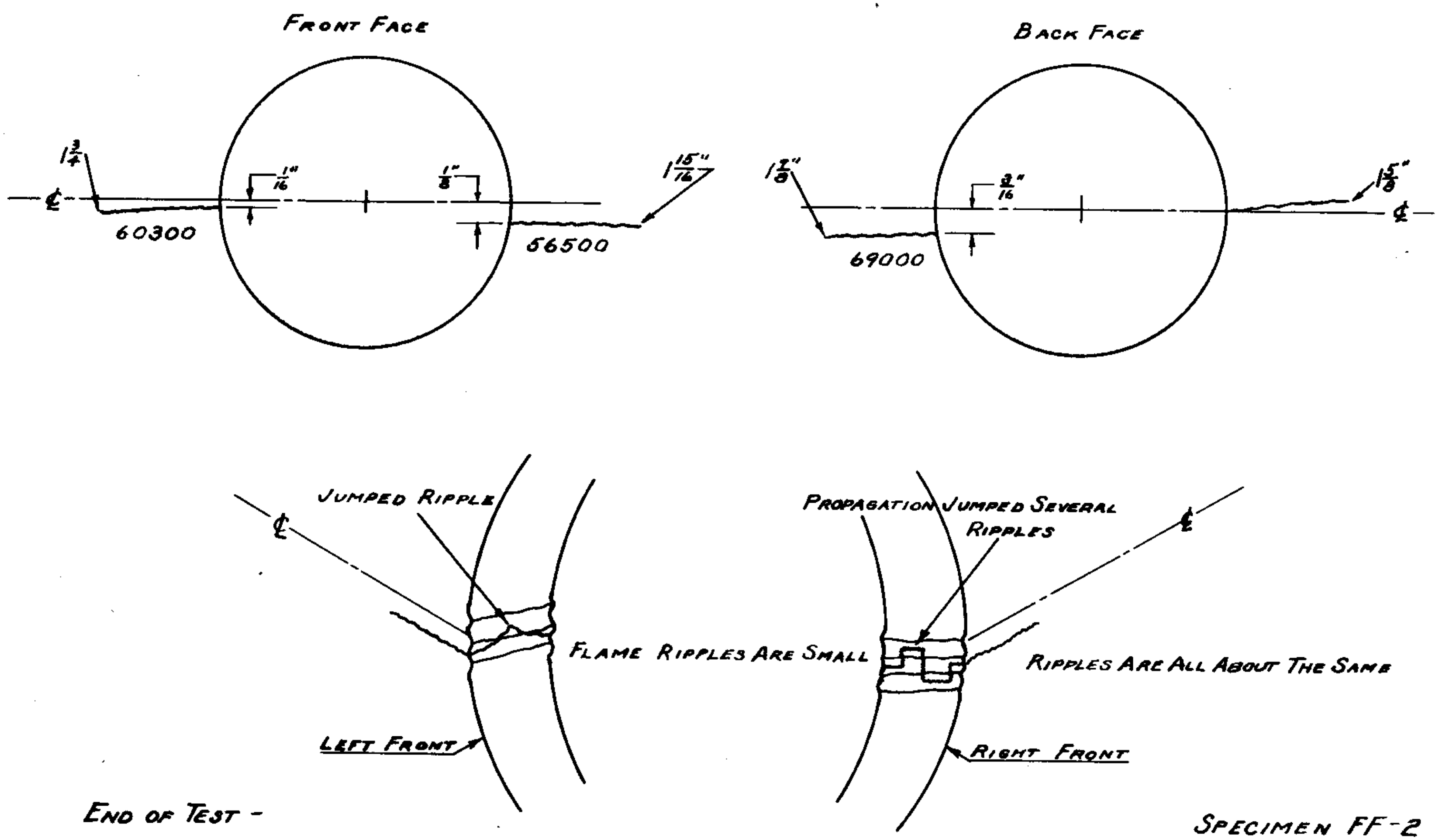
LOCATION OF FATIGUE FAILURES



END OF TEST -
86700 CYCLES

SPECIMEN FF-1
FIGURE 16

LOCATION OF FATIGUE FAILURES

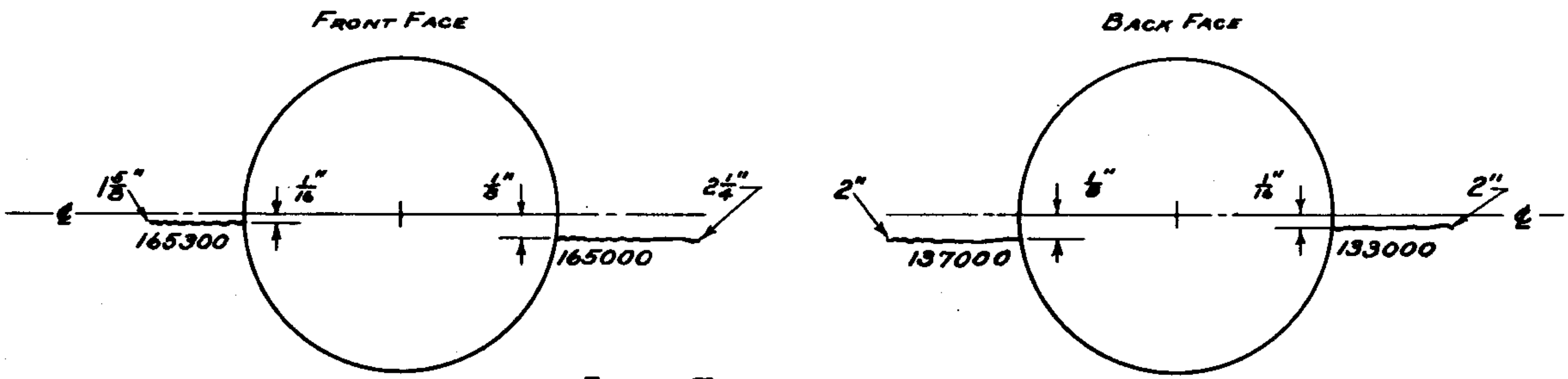


End of Test -
76650 Cycles

Specimen FF-2

Figure 17

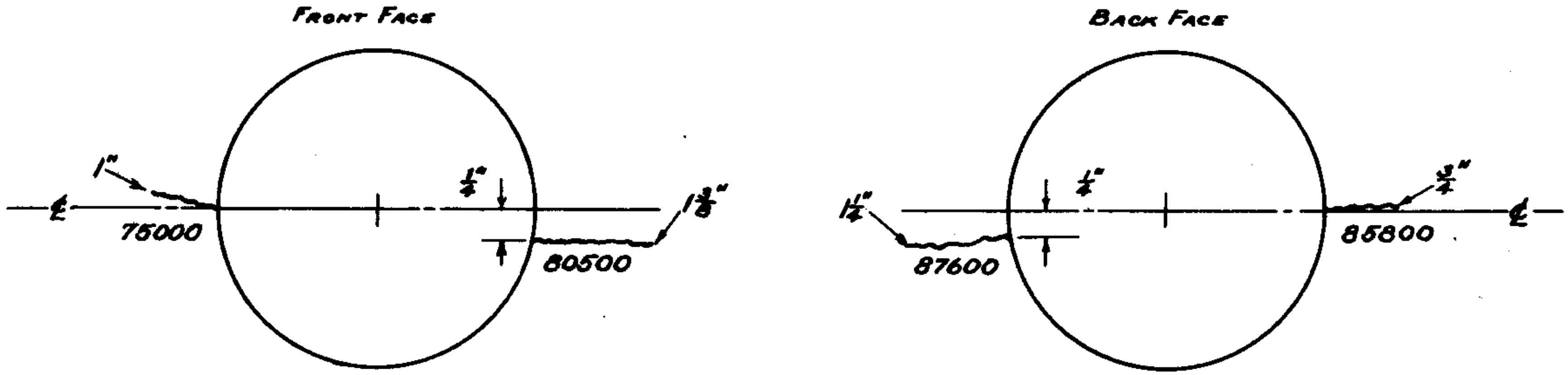
Location of Fatigue Failures



END OF TEST - 171,000 CYCLES

SPECIMEN FM-1

FIGURE 18a

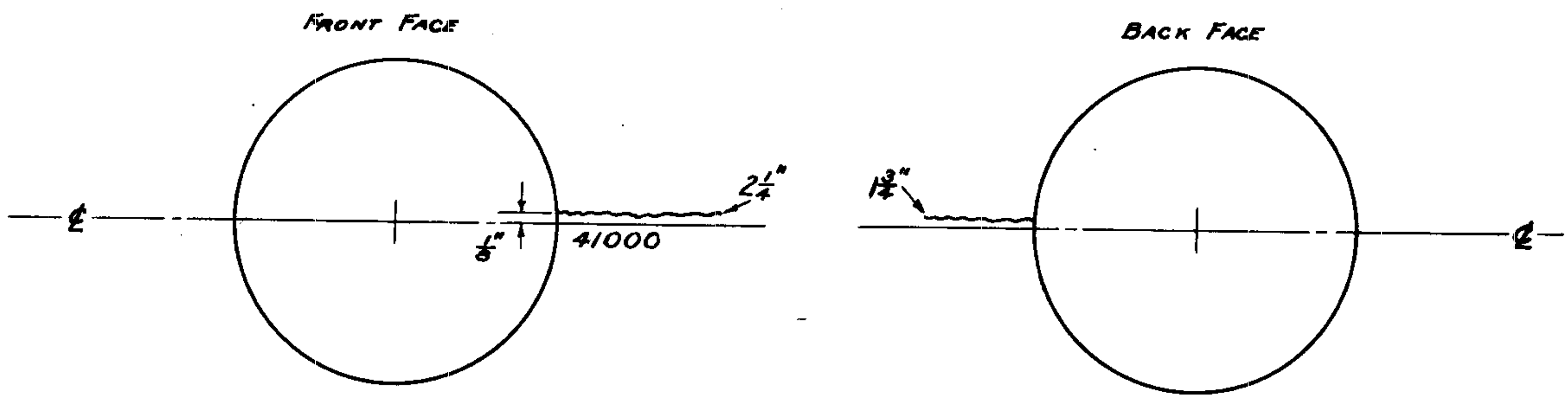


END OF TEST - 89000 CYCLES

SPECIMEN FM-2

LOCATION OF FATIGUE FAILURES

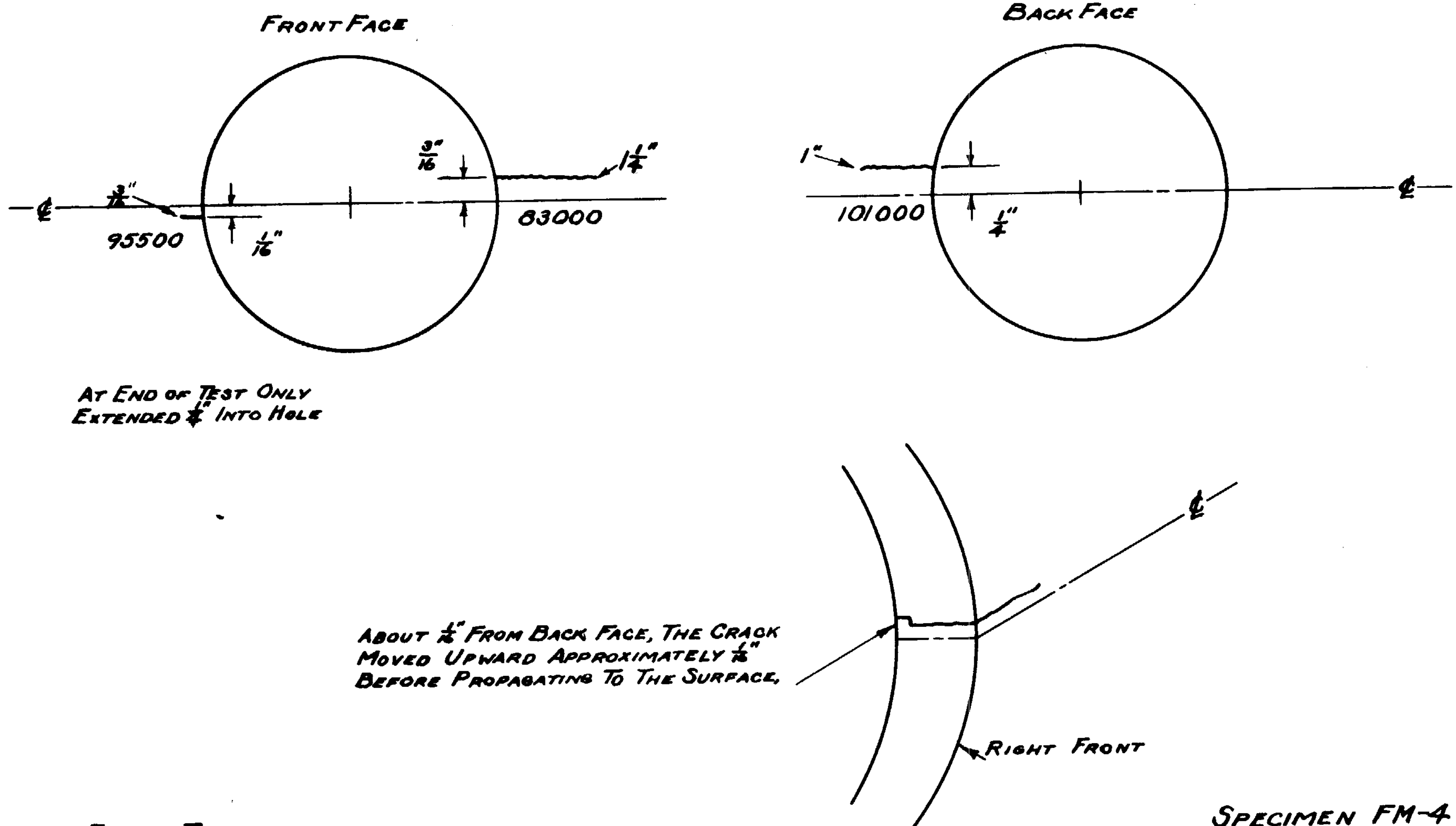
FIGURE 18b



END OF TEST -
68900 CYCLES

LOCATION OF FATIGUE FAILURES

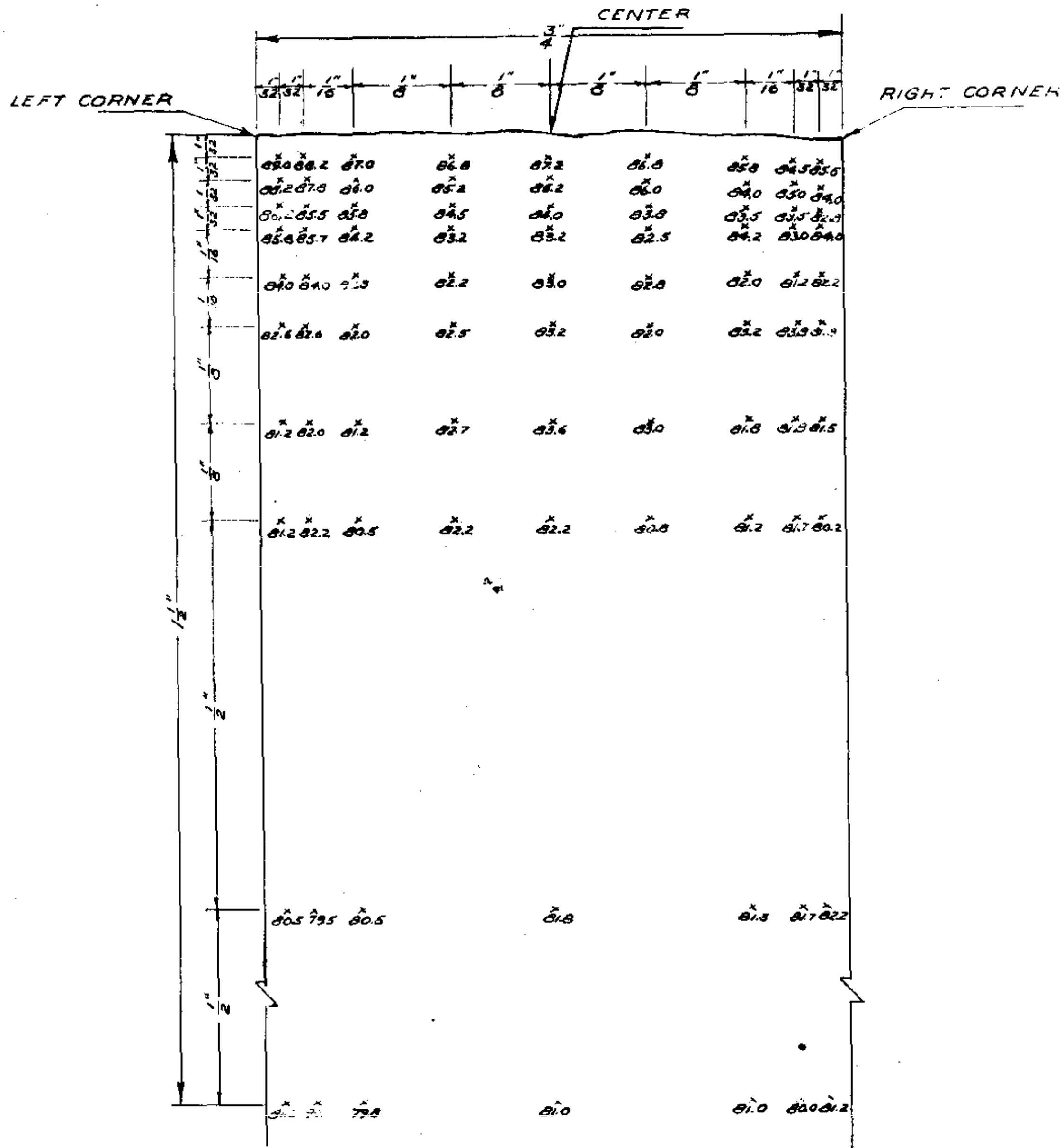
SPECIMEN FM-3
FIGURE 19



SPECIMEN FM-4

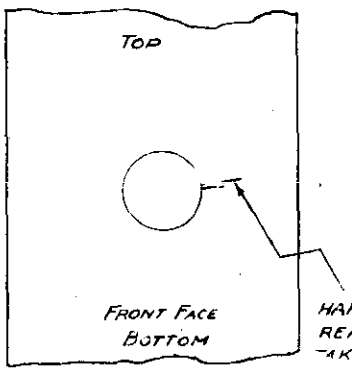
FIGURE 20

LOCATION OF FATIGUE FAILURES



SECTION FROM SPECIMEN FD-3

ALL READINGS ARE ROCKWELL SUPERFICIAL "15T" VALUES



SPECIMEN FD-3

HARDNESS READINGS TAKEN ON SECTION IMMEADIATELY ADJACENT TO FATIGUE FRACTURE

CONVERSION TO B.H.N.

15 T	BHN (3000)Kg.
89.0	172
88.0	162
87.0	155
86.0	144
85.0	137
84.0	130
83.0	121
82.0	117
81.0	112
80.0	107

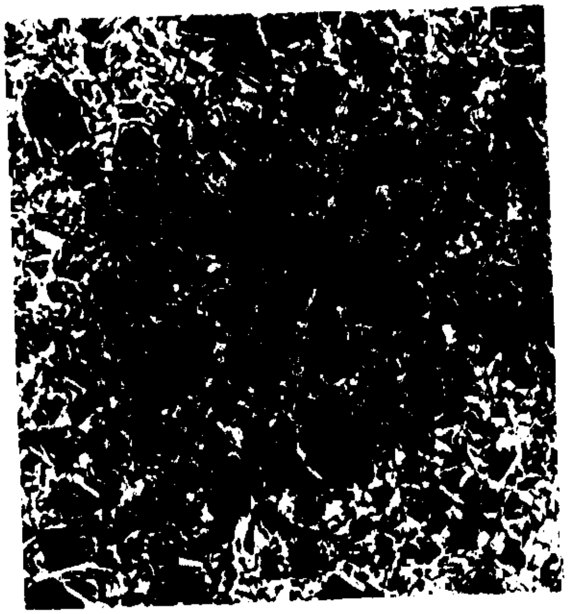
HARDNESS SURVEY
NEAR THE FRACTURE

SPECIMEN FD-3

FIGURE 21

FATIGUE SPECIMEN
FD-3

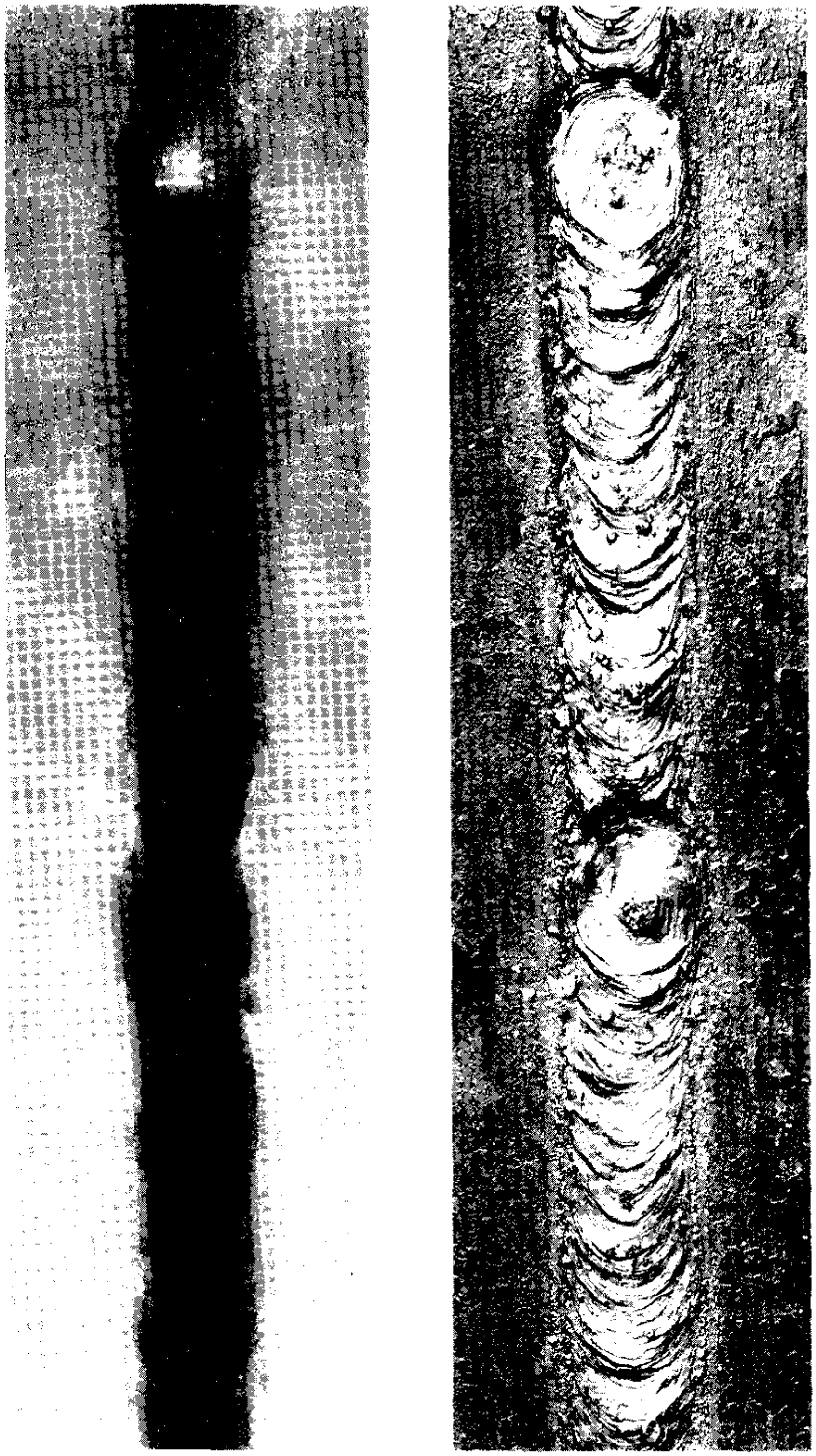
FATIGUE SPECIMEN
FF-1



TENSILE COUPON # 1

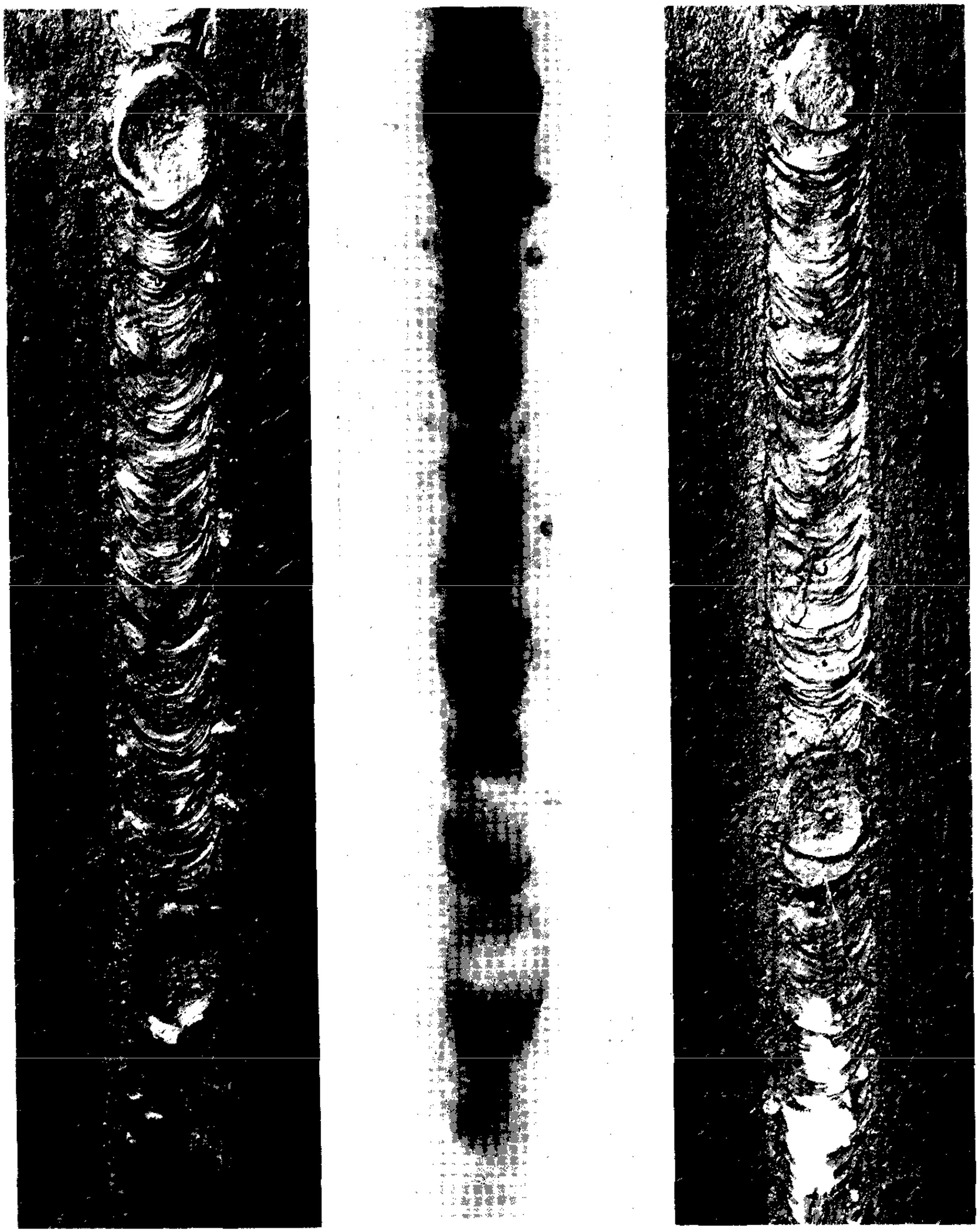
TENSILE COUPON # 2

FIGURE 22: PHOTOMICROGRAPHS OF SURFACES ORIENTED AS SHOWN IN FIG. 21. MAGNIFICATION: 200X. 2% NITAL ETCH. THE EDGE OF THE HOLE IS AT THE LEFT OF THE UPPER PHOTOGRAPHS.



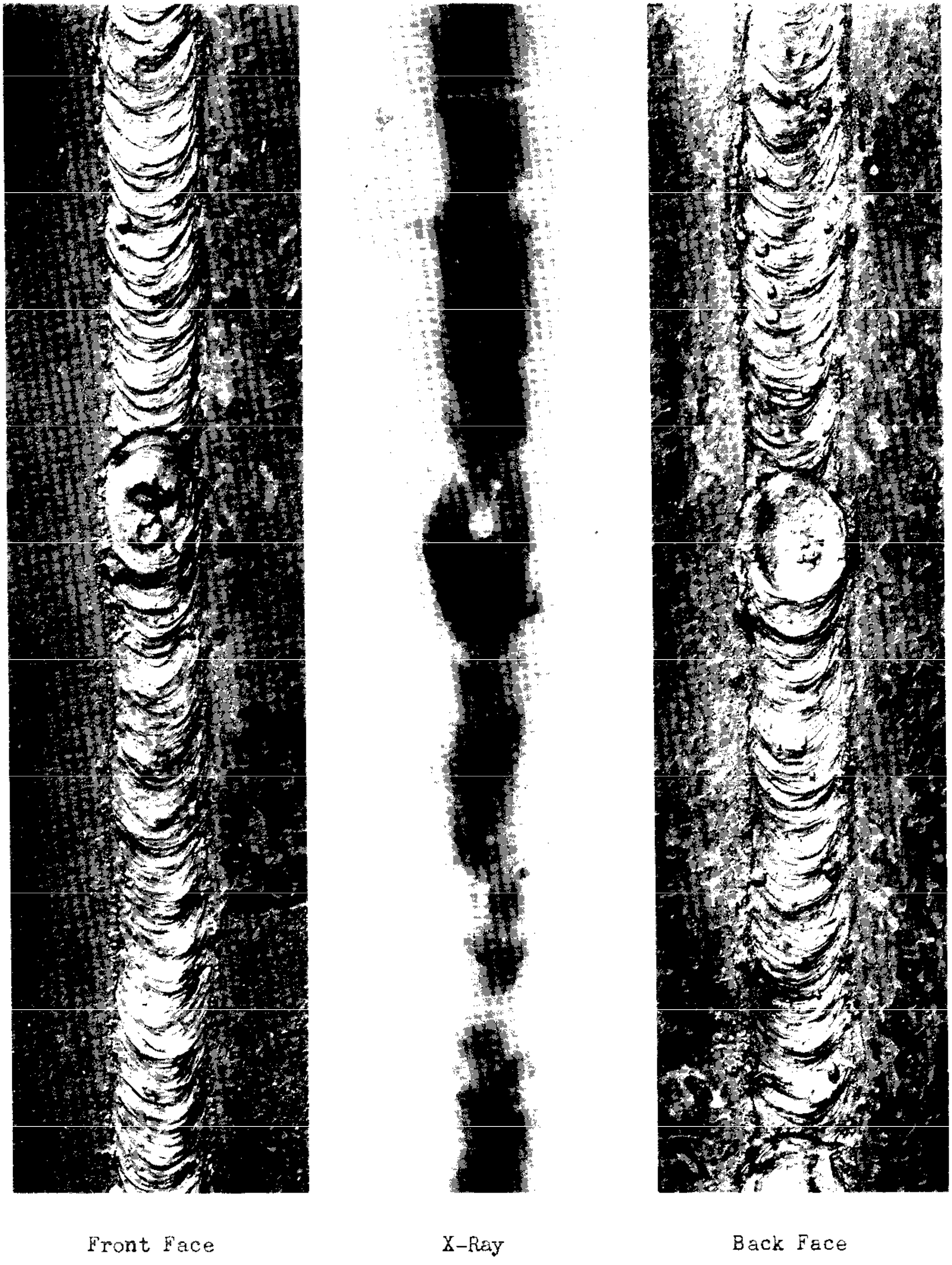
X-Ray Back Face

Figure 23 Specimen AA-6 16 - 24 in. From Top



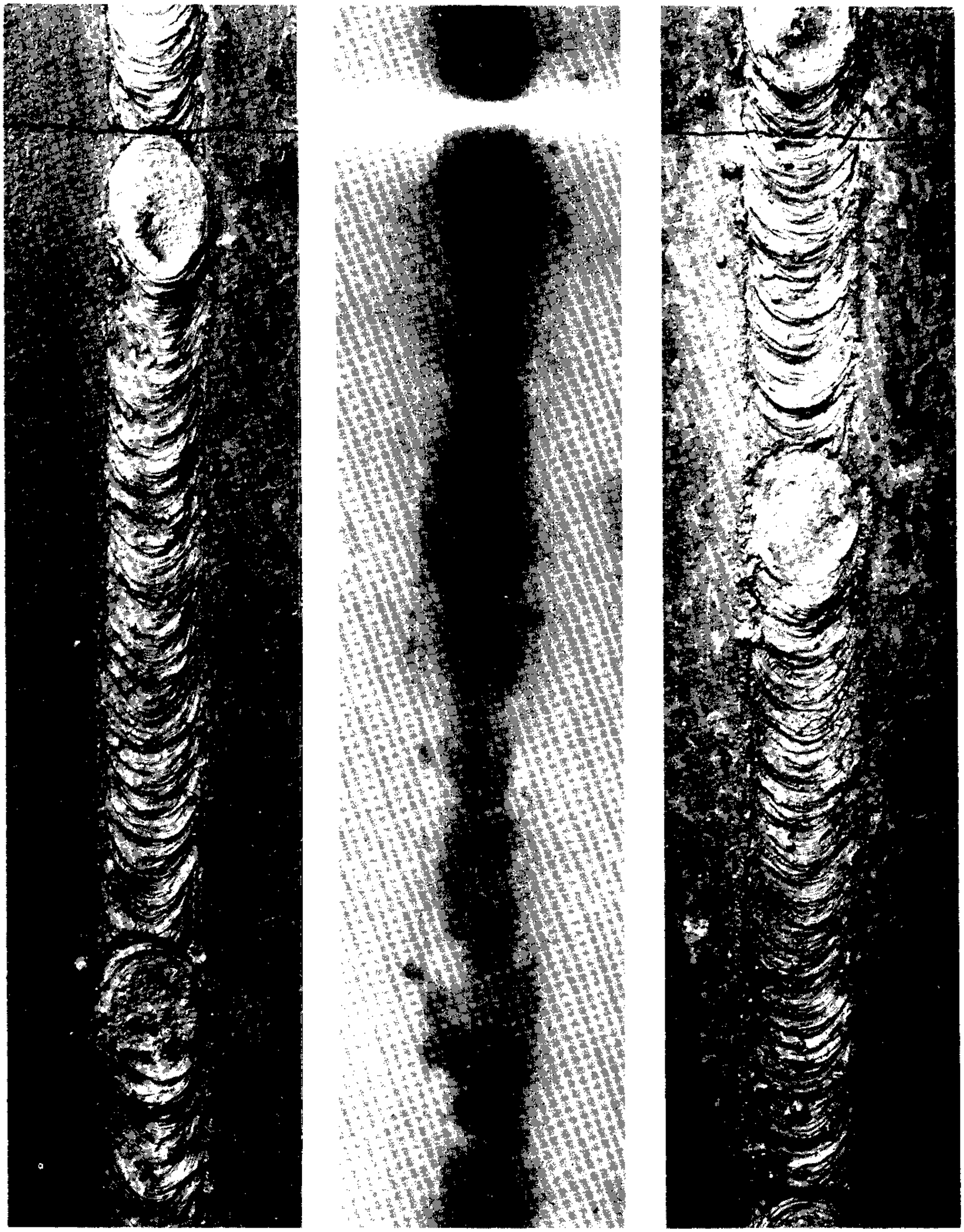
Front Face X-Ray Back Face

Figure 24 Specimen DE-3 40 - 48 in. From Top



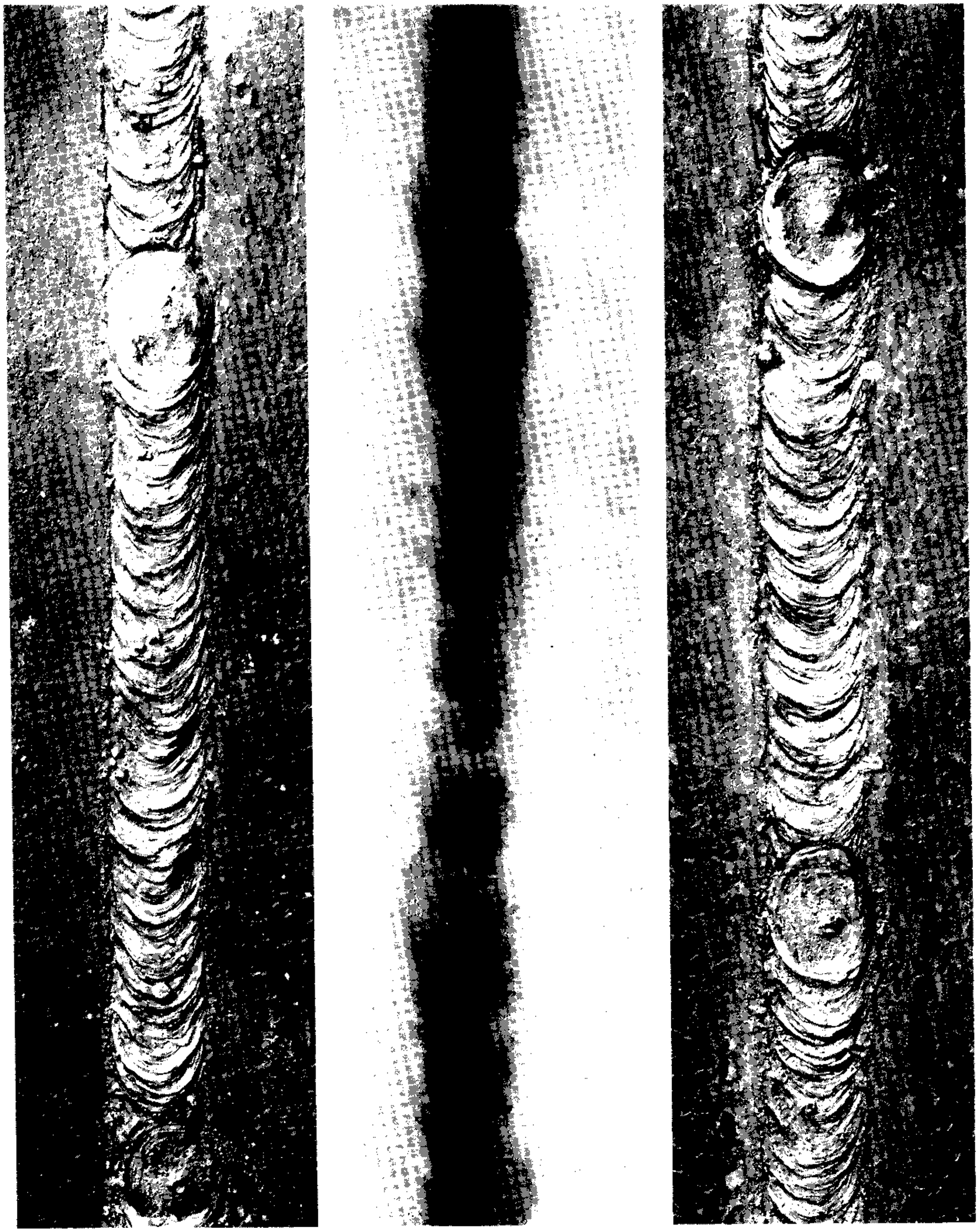
Front Face　　X-Ray　　Back Face

Figure 25　　Specimen EE-3　　16 - 24 in. From Top



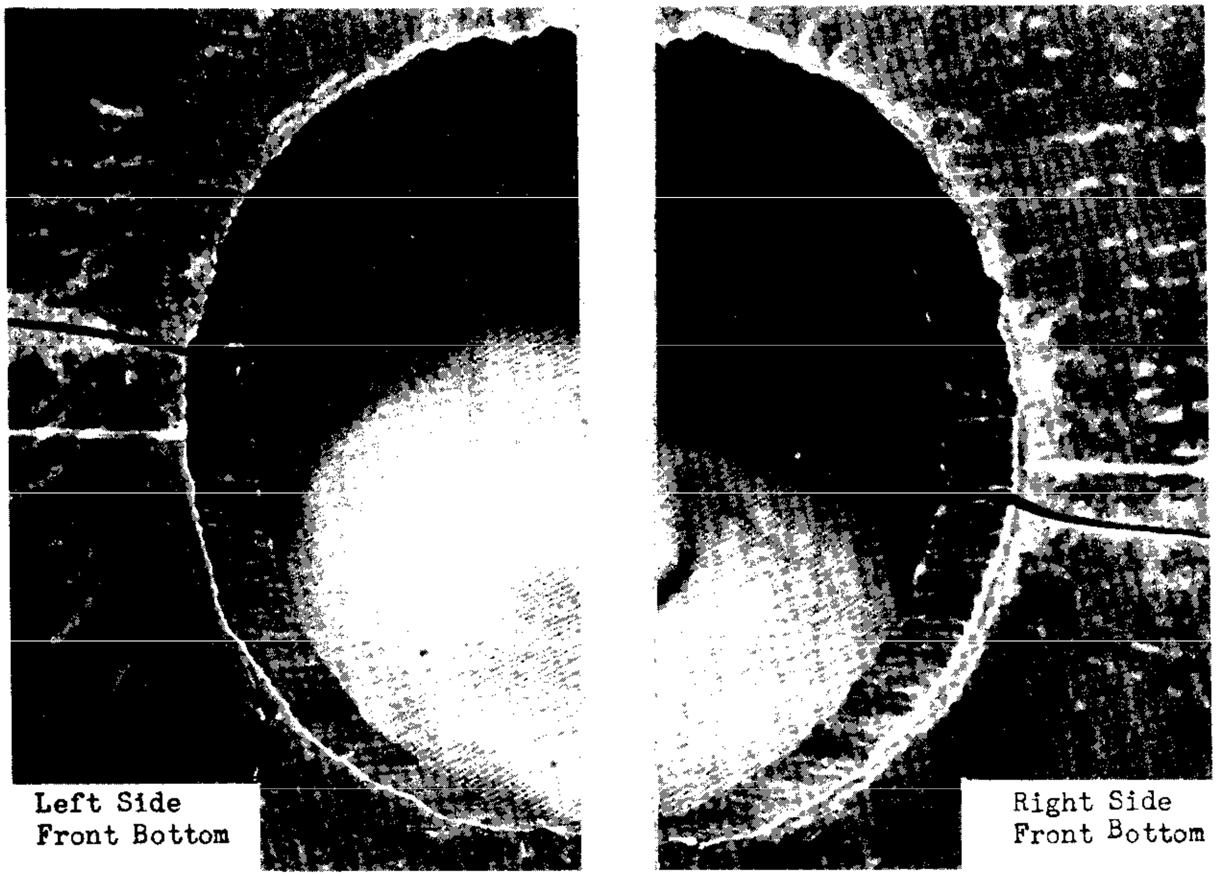
Front Face X-Ray Back Face

Figure 26 Specimen EE-3 24 - 32 in. From Top

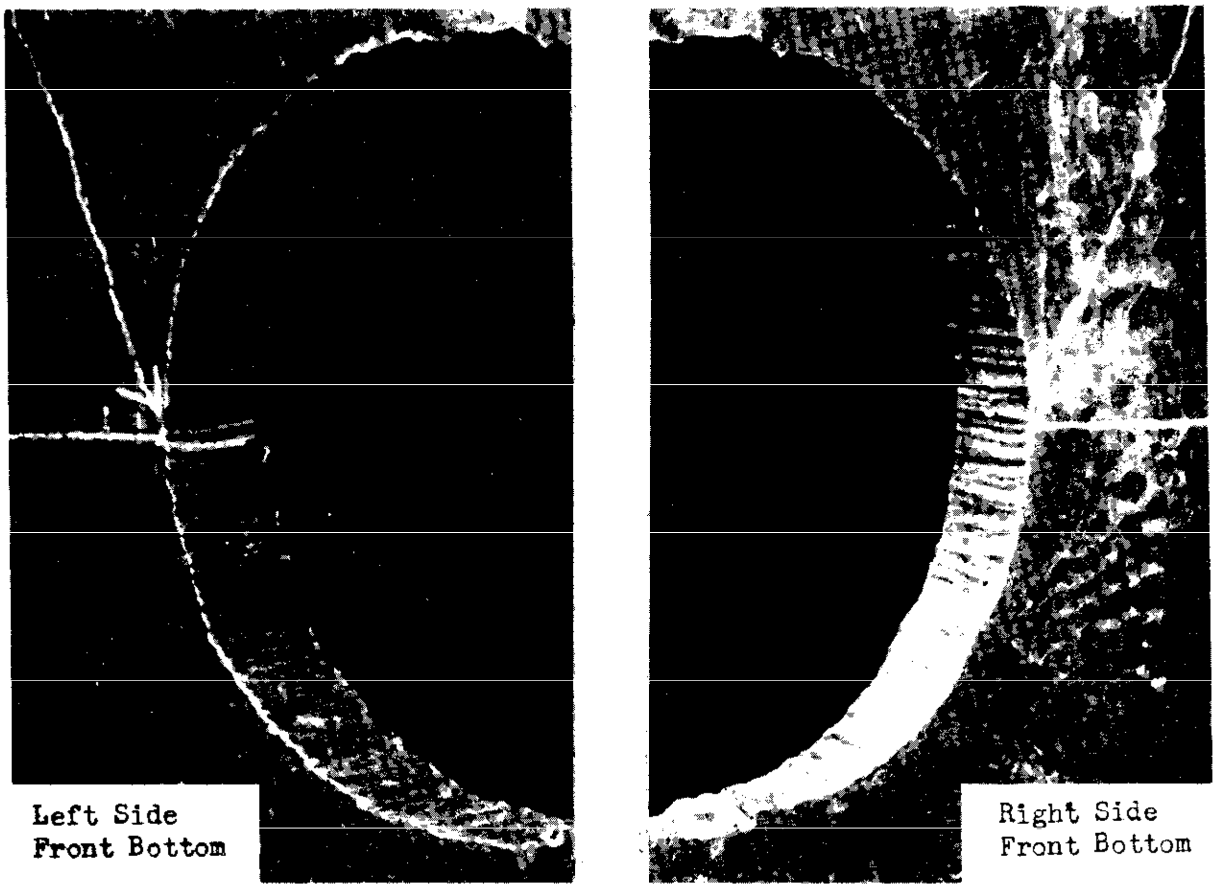


Front Face X-Ray Back Face

Figure 27 Specimen EE-3 40 - 48 in. From Top



Specimen FA-3 Figure 28



Specimen FA-4 Figure 29

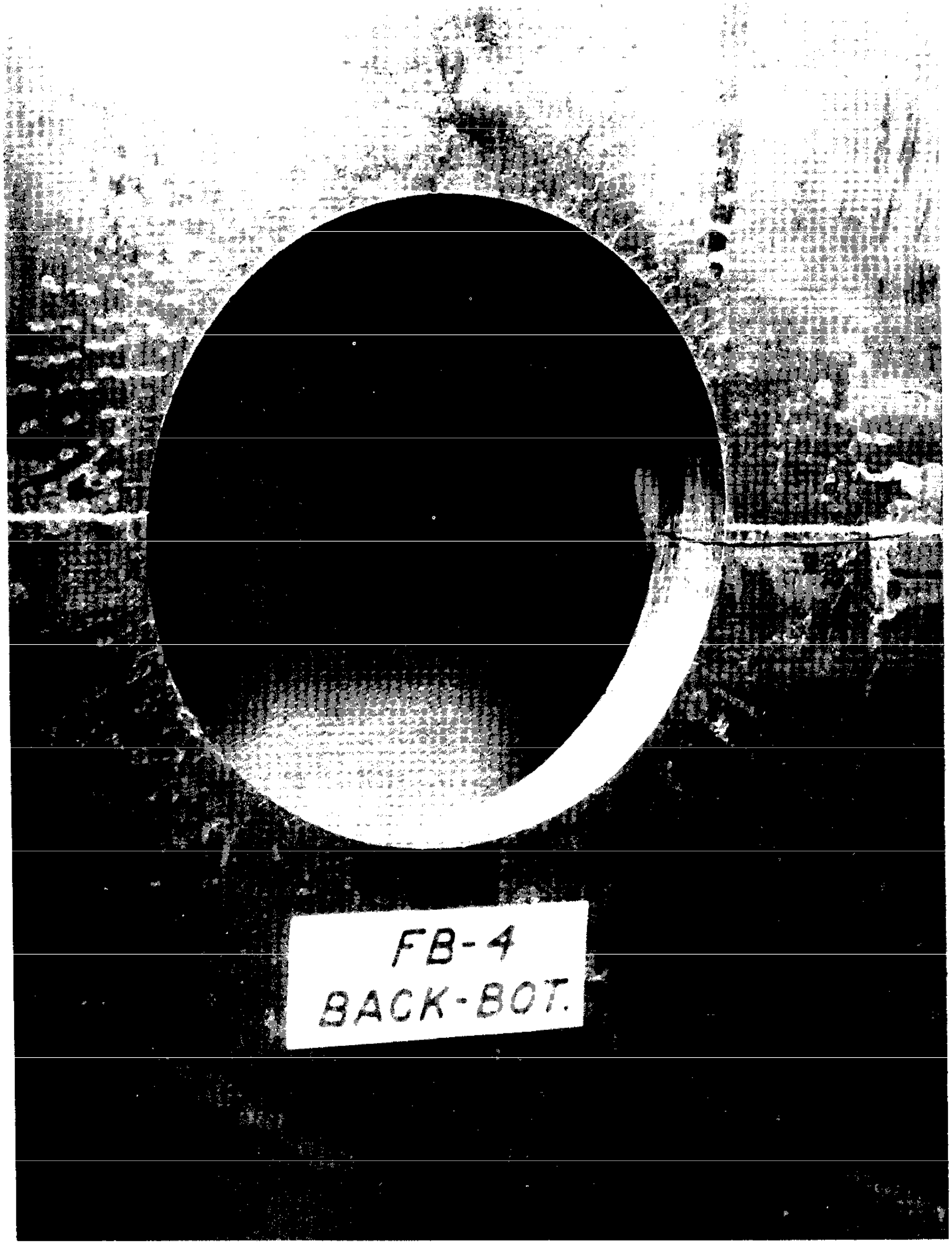


Figure 30 Specimen FB-4 Back Bottom

Figure 31 Specimen FD-1 Back Bottom

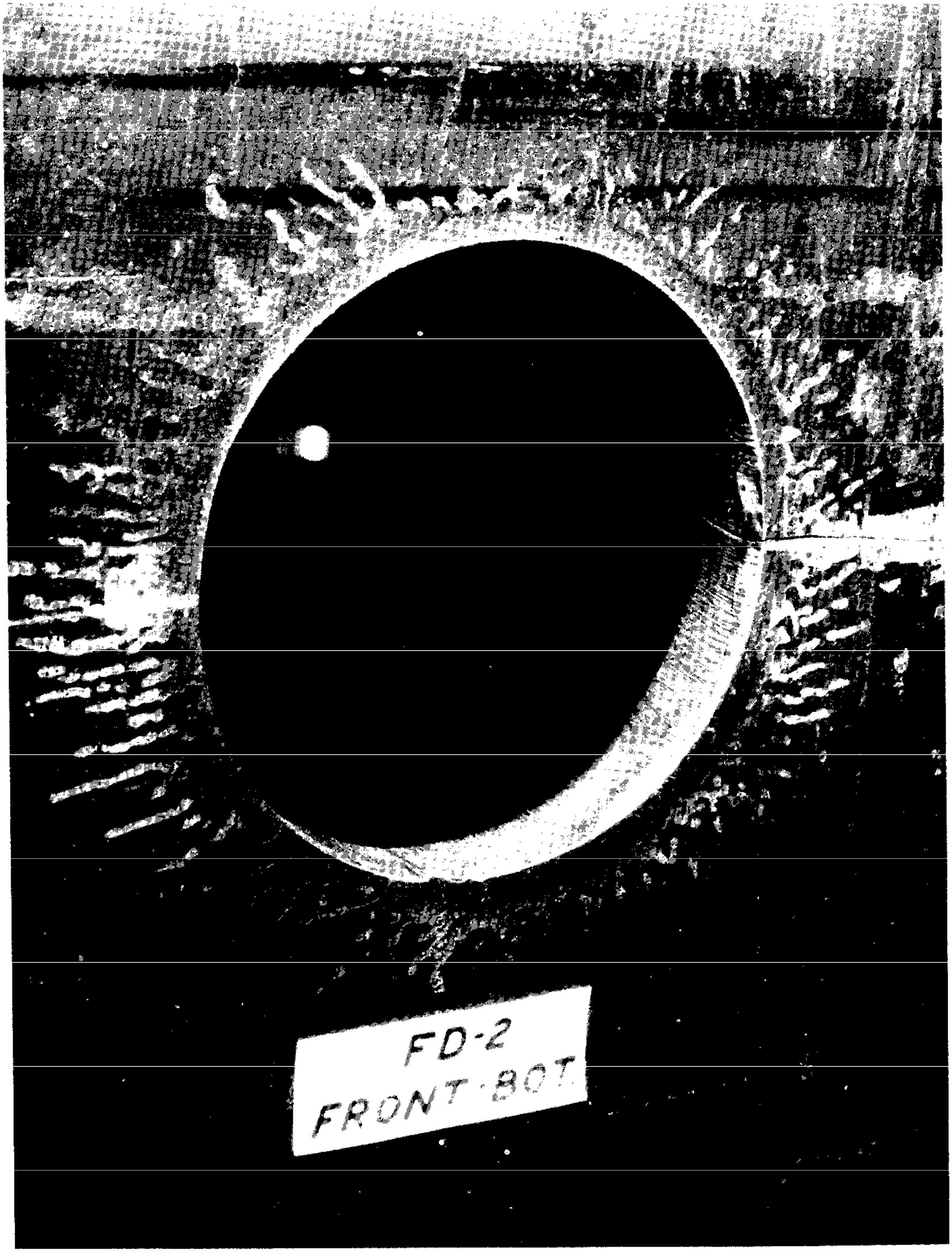


Figure 32 Specimen FD-2 Front Bottom

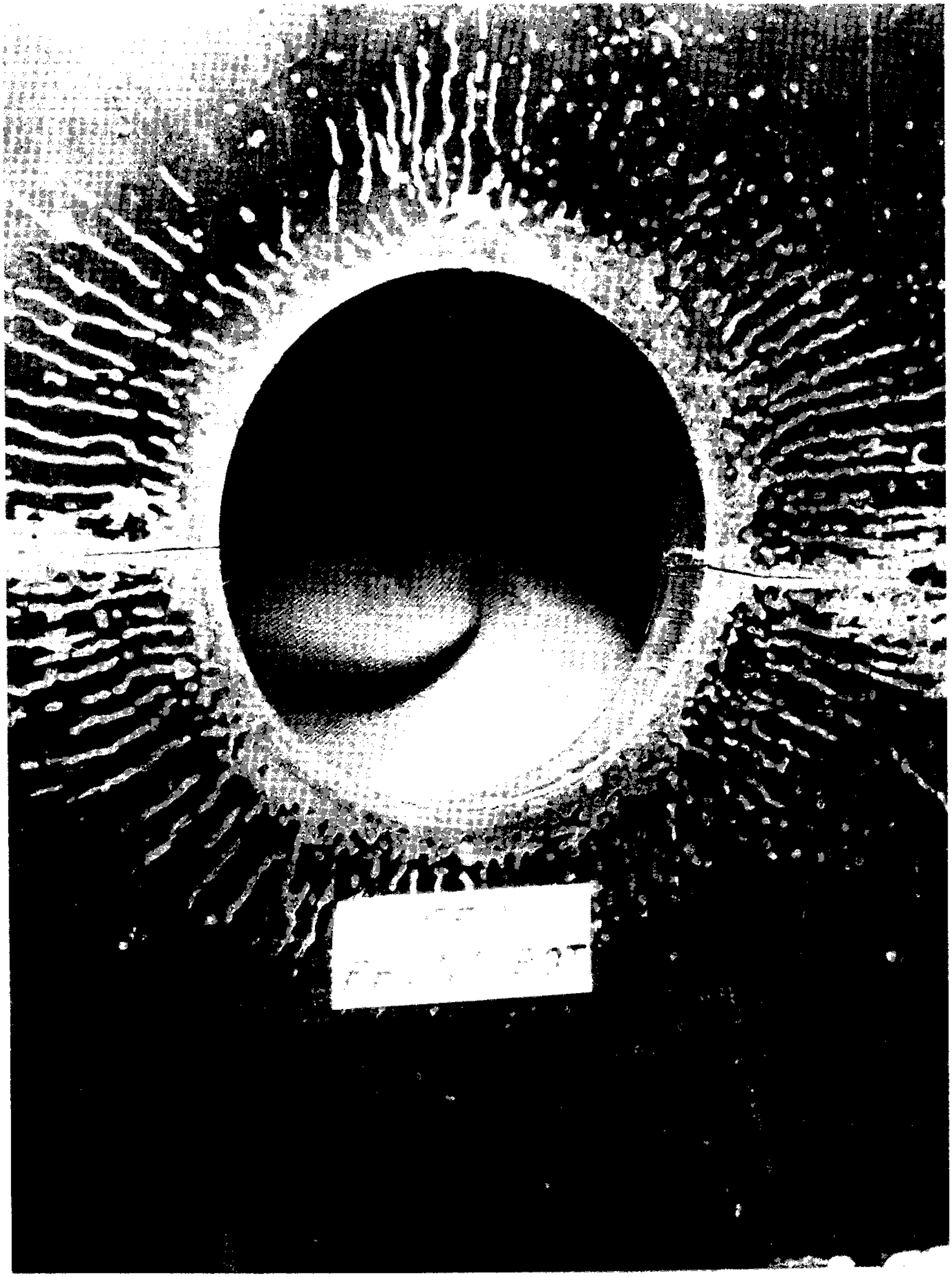


Figure 33 Specimen FF-2 Front Bottom

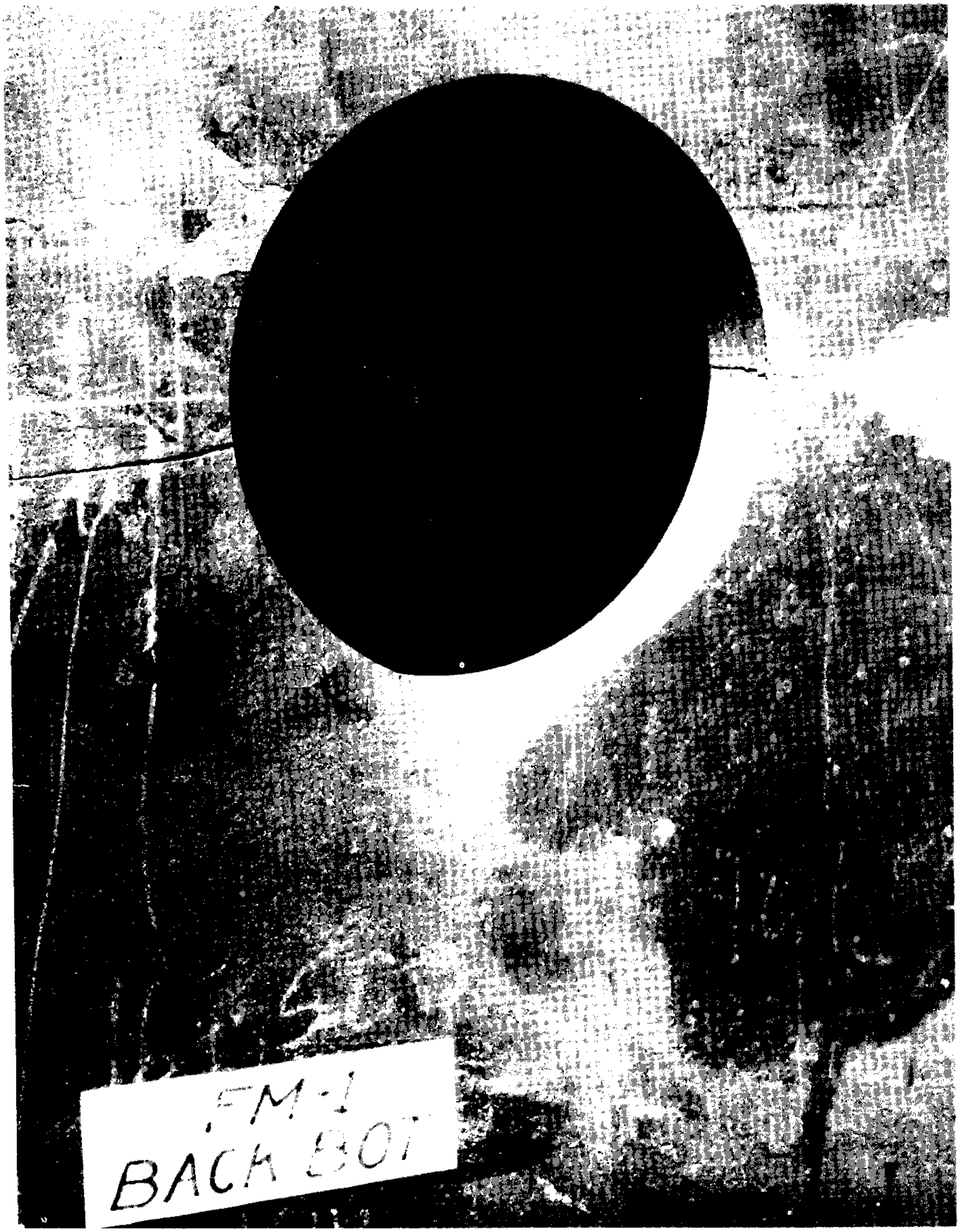
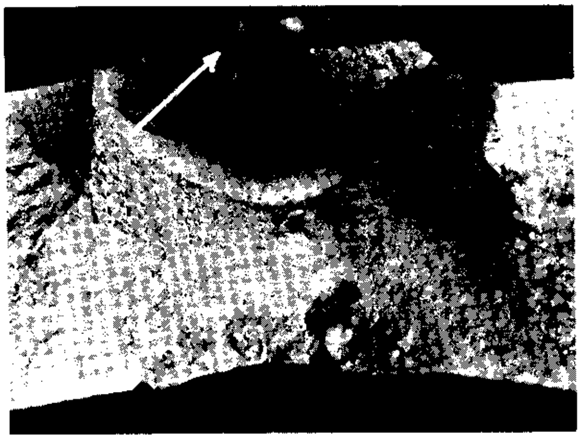


Figure 34 Specimen FM-1 Back Bottom

Top

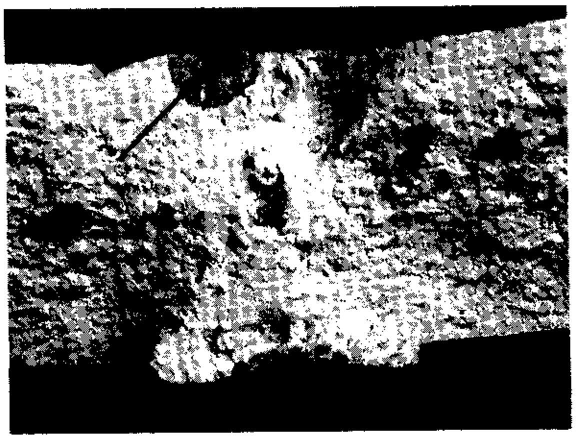


Bottom

Fatigue Crack 1-V

Specimen AA-6 Figure 35

Top

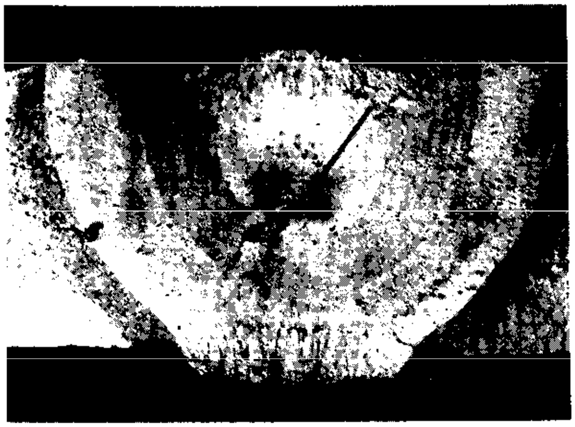


Bottom

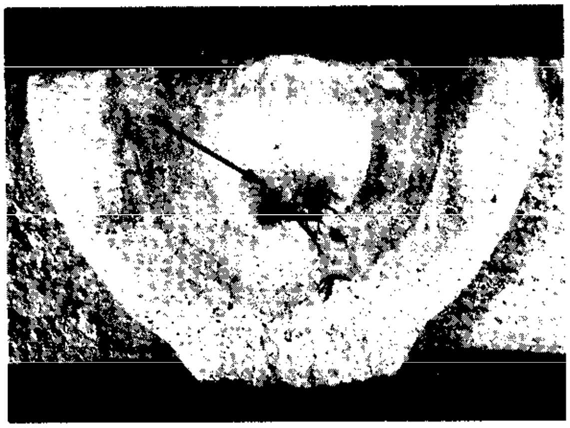
Front Face

Fatigue Crack 1-X

Specimen DE-3 Figure 36



Top

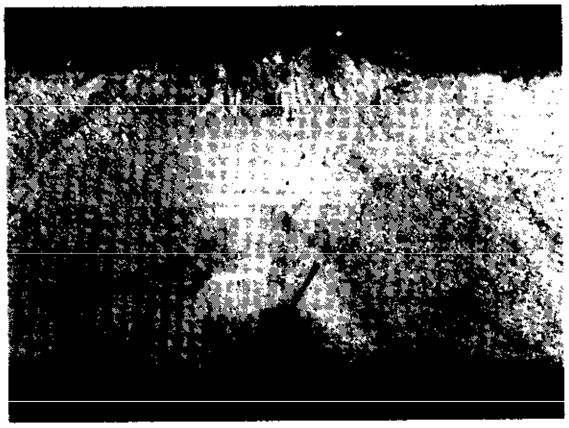


Bottom

Fatigue Crack 3-X

Specimen EE-3 Figure 37

Top



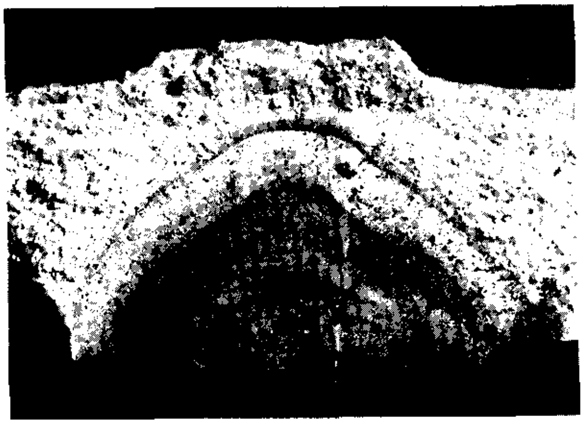
Bottom

Front Face

Fatigue Crack 1-V

Specimen EE-3 Figure 38

Top

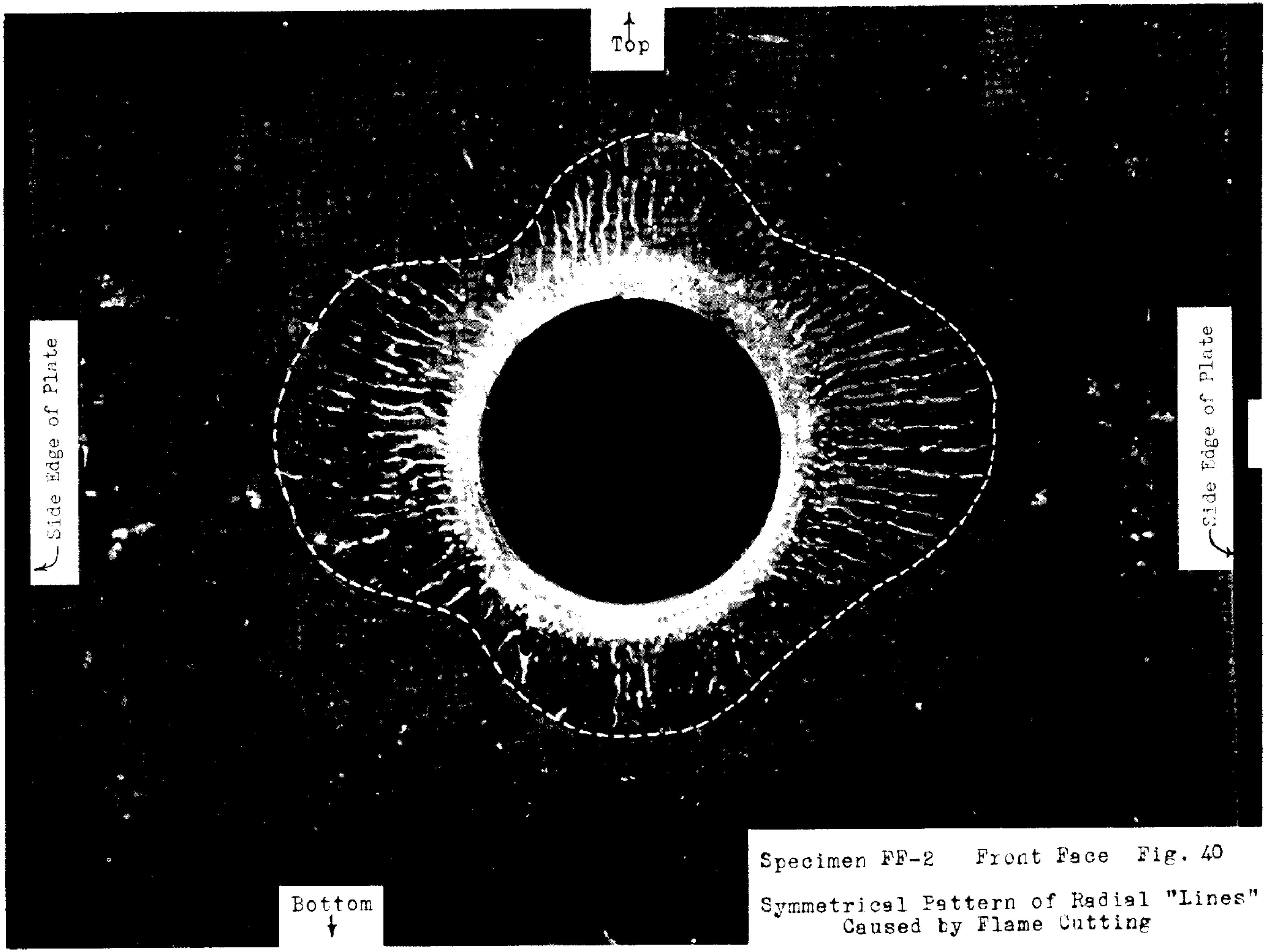


Bottom

Front Face

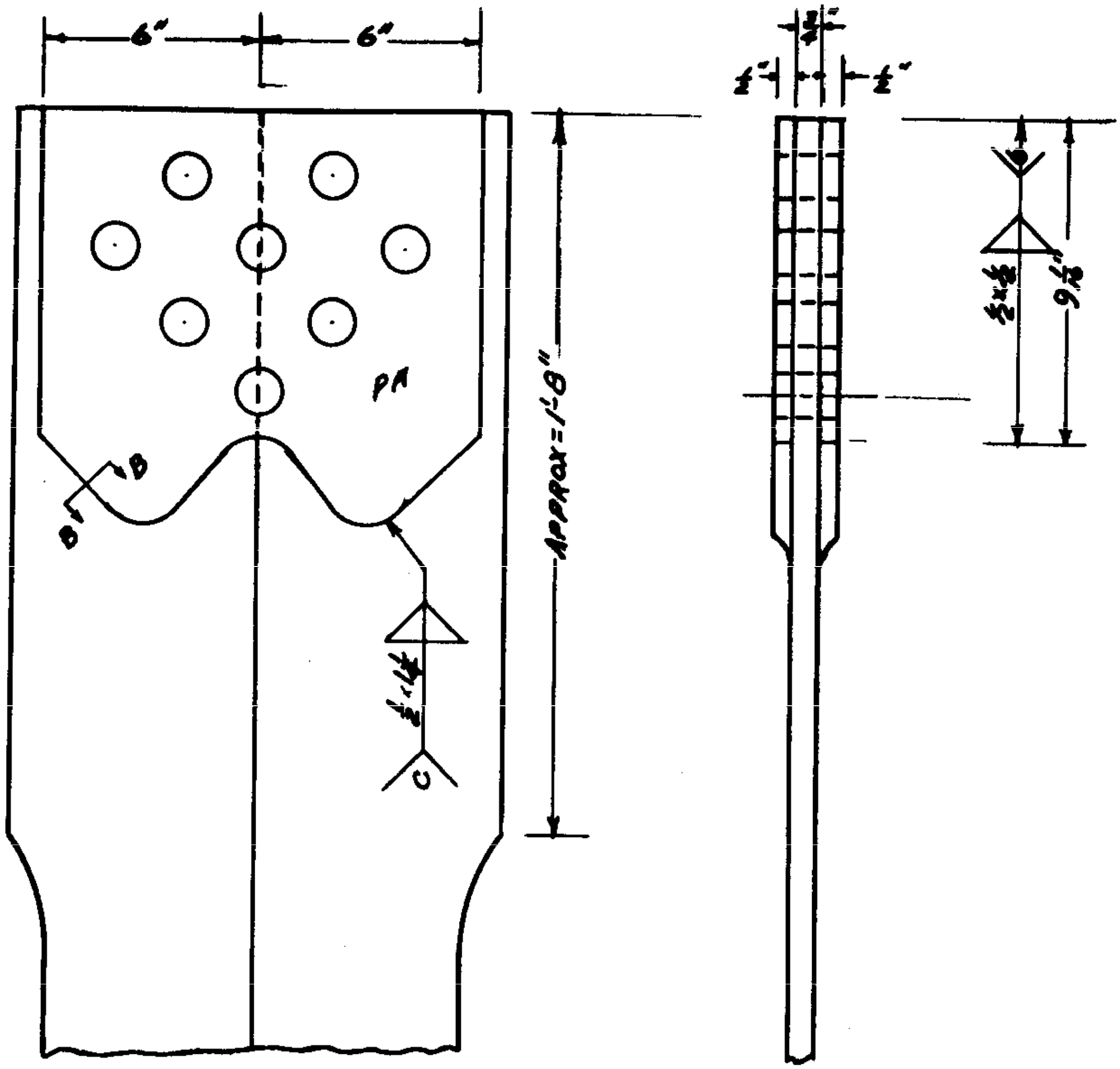
Fatigue Crack 2-V

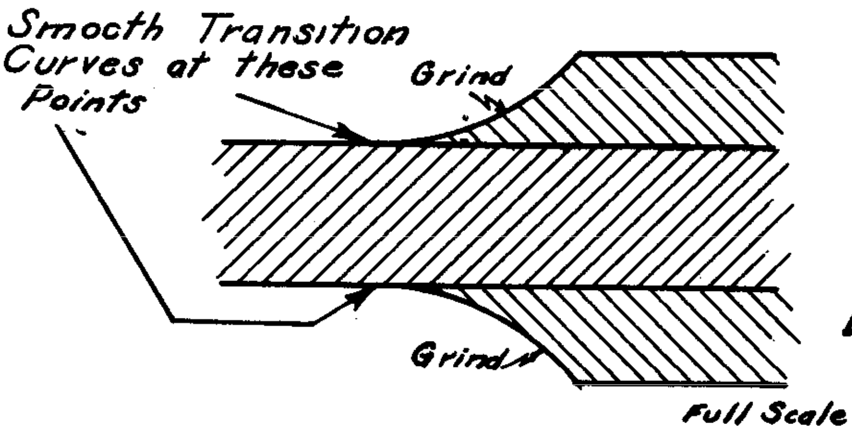
Specimen EE-3 Figure 39



Specimen FF-2   Front Face   Fig. 40

Symmetrical Pattern of Radial "Lines"
Caused by Flame Cutting





SECTION BB

END CONNECTION DETAIL

Figure 41

Appendix A

CHARACTERISTICS OF STEELS

A Steel

Yield Point	=	37,900 psi.
Ultimate Strength	=	59,900 psi.
Elongation in 2 inches	=	33.5%

Chemical analysis, deoxidation, charpy impact data and other inoormation concerning this steel may be found in a separate report[4].

Project Steel SR-89

For 1/2" x 2", (.505), test specimen:

Yield Point (lower)	=	35,000 psi.
Nominal Tensile Strength	=	65,300 psi.
Elongation	=	39%
Reduction of Area	=	64%
Hardness	=	15T78

For 3/4" x 1 1/2" x 8" rectangular test specimen:

Yield Point (lower)	=	34,200 psi.
Nominal Tensile Strength	=	64,500 psi.
Elongation	=	45%
Hardness	=	15T79

Charpy impact tests were peroremd on the Project SR-89 steel by Professor M. Gensamer of the Penn State College in the same manner as he tested other steels[4] for the War Metallurgy Committee. The following results have been transmitted to the authors by private communication.

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[4]See Reference.

Four sets of specimens were tested, these being (1) standard Charpy-keyhole notched bars, (2) standard Charpy-V-notched bars, (3) 5% prestrained specimens with standard keyhole notch, and (4) 10% prestrained specimens with standard key-hole notch.

Three specimens were tested at each testing temperature, and the energy absorption curves drawn approximately through the average of these values.

Listed below are the estimated temperatures for 50% and 25% energy absorption.

Specimen Type	Temp. of 50% E.A.	Temp. of 25% E. A.
Std. Keyhole	0°F	-10°F
Std. V-notch	60°F	30°F
Keyhole-5% Prestrain	40°F	20°F
Keyhole-10% Prestrain	45°F	25°F

An examination of the energy absorption curves as a function of temperature indicates for the two steels no outstanding difference in their energy absorption characteristics.

The analysis of this steel, which has been submitted by the manufacturer, is as follows:

C - .22; Mn - .55; P - .015; S - .040.

Appendix B

CONSTRUCTION OF SPECIMENS WITH WELDMENT

Although the procedure for the construction of specimens with weldment is given in detail in previous reports[1,2] a brief resume of the welding techniques is given here as a basis for evaluation of the results shown in Tables 1, 2 and 4.

Review of Welding Procedure

A Lincoln Arc Welder, Type SAE 300-40 NEMA, 300 Amperes capacity, electrode E6010, and direct current with the electrode positive, were employed on all welded specimens.

All longitudinal welds were of symmetrical double-V type with equal number of passes on each side. The "continuous" method of laying beads was employed only in specimens AA-1 and 2. All others were made with the "back-step" technique. In general, each pass on a given specimen started at the same end.

The laying of weld beads to join the edges of two, six inch wide, plates nearly 8 feel long causes, if the plates are unrestrained, severe bowing, climbing of one beveled edge over the other, and similar distortions undesirable in a test specimen. Such over-riding of beveled edges resulted in poor root fusion and slag inclusions in some six or seven specimens constructed during the early phases of the project. Simple clamping of the ends of the plates to steel horses (Restraint I) did not control the distortion. Three C-shaped clamps bearing on channels separated from the specimen by rollers (Restraint II), plus the judicious placing of weld beads on alternate sides so as to control the distortion, resulted in flat specimens. However, this welding procedure was discarded as contrary to industrial practice in which a pass is completed on one side at a time.

[1,2] See Reference

Experimentation and study resulted in a technique identified as Restraint III in which the plates, located on rollers between a rigid plane table and heavy clamps, were permitted to move only in the plane parallel to their surfaces. This technique, plus extensive chipping of the first pass, resulted in nearly perfect welds as may be seen from radiographs and photographs of sections shown previously[2]. Figs. 23-27 inc. illustrate welds which are typical of the quality of the welds obtained with this technique.

Review of the OSRD Reports[3] on investigations of the effect of various welding procedures on residual stresses in ship welds and discussions with representatives of the Bureau of Ships and the War Metallurgy Committee, confirmed the conclusion that specimens constructed under Restraint III would have residual stresses very little, if any, different from those constructed before Restraint III was employed. From these reports it was concluded 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...."

Hence, although the three restraints involved superficially different welding procedures, it is believed that the resultant products are sufficiently identical basically to permit adequate comparison of fatigue behavior.

The four specimens with reinforced central openings involved only minor construction difficulties such as the fabrication of the collar insert and its proper positioning. Care was exercised to space the consecutive sequence of each weld bead so that no craters occurred at the rounded corners of the insert.

[2,3] See Reference

Appendix C

FABRICATION OF SPECIMENS WITH UN-REINFORCED HOLES

The dimensions of these specimens are shown in Figure 2.

The equipment used and general fabrication information is given in Table VI. A discussion of pertinent procedures as related to each group of specimens is given in the following sections.

Fabrication of Hole

Groups FA, FB, FC (Hand Flame Cut) - At the intersection of the center lines of the specimens, circles of the proper diameter (FA - 4 1/8" dia., FB - 4" dia., FC - 3 1/4" dia.) were scribed and punch marked to produce a pronounced path along which the hand flame torch could be directed manually.

Flame cutting (started from a flame pierced opening through the plate at the center of the hole) was performed along the longitudinal center line to the upper edge of the circle and continuously was carried clockwise around the punch marks to cut half of the scribed path. The second cutting operation, initiated at the upper point, progressed counter-clockwise to complete the construction of the hole. This relative sequence offered an uninterrupted flame pass at the sides of the opening where the greatest stress concentration occurs under longitudinally applied load.

The only exception to this established procedure for the manual flame cutting was the first specimen (FA-1) where the flame cut was directed along the transverse center line to the right and continued counter-clockwise along the circle to produce three-quarters of the hole--all in one operation. The remaining quadrant was removed by starting the flame cut of the transverse center line and traveling in a clockwise direction. This procedure resulted in a slight notch on the inside of the hole (at the transverse center line) where the second flame cutting operation was initiated. However, the surface was not excessively rough as compared with the ripples or grooves formed by the manual operation of the torch.

Groups FD, FE, FF (Machine Flame Cut) - The 4 1/4" diameter holes in the specimens of these groups were flame cut by means of a planograph flame cutting machine with a magnetic tracer which automatically traversed the outline of the opening. A 7/16" diameter hole, drilled through the plate at the intersection of the longitudinal and transverse center lines, facilitated the initial flame cut. The mounted torch was manually directed in the longitudinal direction to the upper edge of the hole where the machine was placed under automatic control to clockwise sweep a radius cut of the desired dimension.

The resultant surface of these holes was much more even and regular than those openings cut by hand; the flame cut ripples were small and evenly spaced with no abrupt or jagged interruptions of the surface.

Group FM (Bored) - To construct these holes, machine operations were performed in which no heat input was experienced by the specimens. A series of 1/4" diameter holes were drilled very close to each other on a 4" diameter, and the remaining narrow strips of metal between the 1/4" holes were cut with a fine chisel to remove the greater portion of the core constituting the opening. With two heavy passes, a vertical boring mill cut away most of the remaining metal. The third pass was light and for the last cut the tool was carefully ground and an exceptionally light pass (.005" to .010") was taken to produce very smooth machine finish.

Treatment of Surface and

Edge of Holes

Groups FB, FE (Ground) - In these two groups, the inside surface of the holes were initially rough ground to remove the grooves created by flame cutting. The final grinding, accomplished with a fine grit wheel, eliminated the faint scratches of the first rough grinding and produced a smooth surface. In both cases, the hand operated grinders were rotated concentrically with the hole to prevent the formation of scratches across the depth of the plate on the inside surface and to assure roundness of the opening. By visual examination the resultant surface appeared as smooth as that of the machine bored hole described above.

For group FB, the grinding removal process did not involve over a 1/16" depth of the metal. Since the single specimen of the FE series had very small flame ripples (machine flame cut), it necessitated less removal of burned metal than those of the FB group.

Group FC (Semi-bored) - The 3 1/4" diameter hole (manually flame cut) of the only specimen in this series was enlarged to 4 1/4" diameter by means of a vertical boring mill. The finishing or last cut was performed much in the manner of that employed in completing the hole in the FM series.

Group FF (Heat Treated) - The inside surface of the hole in the two specimens of this group were heat treated to soften the flame cut surface. This result was achieved by producing a cherry red heat of the metal but yet not destroying the surface geometry of the small flame cut ripples (machine flame cut) through the excessive application of heat. A special type of torch, whose tip had many perforations to produce a wide flame and whose tip diameter was that required for a 3/4" thick plate, was mounted on a radiograph machine in such a manner that the flame was directed perpendicularly upon the surface to be softened. When placed into automatic operation, the radiograph caused the special torch to sweep evenly the inside surface of the hole.

Initially the flame cut surface of the upper edge of the hole on the longitudinal axis was heated to the required cherry red. Once achieved, the radiograph was placed into automatic operation; and, its rate of travel was such that as the torch moved beyond the local heated zone, the metal immediately cooled sufficiently to cause the cherry red color to disappear. The process was performed once around the hole to create the softening effect. At no region in the two specimens were the characteristic ripples destroyed.

Group FB, FE, FM - Both the grinding and boring processes formed small burrs of metal at the edges of the holes in the specimens of these groups. To eliminate any detrimental effects which might result as a product of serrated edges, the burrs were carefully removed by means of a burring tool; considerable care was employed to hold the tool flat with the surface so as to minimize tool marks. As an added precaution, the burred areas were lightly honed with a fine stone to produce a barely discernible radius on the edges of the holes.

In all specimens which entailed flame cutting, the specimen plate was situated in the horizontal position with the cutting flame in the vertical plane. Proper precaution assured satisfactory perpendicularity of the cutting torch to the surface of the plate.

All holes were measured along four axes (transverse, longitudinal, and at two planes 45 degrees to the former two directions) to verify the roundness of the opening. No dimenstions varied beyond approximately + or -2%.

Flame Stresses

In a previous report[2] mention was made of the possible residual stresses which may be created around a flame cut hole in a plate. Additional interesting evidence has been observed in the flame cutting of the holes in the FF series under ideal fabricating conditions; planograph type of flame cutting machine which traversed the outline of the opening at an even rate of torch travel.

In this case (Specimen FF-2, Fig. 40) the radial "lines", where the scale has been removed, were more pronounced and also formed a more definite pattern (outlined by a dotted line in the photograph) than the previously described specimen. All holes cut in this manner experienced the symmetrical pattern on both faces of the plate. Along the transverse axis, the lines are the longest; at the 45 degree planes, the effect is almost negligible; and on the longitudinal center line, an intermediate magnitude of this effect prevails.

These shear lines, which appeared as the holes were machine flame cut, are believed to be evidence of the existence of considerable residual stress in the local region about the hole. The additional heat treatment of the two specimens in the FF series did not alter or augment this initial pattern to any observable extent.

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[2]See Reference

Appendix D

TEST PROCEDURE AND STRESS DETERMINATION

All specimens were tested and the stresses to which they were subjected were determined in the manner described in detail in previous reports.

With the exception of the MB group, all specimens were tested in one of two 400,000 lbs. machines which apply cyclic ranges of tensile loading (zero to tension, or tension to tension). The geometric capacity of these machines enables the testing of specimens 2 ft. wide by 8 ft. long with approximately 6 ft. between grips. The small control specimens (four test pieces, MB group) were investigated in a much lighter but basically similar fatigue machine.

By manual control the temperature of the laboratory in which the tests were carried out was maintained between 72° and 76°F, except for occasional instances when the temperature fell as low as 68°F, or at other times reached 80°F. However, both the two extremes never occurred within a 12 hour period. It is believed that such gradual fluctuations of temperature had no effect upon fatigue life of the specimens.

Stress Ranges

The majority of the specimens were subjected to a nominal stress range of 0-30,000 psi. tension; four others experienced a stress range of approximately 0-20,000 psi. tension--values of stress ranges for all specimens are given in Tables I to V "Summary of Test Results".

Once the desired load upon the test piece had been attained (usually with 1700 cycles or less), the fatigue machine was placed into continuous operation until fracture occurred or until 300,000 cycles was attained (unless otherwise noted in Tables I to V).

A visual examination for cracks, employing a strong light and thin oil, was made every 2,000 cycles, or oftener as advisable. Strain readings and stress computations 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.

To determine the load on the large specimens, a 10-inch Whittemore Strain Gage with a ten-thousandth dial was employed; for the small (MB group) specimens, an 8-inch Berry Strain Gage was used. In all cases, strain measurements were taken at many judiciously selected points on both faces of the specimens. Such locations were shown previously.[1, 2] The "average stress range" is defined as that stress range determined from the average of the strain readings at all gage points for the maximum, or the minimum load, respectively. In the case of the longitudinally welded specimens the most highly stressed gage length was determined and is defined as the "Critical Point".* Once the fatigue fracture was definitely established, it was possible to compute the particular stress range (local average) at the gage locations adjacent to the crack.

Since the Yield Point of the steel in the parent plates is not much above 30,000 psi., care was exercised in loading the longitudinally welded specimens so that the stress at the Critical Point* was as close to the 30,000 psi. stress range as possible but did not exceed this value.

One of the four specimens tested at the lower stress range was loaded in a manner discussed in Appendix F. For the other three specimens, it was then decided that a more practical procedure from the viewpoint of design would be a loading such that the Average Upper Limit would be + 20,000 psi. In the application of this load it was unnecessary to check the stress performance

*See definition, Sec. III

[1,2]See Reference

of a critical gage length as in the former procedure. Instead, the strain at all gage points was recorded and averaged for a load below that required. The load was then increased in steps until the Average Upper Limit was as close to + 20,000 psi. as practical.

The load on the specimens with reinforced holes (B and C groups) was increased until the stress at the "Critical Point" was equal to or very slightly above 30,000 psi. according to the same procedure as followed for the longitudinal welds.

For specimens with un-reinforced holes the load was so adjusted that the stress range (applied load divided by net area) at the net cross-sectional area of the hole, varied only nominally from 0-30,000 psi. The applied load was determined from the average of the strain measurements at twenty locations distant from the hole.

For the reinforced holes (B and C), the local average stress was evaluated from readings on the face of the plate adjacent to the fracture--four possible areas could be considered (front and back of either the top or bottom end of the specimen). For the un-reinforced holes the local average stress range was computed from all strain measurements taken on the same side of the plate as that for which initial failure occurred.

Appendix E

HARDNESS SURVEY

Introduction

Since it is known that a flame cut edge of mild steel plate is considerably harder than the body of the plate, the question was raised if considerable variations of hardness at the surfaces of the burned holes existed from specimen to specimen, and if so, could a correlation be established with the spread in the observed cycles-to-fracture for various specimens. The observations of hardness and of metallurgical structure reported herein were made to determine if a more thorough survey would be desirable. Accordingly specimens to study were chosen which, from the information at hand, appeared most likely to show interesting results.

Since specimens FM-1 and FM-3 had no heat input, no hardness surveys were undertaken for these specimens; instead, microscopic examinations were made of sections adjacent to the hole.

Location of samples for Hardness and Microscopic study

A prism was milled from the region close to the hole and was later lightly ground to final dimensions (2" x 3/4" x 3/8") suitable for Rockwell Superficial "15T" hardness measurements. These measurements were made on a surface which had been located as close to the fatigue crack as possible, see Fig. 21, and which extends, at one end, to the edge of the hole. More specifically, this surface is bounded on opposite sides by the front and back of the specimen, on one end by the inside surface of the hole, and on the other by a saw cut so as to make the surface approximately two inches long. The "right corner" of the prism surface is defined as the intersection of the edge lying in the flame cut surface of the hole. In two cases, prisms were also cut from the top of the hole in order to find if a detectable amount of work hardening had occurred at the transverse section.

Prisms for microscopic examination were obtained in the same manner, but were loeated along the circumference of the hole about 1/2" from the fatigue fracture.

Results of Hardness Measurements:

Rockwell Superficial hardness values obtained for several specimens are given in the following table. The numbers in parenthesis are Brinell values obtained from a conversion table. The plate metal 1 1/2 inches from the flame cut surface had an average hardness of 15T81.

Sample from Specimen No. (See Fig. 21)	Hardness values across a section and as close to the flame cut edge of the hole as is possible.		
	At "Left Corner"	"Center"	At "Right Corner"
FA4	15T 88.2 (164)	15T 87.8 (160)	15T 87.0 (153)
FD1	15T 88.3 (166)	15T 89.0 (172)	15T 89.0 (172)
FD3	15T 89.0 (172)	15T 87.2 (155)	15T 85.5 (141)
FE1	15T 87.2 (155)	15T 86.3 (148)	15T 84.9 (136)
FF1	15T 86.0 (144)	15T 85.6 (141)	15T 85.0 (137)
FA2 ("Top of Hole")	15T 87.7 (160)	15T 85.0 (137)	15T 87.8 (160)
FF1 ("Top of Hole")	15T 84.8 (136)	15T 85.2 (139)	15T 84.3 (132)

Measurements on a portion of the flame cut surface, see Figure 21, after lightly sanapapering the surface, gave values up to 15T90, but are not entirely satisfactory because the unevenness of the surface (ripples, etc.) made the observations difficult. It is clear from the microscopic examination and from other considerations that the hardness of the surface is probably greater than any of the values given here.

Two conclusions may be made:

(a) Significant hardening of the metal at the surface of the hole results from the flame cutting operation.

(b) The flame softening operation performed on specimen FF-1 has reduced the hardness probably more than is shown by these measurements and may be responsible for the greater fatigue life observed. Decarburization has occurred as seen in Figure 22.

Since residual stresses of the order of yield values may result from flame cutting operations[5], it was thought desirable to determine the yield and ultimate strength for material similar to that found at the surface of the flame cut hole in these specimens.

After consideration of the values given in the preceding table, a hardness of 15T89 was arbitrarily chosen as representative of the state of the material at the edge of the hole. A modified Jominy bar, prepared from a sample of the steel, was employed to estimate the proper quench to attain the above hardness in a test specimen.

Two 0.505 tensile coupons six inches long between grips and with an extra cylindrical section $1\frac{1}{4}$ inches long were heated to 1600°F in Houghton liquid bath No. 168, and then quenched in a water bath at the temperature given in the table below. The long axis of the bar was parallel to the water surface when

[5]See References.

plunged into the water. The cylindrical stub was cut off and prepared for microscopic examination. Hardness measurements were made on both the stub and portions of the test length of the 0.505 coupon. Procedures were such that it is felt confident that the measurements taken are indicative of the values throughout the bar. The results of the two 0.505 coupons, so prepared, are given below:

Physical Property	Coupon #1	Coupon #2
0.2% yield strength	61,200 psi.	54,000 psi.
Nominal Tensile Strength	102,400 psi.	98,300 psi.
Elongation	11% on 2"	*
Reduction of Area	32%	39%*
Hardness	15T 89	15T 87.5
Quenches in water at	100°F	90°F

*Specimen ruptured outside gage length

Photomicrographs of sections from each of the two tensile coupons, and from each of two fatigue specimens are shown in Figure 22. No significant difference in structure is seen between the coupons and specimen FD-3; likewise for FA-4, see next section.

Tensile tests on 3/4" x 1 1/2" x 8" rectangular bar prepared from a piece of the 3/4" plate stock give the following values:

Yield point (lower)	34,200 psi.
Nominal Tensile Strength	64,500 psi.
Elongation	45%
Hardness	15T 79

Elsewhere in this report evidence is presented of plastic flow in the plate as a result of flame cutting the central hole. It appears that the stresses associated with the flame cut edge may be very large.

Microscopic Examinations

Comments concerning the specimens are given below:

Specimen FA 4: Hand Flame Cut Hole - 12,000 cycles @ -400 to 30,700 psi. Metal is clean. Body of metal has structure of ferrite and pearlite with very slight banding. This banding is not detrimental. Cut edge is pearlitic due to rapid cooling from above critical temperature. No free ferrite at edge. Heat affected region approximately 3/64 inches thick.

Specimen FD 3: Machine Flame Cut Hole - 21,500 cycles @ 0 to 30,300. Metal is clean. Body of metal has same structure as FA 4 with somewhat more banding. It is again unlikely that this degree of banding is detrimental. Heat affected region is narrower than FA 4, being approximately 1/32 inch thick. It appears that the cooling rate at the edge of the hole was more rapid than in FA 4. Cut edge is pearlitic. No free ferrite at edge of hole.

Specimen FF-1: Machine Flame Cut Hole, torch drawn - 58,000 cycles @ 250 to 29,900 psi. Body of plate is slightly banded structure of ferrite and pearlite. Same as FD 3 and nearly same as FA 4. Edge of hole is slightly decarburized to depth of less than 0.01 inch. See Figure 22. Corners of hole are not decarburized and exhibit fine pearlitic structure. Heat affected region generally made up of coarse ferrite and pearlite in Widmanstatten pattern extending to approximate depth of 5/32 inch.

The following two observations show that the differences in the two steels are of small magnitude and are inadequate to explain the spread in results of FM-1 and FM-3.

Specimen FM-3: Machined Hole 42,000 cycles @ -350 to 30,100 psi.

Same steel as previous specimens.

Same structure as previous specimens.

Same slight banding, but no noticeable defects.

Specimen FM-1: Machined Hole 133,000 cycles @ -200 to 30,400 psi.

Same structure as FM-3 with <u>less</u> banding. No significant differences from FM-3.

Appendix F

THE APPLICATION OF LOAD TO SPECIMEN AE-3

Since specimen AE-3 was the first of four specimens to be subjected to a nominal stress range of 0-20,000 psi tension, a certain amount of speculation was raised as to the manner in which to stress this test piece. Prior to this time all specimens had been loaded at a nominal stress range of 0-30,000 psi tension and a definite loading procedure had been established. As one might expect, the minor local irregularities in a specimen created local stresses of different magnitudes when load was applied, and thus all gage points could not simultaneously be raised to exactly +30,000 psi. Since it has been predetermined not to stress any local region of the test plate beyond +30,000 psi (explained in Appendix D), that gage point which indicated the largest strain at an applied stress slightly below operating load was employed as a control. Then, the mechanism of the fatigue machine was successively adjusted until the strain at the controlling gage length corresponded to a stress of 30,000 psi tension or only slightly above. (See Table 1). Obviously, the applied average stress for the entire specimen would be slightly below the +30,000 psi.

Initially, it was decided to employ the above procedure for loading the specimens to be studied at the lower stress range, wherein the most highly stressed gage point would be subjected to an upper limit of +20,000 psi. However, since this was the first time that the fatigue machine was adjusted to operate at light loads, the desired stress of +20,000 psi at the critical point was exceeded by approximately 6,000 psi for about 3 cycles of loading.

After some discussion concerning this specimen, it was decided to decrease the applied load so that the control gage point would experience an upper limit of ±20,000 psi. For this specimen, the local abnormalities were such that the average load on the specimen was reduced to ±17,300 psi; one of the widest spreads observed in the entire program.

It was recognized that, since this over-loading prior to the cyclic testing relieves the severe residual stress state in the weld and since the lowering of the applied load reduces the limits of the stress range equally, this particular specimen should offer a more satisfactory length of cyclic service than if it had not been subjected to the overload. However, it was thought that the results obtained from this specimen would be interesting and could serve as a guide in future phases of the investigation. Although this specimen was operated to 3 1/2 times the cycles at which fracture occurred in similar specimens which were loaded at a stress range of 0-30,000 psi tension, it is now believed that it would have been more valuable if the specimen could have been operated until a fracture had developed.

Appendix G

OBSERVATIONS CONCERNING THE CONSTRUCTION OF

INDIVIDUAL WELDED SPECIMENS

The following specimens are those constructed since the last progress report.

A - Longitudinal Welded Specimens.

Restraint III was employed.

Specimen AE-3: In passes #5 and #6, the electrode was weaved slightly more than in the previous weld passes in order to build up the resultant bead. All the weld passes were of a satisfactory nature.

Specimen AA-6: The welder found it difficult to control a considerable amount of "arc-blow" (especially at the ends of the specimen) which occurred during pass #1. A more pronounced arc-blow occurred during pass #2; various relative locations of the "ground clamp" were investigated to eliminate this phenomenon without complete success. Pass #3 had considerable arc-blow. After each of these weld passes, the weld metal was very carefully chipped out to remove any possible flaws in the weld. Very little arc-blow was experienced in pass #4. From this point on, all the beads were satisfactory.

Specimen DE-3: No comment.

Specimen EE-3: A certain amount of arc-blow prevailed during pass #1. However, the arc-blow was greatly diminished on subsequent passes. In pass #5, the electrode was weaved more than normally to aid in the build-up of the bead where the groove was deep.

B - Specimen with Reinforced Hole

Specimen B-3: The last specimen (B-3) in this series was fabricated in the manner of the specimens of this group previously described. In pass #2 some difficulty was encountered in building up the vertical leg of the fillet, because of the 1/8" gap that existed between the ring and the plate. At no rounded corner of the ring was there a crater which might initiate fatigue cracks.

C - Welding Information

The information with regard to the welding details for each specimen (tested since the last report) is given in the following table. For all specimens Vertex E6010 electrodes were employed.

Specimen	Pass Number	Face on which made	Amperage	Voltage	Electrode Size
AL-1	1	Back	125	28	5/32
	2	Back	190	28	3/16
	3	Front	150	28	5/32
	4	Front	220	28	3/16
	5	Back	210	28	3/16
	6	Front	210	28	3/16
AL-2	1	Back	135	28	5/32
	2	Back	200	28	3/16
	3	Front	150	28	5/32
	4	Front	200	28	3/16
AL-3	1	Front	145	26	5/32
	2	Back	160	26	5/32
	3	Back	220	28	3/16
	4	Front	220	28	3/16
	5	Back	220	28	3/16
	6	Front	220	28	3/16
EE-3	1	Back	130	28	5/32
	2	Back	200	28	3/16
	3	Front	150	28	5/32
	4	Front	200	28	3/16
	5	Front	200	28	3/16
	6	Back	200	28	3/16
DE-3	1	Back	130	28	5/32
	2	Back	220	28	3/16
	3	Front	145	28	5/32
	4	Front	210	28	3/16
	5	Back	210	28	3/16
	6	Front	210	28	3/16
B-3	1	Front	150	28	5/32
	2	Back	150	28	5/32
	3	Front	140	28	3/16
	4	Back	140	28	3/16

Appendix H

DESCRIPTION OF FATIGUE FRACTURES

The fatigue fractures on each of the three types of specimens recently tested (longitudinal welds, plain openings, and reinforced holes) are briefly described with references to diagrams and photographs which present pertinent information.

Longitudinal Weld Specimens

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", Table I.

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.

The radiographs of the welds are typical of the quality of the welds.

Specimens with Openings

Where necessary, brief comment is made concerning these fractures. However, the major portion of the information is given in Figures 35-39 incl.; salient points are brought out either in the photographs or drawings of the various specimens.

The lower edge of all the photographs is the bottom end of the specimen; whether it is the front or back face is indicated on each photograph.

Specimen AA-6:

Location of Crack, Figure 5

Crack I-V, 583,000 cycles, back face, middle third of the test length. The fracture, which started at a small pin hole in a crater, propagated slowly since at the end of the test (665,700 cycles) the crack extended only across the weld surface and 1/8" into the parent plate on one side of the weld. The fracture (Fig. 35) definitely shows incipient failure at the surface with propagation from the pin hole in the weld metal.

Specimen DE-3: During the fatigue test no evidence of fracture developed which could be visually detected. However, Radiographs of the test length showed slight evidence of one small fracture.

Location of Crack, Fig. 6.

Crack I-X. The sectioning of the weld corroborated the existence of the small fracture on the back face, lower third of the test length. A small pit hole in a crater initiated fracture. At the end of the test (840,600 cycles) this fracture (Fig. 36) was very small. From the very dark oil stained appearance of the crack, a definite possibility existed that this fracture was arrested during the test. Had the crack occurred slightly before the test termination, the fracture surface would be light colored in appearance.

Location of Cracks, Fig. 7.

Crack I-V, 151,000 cycles, front face, middle third of test length. The crack appeared adjacent to the edge of a crater at a small ripple in the weld metal. At 193,000 cycles the propagation of the fracture extended to the back face; and, it became 3 inches long by the end of the test (215,000 cycles). The fracture (Fig. 38) reveals that its incipient stage occurred on the front face of the weld.

Crack 2-V, 180,000 cycles, lower third of the test length of the front face. A small ripple at the end of a crater created the danger point for fracture.

At 201,000 cycles the crack was 1" wide on the front face; and by the end of the test, it had reached the rear face of the specimen. The fracture (Fig. 39) indicates initial failure at the front face.

Crack 3-X, Middle third of the test length. Radiographs of the weld indicated a fracture which was verified by the sectioning of the weld (Fig. 37). Poor root fusion initiated the fracture which then propagated outward toward the two faces. Although this fracture was not detected during the fatigue test, it started after crack No. I-V since it is a smaller crack.

Group FA

Specimen FA-3, Fig. 28; Locatioh of Cracks, Fig. 9.

Specimen FA-4, Fig. 29; Location of Cracks, Fig. 10.

In both of these specimens, the inside surface geometries of the holes were similar to each other and equivalent to those previously reported (FA-1 and 2). A jagged ripple on the left side of specimen (FA-3) initiated failure on that particular region of the hole. However, it could not have been an excessively severe condition for the crack on the opposite side of the hole appeared at approximately the same number of cycles.

Both specimens evidence rapid propagation of fracture across the inside flame cut surface of the hole after the cracks had started at one of the holes' edges.

Group FB

Specimen FB-3, Location of Cracks, Fig. 11

Specimen FB-4, Fig. 30, Location of Cracks, Fig. 12

A photograph of only one specimen (FB-4) is presented to indicate the typical character of the test surfaces in each of these two specimens. Two test pieces (FB-1 and 2) tested previously had similar surfaces.

These specimens experience somewhat slower propagation of the fatigue cracks, as compared to the FA group, across the depth of the holes once they had formed on the edges of the openings.

Group FD

Specimen FD-1, Fig. 31; Location of Cracks, Fig. 13

Specimen FD-2, Fig. 32; " " " Fig. 14

Specimen FD-3, " " " Fig. 15a.

The two photographs indicate the general character of the flame cut surfaces as produced by machine flame cutting. The flame ripples were small and regular in form as compared to the product of the manually flame cut openings (Group FA).

Once initiated, the fatigue cracks spread rapidly across the flame cut surface—approximately equal to the propagation experienced in the FA group.

Group FE

Specimen FE-1. Location of Cracks, Fig. 15b.

No photographs of either the inside flame cut surface of the holes or of the fatigue cracks are shown, since these characteristic features were similar to those possessed by the FB series.

In this case, the crack propagation across the ground surface of the hole was slow.

Specimen FF-1. Location of Cracks, Fig. 16

Specimen FF-2, Fig. 33, " " " Fig. 17

The one photograph (FF-2) is typical of the inside surface geometry of the holes for both specimens, since their flame cut boundaries were identical in physical character. When compared to the FD group of specimens, their similarity is pronounced.

Travel of the fatigue fracture in these two specimens was moderately rapid and was approximately equal to the rate of propagation undergone by the FB and FC group of specimens.

Group FM

Specimen FM-1, Fig. 34, Location of Crack, Fig. 18a.

Specimen FM-2, " " " Fig. 18b.

Specimen FM-3, Location of Crack, Fig. 19.

Specimen FM-4, " " Fig. 20.

The one photograph (FM-1) is indicative of all four specimens as to the type of surface finish and to the form assumed by the fatigue cracks. In this group, all the fatigue cracks propagated slowly across the surface of the hole--a characteristic similar to that found for Specimen FE-1.

Many of these specimens with un-reinforced openings presented an interesting aspect as to the form or shape assumed by the fatigue fracture in its propagation across the inside surface of the holes. In a few of the test pieces, in which the inside surface boundary remained as flame cut, the crack generally pursued the path created by the bottom of a ripple. However, at certain points in its travel, the fracture propagated in a path perpendicular to the previously formed portion of the crack and subsequently progressed to the adjoining ripple where it would continue to spread in the normal fashion along the ripple itself. A portion of the specimens with bored or ground holes also produced a similar phenomenon. This is both interesting and odd, for the common conception and experience presupposes the formation and spread of these fractures to occur at right angles to the applied stress. Yet, the photographs presented herein definitely reveal this peculiar path of fracture at local regions.

Group B

Specimen B-3, Location of Cracks, Fig. 8

No photographs or radiographs were taken of this specimen since records of the two specimens formerly tested did not reveal any important information. Therefore, it was felt that the information to be obtained did not warrant the expenditure of time and money.

All fractures were similar to those which appeared in specimens B-1 and 2 with the same rapid propagation of cracks once they had formed.