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FATIGUE BEHAVIOR OF AXIALLY LOADED WELDMENTS IN HY-80 STEEL

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UNIVERSITY OF ILLINOIS
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FATIGUE BEHAVIOR OF AXIALLY LOADED
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A REPORT OF AN INVESTIGATION CONDUCTED

by

THE CIVIL ENGINEERING DEPARTMENT
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DEPARTMENT OF CIVIL ENGINEERING
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SYNOPSIS

Axial load fatigue tests on several types of weldments in heavy chemistry HY-80 steel are reported in the life range between 10,000 and 100,000 cycles. Included in the studies are the effect of surface geometry in butt welds and the effect of various cyclic conditions of loading. The data are supplemented by metallurgical studies of typical welds.

The test results indicate that the fatigue resistance of sound welds in high strength steels (of the HY-80 type) is considerably higher than that of welds in medium carbon or low alloy steels in the life range up to approximately 10^5 cycles. When greater repetitions of load have to be resisted, there appears to be very little difference in the fatigue resistances of the various steels. The high strength steels have been found to be more fatigue notch sensitive than the lower strength steels and highly susceptible to even the most minor internal discontinuities.

The metallurgical studies indicate that the effects of geometrical discontinuities (external or internal) are much more effective in reducing the fatigue strength of the welded members than the metallurgical factors introduced by welding.

FATIGUE BEHAVIOR OF AXIALLY LOADED WELDMENTS IN HY-80 STEEL

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FATIGUE BEHAVIOR OF AXIALLY LOADED WELDMENTS IN HY-80 STEEL

1. INTRODUCTION

1.1 GENERAL CONSIDERATION OF PROBLEM

The past few years have seen a marked increase in the use of new high strength structural steels for the fabrication of welded structures. However, this application of the materials has raised a number of questions, one of which is the possibility of failure in such structures when they are subjected to repeated loads.

It is well known that welds, or for that matter any stress concentration, can have a marked influence on the fatigue behavior and possibly cause failures in metals that are subjected repeatedly to nominal stresses considerably below their static ultimate strength. In general, the conditions associated with fatigue failures include one or more of the following:

(a) Stress concentrations,

(b) Repetitions of stress,

(c) Large amplitudes and/or high mean stresses.

The role played by a weld in fatigue is generally associated with three factors. First, in a majority of cases, a weld constitutes a sudden dimensional discontinuity which in turn acts as a stress concentration. The effect of this stress concentration in reducing the fatigue strength of structural components is well known.

The second factor is the change of properties resulting from metallurgical changes brought about by the welding. For example, the structure of the base metal in the heat affected zone, e.g., the part of the parent metal affected by the weld, is heated in such a manner that grain coarsening results. This change in grain structure is usually accompanied by a change in physical properties of the parent material.

The third factor contributed by welding is the residual stresses imparted to the weldment. Since residual stresses may change the local cyclic conditions of stressing, there is reason to believe that they also may have an influence on the fatigue behavior of a weldment. Over the years, this has been the subject of considerable controversy and of much research.

In addition to the above discussed role played by a weld, there are several other inherent factors which should be mentioned. It is well known that materials respond differently to the effect of stress concentrations in fatigue; the high strength materials are affected more than the low strength materials. Thus, the high strength materials are said to have a higher fatigue notch sensitivity. Secondly, it may be expected that various steels will respond differently to the metallurgical changes imparted by welding. Lastly, one might consider that fatigue fractures consist of two stages--the initiation and the propagation of the cracks, each of which may be governed by different criteria.

The problem of fatigue in welded structures is further complicated by the fact that it is practically impossible to obtain perfectly sound welds or to duplicate welds in the strict sense. Also, at present, there are no satisfactory methods available for assessing accurately the effect of weld flaws on the fatigue behavior of weldments.

1.2 EXISTING FATIGUE DATA

Relatively little information is available concerning the fatigue behavior of weldments in high strength steels of the HY-80 type. Most of the published fatigue data is for weldments in ASTM A-7 medium carbon mild steel. In addition, most of the available data are concerned with long life fatigue behavior (in the range 10^5 to 2×10^6 cycles). As a result, it is not possible at present to provide realistic predictions of the fatigue behavior of weldments in the high strength quenched and tempered steels, especially at high service stresses.

1.3 OBJECT AND SCOPE OF INVESTIGATION

The current research program was initiated to study and evaluate the high stress-low life fatigue behavior of weldments in heavy chemistry (1 1/2-in. thick), HY-80 steel. The study has been divided into two phases:

(a) A series of exploratory tests to provide information concerning the general fatigue behavior of several types of weldments in HY-80 steel.

(b) A series of tests to provide fatigue data for the more commonly used weldments under a variety of cyclic and geometrical conditions.

The studies include fatigue tests on plain as-rolled plates, longitudinal butt welds, fillet-welded transverse attachments, full penetration transverse attachments and tees, longitudinal fillet welded joints and transverse butt welds. Metallurgical examinations of typical specimens have been conducted to determine the metallurgical changes imparted due to the various welding procedures used and to evaluate the effect these changes might have on the fatigue behavior of the members.

A limited number of exploratory tests on a 3/4-in. HY-80 steel have been conducted also to provide comparisons with the tests on the 1 1/2-in. heavy chemistry material.

The present report covers the studies made during the period 1 May 1959 to 30 June 1960. The results of approximately 80 fatigue tests are reported.

2. DESCRIPTION OF MATERIALS AND TESTS

2.1 MATERIALS

The heavy chemistry (1 1/2-in. thick) HY-80 steel used for the tests reported herein was from two different heats. The physical characteristics and chemical compositions of these heats are summarized in Tables 1 and 2 respectively. In Table 1 and in the general test program, letter designation has been used to differentiate between the different heats. All specimens numbers with a prefix 'HL' were fabricated from heat No. 20995 and those with a prefix 'V' were fabricated from heat No. 19595-1.

A limited number of exploratory fatigue tests were conducted on a 3/4-in. HY-80 steel available in the laboratory. The letter designation used for this steel is 'YS'. It's physical properties* are included in Table 1.

The welding electrodes employed throughout the program were of MIL 11018 grade. The electrodes were conditioned prior to welding by baking at 800°F for two hours and then storing in an oven at 200 to 300°F until used.

2.2 TEST SPECIMENS

The specimens used in the test program had an overall length of 4'-0" and a reduced section in the center. Details of the different types of specimens are given in Fig. 1. For all types of specimens, except type k, the general profile was the same--a 5-in. long straight test section was provided in the middle with a transition radius of 9 in. The width of the test section was governed by the cyclic stress to be applied and the capacity of the testing machine.

* A chemical analysis of this material is not available.

In all but one type of specimen (type d) flame cut blanks of the appropriate length were employed and the specimens fabricated as described in Section 2.3. For the type d specimens, a short central test blank was prepared which was butt welded to pull heads salvaged from previously tested specimens.

2.3 FABRICATION OF SPECIMENS

For the preparation of plain plate specimens, 9-in. by 48-in. flame cut blanks were first drilled at the ends and the profile of the specimen then machined to the final dimensions indicated in Fig. 1(a). No material near the test section was removed by flame cutting.

As a first step in the preparation of the welded specimens, the operator and the welding procedure were qualified in accordance with standard practice.(1,2)*

After the welding procedure was established the edges of the blanks were prepared for welding and all mill scale and undesirable material was ground off in the area where the weld was to be deposited. The specimen was then securely clamped in a jig which could be rotated about a horizontal axis so that all welding could be done in the flat position. The preheat was applied, the temperatures being measured with the aid of a pyrometer, and the specimens welded in accordance with the qualified procedures. The members were then allowed to cool in the jig until they attained room temperature.

The welding technique employed for welding of the heavy chemistry HY-80 was the so-called string or tempering bead technique. In this technique, the first or outside pass of each layer of weld metal (particularly the outer or last layer) was deposited against the base plate with the following passes

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* Numbers in parantheses refer to corresponding entries in the bibliography.

deposited in a manner to overlap the first pass without touching the base plate. This procedure ensures that the deposition of successive passes causes a tempering effect on the preceding passes.

The rates of travel recorded for the welding procedures are minimum values so that the heat inputs did not exceed the specified values.

Subsequent to the welding and machining of the specimens, the edges of all specimens, except the longitudinal fillet welded points, were draw filed. The welds from which the reinforcement was to be removed were ground with a portable disc grinder. The grinding was started with a 36 grit wheel and then finished with a 120 grit wheel in such a manner that the final marking from the grinding were parallel to the direction of loading.

2.3.1 Transverse Butt Welds

The blanks for the transverse butt welds were saw cut and the edges beveled for a double-V butt weld with a 60° included angle. The details of the welding procedures employed for these members are presented in Figs. 5, 7, 8 and 10. In each case a 4-in. length of weld was prepared and then the test section finished to the 2 1/2-in. width shown in Fig. 1(b).

Welding procedure A (Fig. 5) was used exclusively for the 3/4-in. HY-80 plate. Procedures B, C and D were used for the 1 1/2-in. thick HY-80 plate material.

Initially there were three specimens (Specimens HL-4, 5 and 6) prepared with welding procedure B. These three specimens were tested and in each case the fatigue crack initiated at the edge of the weld, thereby suggesting that the procedure was suitable to produce sound welds for fatigue loading. The next set of specimens (V-1 to V-9) were prepared with this same procedure. The static tensile tests of specimens V-1 and 2 again suggested that the weld procedure was suitable. However, of the seven remaining specimens of this group, all of which were tested in fatigue, five failed in the weld metal. For this reason the welding procedure was revised to procedure C (Fig. 8). Of the specimens prepared with this procedure (Specimens V-10 to V-22), only two failed in the weld.

In an effort to obtain a smoother weld profile for the butt welds, welding procedure D (Fig. 10) was used. This procedure required 24 passes in 12 layers instead of the 10 layers used in procedures B and C.

Typical macrographs for the four welding procedures for transverse butt welds are shown in Figs. 6, 9 and 11.

2.3.2. Longitudinal Butt Welds

The welding procedures for the longitudinal butt welds are presented in Figs. 12 and 13. These procedures (E and F) are essentially the same as procedure C for the transverse butt welds. The principal difference lies in the weld lengths and the positions of the change of electrode.

Welding procedure E was used for the type d longitudinal butt welds (Fig. 1). The blanks were then butt welded to the pull heads with a procedure similar to that used for the transverse butt welds.* The weld reinforcement of the pull head butt welds was machined flush prior to testing.

Welding procedure F (Fig. 13) was used for the type c longitudinal butt weld specimens (Fig. 1). In this procedure, the positions for change of electrode in the central 12-in. length of the weld were controlled, the other conditions being the same throughout. All weld passes were started or stopped in the center of the specimen; the effect of this procedure will be discussed in Chapter 3.

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* This procedure was not recorded.

Typical macrographs of welds from procedures E and F are presented in Fig. 14.

2.3.3 Fillet-Welded Transverse Attachments

The specimens with fillet-welded transverse attachments, shown in Fig. 1(e), were welded in accordance with procedure G of Fig. 15. The 3/8-in. fillet welds were deposited in two passes. No special joint preparation was required except for the cleaning of the surface by grinding. The weld passes were deposited in the flat position and successive weld passes were deposited in opposite directions.

A typical macrograph for welding procedure G is shown in Fig. 16

2.3.4 Full Penetration Transverse Attachments and Tees

Specimens with full penetration transverse attachments and tees (types f, g and h of Fig. 1) were welded in accordance with procedures H, J and K, presented in Figs. 17, 19 and 21, respectively. The procedures were similar, the maximum heat input was kept at 40,000 Joules per inch of weld, and the preheat and interpass temperatures at 200°F.

Typical macrographs of welds from each of the welding procedures H, J and K are shown in Figs. 18, 20 and 22, respectively.

2.3.5 Longitudinal Fillets

Specimens with longitudinal fillets, details of which are shown in Fig. 1(k), were geometrically different from all the other specimens tested. These specimens consisted of two outside plates having a reduced thickness in the test section and a single inside plate. The outside plates were machined to the required dimensions before being welded to the inside plate.

The welding procedure employed for these specimens is shown in Fig. 23 and is designated as procedure L. The fillets were deposited in a single pass and the length of the fillets varied for each of the specimens tested. For specimen HL-13 the fillet was 4 in. long and was deposited as a continuous weld. Specimens HL-14 and HL-15 had fillet lengths of 6 in. and 8 in. respectively, being deposited with a change of electrode at mid-length as indicated in Fig. 23.

2.4 PREPARATION OF SPECIMENS FOR METALLURGICAL EXAMINATION

After each fatigue test, the test section of the specimen was removed and the pull heads discarded. The metallurgical examinations have been made on small sections of the specimen taken from positions near the point of initiation of the fatigue cracks.

The sections thus obtained were prepared for metallurgical examination by standard polishing techniques. The sections were etched using a two percent nital solution and then examined. The results of the metallurgical examinations are described in Chapter 3.

2.5 TESTING EQUIPMENT

All the fatigue tests reported herein were conducted at room temperature in an ordinary non-corrossive environment using University of Illinois 200,000 lb. lever type fatigue machines. The speed of these machines is approximately 200 cycles per minute.

The essential features of the fatigue machines are shown schematically in Fig. 2. A variable throw eccentric transmits the force through a dynamometer to a lever which, in turn, transmits the force to the upper pull head at a multiplication ratio of approximately 15 to 1. The force that is exerted on the specimen originates in the double throw eccentric which is adjusted to give the desired range of load before the test is started. The maximum load is controlled by the adjustable turnbuckle mounted between the eccentric and the dynamometer.

A general view of the fatigue testing machines is presented in Fig. 3. In Fig. 4, a transverse butt welded specimen is shown bolted in a machine.

2.6 TESTING PROCEDURES

All of the fabricated specimens were subjected to close visual inspection for cracks upon completion of welding and prior to testing. Many of the specimens were checked for cracks using a magnetic particle crack detection procedure. However, in no case were any cracks found.

A number of the transverse and longitudinal butt welds were X-rayed prior to testing. A rating of these specimens is presented in Table 12 and a correlation of these ratings with the actual test data is presented in Section 3.8.

The criterion for failure of the specimens, as far as feasible, was taken as the number of cycles at which approximately half the cross-sectional area of the specimens had been fractured. This could not be followed in all cases because the automatic microswitches on the fatigue machines did not always stop the machines before the members had fractured half way through. In cases where the complete specimen was fractured, no attempt was made to correct the life to that for which approximately half the cross-sectional area would have fractured. There are two reasons for this. First, there are not sufficient data available to determine the rate of crack growth in welded members under repeated loads. And, second, laboratory observations have indicated that fatigue cracks usually take a fairly small percentage of the total fatigue life to propagate in the type of members used. Also, if one considers the inherent scatter associated with fatigue testing, it does not seem necessary to make small corrections of the nature discussed above.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 EVALUATION OF FATIGUE STRENGTH

To compare numerically the results of fatigue tests of specimens tested at different stress levels, fatigue strengths corresponding to failure at particular lives have been computed using the equation

$$F = S \left(\frac{N}{n}\right)^{k}, \qquad \text{Eq. (3.1)}$$

where S is the stress at which the specimen failed after N cycles, n is the number of cycles for which the fatigue strength F is desired and k is an experimentally determined parameter.

Equation (3.1) is an empirical equation, derived on the basis of laboratory observations[3] and is based on the assumption that the finite part of the S-N relationship, when plotted to a logarithmic scale, can be represented by a straight line. Laboratory investigations have revealed that k, the slope of the S-N curve, is a function of the material properties, the geometry of the specimen, and the cyclic loading to which it is subjected. As a result, the computed values of fatigue strength are only approximations. Nevertheless, because of the logarithmic nature of the relationship, the error associated with values of computed fatigue strengths resulting from any error in the assumed value of k are generally relatively small.

The results of all series of fatigue tests in this study have been plotted on a logarithmic basis using nominal stresses and average curves drawn through these data. A value of k was assumed initially and the fatigue strengths for two lives computed. The average values of these fatigue strengths were then used to determine a new value of k and the process repeated until the assumed and computed values of k coincided. A scatter band parallel to the average curve has been shown in most instances.

3.2 FATIGUE TESTS OF PLAIN AS-ROLLED SPECIMENS (AXIAL TENSION)

The results of fatigue tests on plain plate specimens in the as-rolled condition are presented in Table 5 and are shown diagramatically in Fig. 24. Six fatigue tests on a zero-to-tension stress cycle were conducted on two different thicknesses of HY-80 steel.

Also shown in Fig. 24 are the results of fatigue tests conducted on similar specimens of two other quenched and tempered steels[4,5] having static tensile strengths of 108.0 ksi and 123.0 ksi. Thus the data provide an indication of the fatigue behavior of four steels with ultimate strengths ranging from 94.0 ksi to 123.0 ksi. An average curve (heavy line in Fig. 24) has been drawn through the experimental points. The results of the fatigue tests on the 1 1/2-in. thick HY-80 fall near the average curve for the several quenched and tempered steels. However, the 3/4-in. HY-80 results seem to be consistently below the average curve; a second curve has been shown for these points (lower curve in Fig. 24).

One of the plain plate specimens, specimen HL-1, was tested with instrumentation to determine the magnitude of bending introduced by the fatigue machine. The specimen was instrumented with SR-4 strain gages and strain records made throughout the course of the test. The strain data indicated that the maximum variation of the stress on any of the four faces was $\pm$ 15 percent from the average stress on the specimen. This is comparable to having the load applied with an eccentricity of approximately 1/25 in.

In the course of instrumenting specimen HL-1, the mill scale was removed from the surfaces of the specimen in the test section. The effect of this treatment is reflected in the results of the fatigue test of this specimen as shown in Table 5. Whereas specimens HL-2 and HL-3 failed after 437,600 and 701,900 applications of loading respectively, specimen HL-1 did not fail in

3,321,200 applications of the same loading. This clearly demonstrates the effect of the mill scale or the surface condition on the fatigue behavior of the plate alone.

The fatigue failures of all the plain plate specimens initiated at the start of the fillet radius (at the end of the test section), due to the discontinuity in the section at that point. All the fatigue cracks initiated at the surface. In one particular case (specimen HL-3), a secondary crack initiated subsequent to the initiation of the primary crack. Photographs of the two faces of specimen HL-3 showing the two fatigue cracks are presented in Fig. 25.

3.3 STATIC TESTS OF TRANSVERSE BUTT-WELDED JOINTS

To determine the static strength of butt-welded joints in the heavy chemistry HY-80 being used in the program, two butt-welded specimens, V-1 and V-2, were tested to failure under static tensile loading. These specimens were prepared using welding procedure B (Fig. 7) and the profile shown in Fig. 1(b). The specimens were tested with the weld reinforcement in place.

The results of these two tests are presented in Table 4. Both specimens fractured in the base metal a short distance away from the weld and at a tensile strength of approximately 94.0 ksi. This is about 7 percent lower than the coupon strength of the plate material. However, since the welded specimens failed away from the weld (in the unaffected parent metal), the strengths can be considered representative and within the range expected from the parent plate.

3.4 FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS (AXIAL TENSION)

The results of the fatigue tests conducted on transverse butt welds in axial tension (zero-to-tension) are presented in Tables 6 and 7. These members were tested in three different geometrical conditions, the as-welded condition, with the reinforcement removed from both sides or from one side only.

3.4.1 Specimens in the As-Welded Condition

The profile of the specimens for these tests is shown in Fig. 1(b); the details of the tests and the test results are shown in Table 6. For all of the specimens tested, failure initiated at the edge of the weld reinforcement and then propagated through the base metal. An S-N diagram for these tests is presented in Fig. 26. The average curve on this diagram represents the results of the tests on butt welds in the heavy chemistry HY-80, all of which were tested at stresses which produced failure at lives in the range between 20,000 and 300,000 cycles. The results of several tests on joints in 3/4-in. plate, also shown in Fig. 26, do not seem to fall in line with the data from the heavy chemistry 1 1/2-in. thick HY-80 and have not been included in the average curve. It will be noted that the data for the 1 1/2-in. material fall within a fairly narrow scatter band.

Typical fracture surfaces and locations of fatigue cracks relative to the weld reinforcement are shown in Fig. 35.

3.4.2 Specimens with Reinforcement Removed

The results of tests on specimens for which the reinforcement had been removed are given in Table 7 and are shown diagrammatically in Fig. 27. Of the specimens tested, only one specimen fractured at the edge of the weld. For all the other specimens, failure initiated in the weld.

The removal of the weld reinforcement removes the dimensional discontinuity on the surface of the specimen at the edge of the weld and, as a result, it can be expected that the fatigue strength of the member would be increased. At the same time, however, the removal of the reinforcement can be expected to increase the significance of internal flaws. To realize fully the advantage of the removal of the weld reinforcement would thus require welds which are free of internal flaws.

The results obtained in the tests on members with the weld reinforcement removed are in agreement with the behavior discussed above. However, it must be borne in mind that the degree to which the weld flaws affect the fatigue resistance is undoubtedly a function of the shape, size and location as well as the orientation of the flaws. In cases where serious flaws are present, the fatigue resistance of a member for which the reinforcement has been removed may be less than that of a joint tested with the reinforcement in place. At present there is but little information available concerning the effect of weld flaws on the fatigue resistance of welded joints.

Because of the many factors involved, it becomes extremely difficult to interpret the results of weld failure tests when the reinforcement has been removed. However, an attempt has been made to evaluate the results of the present tests by the curves shown in Fig. 27. The two specimens exhibiting the poorer lives were arbitrarily neglected and the curves sketched through the remaining points.

Typical fractures of transverse butt welds with reinforcement removed are presented in Figs. 38 and 39*.

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* In Fig. 39(c) the crack has been accentuated by marking it with ink.

3.4.3 Analysis of Data

Figure 28 shows a summary of the fatigue test results obtained on transverse butt welds in a zero-to-tension cycle. Also shown is the average S-N curve for the plain, as-rolled plate specimens from Fig. 24.

In Fig. 28, it is evident that when a transverse butt weld is introduced in a plate, the fatigue resistance drops from curve d to curve a. The difference between these two curves represents both the geometrical and metallurgical effect of welding.* The removal of the reinforcement of the weld on one side improved the fatigue resistance from curve a to curve b, whereas if the reinforcement is removed from both sides, the fatigue resistance is improved from curve a to curve c. The difference between curve c and d then would appear to represent the metallurgical effect of the welding process or the effect of internal weld flaws.

Even though curves b and c are approximate, the trend in behavior discussed above can be visualized readily from the comparisons presented in Fig. 28. In addition, it appears that at very high stresses (near the yield point of the material) the weld and metallurgical effects became insignificant. At the lower cyclic stresses the various factors associated with welding appear to have a much more pronounced effect on the fatigue resistance of the plates with transverse butt welds. However, it should be emphasized that curves b and c, Fig. 28 (and the curves in Fig. 27) are very approximate and require further verification.

Another point which has been observed in these data is that the magnitude of the effect of a transverse butt weld in a plate becomes increasingly more significant with a decrease in the stress level or an increase in life.

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* It is assumed that in these tests the residual stresses had a negligible effect on the behavior of transverse butt-welded joints.

This observation is illustrated in Fig. 29. Here it is clear that the reduction in fatigue resistance of a plain plate, due to the presence of a transverse butt weld, is almost insignificant at a life of approximately 20,000 cycles, is almost 32 percent at a life of 10^5 cycles and 55 percent at a life of 10^6 cycles. A similar comparison with average data for ASTM A-7 and A-242 steels[(6)] is given below.

Steel	Percentage Reduction in Fatigue Strength of Plain Plate Due to Transverse Butt Weld (in the as-welded condition)	
	10^5 cycles	10^6 cycles
HY-80	32	56
A-7	32	36
A-242	27	30

From these data it appears that there is a significant difference in the effect of a transverse butt weld at the long lines. Whereas the percentage reduction in fatigue strength at 10^5 cycles is approximately the same for A-7, A-242 and HY-80, the reduction for HY-80 is markedly greater than for A-7 and A-242 at a life of 10^6 cycles. Thus, at the longer life the higher strength steel is more fatigue notch sensitive.

3.5 FATIGUE TESTS OF TRANSVERSE BUTT WELDS (COMPLETE REVERSAL)

The results of the tests conducted on transverse butt-welded joints under a completely reversed (axial) stress cycle are presented in Tables 8 and 9 and are shown diagrammatically in Figs. 30 and 31. Specimens with reinforcement removed from one or two faces were tested as well as specimens in the as-welded condition.

3.5.1 Specimens in the As-Welded Condition

The results of this series of tests are presented in Table 8. In the thirteen specimens tested, eight failures initiated at the edge of the weld reinforcement and five in the weld. The five joints which failed in the weld were prepared with the same welding procedure (procedure B, Fig. 7). However, the fatigue cracks in two specimens prepared with the initial welding procedure (specimens V-5 and V-7 of Table 8) initiated at the edge of the weld reinforcement. [In specimen V-5, a secondary crack had started inside the weld, see Fig. 9(a)]. The transverse butt welds for the two static tests were prepared with welding procedure B also and failed in the parent metal away from the weld. As a result, it is again evident that weld quality assumes major significance under repeated loads and that the current methods of evaluating welding procedures by means of static bend or tensile tests[1,2] may be inadequate for welded members which are to be subjected to repeated loads.

The results of the tests of the specimens of the present series are shown diagrammatically in Fig. 30. An average S-N curve has been drawn in the figure on the basis of the specimens that failed at the edge of the weld. It will be noted that the scatter band for these specimens is relatively large and that all but two of the weld failures (specimens V-4 and V-6) fall within the scatter band. It thus appears that the flaws present in specimens V-4 and V-6 were major flaws and those in the other specimens exhibiting weld failures were minor flaws which reduced the fatigue resistance of the members no more than the external weld geometry.

Typical fracture locations and fracture surfaces are shown in Fig. 35 for failures at the edge of the weld and Figs. 36 and 37 for failures in the weld. The fracture surfaces in Fig. 36 clearly show the points of initiation of the fatigue cracks.

The fracture surfaces of V-4 and V-6, Fig. 36, indicate that the fractures initiated inside the weld, at discontinuities in the deposited metal. No complete explanation for this behavior is at present available; however, it is believed that the internal discontinuities in these specimens may have been sufficiently severe to sustain a high rate of crack propagation. To further demonstrate this matter consider for instance the results of specimens V-4 and V-25. Both of these tests were conducted at a stress of $\pm$ 40.0 ksi. While the total life of specimen V-4 was 2600 cycles, specimen V-25 withstood 60,000 applications of the same nominal stress up to the point at which the first visible fatigue crack was observed. Specimen V-25 then withstood an additional 2,500 cycles as the fatigue crack propagated through approximately 25 percent of the cross-sectional area--almost the total life of specimen V-4. Thus, it may be concluded that the question of crack initiation and propagation in welds and welded members is in need of further study.

3.5.2 Specimens with Reinforcement Removed

None of the four specimens with reinforcement removed and tested on a fully-reversed cycle exhibited a normal pattern of fracture (Table 9 and Fig. 31). The results of these tests indicate that the members have a fatigue resistance lower than that for the as-welded specimens tested under the same cyclic conditions of loading. Typical fractures for these members are shown in Figs. 38 and 39.

Because of the type of fractures obtained with these specimens, it has not been possible to evaluate fully the fatigue behavior of the members. Nevertheless, these results once more clearly show the importance of the quality of welds when they are subjected to repeated loads.

3.6 TENSILE AND COMPRESSIVE MEAN STRESSES IN FATIGUE TESTS OF TRANSVERSE BUTT WELDS

A limited number of fatigue tests were conducted to study the effect of mean stress on the fatigue behavior of transverse butt welds. The results of these tests are presented in Table 10. Using these data along with some of the test results for a completely-reversed stress cycle (zero mean stress) and a zero-to-tension stress cycle (tensile mean stress), Fig. 32 has been prepared to show the effect of mean stress on the fatigue life of transverse butt welds under alternating stresses of various magnitudes. All these tests were conducted on specimens in the as-welded condition.

Since limited data are available, it is possible only to show the general shape of the relationships. Nevertheless, test data are plotted on Fig. 32 for four different magnitudes of alternating stresses. It is evident that at low alternating stresses, corresponding to longer lives, a variation in the maximum tensile mean stress has little influence on the life whereas an increase in compressive mean stress produces an increase in the life. In other words, the fatigue resistance is almost entirely a function of the range of stress alone for tensile mean stresses at longer lives. On the other hand, as the alternating stress is increased, the curves tend to bend over towards the left, indicating that at higher alternating stresses an increase in the tensile mean stress reduces the life.

Little information is available concerning the effect of low compressive mean stresses. However, there appears to be a sudden transition in the behavior at relatively low compressive mean stresses; an indication of the effect is shown in Fig. 32 for an alternating stress of ± 20 ksi. But, until more experimental data are available, it will be difficult to indicate what effect compressive mean stresses will have at other magnitudes of alternating stress.

With the data obtained to date, it has been possible to construct the approximate modified Goodman Diagram, shown in Fig. 33. Constant life contours have been drawn for lives in the range of 20,000 to 500,000 cycles. It is evident from this presentation that at lives in the neighborhood of 10^6 cycles, the range of stress for a completely reversed stress cycle is approximately the same as that for a zero-to-tension stress cycle. This again shows that at the longer lives the behavior is governed exclusively by the range of stress, the maximum cyclic stress playing only an insignificant role. On the other hand, it is evident from the diagram that as the life decreases and the cyclic stresses increase, the behavior is governed by the maximum stress as well as the range of stress.

In addition to the above evaluation of data in the modified Goodman Diagram, it is possible to examine the effect of variation of either the alternating or the mean stresses on the life. The ordinates for a completely reversed stress cycle correspond to zero mean stress and those representing the points for a zero-to-tension stress cycle correspond to alternating stresses equal to the mean stresses. Thus, using an inclined grid system, the constant life contours in Fig. 33 can be examined as functions of the alternating stress and the mean stress. From such a presentation one can see readily the effect of mean stress, maximum stress, or alternating stresses on the fatigue behavior. The constant life contours meet at a mean stress and maximum stress corresponding to the static strength but diverge as they approach a zero mean stress. Nevertheless, it may be seen that irrespective of the life, the behavior of the joints is governed both by the mean (or maximum stress) and the alternating stress at high mean stresses but, at the lower mean stresses, the relative effects of the alternating and maximum stresses depend upon the life of the member.

Another method of presentation of the test data is shown in Fig. 34. In this presentation, constant life contours for transverse butt welds in the as-welded conditions are presented as a function of the maximum cyclic stress and the stress ratio.* In this instance, as well as in the modified Goodman Diagram of Fig. 33, the constant life contours can be used to predict the fatigue life of a transverse butt-welded joint when subjected to any given cycle of stress. By the same token, the relationships presented in these diagrams can be used as a guide in the development of design requirements for members which are subjected to repeated loads.

It must be emphasized, however, that the discussion presented above is based on a limited amount of data and that the curves have been plotted, in most cases, through only a few points. Nevertheless, the analysis is believed to be indicative of the general trend of fatigue behavior for transverse butt welds. It must also be noted that the analysis is based on specimens exhibiting normal modes of fracture (failure at the edge of the weld reinforcement) and should only be applied to sound welds.

3.7 FATIGUE TESTS OF LONGITUDINAL BUTT WELDS

The results of the fatigue tests of longitudinal butt-welded joints are presented in Table 11 and in Fig. 48. Five such tests were conducted on members in the as-welded condition, three on a zero-to-tension stress cycle and two on a completely-reversed stress cycle. The differences in the fabrication techniques employed for these specimens have already been discussed in Section 3.3.2.

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* The ratio of the minimum stress to the maximum stress.

An approximate S-N curve for the zero-to-tension tests is plotted in Fig. 48. However, since both tests on reversal were conducted at the same cyclic stress, it is not possible to construct an S-N curve for the reversal condition.

From the results of the zero-to-tension tests, it appears that at low lives (less than approximately 10^5 cycles) the fatigue strengths of the longitudinal butt welds are smaller than the corresponding values for transverse butt welds. At lives greater than approximately 10^5 cycles, the opposite is observed, the longitudinal welds have a greater life than the transverse butt welds. On a completely reversed stress cycle, it appears that the fatigue life of a longitudinal butt weld at $\pm$ 30.0 ksi (about 40,000 cycles) is slightly lower than the corresponding value for a transverse butt weld.

Also presented in Fig. 48 is the S-N curve for plain as-rolled plate specimens on a zero-to-tension stress cycle. The slope of the curve for the plain plate specimens is very nearly the same as the slope for the longitudinal butt welds. Thus, at the short fatigue lives and on a zero-to-tension cycle, the reduction in fatigue strength of a plain as-rolled plate due to the introduction of a longitudinal butt weld is equal to approximately 15.0 to 20.0 ksi. This behavior is completely different from that shown in Fig. 29 for transverse butt welds. In the case of the transverse welds, the reduction in fatigue strength was found to increase with an increase in life.

It will also be observed in Fig. 48 that the fatigue life at a range of stress of 60.0 ksi was greater for a zero mean stress (corresponding to the completely-reversed stress cycle) than for a mean stress of + 30.0 ksi (corresponding to the 0 to + 60.0 ksi stress cycle). In other words, both the mean stress as well as the alternating stress appear to have an affect on the fatigue behavior of these specimens in the life range between approximately

10,000 and 50,000 cycles. This was true also for the transverse butt welds, as seen from Fig. 32. However, at longer lives, corresponding to lower alternating stresses, the behavior of longitudinal butt welds will probably be governed primarily by the range of stress as in the case of transverse butt welds (see Fig. 32 and Section 3.6).

Fractures of longitudinal butt welds tested with the reinforcement in place are generally of two types. The fractures start either at the surface of the reinforcement in a weld ripple or, at internal flaws or re-strike positions in the test section.

Three specimens were prepared with welding procedure E (Fig. 12); one of these specimens fractured in the test section at an internal re-strike position and the other two specimens (HL-11 and HL-12) fractured at the end of the test section, again at internal re-strike positions. These fractures are shown in Fig. 49. Both the specimens prepared with welding procedure F (Fig. 13) fractured at the center of the members at internal re-strike positions.

Another factor which needs to be considered in connection with the fatigue behavior of the longitudinal butt welds is the effect of residual stresses. The magnitude of the maximum longitudinal residual stress has been reported to be a function of the length of the weld. For a 1-in. plate, DeGarmo and co-workers(7) have reported an optimum weld length of the order of 20 in. The longitudinal residual tensile stress is high in the center and decreases toward the end of the weld.

It can be expected that the influence of the residual stresses on longitudinal butt welds will be dependent upon the nature and magnitude of the superimposed cyclic conditions. For most members with short lives (high applied stresses) the effect of residual stresses on this life has been very small; however, for members which sustain many cycles of load application, (low applied loads and long lives) the residual stresses have been found to either increase or decrease the fatigue resistance depending upon the sense of the residual stress and of the applied stress. For instance, Trufyakov(8) has reported that at low superimposed tensile stresses, longitudinal residual stresses reduce the life of welded members by as much as 40 percent at the fatigue limit. The reduction becomes smaller at lower lives and is practically negligible at a life of approximately 10^5 cycles. But, in the case of transverse welds, numerous investigations have indicated no significant differences between the fatigue strength of welds tested in the as-welded condition and those tested in the stress-relieved condition.

3.8 X-RAY EXAMINATIONS OF BUTT WELDS

The results of the radiographic examinations of transverse and longitudinal butt welds are presented in Table 12. Also indicated for each specimen are the welding procedure and the location of the primary fatigue crack.

The radiographs have been compared with standard radiographs(9). Except for isolated cases of a slight amount of undercutting, the welds were found to be of excellent quality. Typical radiographs are shown in Figs. 65 and 66.

In spite of the excellent quality of the welds, fatigue failures initiated in the weld of Specimens V-30 to 38 inclusive. These specimens were tested with the reinforcement removed from either one side or both sides. Apparently the weld metal has a lower fatigue strength than the base metal, even though the weld metal has the greater static strength and the radiographic examinations showed the welds to be sound.

The radiographs shown in Fig. 65 (radiographs of Specimens V-1 and V-2 were taken after the joints had been loaded statically to failure) were the only pictures taken of specimens welded using procedure B. Specimens V-4 and V-6, members which had unusually low lives were prepared with the same welding procedure. Since all four of these specimens were welded using the same procedure and by the same operator, it is believed that the specimens were all radiographically sound. Yet, the failures in Specimens V-4 and V-6 occurred internally at low fatigue strengths.

Figure 66 shows a radiograph for Specimen V-33, which was prepared by welding procedure D-2. This specimen when the reinforcement had been removed, also fractured in the weld (see Fig. 38 and Table 9). Thus the D-2 welding procedure, although producing a sound weld, does not always produce a weld metal of adequate fatigue strength.

3.9 METALLURGICAL EXAMINATIONS OF BUTT WELDS

This section is concerned with the metallurgical studies which have been made of the butt welds. The metallurgical examinations of the weldments were made to evaluate the changes in metallurgical structure and physical characteristics that resulted from the welding and to correlate these structures with the fatigue behavior of the weldments. At least one of the specimens prepared with each of the welding procedures was examined. In addition, specimens that fractured at the edge of the weld as well as some that fractured in the weld metal were examined.

3.9.1 Metallurgical Characteristics of the Parent Metal

HY-80 steel is a quenched and tempered, fully killed, fine-grained steel which derives its physical and metallurgical characteristics from the quenching and tempering. The significant features of the chemical composition of this material (see Table 2) are its low carbon content which provides toughness and weldability, the alloying elements which impart hardenability and insure that transformation products form at low temperatures, and the high nickel content which provides greater strength and toughness.

Typical microstructures of the different heats of HY-80 steel employed in this investigation are shown in Fig. 40 (3/4-in. plate), Fig. 41 (1 1/2-in. plate, heat no. 19595-1) and Fig. 50 (1 1/2-in. plate, heat no. 20995). The structures of both heats of 1 1/2-in. thick base metal are almost alike; however, heat no. 20995 appears to have a slightly larger austenitic grain size.

3.9.2 Metallurgical Effects of Welding HY-80 Steel

During welding, the base metal in the vicinity of the weld is subjected to a complex thermal cycle and steep temperature gradients ranging from the original temperature of the metal to its melting point. The effect of this thermal cycle on the metallurgical structure of the base metal is especially noticeable in the region subjected to the higher temperatures. These changes in the base metal depend not only on the temperature to which a particular point is heated but also on the cooling rate at which the heat is dissipated subsequent to the welding operation. The cooling rates, in turn, depend on the rate of heat input, the preheat temperature, the thickness or size of the specimen and the joint geometry. High heat inputs and preheating favor slow cooling whereas heavy sections encourage fast cooling rates. As a consequence, a gradient in metallurgical structure results in the HAZ.*

The metallurgical characteristics of the deposited weld metal may be affected by the composition and type of electrode, the type of joint, and

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* Heat affected zone.

the size of the specimen as well as the nature of the base metal. When the weld metal is built up from a succession of passes or beads, the original metallurgical structure of the inner passes may be partially or completely altered by the heating of the subsequent passes. The weld metal of the first passes are refined by subsequent passes, the extent of the refinement depending upon the cooling rates, the location within the weld, the temperature to which the weld metal is heated, and the composition of the weld metal. Thus, the initial passes in a multi-layer weld usually show greater refinement than the outside layers. This refinement of the weld metal can be seen in the macrographs of the welds presented in Figs. 6, 9, 11, and 14.

The metallurgical gradients in the HAZ due to the welding process can be related also to the hardness in the various regions in the weld and base metal. The hardness increases to a maximum near the junction of the refined and coarsened zones in the HAZ of the base metal. In the transition from the coarsened zone to the fusion line the hardness drops, perhaps somewhat erratically. The hardness of the weld metal itself is dependent on the type and composition of the electrode and the care with which the weld has been deposited. It should however, be noted that the hardness gradients in the transition from the base metal to the weld metal are, to a certain extent, dependent on the location of the line along which the hardnesses are determined.

3.9.3 Microstructures of Transverse Butt Welds

The metallurgical effects of welding HY-80 steel have been discussed in a general manner in the previous section. A more detailed examination of the microstructures of typical transverse butt welds is presented below. The photomicrographs of the various procedures are presented in Figs. 41 to 47.

SPECIMEN YS-4 (WELDING PROCEDURE A)

Procedure A (Fig. 5) was used to weld 3/4-in. HY-80 plate. Because the plates were relatively thin, the cooling rate subsequent to welding was lower than in the welds in the heavy chemistry HY-80. As a consequence, the resulting structure in the HAZ near the fusion line is a Widmanstätten pattern of pearline and ferrite.*

Farther from the fusion line, the structure of the HAZ is seen to be banded. This is the result of phosphorus segregation, which on slow cooling would give a banded structure. There is also seen to be a grain size gradient in the HAZ.

The lower cooling rates in this specimen also seem to have affected the weld metal structure; it is coarser than the weld metal structure obtained in the 1 1/2-in. plates.

Typical photomicrographs for specimen YS-4 are shown in Fig. 41. A hardness survey near the outer passes indicated the following values: Base metal - 16 to 20, HAZ - 25 to 30, Weld metal - 22 to 25 (Rockwell C).

SPECIMENS V-3, V-4, V-6, V-9 (WELDING PROCEDURE B)

Welding procedure B employed a somewhat higher heat input than procedure A. And, since the plates for the welds prepared with procedure B were heavier than those for the welds prepared with procedure A, the high cooling rate expected in the 1 1/2-in. plate was somewhat offset by the higher heat input. Nevertheless, the cooling rate was such that it prevented the formation of high temperature transformation products while forming a martensitic structure.

The microstructures of the specimens examined were all similar and are shown in Figs. 42 to 44. Near the fusion line, a coarse martensitic

* This structure is generally associated with low cooling rates in low or medium carbon steels and forms at locations where the original austenitic grain size is a maximum.

SPECIMEN V-35 (WELDING PROCEDURE D-2)

Welding procedure D-2 was similar to procedure D-1 except that a higher interpass temperature was employed in procedure D-2 (Fig. 10). As before, no significant difference in metallurgy of the specimen is noticeable from the photomicrographs in Fig. 47 or the macrograph shown in Fig. 11.

Hardness readings taken near the surface passes indicated the following results: Base metal - 19 to 20, HAZ - 33 to 37, Weld Metal - 28 to 31. Hardnesses in the center was: Base metal - 19 to 20, HAZ - 35 to 38, Weld metal - 26 to 31 (Rockwell C).

3.9.4 Microstructures of Longitudinal Butt Welds

Photomicrographs of the two longitudinal butt welds examined metallurgically are shown in Figs. 50 and 51. These specimens were prepared with similar welding procedures (Figs. 12 and 13). Moreover, the welding procedures were identical to those employed for transverse butt welds.

The metallurgical structures in the longitudinal welds appear to be the same as in the transverse butt welds. However, this is to be expected because of the similarity in welding conditions.

A hardness survey near the surface of specimen HL-16 indicated the following results: Base metal - 16 to 18, HAZ - 25 to 39, Weld metal - 22 to 27. In the center the hardnesses obtained were: Base metal 17 to 19, HAZ - 24 to 36, Weld metal - 26 to 33 (Rockwell C).

3.9.5 Analysis of Results

A comparison of the microstructures of the butt welds in the 1 1/2-in. HY-80 steel reveals that, within the differences in the welding procedures employed, there are no significant variations in the metallurgical structure appears to have formed in the base metal and, in the adjacent portion of the HAZ, a fine grained structure developed. The structure of the weld metal was much finer than that of 3/4-in. specimen YS-4. In addition, inclusions were encountered in all of the 1 1/2-in. specimens, as seen in Fig. 42.

A hardness survey of specimen V-5 (also prepared with welding procedure B) is shown in Fig. 9.

SPECIMEN V-20 (WELDING PROCEDURE C)

Welding procedure C was similar to procedure B except that the number of passes was increased from 18 to 20 for procedure C. This change does not seem to have had any significant effect on the metallurgy of the specimens. Photomicrographs of specimen V-20 are shown in Fig. 45 and a hardness survey for this specimen is presented in Fig. 9. A comparison of the hardness readings of V-20 with the hardness readings for V-5 indicates that the HAZ was slightly harder in Specimen V-5, the weld metal hardnesses being about equal.

SPECIMEN V-25 (WELDING PROCEDURE D-1)

The welding proceudre employed for Specimen V-25 differed from welding procedures B and C in that it employed a larger number of passes and a slightly lower interpass temperature. However, as seen from the macrograph of this specimen (Fig. 11) and the photomicrographs (Fig. 46), there is no significant difference in the metallurgy of this specimen from that of the specimens prepared with welding procedures B or C.

A hardness survey near the surface passes in specimen V-25 indicated the following results: Base metal - 16 to 20, HAZ - 32 to 40, Weld metal - 23 to 31. In the center, the hardnesses obtained were: Base metal - 17 to 20, HAZ - 35 to 38, Weld metal - 26 to 31 (Rockwell C).

structures obtained. Nevertheless, there appear to be minor localized variations from specimen to specimen and within a specimen itself.

The welding process produces metallurgical changes which depend on the size of specimen, joint geometry, initial temperature, heat input and the welding technique employed, as well as the characteristics of the base metal and of the welding electrode. In terms of the metallurgical effects of welding and their bearing on fatigue, it is evident that the dimensional discontinuity at the surface of a specimen has a much greater effect on the fatigue behavior than any of the metallurgical factors introduced by welding, provided the weld is free of flaws. The metallurgical structure and the grain size in such a case will only govern the local propagation of the crack which will generally traverse perpendicular to the applied stress.

On the other hand, in cases where weld flaws overshadow the dimensional discontinuity at the surface, the weld flaws will act as nucleii for the initation of fatigue cracks, irrespective of the metallurgy of the HAZ.

On the basis of the results obtained, it appears that the metallurgical factors due to welding assume an important role only in cases where there is no dimensional discontinuity at the surface and the weld is completely free of flaws. However, in this case, even a minor weld flaw becomes important because an internal discontinuity is a more severe stress concentration than a metallurgical gradient.

The two specimens in Table 8 exhibiting extremely poor fatigue lives (V-4 and V-6) did not appear to differ significantly from those specimens having normal lives. Since these specimens fractured completely in the weld, it appears that the poor lives for these specimens were due to internal structural rather than metallurgical causes.

3.10 FATIGUE TESTS OF PLATES WITH FILLET-WELDED TRANSVERSE ATTACHMENTS

The results of the fatigue tests of plates with fillet-welded transverse attachments are presented in Table 13 and shown diagrammatically in Fig. 52. These fatigue tests were conducted on a zero-to-tension stress cycle. For two specimens the attachment was 1/2-in. thick, and for the third specimen it was 1 1/2-in. thick.

From the test results it appears that the fatigue life may decrease with an increase in the thickness of the attachment. This is to be expected, since the thicker attachments participates more fully with the member thereby causing a higher stress concentration at the toe of the fillet welds.

The major factor affecting the fatigue strength of a member with fillet-welded attachments is the stress concentration at the toe of the fillet welds. This stress concentration is, in turn, a function of the geometry of the fillet. If the fillet is deposited or machined to a concave profile, it would be expected to have a smaller effective stress concentration than the as-deposited or triangular profile. Experimental results available in the literature[10,11] confirm this view.

The reduction in fatigue strength resulting from the non-load carrying attachments of the present series appears to be considerably greater than the reduction from load carrying transverse butt welds. At a life of 10^5 cycles, the load carrying capacity of a plate is reduced to a value of one-half when 1 1/2-in. transverse attachments are fillet welded to the plate. However, a transverse butt weld reduces the fatigue strength of the plate by only thirty percent for the same life.

It is apparent that drastic reductions in fatigue strength result from the welding of transverse non-load carrying attachments to plates. These reductions in fatigue strength are a function of the geometry of the attachment and of the stress concentration at the toe of the fillet. In all three specimens tested, fracture initiated at the toe of the weld. The fracture of a typical specimen in this series is shown in Fig. 53.

3.11 FATIGUE TESTS OF PLATES WITH FULL PENETRATION TRANSVERSE ATTACHMENTS

The results of the fatigue tests of plates with full penetration transverse attachments are presented in Tables 14 and 15. The effect of attachments on both sides and on one side only has been studied on a completely-reversed stress cycle. S-N diagrams for these tests are shown in Figs. 55 and 56.

As in the case of fillet-welded attachments, full penetration attachments provide discontinuities at the toe of the welds connecting the attachments to the plate which affect the fatigue strength of the member. As a result, the fractures in these specimens always initiate in the plates at the toe of the weld.

Before discussing the results, it should be mentioned that the profiles of the welds (Figs. 17 and 19) were found to be somewhat difficult to hold when deposited in the horizontal position. The profiles indicated in Fig. 57 are typical of those actually obtained. In most cases, the welds met the main member with a rather sharp curvature and provided a high local stress concentration at which the failures initiated. Since the specimens were all of similar geometry a low scatter was obtained in the results (Figs. 55 and 56).

The fatigue strength of the members with attachments on both sides, because the stress concentrations may be partially additive, would normally be expected to be lower than those with attachments only on one side. A comparison of the S-N curves appears to confirm this condition. However, this difference in fatigue strength is not very great. In fact, at about 10^5 cycles, the two

S-N curves cross. Assuming that the geometry at the toe of the welds where the fractures initiated were reasonably similar, there are two other factors that may have an effect on this behavior. First, the residual stress patterns in the members will be different and undoubtedly unsymmetrical for the specimen with the single attachment. Second, the non-symmetry of the member with an attachment on only one side causes an unsymmetrical stress distribution under a superimposed cyclic stress. These unsymmetrical distributions of stress may tend to reduce the fatigue behavior of the members with single attachments under a reversal of stress, thereby causing the fatigue resistance to be of the same order as for the members with double attachments.

No evaluation can be made of the magnitude of the reduction in fatigue strength produced by the attachments, since no data on plain plates under similar cyclic conditions are available. However, a comparison with the results on transverse butt welds indicates that the full penetration attachments cause a greater reduction in fatigue strength than do the transverse butt welds. Thus, it is evident that the attachments reduce considerably the fatigue strength of the plates.

Typical fracture locations for specimens with full penetration attachments are shown in Fig. 57. As noted previously, the cracks in these specimens initiated at the toes of the welds and then traversed along a path perpendicular to the direction of stressing.

It may be noted that the results obtained are typical only for the profile actually tested. Different fatigue resistances might be obtained with modifications in the weld profile of the members.

3.12 FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS

Six full penetration tee joints of the type shown in Fig. 1(h) have been tested on a completely reversed stress cycle. The details of the tests and the test results are presented in Table 16. Figure 60 shows these results diagrammatically.

Since the welds of the full penetration tee joints must transmit the entire superimposed cyclic load, internal discontinuities in the weld act as stress concentrations and can affect the fatigue behavior. In addition, the external discontinuity at the toe of the weld also acts as a stress concentration. Thus, depending on the quality of the weld, fractures may initiate at the toe of the weld or in the weld. Both types of fracture can be seen in Fig. 61--the primary crack for this particular specimen was at the toe of the weld; however, a weld crack is evident also.

Of the six specimens tested, three specimens failed at the toe of the weld and, in the other three, the fatigue cracks initiated in the weld itself. The S-N diagram shown in Fig. 60 is based on failures at the toe of the weld only, although the other test results are shown also.

Since the entire stress is transmitted through the tee bar and the welds, one might expect that full penetration tees would have a lower fatigue strength than full penetration attachments. A comparison of the results, however, indicates just the opposite at the longer lives (Fig. 63). To explain this behavior, reference is made to Section 3.11, wherein it was noted that the profile of the attachment welds was such that there was a marked stress concentration at the junction of the weld and the main member. Because of this severe geometry, the fatigue resistance of the members with attachments can be expected to be lower than that of the tee joints. On the other hand, the profile of the specimens with full penetration tees is such that the stress concentration at the toe of the weld is not as great as that in the members with attachments, see Fig. 21. This difference in the profiles of the welds can be seen readily in Figs. 57 and 61.

3.13 METALLURGICAL EXAMINATIONS OF FILLET AND FULL PENETRATION WELDS

Because of the differences in joint geometry, the cooling rates and the resulting metallurgical structures in the fillet and full penetration joints can be expected to differ. Then, since the full penetration or fillet-welded attachments do not transmit the principal load through the welds, it would appear that only the initiation or local propagation of the cracks would be affected to any extent by the metallurgical structure or internal flaws. On the other hand, the full load is transmitted by the welds in tee joints; over and above the external discontinuity provided by the weld, any internal flaw in the weld can be expected to function as a potential nucleus for the initiation of a fatigue crack.

3.13.1 Microstructures of Full Penetration Welds

Welding procedures H, J, and K were employed for the preparation of the full penetration welds and are alike except for the geometry of the joints. Typical microstructures obtained with these procedures are shown in Figs. 58, 59 and 62; but for local variations, the microstructures are essentially the same.

In full penetration welds, the highest cooling rate occurs in the last passes. Moreover, the last pass, if deposited near the toe of the weld, may not have an opportunity of being refined by subsequent passes. To refine the structure at the toe of the weld, use has been made of the so-called tempering bead technique (see Figs. 17, 19, and 21). With this technique, the pass nearest the toe of the weld (the 'critical' pass) is deposited first and subsequent passes of this layer one deposited over it. The weld heat from these subsequent passes tempers the transformation product in the HAZ.

3.13.2 Microstructures of Fillet Welds

The microstructures obtained for the double pass fillet welds are shown in Fig. 54. It is at once evident that these microstructures are considerably different than those obtained from the full penetration or the butt welds.

The structure of the weld and the HAZ near the fusion line of the fillets appear to be very coarse. The reason for this is apparently a high cooling rate. The specimen under consideration was a double pass fillet weld, prepared with an energy input slightly higher than that used for the butt welds (Fig. 15). The higher heat input would compensate somewhat for the higher cooling rate of the fillet welds but the cooling rate is still higher than that in the full penetration joints. Thus, a much coarser structure is obtained with the fillet welds.

The deposition of the second pass of a fillet has a tendency to refine the structure obtained by the first pass. Although the second pass would cool somewhat slower than the first pass it would not be subject to further refinement. The net result is that the structure of the two passes is almost alike.

Failures in the members with fillet-welded attachments usually occurred at the toe of the weld due to the sudden geometrical discontinuity. There is no evidence that the metallurgical structure would in any way affect the initiation of the fatigue crack at that point.

3.14 FATIGUE TESTS OF LONGITUDINAL FILLET-WELDED JOINTS

The results of the fatigue tests of three longitudinal fillet-welded joints are presented in Table 17. These tests were conducted on a zero-to-tension stress cycle.

Unfortunately, the outside plates used for the preparation of these specimens (Fig. 1k) were warped considerably. Although the plates were securely clamped together when the welds were deposited, after the clamps were removed, there was a tendency for the outer plates to pull away from the inner plate in all three specimens.

In the tests, the shear on the threat of the welds, in combination with the high residual stresses resulting from the initial distortions and the cooling of the welds caused specimens HL-13 and HL-14 to fail through the welds. This occurred at extremely low lives and is illustrated in Fig. 64. In each case, the failure initiated at the crater end of the weld.

On the other hand, the primary fatigue crack for specimen HL-15 was observed to be in one of the outside plates at the end of the weld. However, almost immediately after the initial crack developed, a second crack initiated in one of the welds from the crater end. The specimen was then subjected to approximately 25,000 additional applications of loading as the weld crack travelled the full length of the weld (a distance of 8 in.). The initial plate crack however, traversed only a distance approximately one inch transverse to the direction of stressing (Fig. 64a) during these additional repetitions of load.

In spite of the warped outside plates for specimen HL-15, the results of the test on this specimen compare favorably with the results of tests on similar specimens in ASTM A-242 steel[12]. The fatigue strength for 100,000 applications of loading for a longitudinal fillet-welded joint in A-242 steel has been reported as 0 to 22.4 ksi. Specimen HL-15 withstood 291,200 applications of a stress which varied from 0 to 25.0 ksi. However, care should be exercised in making direct comparisons on the basis of nominal stresses with data on A-7 steel[10] or A-242 steel because of the variations in the geometry of the specimens. Nevertheless, it appears that the fatigue strength of the HY-80 plates may be at least as great as that of other types of structural steel when assembled with longitudinal fillet welds.

4. SUMMARY

4.1 SUMMARY OF RESULTS

The results of tests completed to date are presented in detail in Chapter 3 and a summary of these results is presented in Table 18.

The results of the fatigue tests of plain plate specimens of HY-80 steel, just as the results of similar studies on other steels reported in the literature, indicate that one of the most important factors governing the fatigue strength of plain plates is the surface condition of the member. By removing the mill scale and polishing the surface, a considerable increase in fatigue strength may be realized. Whereas fatigue ratios* between 0.4 and 0.6 are commonly obtained for as-rolled plate specimens tested on a zero-to-tension axial stress cycle, fatigue ratios up to 0.8 or higher can be obtained for longitudinally polished specimens[20].

The results of the transverse butt-welded joints tested in the as-welded condition indicate that the effect of the applied stresses and of the stress concentration of the weld varies with the life of the member. At longer lives (in the neighborhood of 10^6 cycles) the behavior of such members is governed largely by the range of stress for tensile mean stresses. On the other hand, at shorter lives, for all levels of tensile mean stress, the fatigue behavior of transverse butt welds is primarily a function of the range of stress but, related to some extent also to the maximum cyclic stress. There is only a limited amount of data available concerning the effect of compressive mean stresses. Nevertheless, it appears that compressive mean stresses may increase the fatigue life considerably. However, because of the small amount of data, the validity of this observation in terms of long

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* The ratio of fatigue limit to the static tensile strength.

and short lives or in terms of low or high compressive mean stresses is not known (see Figs. 32 and 33).

The effect of the stress concentration of a transverse butt weld in HY-80 has also been found to be a function of the life (see Fig. 29). The test data indicate that at a life of approximately 20,000 cycles (corresponding to a stress near the yield strength) a butt weld has only a negligible effect on the zero-to-tension fatigue capacity of a plate. However, the effect of the butt weld becomes increasingly more significant with an increase in life; at a life of approximately 500,000 cycles the load carrying capacity of a plate is cut almost in half by the introduction of a transverse butt weld.

The failures of the transverse butt-welded joints when tested with the weld reinforcement in place were invariably associated with and caused by the stress concentration of the weld reinforcement. The effect of this stress concentration appears to be a function of the life as well as the stress cycle, but also depends on the shape of the reinforcement[14,21].

By removing the weld reinforcement in a transverse butt weld, the dimensional discontinuity at the surface is eliminated. An improvement of the fatigue performance would thus be expected and is usually attained. However, the increase in fatigue strength due to the removal of the weld reinforcement is highly sensitive to a weld quality, apparently more so in high strength steels than mild steels.

The removal of the dimensional discontinuity at the surface eliminates a stress concentration but at the same time accentuates the importance of even minor internal flaws, the type of flaws which would normally be over-shadowed by the surface geometry in the as-welded members. The higher fatigue notch sensitivity of the high strength steels appears to reduce or almost eliminate the benefits of the removal of the weld reinforcement for most welds.

The results of fatigue tests on longitudinal butt welds indicate that their fatigue behavior is somewhat different from that of transverse butt welds. The fatigue strengths of the two types of connections are about equal at 10^5 cycles; however, the slopes of the S-N curves are different. As a result, the fatigue strengths of the transverse butt welds were greater at the shorter lives and smaller at the longer lives.

A comparison of the fatigue strengths of transverse and longitudinal butt welds in various steels, including the HY-80, is presented in Tables 19 and 20. There appears to be a considerable variation in the fatigue strength values, but in general $F_{100,000}$ (the fatigue strength for failure at 10^5 cycles) increases with an increase in the static tensile strength of the material for the as-welded member. Although there is a great deal of information on the long-life fatigue behavior of weldments, only in the case of HY-80 is there any significant data on the short-life fatigue behavior.

The results of the exploratory tests on several types of transverse attachments and transverse tee joints also are presented in Chapter 3 and summarized in Table 18. The results indicate a fatigue behavior which is apparently quite different than that of butt welds. This is to be expected because of the marked difference in the geometry of the specimens. By far the most important factor affecting the fatigue performance of the members with transverse attachments or tees is the stress concentration at the toe of the weld and depends upon the geometry of the weld as well as the geometry of the joint itself.

The results of the metallurgical examinations of the welds have revealed that for the welding procedures employed in this study, there were no significant variations in the metallurgical structures obtained. In terms of the metallurgical effects of welding and their bearing on fatigue, it appears that the dimensional discontinuity at the surface of a specimen has a much greater effect on the fatigue strength than any of the metallurgical factors introduced by welding, provided the weld is free of flaws.

4.2 CLOSING REMARKS

A great deal of fatigue information has been obtained in the tests reported in this study. It must be emphasized, however, that many of the comparisons are based on a very limited amount of data. In considering the effects of stress cycles and in the preparation of the modified Goodman diagram, as in the other instances where comparisons have been made, average values of fatigue strengths have been used. Because of the inherent scatter associated with fatigue tests, results of individual tests may vary considerably and consequently the average values must be considered only as approximate, particularly since so few tests have been conducted in each of the test series. Since it is practically impossible to duplicate fully and exactly a particular weld geometry, some of the scatter in the test results is probably associated with this factor. In addition, unless the contrary is stated, the average fatigue strengths refer to the results of tests on welds free of flaws that exhibit normal modes of fracture (failure due to the stress concentration of the weld). Nevertheless, the analyses presented are believed to be indicative of the general trends of fatigue behavior.

One further word of caution should be added in connection with this study; care must be exercised in extrapolating or relating the data of this study to long-life conditions. One of the primary objectives of the present investigation was to study the low-life fatigue behavior of weldments in HY-80 and only a very limited amount of information is available at long lives. In the short life tests it has been found that the stress concentration of certain types of weldments in HY-80 may have a negligible effect at stresses near the yield strength. In addition, information available in the literature suggests that the effects of residual stresses, be they beneficial or harmful, are nearly completely eliminated by high applied cyclic stresses which produce failures at short lives. Although these conditions may be true at short lives for some types of weldments they require further study and experimental confirmation and certainly cannot be extrapolated to long life behavior.

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TABLE 1

PHYSICAL CHARACTERISTICS OF BASE METALS

Material	Designation	Properties in Longitudinal Direction				
		Yield Strength*, ksi	Tensile Strength, ksi	Elongation in 2 in., percent	Reduction in Area, percent	Charpy V Notch, ft-lbs
3/4-in. HY-80	YS	79.5	94.2	22.7	74.6	142**
1 1/2 in HY-80 Heat No. 20995	HL	82.8	101.4	27.3	76.1	138***
1 1/2 in HY-80† Heat No. 19595-1	V	80.5	101.1	29.0	74.8	103***

† Data supplied by the manufacturer.
* 0.2 percent offset
** At $-100^{\circ}F$
*** At $-120^{\circ}F$ (from mill report)

TABLE 2

CHEMICAL COMPOSITION OF BASE METALS

Chemical Content,* percent	Material	
	1 1/2-in. HY-80 Heat No. 20995	1 1/2-in. HY-80 Heat No. 19595-1
C	0.15	0.18
Mn	0.28	0.32
P	0.018	0.01
S	0.019	0.021
Si	0.25	0.20
Ni	2.95	3.01
Cr	1.40	1.47
Mo	0.41	0.48
Cu	0.16	0.20

* Information Supplied by the Manufacturer.

TABLE 3

SUMMARY OF TEST PROGRAM

Specimen Type and Designation (Fig. 1)	Specimen Nos.	Series	Material Details: Nominal Thickness, in.	Material Details: Heat No.	Welding Procedure
Plain Plate - Type a	YS-1, 2, 3	I	3/4	--	-
	HL-1, 2, 3	II	1 1/2	20995	-
Transverse Butt Weld - Type b	YS-4, 5, 6	III	3/4	--	A
	HL-4, 5, 6	IV	1 1/2	20995	B
	V-1 to 9	V	1 1/2	19595-1	B
	V-10 to 22	VI	1 1/2	19595-1	C
	V-23 to 29	VII	1 1/2	19595-1	D-1
	V-30 to 39	VIII	1 1/2	19595-1	D-2
Longitudinal Butt Weld - Type c	HL-10, 11, 12	IX	1 1/2	20995	E
Longitudinal Butt Weld - Type d	HL-16, 17	X	1 1/2	20995	F
Fillet Welded Transverse Attachment - Type e	HL-7, 8, 9	XI	1 1/2	20995	G
Full Penetration Transverse Attachment - Type f	V-40 to 44	XIIa	1 1/2	19595-1	H
	HL-19	XIIb	1 1/2	20995	
Full Penetration Transverse Attachment - Type g	V-45 to 49	XIII	1 1/2	19595-1	J
Full Penetration Tee Joint - Type h	V-50 to 54	XIVa	1 1/2	19595-1	K
	HL-18	XIVb	1 1/2	20995	
Longitudinal Fillets	HL-13, 14, 15	XV	1 1/2	20995	L

TABLE 4

RESULTS OF STATIC TESTS OF
TRANSVERSE BUTT WELDED JOINTS IN THE
AS-WELDED CONDITION

(SERIES V)

	Specimen V-1	Specimen V-2
Speed of Loading, in./min.	0.05	0.05
Yield Point,* ksi	78.3	80.4
Tensile Strength, ksi	93.2	95.4
Elongation**, percent	25.6	27.2
Reduction in area, percent	66.9	66.5
Location of Fracture	Base Metal	Base Metal

* By drop of beam.
** In a 5-in. gage length.

TABLE 5

RESULTS OF FATIGUE TESTS OF PLAIN AS-ROLLED PLATE SPECIMENS

(AXIAL TENSION)

Specimen No.	Series	Stress Cycle, ksi	Life	Location of Fracture	Computed Fatigue Strengths,* ksi	
					$F_{100,000}$	$F_{2,000,000}$
YS-1	I	0 to +50.0	390,400	at radius	60.1	39.9
YS-2	I	0 to +50.0	350,000	at radius	59.3	39.4
YS-3	I	0 to +50.0	341,700	at radius	59.1	39.3
HL-1**	II	0 to +50.0	3,321,200+	No failure	----	----
HL-2	II	0 to +50.0	437,600	at radius	61.0	40.5
HL-3	II	0 to +50.0	701,900	at radius***	65.1	43.2

* k = 0.136 (Assumed, see Fig. 24)

** Surfaces of specimen polished for instrumentation (see Sec. 2.3.)

*** Secondary crack initiated in test section (see Fig. 25).

TABLE 6

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION

(AXIAL TENSION)

Specimen No.	Series	Stress Cycle, ksi	Life	Location of Fracture*	Computed Fatigue Strengths***, ksi	
					$F_{20,000}$	$F_{100,000}$
YS-4	III	0 to +30.0	790,300	a	----	----
YS-5	III	0 to +30.0	1,248,000	a	----	----
YS-6	III	0 to +30.0	659,400	a	----	----
HL-4	IV	0 to +30.0	251,000	a	71.1	41.1
HL-5	IV	0 to +30.0	272,000	a	73.0	42.2
HL-6	IV	0 to +30.0	225,000	a	68.4	39.5
V-15	VI	0 to +40.0	161,800	a	81.5	47.1
V-17	VI	0 to +50.0**	25,900	a	----	----
V-19	VI	0 to +60.0	50,300	a	82.1	47.5
V-22	VI	0 to +50.0	89,000	a	83.1	48.0
V-24	VII	0 to +70.0	21,500	a	71.9	41.5
V-26	VII	0 to +60.0	54,000	a	84.1	48.6
V-27	VII	0 to +70.0	30,100	a	80.8	46.5
				Average	77.3	44.6

* a: Failure initiated at edge of weld reinforcement.

** For the first 15,000 cycles (approximately), specimen went into 7,600 psi compression. Not included in average.

*** k = 0.340.

TABLE 7

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED

(AXIAL TENSION)

Specimen No.	Series	Reinforcement Removed From	Stress Cycle, ksi	Life	Location of Fracture*	Computed Fatigue Strengths, ksi $F_{20,000}$	Computed Fatigue Strengths, ksi $F_{100,000}$
V-13	VI	both sides	0 to +35.0	880,200	b	75.7	54.5
V-34	VIII	both sides	0 to +70.0	29,400	b	75.7	54.5
V-35	VIII	both sides	0 to +70.0	7,800	b	--	--
					Average**	75.7	54.5
V-16	VI	one side	0 to +35.0	232,000	a	72.5	44.9
V-36	VIII	one side	0 to +70.0	22,300	b	72.5	44.9
V-37	VIII	one side	0 to +70.0	10,900	b	--	--
					Average***	72.5	44.9

* a: Failure initiated at edge of weld.
b: Failure in weld.

** k = 0.204

*** k = 0.296

TABLE 8

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION

(COMPLETE REVERSAL, AXIAL LOADING)

Specimen No.	Series	Stress Cycle, ± ksi	Life	Location of Fracture*	Computed Fatigue Strengths**, ± ksi	
					$F_{10,000}$	$F_{100,000}$
V-3	V	14.0	436,200	b	--	--
V-5	V	20.0	167,600	a***	74.2	25.4
V-7	V	20.0	282,000	a	95.0	32.4
V-8	V	25.0	111,500	b	--	--
V-6	V	30.0	9,000	b	--	--
V-9	V	30.0	55,300	b	--	--
V-21	VI	30.0	72,700	a	76.8	26.3
V-20	VI	30.0	75,900	a	77.1	26.4
V-4	V	40.0	2,600	b	--	--
V-23	VI	40.0	27,500	a***	64.0	21.9
V-23	VII	40.0	62,500	a	93.7	32.1
V-28	VII	50.0	22,000	a	72.2	24.7
V-29	VII	50.0	20,900	a	70.4	24.1
				Average	77.7	26.6

* a: Failure initiated at edge of weld reinforcement.
b: Failure initiated in weld.

** k = 0.465

*** Secondary crack initiated in weld (see Fig. 9).

TABLE 9

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED

(COMPLETE REVERSAL, AXIAL LOADING)

Specimen No.	Series	Reinforcement Removed From	Stress Cycle, ± ksi	Life	Location of Fracture*
V-38	VIII	both sides	40.0	12,000	b
V-31	VIII	both sides	40.0	35,500	b
V-30	VIII	both sides	45.0 **	25,500	b
V-33	VIII	one side	40.0	22,600	b
V-32	VIII	one side	40.0	23,300	b

* b: Failure initiated in weld.

** Test started at ± 50.0 ksi but after 7,500 cycles, test stress reduced to ±45.0 ksi.

TABLE 10

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION

(VARIATIONS IN TENSILE AND COMPRESSIVE MEAN STRESSES, AXIAL LOADING)

Specimen No.	Series	Stress Cycle, ksi				Life	Location of Fracture*
		Min. Stress	Max. Stress	Mean Stress	Alternating Stress		
V-10	VI	-40.0	0	-20.0	±20.0	1,779,500	b
V-12	VI	-35.0	+5.0	-15.0	±20.0	1,497,800	a
V-39	VIII	-30.0	+10.0	-10.0	±20.0	1,832,900	a
V-14	VI	+20.0	+60.0	+40.0	±20.0	315,700	a
V-18	VI	+40.0	+80.0	+60.0	±20.0	151,900	a
V-11	VI	+30.0	+60.0	+45.0	± 15.0	271,400	a

* a: Failure initiated at edge of weld reinforcement.
b: Failure initiated in weld.

TABLE 11

RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION

(AXIAL LOADING)

Specimen No.	Series	Stress Cycle, ksi	Life	Location of Fracture*	Computed Fatigue Strengths**, ksi	
					$F_{10,000}$	$F_{100,000}$
HL-10	IX	0 to +50.0	39,900	c	61.0	43.8
HL-11	IX	0 to +40.0	255,500	d	63.7	45.8
HL-12	IX	0 to +55.0	34,300	d	65.7	47.2
				Average	63.5	45.6
HL-16	X	±30.0	32,700	c	--	--
HL-17	X	±30.0	44,500	c	--	--

* c: Failure initiated in test section.
d: Failure initiated at start of fillet radius.

** k = 0.144

TABLE 12

RESULTS OF X-RAY EXAMINATIONS OF BUTT-WELDED JOINTS

Specimen No.	Welding Procedure	Location of Primary Fatigue Crack*	Radiographic Rating
		Transverse Butt Welds	
V-1	B	Static Test	Acceptable
V-2	B	Static Test	Acceptable
V-17	C	a	Acceptable
V-19	C	a	Acceptable
V-20	C	a	Acceptable
V-21	C	a	Acceptable
V-22	C	a	Acceptable
V-23	D-1	a	Acceptable
V-24	D-1	a	Acceptable
V-25	D-1	a	Slight undercut. Lack of Penetration?
V-26	D-1	a	Acceptable
V-27	D-1	a	Acceptable
V-28	D-1	a	Slight undercut.
V-29	D-1	a	Acceptable
V-30	D-2	b	Acceptable
V-31	D-2	b	Acceptable
V-32	D-2	b	Acceptable (Inclusion in center)
V-33	D-2	b	Acceptable
V-34	D-2	b	Lack of Penetration?
V-35	D-2	b	Acceptable
V-36	D-2	b	Acceptable
V-37	D-2	b	Acceptable
V-38	D-2	b	Acceptable
V-39	D-2	a	Acceptable
		Longitudinal Butt Welds	
HL-16	F	Internal**	Slight undercut
HL-17	F	Internal**	Very slight undercut

* a: Failure initiated at edge of weld.
b: Failure initiated in weld metal.

** See Sec. 3.6.

TABLE 13

RESULTS OF FATIGUE TESTS OF PLATES
WITH FILLET-WELDED TRANSVERSE ATTACHMENTS
(AXIAL TENSION)

SERIES XI

Specimen No.	Thickness of Attachment, in.	Stress Cycle, ksi	Life	Location of Fracture*
HL-7	1/2	0 to +30.0	141,600	e
HL-8	1/2	0 to +30.0	160,800	e
HL-9	1 1/2	0 to +30.0	103,800	e

* e: Failure initiated at toe of weld.

TABLE 14

RESULTS OF FATIGUE TESTS OF PLATES WITH FULL PENETRATION TRANSVERSE ATTACHMENTS

ON BOTH SIDES (COMPLETE REVERSAL, AXIAL LOADING)

Specimen No.	Series	Stress Cycle, ± ksi	Life	Location of Fracture*	Computed Fatigue Strengths**, ±ksi	
					$F_{10,000}$	$F_{100,000}$
V-40	XIIa	30.0	46,200	f	55.6	21.9
V-41	XIIa	40.0	20,200	f	53.2	21.0
V-42	XIIa	40.0	16,400	f	48.9	19.3
V-43	XIIa	20.0	102,400	f	51.4	20.2
V-44	XIIa	30.0	36,400	f	50.6	19.9
HL-19	XIIb	30.0	29,600	f	46.6	18.4
				Average	51.0	20.1

* f: Failure initiated at toe of weld.

** k = 0.405

TABLE 15

RESULTS OF FATIGUE TESTS OF PLATES WITH FULL PENETRATION TRANSVERSE ATTACHMENT

ON ONE SIDE (COMPLETE REVERSAL, AXIAL LOADING)

Specimen No.	Series	Stress Cycle, ± ksi	Life	Location of Fracture*	Computed Fatigue Strengths**, ±ksi	
					$F_{10,000}$	$F_{100,000}$
V-45	XIII	40.0	30,100	f	68.9	22.4
V-46	XIII	40.0	24,800	f	64.6	21.0
V-47	XIII	20.0	110,900	f	64.8	21.0
V-48	XIII	30.0	49,700	f	65.6	21.3
V-49	XIII	30.0	47,300	f	63.9	20.8
				Average	65.5	21.3

* f. Failure initiated at toe of weld.
** k = 0.487

TABLE 16

RESULTS OF FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS

(COMPLETE REVERSAL, AXIAL LOADING)

Specimen No.	Series	Stress Cycle, ± ksi	Life	Location of Fracture*	Computed Fatigue Strengths**, ±ksi	
					$F_{10,000}$	$F_{100,000}$
V-50	XIVa	30.0	55,000	f	59.8	23.5
V-51	XIVa	30.0	42,100	f***	53.7	21.1
V-52	XIVa	40.0	11,400	g	--	--
V-53	XIVa	40.0	13,900	g	--	--
V-54	XIVa	20.0	132,400	f	57.0	22.4
HL-18	XIVb	30.0	12,900	g	--	--
				Average	57.0	22.4

* f: Failure initiated at toe of weld.
g: Failure initiated in the weld.

** k = 0.405

*** Secondary crack initiated in weld.

TABLE 17

RESULTS OF FATIGUE TESTS OF SPECIMENS WITH LONGITUDINAL FILLETS (AXIAL TENSION)

SERIES XV

Specimen No.	Length of Fillet, in.	Stress Cycle,* ksi	Life	Failure Type**
HL-13	4	0 to +25.0	5,800	h
HL-14	6	0 to +25.0	34,800	h
HL-15	8	0 to +25.0	291,200	j

* Stress on outside plates.

** h: Failure by tearing away of outside plate through weld.
j: Failure across the outside plate (see Fig. 64a).

TABLE 18

SUMMARY OF RESULTS OF FATIGUE TESTS

Specimen Type	Surface Condition	Data shown in Figure	Stress Ratio, R*	k	Average Fatigue Strengths, ksi		
					$F_{10,000}$	$F_{20,000}$	$F_{100,000}$
1 1/2-in. Plain plate	As-rolled	24	0	0.136	--	80.0	65.0
Transverse Butt Weld	As-welded	26	0	0.340	--	77.3	44.6
	Reinforcement Removed 1 side	27	0	0.296	--	72.5	44.9
	Reinforcement Removed 2 sides	27	0	0.204	--	75.7	54.5
	As-welded	30	-1	0.465	77.7	56.0	26.6
Longitudinal Butt Weld	As-welded	48	0	0.144	63.5	57.6	45.6
Full Penetration Attachments, on two sides	As-welded	55	-1	0.405	51.0	38.3	20.1
Full Penetration Attachment, on one side	As-welded	56	-1	0.487	65.5	46.7	21.3
Full Penetration Tee Joint	As-welded	60	-1	0.407	57.0	43.1	22.4

* See Fig. 34.

TABLE 19

COMPARISON OF FATIGUE STRENGTHS OF BUTT WELDS IN VARIOUS STEELS (ZERO-TO-TENSION)

Steel	Thickness, in.	Ultimate Strength, ksi	Yield Strength, ksi	Type of Joint*	Surface Condition	$F_{100,000}$ (average), ksi	Source (See Bibliography)
Low Carbon	1/2	59.0	35.5	a	as-welded	0 to 38.5	(15)
Low Carbon	1/2	59.0	35.5	a	reinforcement off	0 to 49.3	(15)
Japanese H.T.	.79	80.4	49.4	a	as-welded	0 to 59.8	(16)
Low Carbon	3/4	57.4	33.3	b	as-welded	0 to 41.7	(13)
Low Carbon	3/4	57.4	33.3	b	reinforcement off	0 to 48.3	(13)
Low Alloy	3/4	76.7	56.8	b	as-welded	0 to 47.2	(12)
Low Alloy	3/4	73.6	47.8	b	as-welded	0 to 45.1	(12)
Low Alloy	3/4	77.6	53.1	b	as-welded	0 to 42.2	(12)
HY-80	1 1/2	95.0	80.0	b	as-welded	0 to 45.6	Fig. 48
Low Carbon	7/8	61.5	34.5	c	as-welded	0 to 33.1	(14)
Low Carbon	7/8	61.5	34.5	c	reinforcement off	0 to 44.5	(14)
Low Carbon	1/2	59.0	35.5	c	reinforcement off	0 to 35.6	(15)
Japanese H.T.	.79	80.4	49.4	c	as-welded	0 to 45.5	(16)
Low Carbon	3/4	57.4	33.3	d	as-welded	0 to 37.9	(13)
Low Carbon	3/4	57.4	33.3	d	reinforcement off	0 to 35.4**	(13)
Low Allow	3/4	76.7	56.8	d	as-welded	0 to 38.6	(12)
Low Alloy	3/4	73.6	47.8	d	as-welded	0 to 39.4	(12)
Low Alloy	3/4	77.6	53.1	d	as-welded	0 to 39.4	(12)
Low Alloy	3/4	76.0	50.0	d	as-welded	0 to 34.0	(5)
HY-80	1 1/2	95.0	80.0	d	as-welded	0 to 44.6	Fig. 26
HY-80	1 1/2	95.0	80.0	d	reinforcement off	0 to 54.5	Fig. 27
T-1	3/4	108.0	93.0	d	as-welded	0 to 38.5	(5)
T-1	3/4	108.0	93.0	d	reinforcement off	0 to 42.5**	(5)
T-1	1/2	123.0	116.0	d	as-welded	0 to 50.0	(4)

* a: Single V longitudinal butt weld.
b: Double V longitudinal butt weld.
c: Single V transverse butt weld.
d: Double V transverse butt weld.

** Average of both weld and edge failures.

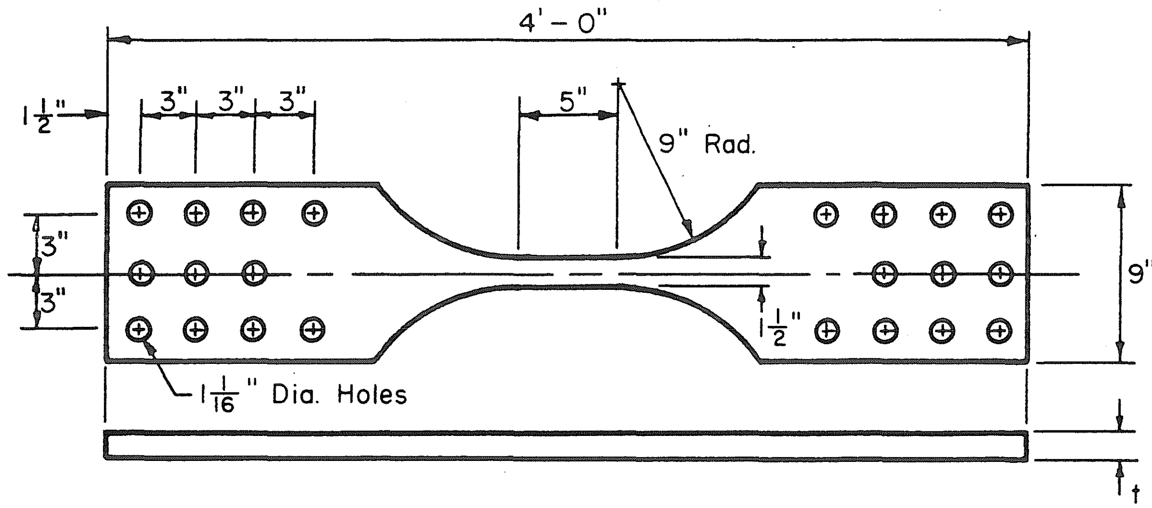
TABLE 20

COMPARISON OF FATIGUE STRENGTHS OF BUTT WELDS

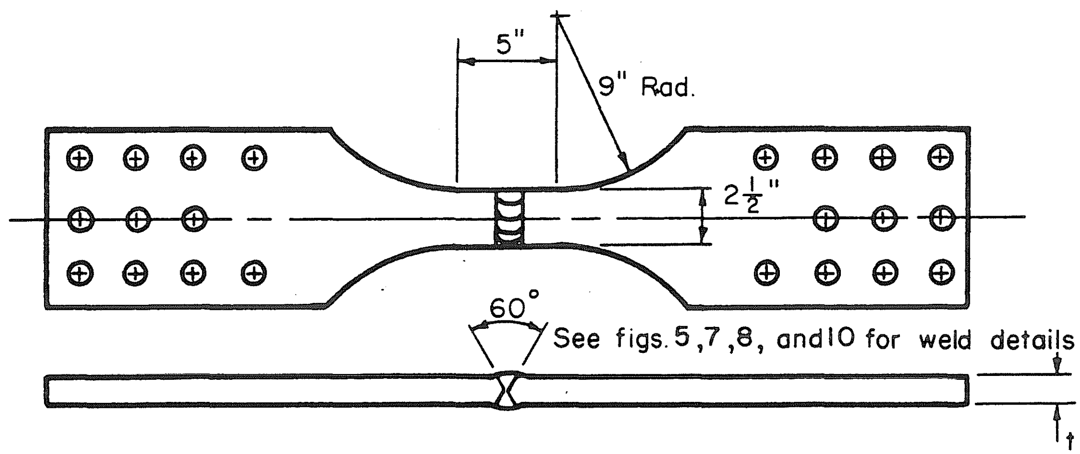
IN VARIOUS STEELS (COMPLETE REVERSAL)

Steel	Thickness, in.	Ultimate Strength, ksi	Yield Strength, ksi	Type of Joint*	Surface Condition	$F_{100,000}$ (average), ± ksi	Source (See Bibliography)
HTS	1/2	77.0	---	a	as-welded	33.8	(19)
Carbon steel	7/8	61.5	34.5	c	as-welded	22.3	(14)
Carbon steel	7/8	61.5	34.5	c	reinforcement off	26.8	(14)
Low Alloy	1/2	83.0	60.0	c	as-welded	25.7	(14)
Japanese H.T.	.79	80.4	49.4	c	as-welded	29.2	(16)
Low Carbon	5/8	62.3	43.0	c	as-welded	22.0	(17)
STS	1/2	103.0	--	c	as-welded	20.0	(19)
HY-80	1 1/2	95.0	80.0	d	as-welded	26.6	Fig. 30
STS	5/8	115.4	96.0	d	as-welded	24.5	(18)
STS	5/8	117.0	94.0	d	reinforcement off	34.0	(17)

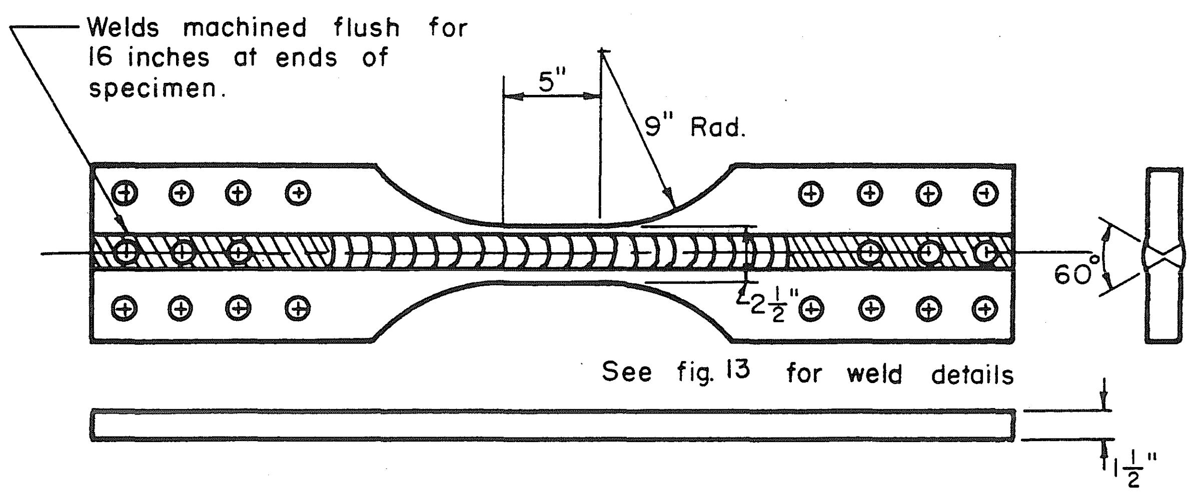
* a: Single V longitudinal butt weld.
c: Single V transverse butt weld.
d: Double V transverse butt weld.



(a) Plain Plate — Type a

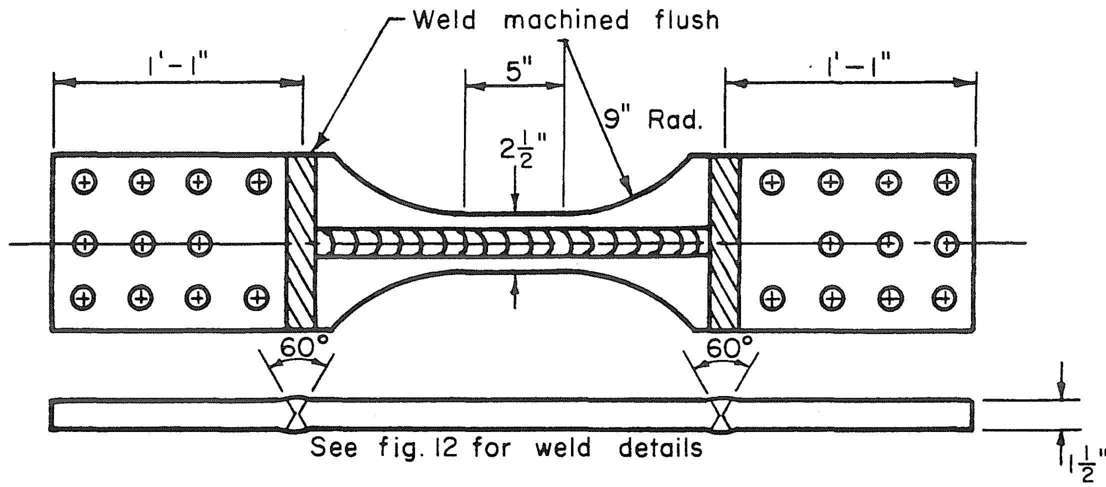


(b) Transverse Butt Weld — Type b

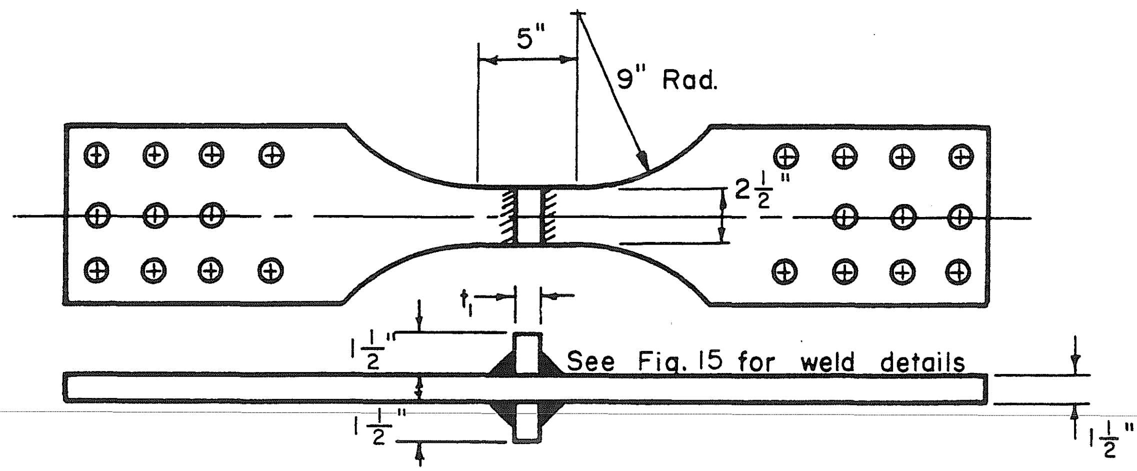


(c) Longitudinal Butt Weld — Type c

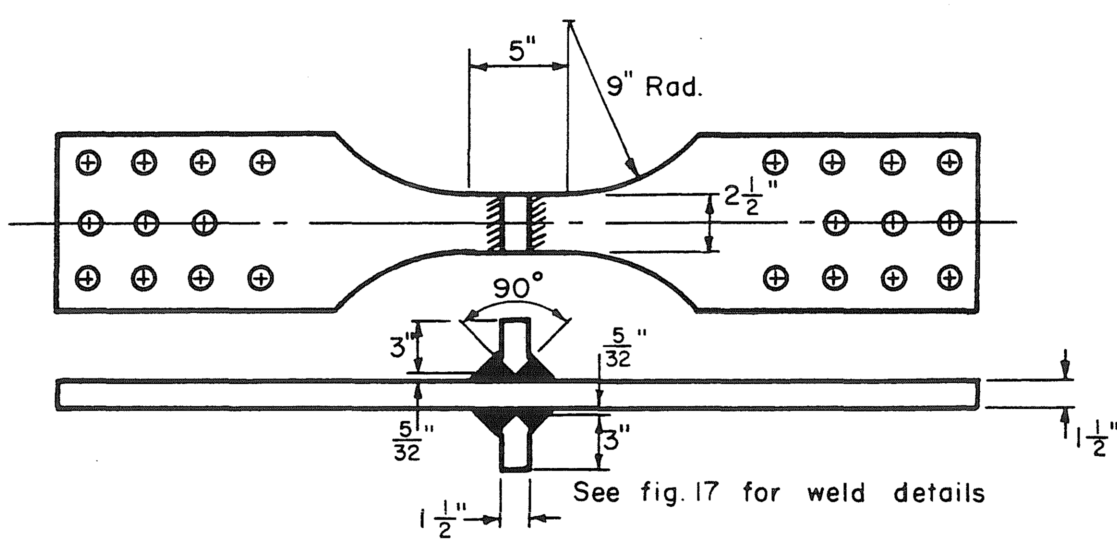
FIG. 1 DETAILS OF TEST SPECIMENS



(d) Longitudinal Butt Weld — Type d

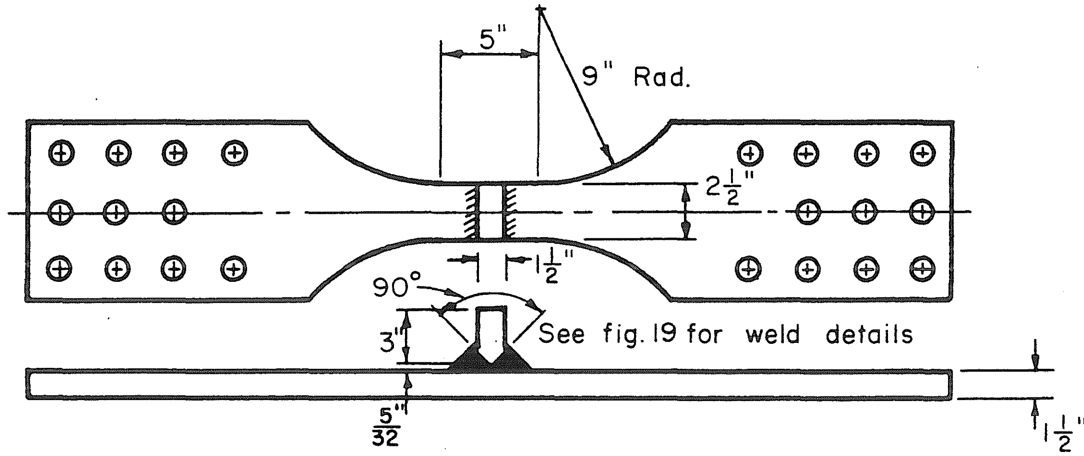


(e) Fillet Welded Transverse Attachment — Type e

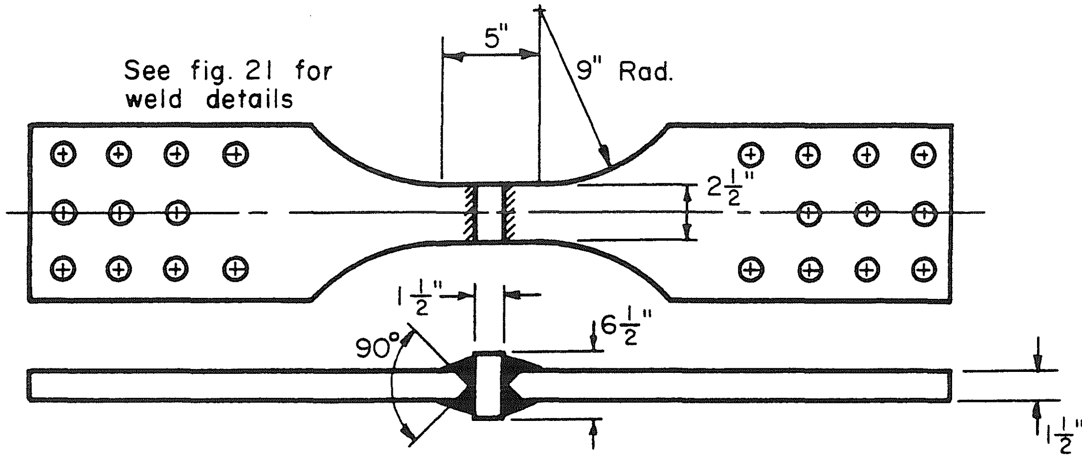


(f) Full Penetration Transverse Attachments — Type f

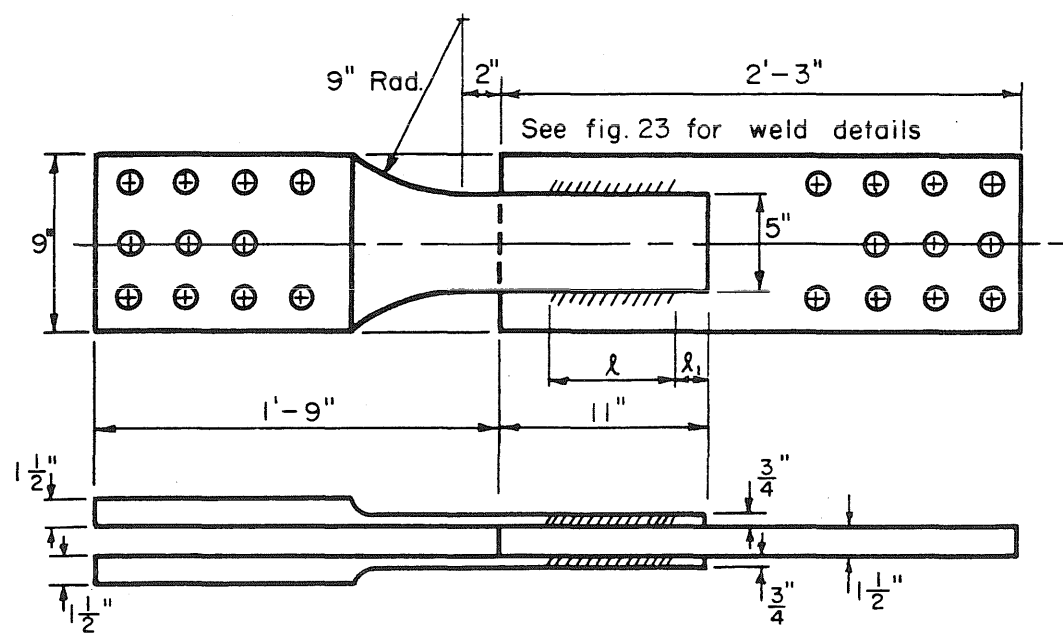
FIG. 1 (Contd.) DETAILS OF TEST SPECIMENS



(g) Full Penetration Transverse Attachment — Type g



(h) Full Penetration Tee Joint — Type h



Spec.	ℓ	ℓ_1
HL-13	4"	3 1/2"
HL-14	6"	2 1/2"
HL-15	8"	1 1/2"

(k) Longitudinal Fillets — Type k

FIG. 1 (Contd.) DETAILS OF TEST SPECIMENS

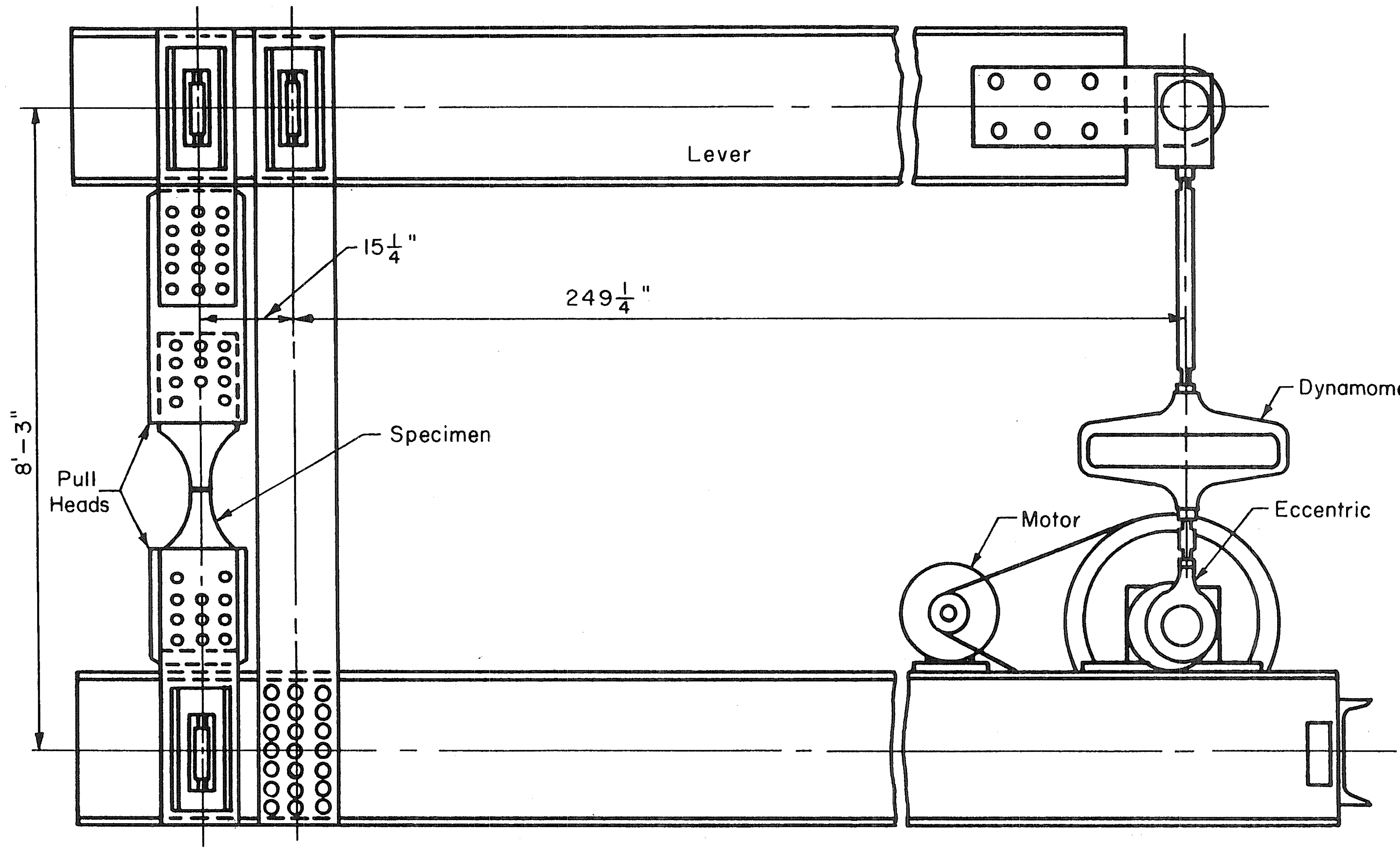


FIG. 2 ILLINOIS' FATIGUE TESTING MACHINE AS USED FOR AXIAL LOADING OF WELDED JOINTS

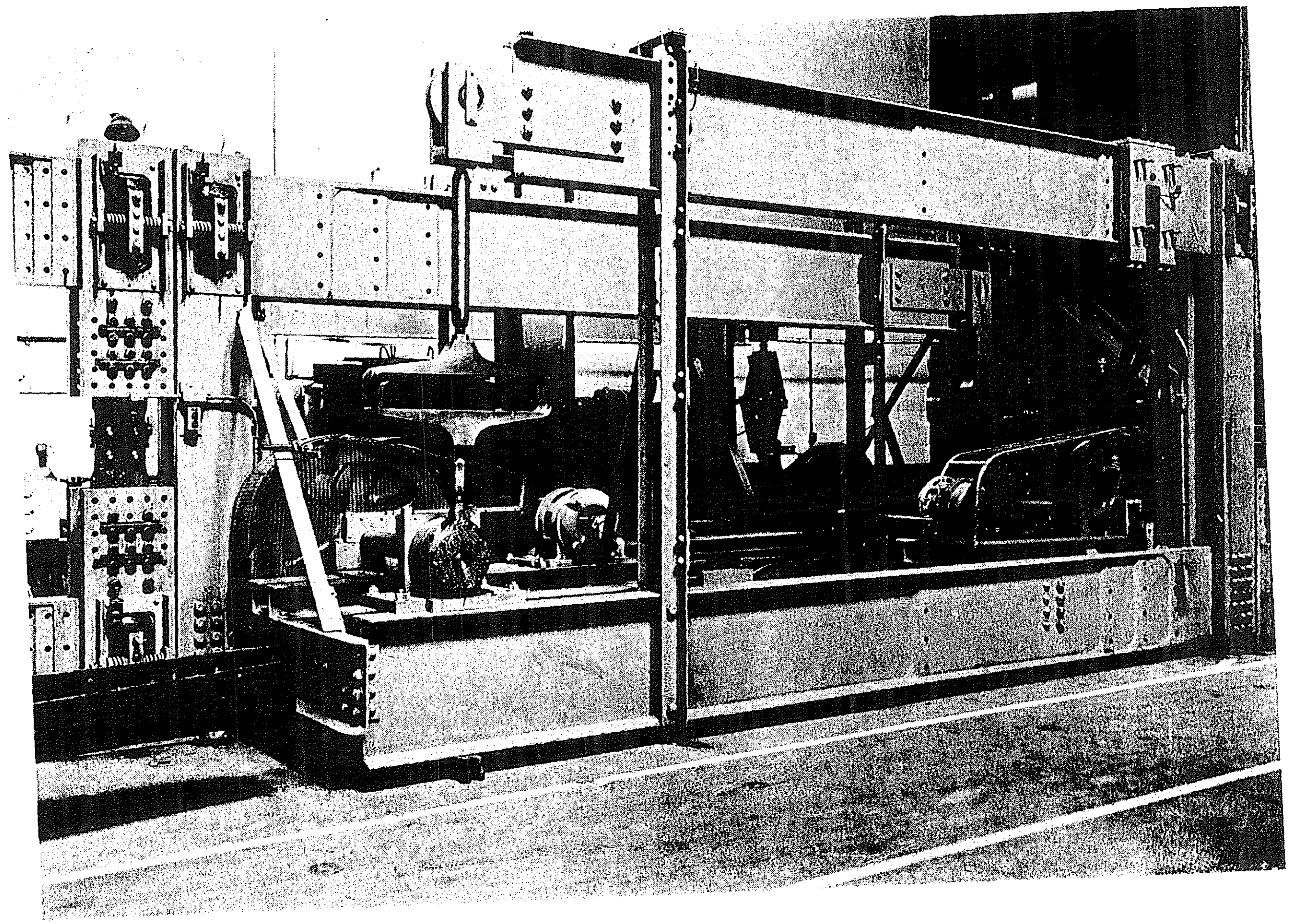


FIG. 3 ILLINOIS' FATIGUE TESTING MACHINES

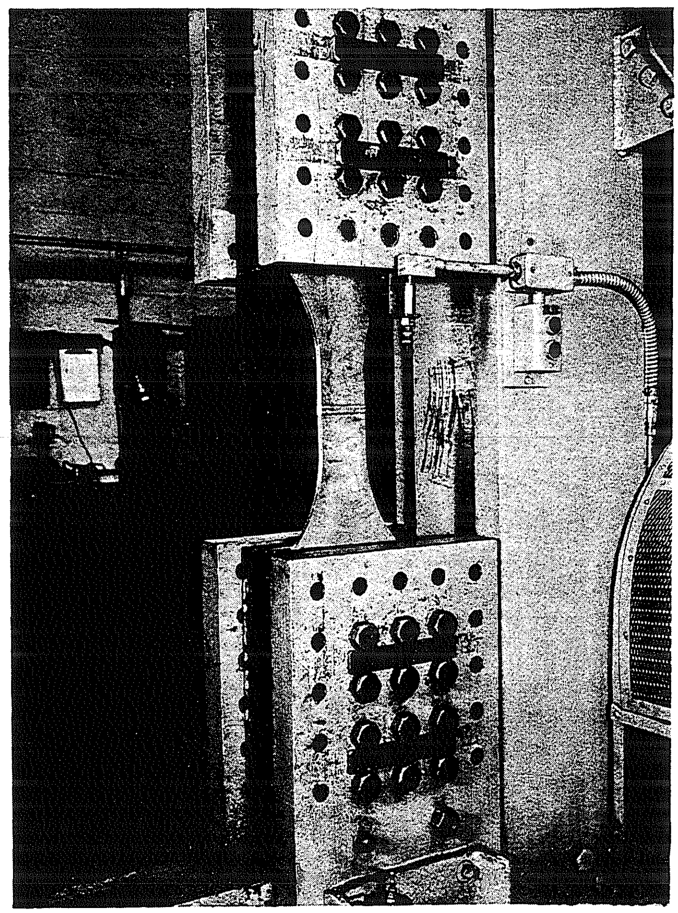
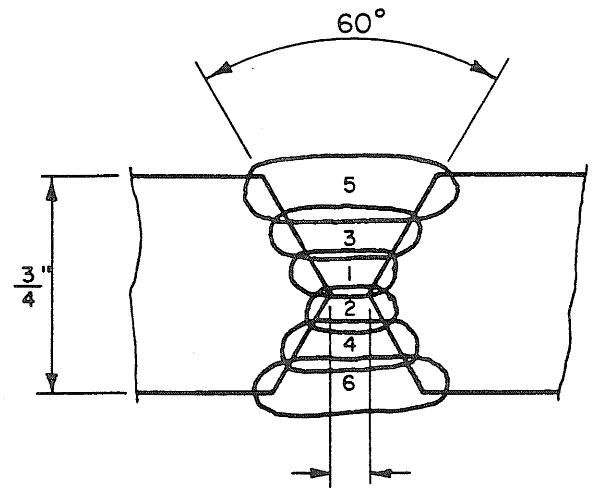
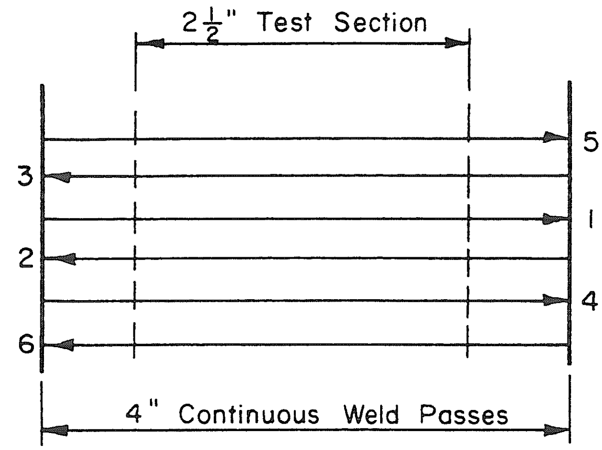


FIG. 4 TRANSVERSE BUTT WELDED JOINT IN FATIGUE MACHINE



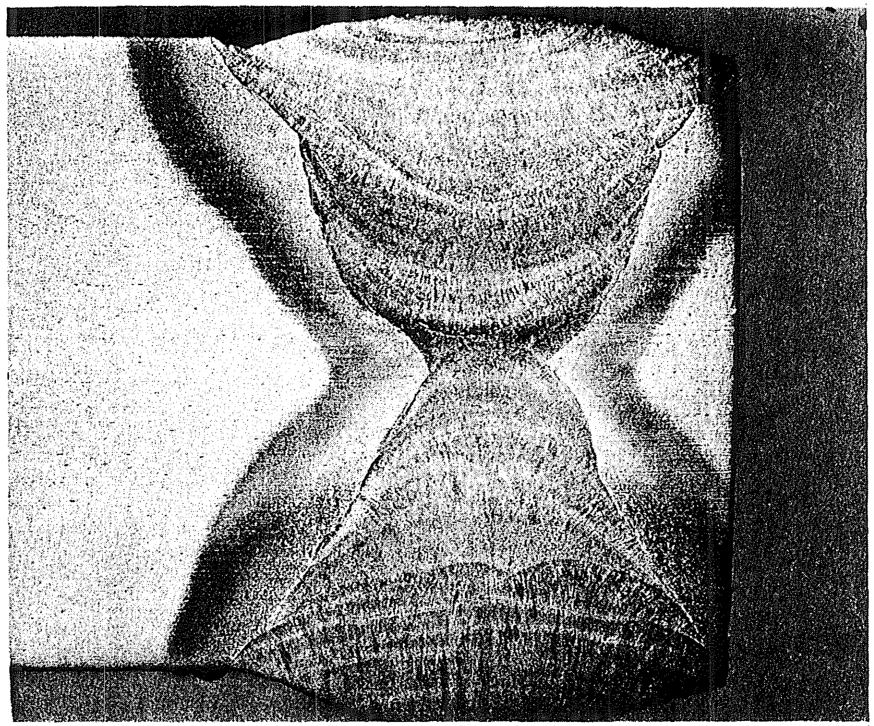


Surface of plate adjacent to weld cleaned by grinding before welding.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	5/32	130	4.8
2	3/16	140	8.0
3	3/16	230	8.0
4	3/16	220	6.9
5	3/16	210	7.0
6	3/16	210	7.0

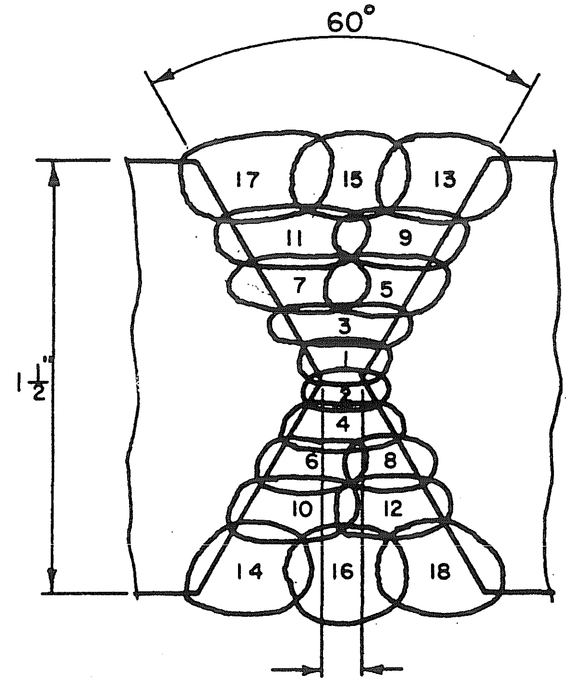
Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 200°F (Maximum)
Heat Input: 40,000 Joules/in. (Maximum)
All welding in flat position
Underside of pass 1 back-gouged with air arc before pass 2.

FIG. 5 WELDING PROCEDURE A
(Transverse Butt Welds)

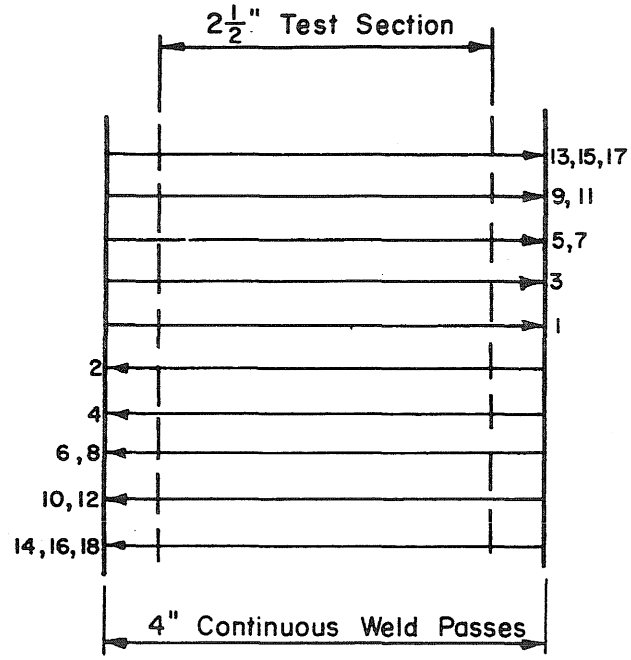


Specimen YS-4

FIG. 6 TYPICAL MACROGRAPH FOR WELDING PROCEDURE A



Root opening $\frac{1}{8}$ in.



Arrows indicate direction of welding.

Surface of plate adjacent to weld cleaned by grinding before welding.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1, 2	$\frac{5}{32}$	140	3.5
3 – 18	$\frac{3}{16}$	230	6.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 150° F

Electrode: MIL 11018

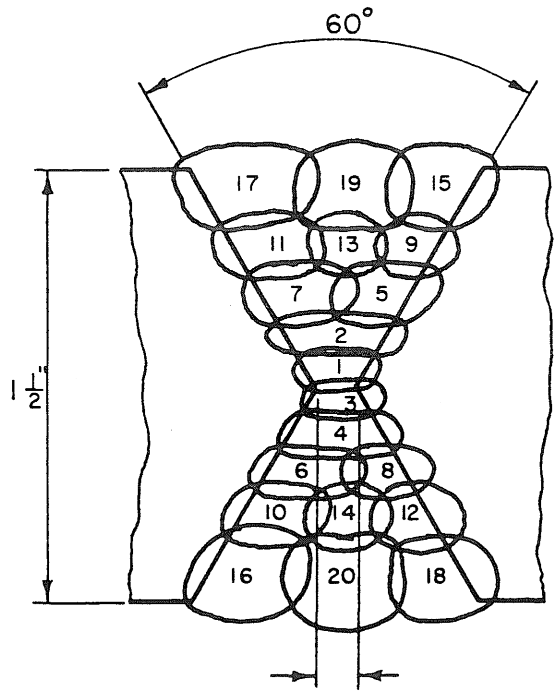
Interpass Temperature: 300° F (Maximum)

Heat Input: 50,000 Joules/in. (Maximum)

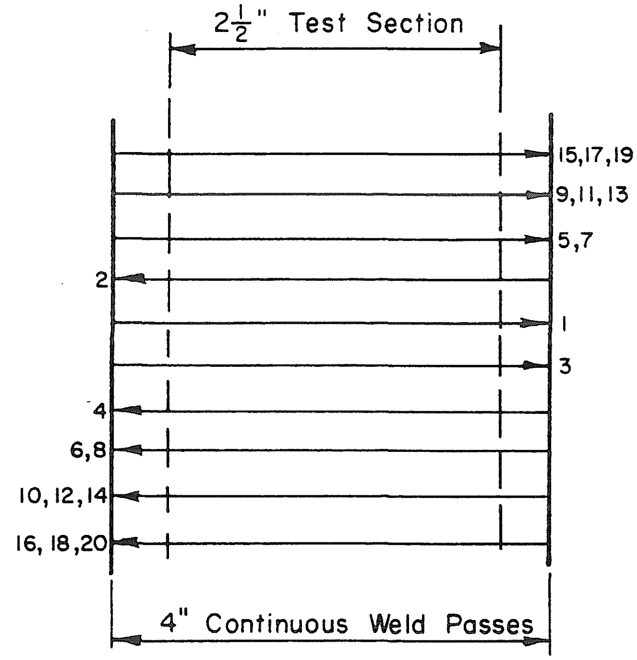
All welding in flat position.

Underside of pass 1 back-gouged with air arc before pass 2.

FIG. 7 WELDING PROCEDURE B (Transverse Butt Welds)



Root opening 1/8 in.



Arrows indicate direction of welding.

Surface of plate adjacent to weld cleaned by grinding before welding.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4 – 20	$\frac{3}{16}$	230	6.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 150° F

Electrode: MIL 11018

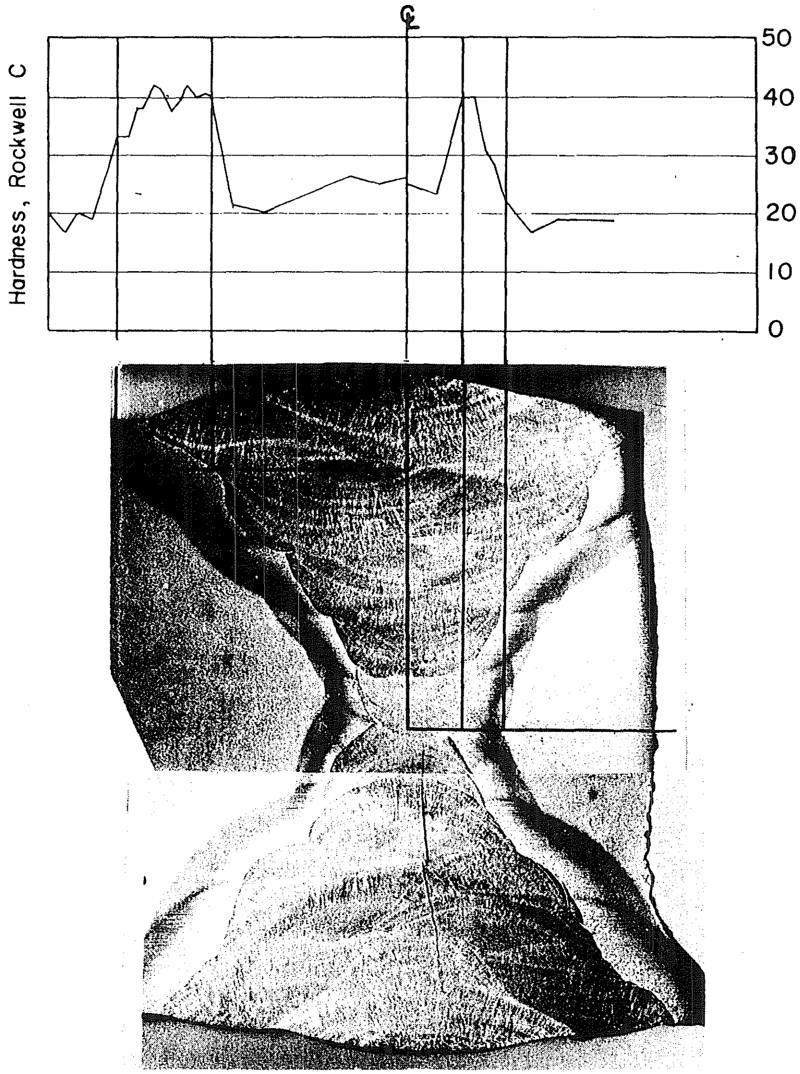
Interpass Temperature: 300° F (Maximum)

Heat Input: 50,000 Joules / in. (Maximum)

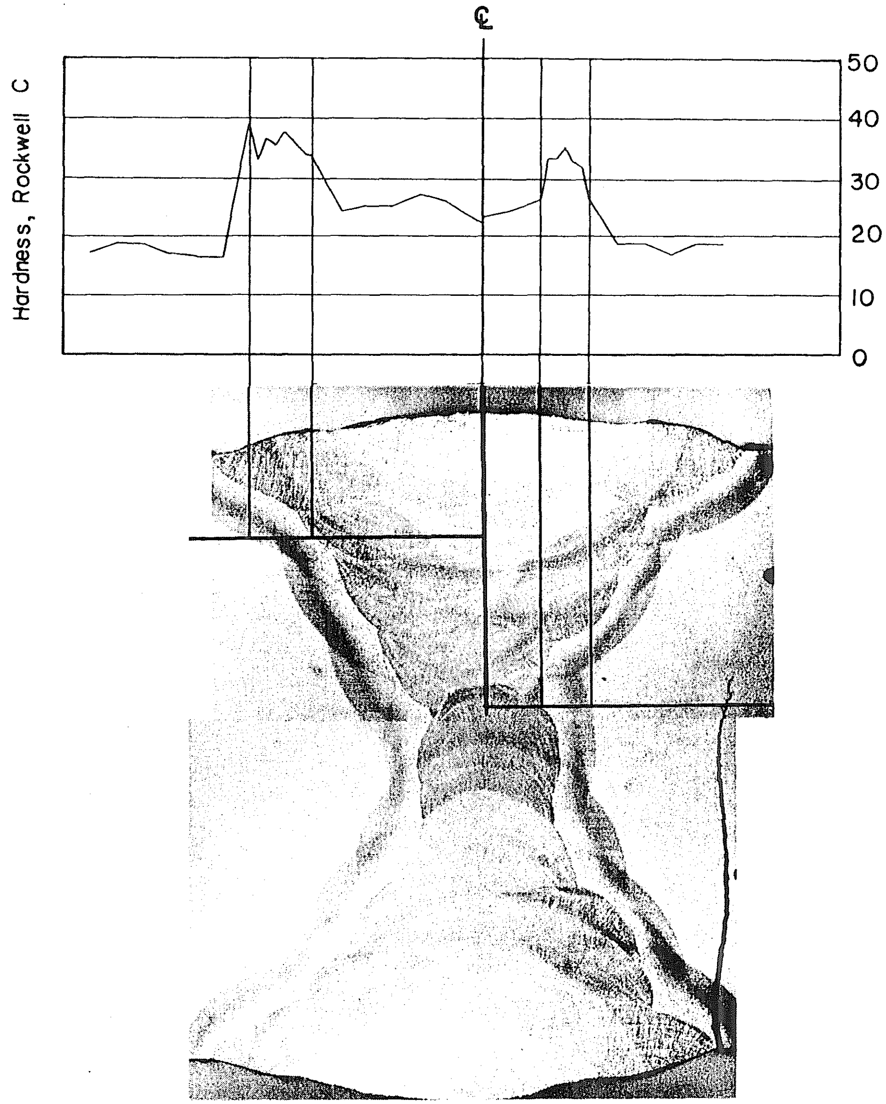
All welding in flat position.

Underside of pass 1 back-gouged with air arc before pass 3.

FIG. 8 WELDING PROCEDURE C
(Transverse Butt Welds)

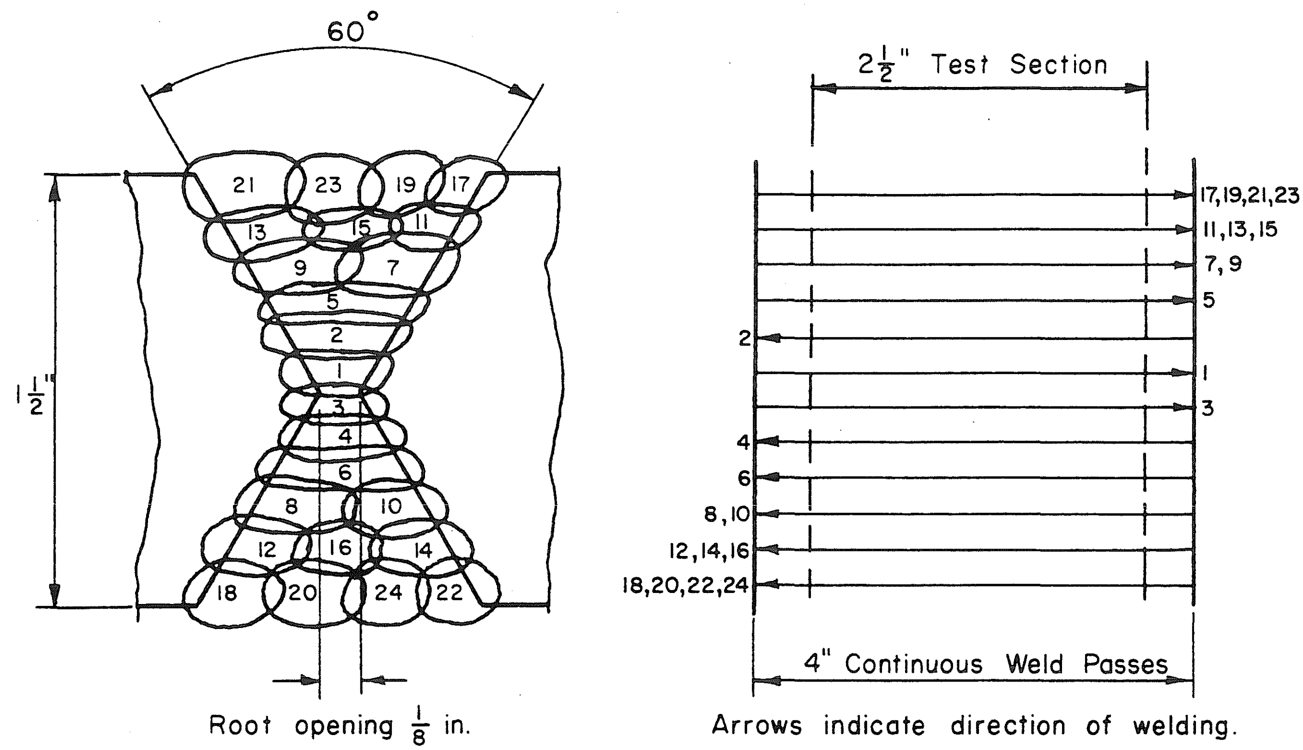


SPECIMEN V-5 (Procedure B)



SPECIMEN V-20 (Procedure C)

FIG. 9 TYPICAL MACROGRAPHS AND HARDNESS SURVEYS FOR WELDING PROCEDURES B AND C



Surface of plate adjacent to weld cleaned by grinding before welding.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	5/32	140	3.5
2	3/16	230	6.0
3	5/32	160	4.0
4 – 16	3/16	230	6.0
17 – 24	3/16	200	5.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 200° F

Electrode: MIL 11018

Interpass Temperature: 200° F (Maximum) Procedure D-1

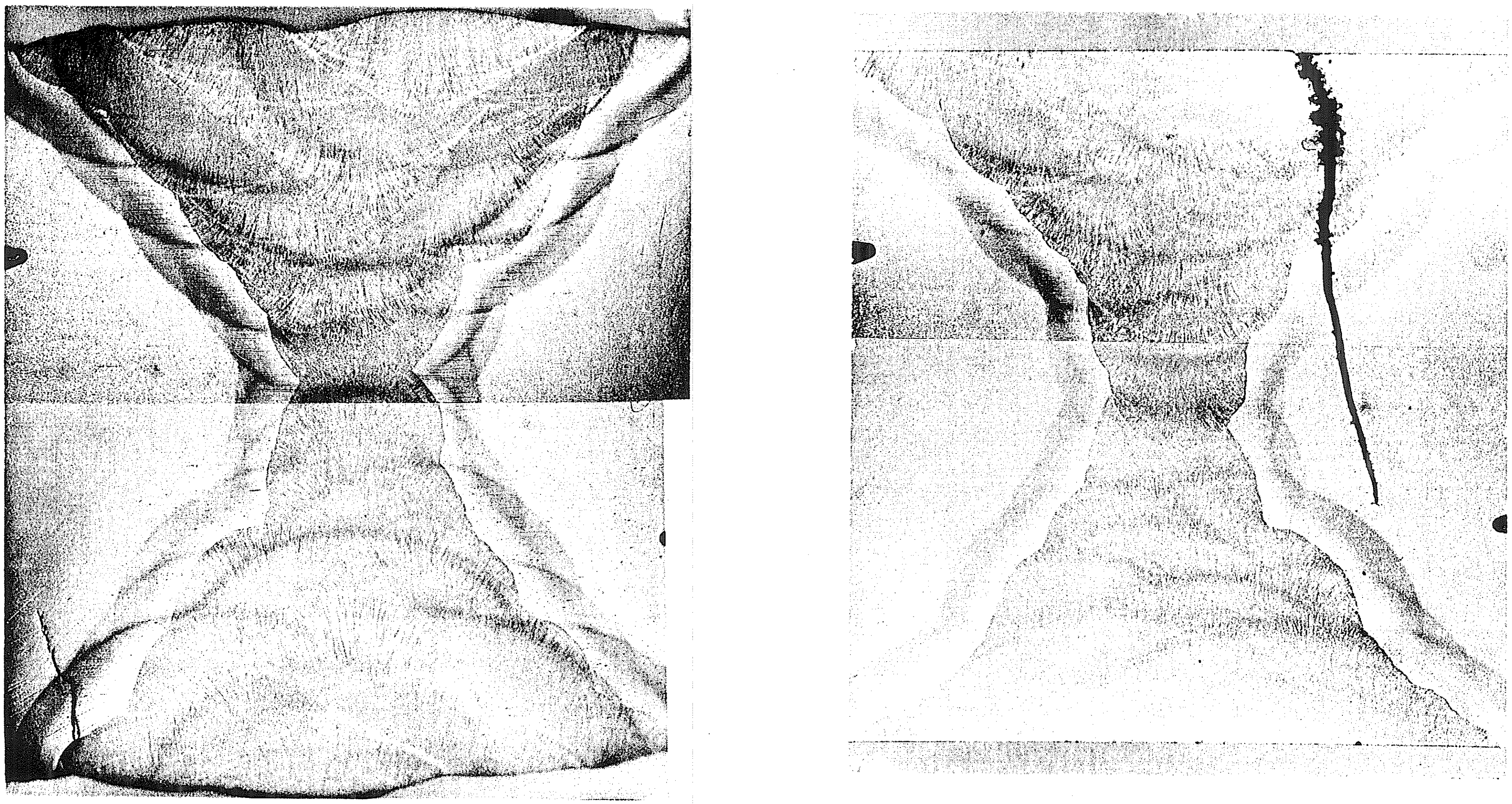
300° F (Maximum) Procedure D-2

Heat Input: 50,000 Joules/in. (Maximum)

All welding in flat position.

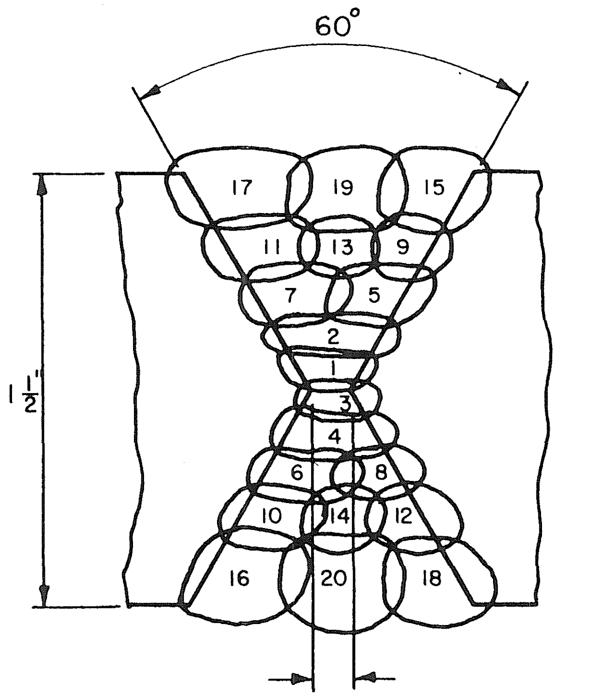
Underside of pass 1 back-gouged with air arc before pass 3.

FIG. 10 WELDING PROCEDURE D
(Transverse Butt Welds)

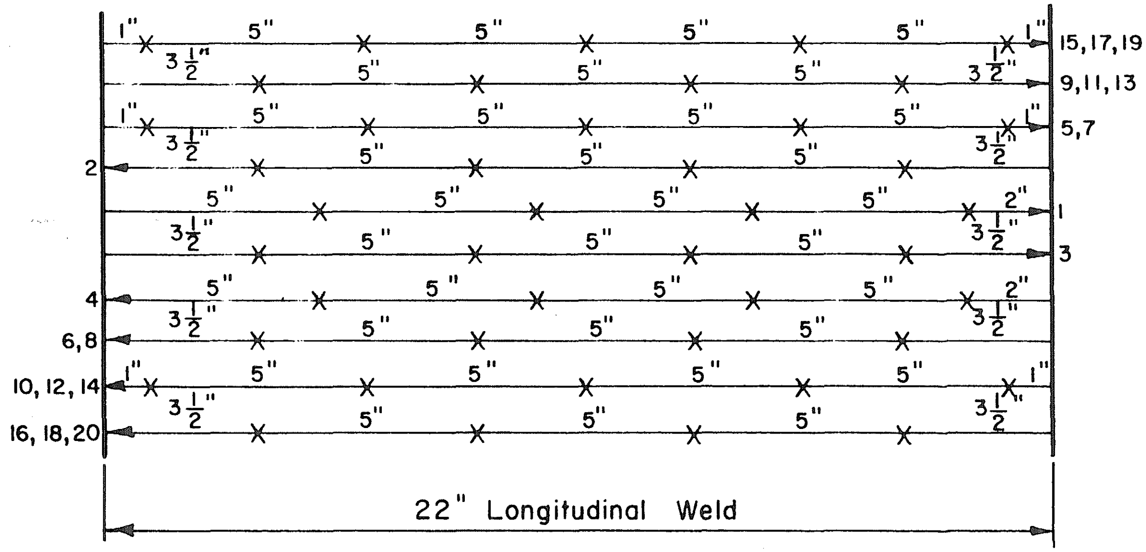


(a) Specimen V-25 (Procedure D-1) (b) Specimen V-35 (Procedure D-2)

FIG. 11 TYPICAL MACROGRAPHS FOR WELDING PROCEDURE D



Surface of plate adjacent to weld cleaned by grinding before welding.

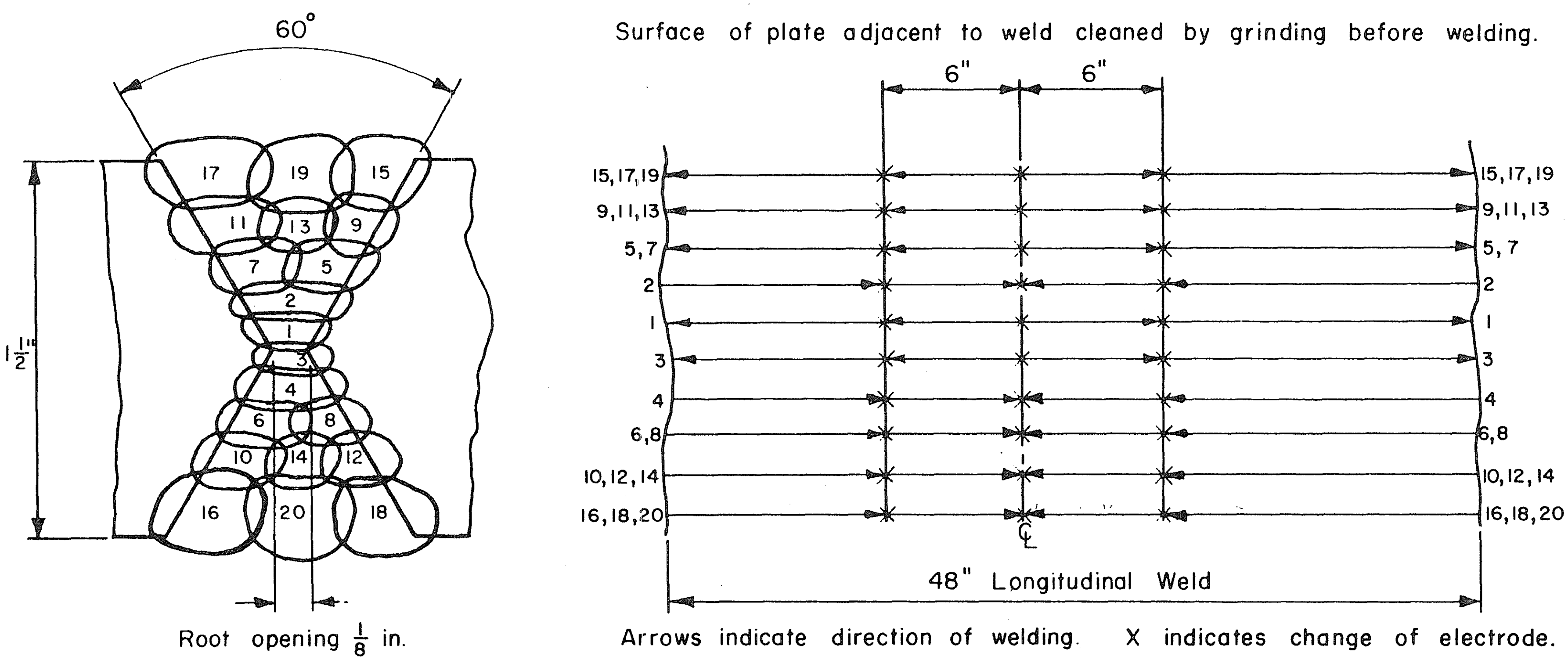


Arrows indicate direction of welding. X indicates change of electrode.

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 300° F (Max.)
Heat Input: 50,000 Joules / in. (Max.)
All welding in flat position.
Underside of pass 1 back-gouged with air arc before pass 3.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4 – 20	$\frac{3}{16}$	230	6.0

FIG. 12 WELDING PROCEDURE E (Longitudinal Butt Welds)

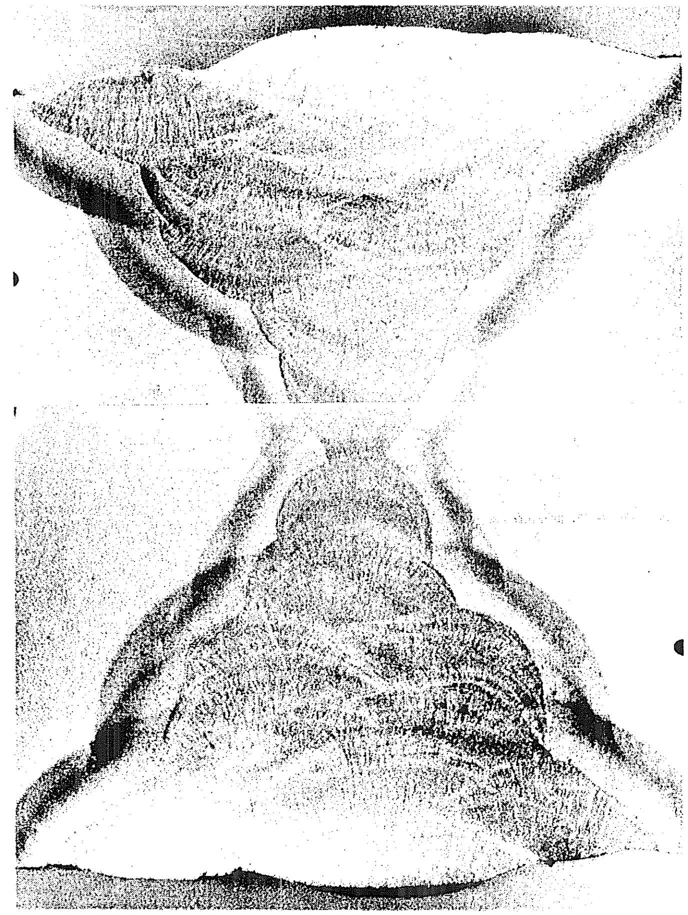


Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4–20	$\frac{3}{16}$	230	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 300°F (Max.)
Heat Input: 50,000 Joules/in. (Max.)
All welding in flat position.
Underside of pass 1 back-gouged with air arc before pass 3.

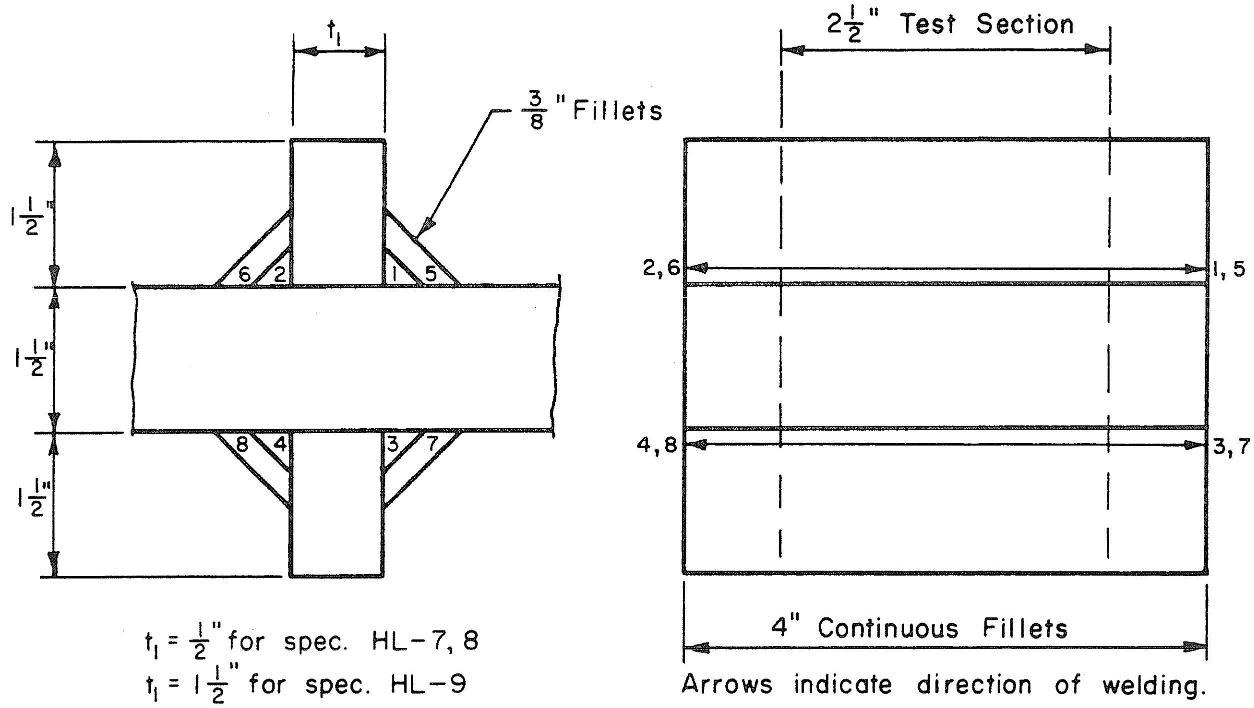
FIG. 13 WELDING PROCEDURE F (Longitudinal Butt Welds)

(a) Specimen HL-11 (Procedure E)



(b) Specimen HL-16 (Procedure F)

FIG.14 TYPICAL MACROGRAPHS FOR WELDING PROCEDURES E AND F



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 – 8	$\frac{5}{32}$	170	4.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 150° F

Electrode: MIL 11018

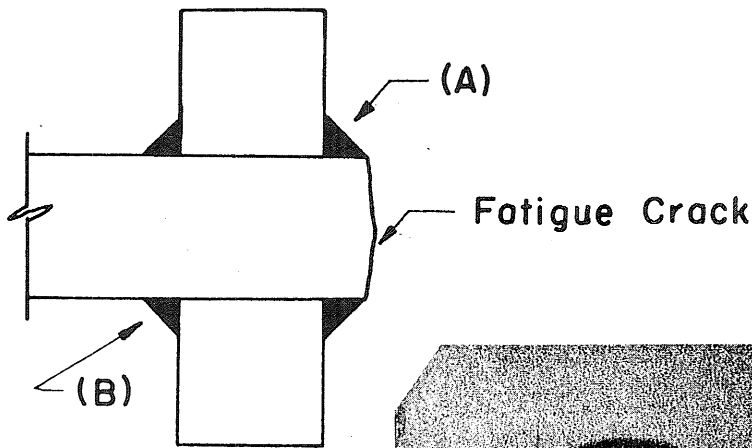
Interpass Temperature: 300° F (Maximum)

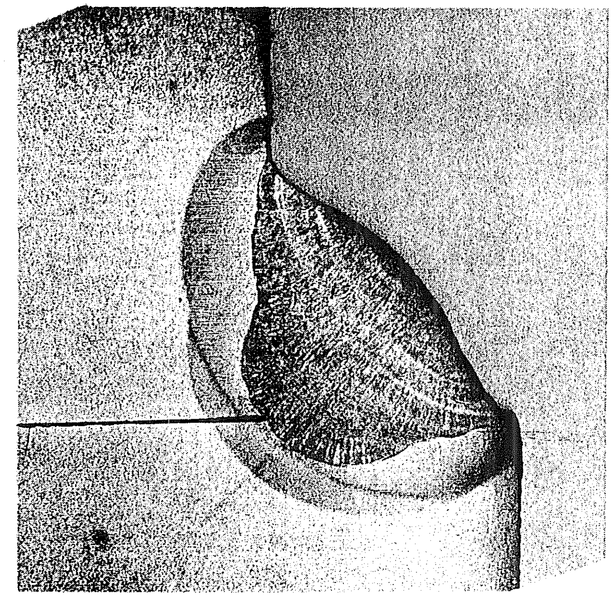
Heat Input: 55,000 Joules / in. (Maximum)

All welding in flat position.

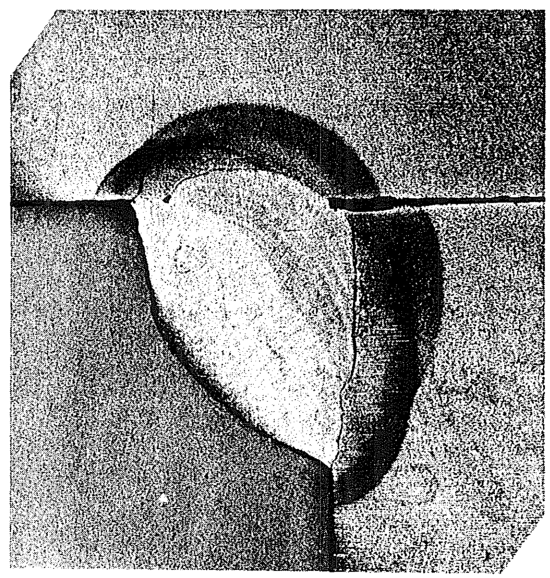
Surfaces cleaned by grinding before welding.

FIG. 15 WELDING PROCEDURE G
(Fillet Welded Transverse Attachments)





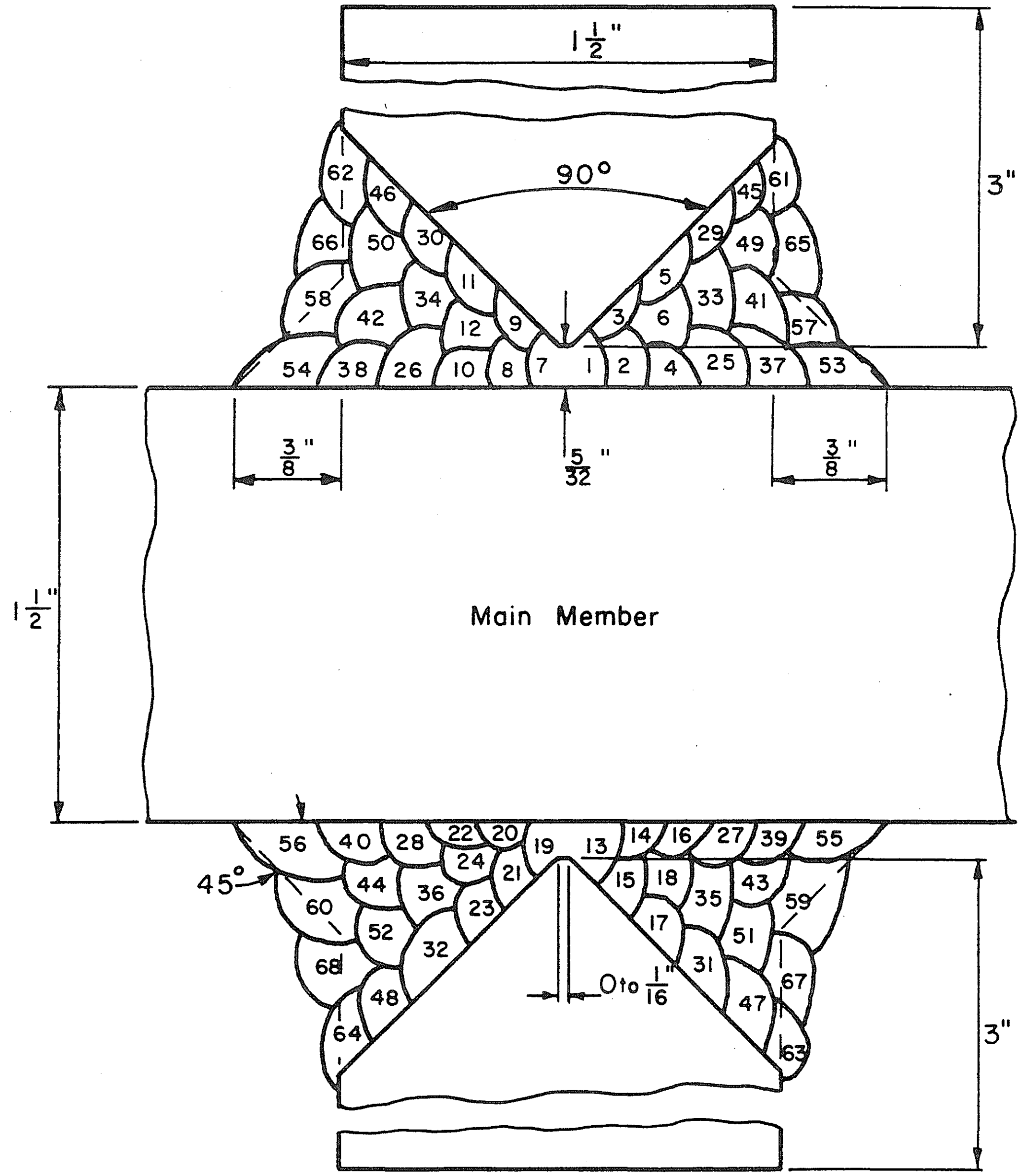
(A)



(B)

SPECIMEN HL-9

FIG. 16 TYPICAL MACROGRAPH FOR WELDING PROCEDURE G



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1–24	$\frac{5}{32}$	170	5.5
25–68	$\frac{3}{16}$	190	6.0

Voltage : 21 Volts
Preheat : 200° F

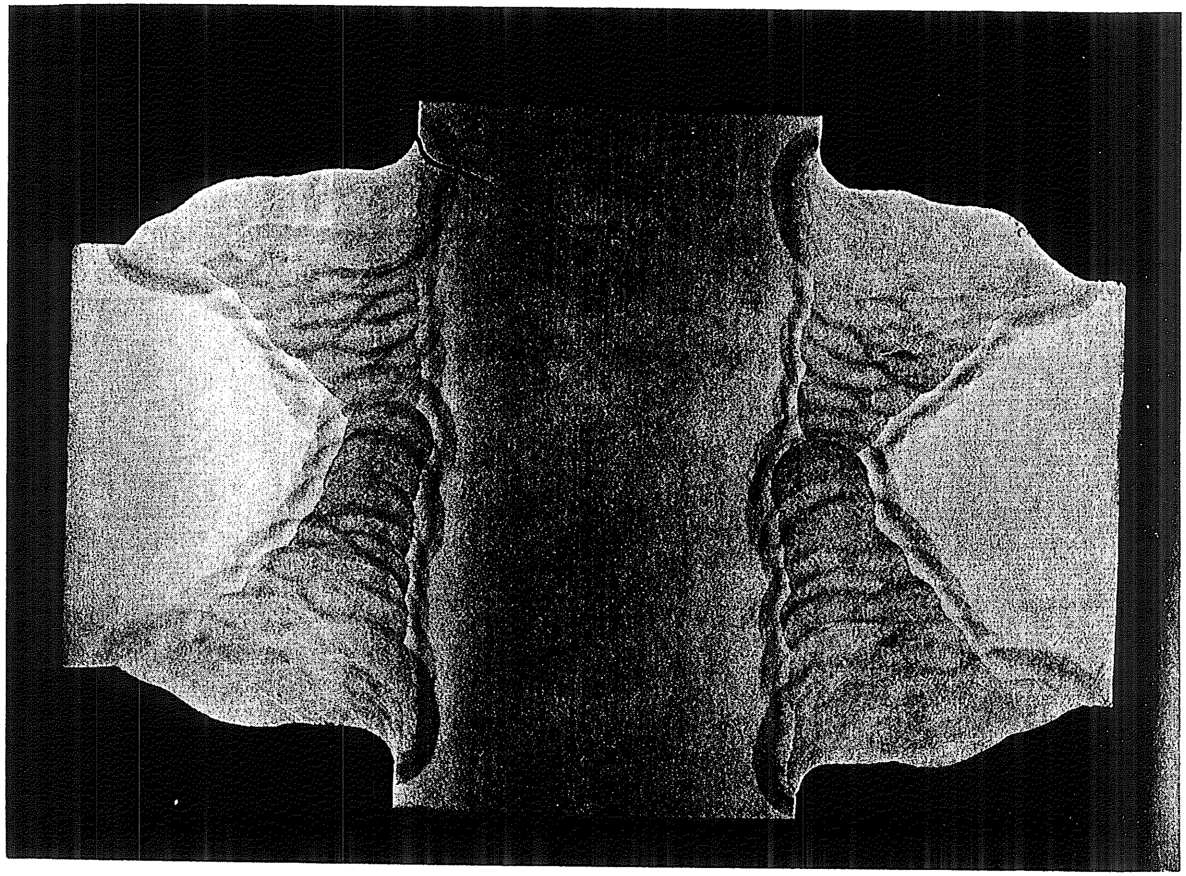
Polarity : D.C. Reversed
Electrode : MIL 11018

Interpass Temp.: 200° F (Max.)
Heat Input : 40,000 Joules/in. (Max.)

Surfaces cleaned by grinding before welding.

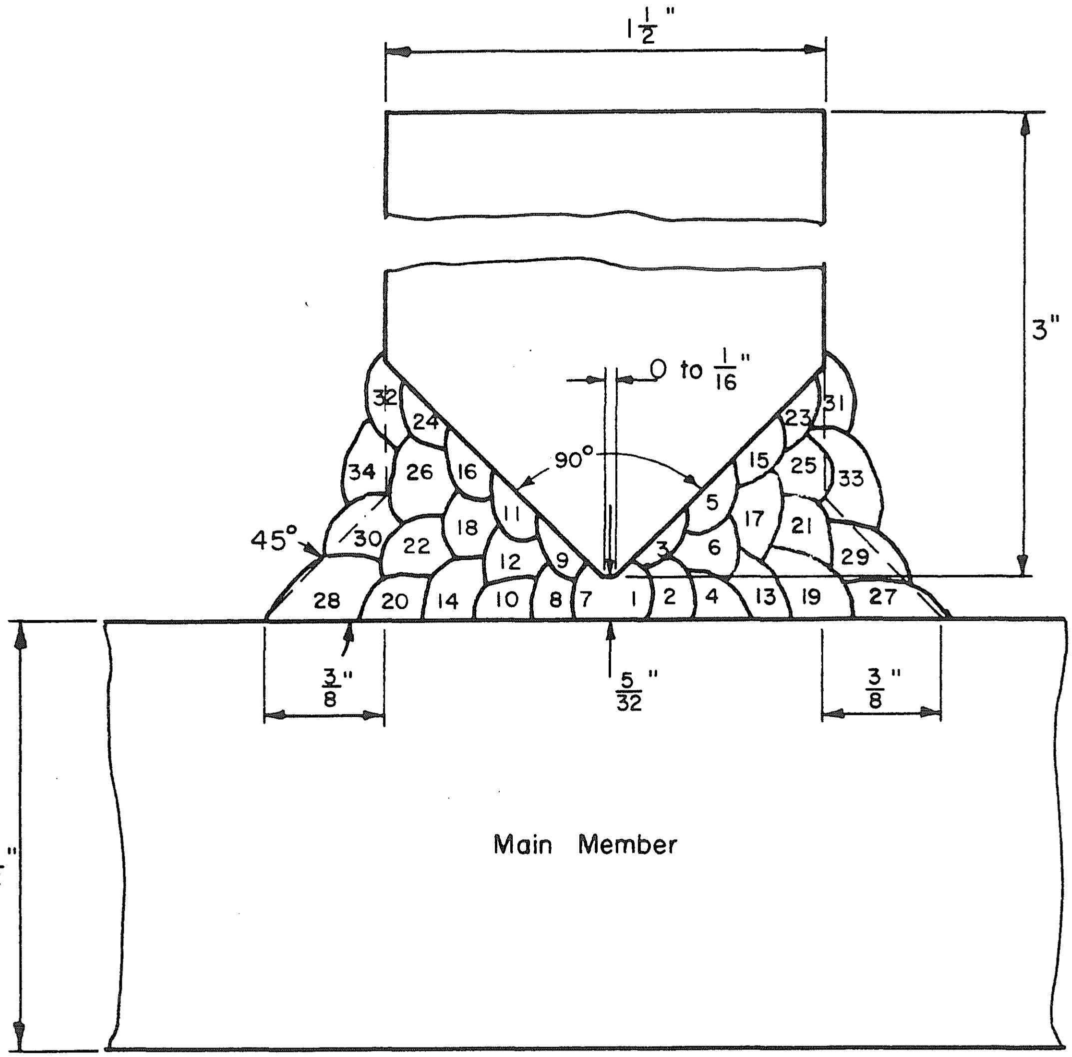
After depositing passes 1-6, root chip. Then deposit passes 7–12. Repeat for other side.

FIG. 17 WELDING PROCEDURE H
(Full Penetration Transverse Attachments)



Specimen V-42

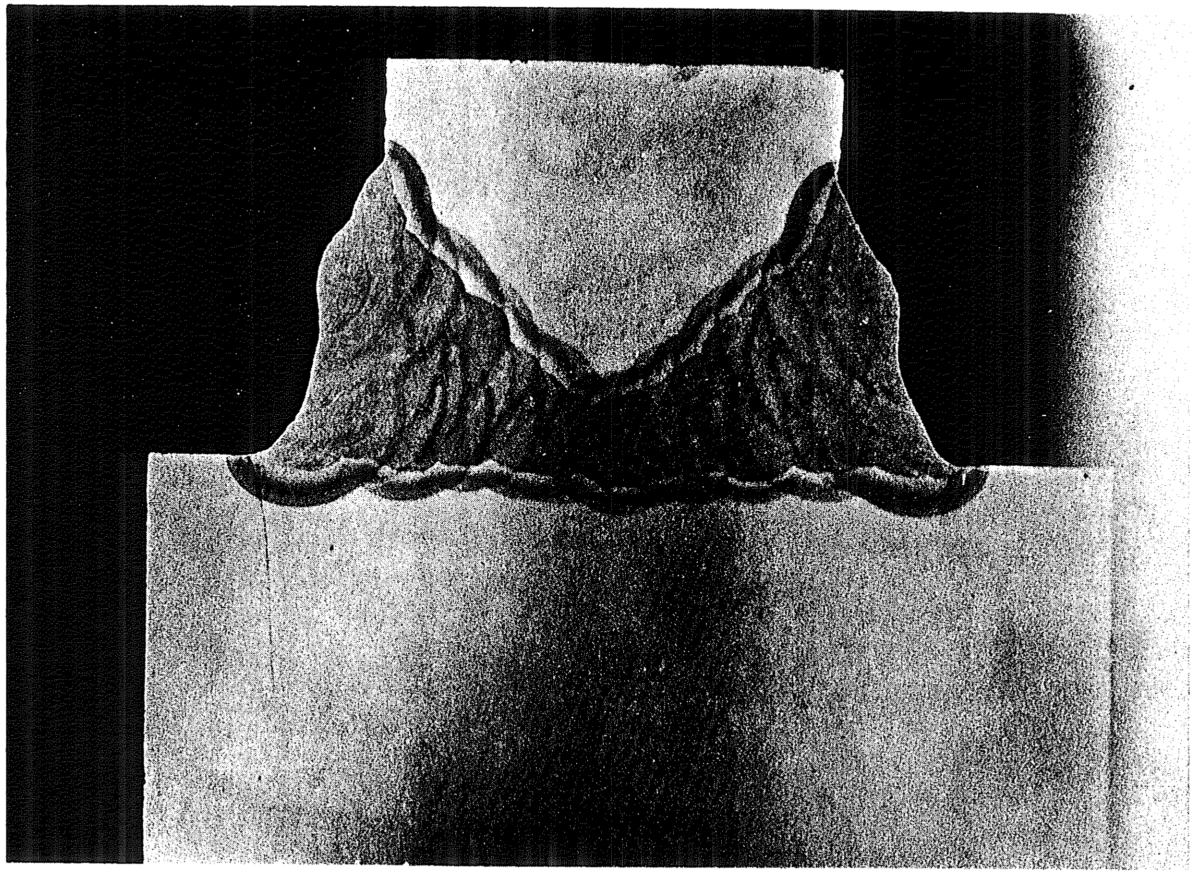
FIG. 18 TYPICAL MACROGRAPH FOR WELDING PROCEDURE H



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 – 12	$\frac{5}{32}$	170	5.5
13–34	$\frac{3}{16}$	190	6.0

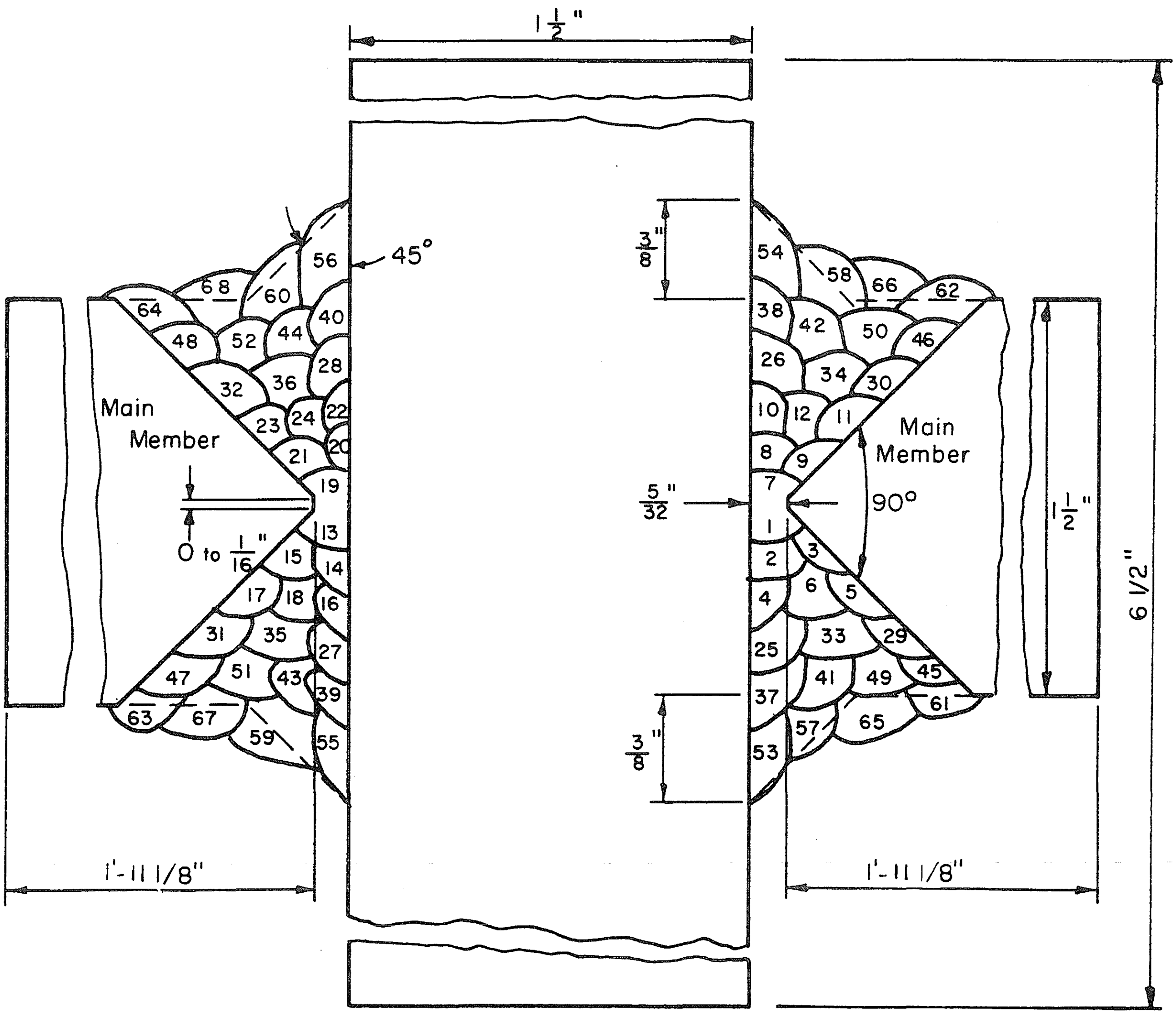
Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 200° F
Electrode: MIL 11018
Interpass Temperature: 200°F (Maximum)
Heat Input: 40,000 Joules/in. (Maximum)
Surfaces cleaned by grinding before welding.
After depositing passes 1 – 6, root chip. Then deposit passes 7 – 34.

FIG. 19 WELDING PROCEDURE J
(Full Penetration Transverse Attachments)



Specimen V-47

FIG. 20 TYPICAL MACROGRAPH FOR WELDING PROCEDURE J



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1–24	$\frac{5}{32}$	170	5.5
25–68	$\frac{3}{16}$	190	6.0

Voltage : 21 Volts

Polarity : D.C. Reversed

Interpass Temp.: 200° F (Max.)

Preheat : 200° F

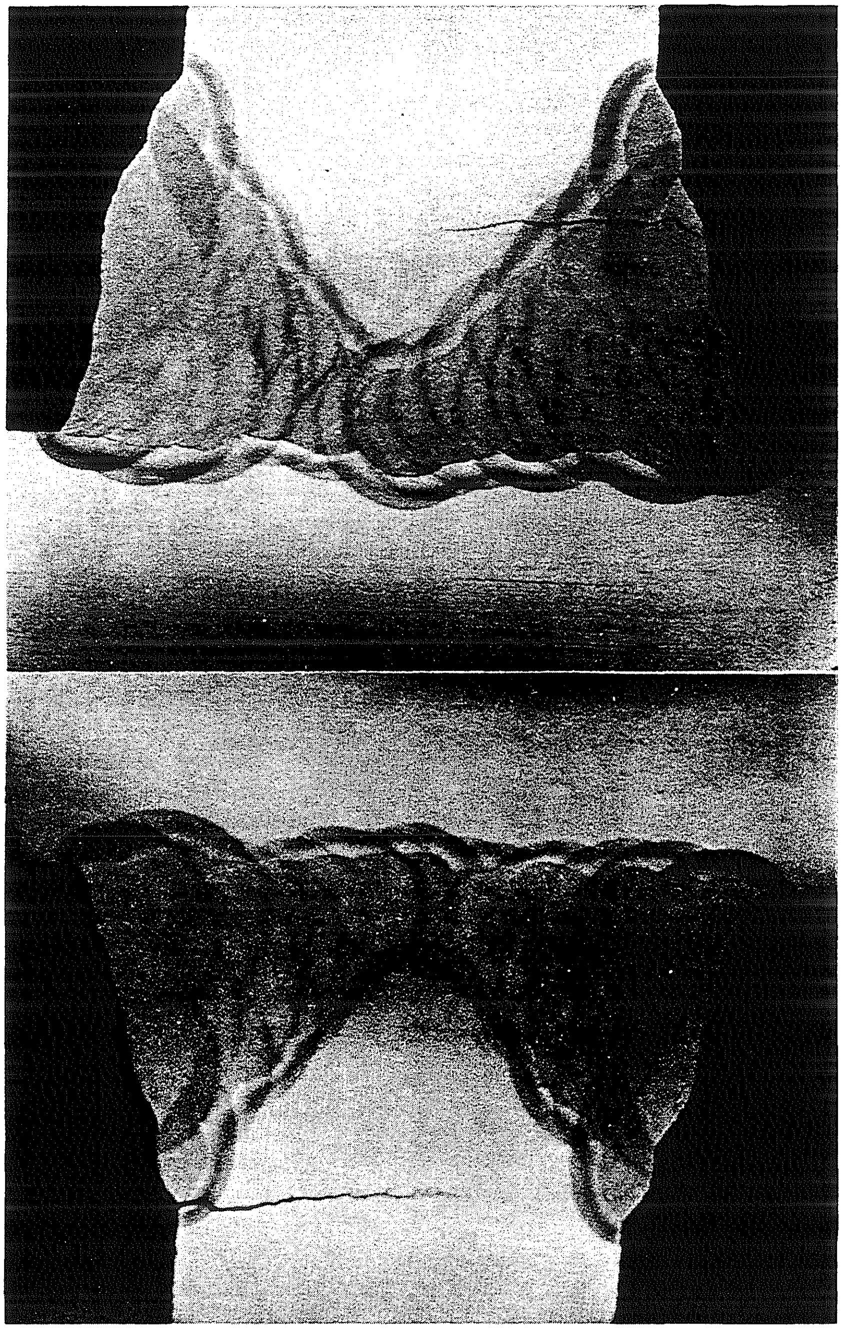
Electrode : MIL 11018

Heat Input: 40,000 Joules/in. (Max.)

Surfaces cleaned by grinding before welding.

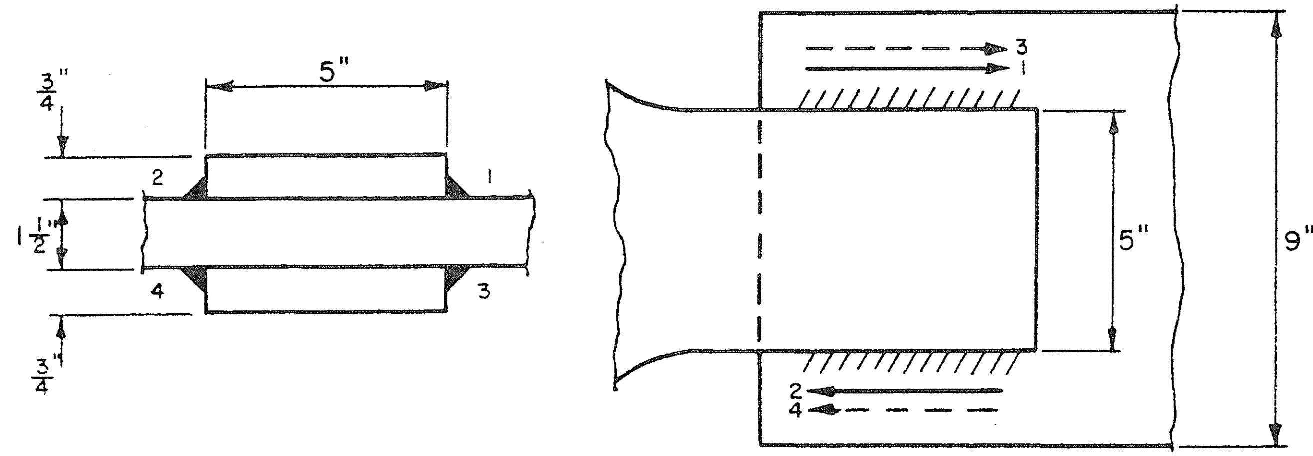
After depositing passes 1-6, root chip. Then deposit passes 7-12. Repeat for other side.

FIG. 21 WELDING PROCEDURE K
(Tee Joint)



Specimen V - 51

FIG. 22 TYPICAL MACROGRAPH FOR WELDING PROCEDURE K



Solid arrows show direction of welding on front face.
Dotted arrows show direction of welding on back face.
Continuous weld for specimen HL-13.
Electrode changed at mid-length of weld for specimen HL-14, HL-15.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 – 4	$\frac{3}{16}$	170	4.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 250° F (Maximum)
Heat Input: 55,000 Joules/in. (Maximum)
Surfaces cleaned by grinding before welding.

FIG. 23 WELDING PROCEDURE L
(Longitudinal Fillets)

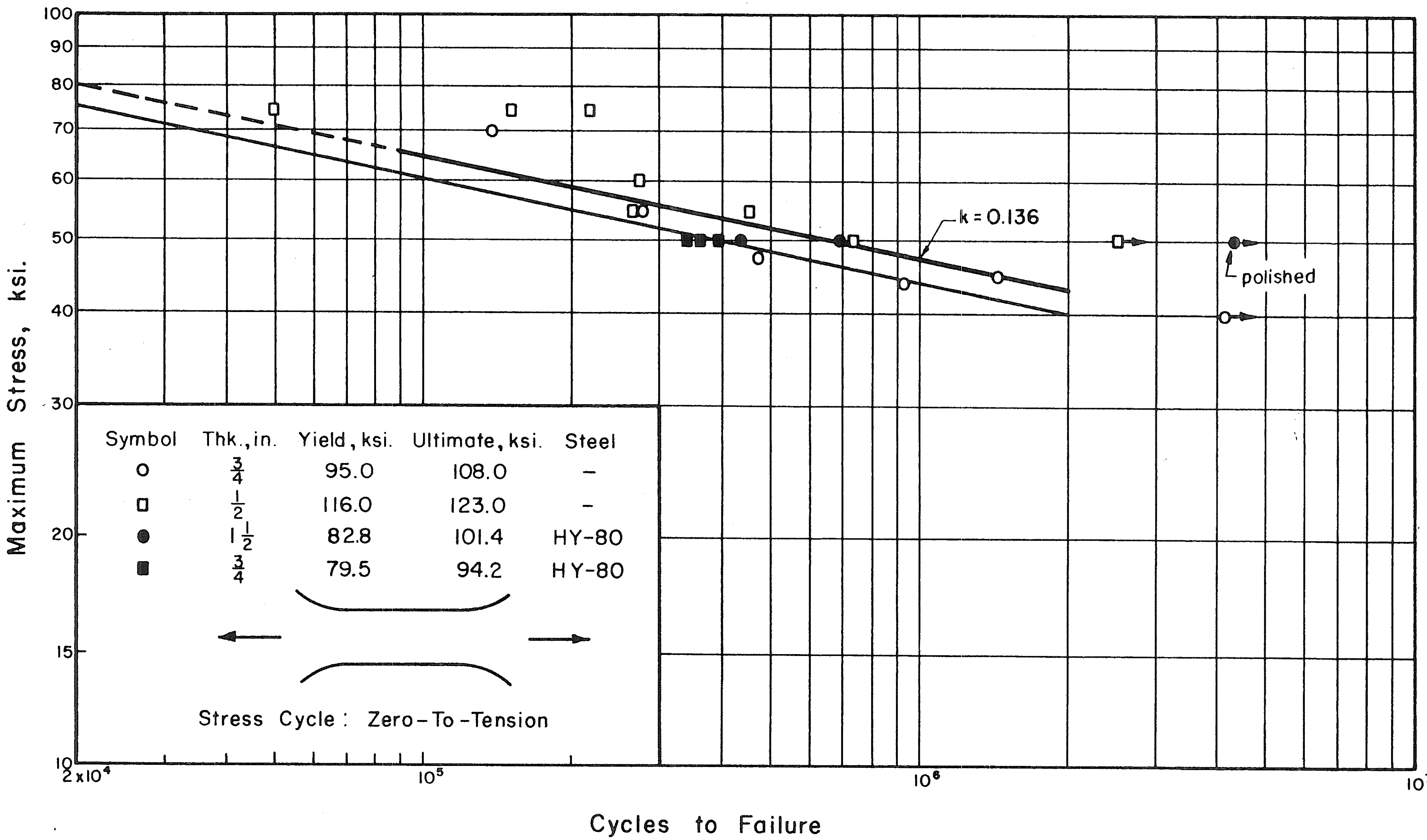
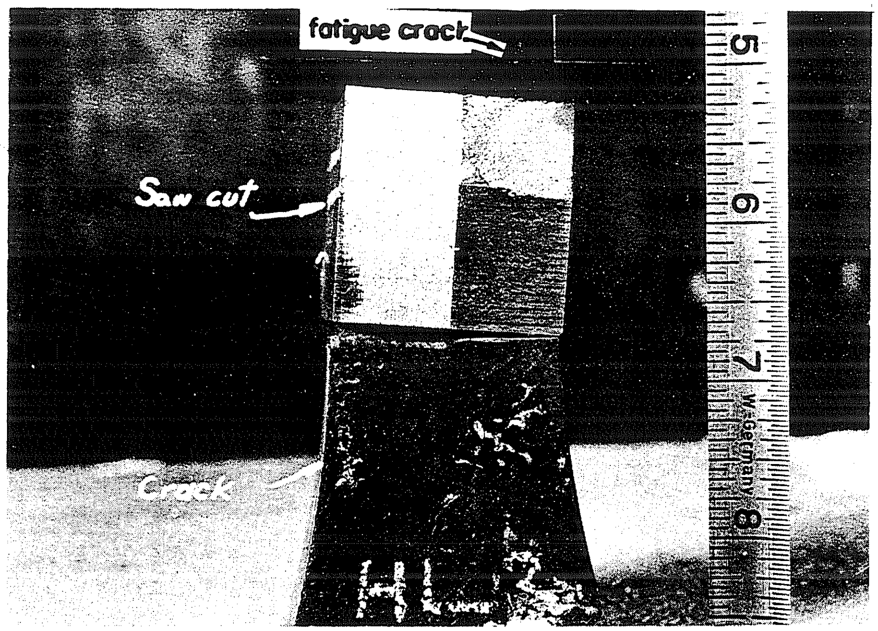
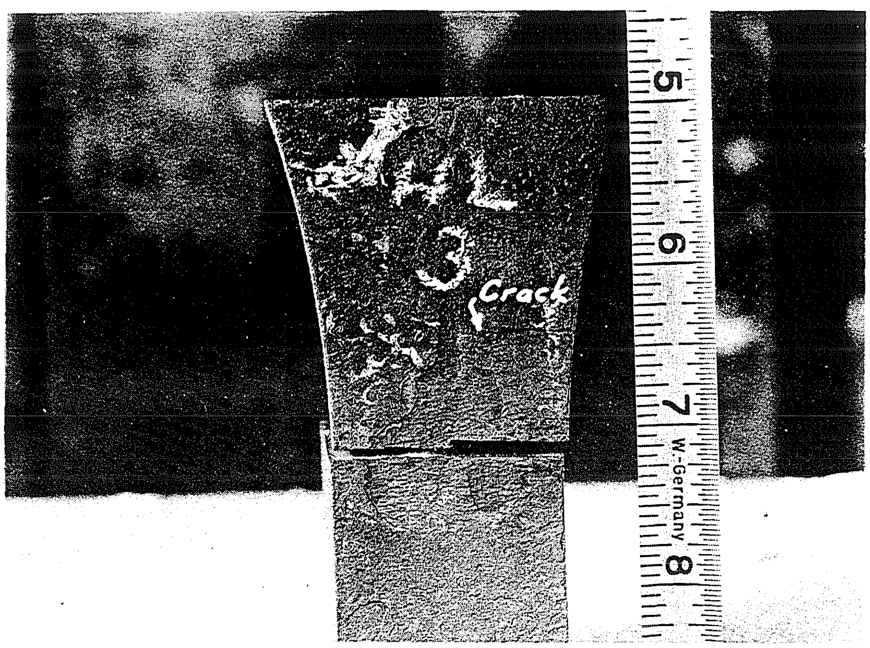


FIG. 24 RESULTS OF FATIGUE TESTS OF PLAIN AS-ROLLED SPECIMENS. AXIAL TENSION.



(a) North Face – Fracture Surface, Second Crack



(b) South Face

FIG. 25 FRACTURE OF SPECIMEN HL-3
(Plain Plate Specimen)

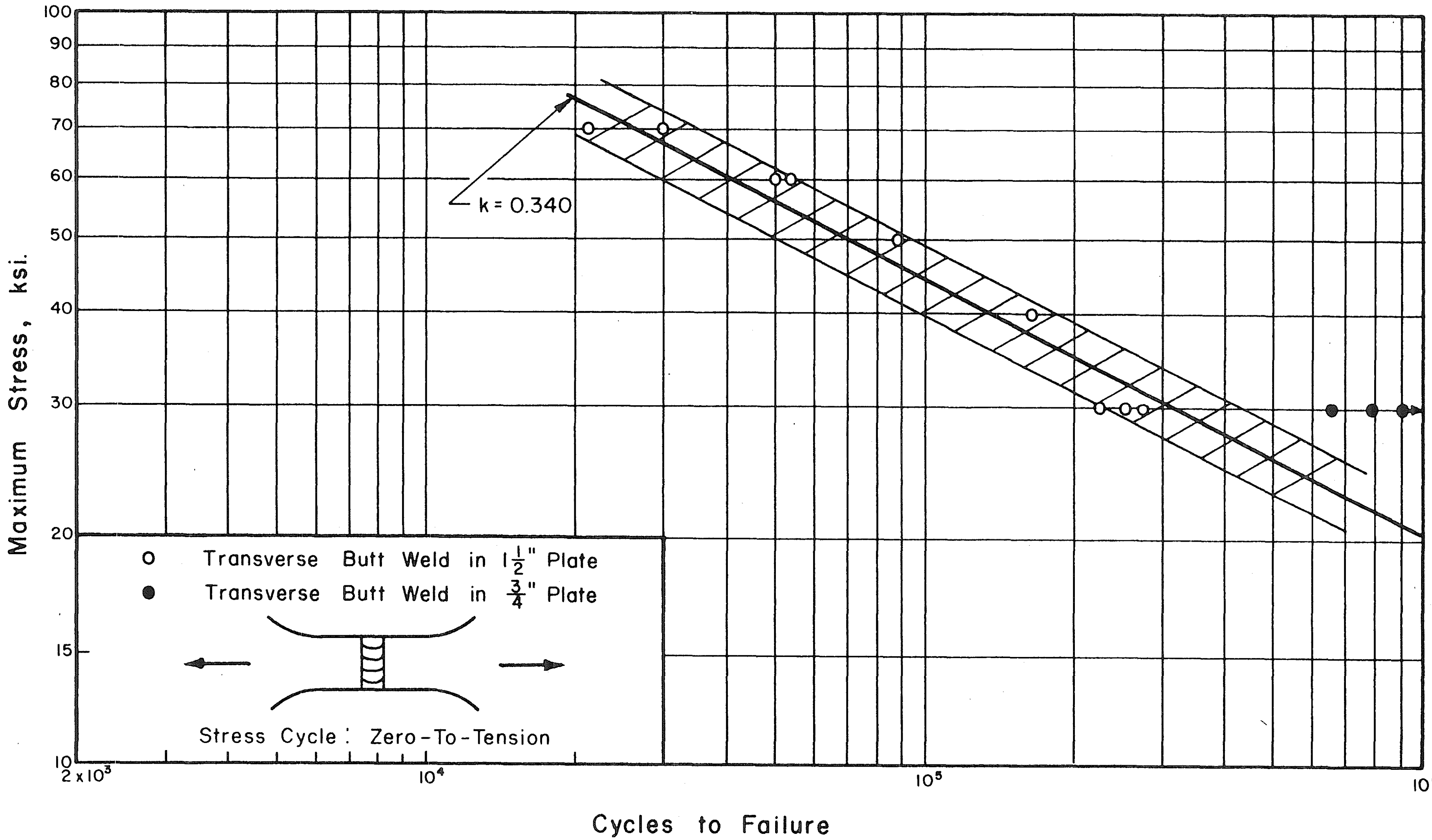


FIG. 26 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION. AXIAL TENSION.

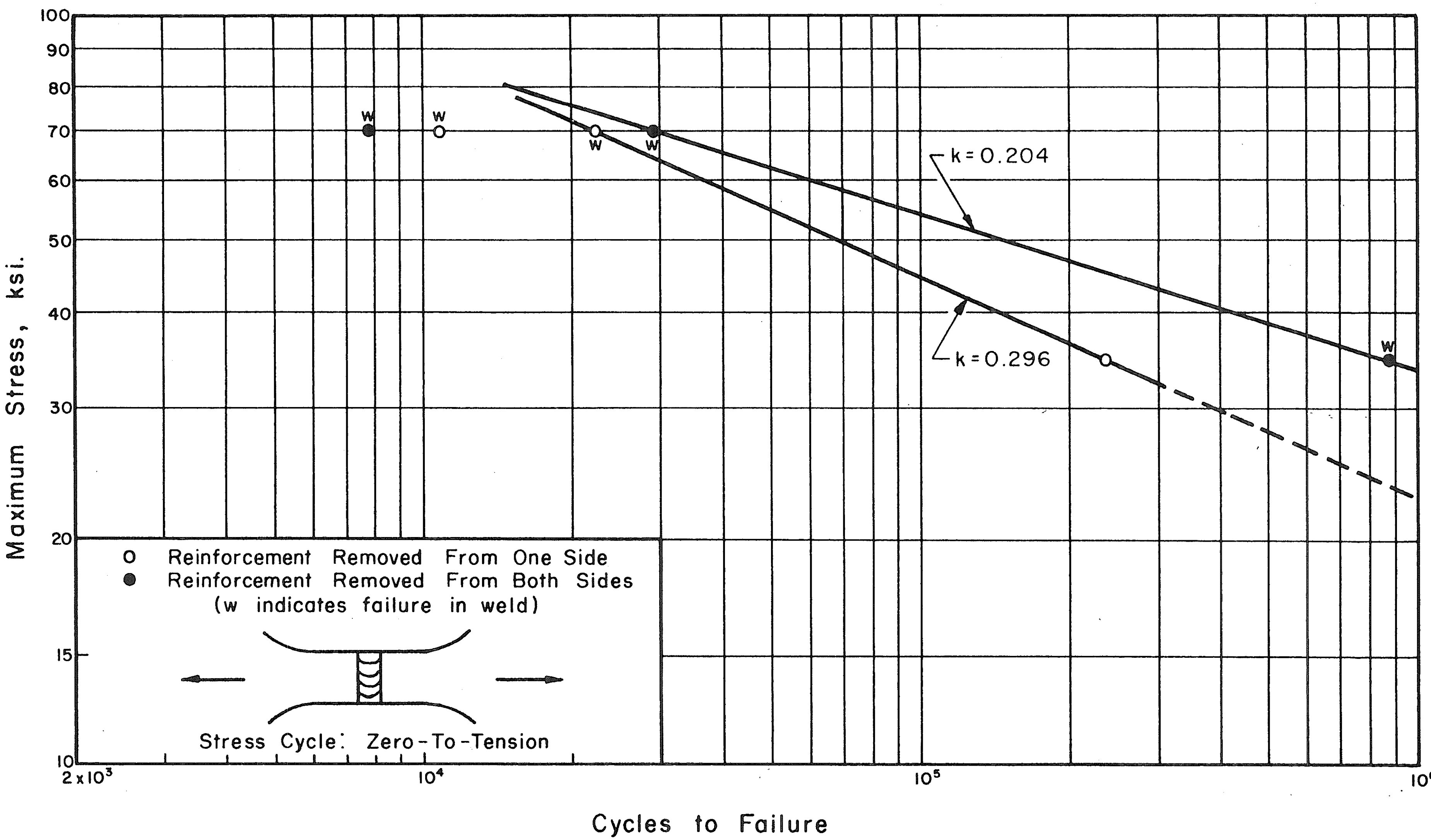


FIG. 27 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED. AXIAL TENSION.

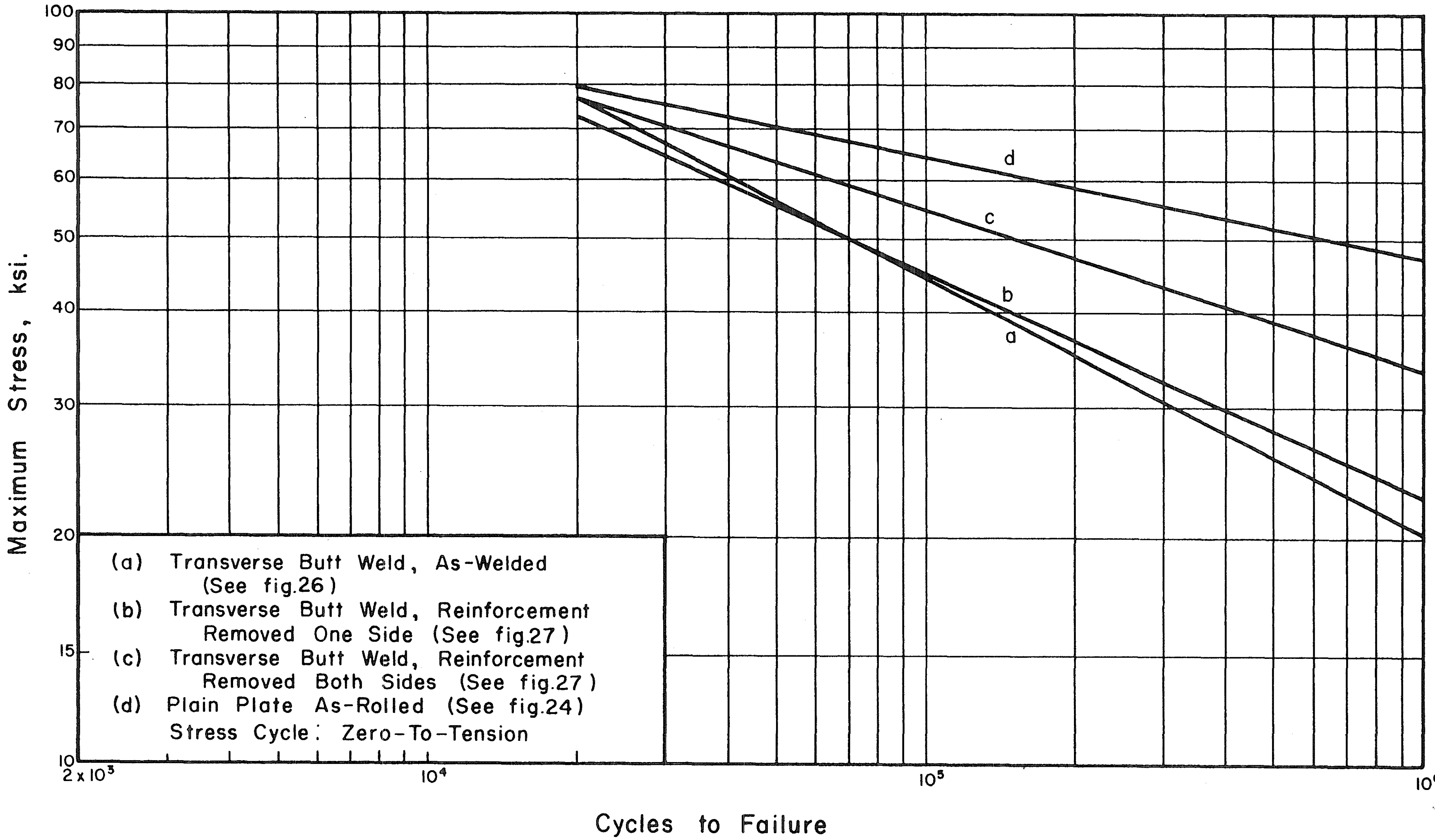


FIG. 28 SUMMARY DIAGRAM SHOWING THE EFFECT OF WELDING AND WELD GEOMETRY ON FATIGUE LIFE. AXIAL TENSION.

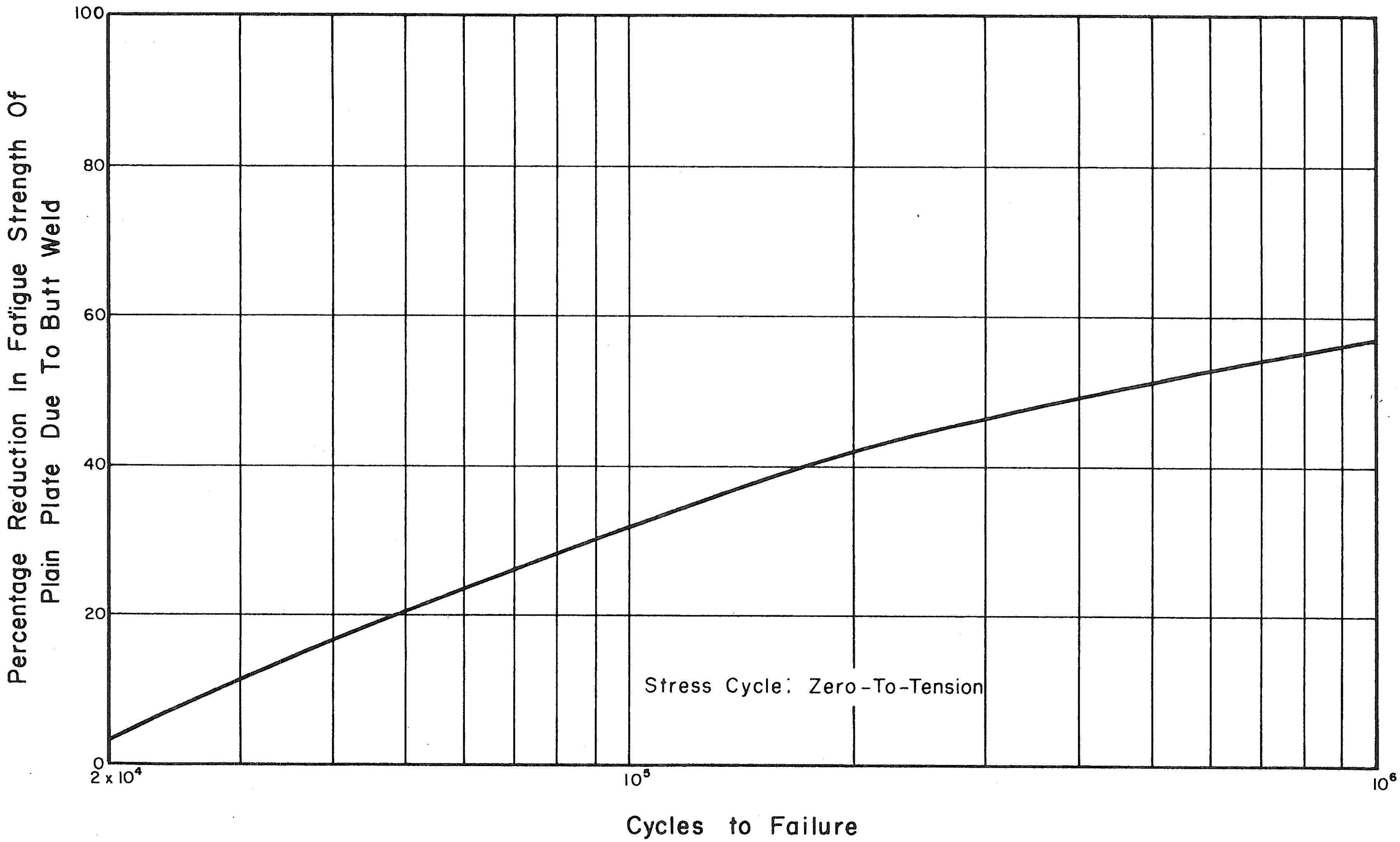


FIG. 29 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO A TRANSVERSE BUTT WELD.

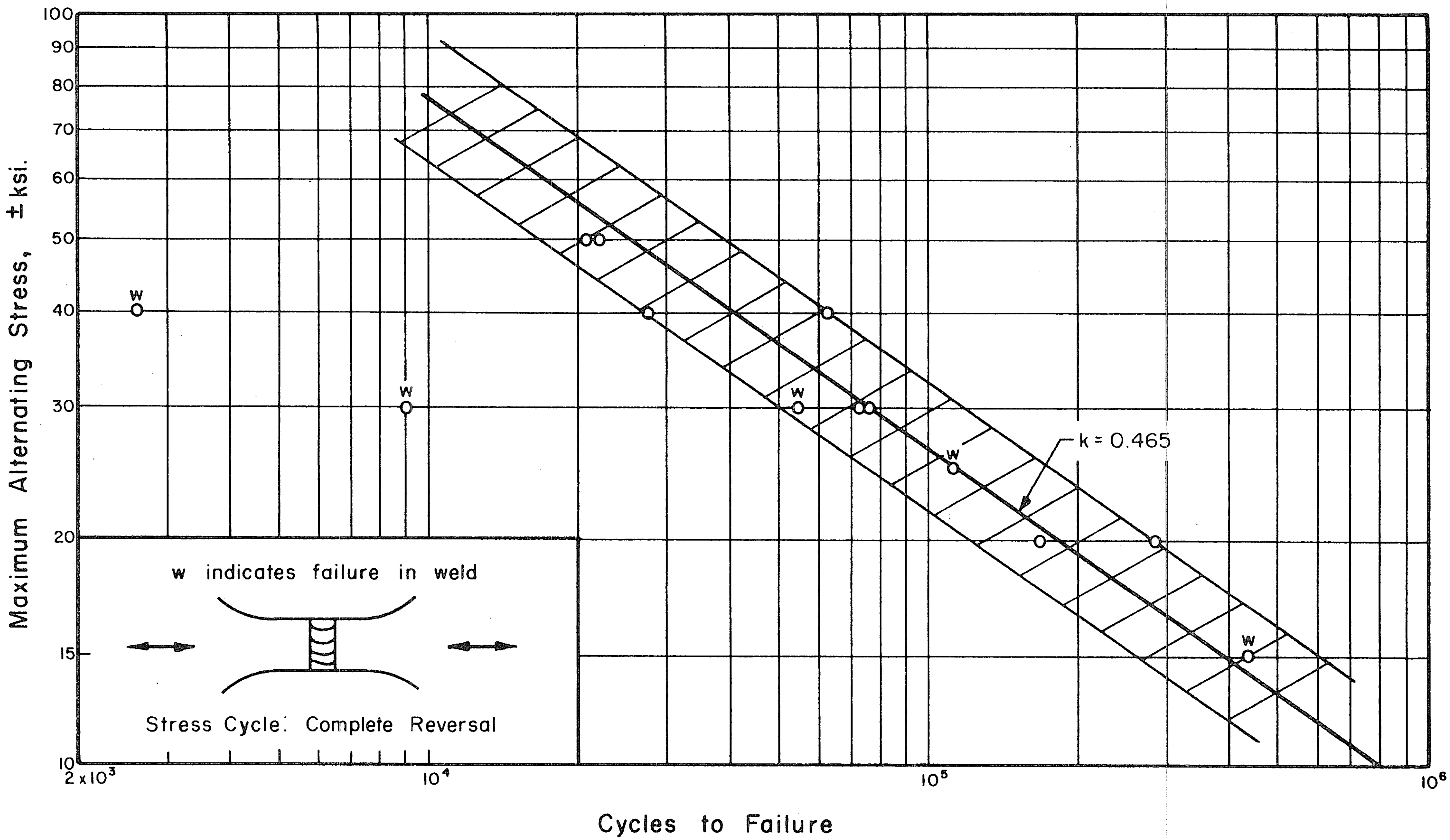


FIG. 30 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION. COMPLETE REVERSAL, AXIAL LOADING.

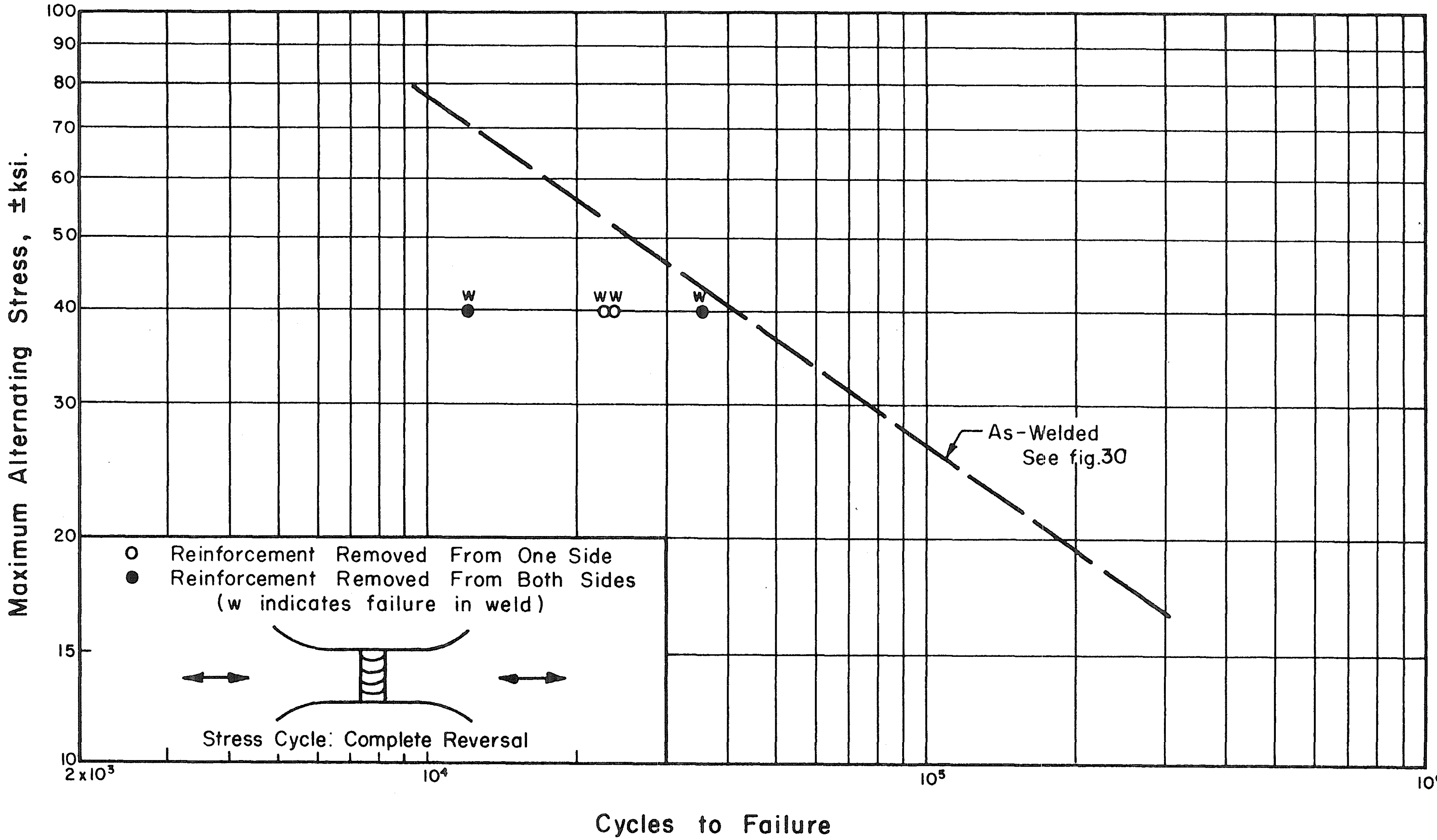


FIG. 31 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED. COMPLETE REVERSAL, AXIAL LOADING.

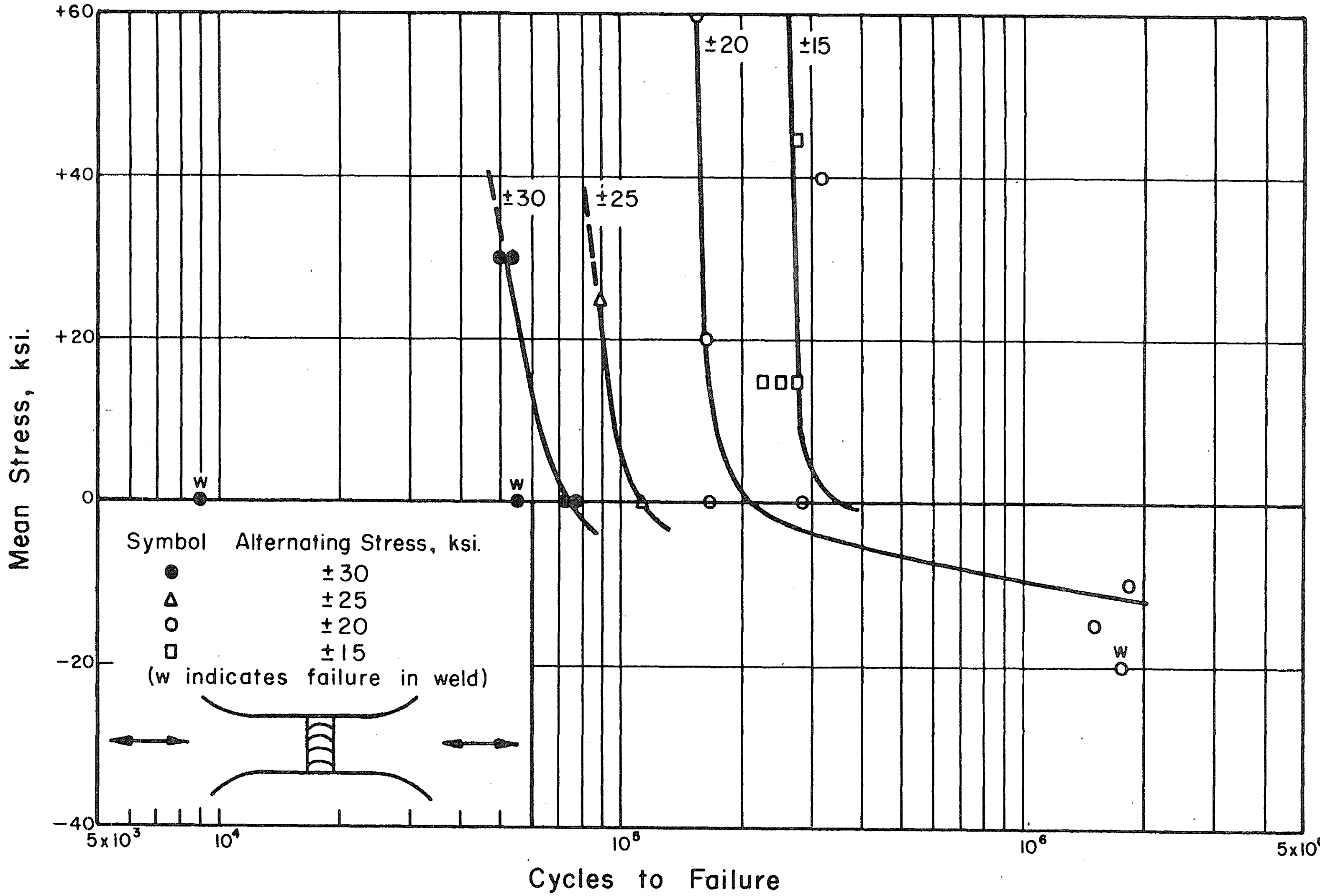


FIG. 32 EFFECT OF MEAN STRESS ON THE FATIGUE LIFE OF AS-WELDED TRANSVERSE BUTT WELDS UNDER ALTERNATING STRESSES OF VARIOUS MAGNITUDES.

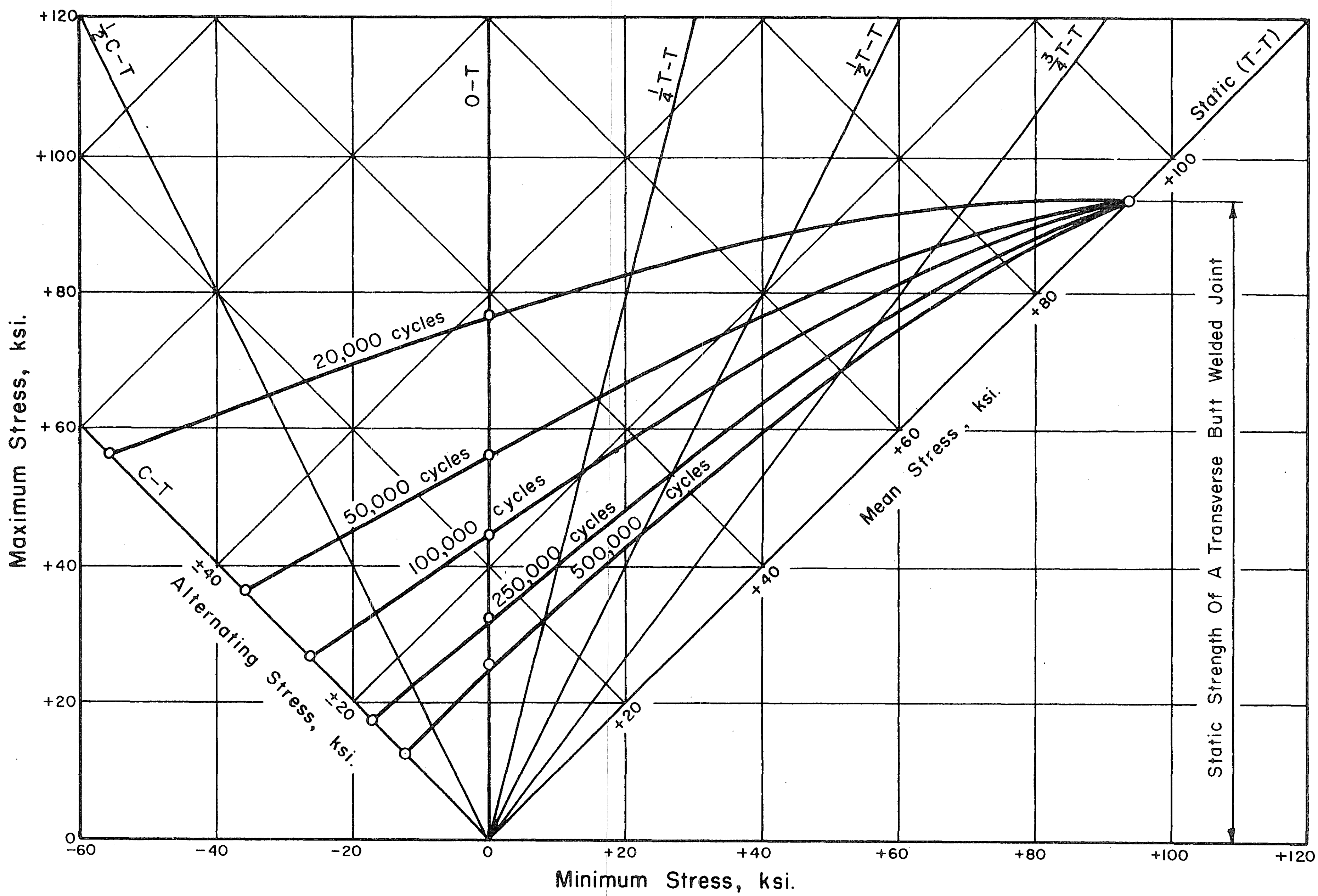


FIG. 33 MODIFIED GOODMAN DIAGRAM FOR TRANSVERSE BUTT WELDS IN HY-80 STEEL, IN THE AS-WELDED CONDITION.

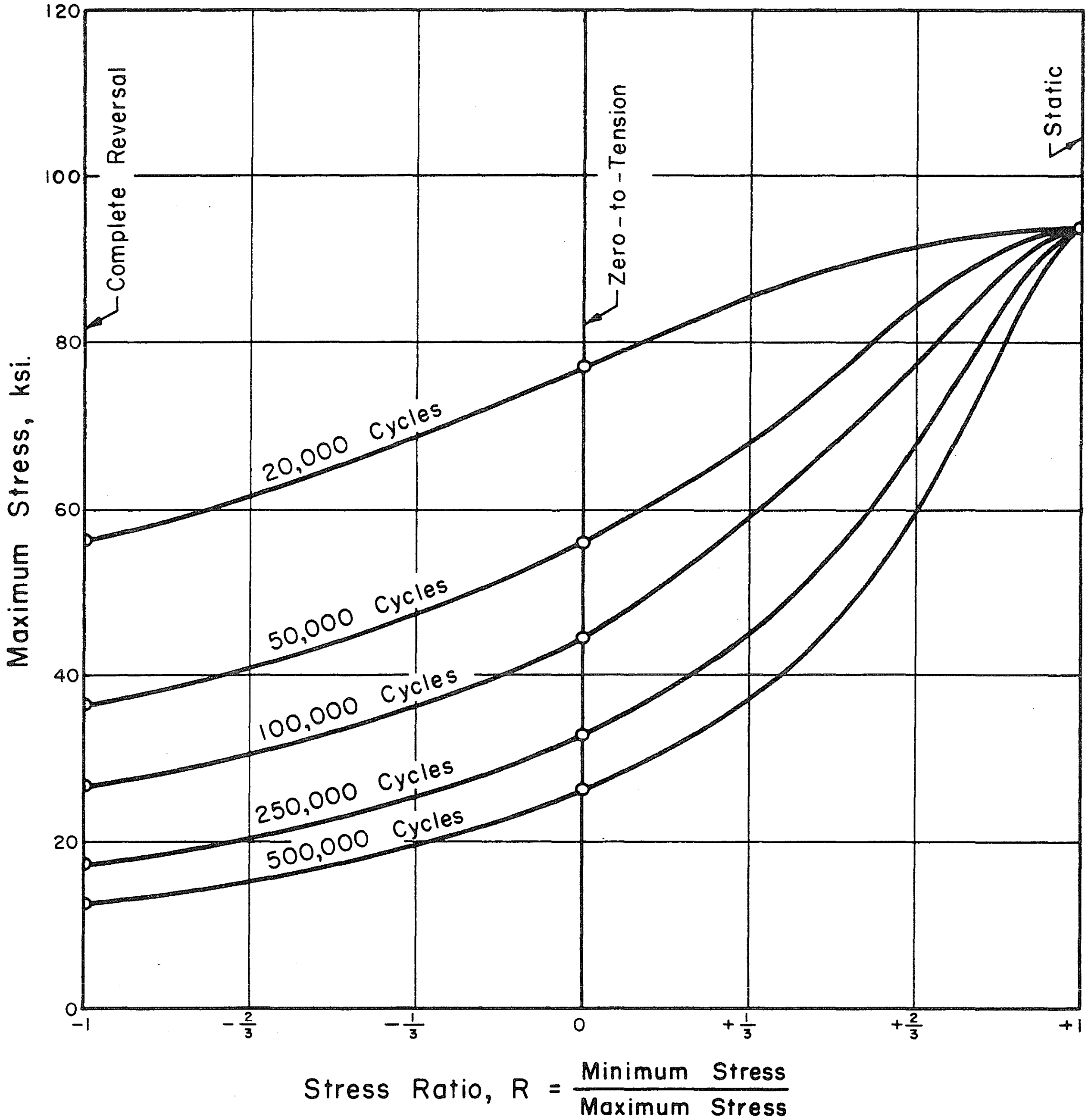
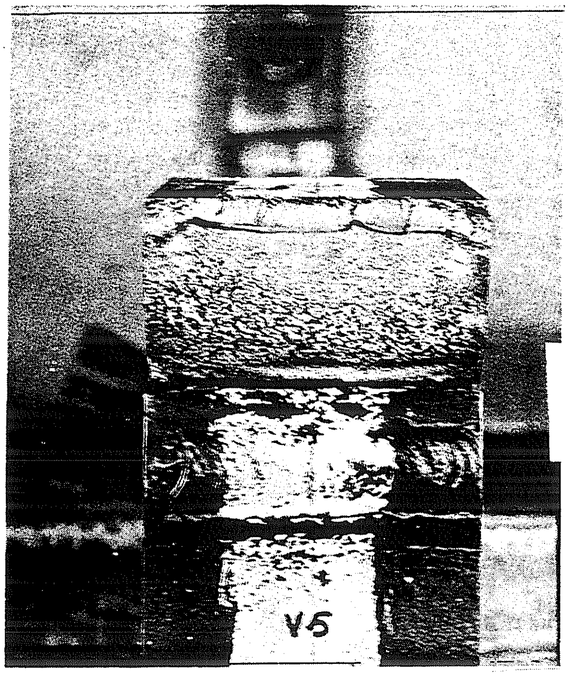
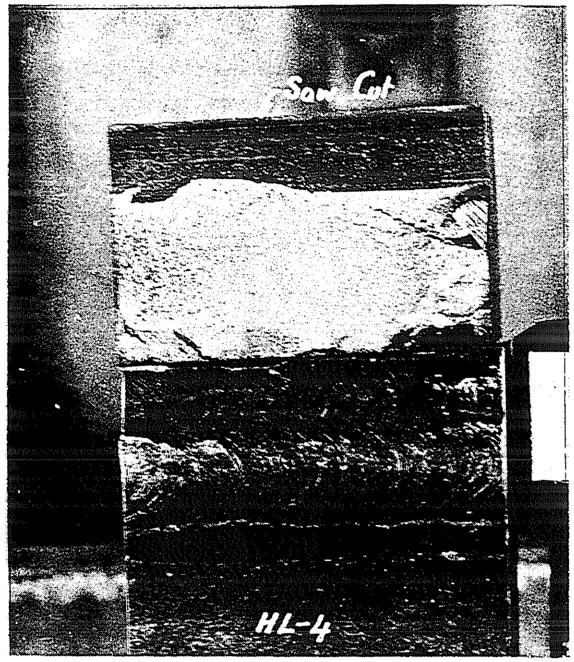


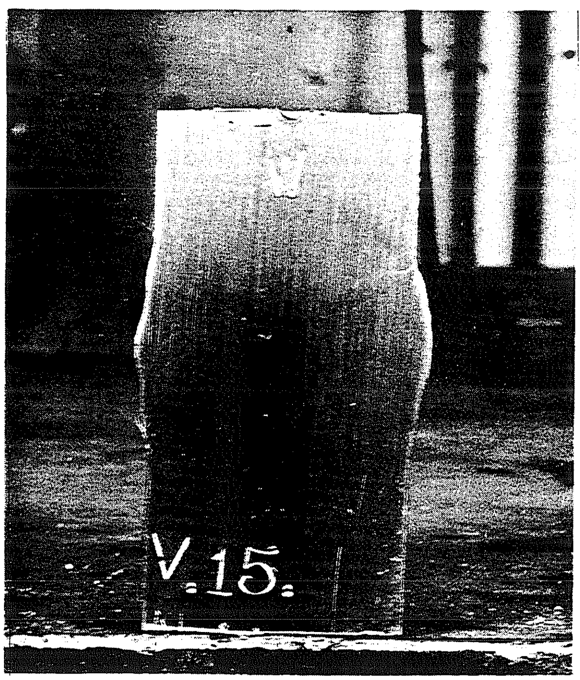
FIG. 34 CONSTANT LIFE CONTOURS FOR TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION AS A FUNCTION OF MAXIMUM CYCLIC STRESS AND THE STRESS RATIO.





(a) V-5 (b) HL-4

Typical Fracture Locations and Surfaces



(c) V-15 (d) V-15

Typical Fracture Location at Edges of Weld

FIG. 35 FRACTURE OF SPECIMENS HL-4, V-5, V-15
(Transverse Butt Welds with Reinforcement in Place, Failure at Edge of Weld)

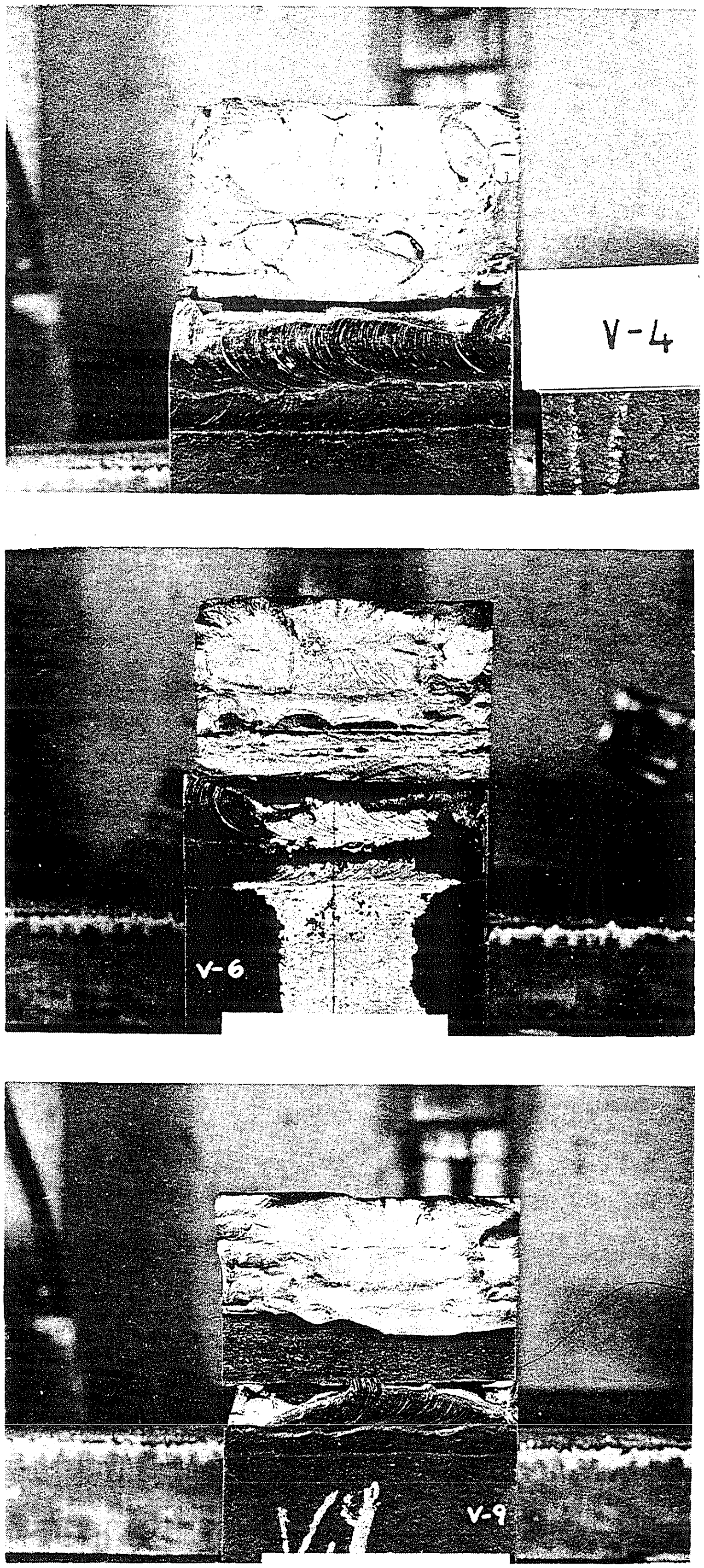
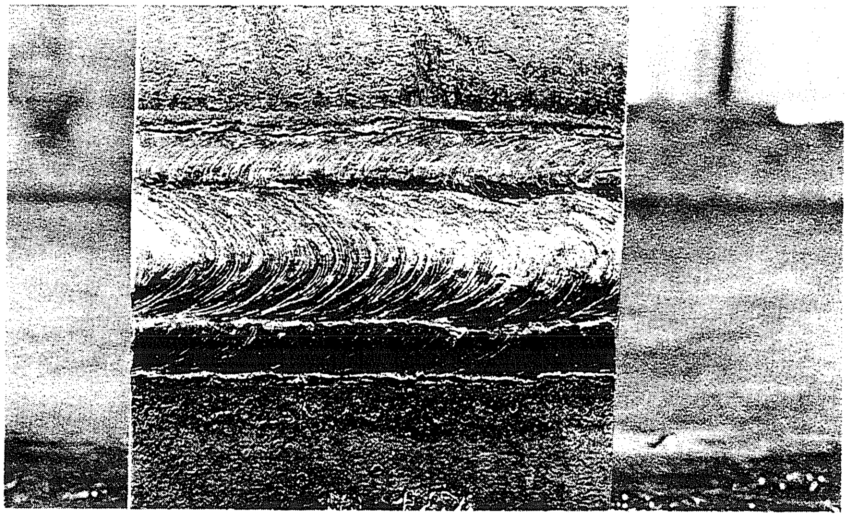
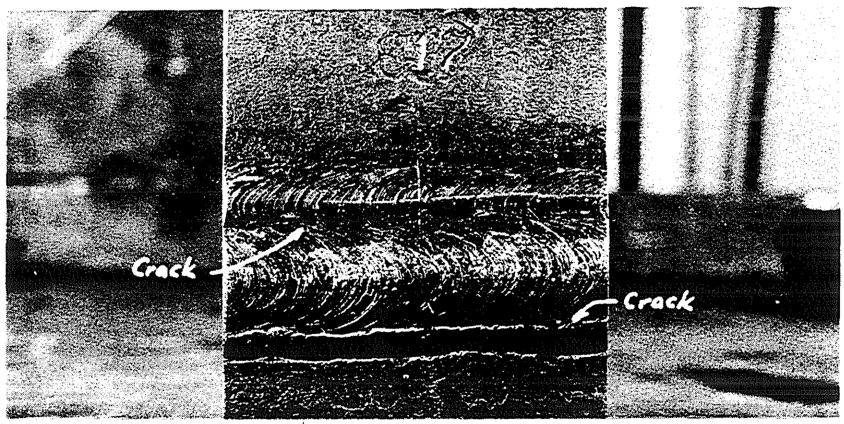


FIG. 36 FRACTURE OF SPECIMENS V-4, V-6, V-9

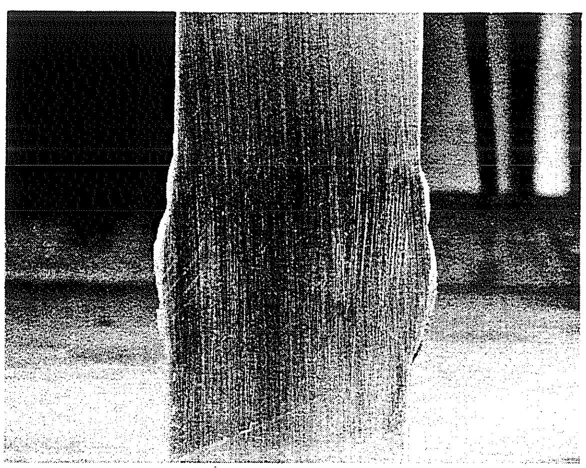
(Transverse Butt Welds with Reinforcement in Place, Failure in Weld)



(a) North Face



(b) South Face

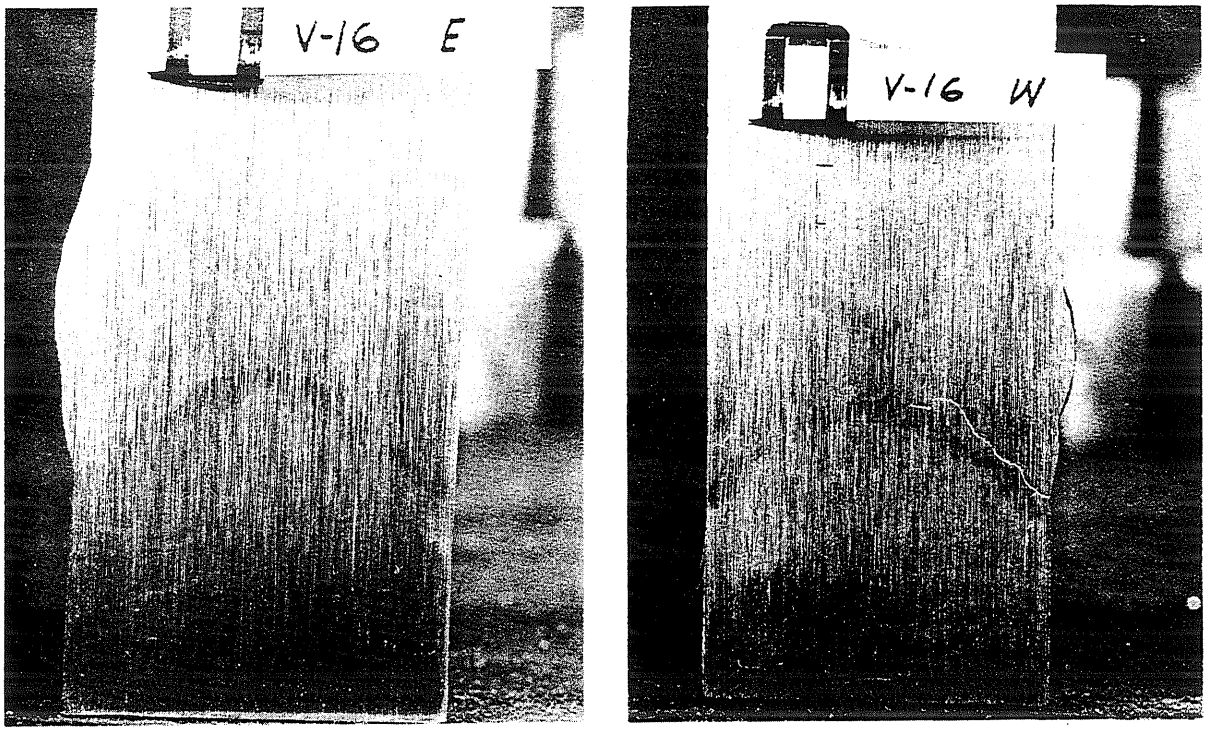


(c) West Face

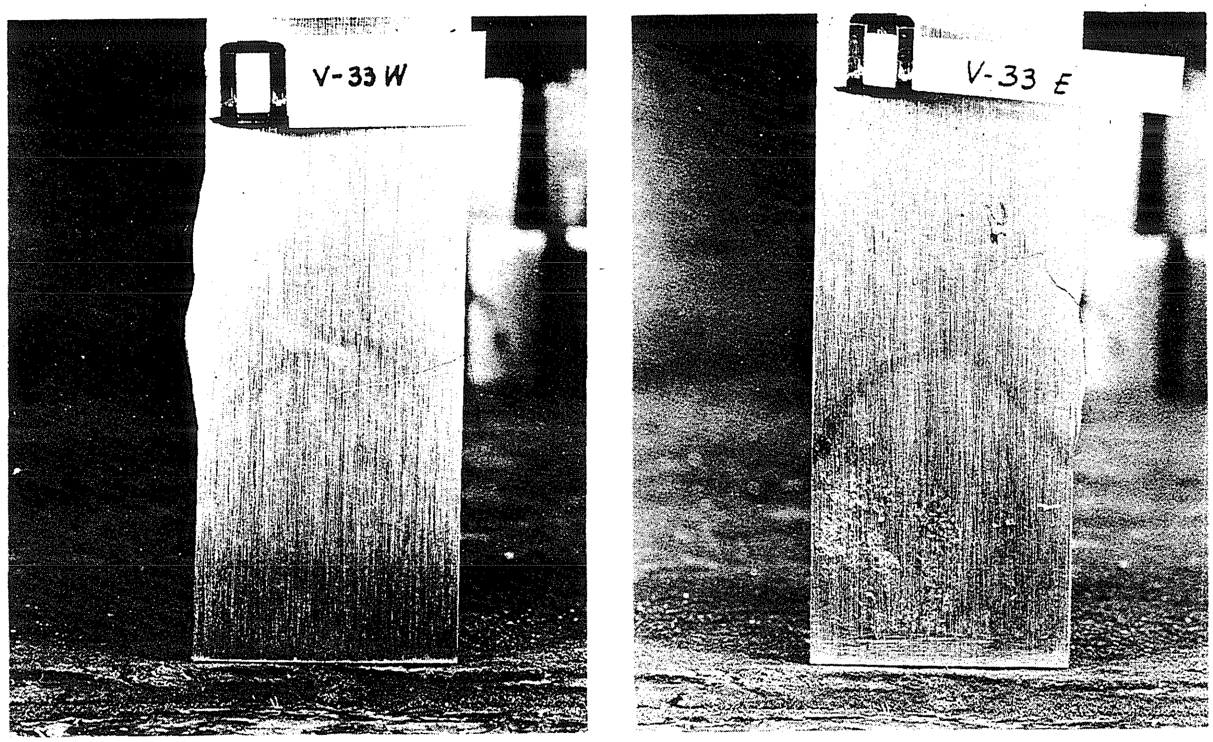
(d) East Face

FIG. 37 FRACTURE OF SPECIMEN V-17

(Transverse Butt Weld with Reinforcement in Place, Failure in Weld)

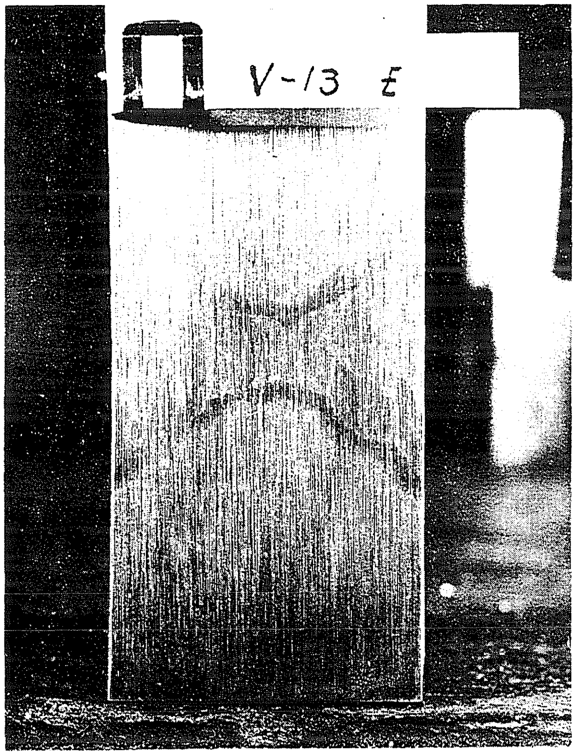


(a) Failure at Edge of Weld

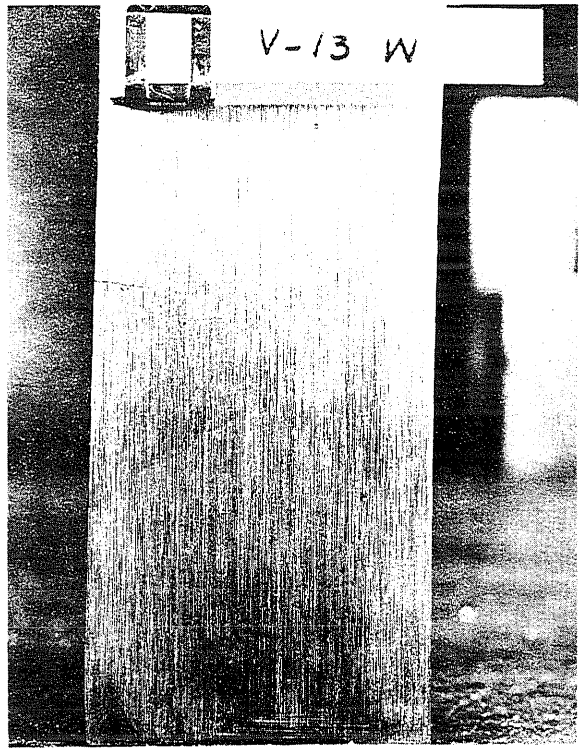


(b) Failure in Weld

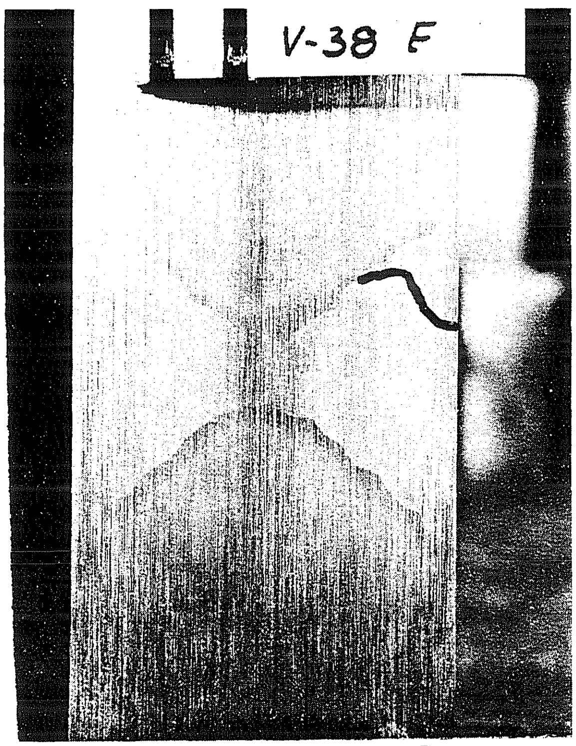
FIG. 38 FRACTURE OF SPECIMENS V-16, V-33
(Transverse Butt Welds with Reinforcement Removed from One Side)



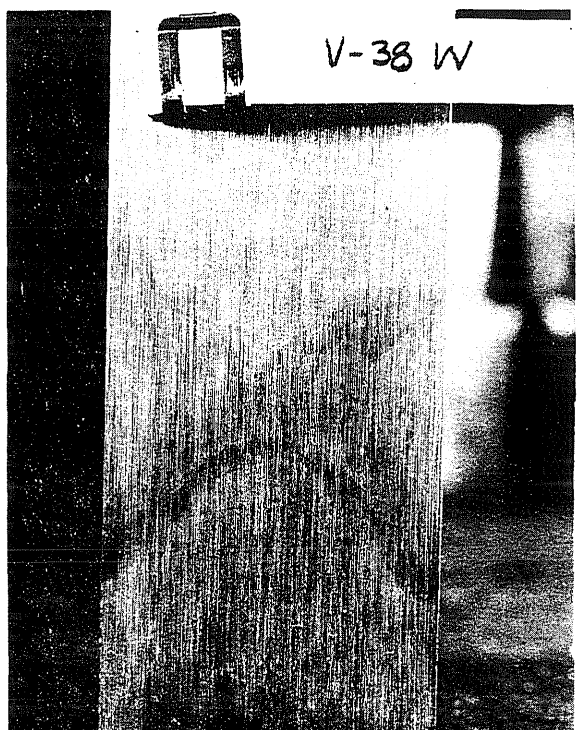
(a) V-13, East Face



(b) V-13, West Face



(c) V-38, East Face



(d) V-38, West Face

FIG.39 FRACTURE OF SPECIMENS V-13, V-38
(Transverse Butt Welds with Reinforcement Removed from Both Sides, Failure in Weld)

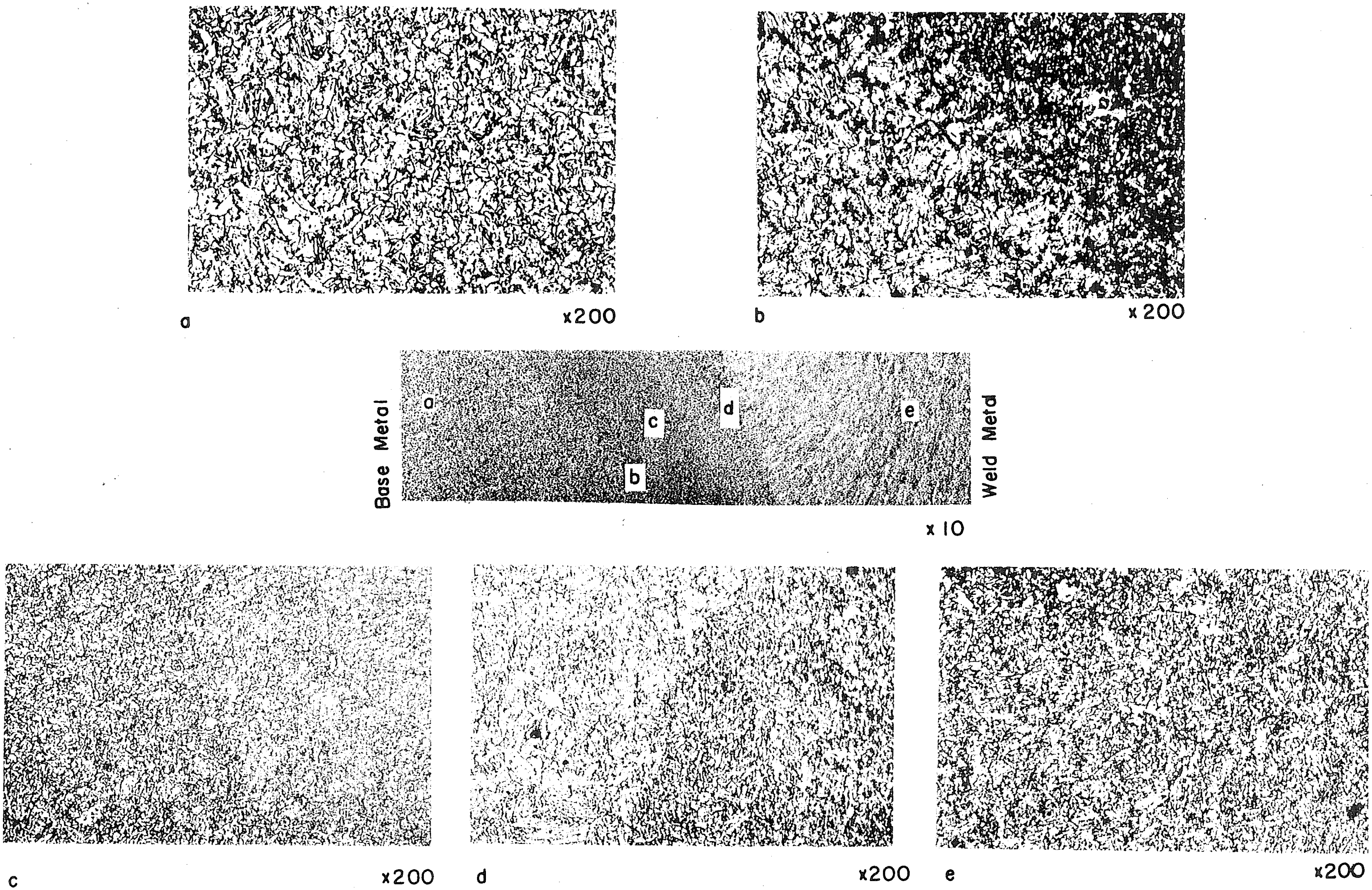


FIG. 40 PHOTOMICROGRAPHS OF SPECIMEN YS-4 – WELDING PROCEDURE A
(Transverse Butt Weld, Reinforcement in Place, Failure at Edge of Weld)

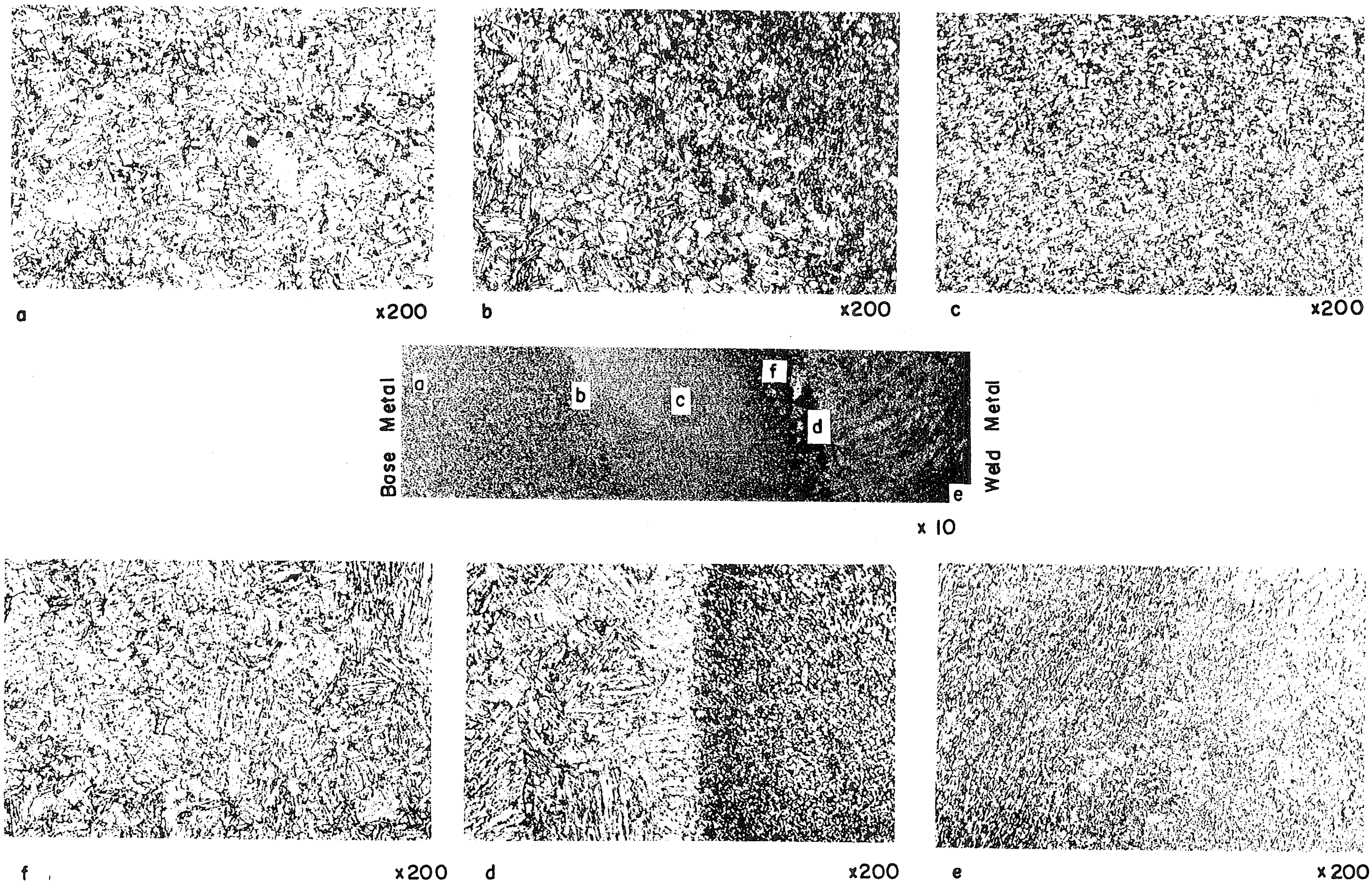


FIG. 41 PHOTOMICROGRAPHS OF SPECIMEN V-3 — WELDING PROCEDURE B
(Transverse Butt Weld, Reinforcement in Place, Failure in Weld)

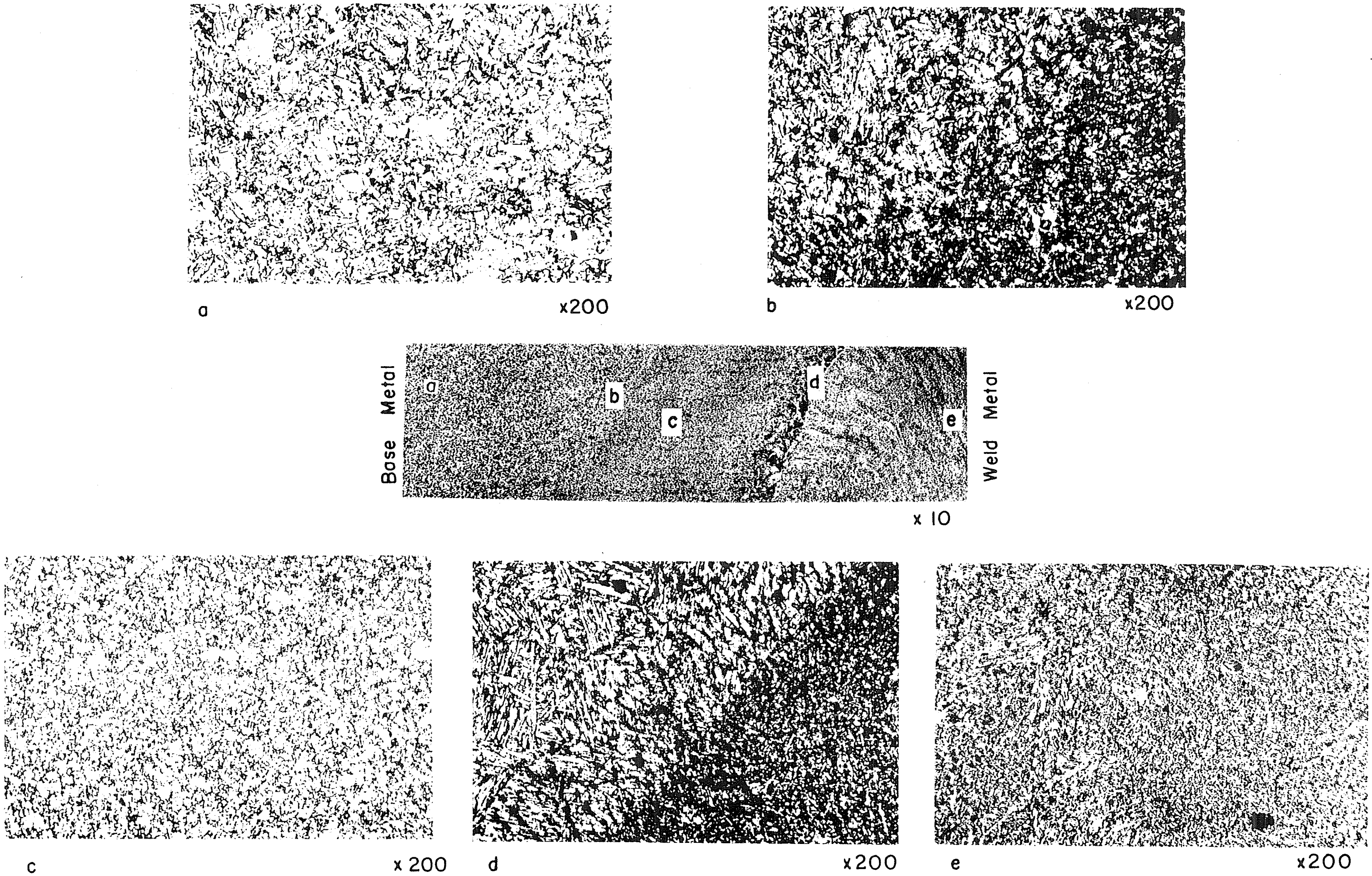


FIG. 42 PHOTOMICROGRAPHS OF SPECIMEN V-4 — WELDING PROCEDURE B
(Transverse Butt Weld, Reinforcement in Place, Failure in Weld)

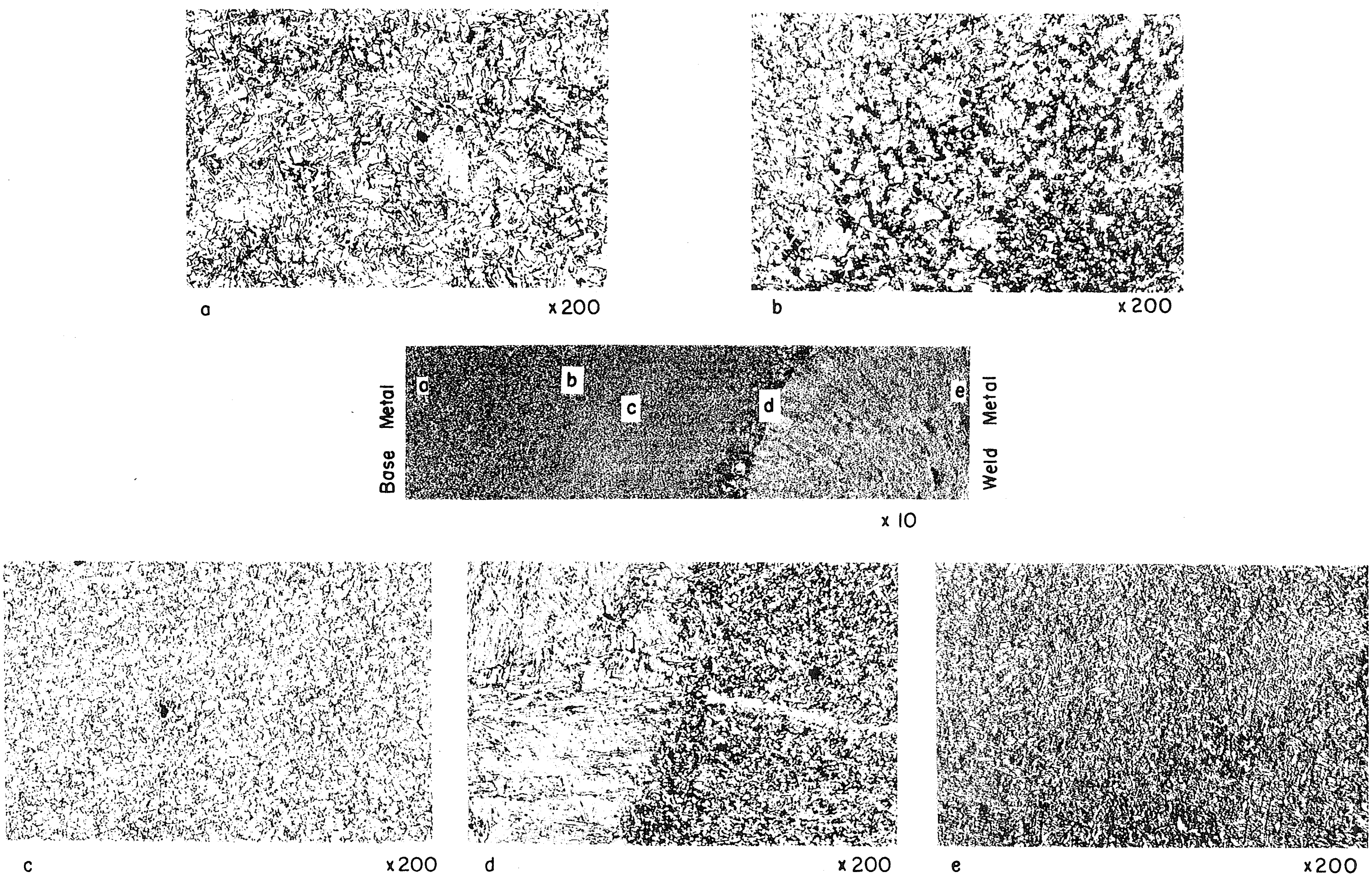


FIG. 43 PHOTOMICROGRAPHS OF SPECIMEN V-6 – WELDING PROCEDURE B

(Transverse Butt Weld, Reinforcement in Place, Failure in Weld)

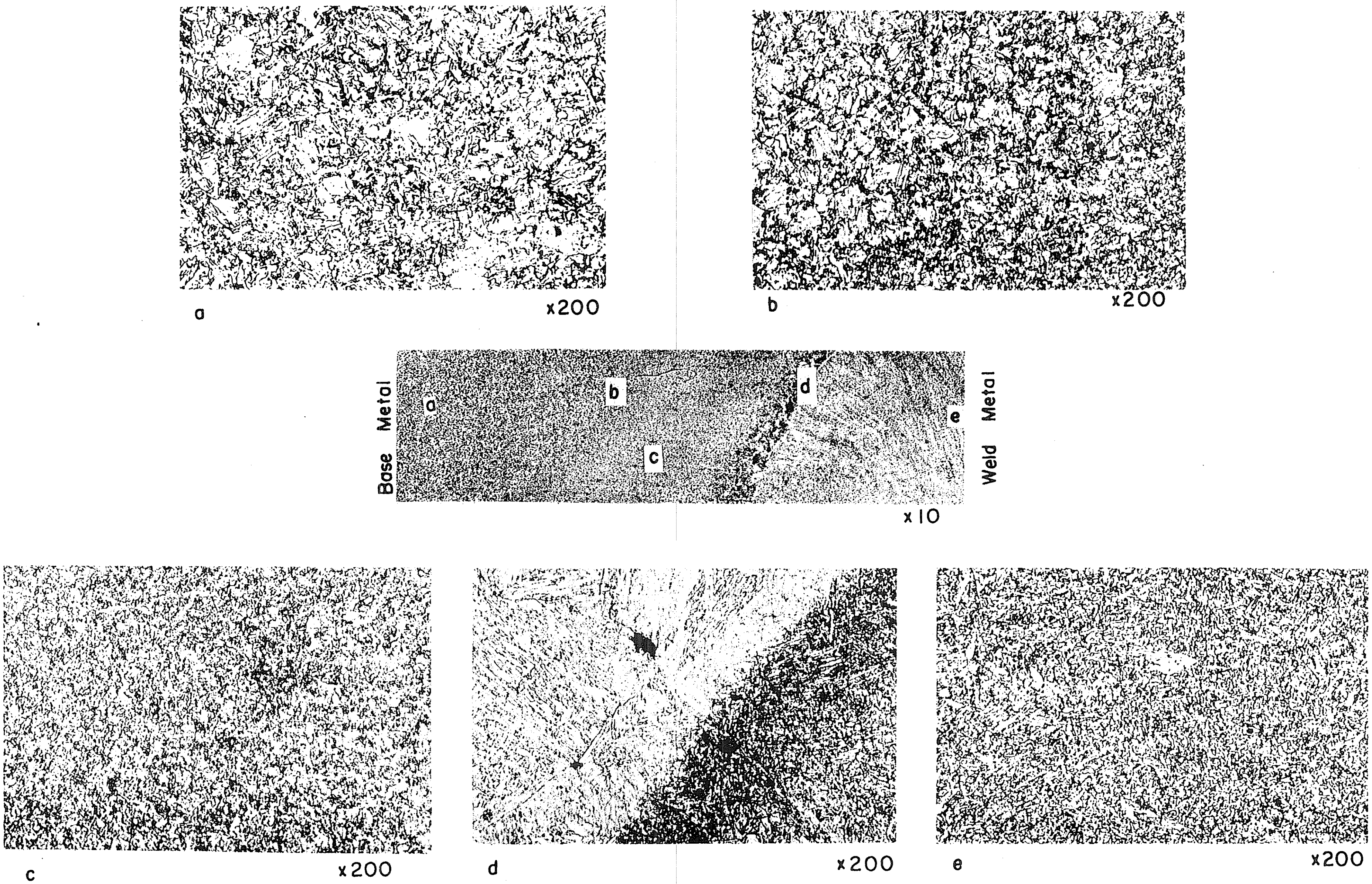


FIG. 44 PHOTOMICROGRAPHS OF SPECIMEN V-9 —WELDING PROCEDURE B
(Transverse Butt Weld, Reinforcement in Place, Failure in Weld)

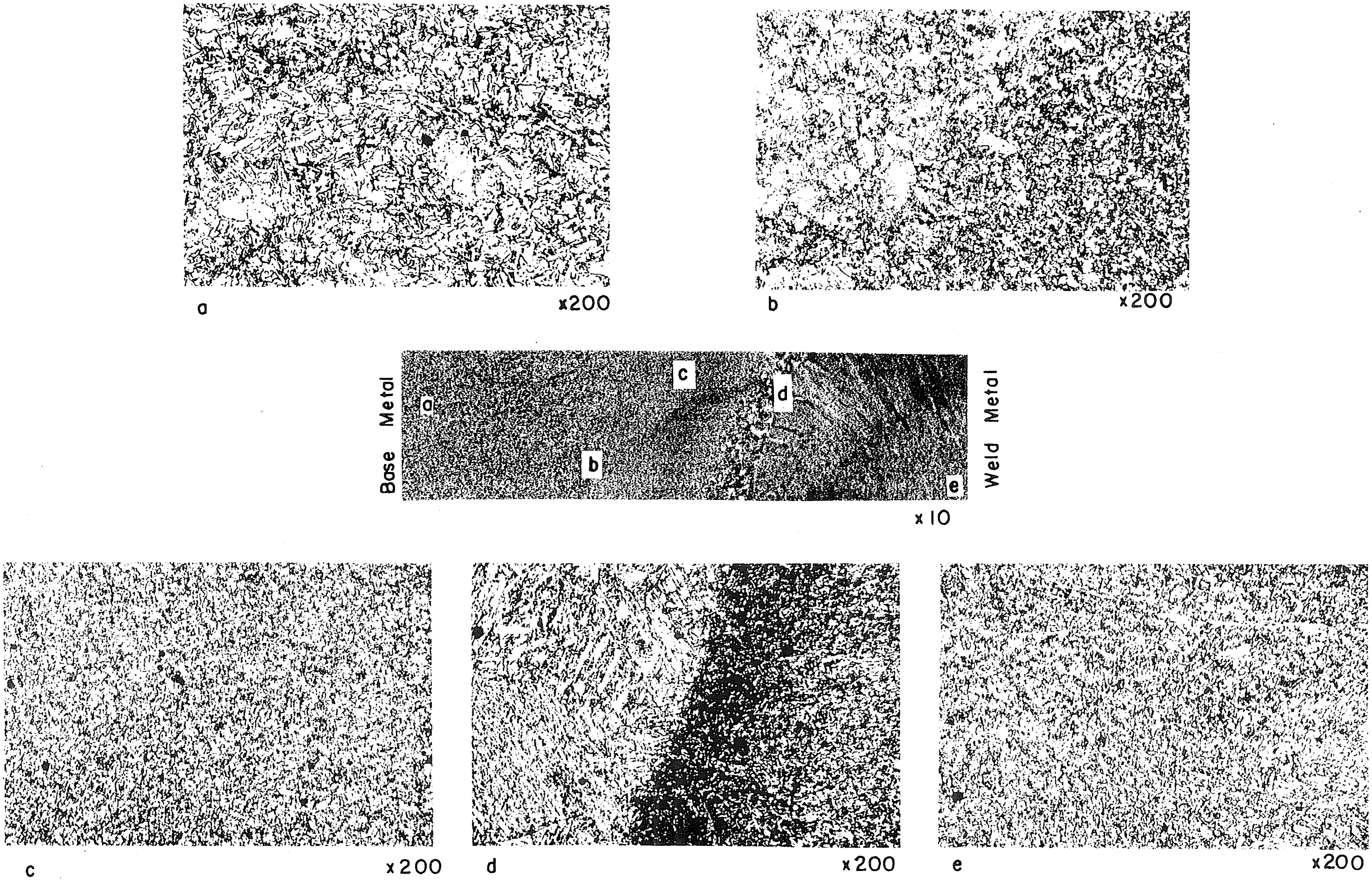


FIG. 45 PHOTOMICROGRAPHS OF SPECIMEN V-20 — WELDING PROCEDURE C
(Transverse Butt Weld, Reinforcement in Place, Failure at Edge of Weld)

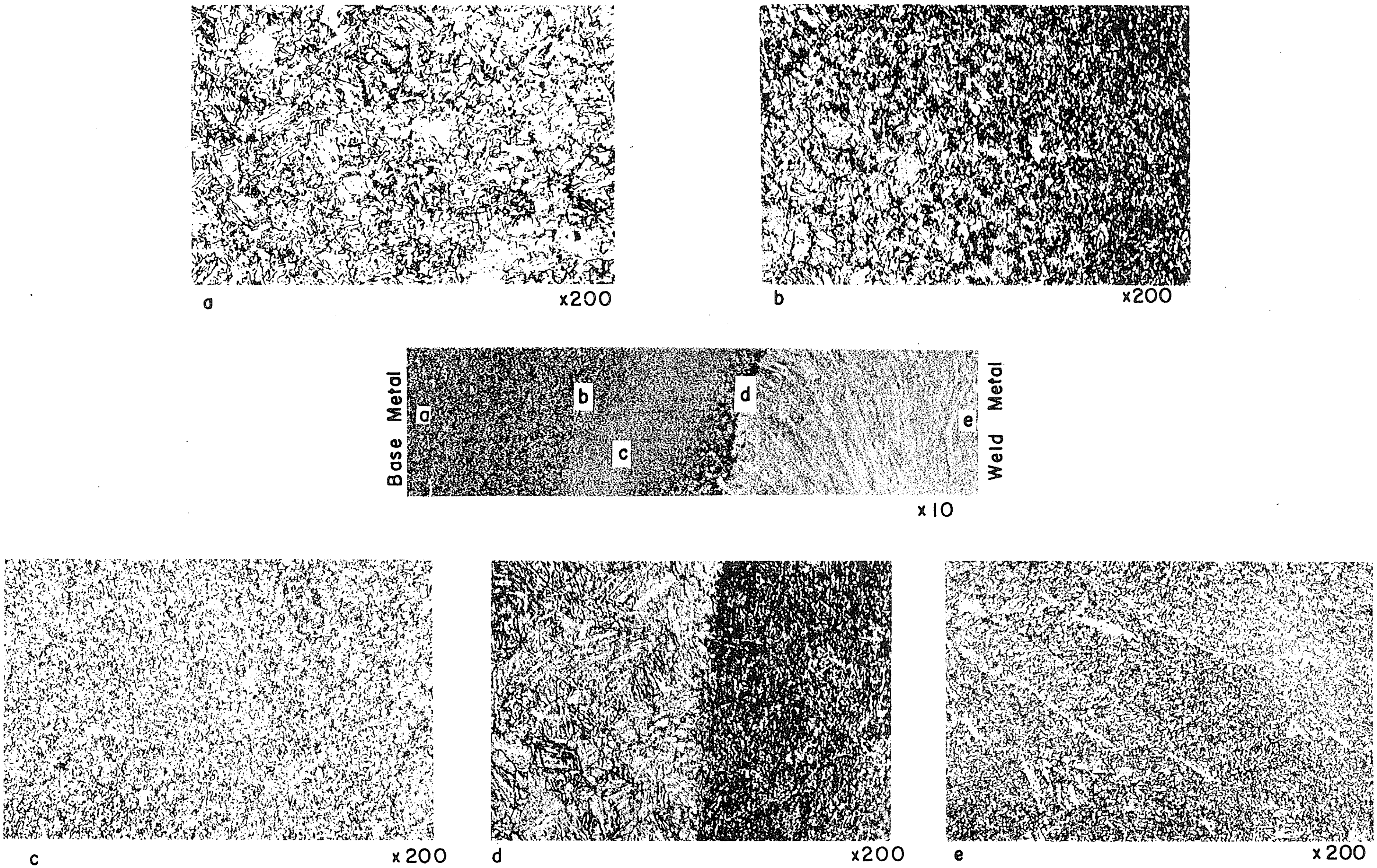


FIG. 46 PHOTOMICROGRAPHS OF SPECIMEN V-25 — WELDING PROCEDURE D-1
(Transverse Butt Weld, Reinforcement in Place, Failure at Edge of Weld)

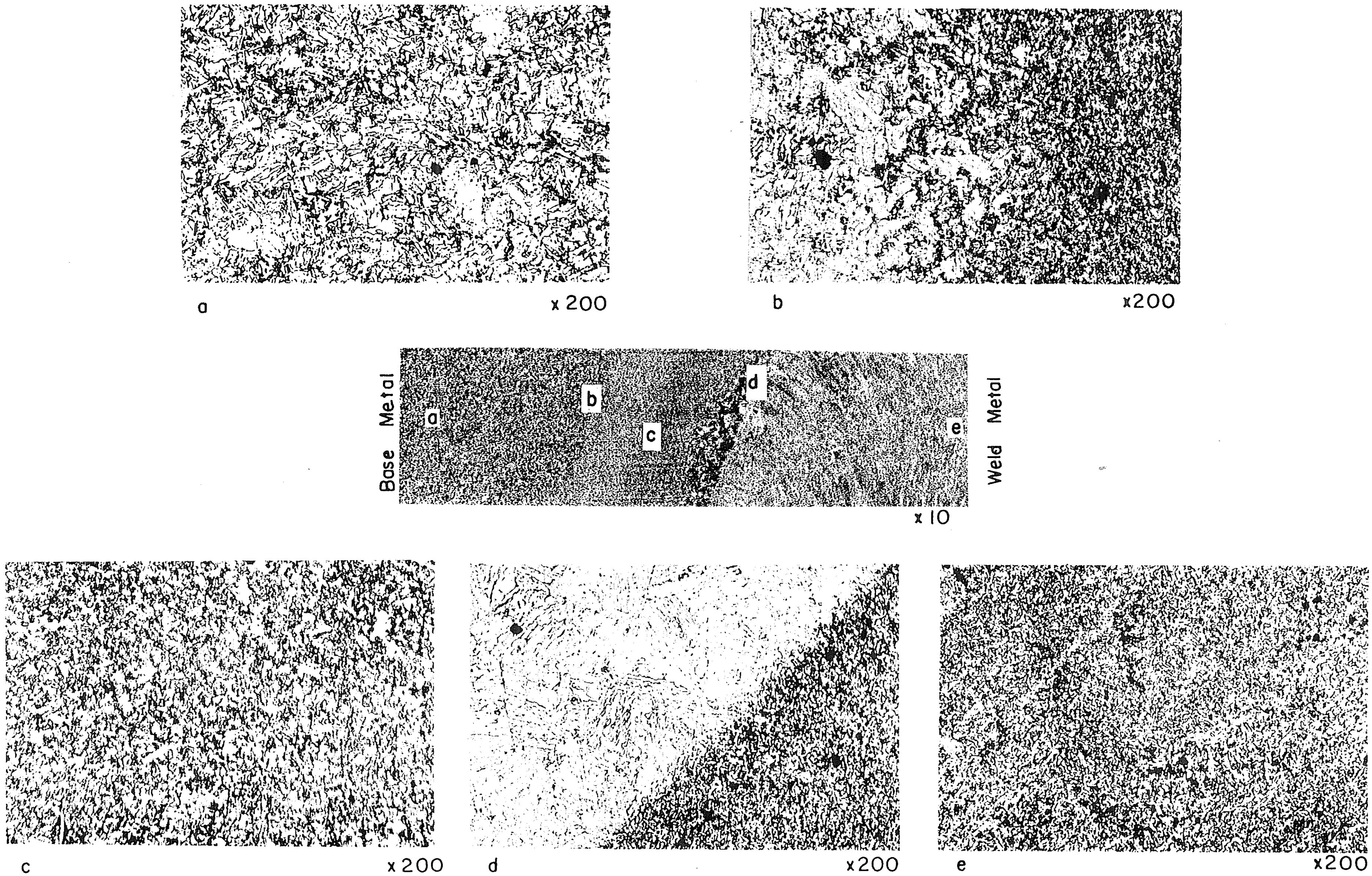


FIG. 47 PHOTOMICROGRAPHS OF SPECIMEN V-35 —WELDING PROCEDURE D-2
(Transverse Butt Weld, Reinforcement Removed from Both Sides, Failure in Weld)

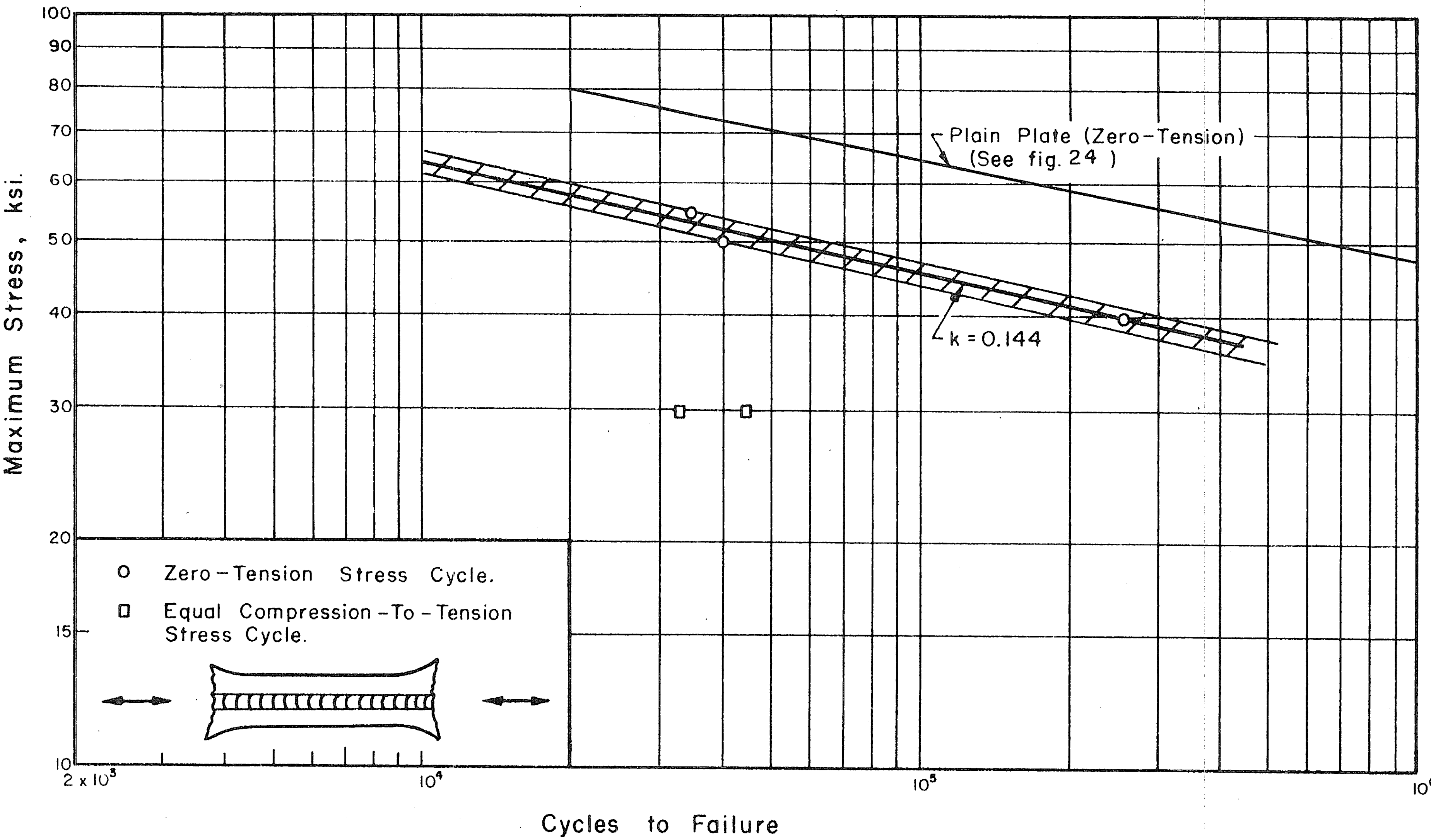
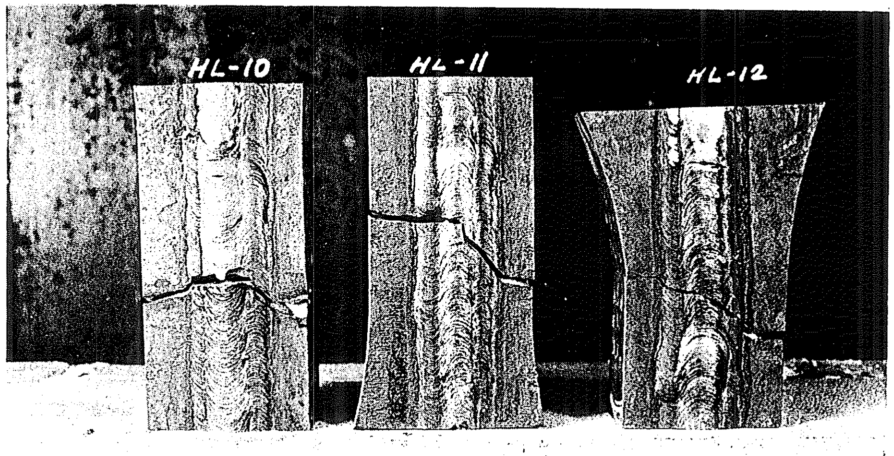
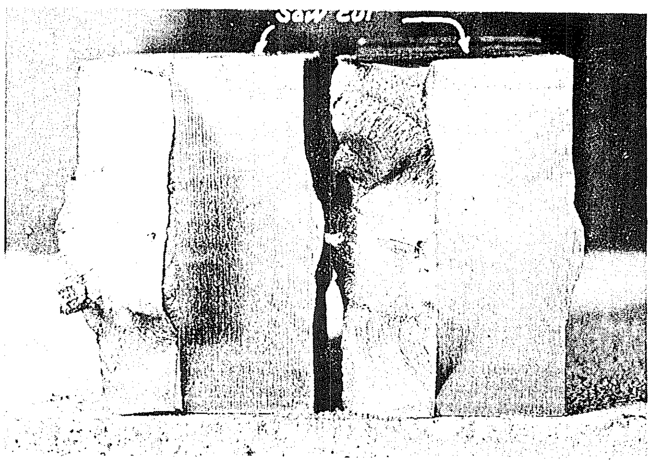


FIG. 48 RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION.

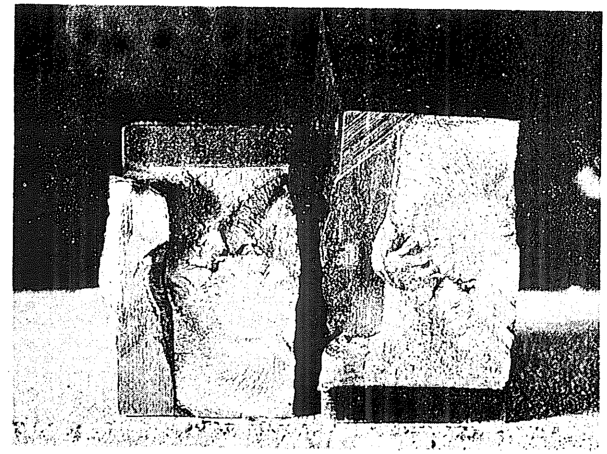


(a) Fracture Locations on West Face



(b) HL-10

(c) HL-11



(d) HL-12

Fracture Surfaces

FIG. 49 FRACTURE OF SPECIMENS HL-10, HL-11, HL-12
(Longitudinal Butt Welds)

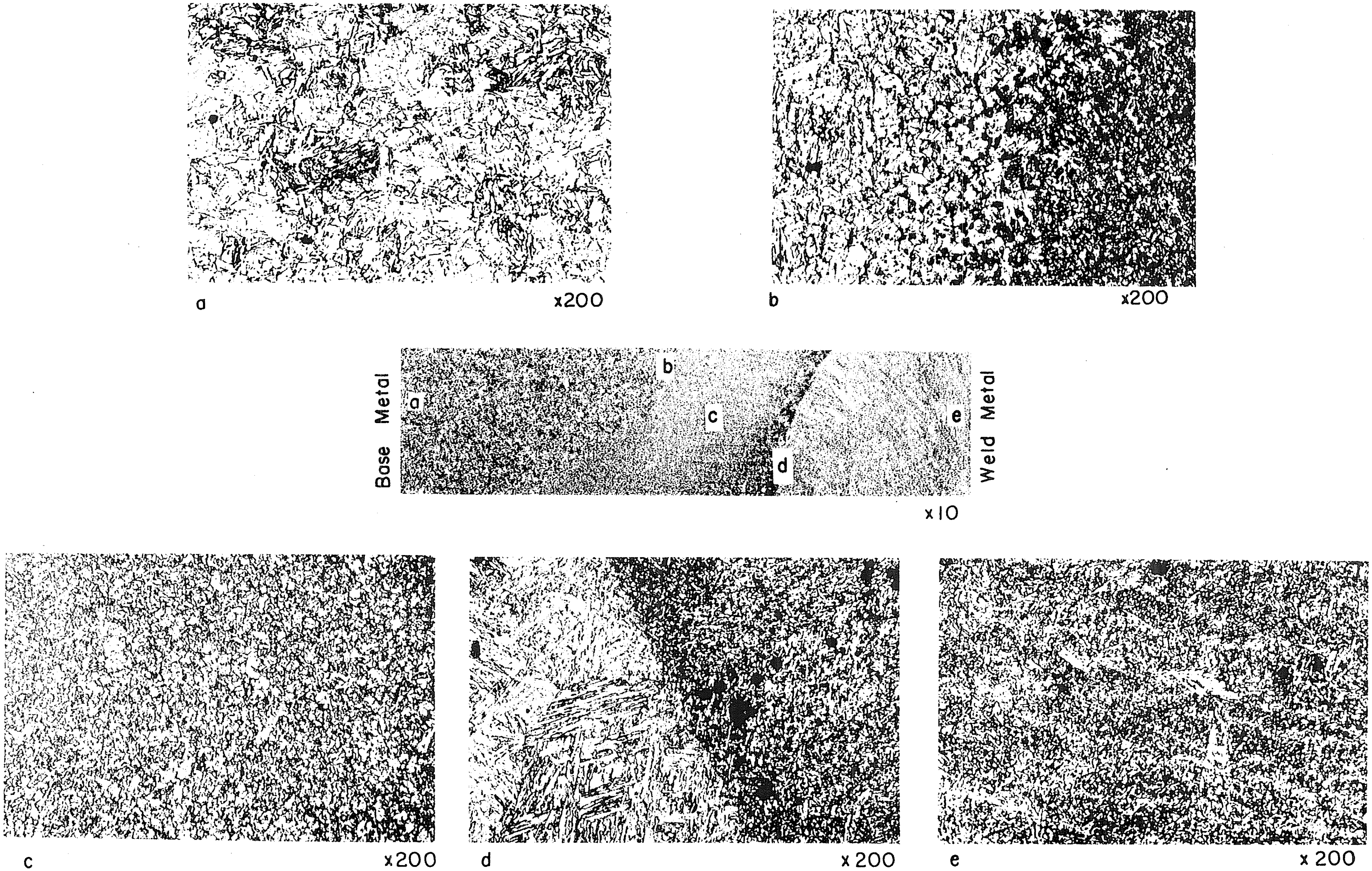


FIG. 50 PHOTOMICROGRAPHS OF SPECIMEN HL-II —WELDING PROCEDURE E
(Longitudinal Butt Weld)

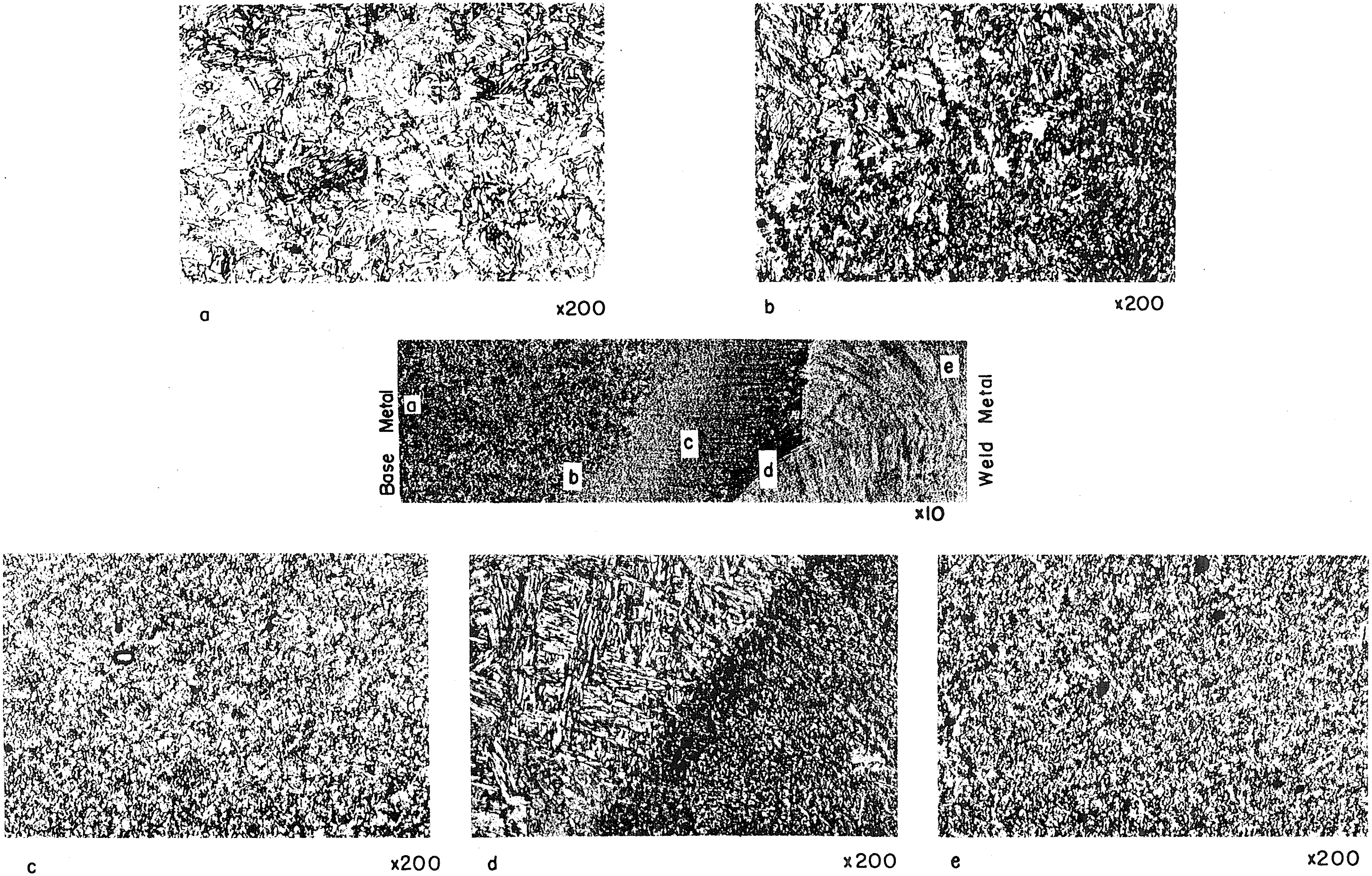


FIG. 51 PHOTOMICROGRAPHS OF SPECIMEN HL-16 — WELDING PROCEDURE F

(Longitudinal Butt Weld)

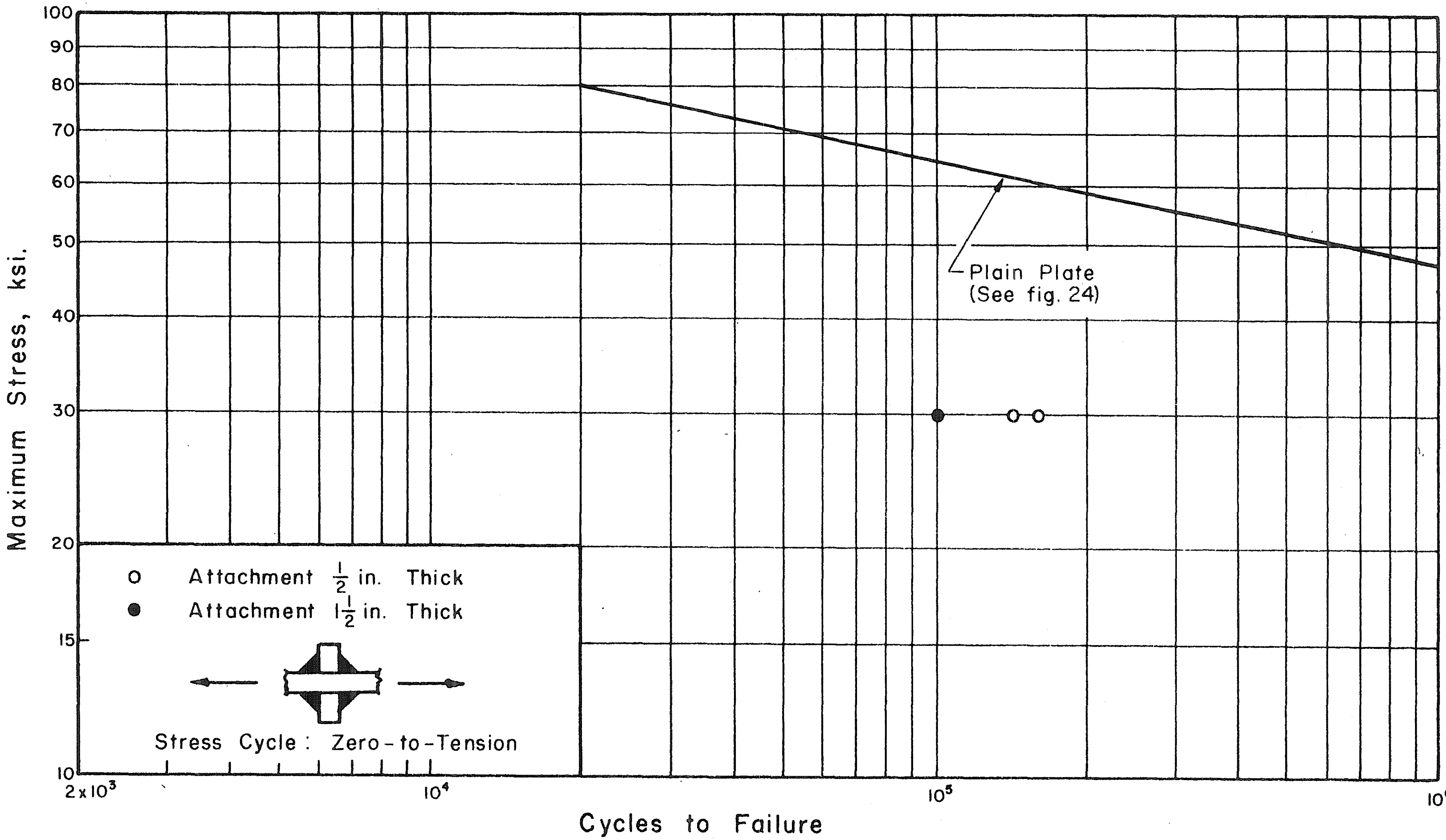
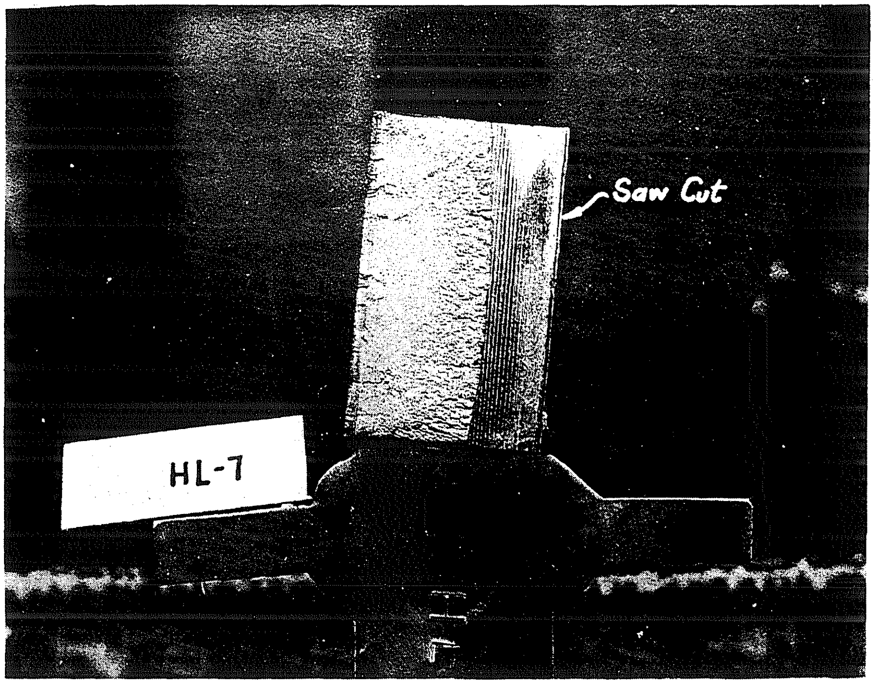
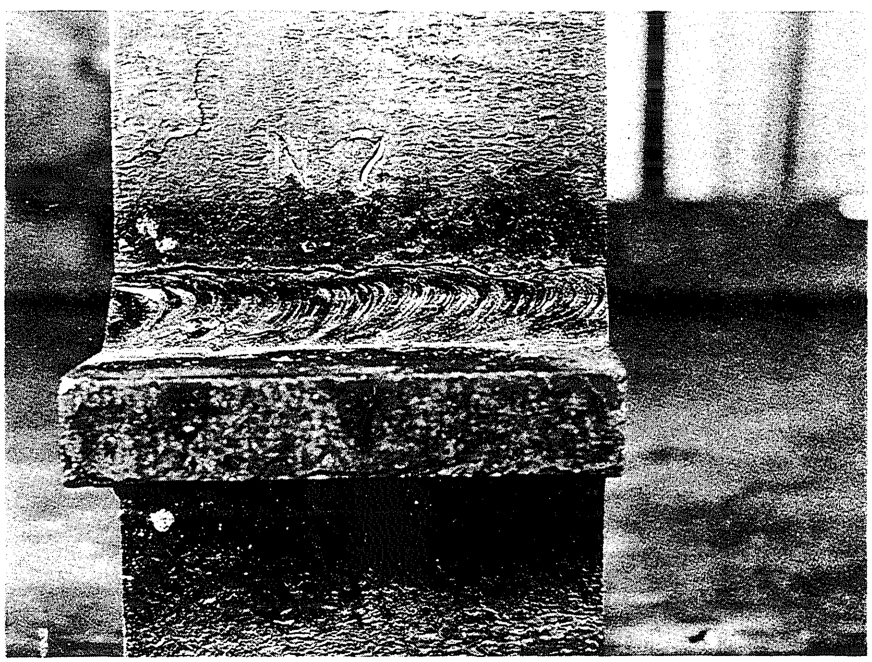


FIG. 52 RESULTS OF FATIGUE TESTS OF PLATES WITH FILLET-WELDED TRANSVERSE ATTACHMENTS. AXIAL TENSION.



(a) East Face



(b) North Face

FIG. 53 FRACTURE OF SPECIMEN HL-7
(Fillet Welded Transverse Attachment)

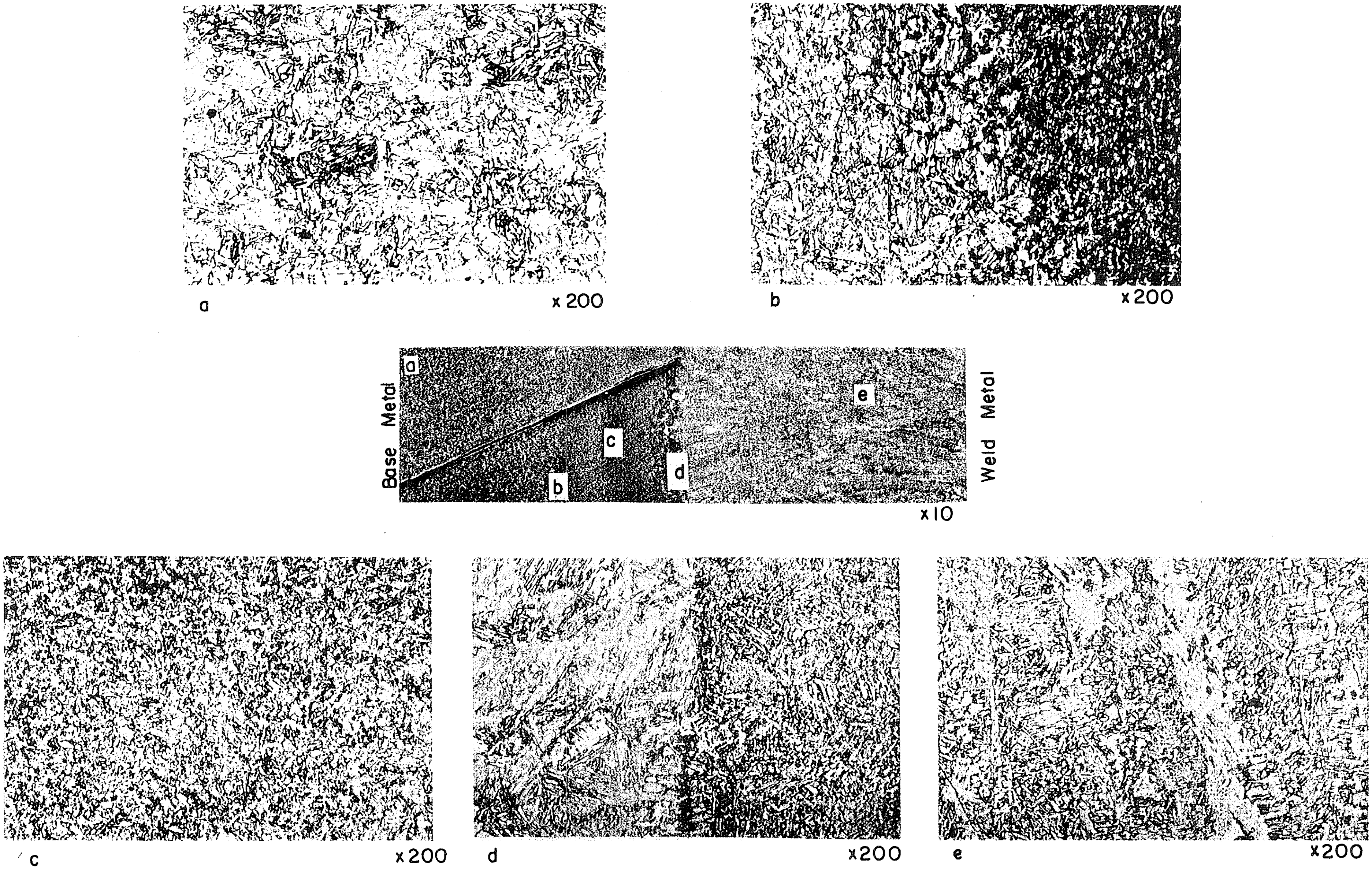


FIG. 54 PHOTOMICROGRAPHS OF SPECIMEN HL-9 — WELDING PROCEDURE G
(Fillet-Welded Transverse Attachment, Failure at Toe of Weld)

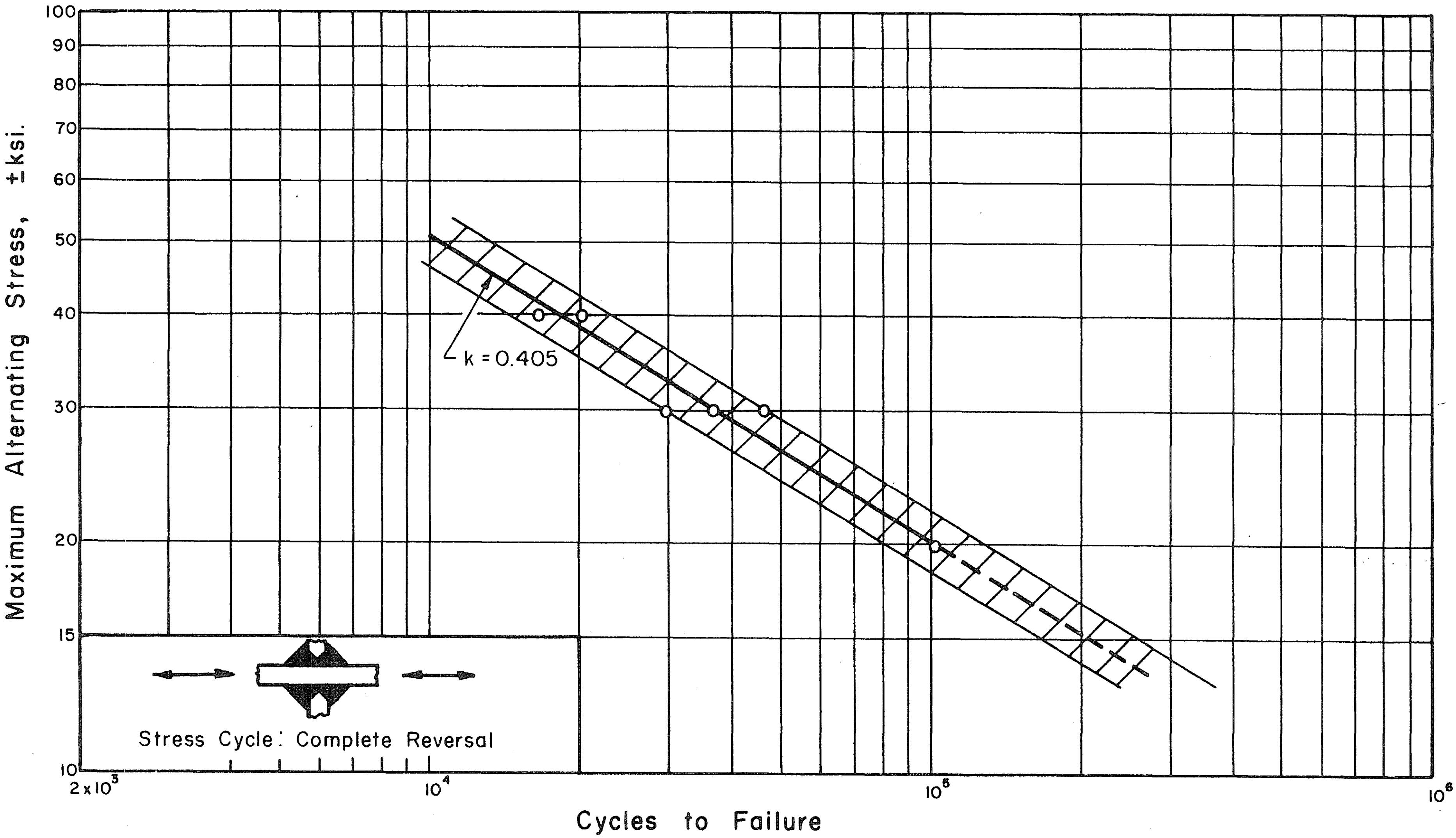


FIG. 55 RESULTS OF FATIGUE TESTS OF PLATES WITH TRANSVERSE ATTACHMENTS — FULL PENETRATION WELDS. COMPLETE REVERSAL, AXIAL LOADING.

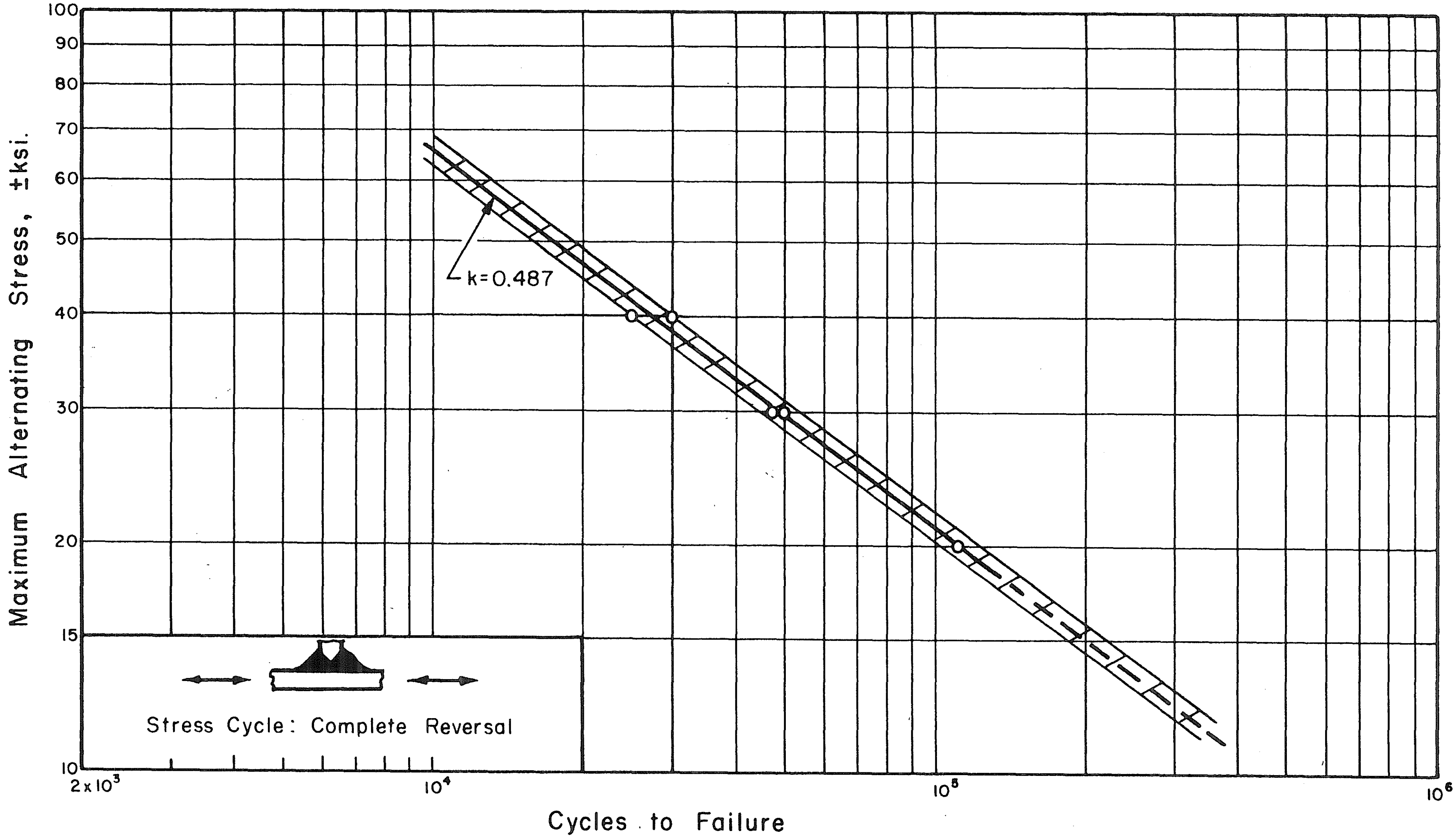
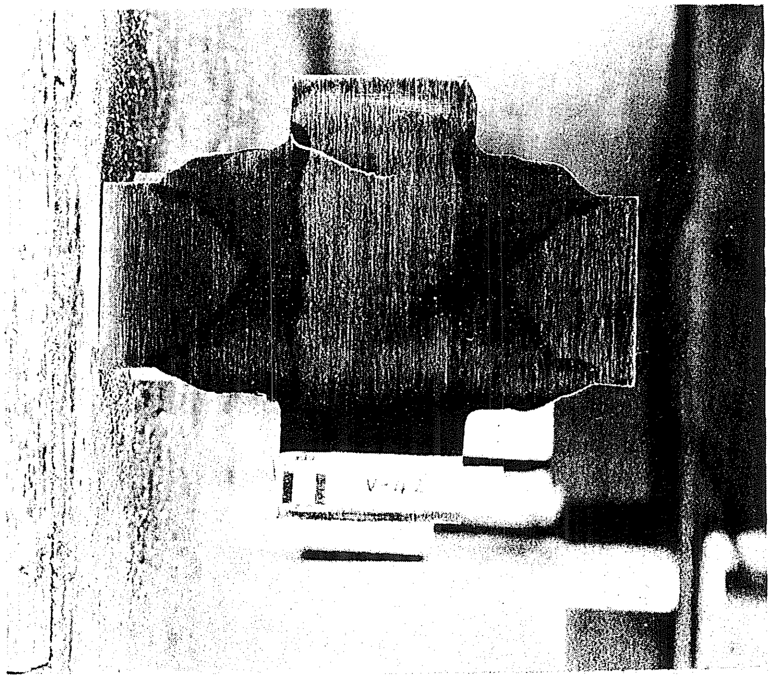
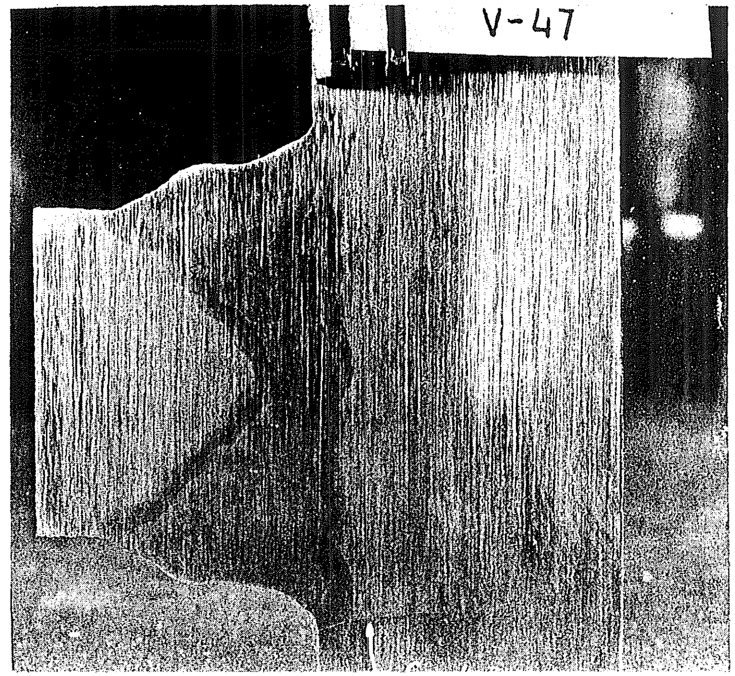


FIG. 56 RESULTS OF FATIGUE TESTS OF PLATES WITH TRANSVERSE ATTACHMENT — FULL PENETRATION WELD. COMPLETE REVERSAL, AXIAL LOADING.



(a) V-42



(b) V- 47

FIG. 57 FRACTURE OF SPECIMENS V-42, V-47
(Full Penetration Attachments)

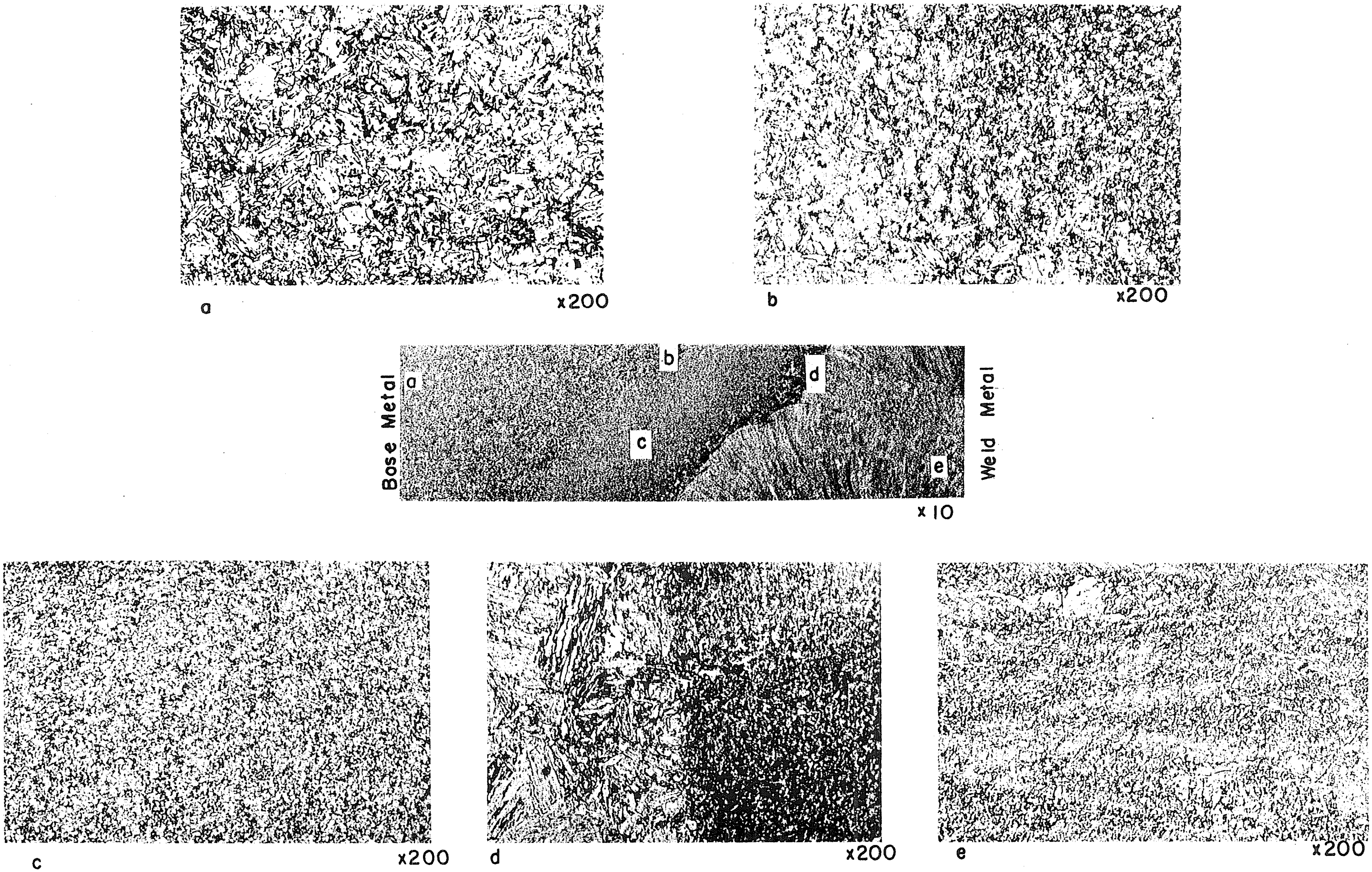


FIG. 58 PHOTOMICROGRAPHS OF SPECIMEN V-42 —WELDING PROCEDURE H

(Full Penetration Transverse Attachments on Both Sides, Failure at Toe of Weld)

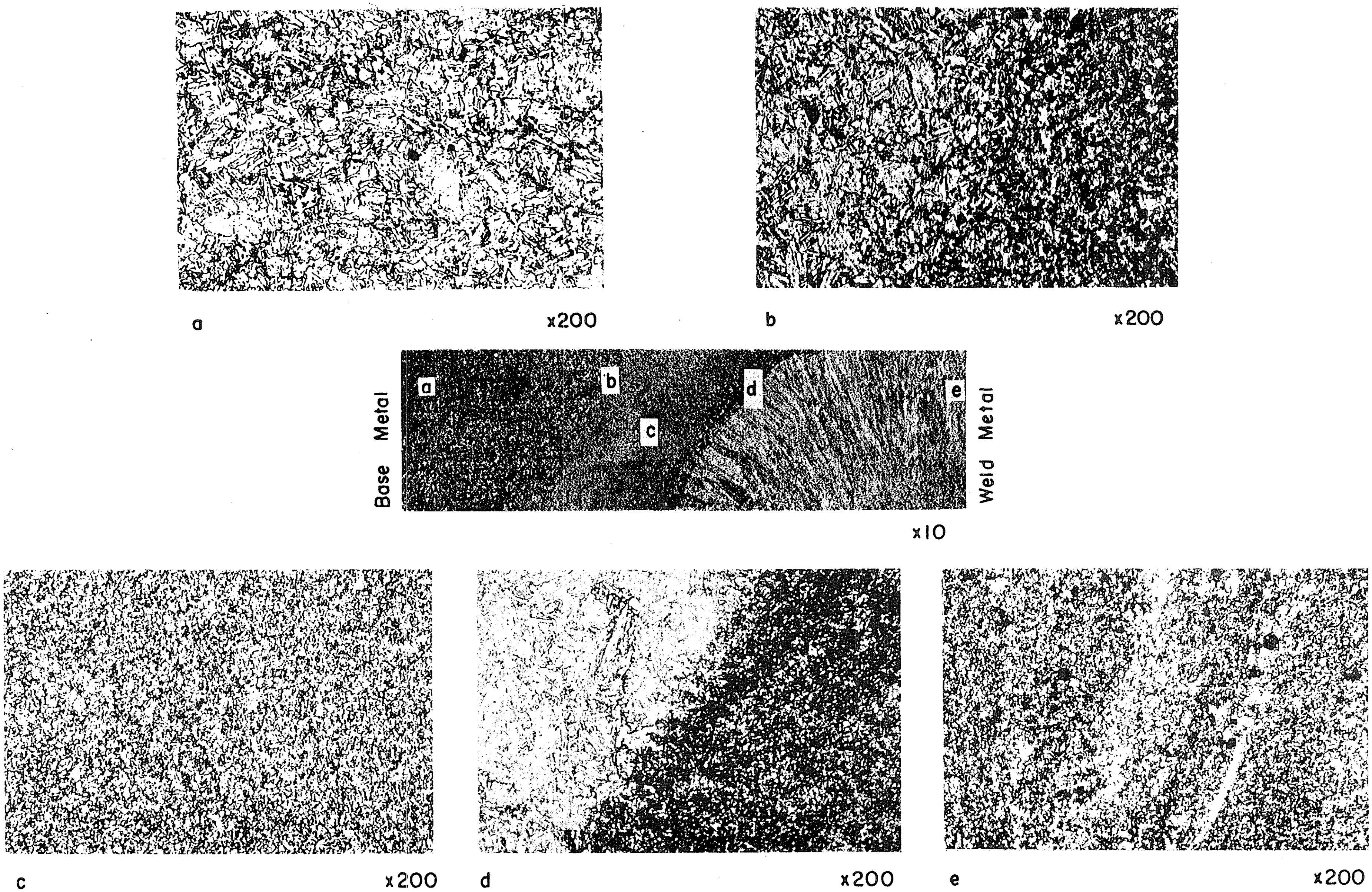


FIG. 59 PHOTOMICROGRAPHS OF SPECIMEN V-47 —WELDING PROCEDURE J
(Full Penetration Transverse Attachment on One Side, Failure at Toe of Weld)

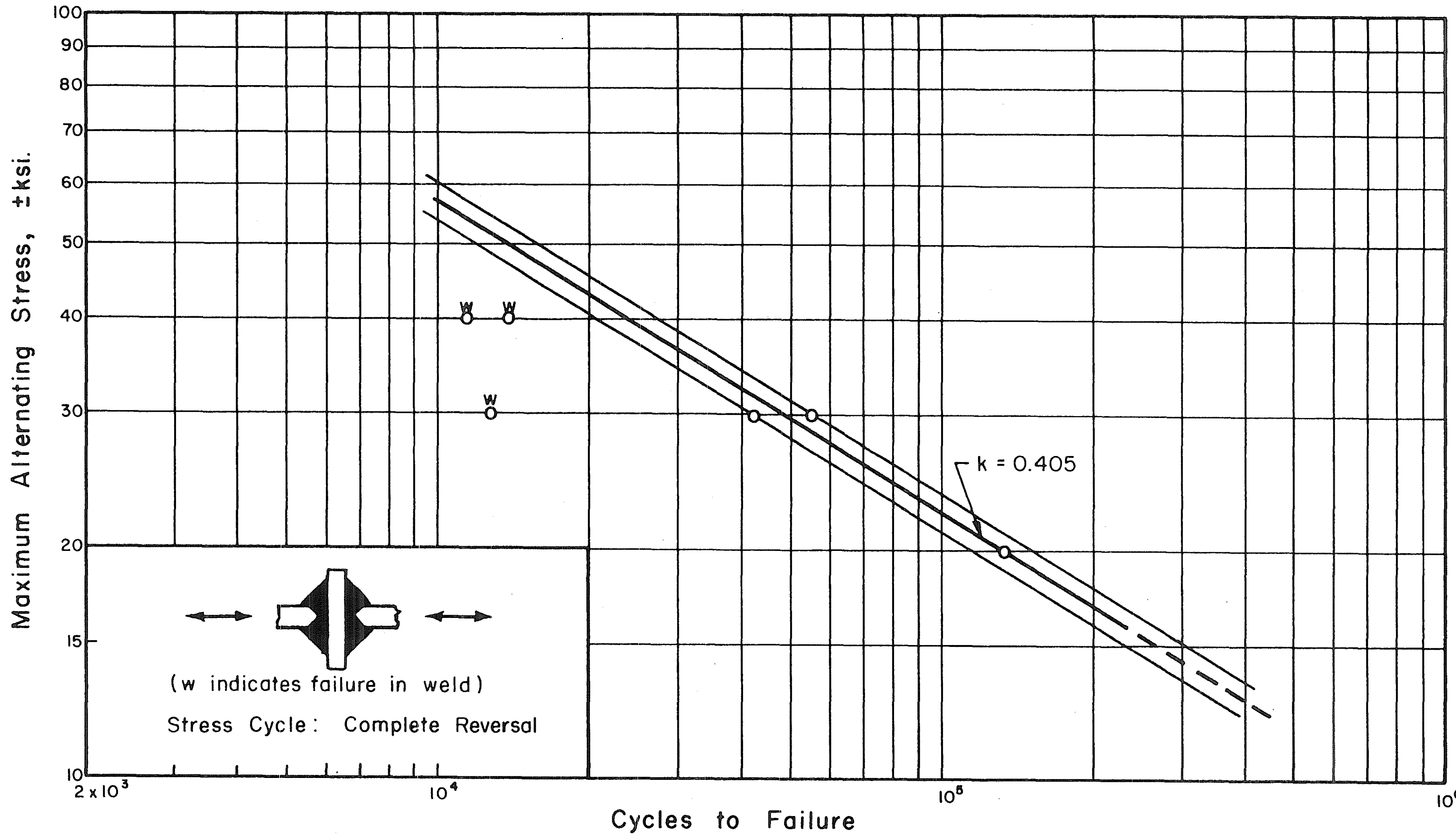
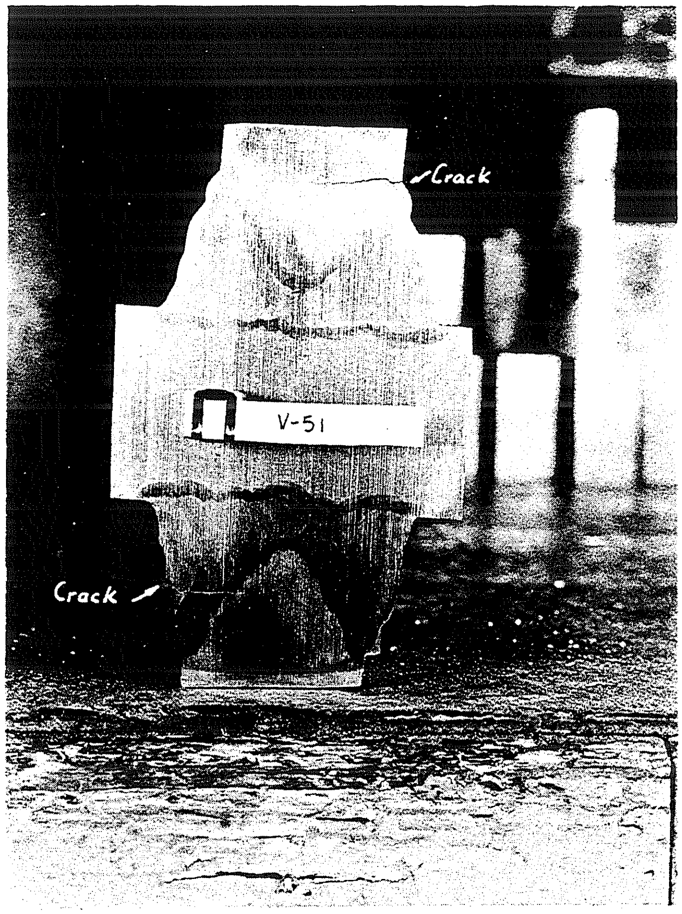


FIG. 60 RESULTS OF FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS. COMPLETE REVERSAL, AXIAL LOADING.



V-51

FIG. 61 FRACTURE OF SPECIMEN V-51
(Full Penetration Tee Joint)

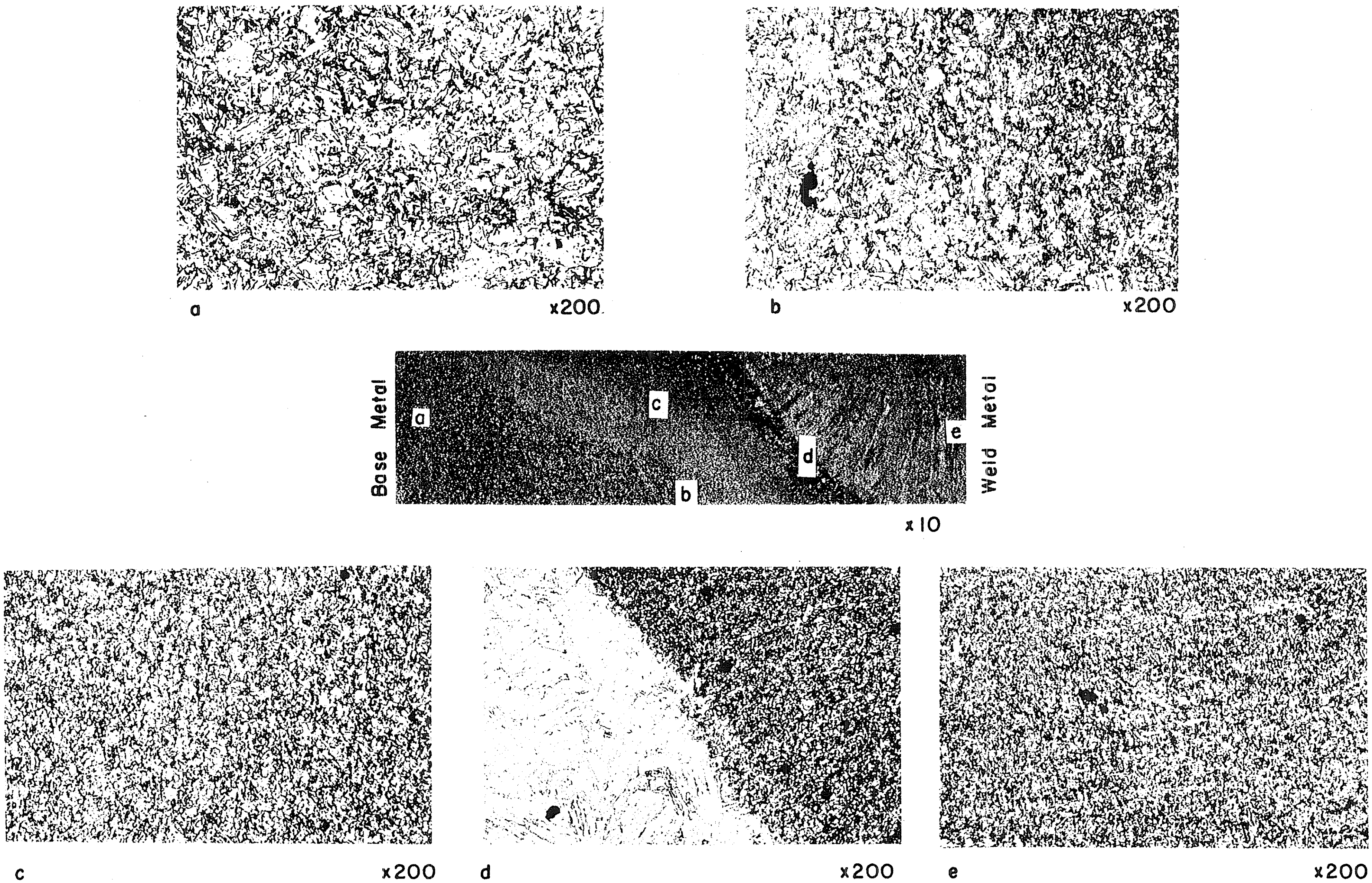


FIG. 62 PHOTOMICROGRAPHS OF SPECIMEN V-51 — WELDING PROCEDURE K

(Full Penetration Tee Joint, Primary Failure at Toe of Weld)

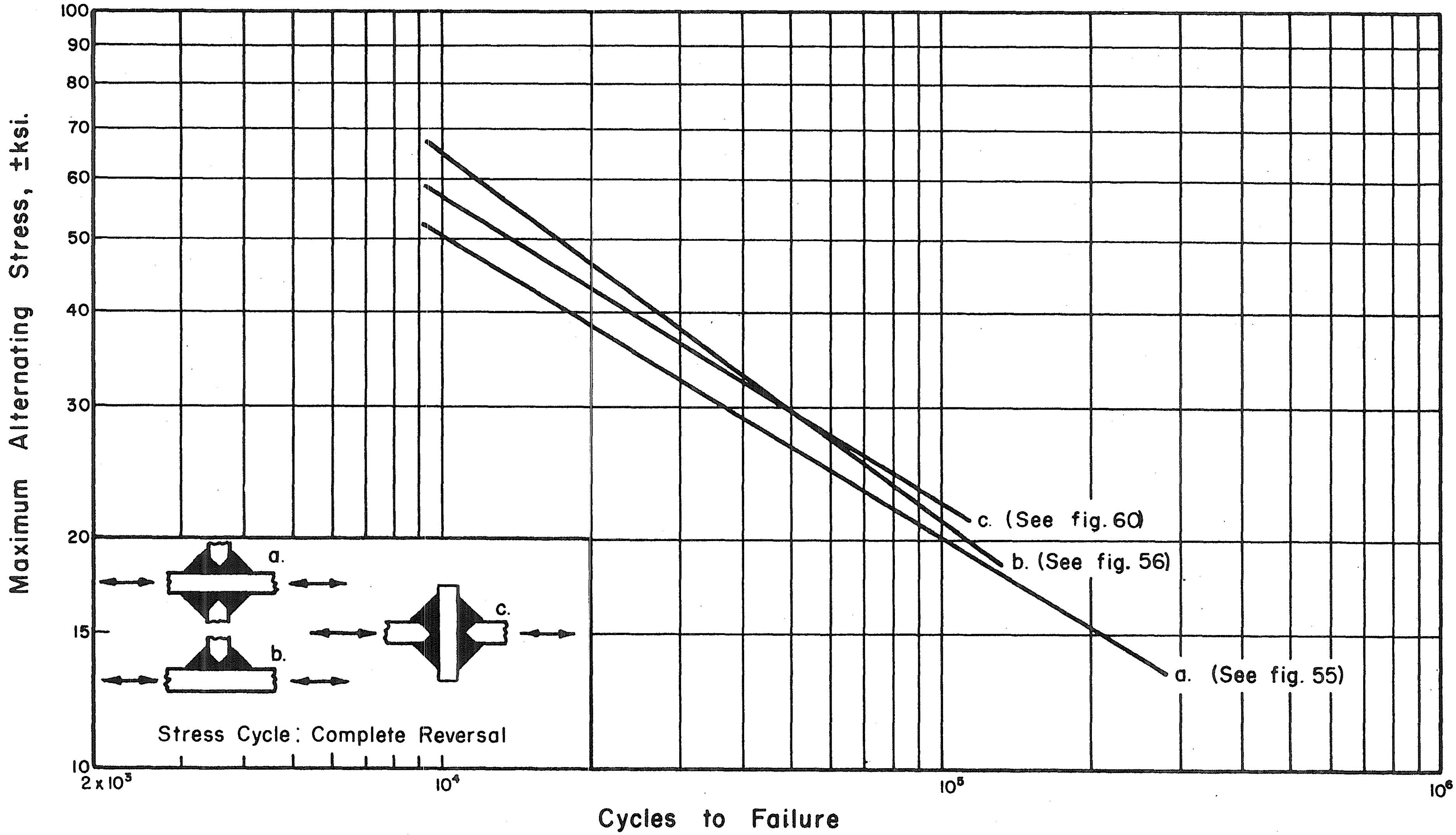
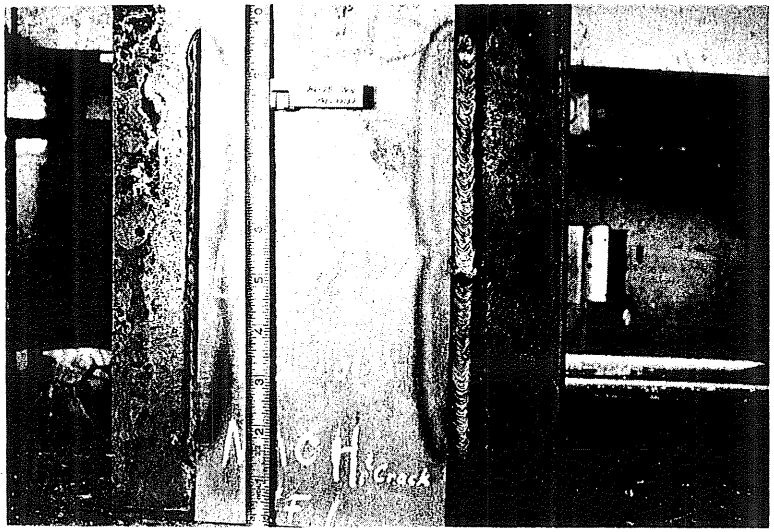
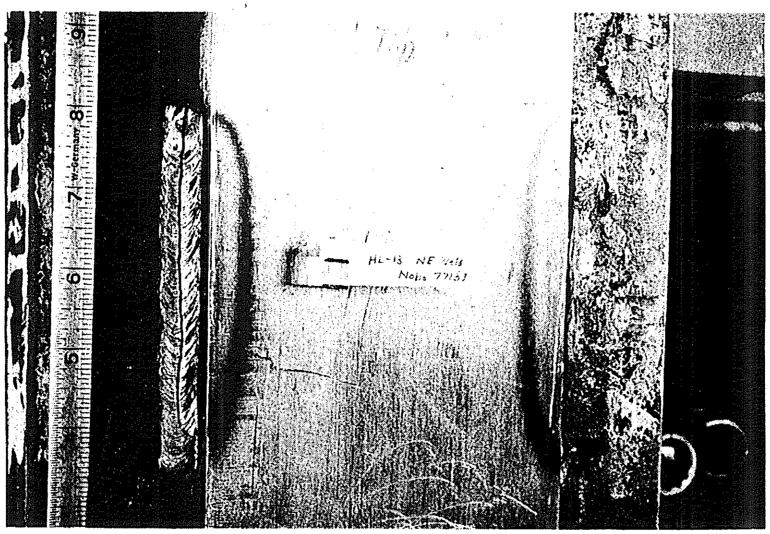


FIG. 63 SUMMARY OF FATIGUE TESTS ON PLATES WITH TRANSVERSE ATTACHMENTS AND FULL PENETRATION TEE JOINT.

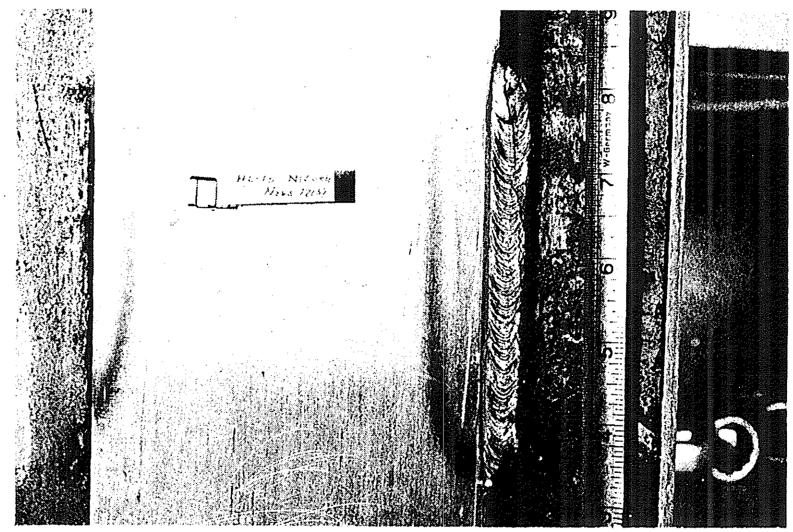


(a) HL-15 (NW weld)

(b) HL-15 (SW weld)

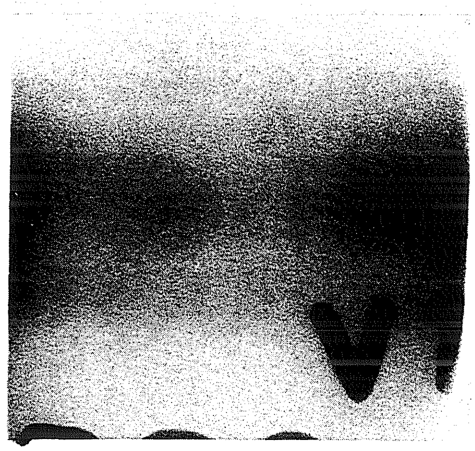


(c) HL-13 (NE weld)



(d) HL-13 (NW weld)

FIG. 64 FRACTURE OF SPECIMENS HL-13, HL-15
(Longitudinal Fillet Welded Joint)



Specimen V-1

Specimen V-2

FIG. 65 RADIOGRAPHS OF SPECIMENS V-1 AND V-2 AFTER STATIC TEST. (Welding Procedure B)

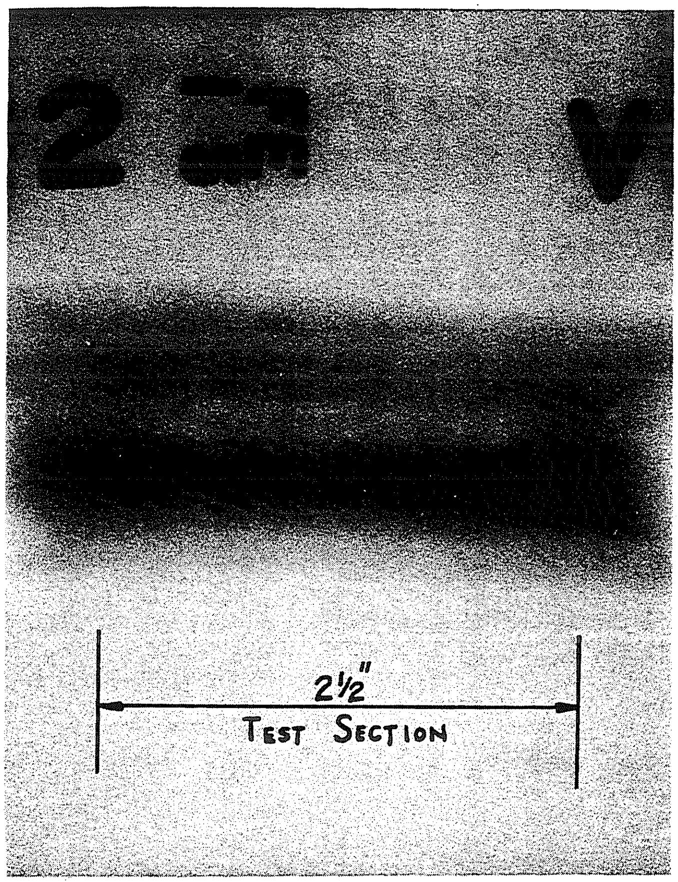


FIG. 66 RADIOGRAPH OF SPECIMEN V-33
(Welding Procedure D-2)