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EFFECT OF WELDING ON THE AXIAL FATIGUE PROPERTIES OF HIGH STRENGTH STRUCTURAL STEELS

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SYNOPSIS

The effect of welding on the axial fatigue properties of a quenched and tempered steel in the life range between 100,000 and 2,000,000 cycles has been investigated on a zero-to-tension and partial tension-to-tension stress cycle. Included in the studies are the effect of surface geometry and the metallurgical changes imparted by the welding.

The test results indicate that the introduction of a transverse butt weld in this steel decreases the fatigue strength corresponding to 2,000,000 cycles by approximately 40 percent. On a zero-to-tension stress cycle, no significant increase has been found in the fatigue strength of welds in the quenched and tempered steel over comparable welds in ASTM A-7 or A-242 steels. The quenched and tempered steel has also been found to be more notch sensitive in fatigue and highly susceptible to even the most minor internal discontinuities.

The data indicate that the superiority of the quenched and tempered steel lies in its ability to resist high mean stresses and is thus eminently suited for applications where high dead to live load ratios are encountered.

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I. INTRODUCTION

1.1 GENERAL CONSIDERATION OF PROBLEM

Recent years have seen a growing interest in the use of high strength structural steels for the fabrication of welded structures. However, the application of these steels has raised a number of questions, one of which is the possibility of fatigue failures in such structures under the action of repeated loads.

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

a) Stress concentrations.

b) Large amplitudes of stress.

c) High maximum stress.

d) Corrossive environment.

The role played by a weld in fatigue is generally associated with three important 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 a stress concentration in reducing the fatigue resistance of structural components is very well known.

The second factor is the change of properties, both physical and chemical, resulting from the welding process. This may be attributed, in part, to the metallurgical changes accompanying the localized heating and rapid cooling. For example, the structure of the base metal in the heat affected zone, i.e., the part of the parent metal affected by the weld, is changed as a result of the heating and cooling cycle in such a manner that grain coarsening results. This change in grain structure is usually accompanied by a change in physical properties of the metal.

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

In addition to the above discussed role played by a weld, there are several other factors that deserve attention. It is well known that materials respond differently to the effect of stress concentrations in fatigue; the higher strength materials are generally affected more than the lower strength materials. Thus, the high strength materials are considered more notch sensitive in fatigue and it is in this sense that this term is employed throughout this report. Secondly, it may be expected that various steels, because of variations in their basic characteristics, will respond differently to the various changes imparted by welding. Lastly, one might consider that fatigue fractures consist of two stages - the initiation and the propagation of 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 welded members.

1.2 EXISTING FATIGUE DATA

Relatively little information is available concerning the fatigue behavior of welded members in high strength structural steels, especially those of the quenched and tempered type. Most of the published fatigue data is for welded members in ASTM A-7 steel with some data on low alloy steels of the ASTM A-242 type.

Published fatigue data on high strength steels have led to the general belief that high strength steels have little advantage over ordinary mild steels under conditions of repeated loadings. For instance, it has been reported (3)* that the fatigue strength** of a butt-welded joint in ASTM A-242 steel may be only 7 to 17 percent higher than that of a comparable weld in ASTM A-7 steel on a zero-to-tension stress cycle (depending on the chemical and physical properties of the steel, the type of joint preparation and the orientation of the weld, among other factors). The increase in allowable stress for static load design will generally be significantly higher than this percentage.

The observation that high strength steels may show little advantage over ordinary steels in the welded condition when subjected to repeated

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* Numbers in parentheses refer to correspondingly numbered items in the bibliography.

** Unless otherwise stated, the term 'fatigue strength' is used throughout this report to represent the fatigue strength corresponding to 2,000,000 cycles.

loadings can be further illustrated by a comparison of fatigue ratios* for a particular type of welded member, as shown below.

Steel	Ultimate Strength, ksi	Type of Member	$F_{2,000,000}$ (zero-to-tension) ksi	Fatigue Ratio	Source
ASTM A-7	57.4	Plain Plate (As-Rolled)	34.6	0.603	(3)
ASTM A-7	57.4	Transv. Butt (As-Welded)	24.0	0.417	(3)
T-1	123.0	Plain Plate (As-Rolled)	50.0	0.406	(1)
T-1	123.0	Transv. Butt (As-Welded)	21.0	0.171	(1)

It is apparent that the fatigue ratios for both plain as-rolled plates and transverse butt-welded joints are considerably lower for the higher strength steel.

The observation that high strength steels are more notch sensitive than ordinary structural steels, however, requires some special comments on the use of the high strength steels. Besides the superiority of these steels under static loading conditions, it can be expected that the higher strength steels should be able to withstand higher repeated loadings at high mean stresses than A-7 type steel because of this superior static strength. Available information indicates that under conditions of repeated loading, high strength steels are in fact superior to ordinary steels in two cases. The first case is one in which the fluctuation of the applied stress (the range of stress) is relatively small. Such a case arises where the dead

* The ratio of fatigue strength to the ultimate tensile strength.

load stresses are considerably higher than the live load stresses. The second case where high strength steels have been found to be superior to ordinary steels is in applications where the number of repetitions is quite low.

1.3 OBJECT AND SCOPE OF INVESTIGATION

Any welding process involves the generation of a considerable amount of heat. The mechanical properties, as well as the metallurgical structure, of a metal exposed to the complex thermal cycle involved in welding are consequently subject to change. These changes are largely dependent on the conditions of welding and the rate of cooling, in addition to the characteristics of the parent and deposited metal. As a result it is to be expected that a welding process will influence the properties of steels in varying degrees, the most seriously affected being the steels which owe their physical characteristics to certain types of heat treatment or whose properties are susceptible to great changes by heat treatment.

The steel which forms a major part of the investigation reported herein derives its physical characteristics from a process of quenching and tempering. As noted above, this steel is thus likely to be considerably affected by any welding process.

The present investigation was initiated to study quantitatively the effect of welding on the fatigue properties of a quenched and tempered steel. The reduction in fatigue resistance due to the presence of a weld is largely a result of the dimensional discontinuity at the weld and partly due to the metallurgical changes introduced. In addition, some loss in fatigue resistance is to be expected because of the intrinsic change in homogeneity caused by the welding.

To investigate the separate effects of the various factors on the fatigue resistance, a transverse butt-welded specimen was selected. Tests were conducted on specimens in the as-welded condition, with the reinforcement removed and in a heat-treated condition. The base for the computation of reduction in fatigue strength due to the various effects of welding was taken as the fatigue strength of plain as-rolled plates. These tests were conducted on a zero-to-tension stress cycle.

In addition to the above tests, one series of fatigue tests on as-welded transverse butt welds were conducted on a cycle of stress varying from a partial tension-to-maximum tension. However, in these tests the maximum tension was held constant.

A limited number of fatigue tests on transverse butt welds in a commercial ASTM A-242 steel were also conducted. The available material limited the study to one series of zero-to-tension tests on transverse butt welds in the as-welded condition.

Metallurgical examinations of typical specimens have been conducted to determine the metallurgical changes imparted due to the welding and heat treatment process and to evaluate the effect these changes might have on the fatigue behavior of the members.

1.4 ACKNOWLEDGMENTS

The tests described in this report are the results of an investigation conducted in the Engineering Experiment Station of the University of Illinois. The program was carried out under the joint sponsorship of the Engineering Foundation, the American Iron and Steel Institute, the Chicago Bridge and Iron Foundation and the Welding Research Council. The Fatigue of Welded Joints Committee of the Welding Research Council acted in an advisory capacity.

The investigation constitutes a part of the structural research program of the Civil Engineering Department of the University of Illinois under the general direction of Dr. N. M. Newmark, Head of the department, and under the general supervision of W. H. Munse, Professor of Civil Engineering. The research was carried out by R. K. Sahgal, Research Assistant in Civil Engineering and under the supervision of J. E. Stallmeyer, Professor of Civil Engineering. The metallurgical studies were carried out under the direction of Professor W. H. Bruckner.

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II. DESCRIPTION OF MATERIALS AND TESTS

2.1 MATERIALS

The quenched and tempered steel used in this investigation was supplied in 3/4 in. plates from a single heat. The chemical composition and physical characteristics of the steel are presented in Tables 1 and 2, respectively.

The chemical composition and physical characteristics of the ASTM A-242 steel used for the exploratory series of tests are also given in Tables 1 and 2, respectively. In Table 2, two sets of properties are described for the ASTM A-242 steel; in the as-received condition and the heated condition. This heat treatment* was carried out in order to correct for difficulties encountered in welding. The treatment is discussed in Section 4.1. It should be pointed out that the heat treatment significantly lowered the yield and ultimate strength of the material. This change was accompanied by an increase in the ductility of the material as appraised by the elongation.

Both E11016 and E12016 grade electrodes were employed in welding the quenched and tempered steel. For welding the ASTM A-242 steel, electrodes of E7016 grade were used. All electrodes were stored in an oven at 200 to 300°F until used.

2.2 TEST SPECIMENS

The specimens used in the test program had a width of 12 in., an overall length of 48 in., and a reduced section at the center. Details of the plain plate and transverse butt-welded specimens are shown in Fig. 1.

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* See Table 2.

The first series of transverse butt-welded joints was prepared as shown in Fig. 1(b). Some of the subsequent tests employed a central test section butt-welded to pull heads salvaged from previously tested specimens. The welds connecting the pull heads to the central test section are referred to in this report as 'pull head welds' and in each case were ground flush. The minimum distance from the pull head welds to the central test weld was kept greater than 7 in. to eliminate any effect of the pull head weld on the test weld.

2.3 FABRICATION OF SPECIMENS

For the preparation of plain plate specimens, 12 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 (6). After the welding procedure had been 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 that could be rotated about a horizontal axis so that all welding could be carried out in the flat position. The members were then welded and allowed to cool in the jig until they reached room temperature.

The rates of travel recorded for the welding procedures (Figs. 3,4) were minimum values so that the heat inputs did not exceed the specified values.

All transverse butt welds were of the double-Vee type with a 60 deg. included angle. The details of the welding procedures employed for these members are presented in Figs. 3 and 4. In each case a 7 in. length of weld was prepared and then the test section finished to the 5 in. width shown in Fig. 1(b).

The 7 in. length of weld was too long to allow the completion of a single pass without changing electrodes. In order to more closely control the duplication of the specimens, the changes in electrode were made at fixed points as shown in Figs. 3 and 4. By the use of this procedure, every pass of the weld was stopped and restarted within the test section. Adjacent passes were welded from opposite directions and changes of electrodes did not occur one over the other.

Welding procedure A (Fig. 3) was used for only 6 specimens (see Table 5). All subsequent welds were prepared with welding procedure B (Fig. 4). The electrode employed in each case is specified along with the results of the fatigue tests in Tables 5 through 12. It should be noted that no preheat was employed in the preparation of the welds.

Welding of the test section (in cases where central test section blanks were employed with previously used pull heads) to the pull heads was carried out in a manner similar to that described above, with no control being exercised over the positions of change of electrode.

Subsequent to the welding and machining of the specimens, the edges of all specimens were draw filed. The welds from which the reinforcement was to be removed were ground flush 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 markings from the grinding were parallel to the direction of loading.

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 unless they were to be used subsequently as mentioned in Section 2.3. The metallurgical examinations were carried out 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 using 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 Chapters 3 and 4.

2.5 TESTING EQUIPMENT

All of the fatigue tests reported herein were conducted at room temperature in an ordinary non-corrosive 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 Illinois 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.

2.6 TESTING PROCEDURES

All of the fabricated specimens were subjected to a thorough visual inspection for cracks upon completion of welding and prior to testing. However, in no case were any cracks found.

Failure of the specimens, as far as feasible, was taken as that point at which approximately half the cross sectional area of the specimen had fractured. This procedure 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 complete fracture occurred, no attempt was made to correct the life to that for which approximately half the cross sectional area would have fractured. There are several reasons for following this procedure. First, there is not sufficient information available to determine the rate of crack growth in welded members under repeated loads. Second, laboratory observations have indicated that the number of cycles required for fatigue cracks to propagate through the type of members tested is usually a small percentage of the total fatigue life. Finally, if one considers the inherent scatter associated with fatigue testing, small corrections of the nature discussed above are not justified.

2.7 EVALUATION OF FATIGUE STRENGTH

To compare 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

$$F = S \left(\frac{N}{n}\right)^{k} \qquad (2.7)$$

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 (2.7) is an empirical equation, derived on the basis of laboratory observations (7) 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 characteristics, the geometry of the specimen and the cyclic conditions of 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 is generally relatively small.

The results of all series of fatigue tests in this study have been plotted on a logarithmic basis using nominal applied stresses, and average curves have been drawn for these data. A value of k was assumed initially and the fatigue strength 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.

The number of cycles at which the fatigue strengths were computed were taken as 100,000 and 2,000,000. The latter value, 2,000,000 cycles, is an arbitrary value, sometimes considered to represent the number of repetitions of stress certain bridge members would probably be expected to withstand during their normal life span. Furthermore, the S-N diagrams for many types of welded joints tend to become horizontal at approximately 2,000,000 cycles.

The other point at which the fatigue strength has been computed for purposes of comparison has been taken as 100,000 cycles. This, too, is an arbitrary value and was probably originally conceived by investigators for purposes of comparison only. It has been observed from test data that the S-N curves for many types of members can be approximated by a linear relationship in the region between 100,000 and 2,000,000 cycles. The exact shape of the S-N curve is probably not linear for the entire range, but very little information is available to better define it.

III. ANALYSIS AND DISCUSSION OF RESULTS OF TESTS ON QUENCHED AND TEMPERED STEEL

3.1 FATIGUE TESTS OF AS-ROLLED PLATE SPECIMENS

The results of fatigue tests on as-rolled plate specimens are presented in Table 3 and are shown diagramatically in Fig. 5. Six tests were conducted on a zero-to-tension stress cycle.

Also shown in Fig. 5 are the results of fatigue tests reported on similar specimens of two other quenched and tempered steels, T-1 steel (1) and HY-80 steel (2). Data on the physical characteristics of all these steels along with similar data on ASTM A-242 and A-7 steels (the results of which are not shown in Fig. 5) are summarized in Table 4. The S-N curve shown in Fig. 5 is only for the results of the present tests on the 3/4 in. quenched and tempered steel.

From the data presented in Fig. 5, it may be seen that the fatigue ratio and the strengths of the 3/4 in. quenched and tempered steel (reported herein) are lower than those of the 1/2 in. quenched and tempered T-1 steel, reported in Ref. 1. On the other hand, the strengths of the 3/4 in. HY-80 steel are consistently lower than those on the 1 1/2 in. HY-80 steel. It is noteworthy that the above increase or decrease in fatigue resistance is coincident with a similar change in the static tensile strength of the parent material (Table 4).

It is believed that the differences in the fatigue resistance for the 3/4 in. quenched and tempered and 1/2 in. T-1 as-rolled plate specimens as well as those from similar specimens of 3/4 and 1 1/2 in. HY-80 steel are significant enough to warrant a further discussion as to the cause of these differences. However, at present, no simple explanation for these differences in the fatigue strengths is available. The most common explanation is based on the observation that the fatigue resistance of as-rolled plate specimens is primarily a function of the static tensile strength, the fatigue resistance increasing with an increase in the static strength. The data shown in Table 4 and Fig. 5 appear in general to substantiate this position. However, the data on similar as-rolled plate specimens of ASTM A-242 and A-7 steels give considerably higher fatigue ratios. The statement that the fatigue resistance is a function of the static tensile strength cannot, therefore, be accepted as the only factor which contributes to the fatigue strength.

It has been observed that high strength steels are relatively more notch sensitive in fatigue (the stress raisers in the as-rolled plate being the mill scale and the rolling defects) and thus they cannot be expected to show any significant advantage in fatigue resistance over ordinary structural steels. Therefore, the fatigue ratios tend to decrease with an increase in the static tensile strength. That this is so is readily verified from the data in Table 4. It is seen that the fatigue ratio is highest for A-7 steel (i.e., it is the least notch sensitive). The fatigue ratios decrease for the A-242, the HY-80 and the quenched and tempered steels indicating that with an increase in the static tensile strength, the notch sensitivity of the steel increases. There are considerable data available in the literature in support of the above noted behavior (7,9,10).

One interesting fact emerges from the data presented in Table 4. The fatigue ratios for the quenched and tempered, the T-1, and the HY-80 steels are almost the same although the static tensile strengths vary from

94.2 to 123.0 ksi. All these steels have a tempered martensitic structure with differences in hardness level. This suggests that the fatigue resistance of as-rolled plate specimens might also be a function of the metallurgical structure of the parent material. However, such a conclusion would require additional work on a variety of materials. The agreement shown in Table 4 may be purely coincidental and may have been caused by differences in the surface geometry of the specimens. At first glance, it would appear that since these tests were all conducted under axially repeated loads with no intentional stress raiser, there should be no effect of gemoetry. However, if one considers the mill scale and rolling imperfections to be unintentional stress raisers in the as-rolled plate specimens, the effect of geometry could cause differences in the fatigue resistance of the specimens of different thicknesses. However, definite evidence of the effect of geometry is not yet available though isolated test results substantiate the idea that the specimen geometry can cause significant differences in the fatigue resistance (8).

The fatigue failures of all but one as-rolled plate specimen initiated at the end of the fillet radius (at the end of the test section), due to the discontinuity in the section at that point. The exception to this type of failure was specimen FTT-33 in which fracture initiated in the test section. All fatigue cracks initiated at the surface. Photographs of typical fracture locations and fracture surfaces are shown in Fig. 6.

3.2 FATIGUE TESTS OF AS-WELDED TRANSVERSE BUTT-WELDED JOINTS

Results of fatigue tests on as-welded transverse butt-welded joints in the quenched and tempered steel are summarized in Table 5 and are shown diagramatically in Fig. 7. Nine fatigue tests were conducted on a zero-to-tension stress cycle.

Also presented in Fig. 7 are the results of fatigue tests reported on similar specimens of T-1 steel (1) and of two thicknesses of HY-80 steel (2). Pertinent data on all these tests, along with similar data on ASTM A-242 and A-7 steels are presented in Table 6. The straight line S-N curve shown in Fig. 7 is for the results of the present tests on the 3/4 in. quenched and tempered steel only.

It will be noted that the data presented in Fig. 7 for the 3/4 in. quenched and tempered steel falls within a very narrow scatter band. There does not appear to be any significant effect of the difference in electrode employed, probably due to the fact that all specimens failed at the edge of the weld due to the dimensional discontinuity introduced by the weld reinforcement.

As in the case of the as-rolled plate specimens, there are significant differences in the results for the 3/4 in. quenched and tempered steel and 1/2 in. T-1 steel. This same result appears in the data for the two thicknesses of HY-80 steel. However, these differences do not appear to be consistent. In the case of HY-80 steel, the welded joints in the 1 1/2 in. material appear to be inferior at all lines when compared to those in the 3/4 in. material (which has a lower static strength than the 1 1/2 in. HY-80) under conditions of repeated loading. This behavior is in line with expectations (9,11). On the other hand, when T-1 and the quenched and tempered steel results are compared, the welds in the 1/2 in. T-1 material appear to be superior to those in the 3/4 in. material up to fatigue lives in the neighborhood of 300,000 cycles whereas at longer lives the joints in the 1/2 in. material appear to be inferior to those in the 3/4 in. material. In addition, the data on the ASTM A-242 steels presented in Table 6 show that the welds in 1/2 in. material are superior to the welds in 3/4 in. material under conditions of repeated loadings (see also Fig. 19).

In spite of the somewhat contradictory behavior mentioned above for the results of the as-welded transverse butt-welded joints in various steels and for various thicknesses, a pattern seems to emerge. First, it appears that the role played by a weld in fatigue is somewhat different at longer lives than at shorter lives, the exact influence being governed by the geometry of the specimen and the tensile strength of the material, among other factors. This seems to be consistent with recent claims that short life fatigue is a mechanism altogether different from long life fatigue (12). Second, it appears that high strength steels are relatively more sensitive under fatigue conditions to the presence of welds than are ordinary structural steels, i.e., high strength steels are more notch sensitive in fatigue.

From the discussion, it is apparent that the exact role played by welds in fatigue is not yet fully understood. Due to the large number of variables present, the comparisons presented cannot be considered as final proof of their validity. One of the major purposes of the above discussion has been to point out some of the more significant differences in fatigue behavior. It follows then that the available test data must be used with discretion.

It has already been mentioned that all of the transverse butt-welded joints tested in the as-welded condition failed at the edge of the weld reinforcement. Typical fracture surfaces of welds in this series are shown in Fig. 8.

3.3 FATIGUE TESTS OF HEAT-TREATED TRANSVERSE BUTT-WELDED JOINTS

One series of ten transverse butt-welded joints of the quenched and tempered material were tested in a heat-treated condition with the weld reinforcement in place. The purpose of this heat-treatment was simply to alter the characteristics in the region of the weld heat-affected zone (see Sec. 3.7). The heat treatment consisted of heating the completed butt-welded joint to 1650^{o}F, quenching cold in water, and tempering at 1150^{o}F for 30 minutes. Unfortunately, this heat treatment caused 3 specimens (see Table 7) to warp considerably, causing some bending stress to be introduced upon testing. The results for these 3 specimens were consistently lower than for the other specimens and were not included in the averages indicated in Table 7.

The results of the 7 specimens used to obtain an average value of fatigue strength of the heat-treated transverse butt-welded joints are fairly consistent and are plotted in Fig. 10. The average values obtained for $F_{100,000}$ and $F_{2,000,000}$ were 44.9 and 29.6 ksi respectively, an increase of approximately 14.5 percent over corresponding values for the as-welded transverse butt welded joints.

In general, the specimens in this series failed at the edge of the weld reinforcement due to the dimensional discontinuity at the specimen surface. There was one exception; specimen FTT-14 (see Table 7) failed in the pull head weld in which there appeared to be a small internal flaw. Photographs of fracture surfaces of typical specimens in this series are shown in Fig. 11. The somewhat different texture of the fracture surface from that of the as-welded specimens (Fig. 8) is noticeable. Also noteworthy is the marked resemblance of the texture of the fracture surface to that of the plain plate specimens shown in Fig. 6.

3.4 FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS WITH REINFORCEMENT REMOVED

Fatigue tests of transverse butt-welded joints with the weld reinforcement removed were conducted to determine the extent of the effect of the weld reinforcement on the fatigue strength under a zero-to-tension stress cycle.

The removal of the weld reinforcement eliminates 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 weld reinforcement can be expected to increase the significance of internal weld flaws. To realize fully the advantage of the removal of the weld reinforcement would require welds that are completely free of internal flaws.

The results obtained from the tests on members with the weld reinforcement removed are in agreement with the behavior discussed above. Further discussion of the role of weld flaws in fatigue is presented in Sec. 3.5.

In Table 8 are summarized the results of fatigue tests on transverse butt-welded joints tested with the weld reinforcement removed. In all these tests, failure occurred at the edge of the weld. These results are shown diagramatically in Fig. 13. At a life of 2,000,000 cycles removal of the weld reinforcement increased the average fatigue strength by approximately 11 percent.

Three specimens with the weld reinforcement removed failed in the weld metal and exhibited a failure pattern different from that usually encountered for normal sound welds. These are discussed in Sec. 3.5.

3.5 FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS WITH WELD FLAWS

It has been stated in Sec. 3.4 that removal of the weld reinforcement can be expected to increase the significance of internal flaws. This section is devoted to a brief discussion of the role of weld flaws in fatigue and to a presentation of data obtained from fatigue tests of welds with flaws.

It must be noted that the degree to which weld flaws affect the fatigue resistance of a particular type of welded joint in a particular steel is undoubtedly a function of the shape, size, location, and the orientation of the flaw. In cases where serious flaws are present, the fatigue resistance of a member, even with the weld reinforcement removed, may be less than that of a sound joint. On the other hand, under static loading conditions with normal weld flaws, the full static strength of the parent metal is usually developed. In the case of fatigue the internal weld flaws act as stress raisers and as nuclei for the initiation of fatigue cracks. Thus, it is imperative that data be available on the exact nature of the weld flaw to make any quantitative predictions of the effect of weld flaws on fatigue.

Due to difficulties associated with the production and duplication of weld flaws of a desired severity, little quantitative information is available on the subject. Much of the qualitative information on work on the influence of defects on fatigue strength has been summarized by Newman (13). Five types of weld flaws are discussed - cracking, lack of fusion, lack of penetration, porosity and slag inclusions.

In Table 9 are presented the results of transverse butt-welded joints tested with the weld reinforcement removed which failed in the weld metal. There were three specimens in which failure occurred in the central weld and three in which failure occurred in the pull head welds. Because of a lack of quantitative information on the subject, it is extremely difficult to interpret the limited results of weld failure tests when the reinforcement has been removed. In an attempt to overcome this situation, the weld failure tests will be compared on the basis of lives rather than fatigue strengths. In Table 9, for each of the specimens that failed in the weld, the expected life on the basis of sound welds (Table 8 and Fig. 13) has been presented.

The results presented in Table 9 can be separated into two parts. The three specimens which failed in the central test welds had minor weld flaws (Specimen FTT-23, Fig. 14 is typical of this group). The actual lives obtained for these three specimens (Specimens FTT-28, 26, 23, Table 9) are lower than expected but the extent of the reduction in fatigue strengths is not as severe as for the second group which exhibited lack of penetration. Three other specimens (FTT-11, 7, 10, Table 9) each failed in the pull head weld and the actual lives are drastically short of the expected lives. The fracture surfaces of two of these specimens, FTT-7, FTT-10, are shown in Fig. 14. It will be noted that in specimen FTT-7 severe undercutting is present; in spite of the undercutting, the failure of this specimen appears to have initiated internally due to lack of penetration.

In Table 10 are presented the results of three fatigue tests conducted on specimens with the weld reinforcement in place which were stress relieved. In each case, failure occurred in the weld metal due to lack of penetration. Typical fracture surfaces for two of these specimens are shown in Fig. 15.

As before, the lack of penetration of the stress relieved specimens appear to have drastically reduced the fatigue life, and hence fatigue strength.

From the data, it is apparent that the nature of the weld flaw can have a profound influence on the fatigue resistance of welded joints. Whereas minor inclusions can reduce the fatigue life considerably, major flaws like lack of penetration can cause drastic reductions in fatigue lives and fatigue strengths.

It has been mentioned earlier that T-1 steel is relatively more notch sensitive than ordinary steels. The same is true of HY-80 steel. Thus, the drastic reductions in fatigue lives encountered in tests of welds with flaws, as seen from the data presented in Tables 9 and 10 and in Ref. 2, may, to a certain extent, be associated with the characteristics of the parent material i.e., its notch sensitivity in fatigue. Available data on ASTM A-242 and A-7 steels indicate that the role of defects in these steels is not as severe, indicating that these steels are not as notch sensitive as the quenched and tempered steels. This aspect is discussed further in Chapter 4.

3.6 FATIGUE TESTS OF AS-WELDED TRANSVERSE BUTT-WELDED JOINTS

Thus far, results of fatigue tests on transverse butt-welded joints in this quenched and tempered steel conducted on a zero-to-tension stress cycle have been presented. However, welded joints encountered in engineering practice are rarely called upon to resist a cycle of stress varying from zero-to-tension. For example, the cycles of stress to which the usual bridge member is subjected is a function of the initial or dead load carried by the said member. The minimum stress is consequently more or less constant and depends on the type, span, and purpose of the bridge. On the other hand, the maximum stress is a function of the loads. Since the number of applications of the maximum design live load is by no means certain, it may be assumed that the maximum stress in the stress cycle is the static design stress used for the material of the member. Thus, for a bridge member subjected to tension, a cycle of stress varying from an initial tension to a maximum tension may be assumed.

With these facts in mind, a series of tests was conducted on a partial tension-to-tension stress cycle, the maximum stress in all tests being kept at 50.0 ksi and the minimum stress being varied from test to test. In all, four specimens in the as-welded condition were tested, the minimum tension being 0, 12.5, 25.0 and 35.0 ksi, respectively. The results of this series of tests are presented in Table 11 and are shown diagrammatically in Fig. 17. In these tests the maximum stress was kept constant, consequently an increasing stress ratio indicates an increasing minimum stress and a decreasing range of stress.

The results of the tests in this series do not appear to yield a linear variation on the type of plot shown in Fig. 17. It is observed that a stress ratio of 0.70 (corresponding to a dead load to live load ratio of 2.33) represents approximately the value of $F_{2,000,000}$. This value is greater than the ratio of dead load to live load in many bridge members, but may be comparable to that which occurs in long span highway bridges.

With the data obtained, it has been possible to construct the approximate Modified Goodman Diagram shown in Fig. 18. Constant life contours have been drawn for lives of 100,000 and 2,000,000 cycles. It must be emphasized that this diagram is based on very limited data - in fact, no data are available for the completely reversed stress cycle - and is shown for the purpose of bringing out the salient features of the fatigue behavior of as-welded transverse butt-welded joints in this quenched and tempered steel.

From the Modified Goodman Diagram shown in Fig. 18, it appears that in the life range under consideration the behavior of transverse butt-welded joints is governed by the maximum cyclic stress as well as the range of stress. However, since no data are available on a completely reversed stress cycle, a detailed evaluation of the behavior cannot be made.

It is also possible to examine the effect of variation of either the alternating or mean stress on the life by means of the construction shown in Fig. 18. Using an inclined grid system, the constant life contours can be examined as functions of the alternating stress and the mean stress. From such a presentation, one can readily see the effect of mean stress, maximum stress, or alternating stress 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 (complete reversal). It again appears that, irrespective of life, the behavior of the joints is governed both by the mean or maximum stress and the alternating stress.

It must once again be emphasized that the analysis of the data presented above is based on a limited amount of data and that the curves have been plotted through only a few points. Nevertheless, it is believed that the curves are indicative of the general trend of the fatigue behavior for as-welded transverse butt welds in this steel. It must also be noted that the figure 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 METALLURGICAL EXAMINATIONS OF BUTT-WELDED JOINTS

This section is concerned with the metallurgical studies carried out on typical transverse butt welds. The metallurgical examinations of the welds were made to evaluate the changes in metallurgical structure that resulted from the welding process and to correlate these structures with the fatigue behavior of the welded joints.

3.7.1 Metallurgical Characteristics of the Parent Metal

The steel used in these tests is a quenched and tempered, fully-killed, fine-grain alloy steel which derives its metallurgical characteristics from the quenching and tempering. The significant features of the chemical composition of this material (see Table 1) are its low carbon content which provides toughness and weldability, and the use of alloying elements which impart hardenability and insure that transformation products form at low temperatures.

3.7.2 Metallurgical Effects of Welding the Quenched and Tempered 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 or ambient 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 maximum temperature to which a particular point is heated but also on the 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 geometry. High heat inputs and preheating favor slow cooling whereas heavy sections encourage fast cooling rates. As a consequence, a gradient in the metallurgical structure results in the HAZ*.

The metallurgical characteristics of the weld metal may be affected by the composition and type of electrode, the type of joint, and 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 is refined by the subsequent passes, the extent of refinement depending on 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.

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* Heat-affected zone.

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

3.7.3 Microstructures of As-Welded Joints

Specimen FTT-3 was typical of the as-welded transverse double-Vee butt-welded joints. The microstructures of the various zones of the weld of this joint are shown in Fig. 9. The fatigue failure occurred at the edge of the weld reinforcement. It appears that the fatigue crack initiated at the top adjacent to the reinforcement in the HAZ and then traversed almost in a straight line through the base metal rather than following the HAZ.

The base metal of this quenched and tempered steel is made up essentially of tempered martensite. On observation of the martensitic needles, the former grain boundaries of the grains of austenite from which the martensite was formed by the rapid quenching given to this steel in its manufacture can be seen. There is also some retained austenite in the structure, possibly due to the large austenitic grain size or uneven cooling. The black spots appearing on the microstructure (Fig. 9) are inclusions.

Some of the inclusions have an elongated shape, perhaps a consequence of the hot rolling. The inclusions and any retained austenite may lower the static strength, but only slightly.

As a result of the complex thermal cycle involved in welding, a gradient in the metallurgical condition is present. Traversing out into the plate from the center of the weld, one finds the change in metallurgical structure decreases to a point where the welding process has no effect on the base metal.

The plate tempering temperature used in the manufacture of this quenched and tempered steel is high and the zone in the base metal heated below or up to the plate tempering temperature will be unaffected by the weld heat. The next zone, where the plate tempering temperature is exceeded but the lower critical temperature, A_1, is not exceeded is generally termed a 'soft zone'. There will be practically no metallurgical change in this region but the high tempering temperature causes the static tensile strength and the hardness to drop. This soft zone is very narrow and available data on static tests of welded joints indicates that it does not affect the static strength of a welded joint.

The principal metallurgical effect of the welding process starts at the point where the A_1 temperature is exceeded. At such points, some austenite, higher in carbon than the base metal, will form. This austenitic formation appears in the form of small grains which nucleate at the grain boundaries. The density and size of these grains increases as we go towards the zones subject to higher temperatures. These grains continue to form up to the region where the A_3 temperature is exceeded. However, at the rapid cooling rates predominant in this region, the austenite formed will be relatively low in alloy and will transform to bainite on cooling. This region will also contain the original undissolved carbides and ferrites.

Nearer the weld metal where the A_3 temperature is exceeded, the cooling rate is relatively high and a structure of martensite or of bainite will be obtained. In the micrograph of the WM-HAZ interface in Fig. 9, such a structure can be seen.

The weld metal structure for specimen FTT-3 shown in Fig. 9 appears to have a random structure, completely different than the base metal. This is understandable in view of the different composition of the electrode. The weld metal appears to have solidified in columnar grains. Because the flow heat from the weld is highly directional towards the adjacent cold metal, the weld develops distinctly columnar grains perpendicular to the bond. Also present in the weld metal are numerous pearlitic colonies, though these are very small in size.

3.7.4 Microstructures of Reheat-treated Joints

The weld of specimen FTT-31 is typical of the heat-treated transverse butt welds and the microstructures of the various zones for this weld are shown in Fig. 12. This weld was a double-Vee butt weld and the fatigue failure occurred at the edge of the weld reinforcement, as may be seen from the macrograph in Fig. 12.

This weld was prepared in the as-received material. After the weld was deposited, the specimen was subjected to a heat treatment (see Sec. 3.3). Before the heat treatment was carried out no metallurgical examination of the specimen was made; however, it can be assumed that it had a metallurgical structure similar to that of specimen FTT-3 (Section 3.7.3 and Fig. 9) since it was prepared using the same welding procedure. The heat treatment consisted in quenching cold in water from 1650°F, causing a structure of martensite to be formed throughout. This temperature, however, was not high enough to destroy the columnar grain structure of the weld metal (Fig. 12). A tempering of the weld was then carried out at 1150°F, just below the A_1 temperature. The martensite or bainite formed on quenching appears to have become somewhat darker.

The absence of the HAZ in the heat-treated specimen should be noted. A slight gradient in the metallurgical condition is present at the BM-WM interface. Typical micrographs and a macrograph of Specimen FTT-31 are shown in Fig. 12.

3.7.5 Analysis of Results

A 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 seen that the dimensional discontinuity at the surface of a specimen has a greater effect on fatigue than the metallurgical factors introduced by welding, provided the weld is free of flaws. Studies have indicated that the metallurgical structure and the grain size govern only the local propagation of a crack, which generally traverses perpendicular to the applied stress (2). In cases where weld flaws overshadow the dimensional discontinuity at the surface, the weld flaws will act as nuclei for the initiation of fatigue cracks, irrespective of the metallurgy of the HAZ.

3.8 DISCUSSION OF TEST RESULTS

The current tests of transverse butt welds afford a quantitative measure of the effect of geometrical and metallurgical factors on the fatigue strength of transverse butt-welded joints in this quenched and tempered steel. A summary of the S-N curves obtained for the tests on this steel is presented in Fig. 16. It is seen that the introduction of a transverse butt weld in a plate of this steel reduces the value of $F_{2,000,000}$ from 42.8 ksi to 25.8 ksi, a reduction on the order of 40 percent. This reduction takes into account the loss in fatigue strength due to both geometrical as well as metallurgical factors. However, if the external geometrical factor is eliminated by removing the weld reinforcement, the fatigue strength corresponding to 2,000,000 cycles reduces from 42.8 ksi to 28.7 ksi, a reduction on the order of 33 percent. On the other hand, if the metallurgical effects of welding are substantially eliminated (heat-treated specimens), the fatigue strength is reduced from 42.8 ksi to 29.6 ksi, a reduction on the order of 31 percent.

It thus appears that of the 40 percent reduction caused in the fatigue strength of a plate of this quenched and tempered steel due to the introduction of a transverse butt weld, 9 percent is attributable to metallurgical factors alone. Thus approximately 31 percent of the loss in fatigue strength is due to geometrical factors or other factors unaccounted for. These may be internal as well as external geometry, non-homogeneity of welds, possible change of the physical properties of the joint, and residual stresses, among other factors.

The test results on a zero-to-tension stress cycle have indicated that under this stress cycle the fatigue strength of the quenched and tempered steel is not much superior to that of A-7 or A-242 steels on this same stress cycle. However, since the fatigue strength is a function of the maximum stress as well as the range of stress, the advantages of the use of this steel over other structural steels occur under special circumstances. The tests carried out on a partial tension-to-tension stress cycle can be used to demonstrate this point (Fig. 17). The maximum stress used in these tests (50.0 ksi) would be almost impossible to attain in A-7 or A-242 steel without general or limited yielding. Since the fatigue strengths of welds in A-7, A-242 and this quenched and tempered steel are very close to each other on a zero-to-tension stress cycle, it is probable that the same range of stress could be resisted by the ASTM or A-242 steels as long as the maximum stress was below the yield strength. In other words, the <u>mean stress</u> resisted by a weld in the quenched and tempered steel, because of its high yield strength, may be considerably higher than that resisted by a comparable weld in A-7 or A-242 steel. This is where the superiority of this steel lies.

IV. ANALYSIS AND DISCUSSION OF RESULTS OF TESTS ON AN A-242 STEEL

4.1 FATIGUE TESTS OF AS-WELDED TRANSVERSE BUTT-WELDED JOINTS

The fatigue tests conducted on the ASTM A-242 steel did not actually form a part of the primary objective of this investigation. They were essentially of an exploratory nature since it was found that this particular A-242 steel was not readily weldable in the as-received condition. Since only a limited amount of material was available, only five fatigue tests of as-welded transverse butt-welded joints were conducted.

Prior to any fatigue testing, weld qualification tests were conducted using three different welding procedures. However, none of these procedures gave satisfactory results. Two fatigue specimens were finally prepared using welding procedure B (Fig. 4). Results of fatigue tests on these two specimens (RF-1, RF-2) are presented in Table 12. Specimen RF-1 failed at the edge of the weld reinforcement and a gas pocket was visible at the fracture surface. Specimen RF-2 failed in the weld metal, again due to the presence of gas pockets (Fig. 20).

Since a low hydrogen type electrode (E7016) was employed for the above tests, it was thought that the parent metal might itself contain entrapped gases. To investigate this, the parent material was heated to 1400°F in a furnace and allowed to cool over a period of several days in the furnace itself. This heat-treated material was then welded and static tensile tests indicated the weld to be sound. The subsequent fatigue tests of transverse butt-welded joints in this material were conducted after the parent metal was initially heated in the manner described above. The results of these tests (specimens RF-3, 4, and 5) are also presented in Table 12.

One interesting observation from these tests is that the heat treatment of the parent metal in this way permitted sound welds to be obtained. The net effect was to move the point of initiation of the fracture to the critical geomtrical zone of the weld, i.e., the edge of the weld reinforcement. However, this was accompanied by little or no increase in the fatigue resistance of the joints.

The results of the fatigue tests on the A-242 steel are shown diagrammatically in Fig. 19. Also presented on Fig. 19 are the results of fatigue tests reported on other types of ASTM A-242 steels (3,4). Pertinent data on these steels is presented in Table 6. The S-N curve shown in Fig. 19 is for the data on the present tests only.

From the data shown in Fig. 19 it can be seen that most of the data falls in a narrow scatter band. The only exception is the data on 1/2 in. A-242 steel (4) which shows consistently superior fatigue resistance. No explanation for such a behavior is currently available except that it may be due to the difference in the geometry of the specimens.

Failure surfaces of the specimens in the two different conditions are shown in Fig. 20.

4.2 METALLURGICAL EXAMINATIONS OF BUTT-WELDED JOINTS

Two transverse butt-welded joints in A-242 steel were examined metallurgically. These were specimens RF-1 and RF-5. Specimen RF-1 was a weld in the as-received material and specimen RF-5 was in the heat treated material.

4.2.1 Specimen RF-1

This weld was prepared in the as-recieved A-242 steel. The microstructure of the base metal along with that of the different parts of the weld is shown in Fig. 21. The base metal has the structure of an ordinary low carbon steel and consists of pearlite grains in an equiaxed ferritic matrix. The pearlite grains are highly irregular, possibly due to the fact that the pearlite had to form in the austenite retained between the ferrite grains of the matrix.

With a decrease in the distance between the weld metal and the base metal, the temperature attained on welding becomes higher. At the point where the temperature just exceeds the A_1 temperature, the pearlite grains seem to have recrystallized into smaller grains. This condition exists up to the region where the A_3 temperature is attained. In the region where the A_3 temperature is exceeded, an austenitic structure seems to have formed. The high cooling rate in this region is probably the reason that the austenitic structure is homogeneous and fine grained. These austenitic grains are surrounded by ferrite.

In the region next to the weld metal a needle like structure appears and the grain boundaries are distinguishable. This needle like structure is either martensite or bainite and is very similar to the structure obtained near the weld metal in weld FTT-3 in the quenched and tempered steel (Section 3.7 and Fig. 9). The weld metal again has a columnar grain structure, highly irregular in shape. An equiaxed structure is also distinguishable in the weld metal in regions which are farthest from the base metal on that particular weld pass. There does not appear to be any pearlite in the weld metal, possibly due to the low carbon content of the electrode employed.

Typical micrographs for specimen RF-1 are shown in Fig. 21. From the macrograph, also shown in Fig. 21, it can be seen that the fracture occurred in the HAZ.

4.2.2 Specimen RF-5

This particular weld was made after the base metal had been heated to 1400°F and allowed to cool slowly in the furnace. Failure of this specimen occurred at the edge of the weld as can be seen from the macrograph shown in Fig. 22.

The structure of the base metal in this specimen is very similar to that in specimen RF-1 except that the pearlitic grains seem to have spherodized due to the heat treatment which the base metal received prior to welding. In all other respects, the changes introduced by the thermal cycle of welding are essentially the same as in weld RF-1. This can be seen from the microstructures in Fig. 22.

4.3 DISCUSSION OF TEST RESULTS

Since very few tests were conducted in this investigation on the fatigue behavior of transverse butt-welded joints in A-242 steel, no general conclusions can be presented. However, some important observations have been made and are briefly discussed below.

Relatively speaking, ASTM A-242 steels are found to be considerably less notch sensitive than quenched and tempered steels reported herein. This conclusion is based on the observation that there is very little difference in the fatigue strengths of the specimens of A-242 which fail internally (in the weld metal due to flaws) when compared to those which fail at the edge of the weld reinforcement. Thus it appears that only a negligible increase in fatigue strength would accompany the elimination of the internal flaws unless such measures also improve the fatigue resistance at the edge of the weld (the HAZ). Such behavior is attributed to the low notch sensitivity of this group of steels.

A study of the available literature on the fatigue behavior of transverse butt welds in ASTM A-242 steels shows considerable scatter in the results, especially at shorter lives. This fact can be observed in Fig. 19. Again, no apparent reason for such a behavior is available. Undoubtedly, part of the difference is attributable to the different physical and chemical characteristics of these steels. It is also possible that geometry may be a significant factor in causing these differences. For instance, all of the data on the 3/4 in. thick steels can be grouped together in a narrow scatter band in Fig. 19 whereas the data on the 1/2 in. steel is considerably different. This is also illustrated by the Modified Goodman Diagram drawn for three different A-242 steels (Fig. 23). The relative differences in the fatigue strengths corresponding to 100,000 cycles are noteworthy.

V. SUMMARY

5.1 SUMMARY OF RESULTS

The results of axial fatigue tests on as-rolled plate specimens of a quenched and tempered steel and on transverse butt-welded joints in this material in various geometrical and metallurgical conditions have been presented in Chapter 3. Except for one series of tests, all tests were conducted on a zero-to-tension stress cycle. The results of tests of a limited number of transverse butt-welded joints in an A-242 steel are presented in Chapter 4. A summary of all the zero-to-tension test results is presented in Table 13 for ready reference.

From the test data obtained on the quenched and tempered steel, it appears that the introduction of a transverse butt weld in a plate of this steel reduces the value of $F_{2,000,000}$ by approximately 40 percent of which approximately 9 percent is attributable to the metallurgical changes imparted by the introduction of the weld. The balance of the reduction is accounted for by the geometrical factors, as investigated in this study, and to the inherent welding process which necessarily causes a joint with at least some degree of non-homogeneity.

The fatigue test results from transverse butt-welded joints in the quenched and tempered steel on a zero-to-tension stress cycle indicate that the fatigue resistance of this steel is about the same as that of ASTM A-7 or A-242 steels on this stress cycle. However, since the fatigue resistance is a function of the maximum stress as well as the range of stress, the advantages of the use of this steel over ASTM A-7 or A-242 steels can be realized only when it is subjected to higher mean stresses.

Thus, there will be a definite advantage in using the quenched and tempered steel in members subjected to high dead load stresses and when the fluctuating or alternating stress is low. Many such conditions occur in practice; the most notable being in long span highway bridges.

There is a general belief that high strength steels have little, if any, advantage over ordinary steels when subjected to repetitions of loading. The data obtained in this study indicates that such a general statement is misleading and oversimplifies the problem. In the discussion presented above and in Chapter 3, an attempt has been made to clear up this situation by pointing out that fatigue resistance is a function not only of the range of stress but also of the mean stress.

One serious disadvantage of high strength steels of the quenched and tempered type, when used in the welded condition, arises from the high fatigue notch sensitivity of this group of steels. Even minor internal discontinuities in a weld in this steel can act as a point of initiation of a fatigue crack in the weld metal and thereby reduce the fatigue strength; sometimes considerably (Sec. 3.5). Drastic reductions in fatigue strength can be obtained from major flaws. Thus a rigid and thorough inspection of welds becomes imperative. Such inspection will reduce, at least to some extent, the benefits which result from the use of high strength 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 overshadowed by the surface geometry in the as-welded members and which may not be detected by X-ray methods (2). The higher fatigue notch-sensitivity of the high strength steels appears to reduce or almost eliminate the effect of removal of the weld reinforcement for many welds. Relatively speaking, ASTM A-242 steels appear to be considerably less notch sensitive than the quenched and tempered steels (see Chapter 4).

The results of the metallurgical examinations of the welds have revealed 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. The metallurgical factors introduced by welding will assume an important role only in cases where there is no dimensional discontinuity at the surface and the weld is free of flaws. However, in this case, even a minor weld flaw will become important because an internal discontinuity is, in most cases, a more severe stress concentration than a metallurgical gradient.

5.2 CLOSING REMARKS

The results of the present series of tests, along with those from previous investigations, have produced considerable valuable information on the fatigue properties of welds in high strength structural steels. However, it is important to bear in mind that the number of tests are very limited and as such, no dogmatic conclusions can be made.

In all the comparisons presented in the previous chapters and in the preparation of the Modified Goodman Diagrams, use has been made of average values of fatigue strengths. Because of the inherent scatter associated with fatigue tests, results of individual tests may vary considerably and consequently the average values must be considered as such, 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 stated to the contrary, the average fatigue strengths refer to the results of tests on flawless welds 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.

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TABLE I

CHEMICAL COMPOSITION OF BASE METALS

Chemical Content* percent	Material	
	Q-T** Steel	A-242
C	0.12	0.13
Mn	0.75	0.42
P	0.016	0.066
S	0.026	0.025
Si	0.22	0.43
Ni	0.79	0.28
Cr	0.62	0.93
Mo	0.42	0.01
Al	0.019	None
Va	0.012	0.20
Cu	0.32	0.33

* Check Analysis

**In all future tables, Q-T refers to quenched and tempered steels.

TABLE 2

PHYSICAL CHARACTERISTICS OF BASE METALS

Properties in Longitudinal Direction	Material		
	Q-T Steel	A-242	
		As-Received	Heat Treated***
Yield, psi	94,200*	49,500	43,700
Ultimate, psi	108,500	82,000	73,500
Elongation**, percent	21.0	33.0	37.5
Reduction in Area, percent	64.5	69.0	69.0

* 0.2 percent offset

** in 2 in. gage length

*** Material heated to 1400°F and cooled slowly in furnace. (See Sec. 4.1)

TABLE 3

RESULTS OF AXIAL FATIGUE TESTS OF AS-ROLLED PLATE SPECIMENS OF Q-T STEEL (ZERO-TO-TENSION)

Specimen No.	Stress Cycle, ksi	Cycles to Failure	Location of Fracture	Computed Fatigue Strengths*, ksi	
				$F_{100,000}$	$F_{2,000,000}$
FTT-34	0 to +40.0	4,168,200+	No Failure	-	40.0**+
FTT-34 (Retest)	0 to +50.0	302,300	Radius	-	-
FTT-46	0 to +44.0	930,700	Radius	58.8	39.9
FTT-45	0 to +45.0	1,433,300	Radius	63.6	43.1
FTT-35	0 to +47.5	462,100	Radius	58.0	39.3
FTT-33	0 to +55.0	274,400	Test Section	62.7	42.5
FTT-36	0 to +70.0	137,100	Radius	72.9	49.4
			Average:	63.2	42.8+

* $k = 0.130$

** Not included in average.

TABLE 4

SUMMARY OF AXIAL FATIGUE TESTS OF AS-ROLLED PLATES OF VARIOUS STEELS (ZERO-TO-TENSION)

Steel	Thickness, in.	Yield, ksi	Ultimate, ksi	$F_{2,000,000}$ (Zero-to-Tension) ksi	Fatigue Ratio*	Source (See Bibliography)
A-7	3/4	33.3	57.4	34.6	0.603	(3)
A-242(T)	3/4	47.8	73.6	42.5	0.577	(3)
A-242(P)	3/4	56.8	76.7	38.5	0.502	(3)
A-242(Q)	3/4	53.1	77.6	40.0	0.515	(3)
HY-80	1 1/2	80.5	101.1	43.0**	0.425	(2)
HY-80	3/4	79.5	94.2	40.0**	0.424	(2)
Q-T	3/4	94.2	108.5	42.8+	0.394	Table 3
T-1	1/2	116.0	123.0	50.0	0.406	(1)

* Fatigue Ratio = $\frac{\text{Fatigue Strength}}{\text{Ultimate Strength}}$

** Approximate Value.

TABLE 5

RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN THE Q-T STEEL IN THE AS-WELDED CONDITION (ZERO-TO-TENSION)

Specimen	Welding Procedure See Figs. 3 and 4	Electrode	Stress Cycle, ksi	Cycles to Failure	Location of Fracture*	Computed Fatigue Strengths,** ksi	
						$F_{100,000}$	$F_{2,000,000}$
FTT-5	A	E12016	0 to +26.0	1,054,300	a	38.0	25.0
FTT-3	A	E12016	0 to +26.0	1,586,100	a	38.3	25.2
FTT-4	A	E11016	0 to +26.0	1,648,400	a	38.5	25.3
FTT-6	A	E11016	0 to +26.0	2,112,200	a	39.9	26.2
FTT-2	A	E11016	0 to +30.0	596,000	a	38.5	25.3
FTT-1	A	E12016	0 to +30.0	628,000	a	38.8	25.5
FTT-20	B	E11016	0 to +35.0	157,700	a	37.3	24.5
FTT-19	B	E11016	0 to +35.0	197,200	a	38.5	25.3
FTT-39	B	E11016	0 to +50.0	54,400	a	45.9	30.2
					Average:	39.3	25.8

* a = Failure initiated at edge of weld reinforcement.

** k = 0.140.

TABLE 6

SUMMARY OF AXIAL FATIGUE TESTS OF AS-WELDED TRANSVERSE BUTT-WELDED JOINTS IN VARIOUS STEELS (ZERO-TO-TENSION)

Steel	Thickness in.	Yield, ksi	Ultimate, ksi	$F_{2,000,000}$ (Zero-to-Tension) ksi	Fatigue Ratio*	K_e**	Source (See Bibliography)
A-7	3/4	33.3	57.4	23.8	0.415	1.45	(3)
A-242(T)	3/4	47.8	73.6	26.7	0.363	1.59	(3)
A-242(P)	3/4	56.8	76.7	26.3	0.343	1.46	(3)
A-242(Q)	3/4	53.1	77.6	-	-	-	(3)
A-242	1/2	58.7	84.1	28.2	0.335	-	(4)
HY-80	3/4	79.5	94.2	22.0	0.234	1.82	(2)
HY-80	1 1/2	80.5	101.1	16.3	0.161	-	(2)
Q-T	3/4	94.2	108.5	25.8	0.238	1.66	Table 5
T-1	1/2	116.0	123.0	21.0	0.171	2.38	(1)

* Fatigue Ratio $= \dfrac{\text{Fatigue Strength}}{\text{Ultimate Strength}}$

** $K_e = \dfrac{\text{Fatigue Strength of As-Rolled Plate}}{\text{Fatigue Strength of Welded Joint}}$

TABLE 7

RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN THE Q-T STEEL IN THE REHEAT-TREATED CONDITION* (ZERO-TO-TENSION)

Specimen	Welding Procedure See Fig. 4	Electrode	Stress Cycle	Cycles to Failure	Location of Fracture**	Computed Fatigue Strengths,*** ksi $F_{100,000}$	Computed Fatigue Strengths,*** ksi $F_{2,000,000}$
FTT-21	B	E11016	0 to +27.0	4,094,600+	No failure	-	27.0+****
FTT-14	B	E11016	0 to +28.0	3,341,300+	d	-	28.0+****
FTT-22	B	E11016	0 to +28.0	4,138,100+	No failure	-	28.0+****
FTT-16	B	E11016	0 to +31.0	651,200	a	40.3	26.5
FTT-15	B	E11016	0 to +31.0	1,031,800	a	43.0	28.3
FTT-31	B	E11016	0 to +38.0	285,300	a	44.0	28.9
FTT-32	B	E11016	0 to +38.0	1,009,400	a	52.4	34.5
FTT-17	B	E11016	0 to +28.0	445,000	e	-	-
FTT-13	B	E11016	0 to +28.0	447,600	e	-	-
FTT-18	B	E11016	0 to +28.0	864,600	e	-	-
					Average:	44.9	29.6

* After preparation of weld, heat to 1650°F, quench cold in water, temper at 1150°F for 30 minutes.

** a = Failure initiated at edge of weld reinforcement.
e = Failure initiated at edge of weld reinforcement, specimens warped. Not included in average.
d = Failure initiated at edge of weld in pull head weld.

*** k = 0.140

**** Not included in average.

TABLE 8

RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN THE Q-T STEEL WITH THE WELD REINFORCEMENT REMOVED (ZERO-TO-TENSION)

Specimen No.	Welding Procedure See Fig. 4	Electrode	Stress Cycle, ksi	Cycles to Failure	Location of Fracture*	Computed Fatigue Strengths,** ksi	
						$F_{100,000}$	$F_{2,000,000}$
FTT-29	B	E11016	0 to +28.0	2,719,600	a	44.5	29.2
FTT-27	B	E11016	0 to +28.0	2,119,700	a	42.9	28.2
FTT-30	B	E11016	0 to +28.0	1,416,000	a	40.6	26.7
FTT-25	B	E11016	0 to +30.0	1,500,800	a	43.8	28.8
FTT-24	B	E11016	0 to +37.0	532,700	a	46.8	30.8
					Average:	43.7	28.7

* a: Failure initiated at edge of weld.

** k = 0.14.

TABLE 9

RESULTS OF AXIAL FATIGUE TESTS OF DEFECTIVE
TRANSVERSE BUTT-WELDED JOINTS ON THE Q-T STEEL WITH
WELD REINFORCEMENT REMOVED (ZERO-TO-TENSION)

Specimen No.	Welding Procedure See Fig. 4	Electrode	Stress Cycle, ksi	Cycles to Failure	Location of Fracture*	Expected Fatigue Life For a Sound Weld (k = 0.140)
FTT-28	B	E11016	0 to +28.0	814,000	b	2,000,000+
FTT-26	B	E11016	0 to +30.0	945,300	b	1,500,000
FTT-23	B	E11016	0 to +37.0	112,100	b	325,000
FTT-11	B	E12016	0 to +20.0	168,500	d	2,000,000+
FTT-7	B	E12016	0 to +20.0	268,100	d	2,000,000+
FTT-10	B	E11016	0 to +20.0	383,100	d	2,000,000+

* b: Failure initiated in weld metal (central test weld)
d: Failure initiated in weld metal of pull head weld due to lack of penetration. Stress on pull head weld is given above.

TABLE 10

RESULTS OF AXIAL FATIGUE TESTS OF DEFECTIVE TRANSVERSE BUTT-WELDED JOINTS IN THE Q-T STEEL IN THE STRESS-RELIEVED* CONDITION (ZERO-TO-TENSION)

Specimen No.	Welding Procedure See Fig. 4	Electrode	Stress Cycle, ksi	Cycles to Failure	Location of Fracture**	Expected Fatigue Life For a Sound Weld (k = 0.140)
FTT-12	B	E11016	0 to +30.0	127,500	c	600,000
FTT-9	B	E12016	0 to +30.0	177,100	c	600,000
FTT-8	B	E11016	0 to +30.0	220,000	c	600,000

* Stress Relieved for 30 minutes at $1100^{\circ}F$.

** c: Failure initiated in weld metal due to lack of penetration.

TABLE 11

RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN THE Q-T STEEL IN THE AS-WELDED CONDITION
(Partial Tension-to-Tension)

Specimen No.	Welding Procedure See Fig. 4	Electrode	Stress Cycle, ksi	Stress Ratio*	Cycles to Failure	Location of Fracture**	Computed Fatigue Strength,*** ksi	
							$F_{100,000}$	$F_{2,000,000}$
FTT-39	B	E11016	0 to +50.0	0	54,400	a	0 to +45.9	0 to +30.2
FTT-38	B	E11016	12.5 to +50.0	0.25	122,000	a	+12.8 to +51.4	+8.4 to +33.8
FTT-37	B	E11016	25.0 to +50.0	0.50	488,800	a	+31.2 to +62.4	+20.5 to +41.0
FTT-40	B	E11016	35.0 to +50.0	0.70	2,407,500	a	+54.6 to +78	+35.8 to +51.2

* Stress Ratio = $\frac{\text{Minimum Stress}}{\text{Maximum Stress}}$

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

*** k = 0.14

TABLE 12

RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN ASTM A-242 STEEL IN THE AS-WELDED CONDITION (ZERO-TO-TENSION)

Specimen No.	Welding Procedure See Fig. 4	Electrode	Stress Cycle, ksi	Cycle to Failure	Location to Fracture*	Computed Fatigue Strengths,*** ksi	
						$F_{100,000}$	$F_{2,000,000}$
RF-5**	B	E7016	0 to +26.0	898,000	a	35.4	23.3
RF-4**	B	E7016	0 to +26.5	567,600	a	33.9	22.2
RF-1	B	E7016	0 to +30.0	186,900	b	--	--
RF-2	B	E7016	0 to +30.0	437,400	b	--	--
RF-3**	B	E7016	0 to +30.0	691,700	a	39.3	25.8
					Average:	36.2	23.8

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

** Parent metal heated to 1400°F and cooled slowly in furnace prior to preparation of welds.

*** k = 0.140

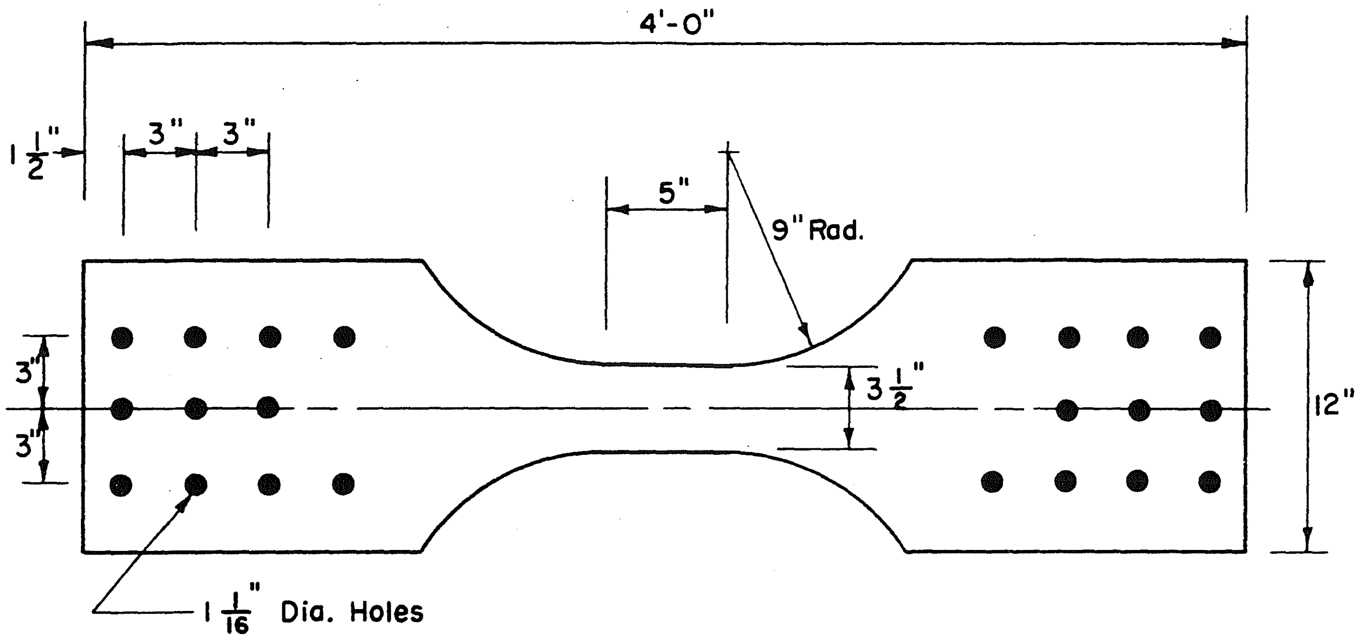
TABLE 13

SUMMARY OF RESULTS OF AXIAL FATIGUE TESTS
(ZERO-TO-TENSION)

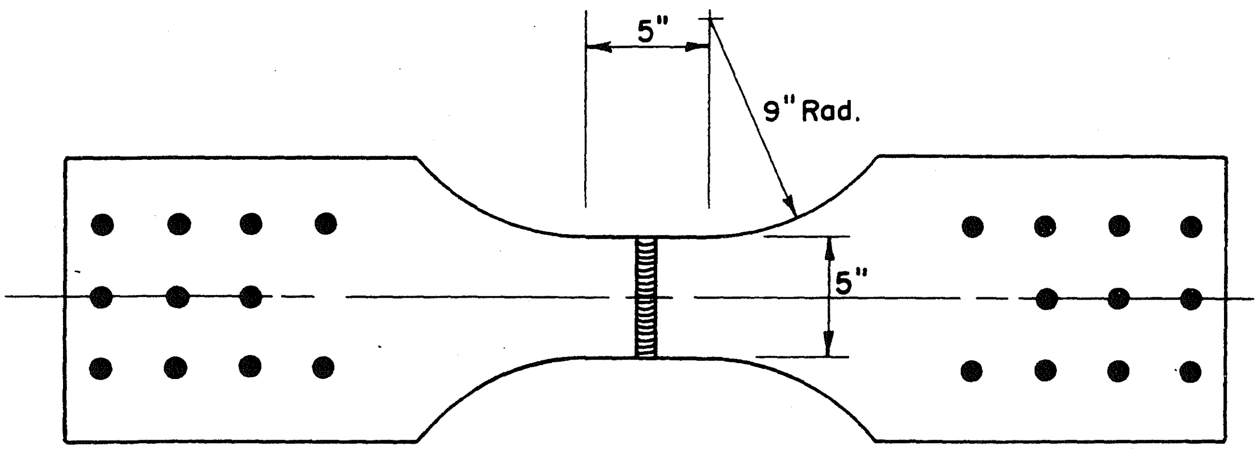
Steel	Type of Specimen	Condition	Average Fatigue Strengths, ksi		k
			$F_{100,000}$	$F_{2,000,000}$	
Q-T	Plain Plate	As-Rolled	63.2	42.8+	0.130
Q-T	Transverse Butt Weld	As-Welded	39.3	25.8	0.140
Q-T	Transverse Butt Weld	Reheat-treated*	44.9	29.6	0.140
Q-T	Transverse Butt Weld	Reinforcement Removed	43.7	28.7	0.140
A-242	Transverse Butt Weld	As-Welded Parent Metal Heated**	36.2	23.8	0.140

* After preparation of weld, heated to 1650°F, quenched cold in water, tempered at 1150°F for 30 minutes.

** Parent metal heated to 1400°F and cooled slowly in furnace prior to preparation of welds.



(a) Plain Plate



(b) Transverse Butt-Welded Joint

FIG. 1 DETAILS OF TEST SPECIMENS

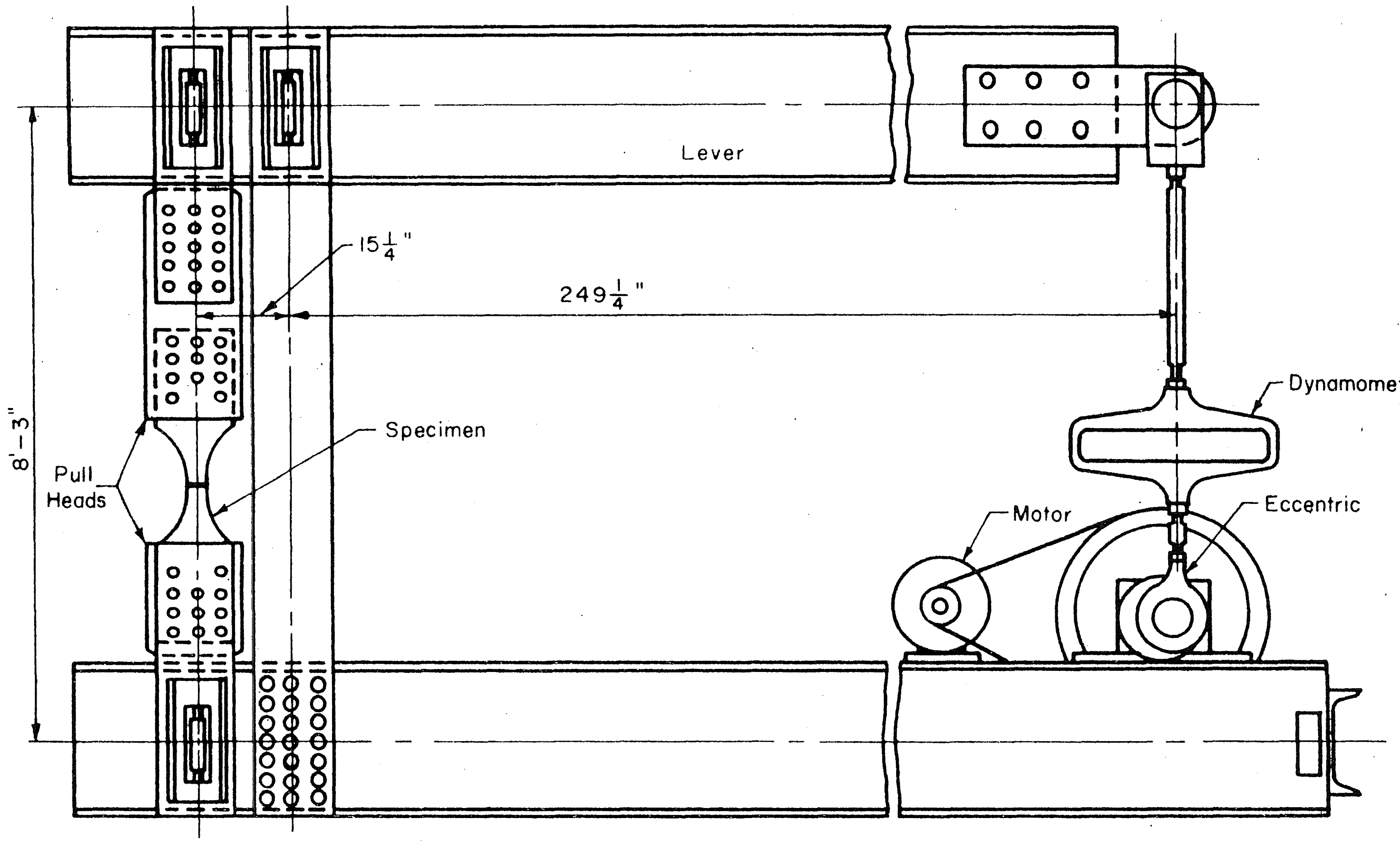
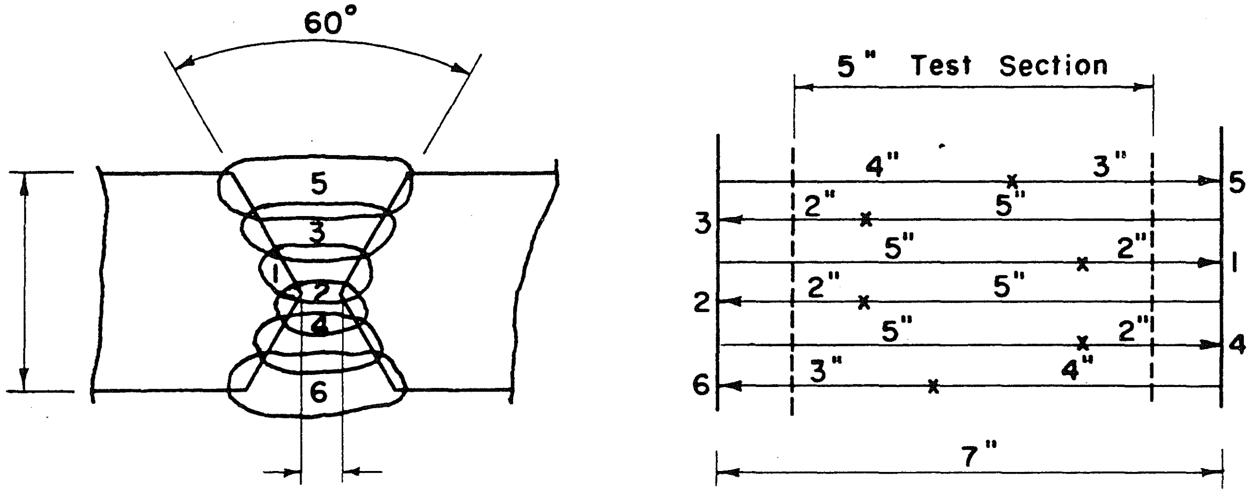


FIG. 2 ILLINOIS' FATIGUE TESTING MACHINE AS USED FOR AXIAL LOADING OF WELDED JOINTS



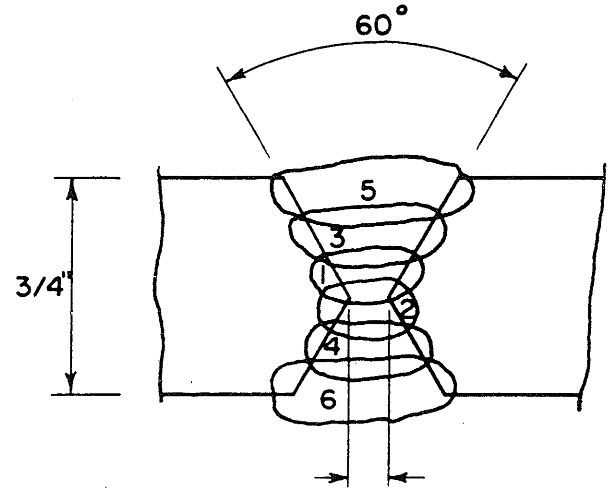
Root Opening — in.

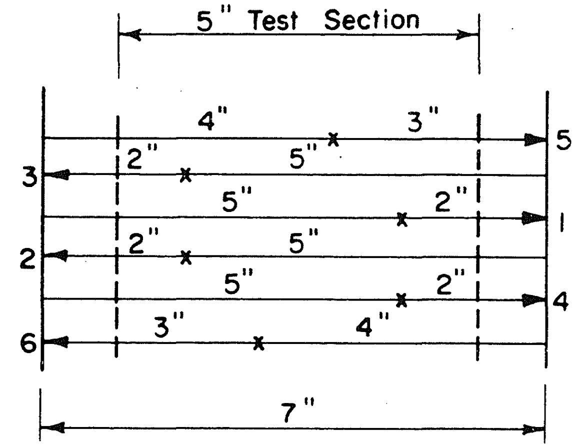
Arrows indicate direction of Welding
x indicates change of Electrode

Pass	Electrode Size, in.	Current, amps	Rate of Travel, in./min.
1	5/32	180	6.0
2	5/32	180	6.0
3-6	3/16	230	5.5

Voltage : 21 volts
Polarity : D.C. Reversed
Preheat : None
Interpass Temp. : 250° F (maximum)
Heat Input : 55,000 Joules/in. (maximum)
Electrode : As specified for individual specimens
Surface of plate adjacent to weld cleaned by grinding
All welding done in flat position
Backchip underside of pass 1 before depositing pass 2

FIG. 3 WELDING PROCEDURE A





Pass	Electrode Size, in.	Current, amps	Rate of Travel, in./min.
1	5/32	130	5.0
2	5/32	140	5.0
3	3/16	275	6.5
4	3/16	250	5.5
5, 6	3/16	225	5.5

Voltage : 21 volts

Polarity : D.C. Reversed

Preheat : None

Interpass Temp. : 250° F (maximum)

Heat Input : 57,000 Joules/in. (maximum)

Electrode : As specified for individual specimens

Surface of Plate adjacent to weld cleaned by grinding

All welding done in flat position

Backchip underside of pass 1 before depositing pass 2

FIG. 4 WELDING PROCEDURE B

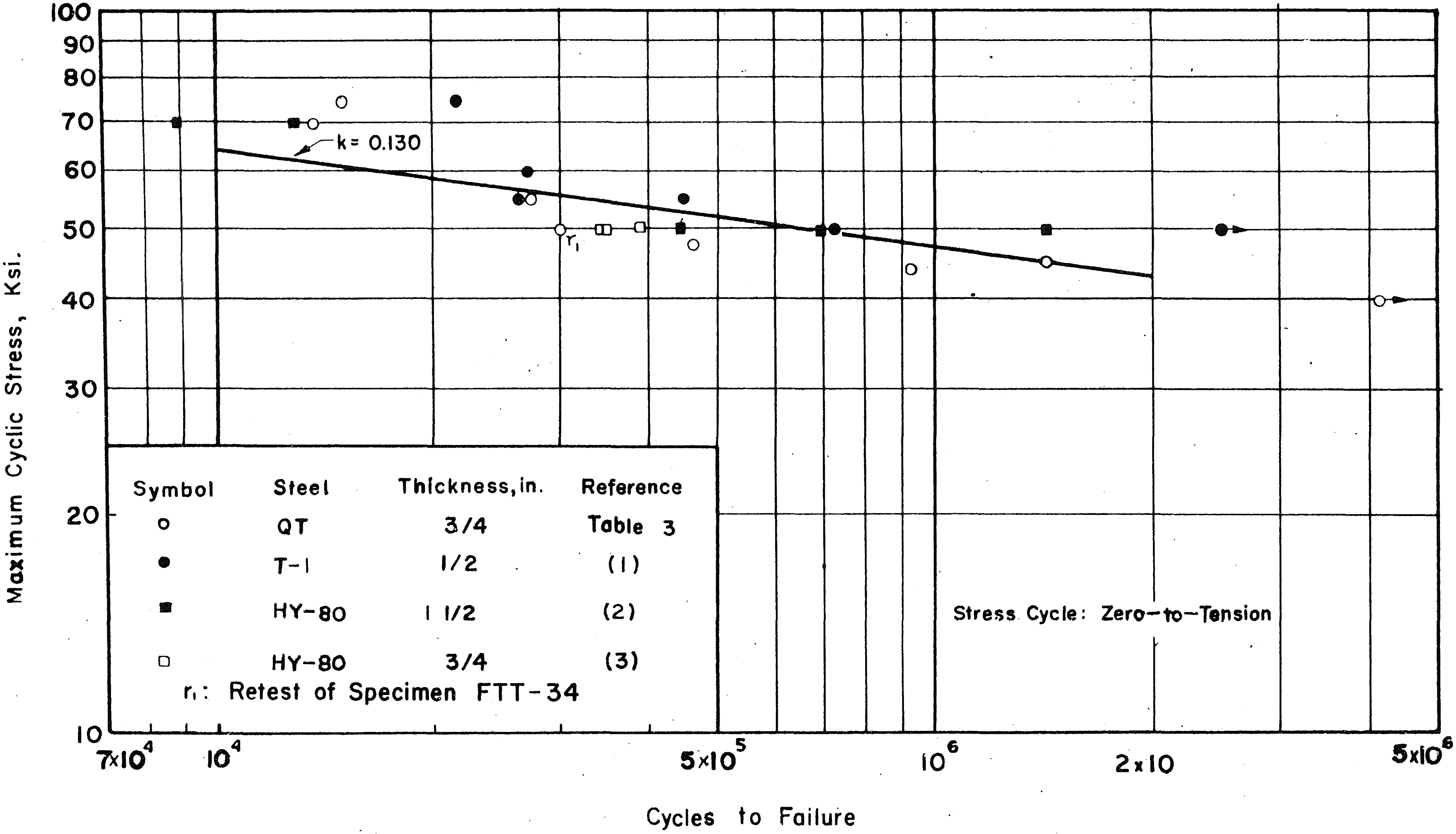
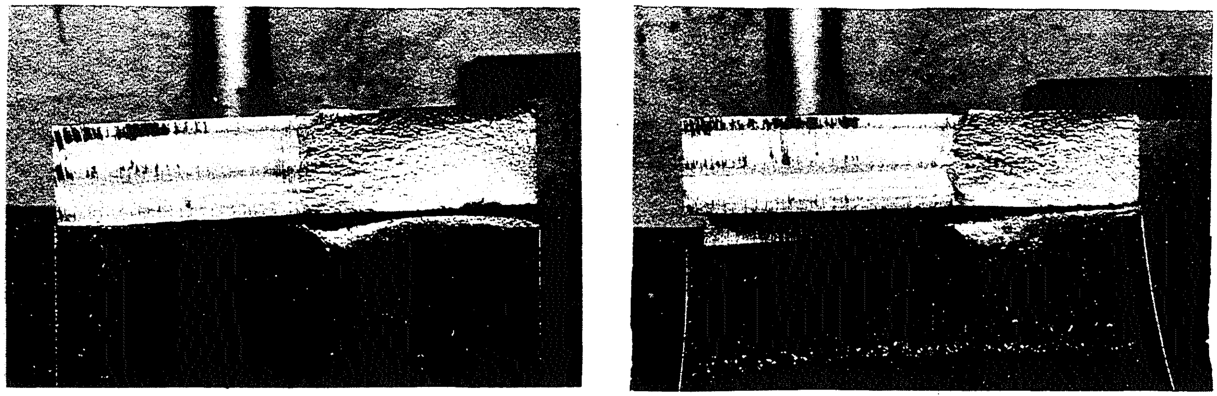
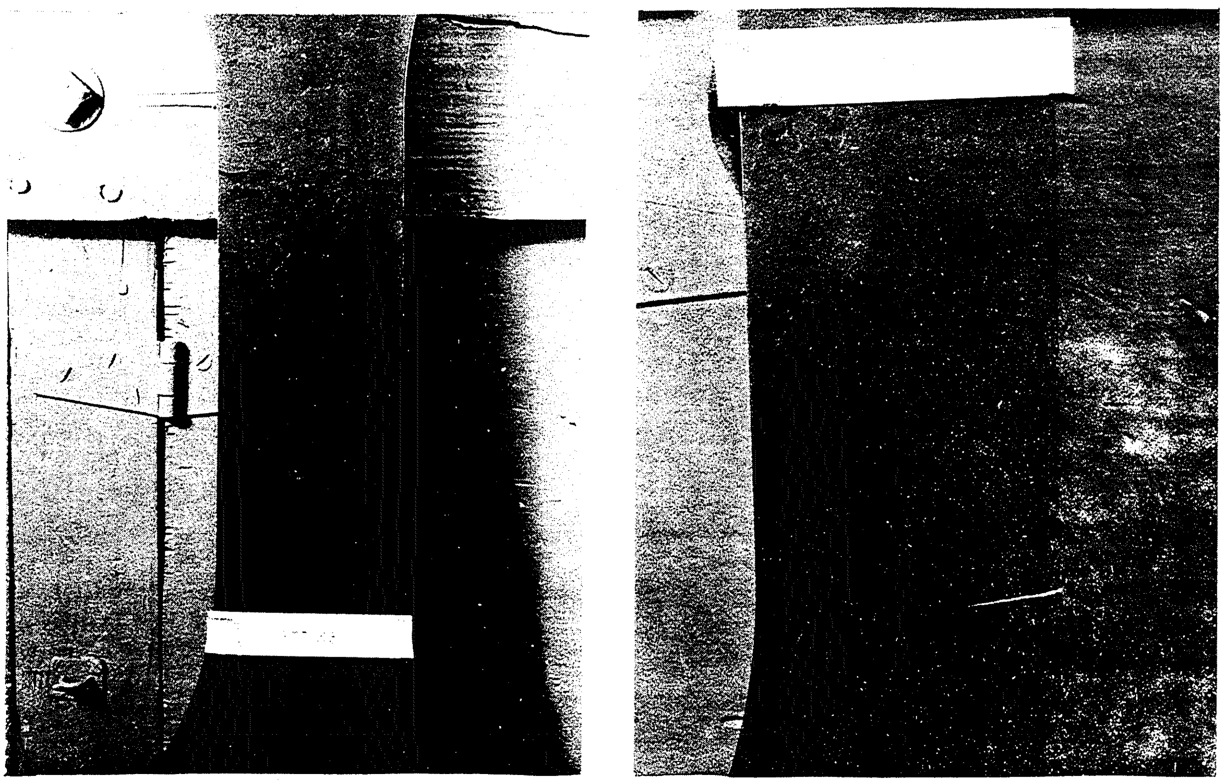


FIG. 5 RESULTS OF AXIAL FATIGUE TESTS OF AS-ROLLED PLATE SPECIMENS OF QUENCHED AND TEMPERED STEEL



FTT-33 FTT-36

a. FRACTURE SURFACES



FTT-33 FTT-36

b. LOCATION OF FRACTURES

FIG. 6 TYPICAL FRACTURE SURFACES OF AS-ROLLED PLATE SPECIMENS OF QUENCHED AND TEMPERED STEEL

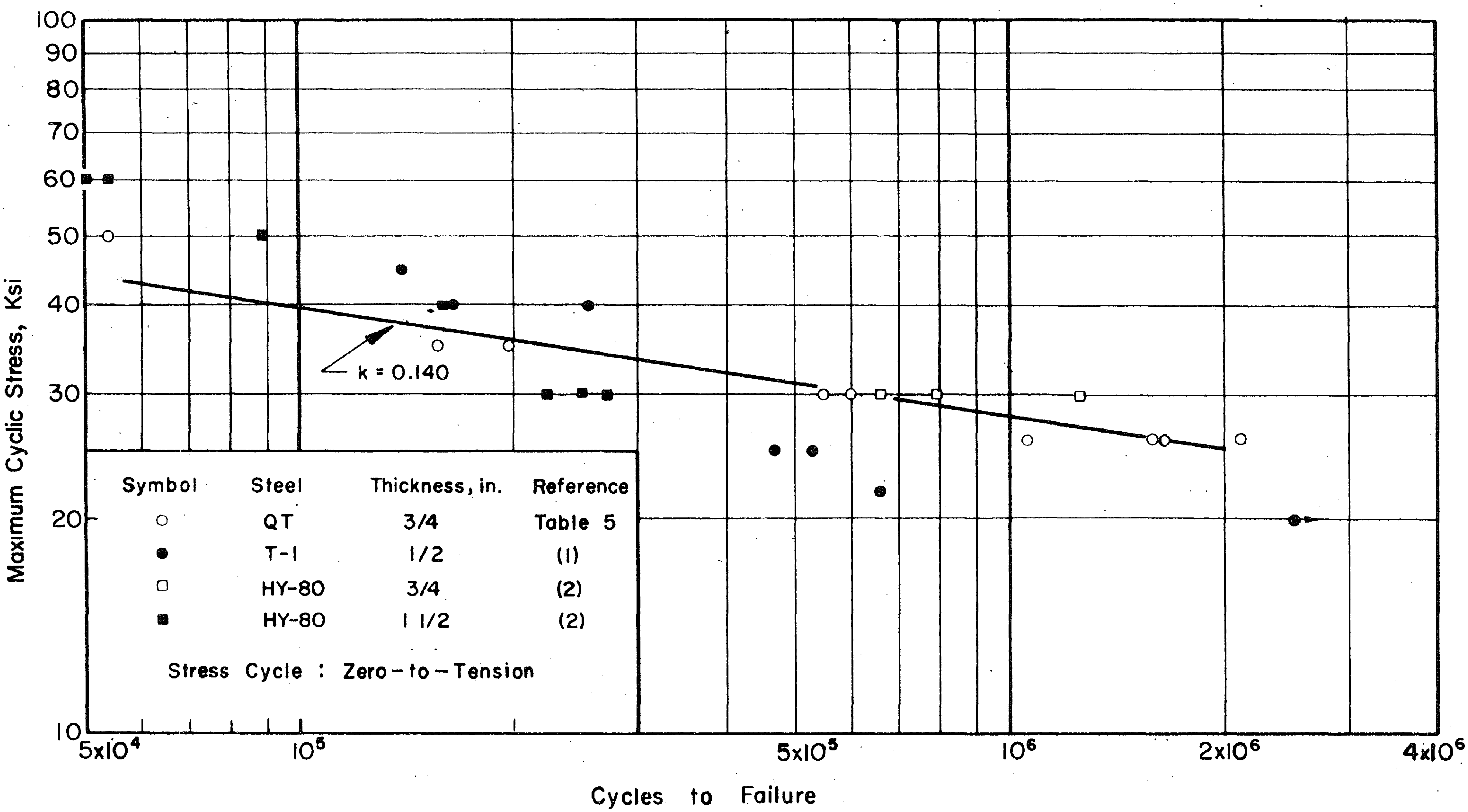
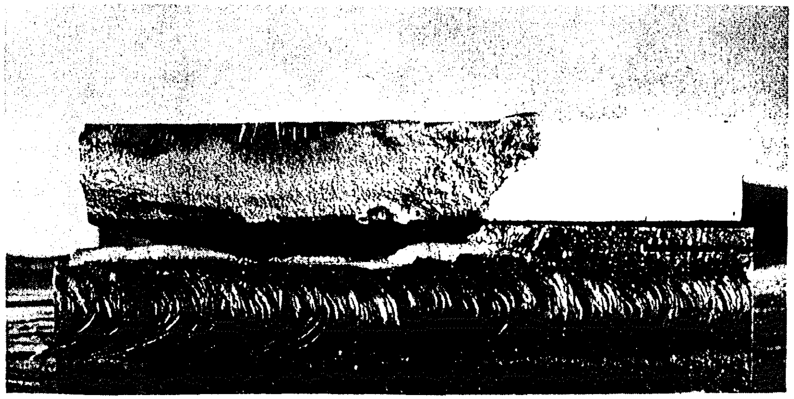
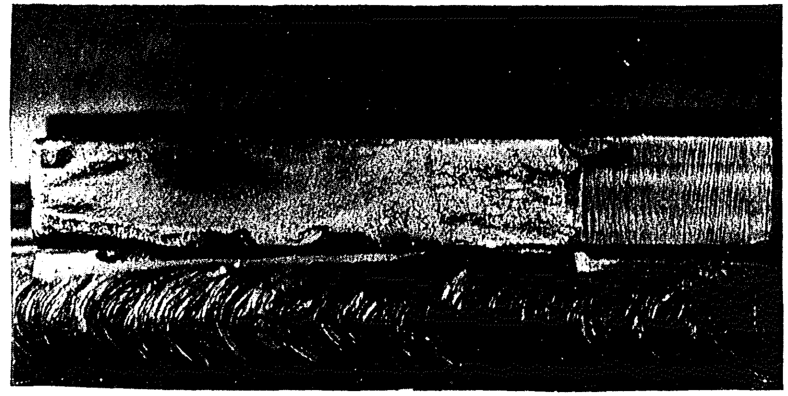


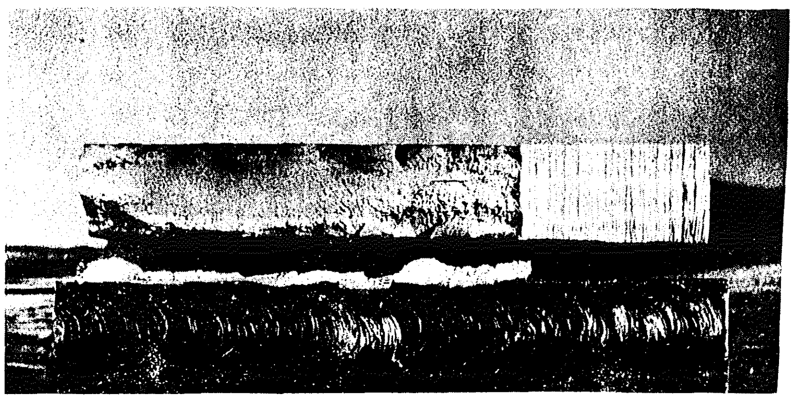
FIG. 7 RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN QUENCHED AND TEMPERED STEEL IN THE AS-WELDED CONDITION



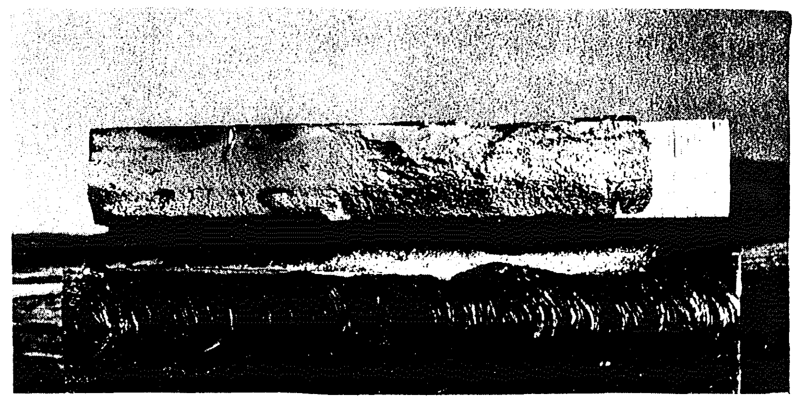
FTT-1



FTT-3



FTT-2



FTT-6

FIG. 8 TYPICAL FRACTURE SURFACES OF AS-WELDED TRANSVERSE BUTT WELDS IN QUENCHED AND TEMPERED STEEL

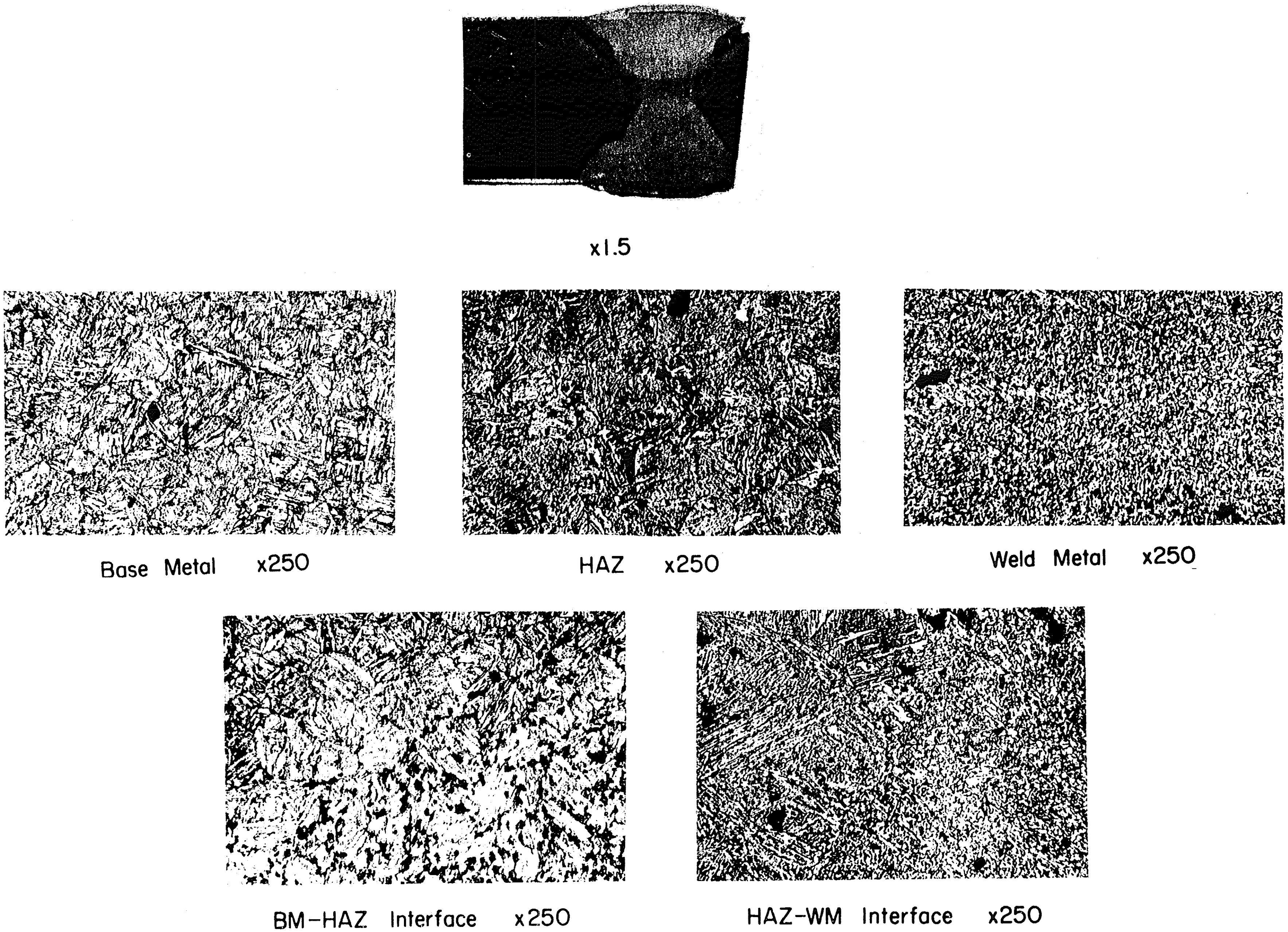


FIG. 9 PHOTOMICROGRAPHS OF SPECIMEN FTT-3 IN QUENCHED AND TEMPERED STEEL (AS-WELDED TRANSVERSE BUTT WELD)

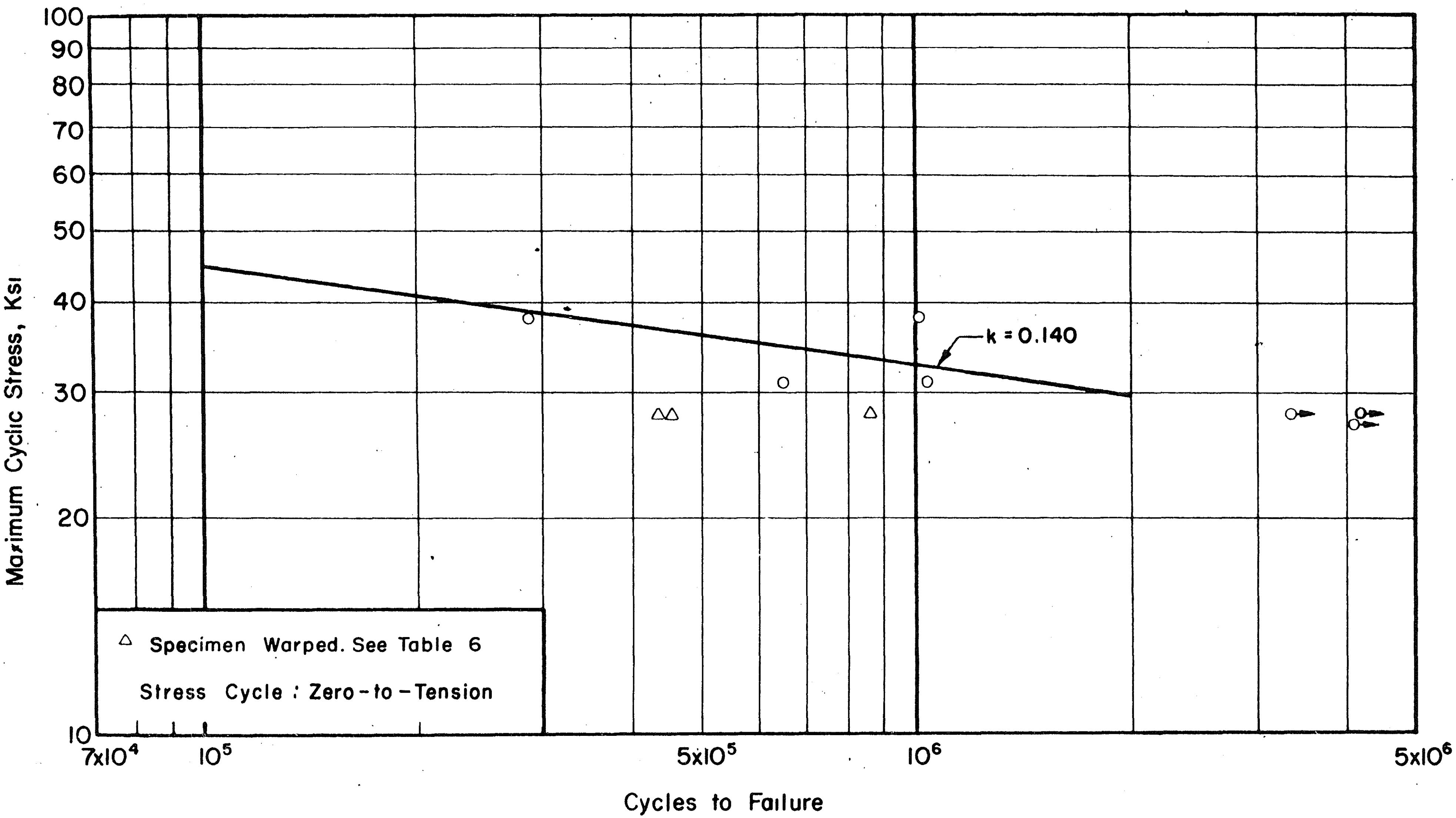
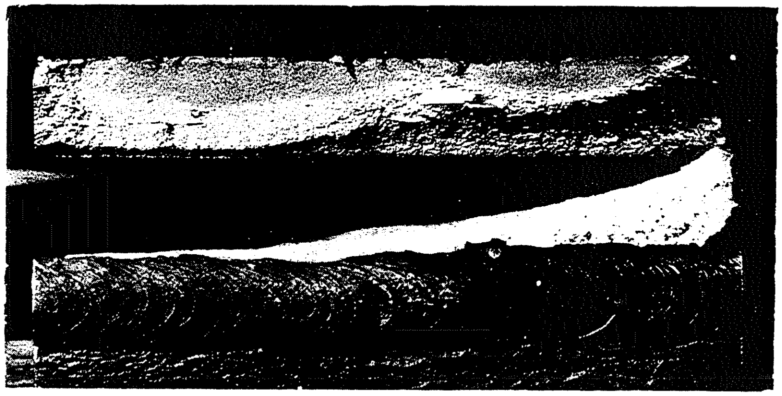
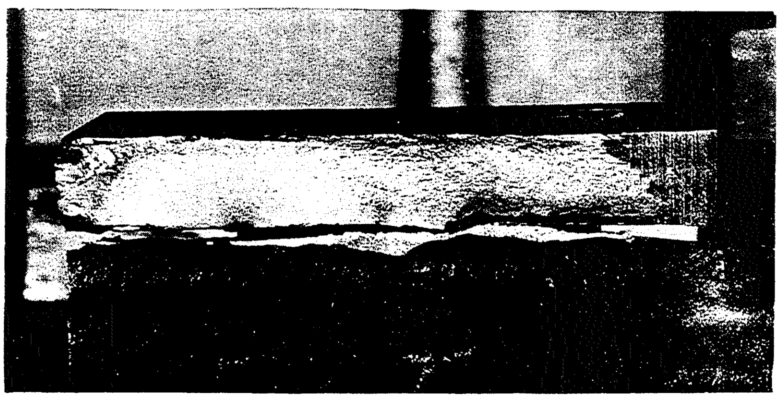


FIG. 10 RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN QUENCHED AND TEMPERED STEEL IN THE HEAT TREATED CONDITION

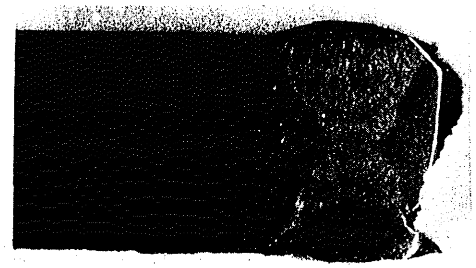


FTT-13

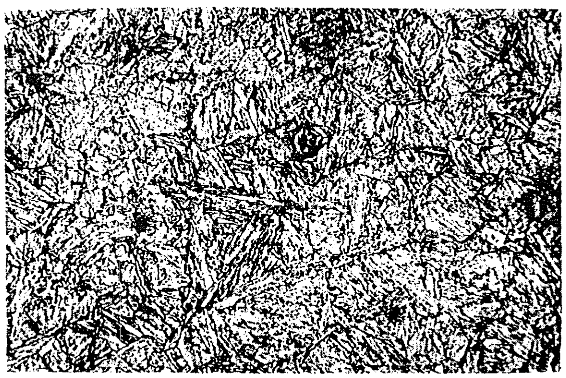


FTT-31

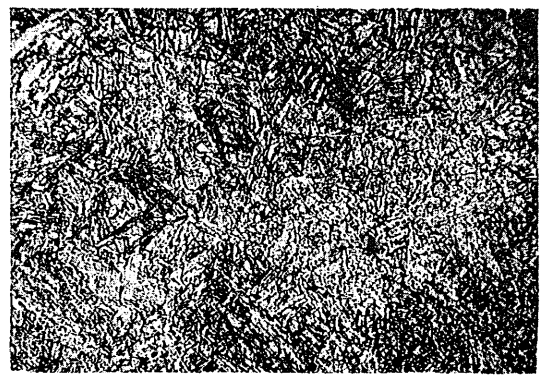
FIG. 11 TYPICAL FRACTURE SURFACES OF HEAT-TREATED TRANSVERSE BUTT WELDS IN QUENCHED AND TEMPERED STEEL



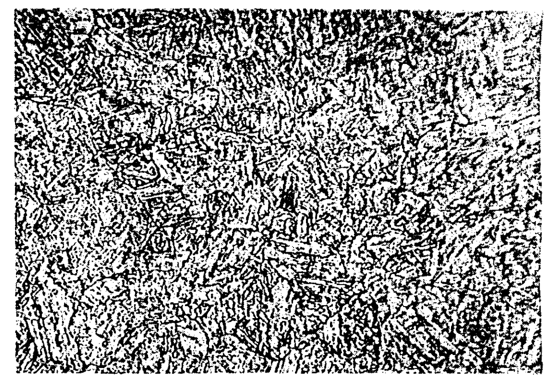
x1.5



Base Metal x250



BM-WM Interface x250



Weld Metal x250

FIG. 12 PHOTOMICROGRAPHS OF SPECIMEN FTT-31 IN QUENCHED AND TEMPERED STEEL (HEAT-TREATED TRANSVERSE BUTT WELD)

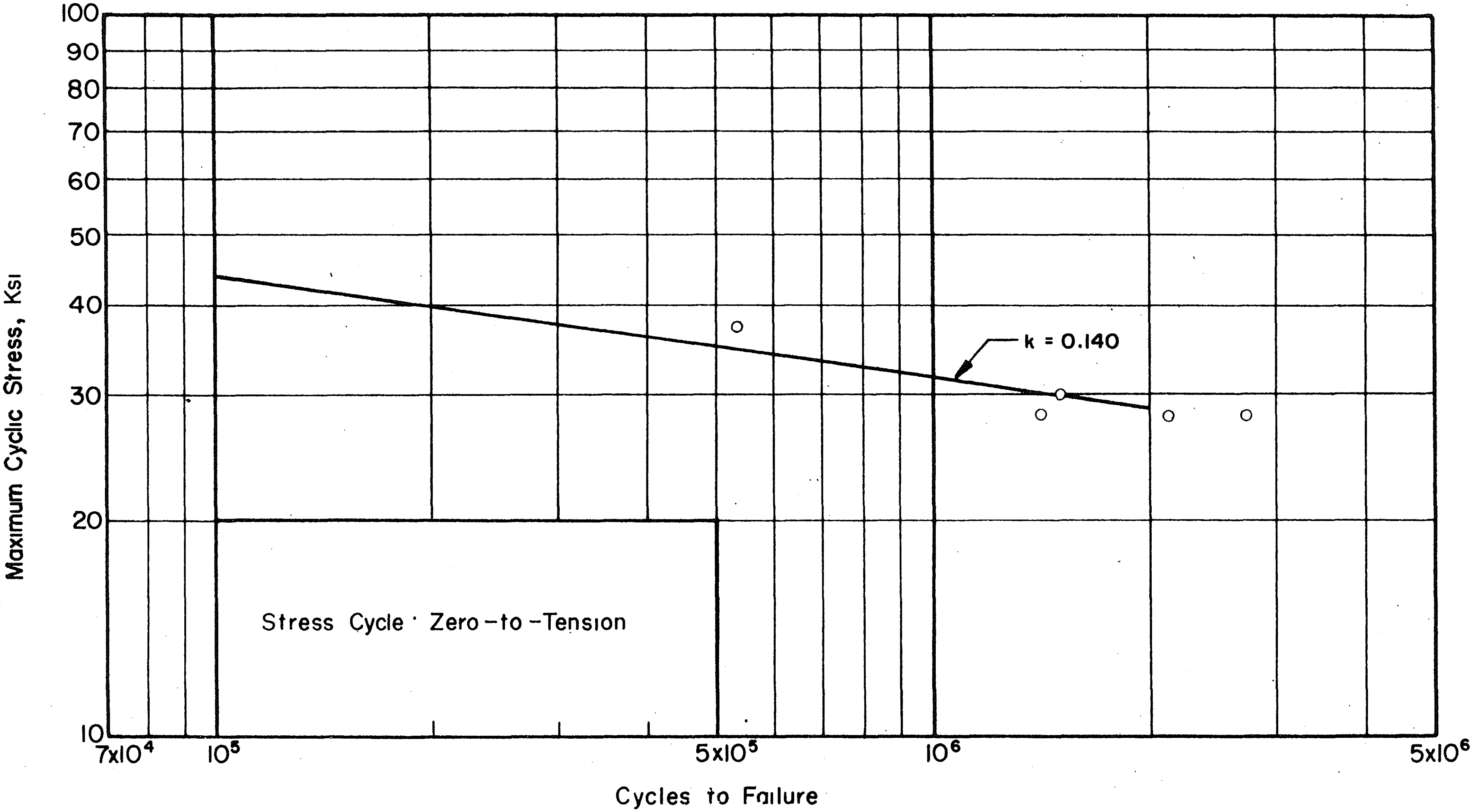
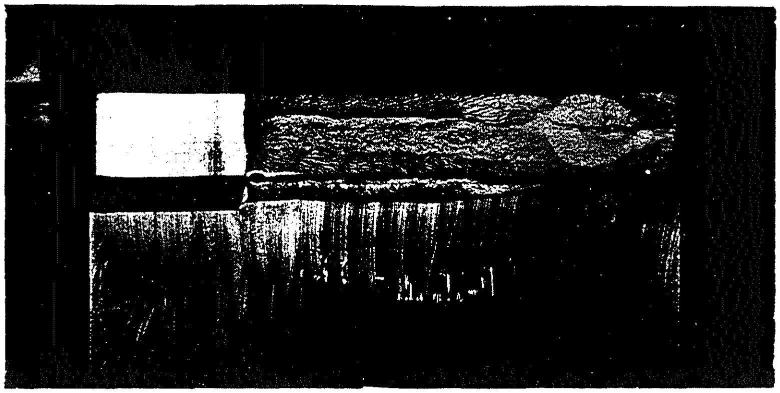
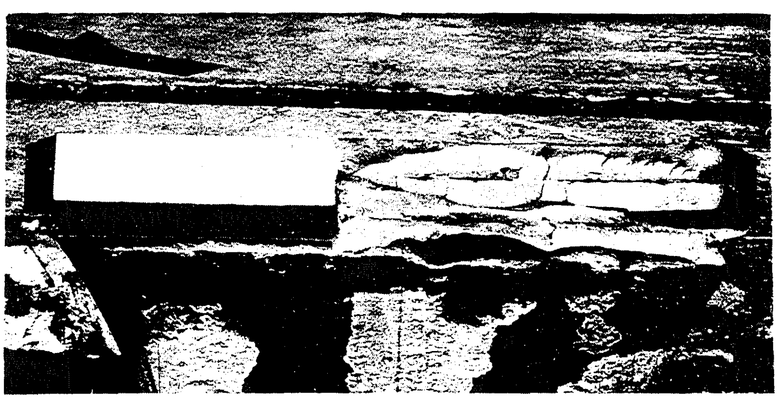


FIG. 13 RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN QUENCHED AND TEMPERED STEEL WITH THE WELD REINFORCEMENT REMOVED



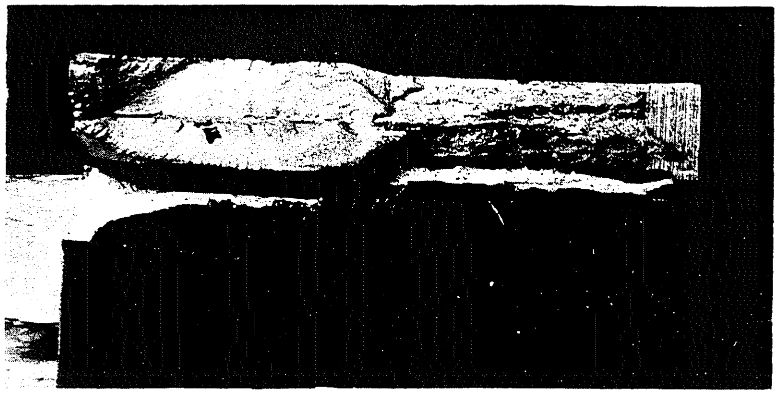
FTT-23

FTT-7

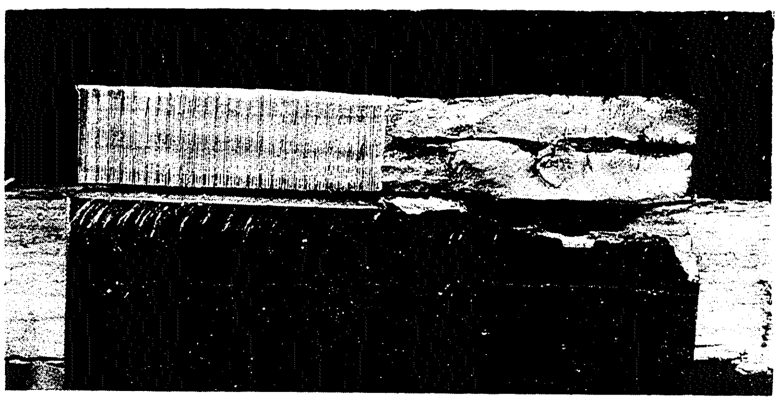


FTT-10

FIG. 14 TYPICAL FRACTURE SURFACES OF DEFECTIVE TRANSVERSE BUTT WELDS IN QUENCHED AND TEMPERED STEEL TESTED WITH THE REINFORCEMENT REMOVED



FTT-8



FTT-9

FIG. 15 TYPICAL FRACTURE SURFACES OF STRESS RELIEVED DEFECTIVE TRANSVERSE BUTT WELDS IN QUENCHED AND TEMPERED STEEL

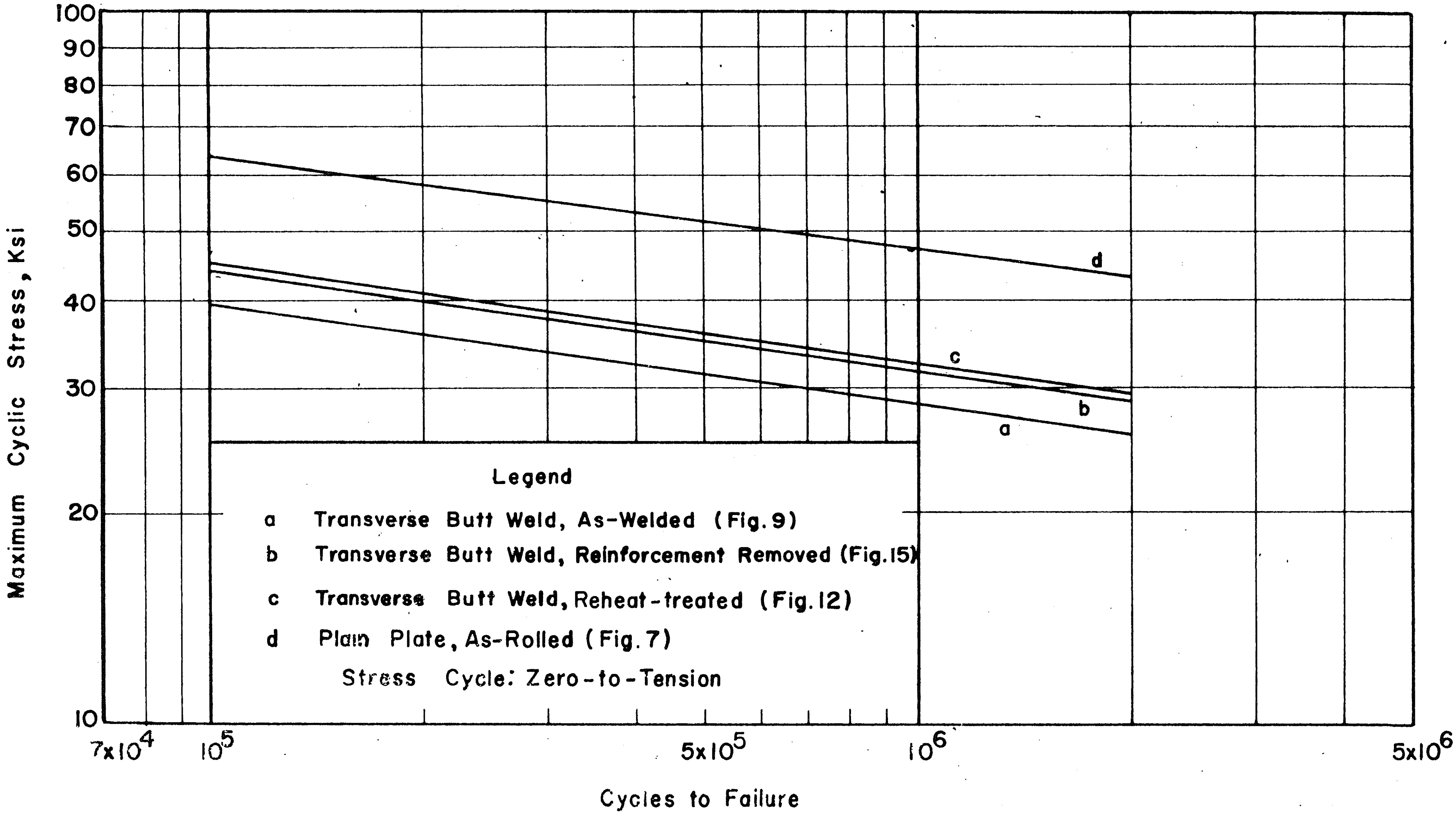


FIG. 16 SUMMARY DIAGRAM SHOWING THE EFFECT OF GEOMETRICAL AND METALLURGICAL FACTORS INTRODUCED BY WELDING ON FATIGUE LIFE OF QUENCHED AND TEMPERED STEEL

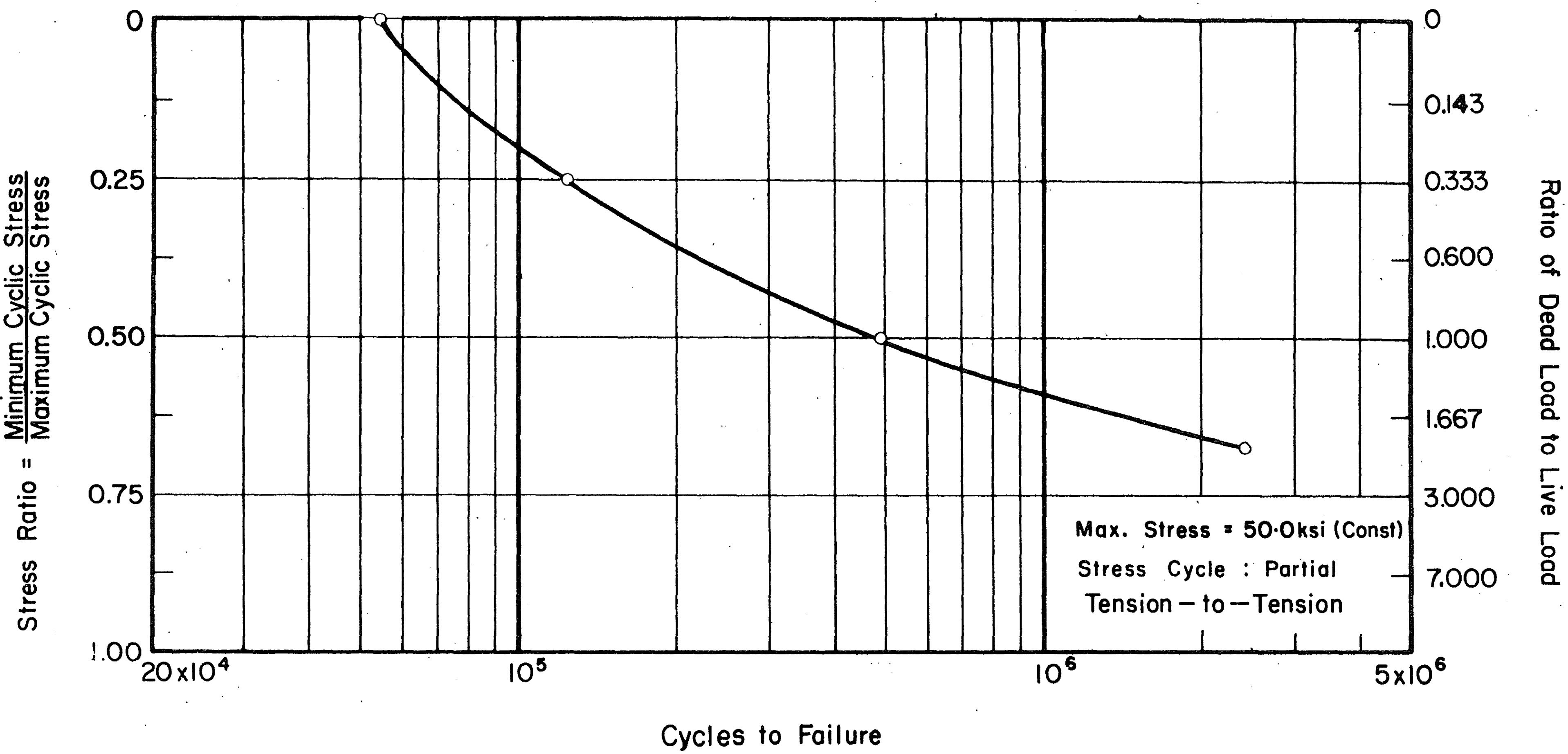


FIG. 17 EFFECT OF STRESS RATIO ON THE FATIGUE LIFE OF A TRANSVERSE BUTT-WELDED JOINT IN THE AS-WELDED CONDITION (QUENCHED AND TEMPERED STEEL)

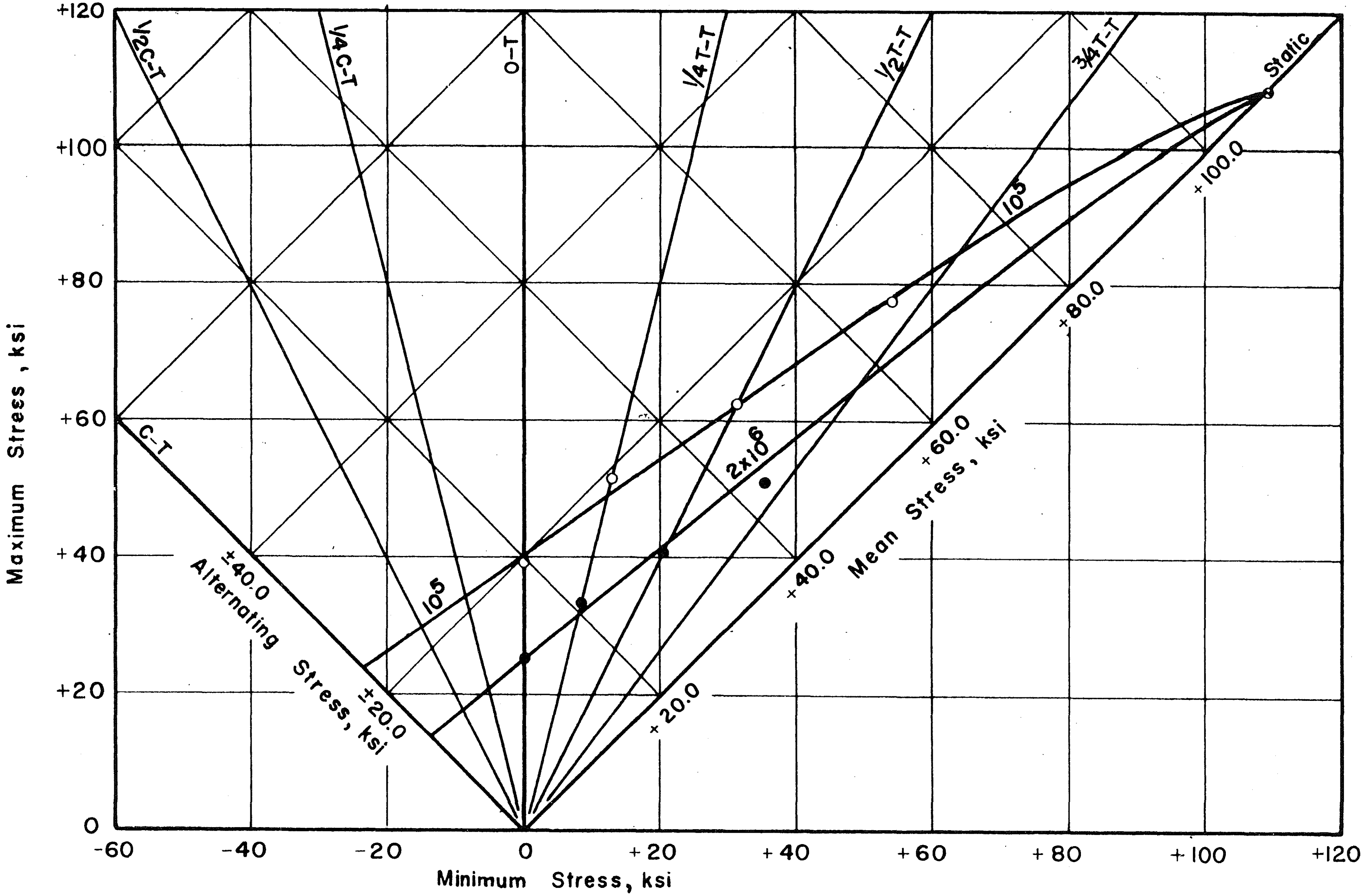


FIG. 18 MODIFIED GOODMAN DIAGRAM FOR AS-WELDED TRANSVERSE BUTT-WELDED JOINTS IN QUENCHED AND TEMPERED STEEL

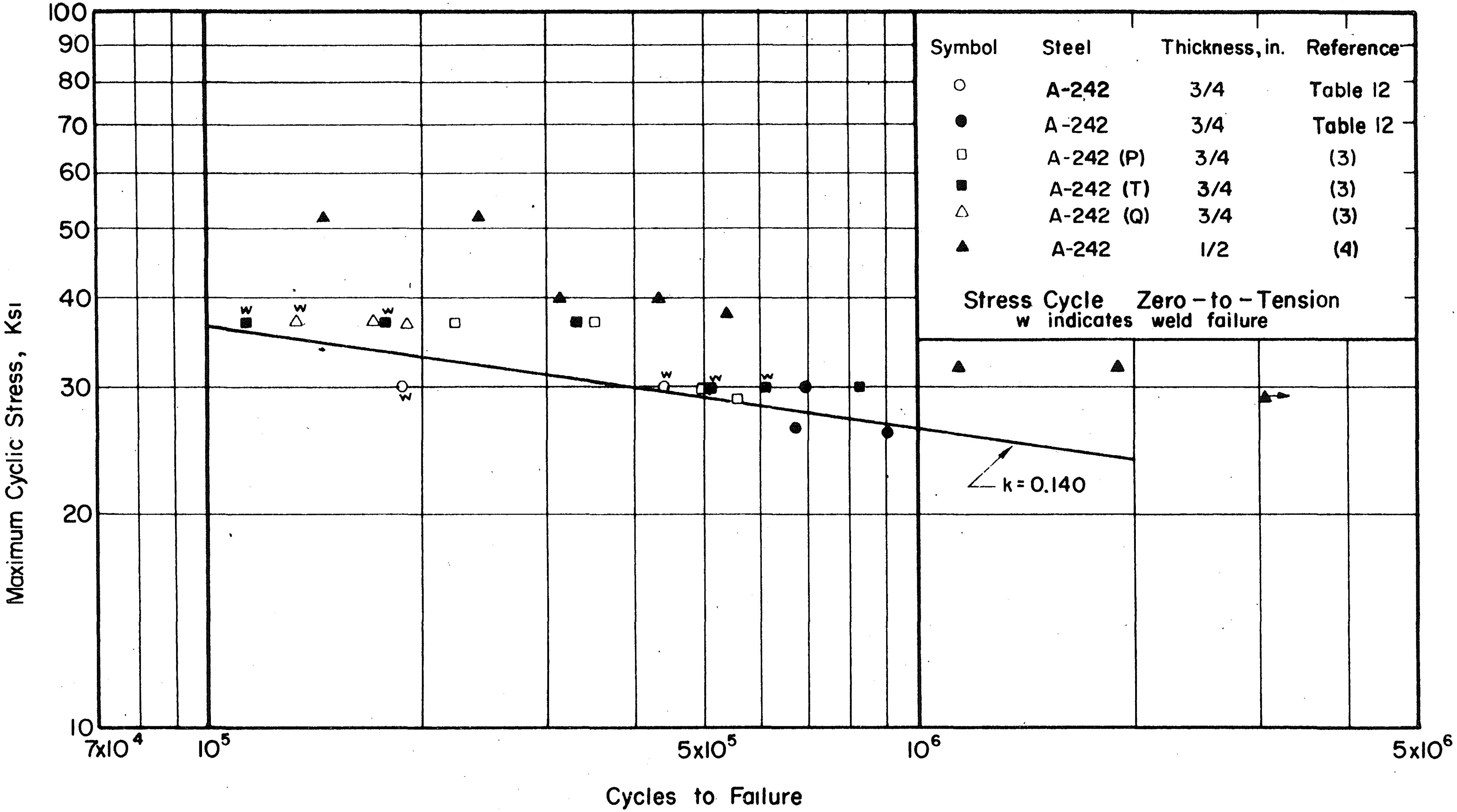
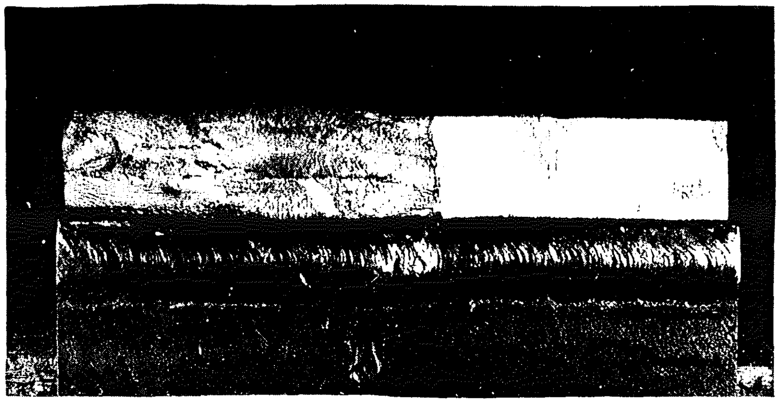
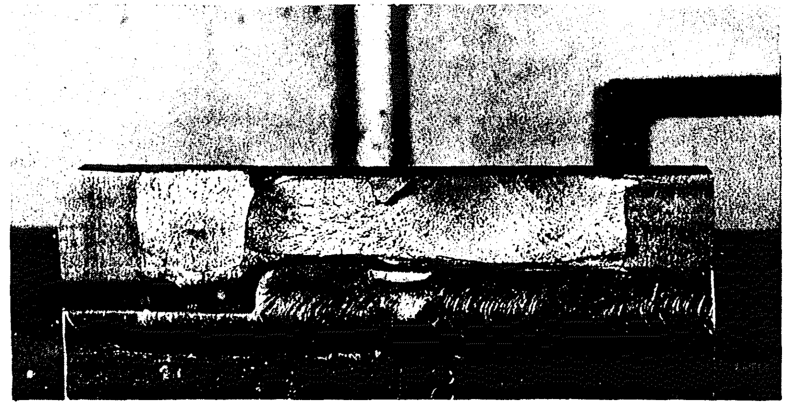


FIG. 19 RESULTS OF AXIAL FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS IN ASTM A-242 STEEL IN THE AS-WELDED CONDITION

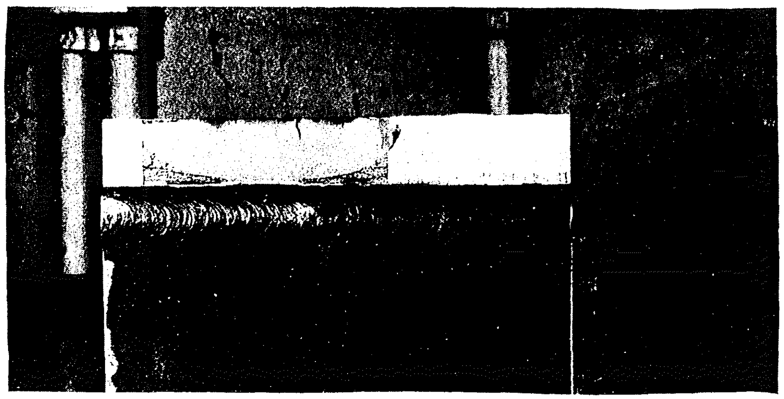


RF-1

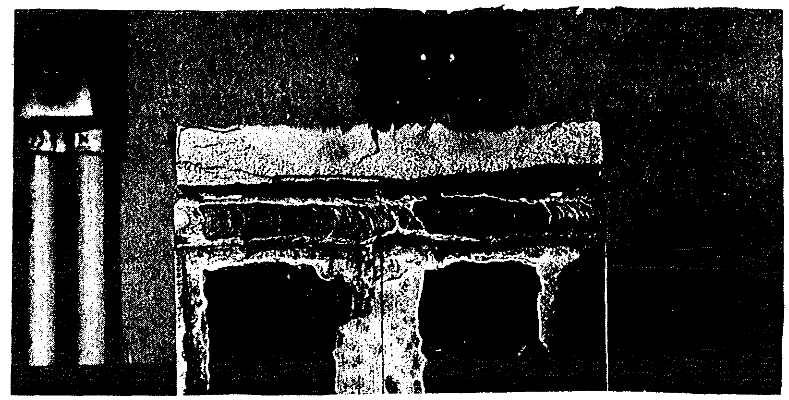


RF-2

a. PARENT METAL IN THE AS RECEIVED CONDITION



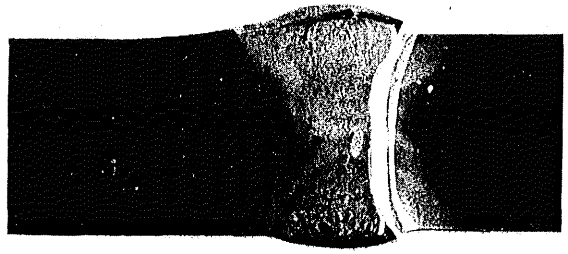
RF-3



RF-4

b. PARENT METAL HEATED TO 1400° F.

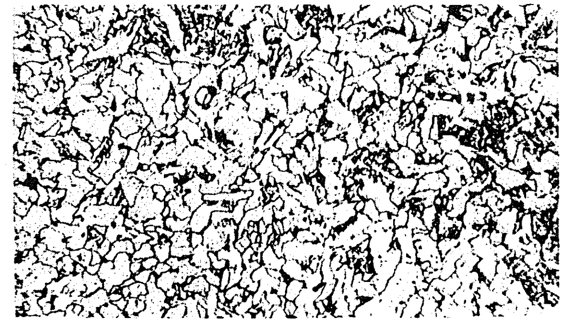
FIG. 20 TYPICAL FRACTURE SURFACES OF AS-WELDED TRANSVERSE BUTT WELDS IN A-242 STEEL



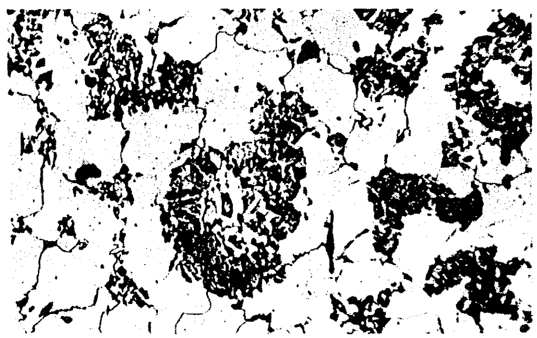
x1.5

Base Metal x250

HAZ x250



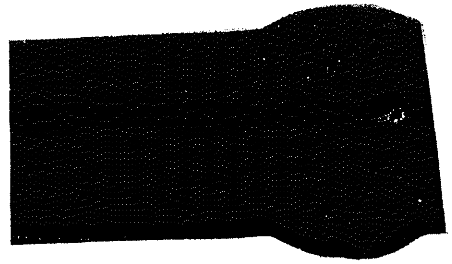
Weld Metal x250



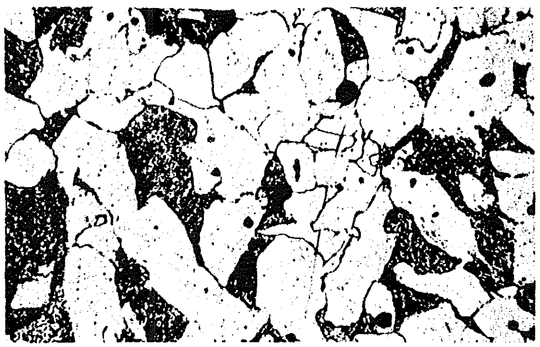
BM-HAZ Interface x250

HAZ-WM Interface x250

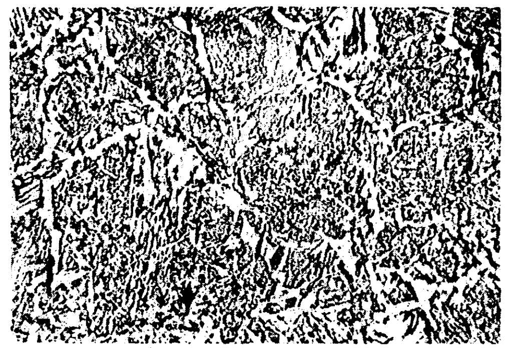
FIG. 21 PHOTOMICROGRAPHS OF SPECIMEN RF-1 IN A-242 STEEL (AS-WELDED TRANSVERSE WELD IN AS RECEIVED MATERIAL)



x1.5

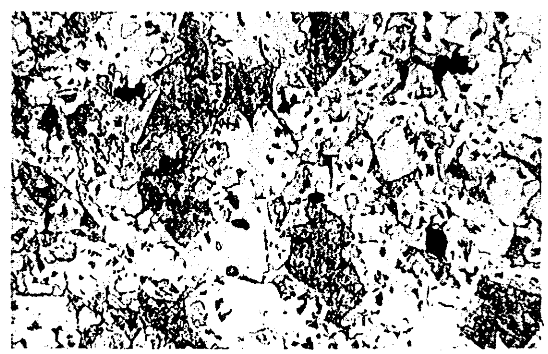


Base Metal x250

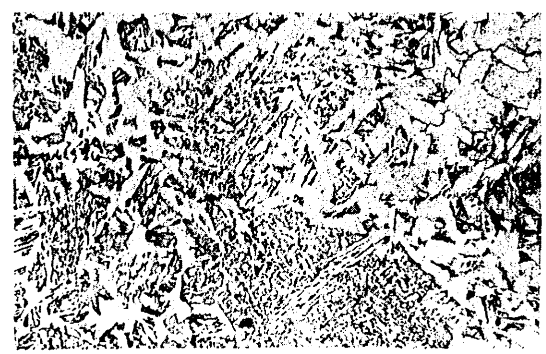


HAZ x250

Weld Metal x250



BM-HAZ Interface x250



HAZ-WM Interface x250

FIG. 22 PHOTOMICROGRAPHS OF SPECIMEN RF-5 IN A-242 STEEL (AS-WELDED TRANSVERSE BUTT WELD IN REHEATED MATERIAL)

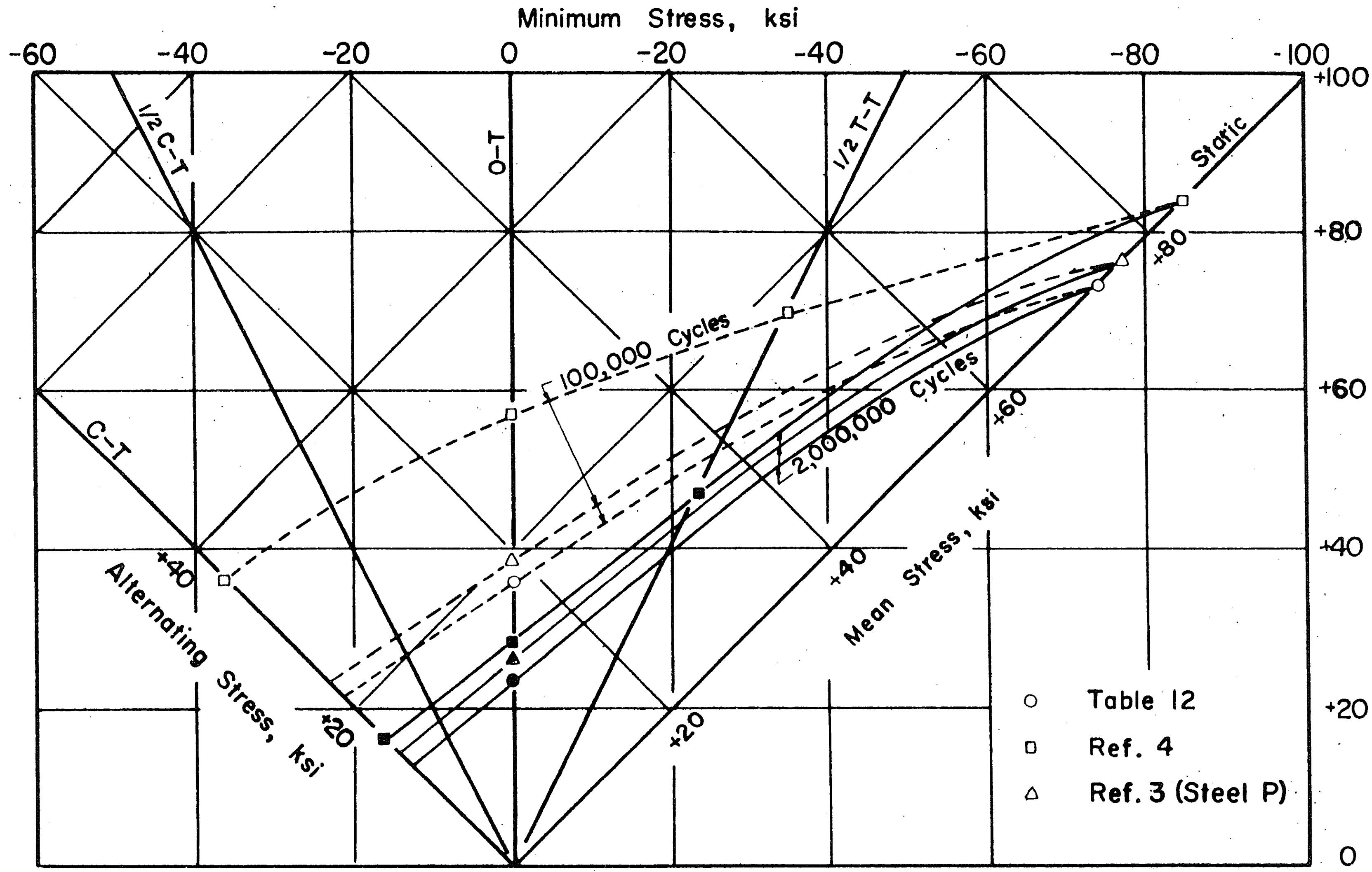


FIG. 23 MODIFIED GOODMAN DIAGRAM FOR AS-WELDED TRANSVERSE BUTT-WELDED JOINTS IN DIFFERENT ASTM A-242 STEELS