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# EFFECT OF NOTCHES ON THE AXIAL FATIGUE PROPERTIES OF STRUCTURAL STEELS



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## SYNOPSIS

The effect of the stress concentration on the zero-to-tension axial fatigue strength of notched members of four structural steels has been studied. For each of the four steels a critical notch severity was found at which a transition in behavior takes place. When the theoretical stress concentration exceeds this critical value the fatigue strength increases instead of continuing to decrease as would normally be expected. The maximum effective stress concentration determined from these tests corresponds to a critical notch severity which is dependent on the material, the geometry of the specimen, and the cyclic conditions of stress.

Microscopic examinations of the roots of the notched specimens which did not fail revealed cracking in most cases. Some of the cracks apparently were non-propagating cracks but the test lives in most cases were insufficient to isolate such cracks positively as non-propagating. A study of other data on non-propagating cracks revealed that the laws governing their formation are not yet fully understood. However, there are indications that the increase in fatigue strength obtained above the critical notch severity is coincident with the formation of non-propagating cracks.

## TABLE OF CONTENTS

# LIST OF TABLES

# APPENDIX

## LIST OF TABLES

Number

## APPENDIX

## LIST OF TABLES (Cont'd.)

Number

# LIST OF FIGURES

LIST OF FIGURES (Cont'd.)

Figure No.

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

# EFFECT OF NOTCHES ON THE AXIAL FATIGUE PROPERTIES OF STRUCTURAL STEELS

## I. INTRODUCTION

### 1.1 General Aspects of the Problem

During the past decade, a number of investigations have been conducted to determine the fatigue properties of high strength structural steels. However, the authors know of no published results where a high strength steel has exhibited an increase in fatigue resistance over ordinary structural steel proportional to the increase in static strength when such steels are tested under conditions approaching those which exist in fabricated structures. The fabrication procedures used always produce stress concentrations, the effect of which is to lower the fatigue resistance of structural steels. For example, an examination of the results of fatigue tests of various structural steels (Sec. 3.6) has shown that in fatigue tests of butt welded joints in ASTM A7 and A242 steels, an increase of approximately 10 per cent in the fatigue strength is obtained for the alloy steel. The yield point of the alloy steel is, however, approximately 50 percent higher than that of the ASTM A7 steel.*

On the basis of data currently available, it appears that for many structures subjected to repetitions of large amplitude and of high mean stress, the use of high strength steels may have little advantage over the use of ordinary low carbon (ASTM A7) structural steel. As a direct consequence of this, bridge specifications in this country and abroad do not permit engineers to take advantage of the superior static strength of members fabricated of high strength steels

* A comparison based on the yield point has been presented because allowable stresses are usually a percentage of the yield. However a comparison based on UTS is probably more rational (Fig. 1).

if those members are required to withstand a large number of repetitions of loading involving large amplitudes and high mean stresses.

A large number of high strength steels have been developed and are being used in structural work. Of these steels, relatively few have been tested to investigate their fatigue properties under the range of conditions which might be encountered in service. To evaluate the fatigue properties of a number of steels through tests of large members and connections would be extremely costly and would require a prohibitive amount of time. The present investigation was initiated to investigate the possibility of developing a method to simulate in a small member the behavior of various types of large joints in structural members fabricated primarily by welding.

Obtaining small, carefully machined laboratory members to simulate the behavior of large welded structural joints presented a number of problems. The fatigue strengths obtained from large members are usually considerably lower than those obtained from small, carefully machined specimens tested in the laboratory. These reductions are primarily caused by stress concentration arising from surface conditions, changes in section, and fabrication processes.

The problem of simulating a welded joint was especially difficult. The presence of a weld, in addition to introducing a geometrical stress raiser by virtue of the discontinuity in the parent metal, introduces several other factors. The more important of these other factors are the metallurgical changes introduced during the process of welding, possible micro and macro cracks, residual stresses, and welding defects.

The metallurgical changes introduced in the process of welding may manifest themselves in a number of different ways. Homogeneous welded joints are not obtained by any of the commonly used methods of welding and there is a gradation in metallurgical conditions in the transition from the parent metal to the weld through the heat-affected zone. This gradation may differ considerably in hardness levels and extent of decarburization. These factors are known to have an adverse effect on the fatigue resistance of metals.

Micro cracking of welds is partly a consequence of the thermal cycle involved in the welding process. It is more likely to occur if the heating and subsequent cooling is non-uniform. In addition, any hydrogen (inherent or introduced) can cause micro cracking. It is well known that cracks can act as points of initiation for fatigue failures.

The influence of residual stresses on the fatigue properties depends on several factors. These factors are geometrical configuration of the joint, cyclic conditions of loading, and the distribution and magnitude of the residual stresses in the critical zone. It is difficult to separate the effects of residual stresses from other factors, both structural as well as physio-chemical, which are usually introduced during the process of introduction of the residual stresses. However, a reasonably good quantitative prediction can be made regarding these effects if experimental conditions are well defined and the influence of these other factors are minimized (14)*.

In addition to the intrinsic change in homogeneity of material due to welding, other factors may provide metallurgical or geometrical stress raisers. Defects may include porosity, inclusions (gas pockets or slag), poor penetration, and shrinkage cracks. Many types of welds have rough surfaces and join the parent metal with some change of section.

The fatigue strength of a welded joint may be expected to approach that of the parent metal only if geometrical and metallurgical effects are completely eliminated. However, this is almost impossible and even by very careful treatment

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* Numbers in parentheses refer to corresponding items in the bibliography.

the fatigue strength of a welded joint could at best be brought up to only 85 or 90 percent of that of the parent metal (14).

To simulate the geometrical and metallurgical stress concentrating effect of a welded member, it was decided to use a small specimen with a circumferential geometrical notch. The choice of the specimens and of the geometrical notches was dictated by the rapid and easy reproduction of specimens as well as the magnitude of stress concentration required. It has been observed experimentally that the reduction in fatigue strength caused by a notch with a theoretical stress concentration factor $K_t$ is not always proportional to a change in $K_t$. The actual reduction in fatigue strength is measured by $K_e$, the effective stress concentration factor.

The difference between $K_t$ and $K_e$ has been found to be dependent on several factors. It varies not only for different materials and types of stress concentrations but also for different sizes of specimens. In addition, the metallurgical structure and the cyclic conditions of loading have been observed to affect these parameters (17). The fundamental cause of this difference between $K_t$ and $K_e$ has been attributed by several investigators to the difference in response of materials subjected to repeated loading from the response observed in static, elastic loading. Also, the analysis on which the theoretical factors are based depends on the assumptions of an isotropic, perfectly elastic, and homogeneous material whose strength properties are influenced by neither time nor temperature. However, actual materials do not lend themselves to such a description. Moreover, the small localized spots (crystals and grain boundaries) in which fatigue cracks are thought to initiate are anisotropic. Localized plastic readjustments may occur in materials at stresses even below the endurance limit which could alter the strength as well as the stress in the material (22).

The extent of theoretical stress concentration introduced by the notch in these small specimens was intended to produce an effective stress concentration equivalent to that which occurs in an actual joint. In other words, the fatigue strength of the two specimens was intended to be equal. Preliminary work on a specimen of ASTM A7 steel was conducted to determine a notch configuration to simulate a particular type of joint. ASTM A7 steel was chosen since a considerable number of test results on large welded and unwelded joints in this material was available (Tables 10-13). After a notch had been selected to simulate the effect of a particular type of joint, tests were conducted on other steels for which data on similar large welded joints were available.

As the tests progressed, it became apparent that our knowledge of the behavior of both welded joints and notched specimens was not sufficient to achieve the original objective. For welded joints, variations in weld geometry, stress conditions in the surface layers, patterns of residual stresses, and UTS of the parent metal gave a considerable range of fatigue strengths and made it difficult to pick out representative values of fatigue strengths of welded joints for purposes of simulation. On the other hand, for notched specimens, it has been observed by several investigators (12, 13, 19, 20, 33, 45) that a specimen with a geometrical notch with a small root radius (and consequently a large value of $K_t$) may have a fatigue strength greater than one which contains a notch with a larger root radius and thus a smaller value of $K_t$, when just the opposite would be expected.

## 1.2 Object and Scope of Investigation

On consideration of the different aspects of the problem, the scope of the investigation was broadened and a program was initiated to evaluate quantitatively the effect of the root radius of a geometrical notch on fatigue life, keeping all other variables constant. Four different materials were investigated and the results are presented in this report.

The results of the tests of notched specimens were compared qualitatively with those from previous investigations on similar specimens. This comparison shows the important role played by such factors as the geometry of the specimen and the cyclic conditions of loading in determining the fatigue strength of notched specimens.

In keeping with the original intent of this study, comparison of the results of fatigue tests on small, carefully machined specimens with previous tests on large structural joints, both welded and unwelded, was made. Some of the factors affecting the fatigue strength of these two types of specimens have been brought out in Sec. 3.6.

Many attempts have been made in the past 50 years to correlate $K_t$ and $K_e$. This is the so-called notch-sensitivity problem. As a part of this investigation, a small study was made of the factors which influence notch-sensitivity and these are discussed briefly. In addition, the effect of the increase in fatigue strength obtained for a notch of extremely small root radius on the notch-sensitivity index of structural steels has been studied.

## 1.3 Definitions and Notation

### Definitions

Range of stress: The algebraic difference of the maximum and minimum stress in a stress cycle, tensile stress being taken as positive and compressive stress as negative.

Mean stress: Half the algebraic sum of the maximum and minimum stress in a cycle.

Alternating stress: The range of stress superposed on the mean stress in a cycle: one-half the range of stress.

Completely reversed cycle: A range of stress where the maximum and minimum stresses are equal in magnitude but of opposite sign.

Endurance limit: The limiting value of the stress below which a material can presumably endure an infinite number of stress cycles.

Fatigue strength: The greatest stress which can be sustained for a given number of cycles without fracture. The life has been taken as 2,000,000 cycles in this report, unless stated otherwise.

Fatigue ratio: The ratio of fatigue strength to the UTS.

Notch: Any type of stress concentration.

Average nominal stress: The applied load divided by the original net area.

Average true stress: The applied load divided by the measured net area at some particular time. This applies only to specimens loaded above the yield point.

S-N curve: The graphical relationship between stress and number of cycles to failure.

Stress gradient: The rate of change stress.

Stress gradient hypothesis: A hypothesis postulating that a relatively steep stress gradient causes a smaller reduction in fatigue strength than a mild one. (See Chapter IV.)

Notch-sensitivity: The susceptibility of materials to succumb to the damaging effects of stress concentrations under repeated loading.

Notch-sensitivity index: A measure of the degree of agreement between $K_e$ and $K_t$.

Notch-sensitivity theory: A theory postulating that the notch-sensitivity of steels increases with an increase in the UTS. (This is also known as the falling fatigue ratio theory).

Notations

$K_t$ = theoretical stress concentration factor based on the classical theory of elasticity of Tresca and St. Venant (15). (The ratio of the maximum local stress to the average nominal stress.)

$K_t'$ = theoretical stress concentration factor based on the Huber-Mises Theory (16).

$K_e$ = Effective stress concentration factor or fatigue strength reduction factor.

$$= \frac{\text{fatigue strength of unnotched specimen at N cycles}}{\text{fatigue strength of notched specimen at N cycles}}$$

q = notch sensitivity index (35).

$$= \frac{K_e - 1}{K_t - 1} \text{ or } \frac{K_e - 1}{K_t' - 1}$$

D = Unnotched diameter of test section of specimen (Fig. 2).

d = Notched diameter of test section of specimen.

$\rho$ = root radius of notch.

UTS = Ultimate Tensile Strength.

N = number of cycles to failure in a fatigue test.

## 1.4 Acknowledgements

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# II. DESCRIPTION OF MATERIALS AND TESTS

## 2.1 Materials

Four structural steels were used in this investigation. The chemical analyses and physical properties of the steels are given in Tables 1 and 2, respectively. The ASTM A7 steel (low carbon steel) is the same as that used by Harris, Nordmark, and Newmark (1) in a previous fatigue investigation of welded connections. One of the ASTM A242 steels (low alloy steel) used in this investigation (designated 'B') has also been used in a previous fatigue investigation in welded joints at the University of Illinois (6)*. The other ASTM A242 steel was used in a recently completed fatigue investigation on welded joints at the University of Illinois (7) and is designated as steel "R". Steels designated as A242 also meet the present specifications for A441. The fourth steel is a high yield strength quenched and tempered constructional alloy steel, abbreviated in the body of the report as QT; at present it has no ASTM designation. Typical microstructures of these steels are shown in Figs. 1 and 2.

## 2.2 Test Specimens

Figure 3 shows the basic form of the three different types of specimens used in this program. The table in the figure presents the variation in minimum diameter of specimens. The three specimen configurations have the same geometric shape, an overall length of 4 in., a 3/4 in. nominal diameter and a straight test section at mid-length 1/4 in. long. The radius of the transition curve was maintained at 2 1/8 in. for all specimens. Specimen type A, having an unnotched diameter of 1/2 in. at the test section, was used for all tests of notched specimens herein. The other two types of specimens were used to determine the

* This steel is designated as steel 'T; in Ref. 6.

fatigue resistance of the materials in the unnotched condition. Type B, which has a test section diameter of 3/8 in. was used for the ASTM A7 steel; type C, with a test section diameter of 1/4 in. was used for the ASTM A242 and QT steels.

All specimens were prepared from 3/4 in. thick plates with the longitudinal axis of the specimen in the direction of rolling. The specimens tested in the polished condition were treated in a manner similar to that used in a previous investigation (25). The final polish was carried out with crocus cloth.

Figure 4 shows the details of the notch configurations and the designations assigned to each of them. No $K_t$ value is given for notch 'Y' because of the sharp discontinuities at the root. However, an approximate value of $K_t$ for this notch could be calculated assuming the existence of a smooth radius at the root based on the assumption that localized yielding during the first few load cycles would erase any sharp change in the section. The notches were not polished after they were machined. They were, however, checked on a comparator at 50 magnifications.

Each of the individual test specimens was given a combination letter-number designation which makes possible identification of the specimen, the steel from which it was fabricated, and the type of notch imposed on it. A typical designation would be: ASB - 15 - V75. Here, the first three letters indicate a series of tests conducted on specimens fabricated from a given material where the third letter identifies the material (see Tables 5 and 6). The first number is the number of the specimen itself. The last letter-number combination identifies the type of notch and the radius of the root in ten thousandths of an inch. The letter designations assigned to the notch configurations are given in Fig. 4.

In more concise form, a specimen in test series ASB would be designated as follows:

ASB-75-V75

- Material B (A242) — ASB
- Specimen 75 — 75
- Notch V — V
- Root radius 0.0075 in. — 75

2.3 Testing Equipment

All tests reported herein were conducted in a 10,000 pound capacity Sonntag Universal Fatigue Testing Machine, Model SF-10-U. A general view of this machine and the attached tension-compression apparatus is shown in Fig. 5. Figures 6 and 7 are interior views of the machine taken at 90° to each other.

This machine is a constant-load type in which the alternating load is obtained from the vertical component of the centrifugal force produced by an adjustable weight turning at a constant speed of 1800 rpm. A friction clutch allows the main motor to reach synchronous speed almost instantaneously while the adjustable weight reaches the same speed within 8 to 12 seconds to prevent momentary overload of the specimen. The position of the adjustable weight determines the amount of applied alternating load (0 to ± 5,000 lb.). The horizontal component of the centrifugal force caused by the rotating mass is absorbed by four flexplates attached to the oscillator of the machine.

The mean load is applied by a separate induction motor which is connected to a gear reduction box. This gear reduction box drives a continuous chain which in turn rotates two sprockets located beneath the lower base plate of the machine. These sprockets are connected to two specially designed screws which possess little or no backlash. These screws either raise or lower the plate which supports the four heavy springs under the oscillator, thereby applying the load to the specimen.

The cabinet of the Sonntag machine is only a shell which supports the test mechanism on twelve springs, three located at each corner. Being entirely spring supported, the test mechanism neither receives nor emits external vibrations which might cause overload of the specimen. This cabinet also houses the electronic equipment and controls which are rigidly attached to it.

Figure 8 shows a view of the attached tension-compression apparatus. The main component is a loading frame to which is attached the upper specimen holder and seating block. The lower seating block is fastened to the oscillating assembly. Hand-lapped specimen holders are used to clamp the specimens in the machine and to assist in obtaining concentric loading.

When a specimen fails, the displacement increases to approximately $\pm$ 1/2 in. allowing two limit switches located at the base of the oscillator to break the main motor circuit. However, the use of these switches results in the fracture surfaces being pounded until they are greatly distorted before the machine actually stops. Since it is often desirable to preserve the fracture surfaces, an additional limit switch was added to the upper plate of the machine along with an adjustable actuator to the oscillator. This actuator could then be adjusted so that only a small displacement, occurring during a test, would break the main motor circuit and stop the machine before total fracture of the specimen. This switch is shown in the foreground in Fig. 7.

During a previous investigation (25), considerable time was spent in calibrating the Sonntag fatigue machine. The results of the dynamic calibration showed the alternating load to be in accordance with the specified value. In the current investigation a check of the preload calibration was made using a

1/2 in. diameter weigh-bar for which the stress strain relationship was known. Within the limits of experimental error, the preload constant, used to set the mean load, agreed with that given by the manufacturer. Only the preload mechanism was re-calibrated since it seemed inconceivable that the adjustable weight could change its load characteristics which depend only on its mass and rotating speed.

### 2.4 Testing Procedure and Presentation of Results

All the fatigue tests reported herein were, in general, conducted at stresses producing failures after 100,000 to 2,000,000 repetitions of load. The tests were conducted at room temperature and no heating of the specimens during testing was observed. In all tests, the stress cycle was one in which the minimum stress was a low nominal tension of approximately 1,000 psi, the maximum stress being a tensile stress. The initial nominal tension was used to ensure proper clamping of the specimen. This stress cycle has been referred to as a zero-to-tension stress cycle.

The stresses used for constructing the S-N diagrams for the notched specimens are average nominal stresses based on the original net area of the specimen before notching. However, for the unnotched specimens, the stresses are average true stresses based on the measured net area.

Failure of a specimen was assumed to occur when a noticeable fatigue crack developed; however, no control was exercised over the depth to which the fatigue crack propagated. This failure criteria might produce a slight inconsistency in the lives of different specimens, but in view of the fact that specimen lives were over 100,000 cycles in almost all cases, and because of the inherent scatter present in fatigue testing, it is felt that the error can be safely ignored.

All of the different series of tests were compared on the basis of fatigue strength corresponding to a particular cyclic life. The comparison was made at 2,000,000 cycles and the maximum stress which a specimen could sustain for 2,000,000 cycles without fracture was termed the fatigue strength corresponding to 2,000,000 cycles, or simply the fatigue strength. It should be mentioned here that other investigators (12,24) have observed that specimens which resist 2,000,000 cycles of loading may have an infinite life.* The error involved in comparisons based on fatigue strengths corresponding to 2,000,000 cycles will be small since the so-called endurance limit will be only slightly less than the fatigue strength corresponding to this life.

For specimens which sustained approximately 4,000,000 cycles of loading, it was assumed that the stress was at or below the fatigue strength corresponding to 2,000,000 cycles and the test was discontinued.

The average variation of life with maximum stress, as shown on the S-N diagrams is usually a linear curve from 100,000 to 2,000,000 cycles when plotted on a logarithmic scale. In cases where test data was insufficient, the part of the plot not determined has been shown by broken lines.

* Assuming the absence of corrosive environment.

## III. EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1 Results of Axial Fatigue Tests of Unnotched Specimens

The tests of unnotched specimens were conducted in order to obtain the basic fatigue properties of the materials which were subsequently investigated in the notched condition. These data provided a base for the computation of the reduction in fatigue strength due to the presence of a notch, compared to the values of $K_t$. In addition, the three high strength steels investigated were tested in the unnotched condition in two surface conditions - the longitudinally polished and the rough-turned conditions. This provided a base for the computation of the reduction in fatigue strength due to the machining and surface defects.

The S-N curves obtained for the unnotched specimens in the longitudinally polished condition on ASTM A7, ASTM A242 (steel B), A242 (steel R) and QT steel are presented in Figs. 9, 10, 11 and 12, respectively. In all cases the fatigue strengths are considerably above the yield values. The results are summarized in Table 3.

Comparing the fatigue strengths of the small longitudinally polished specimens with the fatigue strength of large plate specimens free of intentional stress raisers (Table 10), it can be seen that the small specimens show a considerably higher fatigue strength. It can also be observed in Table 3 that the increase in fatigue strength obtained for small specimens becomes more marked with the increase in UTS. In addition the fatigue ratio for the small specimens increases with the ratio of yield to UTS.

It must be noted that the above comparison is based on average true fatigue stresses and average nominal UTS. This makes the fatigue ratios appear higher than those which would be obtained if average nominal fatigue strengths had been used. In addition, the speed of loading in the fatigue tests was considerably higher than that used in the static tests for the determination of the UTS. It is known that the speed of loading has an effect on the static strength of materials, the higher the speed the greater the static strength. Also, an increased speed of loading gives a more marked increase in the yield strength than in the UTS which may increase only slightly (27). As a result, the ratio of the yield to the UTS will also change with a change in the speed of loading.

The above discussion makes it appear that there are a number of extraneous variables which may have an effect on the comparisons. There is, however, a general trend to be observed from the test results: the fatigue strength increases with UTS and with the ratio of yield to UTS. This is true even for the unnotched specimens tested in the rough-turned condition, the results of which are summarized in Table 4. (See Figs. 11, 13, 14.)

Values of $K_e$ for the unnotched, rough-turned specimens of the three steels so tested have been computed and are presented in Tables 6 and 7. For the steels ASTM A242 (B), ASTM A242 (R), and QT these factors are 1.15, 1.11, and 1.15, respectively. Since the specimens of these three steels were machined in exactly the same manner, the comparison of the values of $K_e$ is reasonably valid. This data does not lend itself to the increasing notch-sensitivity theory, at least not in the range of UTS considered and for the type of stress raisers under consideration.

The only other variable which might appreciably effect the results obtained on the unnotched specimens is the size of the specimens. The unnotched specimens of ASTM A7 steel were 3/8 in. diameter whereas the specimens of the other steels were 1/4 in. diameter. This reduction in diameter was made in order to obtain higher stresses on the high strength steels without overloading the testing machine. The available literature on the subject of size effect lends weight to the feeling that this is not an added variable and that the latter calculations of $K_e$, using the fatigue strengths of the unnotched specimens of a size different from that of the notched specimens, are thus justified. All specimens were axially loaded and in the unnotched, polished condition the absence of any stress raisers eliminated any stress gradients at the surface layers. Consequently there should be no size effect (13).

### 3.2 Results of Axial Fatigue Tests of Notched Specimens of ASTM A7 Steel

The results of ten series of notched specimens of ASTM A7 steel are presented in Figs. 15 through 24. Details of the specimens and a summary of the results are given in Table 5.

In seven series of tests, the root radius of specimens with V type notches (60 deg. flank angle) was changed to give different values of $K_t$. By changing the root radius between the limits of 0.010 in. and 0.0025 in. the corresponding value of $K_t$ was varied between the limits of 3.80 and 7.00 as shown in Table 5. The results of these tests show that the fatigue strength decreases with a decrease in root radius only up to a certain point; after that, any further decrease in the root radius causes an <u>increase</u> in the fatigue strength instead of the decrease normally expected. Consequently, above a certain value of $K_t$ there is no further reduction in fatigue strength. These results suggest that there is a maximum value of $K_e$ and a corresponding minimum fatigue strength for this material. These results agree with the previously reported observation that a notched specimen with a smaller root radius and consequently a larger $K_t$ may be stronger in fatigue than one with a larger root radius and correspondingly lower value of $K_t$.

The variation of fatigue strength with root radius for this steel is shown diagrammatically in Fig. 41. In Fig. 42 the values of $K_t$ are plotted against $K_e$. From these figures it can be seen that a transition takes place in the corresponding relationships. The value of $K_t$ at which transition takes place corresponds to the value of root radius below which no further reduction in fatigue strength occurs. The values of $K_t$ and root radius at which transition takes place have been termed the critical values.

The results of three other series of notched A7 specimens are presented in Figs. 22 to 24. In two of these series, the geometry of the notch was essentially the same as in the previous specimens, the flank angle being changed from 60 deg. to 30 deg. However, the notched diameter of the test section (and consequently the geometry of the specimen) was different and hence a direct comparison of the results of these two series with previous tests is not possible. It is noteworthy, however, that the fatigue strengths of the specimens of these two series are higher than the minimum value obtained in the other seven series (See Table 5). In series ASS-Y, the notch had a 60 deg. flank angle and a flat surface at the bottom, in effect a truncated 'V'. It is very likely that the sharp discontinuities at the root of this notch were erased by plastic deformation after the first few load cycles. The fatigue strength obtained with this notch was on the order of 22,000 psi, only slightly higher than the fatigue strength of series ASS-V100.

### 3.3 Results of Axial Fatigue Tests of Notched Specimens of ASTM A242 Steels

Table 6 summarizes the details of the specimens and the results of the fatigue tests of ASTM A242 steels. The S-N diagrams for the individual series are given in Figs. 25 through 33.

The fatigue strengths obtained from the two ASTM A242 steels are considerably different. In Fig. 41 the fatigue strengths are plotted against the root radius and in Fig. 42 the relationships between $K_t$ and $K_e$ are shown for these two steels. For both of these steels there again exists a critical root radius below which the fatigue strength increases instead of decreasing. As before, this gives a $K_t$ vs. $K_e$ relationship such that at the critical value of $K_t$, corresponding to the critical value of root radius, $K_e$ attains its maximum value. The critical root radius for steels B and R was found to be on the order of 0.050 and 0.010 in., respectively. It should be noted that although the UTS values of these two steels were fairly close, the chemical compositions and the microstructures were different. In view of this, it is understandable that the behavior of the notched specimens in these two steels was different (17).

An important observation can be made from the results of series ASB-Q50. This series had a fatigue strength on the order of 19,000 psi which is lower than the minimum value obtained in the ASB-V series; 21,000 psi shown in Fig. 41. It should be remembered that the geometry of the specimen was different for this series; the size of the specimen was larger than that used in the ASB-V series. It follows from the stress gradient hypothesis (See Sec. 4.1) that it is possible that the larger-sized specimens will show a greater reduction in fatigue strength. This is exactly what the results of this series of tests have shown. It must be pointed out, however, that this same result was not obtained in the tests of A7 specimens.

In the light of the above discussion, the previous statement that for a particular material there exists a minimum value of $K_e$ and a corresponding minimum possible fatigue strength, irrespective of the extent of stress concentration, requires qualification. The minimum fatigue strength referred to above depends not only on the material characteristics (both chemical and physical) but also on the size of the specimen. In Chapter 4 it will be shown that in addition to these factors, the minimum fatigue strength and the maximum $K_e$ depends on the cyclic conditions of loading.

## 3.4 Results of Axial Fatigue Tests of Notched Specimens of QT Steel

A summary of the details of specimens and results obtained on this steel is given in Table 7. The S-N diagrams for the individual series of tests are given in Fig. 34 through 40.

This steel was tested in two conditions: the as-received and the heat-treated condition. Four series of tests were conducted on the material in the as-received condition. Of these series, three were similar to the ones used to establish the root radius vs. fatigue strength relationship for the other steels. Such a relationship for QT steel is also shown in Fig. 41. As seen in Figs. 34, 37, and 39, there was an abnormal amount of scatter in the results of these fatigue tests which made it rather difficult to obtain representative values of fatigue strengths. The value obtained from Fig. 41 for the critical root radius is on the order of 0.009 in. In Fig. 42 the $K_t$ vs. $K_e$ relationship for this steel is shown. This relationship is somewhat different from the $K_t$ vs. $K_e$ relationship for the other steels.

The fourth series of notched tests of QT steel in the as-received condition were on notch Y, the flat type notch. These tests gave a fatigue strength of 35,000 psi, the highest value obtained for this steel.

Three series of fatigue tests on QT steel in the heat-treated condition were conducted. It is known that a process of welding involving complex thermal cycles alters the physical and metallurgical characteristics of a weld heat-affected zone. Since QT steel derives its physical properties by a process of quenching and tempering, a welding process would produce more complex changes in this steel than in an ordinary steel. The heat-treatment was an attempt to simulate the metallurgical structure of a weld heat-affected zone synthetically. It consisted of heating the specimens in a preheated furnace to 1650°F, after which they were removed and allowed to air cool. Figure 2 contains typical micrographs of QT steel in the as-received and the heat-treated condition. In addition, a micrograph of a weld heat-affected zone in this steel has been included (7).

Two types of tests on the heat-treated specimens were conducted. In the first, the notching operation was performed before the heat-treatment (a suffix 'a' has been added to this series), and in the other series the notching operation was performed after the heat-treatment (a suffix 'b' has been added to this series). Only one series was tested in which the notching was performed after the heat-treatment. Thus, results of fatigue tests of geometrically similar specimens in three different conditions were obtained (Table 7). The fatigue strength of the notched specimens in the as-received material was 26,000 psi; for those in which notching was performed before the heat-treatment the fatigue strength was 23,000 psi, and for those in which the notching was performed after the heat-treatment the fatigue strength was 29,000 psi. The decrease in fatigue strength of the specimens notched after the heat-treatment suggests the important role played by the surface condition and the effect of decarburization in fatigue.

An important aspect of the heat-treatment given to QT steel was the change in physical and metallurgical characteristics of the material. The UTS of the material increased due to the heat-treatment by approximately 6 per cent whereas the yield strength decreased by approximately 13.5 per cent. In addition, the per cent elongation was appreciably reduced (Table 2). The heat-treatment to which these specimens were subjected involved temperatures which exceeded the upper critical temperature, $A_3$. Cooling in air caused a rather low cooling rate and the structure obtained was completely different from the original tempered martensitic structure. The structure after the heat-treatment appeared to consist of very small, irregular ferritic grains, whereas the metallurgical structure of the major part of a weld heat-affected zone in QT steel consists of low carbon bainite and ferrite (7, 28). A comparison of the metallurgical structures in Fig. 3 will show that the heat-treatment process described earlier does not impart the same structure as a weld heat-affected zone in QT steel.

### 3.5 Discussion of Results

The results of the fatigue tests have shown that a notch with a small root radius (or high $K_t$) may have a fatigue strength greater than one with a large root radius (or low $K_t$). From the fatigue strength vs. root radius and $K_t$ vs. $K_e$ relationships shown respectively in Figs. 41 and 42 it is apparent that the effect of notches on the axial fatigue properties is dependent on the characteristics of the material. It has already been shown that the fatigue strength is also a function of the geometry of the specimen (Sec. 3.3).

This behavior (i.e. that a notch with a small root radius can be stronger than one with a large root radius) has been observed by several investigators (12, 13, 19, 20, 33, 45), but no satisfactory explanation has been offered so far. Frost (12) has attributed this behavior to the formation of non-propagating cracks*. According to Frost, non-propagating cracks form at the roots of sharp notches below a particular value of root radius (and hence above the corresponding $K_t$). The sharpness of this particular root radius has been found to depend on factors connected with the material

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* For a detailed discussion of non-propagating cracks, see Sec. 4.2.

characteristics, the type of specimen, and the cyclic conditions of loading (12, 41, 42, 43). Experimental evidence suggests that the increase in fatigue strength observed in sharp notches is coincident with the formation of nonpropagating cracks. (See Sec. 4.2).

Frost (12) and Phillips and Heywood (13) have presented axial fatigue test results on notched specimens of mild steel and a quenched and tempered steel which are summarized in Table 8 for ready reference. The results for mild steel are shown diagrammatically in Fig. 43** as a plot of the range of stress (zero mean stress) at endurance against a variation in the root radius of the notch. Also shown in Fig. 43 are the results of the current tests of notched specimens of ASTM A7 steel for which the range of stress (the minimum stress being constant at 1,000 psi) corresponding to a life of 2,000,000 cycles is shown. It will be observed that the general shape of the relationships is similar. However, certain related factors have to be considered in connection with the comparison. First, the cyclic conditions of loading are different. The results of tests from Refs. 12 and 13 are on a completely reversed stress cycle, i.e., zero mean stress. The present tests were on a low nominal tension-to-tension stress cycle, i.e., a tensile mean stress. In addition, in the present tests the minimum stress was held constant and the maximum stress was varied. Thus, the points obtained from the current tests are not strictly comparable to each other since the mean stresses vary. Second, the geometry of the specimens being compared is different. The tests on a completely reversed stress cycle were carried out on specimens of a diameter

** In Fig. 43, the point for zero root radius has been taken from Ref. 26, relating to cracked specimens. According to Frost (12), this point is not strictly comparable to the others, but he suggests that this represents an upper limit to the value for zero notch radius.

larger than the ones on zero-to-tension. Consequently, the reduction in fatigue strength in the larger sized specimens will be greater than in the smaller sized specimens. Third, the materials of the two investigations have different chemical and physical characteristics, though the difference is not great.

Also from the data summarized in Table 8, a $K_t$ vs. $K_e$ relationship for mild steel has been constructed. This is shown in Fig. 44 on which the data obtained on ASTM A7 steel from the current series of tests is also shown. The similarity in the general shape of the relationships is noteworthy.

It will be noted from Fig. 44 that the values of critical $K_t$ for the tests under comparison are very nearly equal. This suggests that for the type of material and specimen under consideration (mild steel or ASTM A7, circular specimens) the mean stress might not be as important a factor as the range of stress in determining the fatigue behavior. Phillips (41) has presented results of fatigue tests on circular specimens of mild steel with cracks which indicate that for this material the criterion for failure is the range of stress alone. If the results of cracked specimens can be taken to represent a behavior similar to that of notched specimens, it may be assumed that for notched circular specimens of mild steel or ASTM A7 steel, the criterion for failure is the range of stress alone.

So far, the discussion has been limited to the results of ASTM A7 steel and mild steel. The other steels tested in the current investigation show results in general agreement with those of ASTM A7 steel. However, indications are that in high strength and quenched and tempered steels the mean stress plays an important role in determining the behavior of notched specimens. The results obtained by Frost (12) on a quenched and tempered steel for a completely reversed stress cycle (zero mean stress) and geometrically larger specimens than those used in the current investigation give a different value of critical $K_t$ than that obtained herein for QT steel. Phillips (41) has found that for circular specimens with cracks, the criterion for failure of a quenched and tempered steel (and an aluminum alloy) is a function of both the range of stress as well as the mean stress. No results of tests on notched circular (geometrically similar) specimens to give the effect of the mean stress on the behavior of a quenched and tempered steel are available at the present time.

It has been assumed that the behavior of notched circular specimens of ASTM A7 steel or mild steel depends upon the range of stress alone whereas for high strength steels, both the range of stress and the mean stress affect the behavior. It must be emphasized that more experimental work is needed to clarify the laws governing the fatigue behavior of these materials. Therefore, as a result of the above assumption, the curves presented in this report to represent the relationship between the fatigue strength and the root radii for the high strength steels are not valid since the test points are not comparable insofar as the mean stress is concerned (Fig. 41). A valid relationship of this type would have to be constructed as a variation of the range of stress, at a constant mean stress, with the root radius. The relationship for ASTM A7 steel is valid, however, if the above assumption is correct.

From the results of fatigue tests of the notched specimens it appears that for the materials investigated, a minimum possible fatigue strength exists for each material, irrespective of the extent of stress concentration introduced. The minimum fatigue strength for a material has already been seen to be dependent on the absolute size of the specimen (Sec. 3.3). Consequently the maximum $K_e$, which is a function of the minimum fatigue strength, is also dependent on the absolute size. Further evidence of this is provided by a comparison of the present results on ASTM A7 steel with those of Frost on mild steel (12). It has been seen from Fig. 44 that for different sizes of specimens and for different cyclic conditions of loading, the critical $K_t$ for these two materials is approximately the same. However, the values of maximum $K_e$ corresponding to the values of critical $K_t$ are considerably different. Ignoring the fact that the materials for these two series of tests are different and assuming that the range of stress governs the behavior of the types of specimens under consideration, it appears that the differences in the values of maximum $K_e$ can be attributed to the difference in the geometry of the specimens.

The fact that an increase in fatigue strength is obtained for values of $K_t$ greater than the critical has a distinct effect on the shape of the $K_t$ vs. $K_e$ relationships. Up to the value of the critical $K_t$, the value of $K_e$ will increase with an increase in $K_t$. Beyond the critical $K_t$, the value of $K_e$ will not increase with any further increase in $K_t$; it will in fact decrease. Thus two distinct parts of the $K_t$ vs. $K_e$ relationship are obtained. However, the dependence of $K_e$ on absolute size and the cyclic conditions of loading would give a series of curves, the transition of each curve taking place at the critical $K_t$ which is determined by the conditions mentioned. In the limiting case the full theoretical effect is attained and the curve will be linear up to the critical $K_t$.

The curves representing the variation of fatigue strength with a change in root radius and the $K_t$ vs. $K_e$ relationships (Figs. 41 and 42) have been drawn from a limited amount of test data. It is quite likely that instead of sharp or sudden changes in the curves, there is a gradual transition. In other words, instead of a critical value of root radius or a critical value of $K_t$, there might be a critical range of these values. This fact may not have been brought out by the results of only a few series of tests.

Before closing a discussion on the behavior of notched specimens of these materials, one other observation should be made concerning the values of $K_e$ for QT steel. The values of $K_e$ obtained for this steel along with the values for the other steels tested are summarized in Table 9. It can be seen that for each particular $K_t$, the maximum $K_e$ obtained is for QT steel. In one particular case ($K_t = 3.80$), the value of $K_e$ obtained for QT steel is even greater than $K_t$. This behavior is unusual for structural steels but, as pointed out by Peterson (14), it is characteristic of hard, quenched and tempered steels and indicates the increased notch-sensitivity in fatigue of this group of steels.

The tests on QT steel in the heat-treated condition have demonstrated the importance in fatigue of changes caused by such a treatment. However, with the heat-treatment applied in these tests it was not possible to simulate the microstructure of a weld heat-affected zone. The metallurgical changes produced by welding have been synthetically produced in this steel (29), but due to the complex process and the equipment necessary, no attempt was made to include such specimens in the present study.

## 3.6 Correlation of Experimental Results with Results Obtained From Large Joints

In Tables 10 to 13, the results of most of the available fatigue tests of large structural connections and joints fabricated by welding and tested on a zero-to-tension stress cycle have been summarized. To facilitate a comparison of the test results, use has been made of the parameter $K_e$ and the fatigue ratios (see Sec. 1.3).

Table 10 is a summary of the average results of previous fatigue tests on several different materials tested in the unwelded condition. A comparison of these data has been made by considering the fatigue ratios. It can be seen that the fatigue ratios for the results considered fall in a fairly narrow range, the minimum value being 0.385 and the maximum 0.612. It is noteworthy that the maximum value is obtained for the steel with the lowest UTS and the minimum value is obtained for the steel with the highest UTS.

Tables 11, 12, and 13 summarize the results for various types of welded joints. The values of $K_e$ corresponding to 100,000 and 2,000,000 cycles have been computed for these results. In general, the values of $K_e$ for transverse and longitudinal butt-welded joints are considerably lower than those of fillet-welded joints; consequently, the latter have the lowest fatigue ratios. This would be expected since fillet-welded joints usually involve sudden changes in section in addition to the presence of the weld resulting in greater stress concentrations which cause greater reductions in fatigue strength.

The fatigue ratios have also been used to compare the data on welded joints. Fig. 45 shows the fatigue ratios for both welded joint and plain plate specimens diagramatically. In Fig. 45, the diagonal lines indicate particular values of the fatigue ratios. It can be seen that the fatigue ratios for the plain plate fatigue tests fall between 0.4 and 0.6, with only two exceptions.

The fatigue strengths obtained from the small, unnotched specimens (Tables 3 and 4) are considerably higher than those of the large plain plate specimens tested in the as-rolled condition (Table 10). The difference in the fatigue strengths appears to increase with the UTS. To bring out the basic reason for these differences, a number of factors should be considered. First, in addition to the presence of mill scale and other surface and rolling imperfections, the number of external and internal defects and discontinuities increases in the large specimens. Second, in axial fatigue tests of small, longitudinally polished specimens, there are virtually no stress gradients in the surface layers whereas the mill scale and surface imperfections in the large plain plate specimens act as stress raisers to set up stress gradients in the surface layers. Thus, when a comparison of test results of these two types of specimens is made, we ignore not only the difference in the external and internal discontinuties but also the difference in the stressing conditions in the surface layers of the test specimens.

Table 14 is a summary of the results of fatigue tests of four different steels obtained from tests with different types of specimens. Values of $K_e$ have been computed for each type of specimen assuming that the maximum attainable fatigue strength is that given by the small, polished specimens*. It can be seen that the values of $K_e$ for the large plain plate specimens with mill scale increase with an increase in UTS. Similar results have also been obtained by Wilson and Thomas (23). These results are indicative of the general trend observed in the past and also in the present tests, i.e., the results of fatigue tests of small, longitudinally polished specimens do <u>not</u> give a true indication of the fatigue strength of materials under conditions encountered in practice. In actual practice, stress raisers arising from surface imperfections, fabrication processes, and unavoidable changes of section tend to reduce the fatigue strength considerably. The undesirable effects of these stress raisers become more critical as the UTS is increased.

In comparing the results of the small notched specimens and large welded connections the major difference is seen to be in the values of $K_e$ even though the fatigue strengths are at comparable levels. A comparison of the values of $K_e$ for the two types of specimens in different steels is presented in Table 15. It can be seen that the values of $K_e$ are different for comparable fatigue strengths and that the difference increases with an increase in UTS. The values of $K_e$ for welded connections are generally much lower than those for

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* This is a reasonable assumption since these specimens were polished longitudinally, i.e., in the direction of applied stress.

specimens with notches at comparable fatigue strengths. The base for calculation of $K_e$ for notched specimens is the strength of small unnotched polished specimens. The base for calculation of $K_e$ for the butt-welded joint is the strength of the plain as-rolled plate. In all cases the strength of the plain machined specimens is considerably higher than the strength of the as-rolled plate. Therefore, since the notched specimens produce the same fatigue strength as the butt-welded joints, the values of $K_e$ for the two conditions must be quite different.

In closing this discussion, it may be stated that our present knowledge of the effect of notches on small specimens is not sufficient. It also appears highly improbable that a particular notch could simulate the behavior of any one type of welded joint in all materials, since different materials respond differently to welding as well as to geometrical stress concentrations. However, partial success was attained in achieving the original objective in that it has been possible to simulate the stress concentrating effect of welding in a small specimen with a geometrical notch.

## IV. NOTCH-SENSITIVITY IN FATIGUE

### 4.1 Theoretical and Empirical Aspects

The introduction of a notch in a statically loaded member causes the stress at the root of the notch to increase markedly. The theoretical stress concentration factor, $K_t$, is defined as the ratio of the maximum local stress to the average nominal stress. Mathematical (15) as well as experimental (32) methods are available for the determination of the maximum stress. The average nominal stress can be computed by the elementary stress formulas.

Neuber's analysis for calculation of stress concentration factors is based on the classical theory of elasticity of Tresca and St. Venant (15). However, biaxial and triaxial fatigue tests have indicated that for ductile materials, the Huber-Mises criterion is obeyed more closely than the Tresca-St. Venant theory. On this assumption, Peterson (16) has peresented values of theoretical stress concentration factors for ductile materials which he has termed $K_t'$. The value of $K_t'$ is never greater than $K_t$ and the maximum possible difference between the two factors is on the order of 15 per cent. The fact that a much larger discrepancy usually exists between $K_t$ and $K_e$ has led to only a limited use of the modified factor $K_t'$.

Since the maximum local stress increases in proportion to $K_t$*, it might be expected that the fatigue strength of the notched specimens, as compared to that of unnotched specimens, would be reduced in proportion to $K_t$. Experimentally, on laboratory specimens, it has been observed that the amount of reduction in fatigue strength is not always directly proportional to $K_t$. The actual reduction is called the effective stress concentration factor or the fatigue strength factor, $K_e$.

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* $K_t'$ has not been used for any computations in this investigation.

The so-called problem of notch-sensitivity in fatigue deals with the correlation of theoretical and effective stress concentration factors. An index of notch effect generally accepted in the field of fatigue of metals is:

$$q = \frac{K_e - 1}{K_t - 1} \text{ or } \frac{K_e - 1}{K_t' - 1}$$

where q is the notch-sensitivity index (35). This equation gives an index of notch effect varying from zero to unity.*

Yen and Dolan (22) have discussed and critically appraised several criteria suggested for the correlation of $K_t$ and $K_e$. It is felt that in the light of the more recent work in this field, the information on this subject has changed to such an extent that a complete re-examination of the problem is required.

Until recent years, it was thought that $K_e$ would always be less than $K_t$. Peterson has attributed this conclusion to the fact that fatigue test data on laboratory specimens was obtained mostly from the soft steels. But recent work on quenched and tempered steels has indicated that $K_e$ can exceed $K_t$ (14). It has also been observed that $K_e$ increases with an increase in the size of the specimen (13, 33, 34).

The factors influencing notch-sensitivity can, in general, be grouped under two broad titles, material characteristics and state of stress. Under material characteristics, the ultimate tensile strength (13), plastic deformation (36), metallurgical structure (17), and hardness level (37) are factors which have been investigated.

* This assumes that $K_e$ can never exceed $K_t$. It has, however, been observed that for certain materials, it is possible to have $K_e$ greater than $K_t$ and hence a notch-sensitivity index greater than unity (see Sec. 3.5 and Ref. 14).

Under the heading state of stress all the variables which can alter a given state of stress, e.g., stress gradients, homogeniety, inclusions, non-propagating and propagating cracks, residual stresses, geometry of specimen, cyclic conditions of loading, etc. should be included. It is felt that one of the reasons why the problem of notch-sensitivity has defied solution for such a long period of time is the fact that the effect of the state of stress has not been given due importance.

The state of stress may also be affected by the so-called size effect observed by several investigators (13, 33, 34). This apparently is not a true size effect. An increase in the size of an element usually involves two important considerations. First, an increase occurs in the number of locations within the material which are possible points of crack initiation. Furthermore, the increase in surface area increases the number of various external defects due to mechanical and surface treatments. Second, in geometrically similar members, an increase in size changes the stress conditions at the surface since the stress gradient diminishes. Thus the state of stress at the surface layers will be different in a small member from that in a large one. To determine the dependence of true or intrinsic size effect on the increase in the number of internal and external discontinuities, it is necessary to carry out fatigue tests under stress conditions which are similar at each point of the surface layer in both the large and small members (i.e., the stress gradients are equal).

As pointed out by Uzhik (21), investigators who claim a size effect have studied the problem under conditions of simultaneous action of these two variables--the discontinuity of stress and the discontinuity of the material. Uzhik (21) has claimed, however, that under conditions in which the relative stress gradients are equal, no intrinsic size effect has been observed, even in axially stressed notched specimens. Uzhik has also presented the mathematical condition to provide similarity of stress conditions in the surface layers in the form:

$$\left[\frac{d\sigma}{dy} \cdot \frac{1}{\sigma_{max}}\right]_{spec\ 1} = \left[\frac{d\sigma}{dy} \cdot \frac{1}{\sigma_{max}}\right]_{spec\ 2}$$

where $\frac{d\sigma}{dy}$ is the rate of change of longitudinal normal stress with respect to a movement along the diametral axis. Stated in words, this means that the relative stress gradients at the surfaces must be equal.

The fact that no size effect has been observed in tests which have provided for continuity of stress conditions at the surface layers lends weight to Uzhik's arguments. Such tests have been reported by Phillips and Heywood (13). No size effect has been observed by these investigators in plain unnotched specimens tested under axial loading over a considerable range of sizes since under such conditions no stress gradients are present. However, a size effect in plain unnotched specimens tested in rotating-bending has been observed (34). This can be explained by the stress gradient hypothesis since the stress gradient diminishes with an increase in size and hence may be only an apparent size effect. In tests of notched specimens, in which a stress gradient is always present, a size effect has again been observed (13, 33).

An explanation of the effect of decreasing the magnitude of the stress gradient by increasing the size has been offered by Peterson (39). According to this explanation, a decrease in the magnitude of the relative stress gradient at the surface layer lowers the ability of the material to deform plastically, thus introducing micro-cracks when stressed. These micro-cracks form the nuclei for fatigue cracks and hence decrease the fatigue strength. When the stress gradient at the surface layer is steep, the material is less notch-sensitive because fatigue cracks are more difficult to initiate and propagation across the grains is hindered, thus resulting in a higher fatigue strength.

Phillips and Heywood (13) have offered a slightly different explanation of the stress gradient hypothesis which postulates that a relatively steep stress gradient causes a smaller reduction in fatigue strength than a mild one. By their explanation the critical operative factor is the average stress over a finite volume of material. With smaller members or with notches of small radii, the steep stress gradients produced cause the average stress over the particular finite volume to be considerably less than the maximum; thus the reduction in fatigue strength is small. With larger members or with large radii notches the stress gradient is not so steep; therefore, the average stress over the same finite volume of material is not much less than the maximum and a greater reduction in fatigue strength results.

Thus far, it has been pointed out that the so-called size effect may not be a true size effect but only an apparent one. It is easily seen that any factor which causes an internal or external discontinuity changes the stress gradient. Non-propagating cracks have been seen to increase the fatigue strength. It is thought that this is related to the stress gradient effect. Specimens with cracks, tested in fatigue, have shown effective stress concentration factors of the order of 2 to 3 depending on the material (26). This, too, appears to be due to the steep stress gradients introduced by the cracks. Internal inclusions would probably act in a manner similar to cracks but very little information is available on this subject.

From the discussion presented and from the results of numerous investigations it may be concluded that the actual reduction in fatigue strength is a function of the geometry of the specimen, the extent of stress concentration, the cyclic conditions of loading, and the material characteristics. With steep stress gradients (obtained with small specimens and sharp notches), the value of $K_e$ increases. Thus the results of small laboratory fatigue tests of notched specimens would only be of limited use for application to large structures with similar stress concentrations unless the stress gradients in the two conditions are equal.

It has been implied, though actually not stated, that under conditions encountered in practice, theoretical stress concentration factors could be used in applications where repeated loadings are critical. Peterson has also made such a suggestion (14). It is, however, essential that caution be exercised in their application to ultra high strength quenched and tempered steels since these materials are very notch sensitive and $K_e$ can exceed $K_t$.

Any discussion of the problem of notch-sensitivity would be incomplete without examining the equation for the notch-sensitivity index ($q = K_e - 1/K_t - 1$) in the light of current results. On the basis of the suggestion that full theoretical stress concentration factors be used, this equation actually becomes unnecessary. This equation has, however, been used extensively to determine values of $K_e$ using Peterson's relation between the notch-sensitivity index and the root radius of the notch. Such relations have been presented by Peterson on the assumption that as $K_t$ increases, the fatigue strength decreases. The results of the present tests (and those of other investigators) have shown that this is not so and that above a critical $K_t$ the fatigue strength increases rather than decreases. This has a marked effect on the relation between the notch-sensitivity index and the root radius.

From the data obtained in this investigation, calculations of notch-sensitivity index, q, have been made for the different steels and are presented in Tables 5, 6, and 7. These values are shown diagrammatically in Fig. 46. The effect of the presence of a critical root radius (corresponding to the critical notch severity) can be distinctly seen in that the rate at which q, the notch-sensitivity index, increases from zero to the value corresponding to the critical root radius is greater than the rate of increase of q above the critical root radius. In other words, the variation of q is not smooth but shows transition at (or in the region of) the critical root radius.

The fact that $K_e$ (and q) is a function of the geometry of a specimen as well as the cyclic conditions of loading means that a particular relationship between q and root radius is valid only for the conditions under which it is derived. The notch-sensitivity index will increase with an increase in the absolute size and will change if either the mean stress or the range of stress is changed. Consequently, a series of such relationships would be obtained for different experimental conditions.

### 4.2 The Significance of Non-Propagating Cracks

During the past few years, much information has been published on the subject of non-propagating cracks, the conditions under which they form, and their characteristics. Reference has been made in this report to such cracks as a possible explanation of the observed behavior of notched specimens. It is felt that a discussion of this topic is warranted since non-propagating cracks appear to play a vital role in determining the fatigue behavior of notched specimens.

As the name suggests, non-propagating cracks are cracks which do not propagate under conditions in which they form. In 1951, Fenner, Owen, and Phillips (31) showed that under reversed direct stress at zero mean stress, a fatigue crack could form at low nominal stresses in less than 50,000 cycles of loading at the root of notched specimens of mild steel. It was found that at the low nominal stress under which the crack formed, no further growth of the crack occurred, even after 100 million cycles of loading.

In 1955, Frost (30) carried out a series of tests on an aluminum alloy and found results similar to the above. Crack depths were measured and compared with the theoretical* depth of material at the root of a notch which was subjected to a stress greater than the nominal fatigue strength of the virgin material. Excellent agreement was obtained between the measured crack lengths and the theoretical values.

More recently, Frost attempted to experimentally define the conditions of formation of non-propagating cracks in circular specimens with circumferential notches under reversed direct stress and zero mean stress (12). His results showed that non-propagating cracks form at or above a certain value of $K_t$ at stresses below** the nominal endurance of the specimen. Below this value of $K_t$, non-propagating cracks do not form, i.e., all cracks will be propagating. The results show that the $K_t$ below which non-propagating cracks do not form coincides with the $K_t$ above which no further reduction in fatigue strength occurs, the critical $K_t$. Frost has attributed the observed behavior of notched specimens to the formation of non-propagating cracks which necessarily bring about a vital change in the state of stress around the notch root. This is discussed later. It should be mentioned here that in the investigation under reference, no tests to determine the effect of mean stress on the formation of cracks were made.

In a later investigation, Frost and Dugdale (42) outlined the conditions for obtaining non-propagating cracks in notched plate specimens. Tests were conducted to investigate the effect of mean stress as well as range of

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* Using the maximum principal stress theory, assuming a deep hyperbolic notch.

** There is also a lower limit to the nominal stress below which no cracking occurs.

stress. The results of this investigation suggested that for plate type specimens, the initiation of cracks is governed by the range of stress. This initiating stress was found to agree fairly well with the theoretical stress necessary to initiate a crack (obtained by dividing the endurance limit of the virgin material by the theoretical stress concentration factor). On the other hand, for the variation of mean stress and the range of stress investigated, the stress necessary for the growth of the cracks was found to be independent of the notch radius. At the same time, unless the compressive mean stress is too great, the growth of a crack was found to depend on the greatest tensile stress in the cycle. It thus appears that both the range of stress as well as the mean cyclic stress are important factors in determining the initiation and propagation of cracks in plate type notched specimens.

At present it is not known whether the observations of the conditions of formation of cracks made on plate type notched specimens can be extended to circular specimens and vice versa. There is some evidence, however, that the behavior of fatigue cracks in thin sheet metal is quite different from that of cracks in thicker plates and circular specimens (41).

Phillips (41) reported some data on the behavior of specimens with cracks as stress raisers. No evidence was found to substantiate the general feeling that cracks are the most effective form of stress raisers. Strength reduction factors for cracks, under conditions of zero mean stress were found to be fairly low (on the order of 2 to 3). In addition, these factors were found to be almost as high for mild steel as for a high strength, quenched and tempered steel. However, the effect of cyclic conditions on the behavior of a crack was found to be dependent not only on the material but also on the type of specimen. For cracked, circular specimens of mild steel, the range of stress at the endurance limit was found to be the same for a cycle of positive or tensile mean stress as for a cycle of zero mean stress. It must be emphasized that this behavior is confined to mild steel. According to Phillips, similar work on a quenched and tempered steel (and an aluminum alloy) indicated that the maximum tensile stress of the cycle at the endurance limit cannot exceed that of a cycle with zero mean stress. Thus, for circular specimens in the cracked condition, the criterion of fatigue failure for mild steel appears to be the range of stress whereas for the quenched and tempered steel (and the aluminum alloy), the criterion is the maximum (tensile) stress.

Summarizing the above discussion, it can be said that the behavior (initiation and propagation) of cracks is dependent on the material, type of specimen, extent of stress concentration, and the cyclic conditions of loading. It may also be said that cracks are not the most effective type of stress concentration.

A tentative explanation of the effect of the formation of non-propagating cracks has been offered by Frost (30) on the basis of stress gradients and the finite volumes or the layer theory. Coffin (43) has given an explanation based on cyclic plastic strains. The explanation of the action of non-propagating cracks given by Frost (30) is based on experimental observations. The agreement of measured full grown crack lengths with that of theoretical depths of material subjected to stresses greater than the endurance of the virgin material has already been mentioned. This depth of material depends on the stress field generated by the notch. The non-propagation of cracks suggests that the critical operative factor is the average stress over a finite volume of material, i.e., the so-called layer theory. The layer theory explains the reason why sharp notched specimens with cracks may be stronger than ones which are not so sharp or without cracks. The stress gradients set up by a sharp notch or a crack will be so steep that a high superimposed stress is necessary to create a stress of sufficient magnitude over the critical layer of material. Under no superimposed stress, steep stress gradients cause an average stress over the critical layer or finite volume which is less than the maximum, thus causing a smaller reduction in fatigue strength.

The stress field generated by a crack, when superimposed on the stress field of the notch, gives an intermediate stress field (26). This would mean that the resultant stress field broadens. This resultant stress field will ultimately be the decisive factor in determining the nature of the crack. Since the stress gradient at the tip of a crack is always very steep, the stress gradient generated by the theoretical stress concentration will play an important role. The resultant gradient caused by a high $K_t$ will be steeper than one caused by a low $K_t$, and as explained before, will cause less damage.

The explanation given by Coffin (45) to explain the non-propagation of cracks is based on the assumption that a small crack can transmit compression without any stress concentrating effect of the crack. Coffin reasons that under the action of an external cyclic load the stress and strain are fully reversed for a notch, but when a crack is present the full reversal does not occur. For a stress concentration to occur in compression, the crack must grow to a length beyond the influence of the notch. According to Coffin, when the notch plastic strain is low in relation to the plastic strain at the tip of the crack, the crack will continue to propagate. This mechanism has been used to explain experimental observations. Since the plastic strain would not change significantly due to the change in mean stress in a cycle, this has been interpreted to mean that the mean stress would not affect the stress necessary to initiate a crack. It has been observed that a tensile mean stress requires a higher $K_t$ for the formation of non-propagating cracks (42). This means that the cyclic plastic strain is increased due to the opening up of the crack during a greater portion of the cycle. On the other hand, a compressive mean stress has been observed to require a lower $K_t$ for the formation of non-propagating cracks. This follows as a result of the decrease in the cyclic plastic strain due to the closing of the crack in a greater portion of the cycle.

It might be added that the shapes of the cracks are, generally, not very important. This stems from the experimental observation made by Post (44) that the stress gradient around the tip of a crack is so severe that the shape of the crack has a negligible effect on its distribution. This, of course, is confined to the normal cracks observed and does not hold for very large cracks.

## 4.3 Microscopic Examination of the Roots of Notched Specimens

In the current investigation, microscopic examination of the roots of notched specimens of ASTM A7 steel were made. All the specimens which did not fail were sectioned, polished, and etched* in the usual manner. The specimens were examined at magnifications up to 500 and the results are presented in Table 16. Photographs of typical cracks are presented in Figs. 47 through 51.

Cracks were found in all the specimens examined. In certain cases, rather broad cracks were present whereas in others extensive local breakdown appears to have occurred at the notch root. Most of the cracks were highly irregular in shape.

In this material, four specimens were examined which had a theoretical stress concentration factor, $K_t$, greater than the critical (i.e., beyond which the fatigue strength increased instead of decreasing). These are specimens ASS-272, 269, 281, and 280. In specimens ASS-272 and 269, (Figs. 48 and 49) the cracks were fairly regular but those in specimen ASS-281 (Fig. 48) were very

* Using two per cent Nital.

irregular. In this specimen, extensive breakdown at the root of the notch seems to have occurred. Some secondary cracking also appears to have begun. In specimen ASS-280 (Fig. 48), the crack is regular but it is accompanied by extensive local breakdown at the root of the notch. The stresses used for these specimens were such that failure did not occur in 2,000,000 cycles; presumably these stresses were very close to the endurance limit. It may be mentioned that the lives of the specimens were such that positive identification of a non-propagating crack was virtually impossible. However, because these specimens had a $K_t$ greater than the critical, these cracks were most probably non-propagating. Phillips made the observation (41) on cracked specimens that the mean stress has no effect on the behavior of cracks in mild steel. This means that the conditions outlined by Frost for zero mean load apply to the results of the present tests on a tensile mean load. This lends weight to the thought that these cracks were non-propagating. In addition, tests were conducted on a constant load fatigue machine; therefore, if a crack formed it should have propagated to failure unless other factors inhibited such propagation.

In all the other specimens examined, the value of $K_t$ was less than the critical. All these specimens contained cracks. As mentioned in Sect. 4.2, the conditions outlined by Frost may also be applied here. According to these conditions non-propagating cracks in these specimens cannot form. The presence of cracks in these specimens would then indicate that these cracks were propagating and that the stresses at which the cracks formed were either at or above the nominal endurance limit. It is quite possible that these specimens would have fractured if the tests had been continued longer. Some evidence of this possibility has been offered by Hyler and co-workers (46). According to this evidence, propagation of a fatigue crack is quite slow over a considerable portion of the life of a specimen. However, at some stage acceleration of the propagation of the crack may take place and final failure may occur at a small percentage of the total life. Such an observation has been made by other investigators (47, 48). In addition, Head states that a crack could initiate at as early as 10 per cent of the estimated life and spend the rest in propagating (40).

The shapes of the cracks in the specimens with $K_t$ less than the critical is again highly irregular (Figs. 49 to 51). Specimen ASS-242, shown in Fig. 50 reveals extensive local breakdown at the root of the notch.

The essential details of the observations of the cracks can be summarized as follows:

(a) Cracks usually form perpendicular to the direction of loading and seem to grow indiscriminately, passing through the grains.

(b) Fatigue cracks may initiate on the surface at some distance away from the minimum section diameter.

(c) Extensive localized breakdown of material may occur at the root of the notch.

(d) Localized breakdown of grains in the path of the crack may occur.

(e) The contour of the root of the notch may be altered as a consequence of the deformation during cyclic stressing. (See Fig. 47.)

In this discussion, the effect of machining stresses and cold working introduced in machining the notches has not been considered. Experimental evidence suggests, however, that although the surface finish of a notch may appreciably change the fatigue life, the growth of cracks is independent of the surface state (46, 49).

In closing this discussion, it must be stated that the results of the microscopic examination of the roots of specimens of ASTM A7 steel are not conclusive in themselves. The nature and conditions of formation of non-propagating cracks was not the primary objective of the study at hand, hence the tests were in general terminated in less than four million cycles. The roots of notched specimens of steels other than ASTM A7 were not examined since the conditions of formation of cracks in these steels under conditions of tensile mean load are as yet unknown.

# V. SUMMARY

The results of the present investigation have thrown considerable light on the basic fatigue behavior of notched members, and an attempt has been made in the preceeding chapters to emphasize the role of the significant variables. Only during the past decade has a concentrated effort been directed at understanding the basic action of stress concentrations in fatigue as compared to the earlier empirical and semi-empirical approaches. The authors hesitate to draw conclusions in this developing field of study for the simple reason that as yet there is insufficient data for an acceptable theory of the nature of initiation and propagation of fatigue failures. However, the general pattern of the possible overall solution to the problem is gradually emerging.

Some of the more important observations made as a result of this study are:

(a) In small (circular) notched specimens, there exists a critical notch severity which when exceeded does not cause any further decrease in fatigue strength and may actually cause an increase in fatigue strength. The critical notch severity at which transition in behavior takes place appears to be dependent on the material characteristics, the geometry of the specimen, and the cyclic conditions of loading (the range of stress as well as the mean stress). The critical or maximum value of $K_e$ is governed by the same factors.

(b) In general, values of $K_e$ obtained were found to be less than $K_t$. However, for QT steel (a quenched and tempered, fine grained material) values of $K_e$ greater than $K_t$ may be obtained. In addition, the variation in fatigue strength with a change in $K_t$ is not as great in the quenched and tempered steel as it is in low carbon (ASTM A7) or low alloy (ASTM A242) steel.

(c) The relationship between $K_t$ and $K_e$ can be separated into two distinct parts. Below the critical $K_t$, $K_e$ decreases. In the limiting case, $K_e$ will be equal to $K_t$ up to the critical $K_t$ and then either decrease or attain a constant value.

(d) Changing the original metallurgical structure of QT steel by heat-treatment causes the fatigue strength of notched specimens in this steel to drop appreciably. However, if the notch is introduced after the original metallurgical structure has been changed, the fatigue strength increases instead of decreasing. This suggests the vital role played by the decarburization introduced in the process of changing the original metallurgical structure.

(e) It appears possible to simulate the stress concentrating effects of welding in any material by means of a geometrical notch. However, it does not appear possible to simulate these effects in all materials by means of a single notch configuration. This is due not only to the different response of materials to the effect of stress concentrations but also to the metallurgical effects of welding.

(f) The fatigue strength of large unwelded specimens is considerably lower than that of small polished specimens. This is primarily attributable to the increase in internal defects and to surface conditions such as rolling imperfections and mill scale. This difference in fatigue strength appears to increase with an increase in the UTS of the material.

(g) At present, no proven relationship exists by which the results of fatigue tests of small-scale specimens with stress concentrations can be extrapolated for determining the effect of similar stress concentrations on large-scale applications. It is therefore suggested that for members with stress concentrations employed in usual practice, the full theoretical stress concentration effect be used with the limiting theoretical effect being the critical value of $K_t$ for the particular material, type of member, and cyclic conditions of stress....

In members with stress concentrations which are subject to limitations of size and weight, fatigue tests of the full-sized members should be conducted to determine the extent of actual reduction in fatigue strength and the member then designed accordingly until a method of extrapolating fatigue strengths from laboratory specimens is developed. Pending such a development, the use of the full theoretical stress concentration will lead to conservative designs if fatigue tests of the full-sized members are not conducted.

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TABLE 1

CHEMICAL COMPOSITION OF STEEL PLATES

| Steel | Designation | Chemical Content in Percent* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | P | S | Si | Cu | Cr | Ni | Al | Va | Mo |
| ASTM A7 | S | 0.17 | 0.68 | 0.016 | 0.039 | 0.03 | ND | ND | ND | ND | ND | ND |
| QT | C | 0.15 | 0.83 | 0.013 | 0.015 | 0.28 | 0.19 | 0.54 | 0.93 | 0.031 | ND | ND |
| ASTM A242 | B** | 0.23 | 1.05 | 0.022 | 0.027 | 0.09 | 0.27 | 0.10 | 0.65 | None | 0.13 | 0.02 |
| ASTM A242 | R | 0.13 | 0.42 | 0.066 | 0.025 | 0.43 | 0.33 | 0.93 | 0.28 | None | 0.20 | 0.01 |

* Check Analysis

** Designated as T in Ref. 6

ND--Not Determined

TABLE 2

PHYSICAL PROPERTIES OF STEEL PLATES

| Steel | Designation | Yield Strength psi | Ultimate Tensile Strength psi | Elongation percent | Reduction in Area percent |
|---|---|---|---|---|---|
| ASTM A7 | S | 34,500 | 56,900 | 33.0*** | 62.0 |
| ASTM A242 | B† | 47,800 | 73,600 | 27.0*** | 58.0 |
| ASTM A242 | R | 49,900 | 75,500 | 28.5*** | 69.3 |
| QT | C | 111,900* | 126,600 | 22.0** | 69.1 |
| QT**** | C | 97,000* | 134,100 | 15.7** | 55.4 |

* Based on 0.2 percent offset

** Based on 2 in. gage length

*** Based on 8 in. gage length

**** Material heated to 1650°F. and allowed to air cool

† Designated as T in Ref. 6

TABLE 3

RESULTS OF FATIGUE TESTS OF SMALL

POLISHED SPECIMENS IN THE UNNOTCHED CONDITION

| Steel | Fatigue Strength Zero-to-Tension psi | Fatigue Ratio | Yield Strength / UTS |
|---|---|---|---|
| ASTM A7 | 47,000 | 0.826 | 0.608 |
| ASTM A242 (B) | 62,000 | 0.842 | 0.650 |
| ASTM A242 (R) | 68,000 | 0.900 | 0.660 |
| QT | 122,000 | 0.964 | 0.884 |

TABLE 4

RESULTS OF FATIGUE TESTS OF SMALL ROUGH-TURNED

SPECIMENS IN THE UNNOTCHED CONDITION

| Steel | Fatigue Strength Zero-to-Tension psi | Fatigue Ratio |
|---|---|---|
| ASTM A242 (B) | 54,000 | 0.732 |
| ASTM A242 (R) | 61,000 | 0.809 |
| QT | 106,000 | 0.837 |

TABLE 5

SUMMARY OF RESULTS OF AXIAL FATIGUE TESTS ON ASTM A7 STEEL

| Series | Specimen Diameter in. | | Notch Details | | $K_t$ | Fatigue Strength Zero-to-Tension psi | $K_e$ | q |
|---|---|---|---|---|---|---|---|---|
| | D | d | ρ, in. | α, deg. | | | | |
| ASS* | 0.375 | - | - | - | 1.00 | 47,000 | 1.00 | - |
| ASS-V100 | 0.500 | 0.400 | 0.0100 | 60 | 3.80 | 21,500 | 2.19 | 0.425 |
| ASS-V80 | 0.500 | 0.400 | 0.0080 | 60 | 4.20 | 21,250** | 2.21 | 0.378 |
| ASS-V75 | 0.500 | 0.400 | 0.0075 | 60 | 4.35 | 21,000 | 2.24 | 0.370 |
| ASS-V65 | 0.500 | 0.400 | 0.0065 | 60 | 4.65 | 20,500 | 2.29 | 0.353 |
| ASS-V50 | 0.500 | 0.400 | 0.0050 | 60 | 5.15 | 19,000 | 2.47 | 0.354 |
| ASS-V35 | 0.500 | 0.400 | 0.0035 | 60 | 6.00 | 20,000 | 2.35 | 0.270 |
| ASS-V25 | 0.500 | 0.400 | 0.0025 | 60 | 7.00 | 25,000 | 1.88 | 0.146 |
| ASS-P50 | 0.500 | 0.437 | 0.0050 | 30 | 4.75 | 21,000 | 2.24 | - |
| Ass-Q50 | 0.500 | 0.422 | 0.0050 | 30 | 4.96 | 23,000 | 2.05 | - |
| ASS-Y | 0.500 | 0.400 | Flat Notch | 60 | - | 22,000 | 2.14 | - |

* Unnotched, longitudinally polished

** Estimated value, see Fig. 16

TABLE 6

SUMMARY OF RESULTS OF AXIAL FATIGUE TESTS ON ASTM A242 STEELS

| Series | Specimen Diameter in. | | Notch Details | | $K_t$ | Fatigue Strength (Zero-to-Tension) psi | $K_e$ | q |
|---|---|---|---|---|---|---|---|---|
| | D | d | ρ, in. | α, deg. | | | | |
| STEEL 'B' | | | | | | | | |
| ASB* | 0.250 | ----- | ---------- | -- | 1.00 | 62,000 | 1.00 | ----- |
| ASB** | 0.250 | ----- | ---------- | -- | ---- | 54,000 | 1.15 | ----- |
| ASB-V100 | 0.500 | 0.400 | 0.0100 | 60 | 3.80 | 23,000 | 2.70 | 0.607 |
| ASB-V75 | 0.500 | 0.400 | 0.0075 | 60 | 4.35 | 22,000 | 2.82 | 0.543 |
| ASB-V50 | 0.500 | 0.400 | 0.0050 | 60 | 5.15 | 21,000 | 2.95 | 0.470 |
| ASB-V25 | 0.500 | 0.400 | 0.0025 | 60 | 7.00 | 28,000 | 2.21 | 0.202 |
| ASB-Q50 | 0.500 | 0.422 | 0.0050 | 30 | 4.96 | 19,000 | 3.26 | ----- |
| ASB-Y | 0.500 | 0.400 | Flat Notch | 60 | ---- | 23,500 | 2.64 | ----- |
| STEEL 'R' | | | | | | | | |
| ASR* | 0.250 | ----- | ---------- | -- | 1.00 | 68,000 | 1.00 | ----- |
| ASR** | 0.250 | ----- | ---------- | -- | ---- | 61,000 | 1.11 | ----- |
| ASR-V100 | 0.500 | 0.400 | 0.0100 | 60 | 3.80 | 23,500 | 2.90 | 0.679 |
| ASR-V50 | 0.500 | 0.400 | 0.0050 | 60 | 5.15 | 26,000 | 2.61 | 0.388 |
| ASR-V25 | 0.500 | 0.400 | 0.0025 | 60 | 7.00 | 32,000 | 2.13 | 0.188 |

*Unnotched, Longitudinally polished

**Unnotched, Rough turned

## TABLE 7

SUMMARY OF RESULTS OF AXIAL FATIGUE TESTS ON QT STEEL

| Series | Specimen Diameter in. | | Notch Details | | $K_t$ | Fatigue Strength (Zero-to-Tension) psi | $K_e$ | q |
|---|---|---|---|---|---|---|---|---|
| | D | d | ρ, in. | α, deg. | | | | |
| ASC* | 0.250 | ----- | ---------- | -- | 1.00 | 122,000 | 1.00 | ----- |
| ASC** | 0.250 | ----- | ---------- | -- | ---- | 106,000 | 1.15 | ----- |
| ASC-V100 | 0.500 | 0.400 | 0.0100 | 60 | 3.80 | 26,000 | 4.70 | 1.321 |
| ASC-V100a*** | 0.500 | 0.400 | 0.0100 | 60 | 3.80 | 23,000 | ---- | ----- |
| ASC-V100b**** | 0.500 | 0.400 | 0.0100 | 60 | 3.80 | 29,000 | ---- | ----- |
| ASC-V50 | 0.500 | 0.400 | 0.0050 | 60 | 5.15 | 27,000 | 4.52 | 0.848 |
| ASC-V50a*** | 0.500 | 0.400 | 0.0050 | 60 | 5.15 | 19,000 | ---- | ----- |
| ASC-V25 | 0.500 | 0.400 | 0.0025 | 60 | 7.00 | 28,000 | 4.36 | 0.560 |
| ASC-Y | 0.500 | 0.400 | Flat Notch | 60 | ---- | 35,000 | 3.49 | ----- |

* Unnotched, Longitudinally polished

** Unnotched, Rough turned

*** Heated to 1650°F., Air cooled, Notched before heat treatment.

**** Heated to 1650°F., Air cooled, Notched after heat treatment.

TABLE 8

SUMMARY OF RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS FROM OTHER INVESTIGATIONS

| Material | Specimen Diameter in. | | Notch Details | | Fatigue Strength* psi | $K_t$ | $K_e$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| | D | d | ρ, in. | α, deg. | | | | |
| MILD STEEL | 0.977 | ---- | ------- | -- | 31,360 | ---- | ---- | 12 |
| 0.15 C<br>0.45 Mn | 1.700 | 1.30 | 0.050 | 55 | 9,520 | 3.3 | 3.3 | 12 |
| 0.014 S | 1.700 | 1.30 | 0.010 | 55 | 8,400 | 6.6 | 3.7 | 12 |
| 0.015 P<br>UTS = 65.0 ksi | 1.700 | 1.30 | 0.004 | 55 | 7,620 | 10.0 | 4.1 | 12 |
| MILD STEEL | 0.560 | ---- | ------- | -- | 32,260 | ---- | ---- | 13 |
| 0.11 C<br>0.43 Mn | 1.700 | 1.30 | 0.025 | 55 | 8,510 | 4.4 | 3.8 | 13 |
| 0.021 P | 1.700 | 1.30 | 0.002 | 55 | 8,510 | 14.0 | 3.8 | 13 |
| 0.012 S<br>UTS = 58.7 ksi | 1.700 | 1.30 | 0.200** | -- | 15,000 | 1.9 | 2.15 | 13 |

* Corresponding to the endurance limit on a completely reversed stress cycle.

** Semi-circular groove.

TABLE 8 (Cont'd)

SUMMARY OF RESULTS OF AXIAL FATIGUE TESTS ON
NOTCHED SPECIMENS FROM OTHER INVESTIGATIONS

| Material | Specimen Diameter in. D | Specimen Diameter in. d | Notch Details $\rho$, in. | Notch Details $\alpha$, deg. | Fatigue Strength* psi | $K_t$ | $K_e$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| Ni-Cr STEEL<br>0.43 C<br>0.65 Mn<br>0.012 S<br>0.012 P<br>2.64 Ni<br>0.75 Cr<br>0.58 Mo<br>0.05 Va<br>0.32 Si<br>UTS = 141.0 ksi | 0.977 | ----- | ------- | -- | 82,400 | ---- | ---- | 13 |
| | 0.990 | 0.850 | 0.0050 | 55 | 16,900 | 4.6 | 4.6 | 12 |
| | 1.250 | 0.850 | 0.0050 | 55 | 11,300 | 8.0 | 7.9 | 12 |
| | 1.700 | 1.300 | 0.0020 | 55 | 10,500 | 14.0 | 7.9 | 13 |
| | 1.700 | 1.300 | 0.0250 | 55 | 17,200 | 5.0 | 4.8 | 13 |
| | 0.564 | 0.524 | 0.0025 | 55 | 34,200 | 5.8 | 2.4 | 13 |

* Corresponding to the endurance limit on a completely reversed stress cycle.

TABLE 9

SUMMARY OF EFFECTIVE STRESS
CONCENTRATION FACTORS FOR STEELS INVESTIGATED

| Notch | $K_t$ | Values of $K_e^*$ Obtained | | | |
|---|---|---|---|---|---|
| | | A7(S) | A242(B) | A242(R) | QT(C) |
| V100 | 3.80 | 2.19 | 2.70 | 2.90 | 4.70 |
| V75 | 4.35 | 2.24 | 2.82 | ---- | ---- |
| V50 | 5.15 | 2.47 | 2.95 | 2.61 | 4.52 |
| V25 | 7.00 | 1.88 | 2.21 | 2.13 | 4.36 |
| Q50 | 4.96 | 2.07 | 3.26 | ---- | ---- |
| Y | ---- | 2.14 | 2.64 | ---- | 3.49 |

* Effective stress concentration factor for a fatigue strength corresponding to a fatigue life of 2,000,000 cycles on a zero-to-tension stress cycle.

TABLE 10

AVERAGE RESULTS OF PREVIOUS AXIAL FATIGUE TESTS ON PLAIN PLATE SPECIMENS ON A ZERO-TO-TENSION STRESS CYCLE

| Material | UTS psi | Thickness in. | Width in. | Surface Condition | Fatigue Strength, psi $F_{100,000}$ | Fatigue Strength, psi $F_{2,000,000}$ | Fatigue Ratio | Ref. |
|---|---|---|---|---|---|---|---|---|
| A7 | 57,400 | 3/4 | 5 | as-rolled | 53,500 | 34,600 | 0.602 | 1 |
| A7 | 57,400 | 3/4 | 5 | mill scale off | ------ | 35,300* | 0.612 | 1 |
| A7 | 54,500 | 3/4 | 5 | as-rolled | ------ | 30,300* | 0.555 | 2 |
| Si Steel | 80,700 | 3/4 | 5 | as-rolled | ------ | 35,800* | 0.444 | 2 |
| A7 | 61,300 | 7/8 | 5 | as-rolled | 49,800 | 31,600 | 0.514 | 3 |
| A7 | 61,300 | 7/8 | 5 | mill scale off | 59,600 | ------ | ----- | 3 |
| A7 | 58,900 | 1/2 | 3 | as-rolled | 49,100 | 34,700 | 0.590 | 5 |
| A7 | 58,900 | 7/8 | 5 | as-rolled | 44,500 | 29,500 | 0.501 | 5 |
| A242 (P) | 76,700 | 3/4 | 4 | as-rolled | 53,500 | 38,500 | 0.502 | 6 |
| A242 (T) | 73,600 | 3/4 | 4 | as-rolled | 57,800 | 42,500 | 0.577 | 6 |
| A242 (Q) | 77,600 | 3/4 | 4 | as-rolled | 55,300 | 40,000 | 0.515 | 6 |
| QT | 107,000 | 3/4 | 3 1/2 | as-rolled | 62,200 | 41,100 | 0.385 | 7 |
| T-1 | 123,000 | 1/2 | 3 1/2 | as-rolled | 76,000 | 50,000 | 0.407 | 8 |
| A7 | 57,400 | 3/4 | 5 | as-rolled | 53,500 | 34,600 | 0.603 | 10 |
| A7 | 63,800 | 3/4 | 5 | as-rolled | ------ | ------ | ----- | 11 |
| C Steel | 61,800 | 3/4 | 5 | as-rolled | ------ | 30,300 | 0.490 | 23 |
| Si Steel | 80,800 | 3/4 | 5 | as-rolled | ------ | 35,800 | 0.440 | 23 |
| Ni Steel | 99,000 | 3/4 | 5 | as-rolled | ------ | 39,500 | 0.400 | 23 |

* Data taken from Ref. 23

TABLE 11

AVERAGE RESULTS OF PREVIOUS AXIAL FATIGUE TESTS ON TRANSVERSE BUTT WELDED JOINTS ON A ZERO-TO-TENSION STRESS CYCLE

| Material | UTS psi | Thickness in. | Electrode | Reinforcement | Length of Weld, in. | Fatigue Strength psi $F_{100,000}$ | Fatigue Strength psi $F_{2,000,000}$ | $K_e$ for Number of Cycles 100,000 | $K_e$ for Number of Cycles 2,000,000 | Fatigue Ratio | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A7 | 57,400 | 3/4 | E6010 | on | 5 | 34,900 | 24,000 | 1.54 | 1.44 | 0.418 | 1 |
| A7 | 57,400 | 3/4 | E6010 | off | 5 | 33,300 | 21,800 | 1.60 | 1.59 | 0.380 | 1 |
| A7 | 57,400 | 3/4 | E7016 | on | 5 | 37,900 | 23,800 | 1.41 | 1.46 | 0.415 | 1 |
| A7 | 57,400 | 3/4 | E7016 | off | 5 | 35,400 | 29,100 | 1.51 | 1.19 | 0.508 | 1 |
| A7 | 54,500 | 3/4 | - | on | 5 1/2 | - | 21,800 | - | 1.40 | 0.400 | 2 |
| A7 | 54,500 | 3/4 | - | off | 5 1/2 | - | 27,900 | - | 1.08 | 0.511 | 2 |
| A7 | 54,500 | 3/4 | - | on | 5 1/2 | - | 22,800 | - | 1.33 | 0.419 | 2 |
| Si Steel | 80,700 | 3/4 | C-Mo type | on | 6 | - | 24,000 | - | 1.49 | 0.298 | 2 |
| Si Steel | 80,700 | 3/4 | C-Mo type | off | 6 | - | 23,700 | - | 1.51 | 0.294 | 2 |
| A7 | 61,300 | 7/8 | - | on | 5 | 33,100 | 22,500 | 1.51 | 1.41 | 0.366 | 3 |
| A7 | 61,300 | 7/8 | - | off | 5 | 44,500 | 26,300 | 1.12 | 1.20 | 0.429 | 3 |
| A7 | 59,000 | 7/8 | E6012 | on | 5 | 34,700 | 21,200 | 1.41 | 1.46 | 0.360 | 4 |
| A7 | 62,300 | 7/8 | E6030 | on | 5 | 31,600 | 21,500 | 1.54 | 1.44 | 0.345 | 4 |
| A7 | 60,200 | 7/8 | E6010 | on | 5 | 30,800 | 21,200 | 1.59 | 1.46 | 0.351 | 4 |
| A7 | 63,300 | 7/8 | - | on | 5 | 34,000 | 22,300 | 1.44 | 1.39 | 0.351 | 4 |
| A7 | 58,900 | 1/2 | E6010 | off | 3 | 35,600 | 28,900 | 1.38 | 1.20 | 0.490 | 5 |
| A7 | 58,900 | 1/2 | E6012 | off | 3 | 38,100 | 26,500 | 1.29 | 1.31 | 0.451 | 5 |
| A242 (P) | 76,700 | 3/4 | E7016 | on | 4 | 38,600 | 26,300 | 1.38 | 1.47 | 0.344 | 6 |
| A242 (T) | 73,600 | 3/4 | MIL180 | on | 4 | 39,400 | 26,700 | 1.47 | 1.58 | 0.364 | 6 |
| A242 (Q) | 77,600 | 3/4 | MIL180 | on | 4 | 39,400 | - | 1.40* | -* | - | 6 |
| A242 (R) | 75,500 | 3/4 | E7016 | on | 5 | 34,000 | 24,100 | 1.64 | 1.60 | 0.319 | 7 |
| QT | 107,000 | 3/4 | E11016 | on | 5 | 38,100 | 25,600 | 1.63 | 1.60 | 0.240 | 7 |
| QT | 107,000 | 3/4 | E12016 | on | 5 | 38,800 | 24,900 | 1.61 | 1.65 | 0.233 | 7 |
| QT | 107,000 | 3/4 | E11016 | off | 5 | 42,500 | 27,600 | 1.46 | 1.49 | 0.259 | 7 |
| T-1 | 123,000 | 1/2 | E12015 | on | 3 1/2 | 50,000 | 21,000 | 1.52 | 2.38 | 0.171 | 8 |

* Estimated values.

## TABLE 12

AVERAGE RESULTS OF PREVIOUS AXIAL FATIGUE TESTS ON LONGITUDINAL BUTT WELDED JOINTS ON A ZERO-TO-TENSION STRESS CYCLE

| Material | UTS psi | Thickness in. | Electrode | Reinforcement | Length of Weld, in. | Fatigue Strength psi | | $K_e$ for Number of Cycles | | Fatigue Ratio | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $F_{100,000}$ | $F_{2,000,000}$ | 100,000 | 2,000,000 | | |
| A7 | 57,400 | 3/4 | E6010 | on | 20 | 37,400 | 24,500 | 1.44 | 1.42 | 0.426 | 1 |
| A7 | 57,400 | 3/4 | E6010 | off | 20 | 39,800 | 29,600 | 1.34 | 1.17 | 0.515 | 1 |
| A7 | 57,400 | 3/4 | E7016 | on | 20 | 41,700 | 26,300 | 1.28 | 1.32 | 0.457 | 1 |
| A7 | 57,400 | 3/4 | E7016 | off | 20 | 48,300 | 30,200 | 1.10 | 1.15 | 0.526 | 1 |
| A7 | 59,100 | 1/2 | E6010 | on | 32 | 38,500 | 24,300 | 1.28 | 1.30 | 0.409 | 5 |
| A7 | 59,100 | 1/2 | E6010 | off | 32 | 49,300 | 25,300 | 1.00 | 1.26 | 0.427 | 5 |
| A242 (P) | 76,700 | 3/4 | E7016 | on | 19 | 47,200 | 28,200 | 1.13 | 1.36 | 0.369 | 6 |
| A242 (T) | 73,600 | 3/4 | MIL180 | on | 19 | 45,100 | - | 1.28 | - | - | 6 |
| A242 (Q) | 77,600 | 3/4 | MIL180 | on | 19 | 42,200 | - | 1.31 | - | - | 6 |

TABLE 13

AVERAGE RESULTS OF PREVIOUS AXIAL FATIGUE TESTS
ON FILLET WELDED JOINTS ON A ZERO-TO-TENSION STRESS CYCLE

| Material | UTS psi | Type of Fillet | Electrode | Fatigue Strength psi | | $K_e$ for Number of Cycle | | Fatigue Ratio | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $F_{100,000}$ | $F_{2,000,000}$ | 100,000 | 2,000,000 | | |
| A7* | 57,400 | Longitudinal Fillets 'A' | E6010 | 21,500 | - | 2.49 | - | - | 10 |
| A7* | 57,400 | Longitudinal Fillets 'A' | E7016 | 22,700 | - | 2.35 | - | - | 10 |
| A7* | 57,400 | Longitudinal Fillets 'B' | E6010 | 27,000 | - | 1.97 | - | - | 10 |
| A7* | 57,400 | Longitudinal Fillets 'B' | E7016 | 27,900 | - | 1.92 | - | - | 10 |
| A7 | 61,000 | Longitudinal Fillets 'W' | - | 15,300 | 7,000 | 3.5 | 4.95 | 0.114 | 9 |
| A7 | 61,000 | Longitudinal Fillets 'Z' | - | 21,600 | 8,100 | 2.47 | 4.27 | 0.133 | 9 |
| A7 | 61,000 | Longitudinal Fillets 'T' | - | 21,000 | - | 2.55 | - | - | 9 |
| A7 | 61,000 | Longitudinal Fillets 'U' | - | 20,100 | - | 2.66 | - | - | 9 |
| A7 | 61,000 | Longitudinal Fillets 'V' | - | 14,200 | - | 3.76 | - | - | 9 |
| A7 | 61,000 | Longitudinal Fillets 'EZ' | - | 21,600 | - | 2.47 | - | - | 9 |
| A7 | 62,250 | Longitudinal Fillets | E6010 | 27,200 | 19,700 | 1.96 | 1.76 | 0.316 | 11 |
| A7 | 57,400 | Tee Fillets | E6010 | 22,600 | 11,300 | 2.36 | 3.07 | 0.197 | 10 |
| A7 | 57,400 | Tee Fillets | E7016 | 25,700 | 12,200 | 2.08 | 2.84 | 0.212 | 10 |
| A7 | 57,400 | Tee Fillets | MIL180 | 28,700 | 15,800 | 1.96 | 2.19 | 0.275 | 10 |
| A7 | 63,200 | Tee Fillets | E6012 | 19,100 | 9,630 | 2.80 | 3.6 | 0.152 | 11 |
| A7 | 63,700 | Transverse Fillets Single Pass | - | 30,300 | 18,500 | 1.77 | 1.88 | 0.291 | 11 |
| A7 | 63,700 | Plates connected with fillets | - | 21,640 | 9,640 | 2.47 | 3.60 | 0.157 | 11 |
| A7 | 63,700 | Combined Longitudinal and transverse fillets | - | 28,300 | 20,500 | 1.89 | 1.69 | 0.322 | 11 |
| A7 | 64,500 | Channels connected to Plates with Fillets | - | 16,650 | 9,070 | 3.21 | 3.83 | 0.140 | 11 |
| A242 (P) | 76,700 | Longitudinal Fillets | E7016 | 22,400 | - | 2.39 | - | - | 6 |
| A242 (P) | 76,700 | Tee Fillets | E7016 | 23,000 | 12,300 | 2.33 | 3.14 | 0.160 | 6 |

* Material same as used in Ref. 1.

## TABLE 14

### AXIAL FATIGUE STRENGTHS OF STRUCTURAL STEELS OBTAINED FROM TESTS OF DIFFERENT TYPES OF SPECIMENS

| Material | Type and Finish of Specimen | UTS ksi | $F_{2,000,000}$ | Fatigue Ratio | $K_e$ | Source |
|---|---|---|---|---|---|---|
| ASTM A7 | 3/8 in. dia., unnotched, polished* | 56.9 | 47.0 | 0.826 | 1.00 | Table 5 |
| ASTM A7 | 3/4 in. plate, as-rolled, 5 in. wide | 57.4 | 34.6 | 0.602 | 1.36 | Ref. 1 |
| ASTM A242 | 1/4 in. dia., unnotched, polished* | 73.6 | 62.0 | 0.842 | 1.00 | Table 6 |
| ASTM A242 | 1/4 in. dia., unnotched, rough turned | 73.6 | 54.0 | 0.734 | 1.15 | Table 6 |
| ASTM A242 | 3/4 in. plate, as-rolled, 4 in. wide | 73.6 | 42.5 | 0.577 | 1.46 | Ref. 6 |
| QT | 1/4 in. dia., unnotched, polished* | 126.6 | 122.0 | 0.964 | 1.00 | Table 7 |
| QT | 1/4 in. dia., unnotched, rough turned | 126.6 | 106.0 | 0.837 | 1.15 | Table 7 |
| T-1 | 1/2 in. plate, as-rolled, 3 1/2 in. wide | 123.0 | 50.0 | 0.407 | 2.44 | Ref. 8 |

* In the longitudinal direction.

TABLE 15

COMPARISON OF EFFECTIVE STRESS CONCENTRATION FACTORS OF NOTCHES AND TRANSVERSE BUTT WELDS WITH COMPARABLE FATIGUE STRENGTHS

| Type of Specimen | UTS psi | Fatigue Strength* (Zero-to-Tension) psi | $K_e$** | Results from |
|---|---|---|---|---|
| ASTM A7 STEEL | | | | |
| Notched, $K_t$ = 7.0 | 56,900 | 25,000 | 1.88 | Table 5 |
| Transverse Butt Weld | 57,400 | 24,000 | 1.44 | Ref. 1 |
| ASTM A242 STEEL (B) | | | | |
| Notched, $K_t$ = 7.00 | 73,600 | 28,000 | 2.21 | Table 6 |
| Transverse Butt Weld* | 73,600 | 26,700 | 1.58 | Ref. 6 |
| QT STEEL | | | | |
| Notched, $K_t$ = 3.80 | 126,600 | 26,000 | 4.70 | Table 7 |
| Transverse Butt Weld | 107,000 | 25,600 | 1.60 | Ref. 7 |

*In Ref. 6, this steel is designated as 'T'.

**For notched specimens, the basic fatigue strength taken was that of polished specimen whereas for welds it was that of plate specimens in the as-rolled condition.

TABLE 16

RESULTS OF MICROSCOPIC EXAMINATION OF THE ROOTS OF NOTCHED SPECIMENS OF ASTM A7 STEEL WHICH DID NOT FAIL

| Specimen | Root Radius* $\rho$, in. | $K_t$** | Maximum Stress*** psi | No. of Cycles $10^3$ | Notch Root Shown In |
|---|---|---|---|---|---|
| ASS-272 | 0.0025 | 7.00 | 25,000 | 2,897+ | Fig. 47 |
| ASS-269 | 0.0025 | 7.00 | 25,000 | 2,849+ | Fig. 48 |
| ASS-281 | 0.0035 | 6.00 | 21,000 | 5,399+ | Fig. 48 |
| ASS-280 | 0.0035 | 6.00 | 20,000 | 3,969+ | Fig. 48 |
| ASS-190 | 0.0050 | 5.15 | 19,000 | 5,357+ | Fig. 49 |
| ASS-191 | 0.0050 | 5.15 | 19,000 | 5,219+ | Fig. 49 |
| ASS-199 | 0.0065 | 4.65 | 20,000 | 5,366+ | Fig. 49 |
| ASS-240 | 0.0075 | 4.35 | 20,000 | 6,365+ | Fig. 50 |
| ASS-242 | 0.0075 | 4.35 | 21,000 | 5,417+ | Fig. 50 |
| ASS-254 | 0.0100 | 3.80 | 21,000 | 4,921+ | Fig. 51 |
| ASS-255 | 0.0100 | 3.80 | 21,000 | 5,356+ | Fig. 51 |

*Critical $\rho$ = 0.004 in.

**Critical $K_t$ = 5.67.

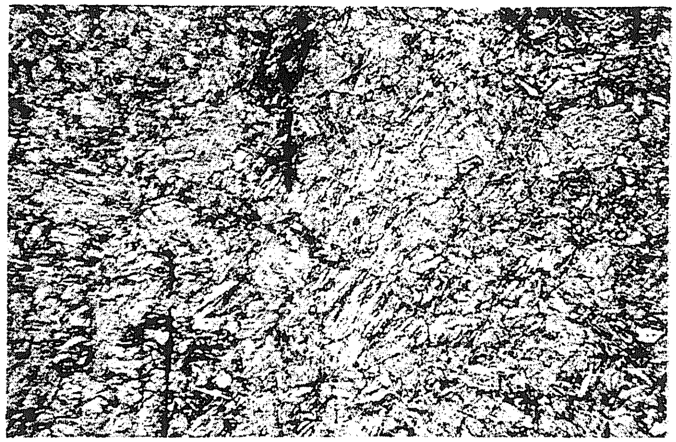
***Minimum stress for all specimens = 1,000 psi.

A-7 x250

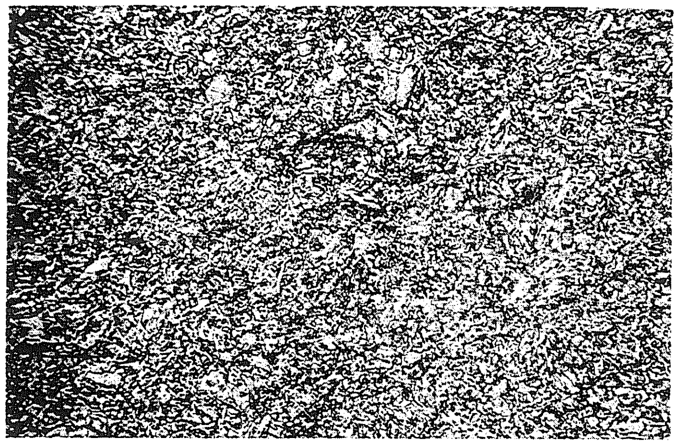
A-242(R) x250

A-242(B) x250

FIG. 1 TYPICAL MICROSTRUCTURES OF STEELS

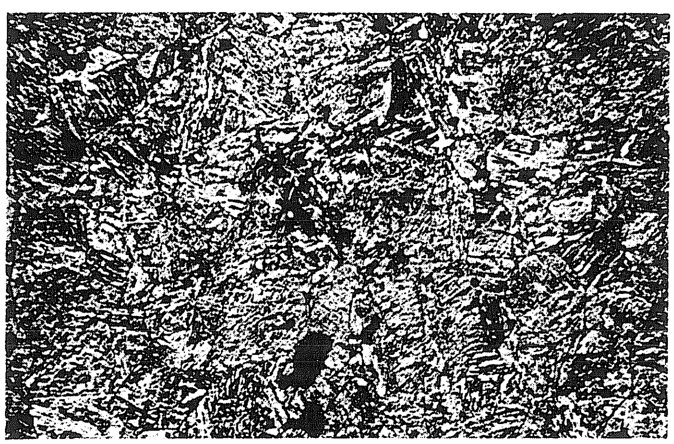


QT, as received x250



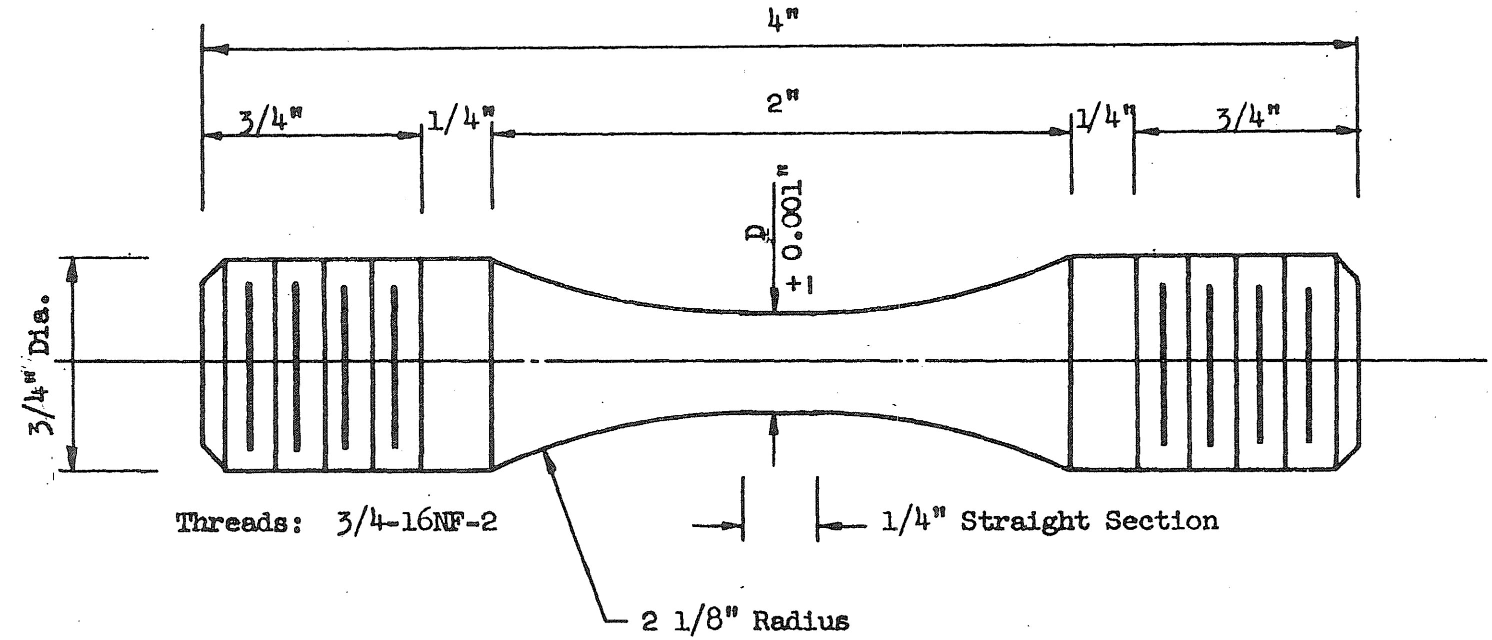
QT, heat-treated x250

FIG. 2(a) TYPICAL MICROSTRUCTURES OF STEEL



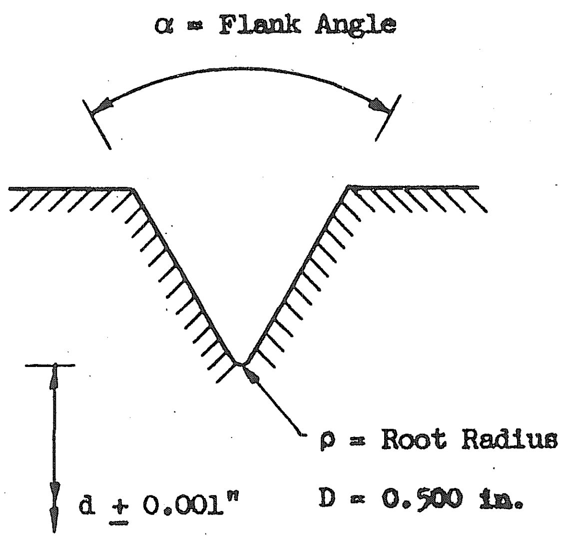
HAZ in QT x250

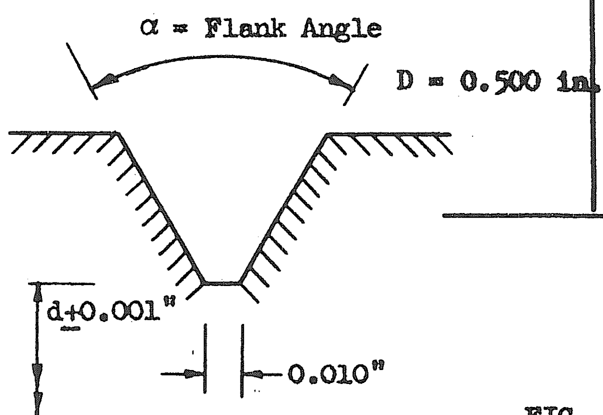
FIG. 2(b) TYPICAL MICROSTRUCTURE OF A WELD HEAT-AFFECTED ZONE IN QT STEEL




| Specimen Type | D |
|---|---|
| A | 1/2" (All Notched Specimens) |
| B | 3/8" (Unnotched Specimens A7) |
| C | 1/4" (Unnotched Specimens A242, QT) |

FIG. 3 DETAILS OF AXIAL FATIGUE SPECIMENS




| Detail of Notch | Designation of Notch | α deg. | ρ in. | d in. | $K_t$ |
|---|---|---|---|---|---|
| (upper drawing) | V100 | 60 | 0.0100 | 0.400 | 3.80 |
| | V80 | 60 | 0.0080 | 0.400 | 4.20 |
| | V75 | 60 | 0.0075 | 0.400 | 4.35 |
| | V65 | 60 | 0.0065 | 0.400 | 4.65 |
| | V50 | 60 | 0.0050 | 0.400 | 5.15 |
| | V35 | 60 | 0.0035 | 0.400 | 6.00 |
| | V25 | 60 | 0.0025 | 0.400 | 7.00 |
| | P50 | 30 | 0.0050 | 0.437 | 4.75 |
| | Q50 | 30 | 0.0050 | 0.422 | 4.96 |
| (lower drawing) | Y | 60 | - | 0.400 | - |

FIG. 4 DETAILS AND DESIGNATION OF NOTCHES

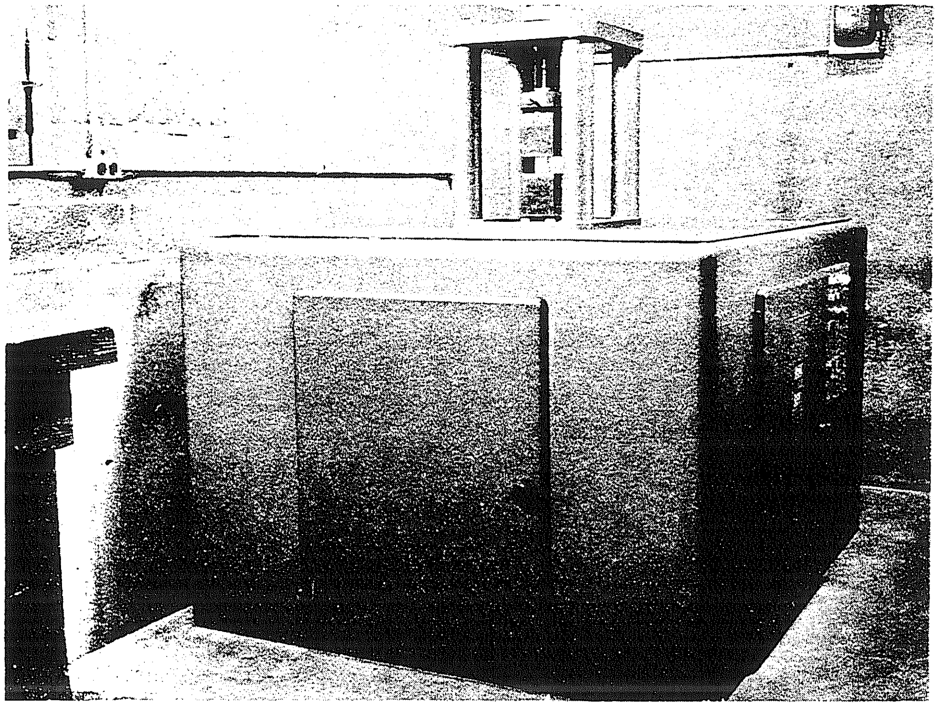


FIG. 5 GENERAL VIEW OF SONNTAG FATIGUE TESTING MACHINE

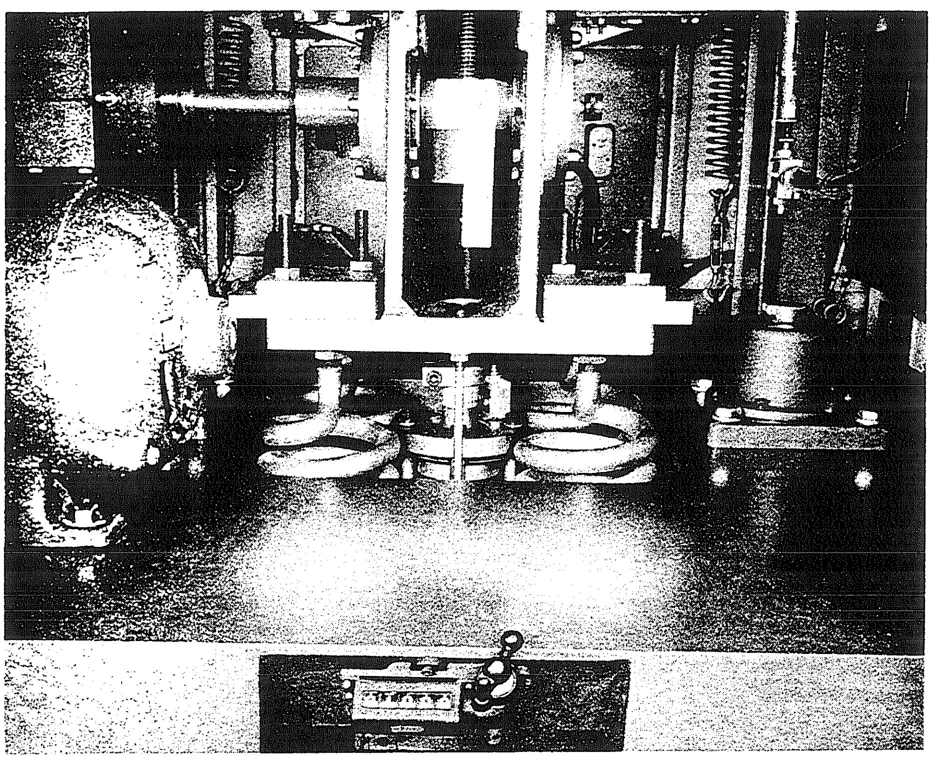


FIG. 6 INTERIOR VIEW OF THE SONNTAG MACHINE SHOWING THE OSCILLATOR, ITS SUPPORTING MECHANISM AND THE PRELOAD COUNTER

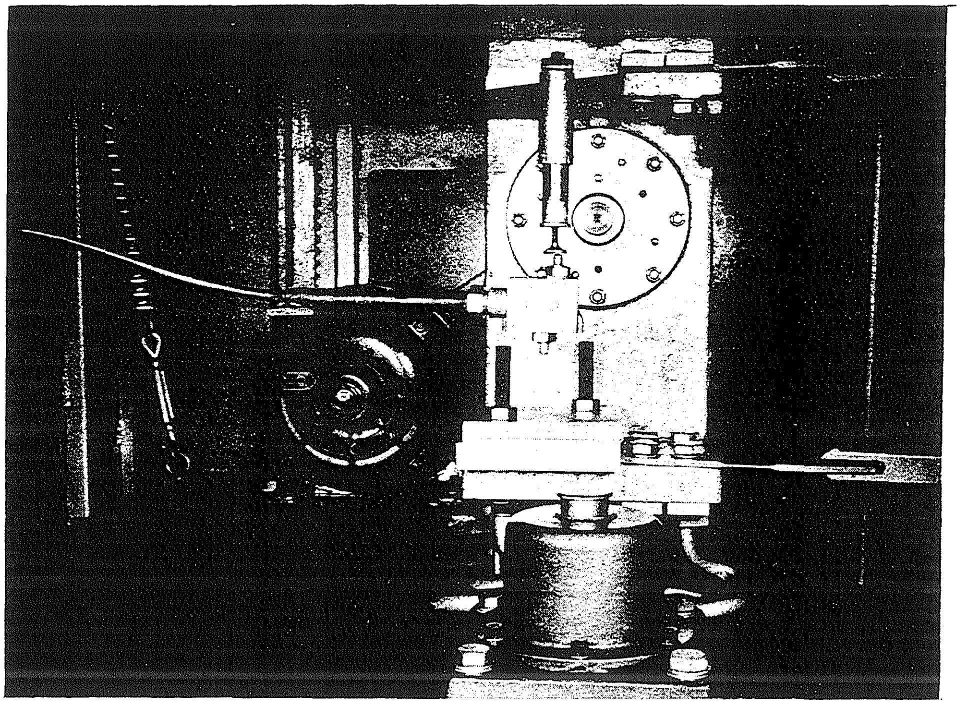


FIG. 7 INTERIOR VIEW OF THE SONNTAG MACHINE SHOWING THE OSCILLATOR AND THE ADDITIONAL LIMIT SWITCH

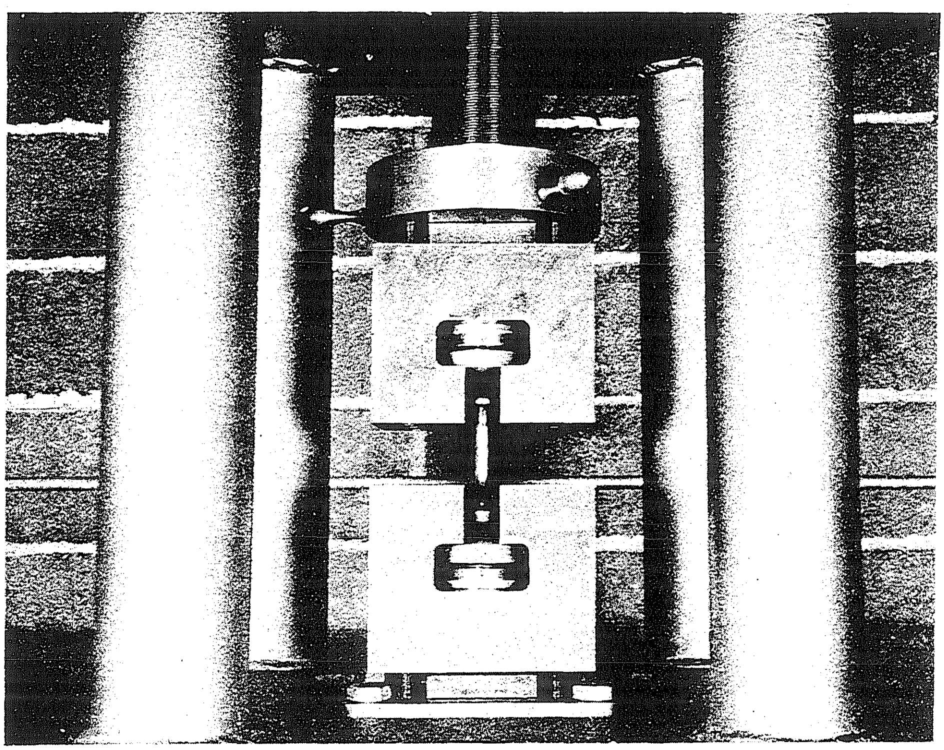


FIG. 8 SIDE VIEW OF SONNTAG TENSION-COMPRESSION APPARATUS

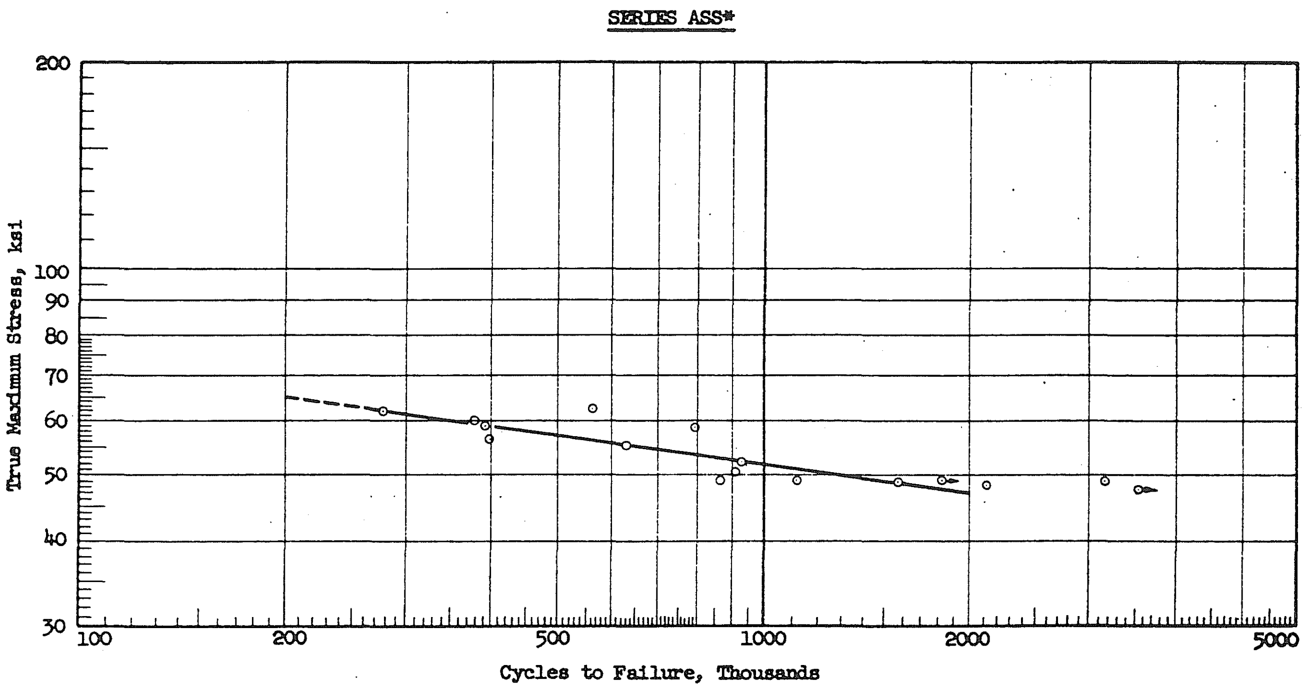



FIG. 9 RESULTS OF AXIAL FATIGUE TESTS ON THREE-EIGHTH INCH DIAMETER LONGITUDINALLY POLISHED UNNOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS*

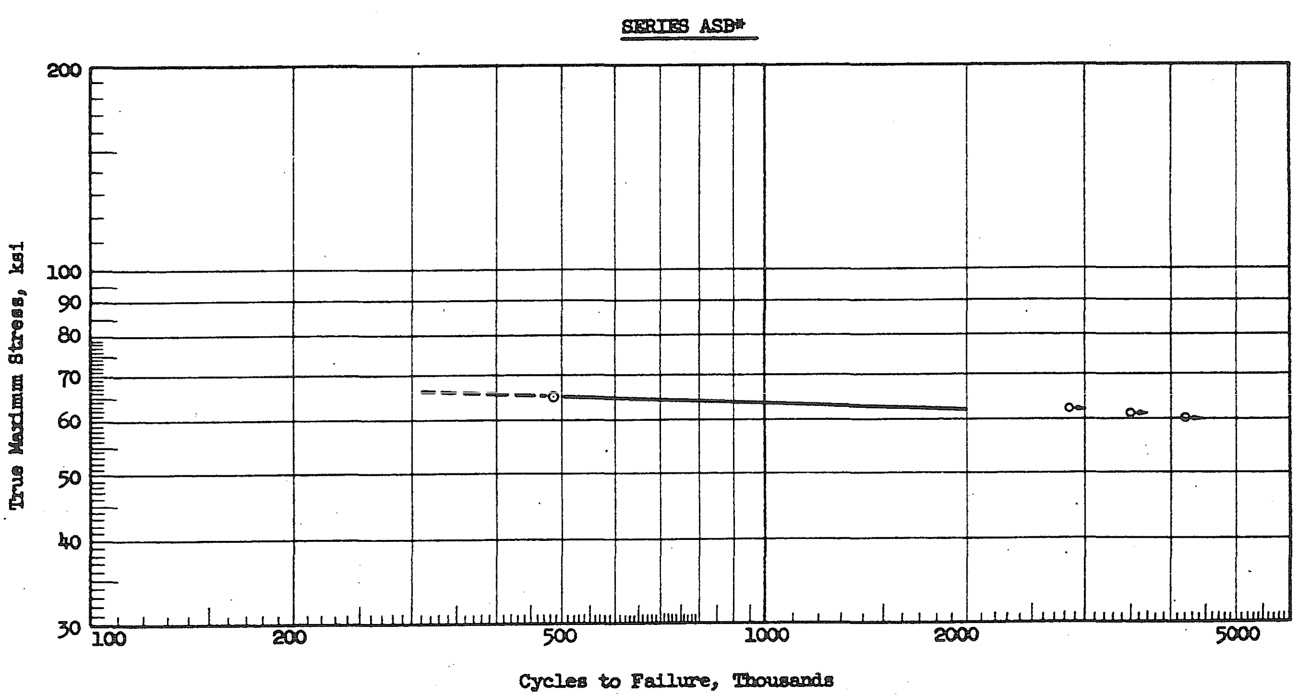



FIG. 10 RESULTS OF AXIAL FATIGUE TESTS ON ONE-QUARTER INCH DIAMETER LONGITUDINALLY POLISHED UNNOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB*

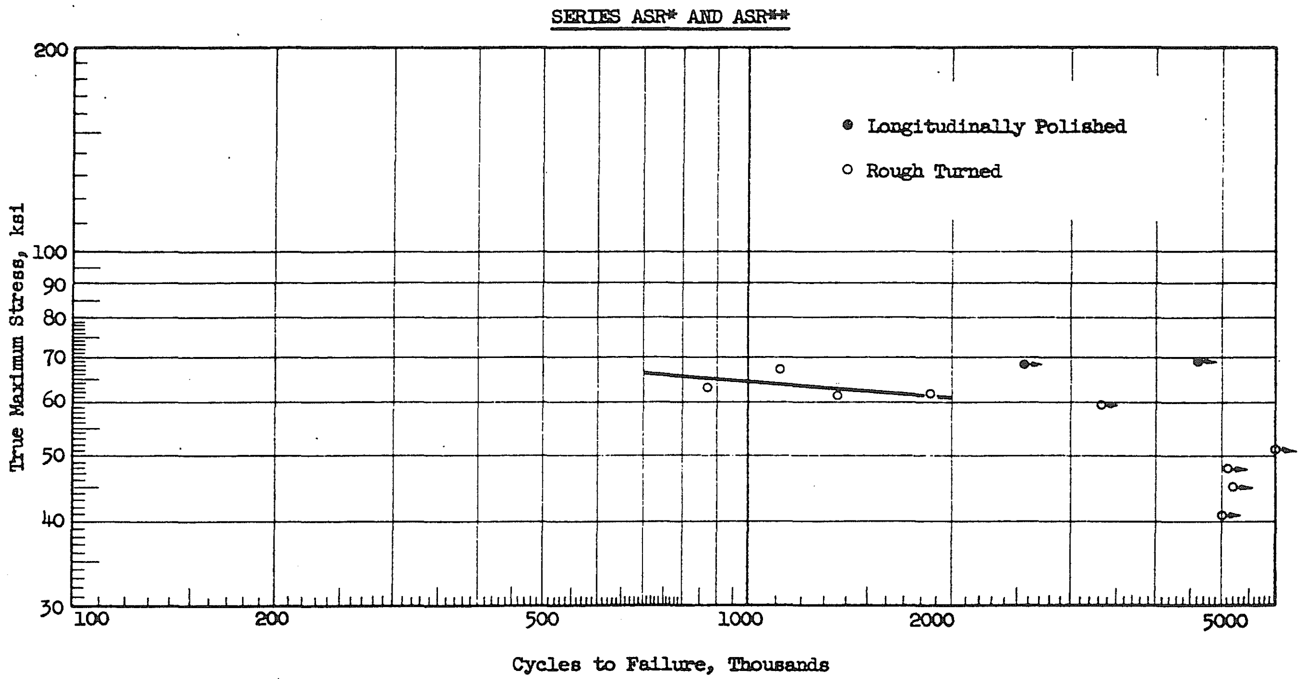



FIG. 11 RESULTS OF AXIAL FATIGUE TESTS ON ONE-QUARTER INCH DIAMETER UNNOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION R), SERIES ASR* AND ASR**

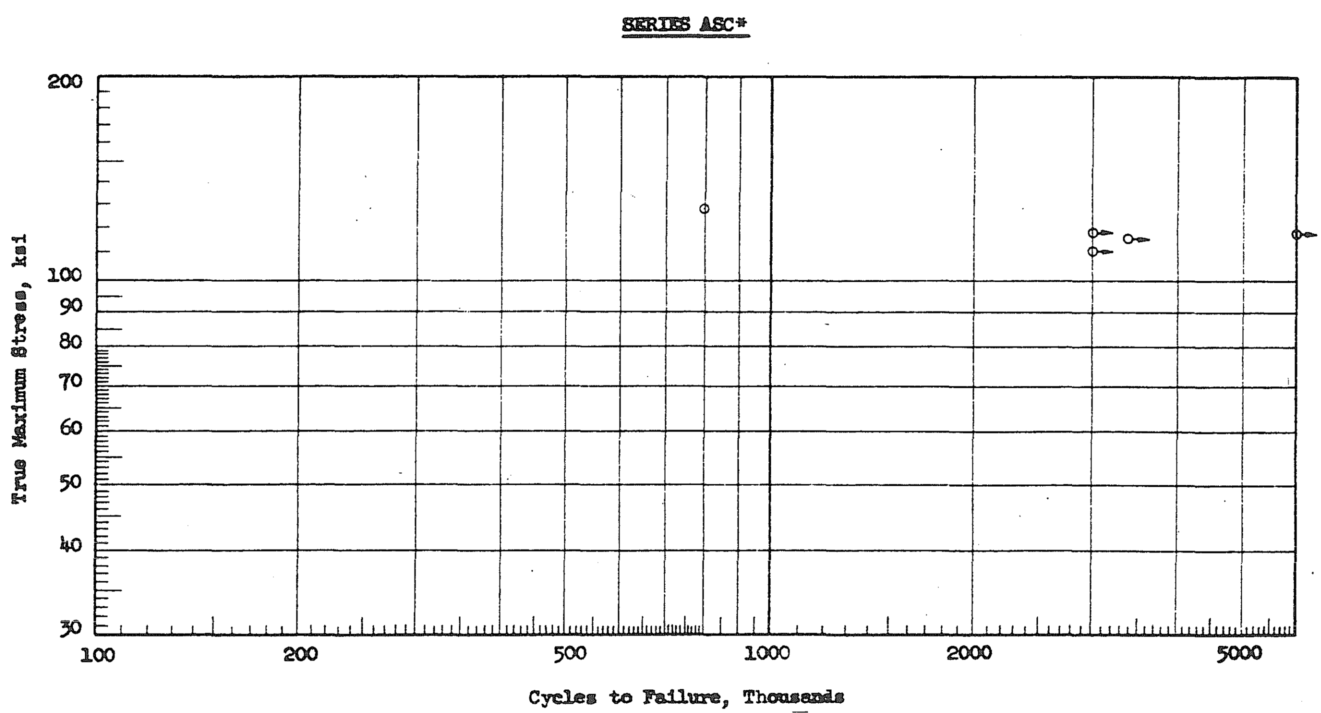



FIG. 12 RESULTS OF AXIAL FATIGUE TESTS ON ONE-QUARTER INCH DIAMETER LONGITUDINALLY POLISHED UNNOTCHED SPECIMENS OF QT STEEL, SERIES ASC*

**SERIES ASB****

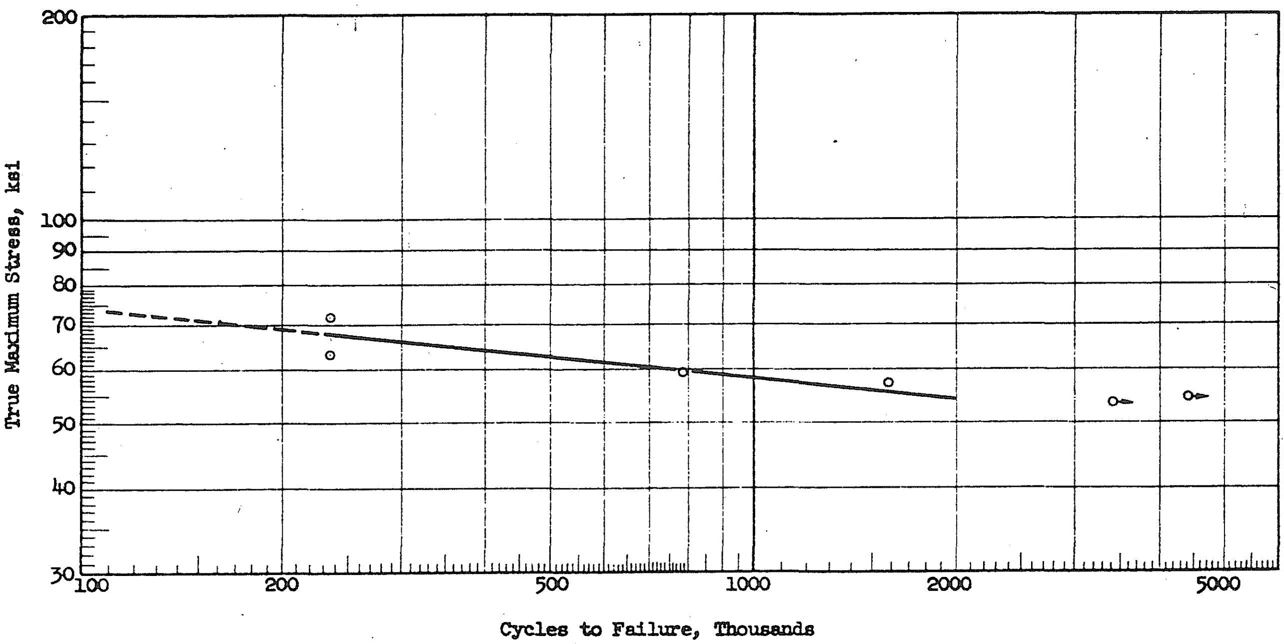



FIG. 13 RESULTS OF AXIAL FATIGUE TESTS ON ONE-QUARTER INCH DIAMETER ROUGH TURNED UNNOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB**

**SERIES ASC****

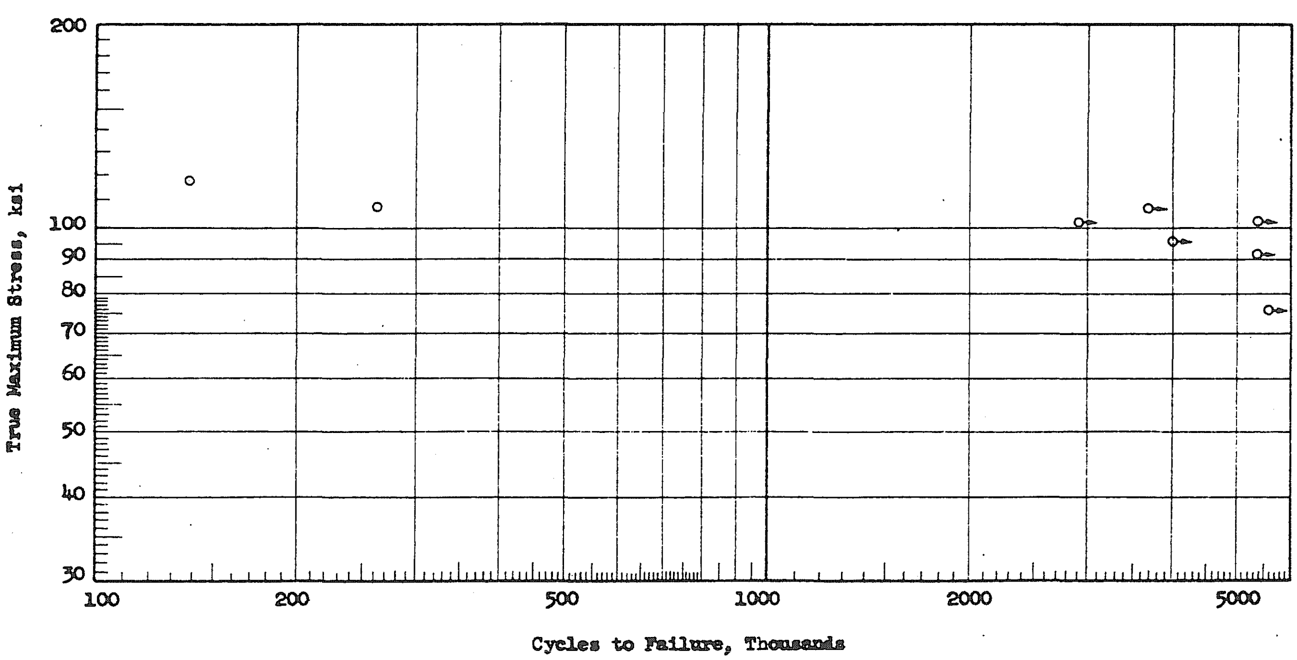



FIG. 14 RESULTS OF AXIAL FATIGUE TESTS ON ONE-QUARTER INCH DIAMETER ROUGH TURNED UNNOTCHED SPECIMENS OF QT STEEL, SERIES ASC**

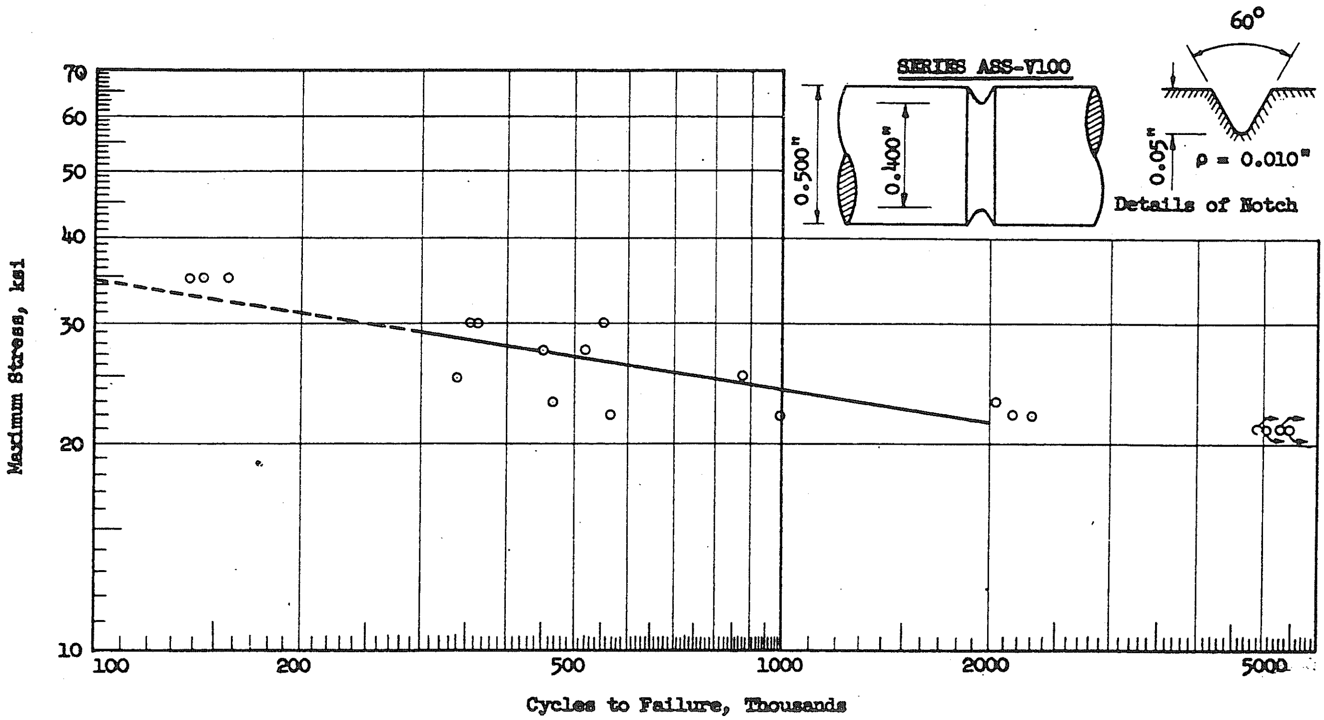



FIG. 15 **RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V100**

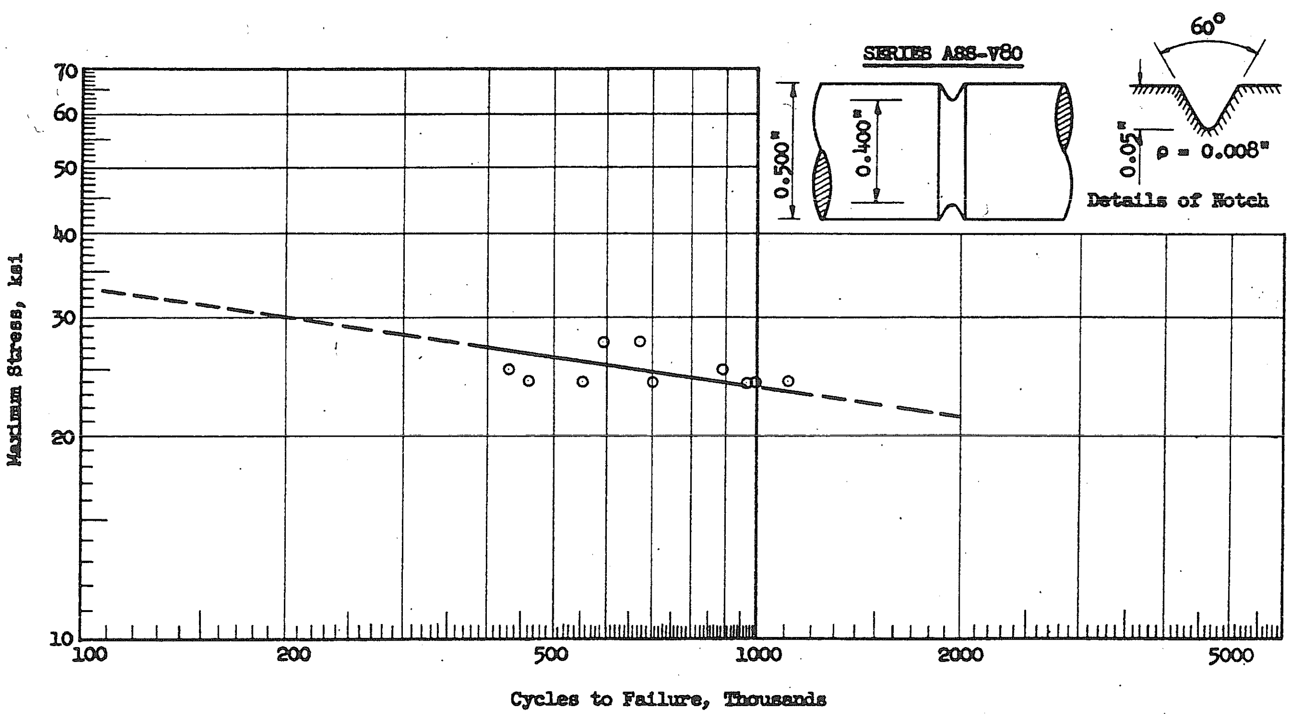



FIG. 16 **RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V80**

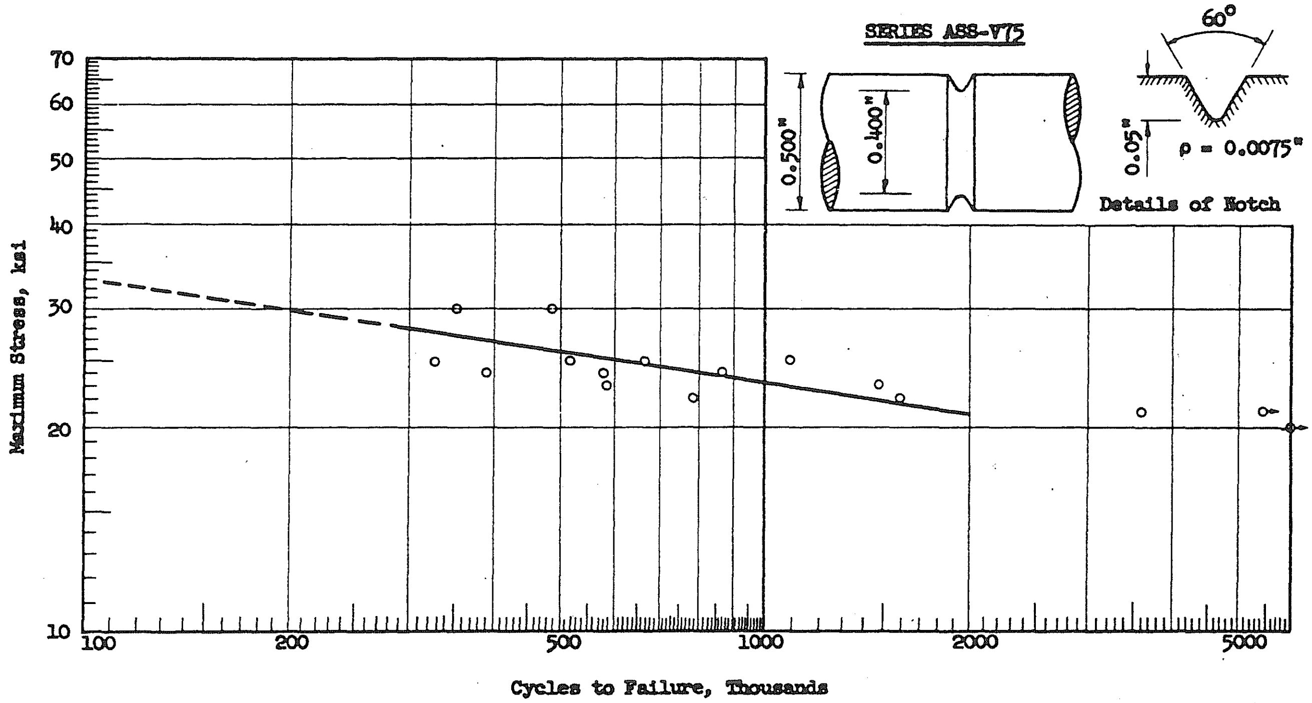



FIG. 17 **RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V75**

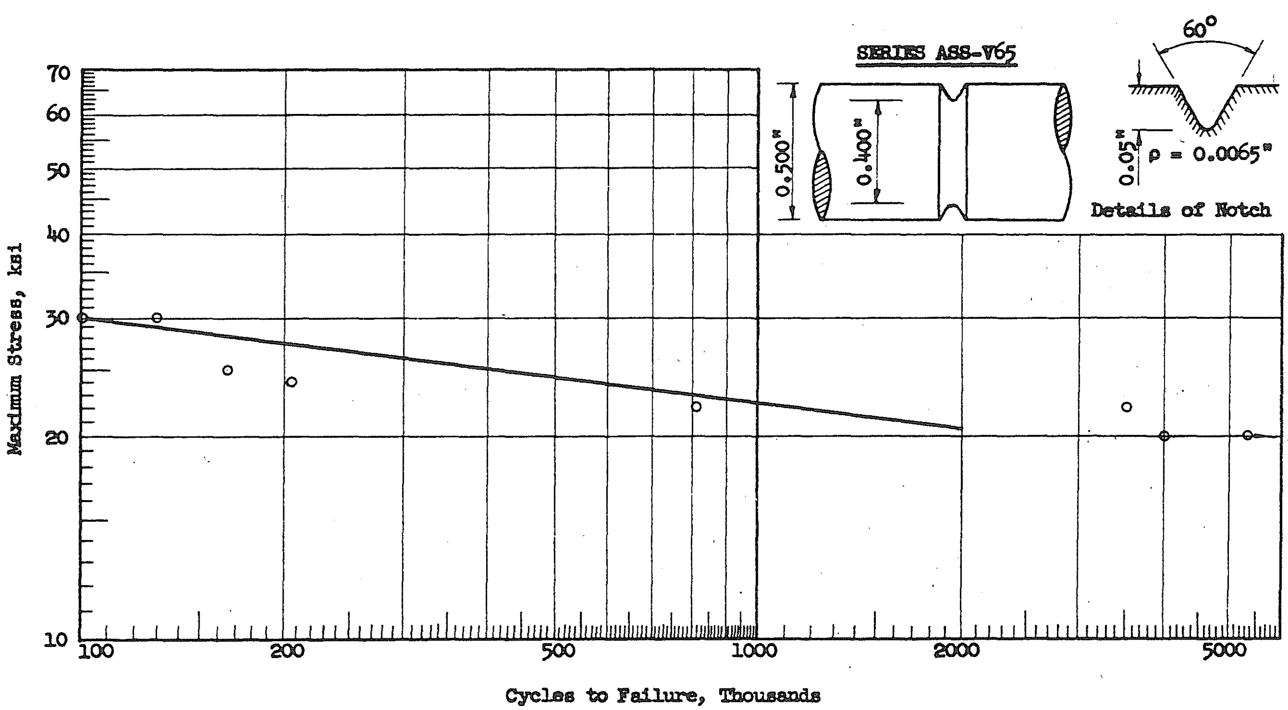



FIG. 18 **RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V65**

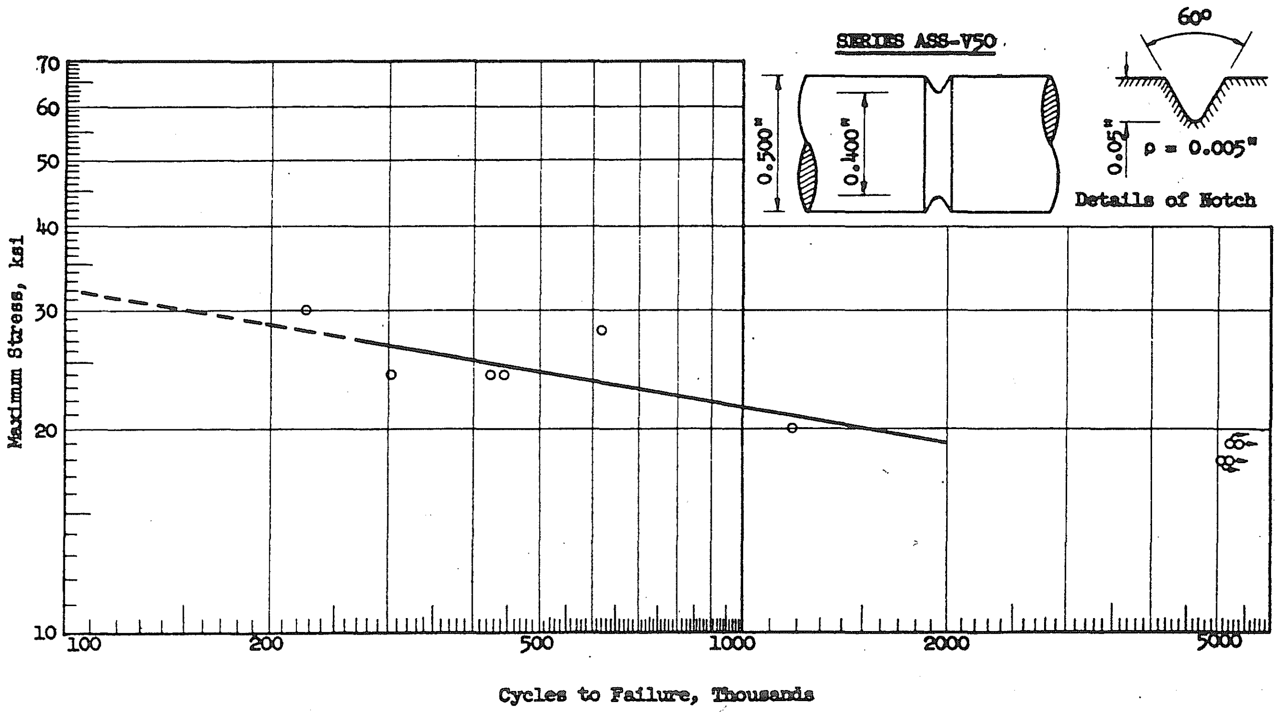



FIG. 19 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V50

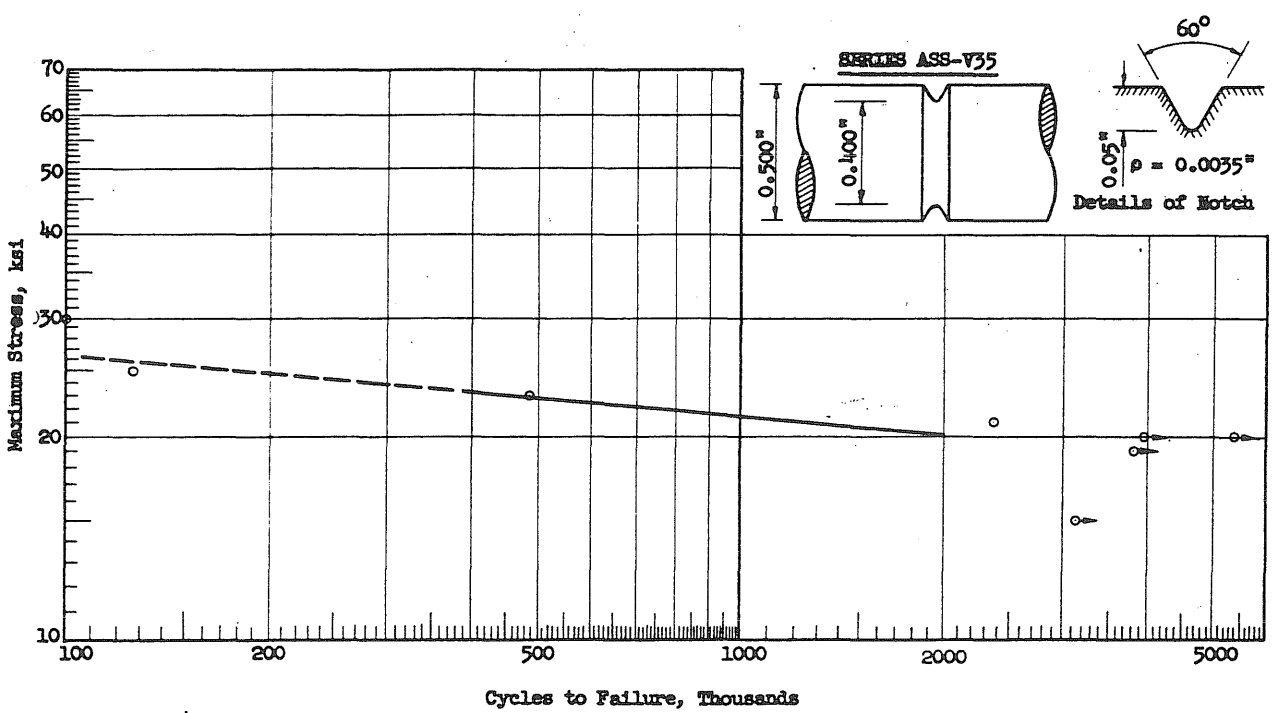



FIG. 20 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V35

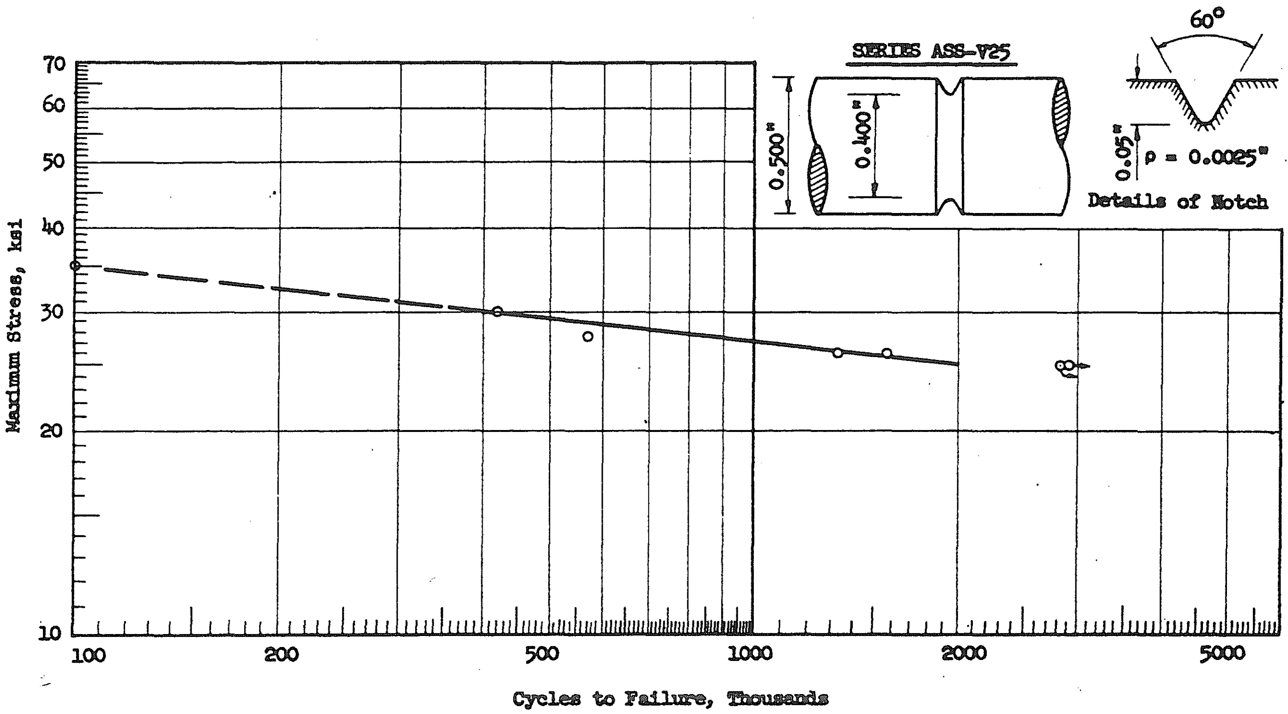



FIG. 21 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-V25

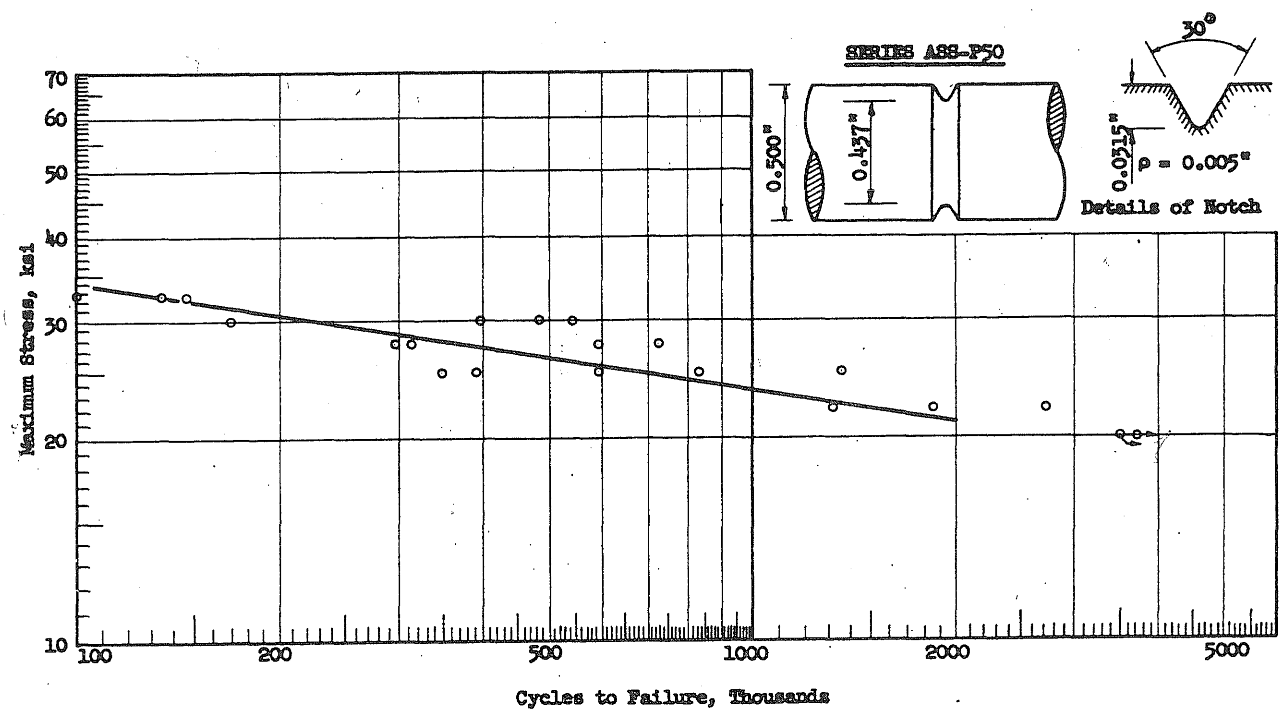



FIG. 22 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-P50

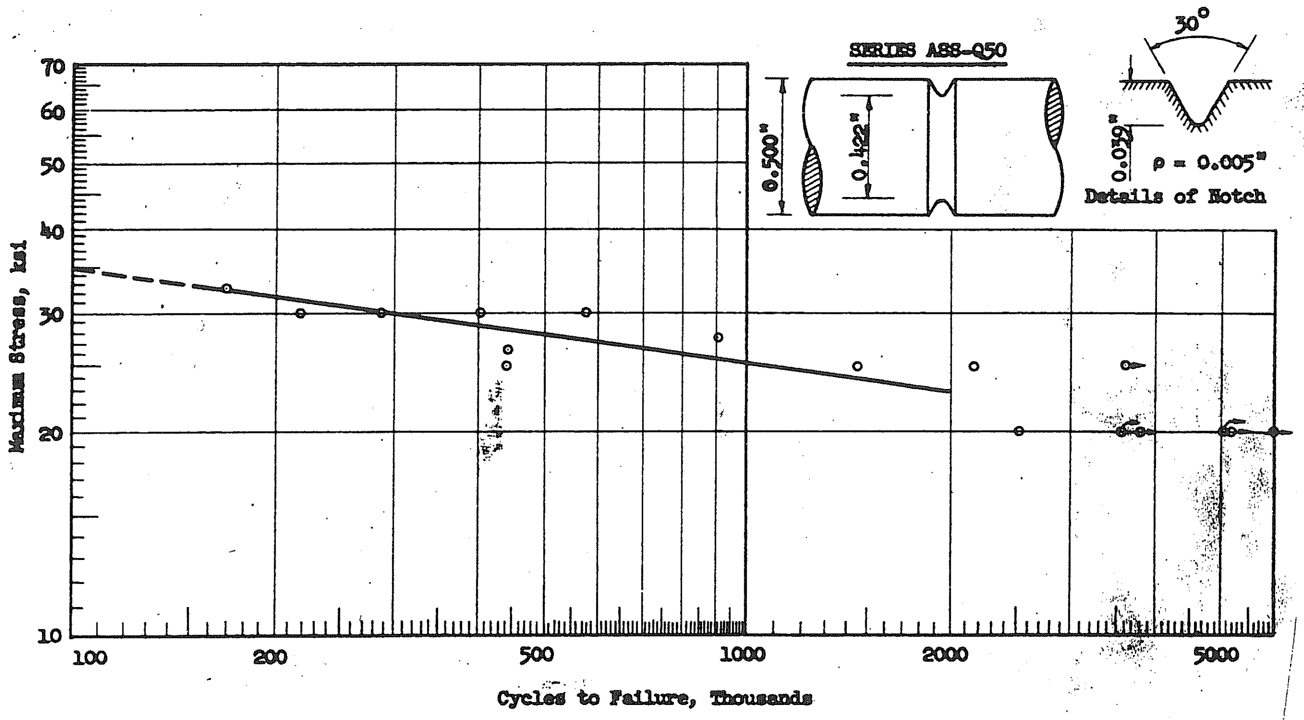



FIG. 23 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-Q50

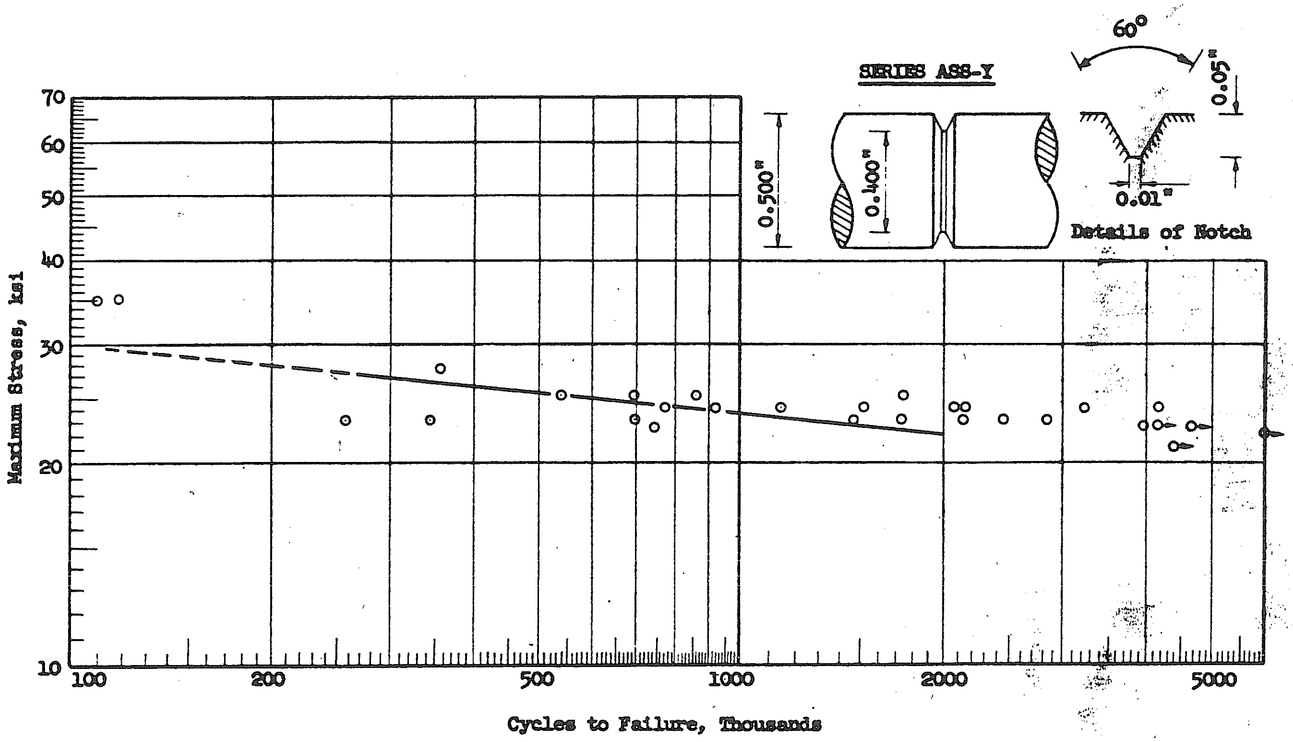



FIG. 24 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-7 STEEL, SERIES ASS-Y

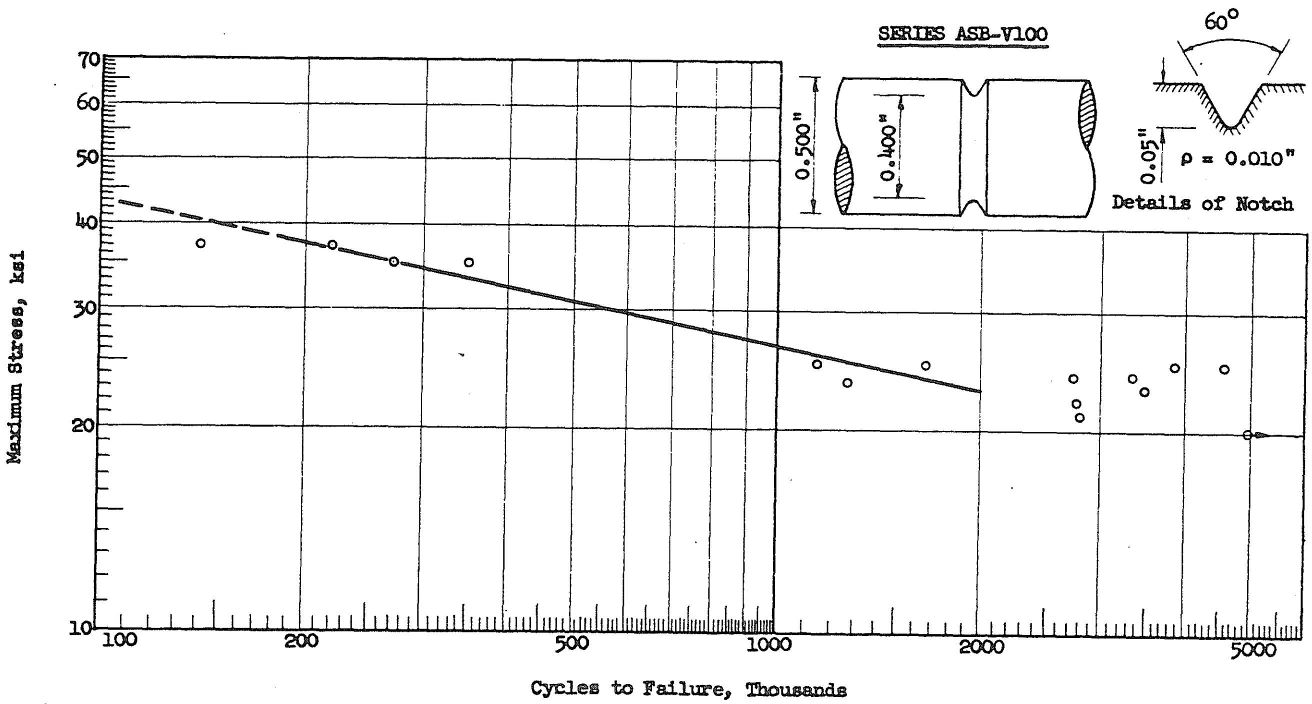



FIG. 25 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB-V100

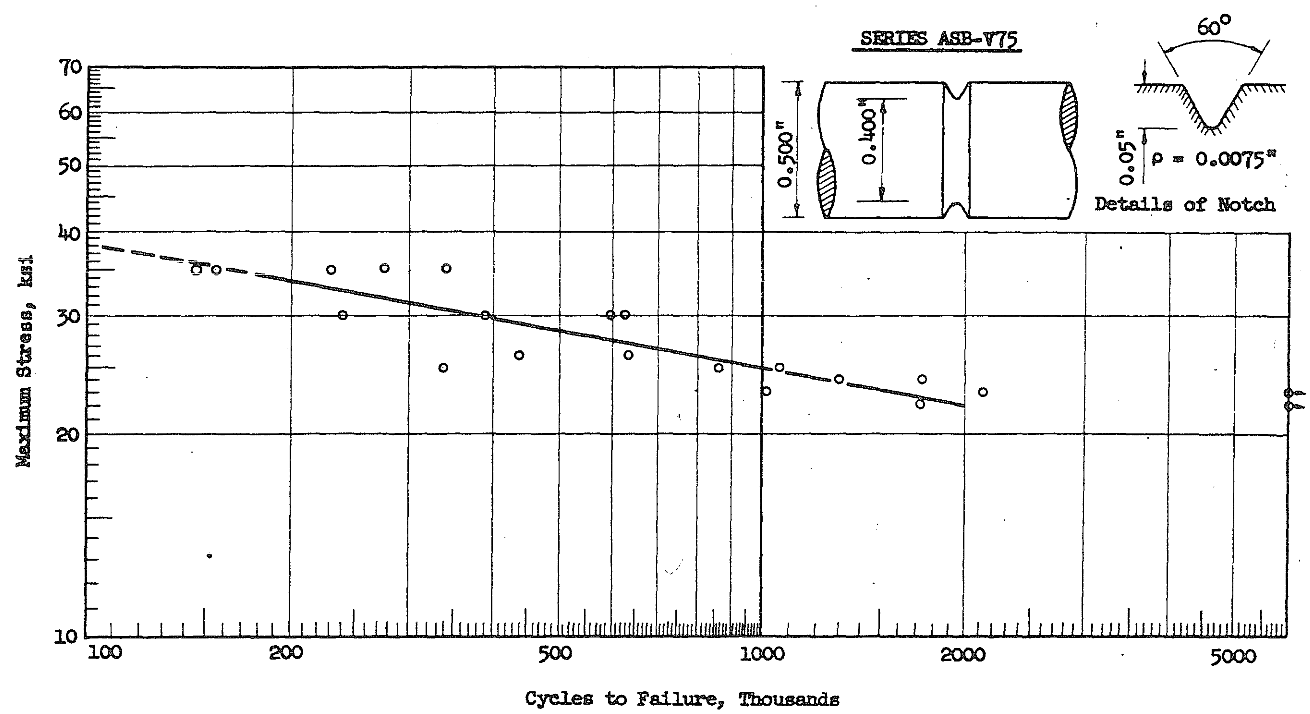



FIG. 26 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB-V75

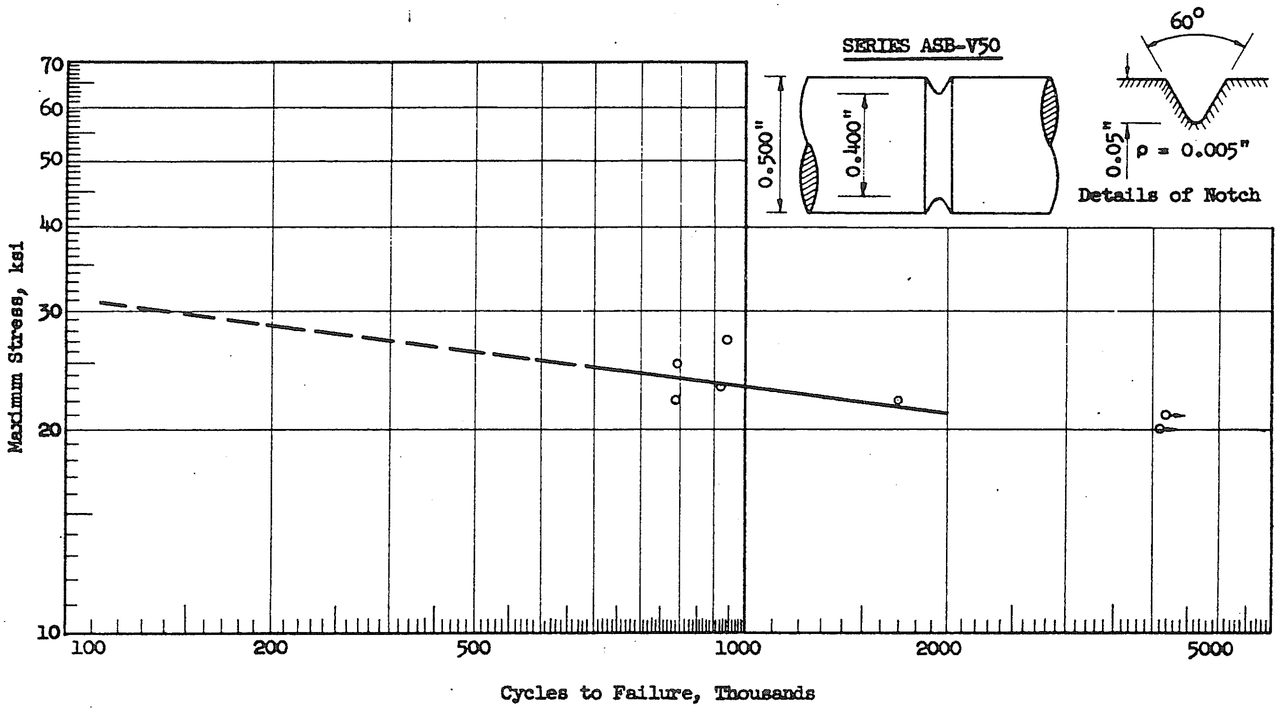



FIG. 27 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB-V50

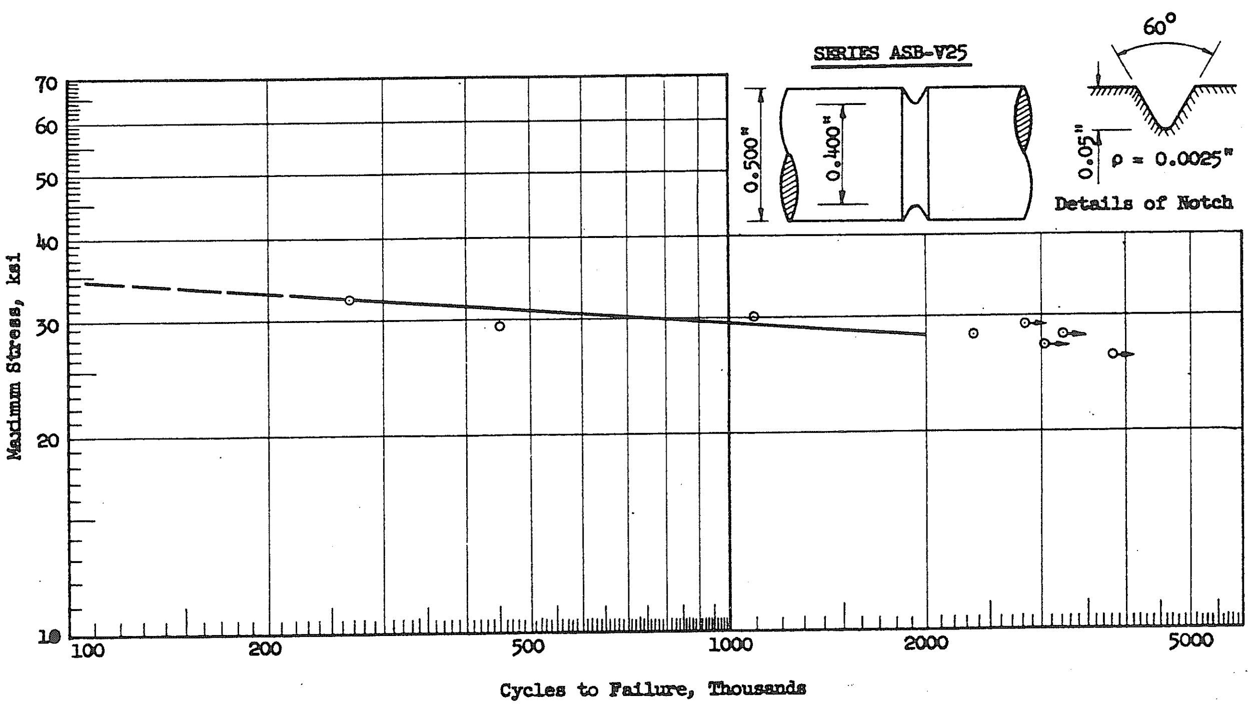



FIG. 28 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB-V25

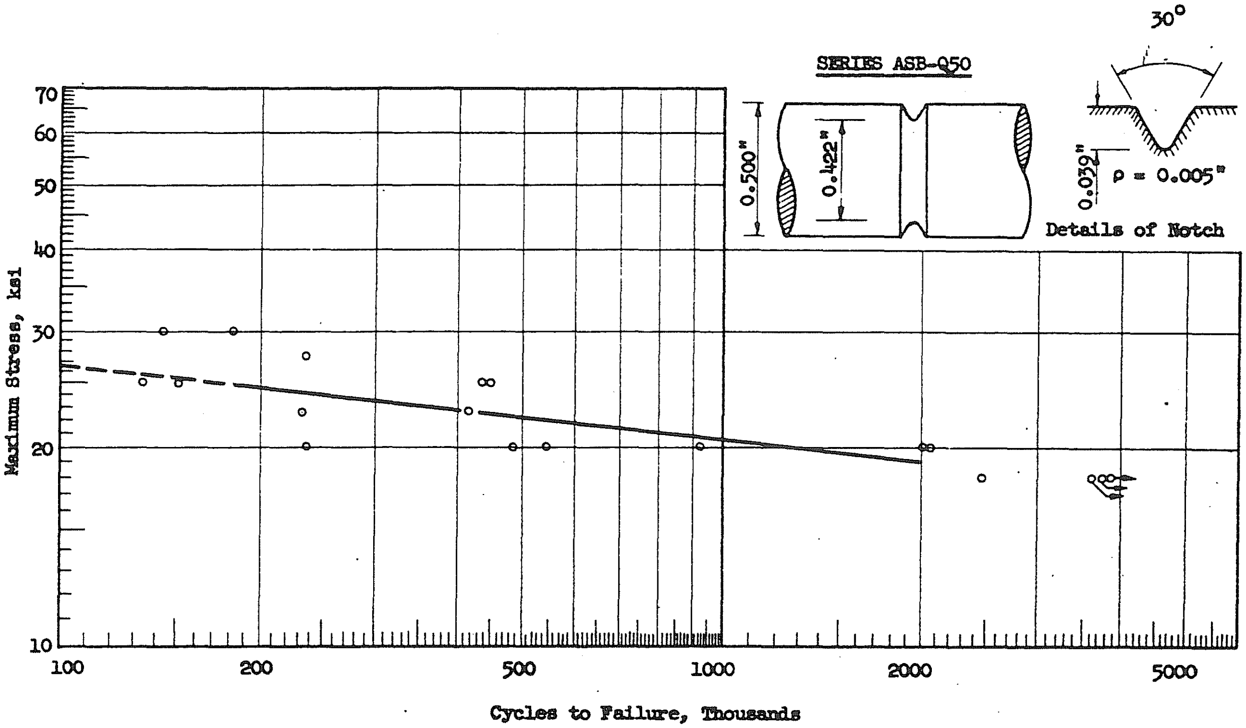



FIG. 29 **RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB-Q50**

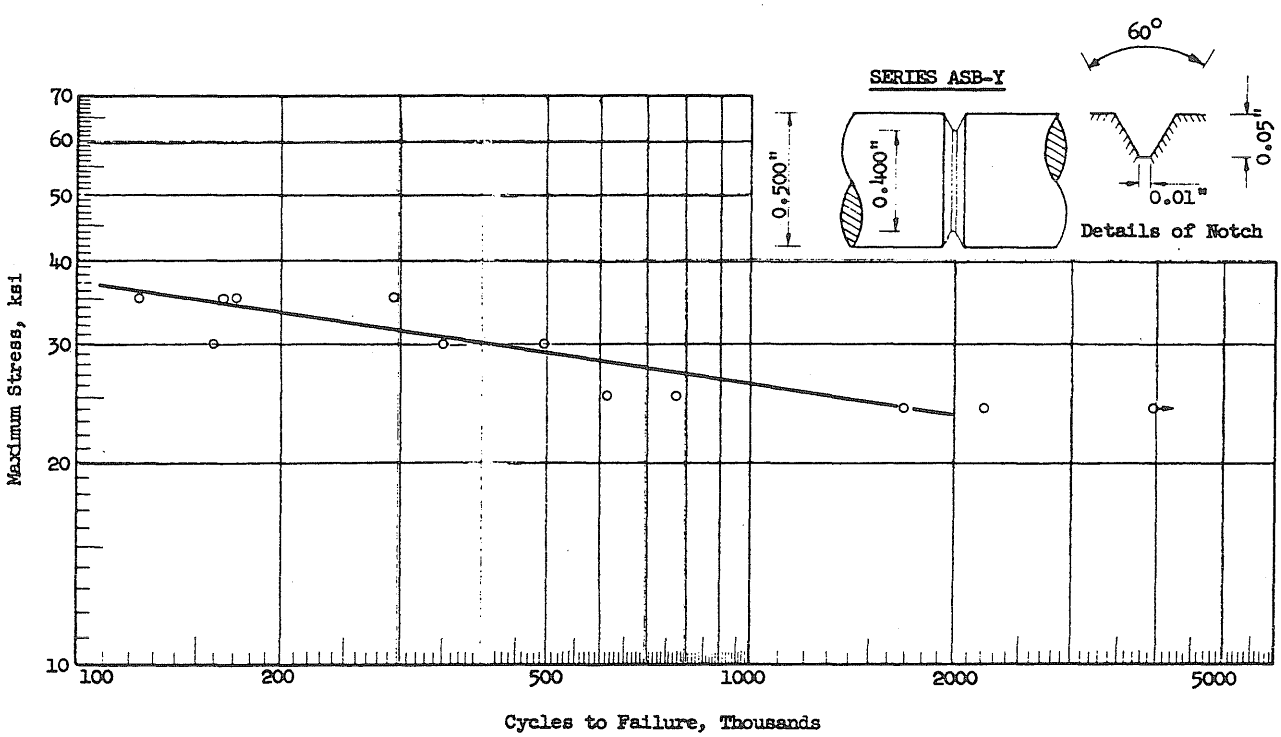



FIG. 30 **RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION B), SERIES ASB-Y**

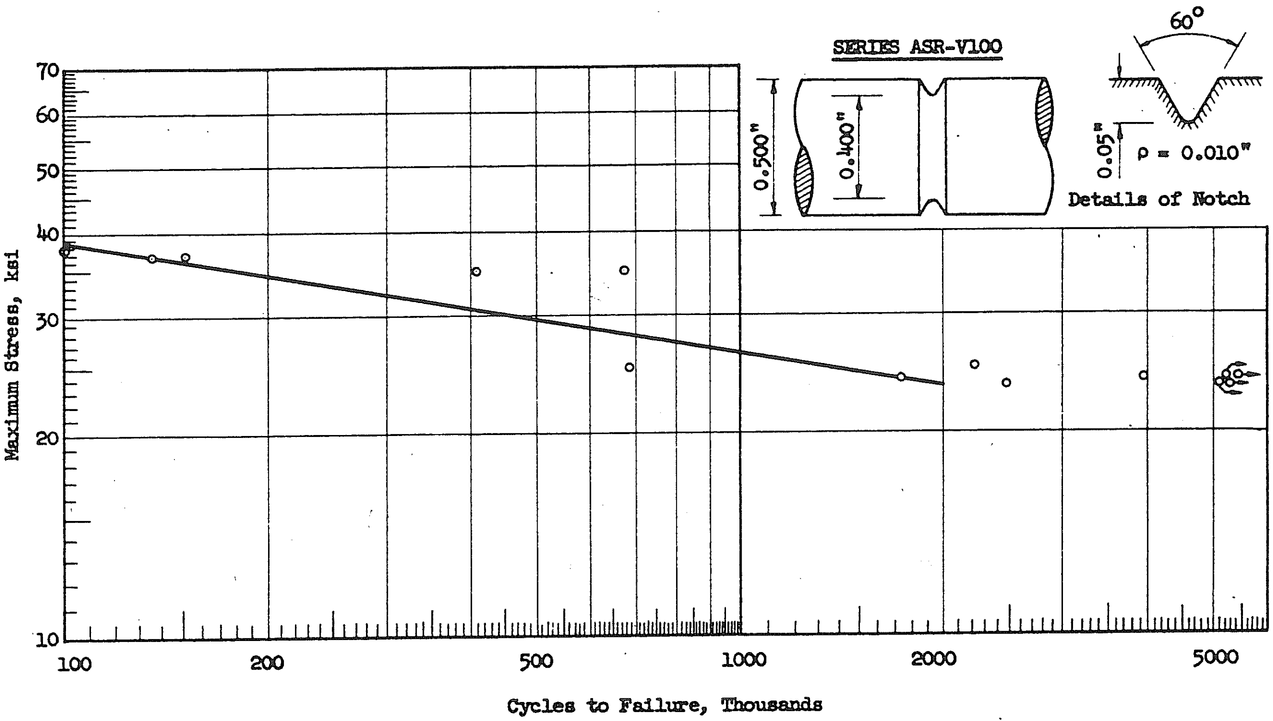



FIG. 31 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL ( DESIGNATION R), SERIES ASR-V100

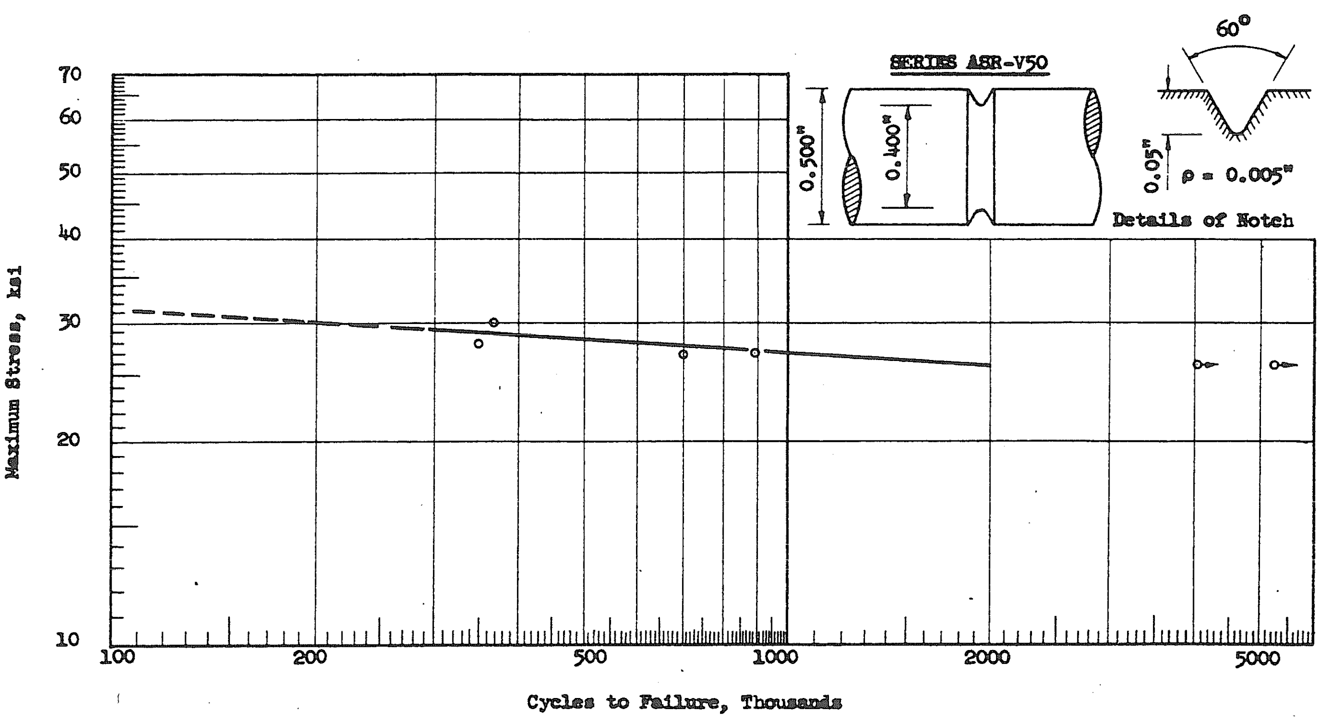



FIG. 32 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION R), SERIES ASR-V50

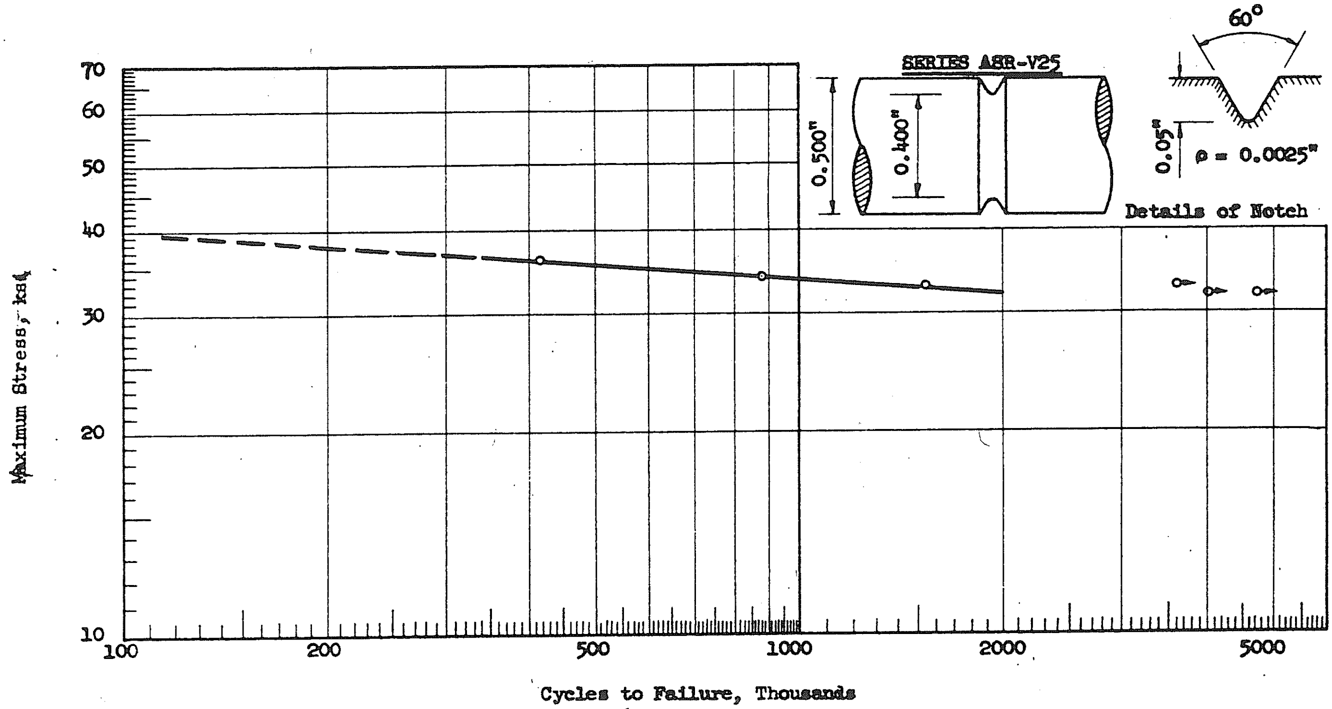



FIG. 33 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF A-242 STEEL (DESIGNATION R), SERIES ASR-V25

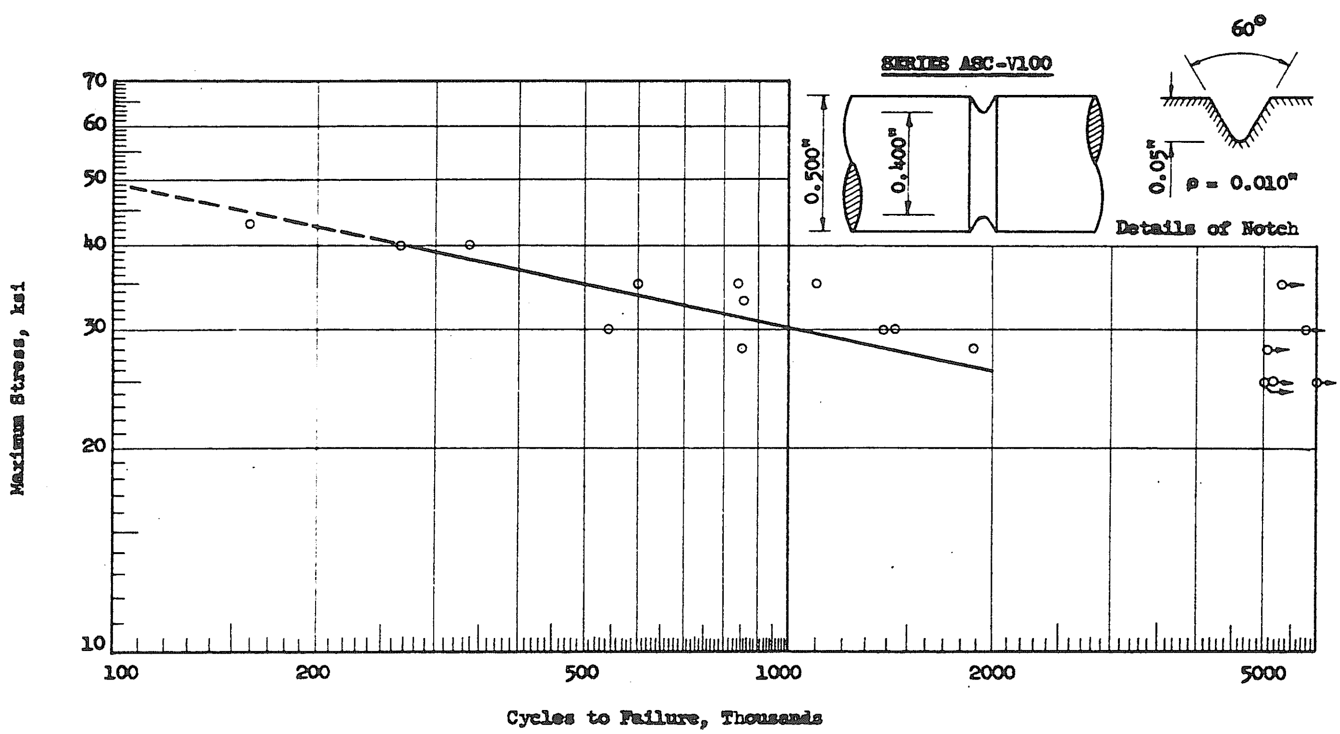



FIG. 34 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF QT STEEL, SERIES ASC-V100

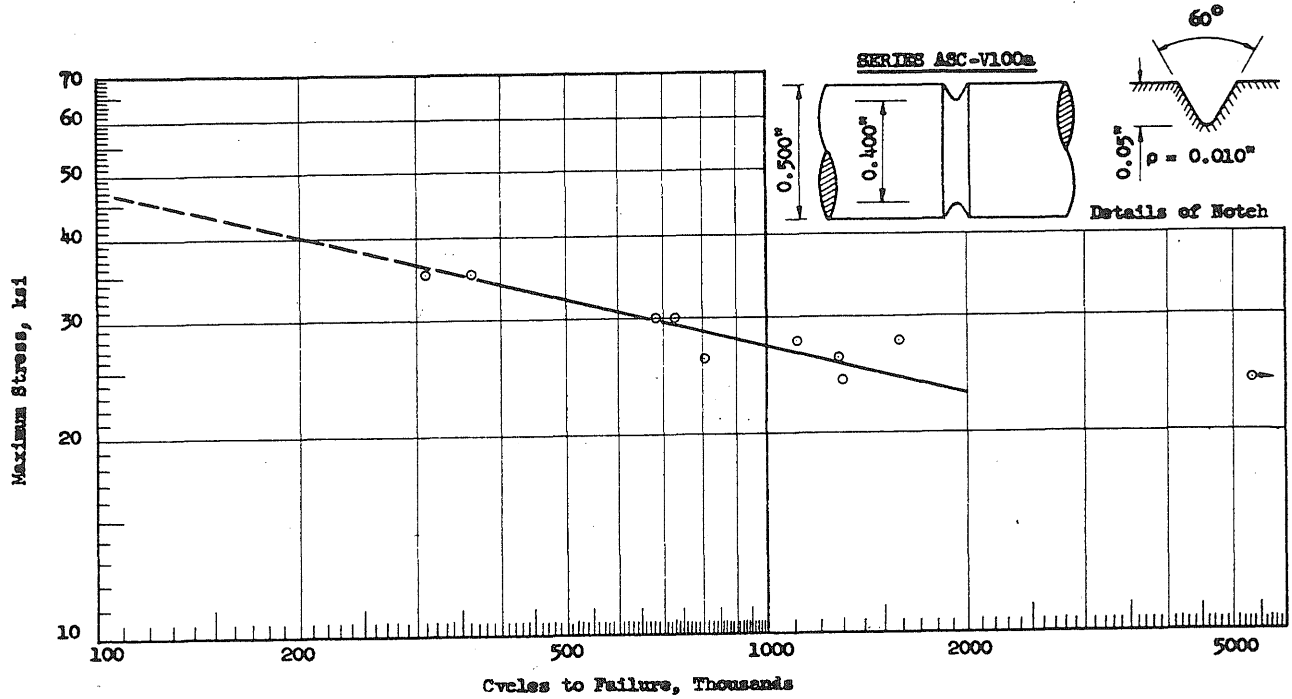



FIG. 35 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF HEAT-TREATED QT STEEL (NOTCHED BEFORE HEAT TREATMENT), SERIES ASC-V100a

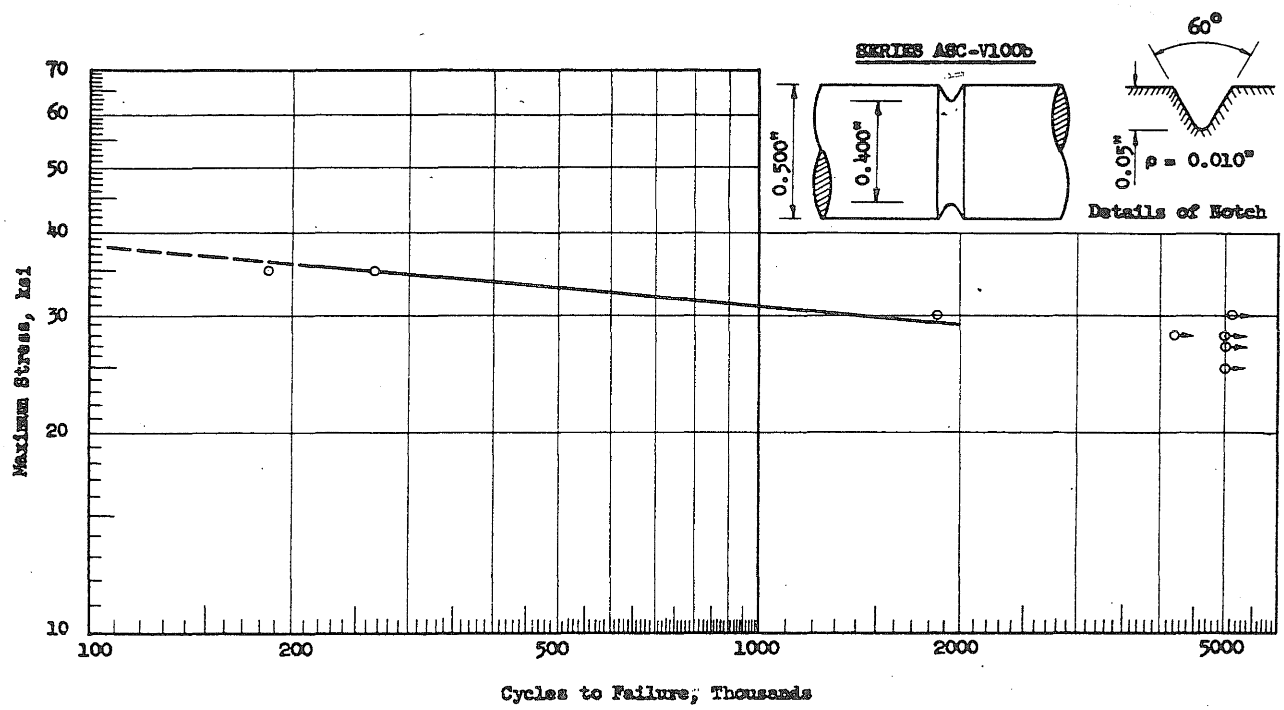



FIG. 36 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF HEAT-TREATED QT STEEL (NOTCHED AFTER HEAT TREATMENT), SERIES ASC-V100b

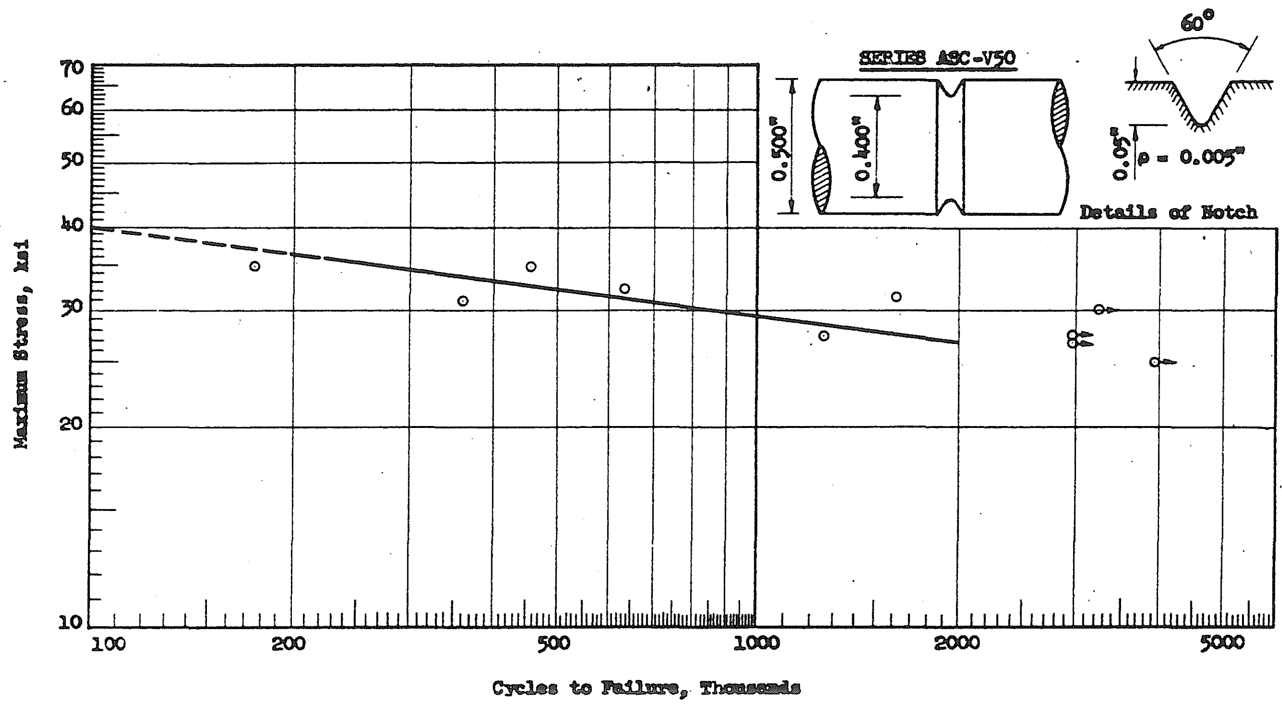



FIG. 37 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF QT STEEL, SERIES ASC-V50

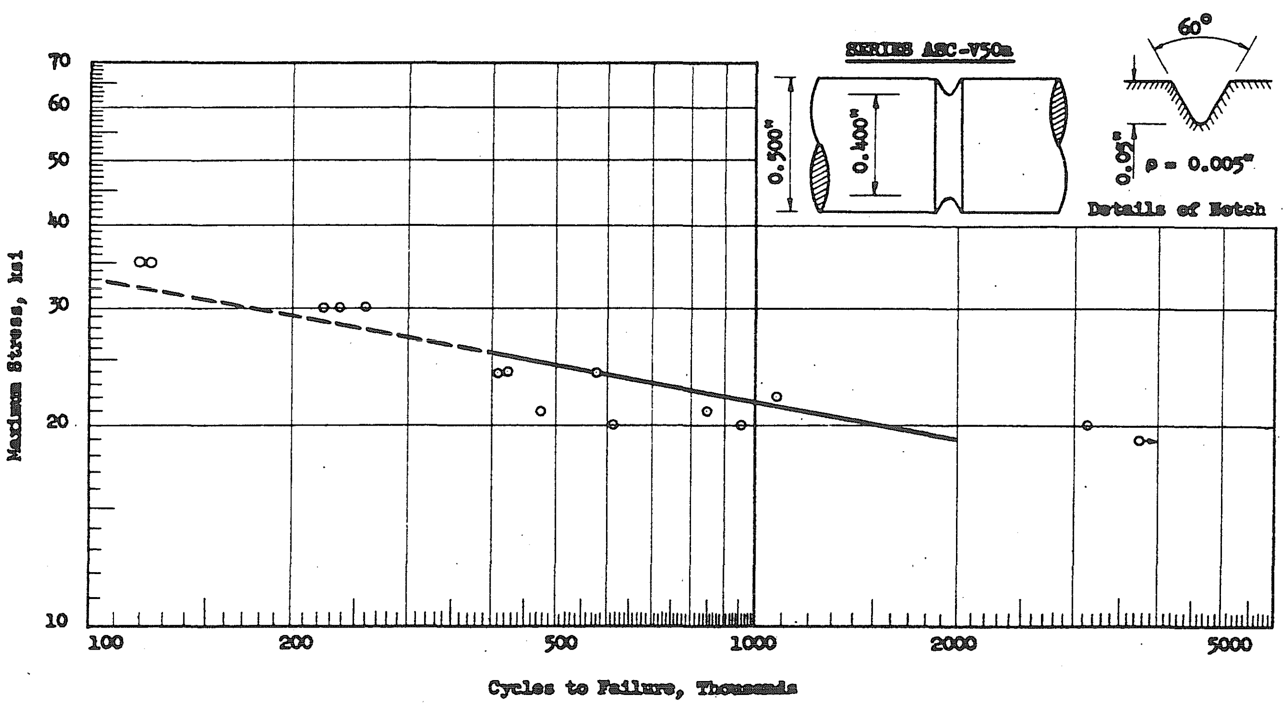



FIG. 38 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF HEAT-TREATED QT STEEL (NOTCHED BEFORE HEAT TREATMENT), SERIES ASC-V50a

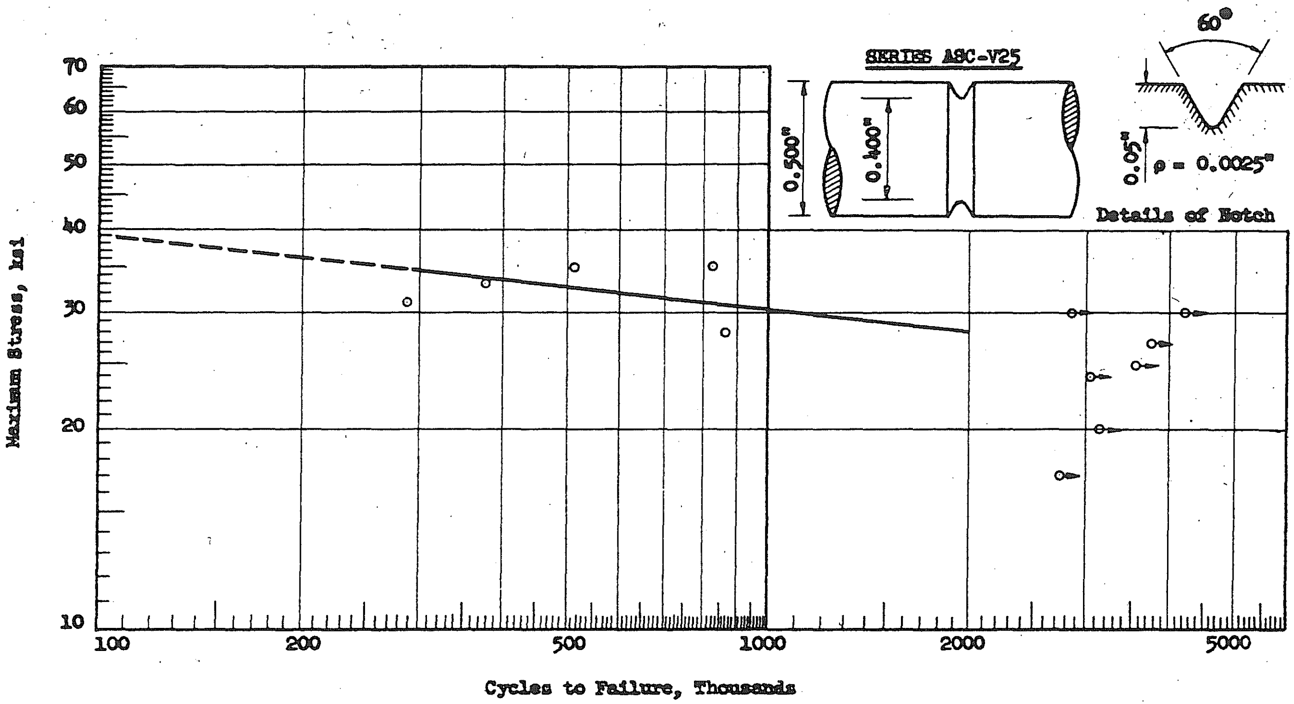



FIG. 39 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF QT STEEL, SERIES ASC-V25

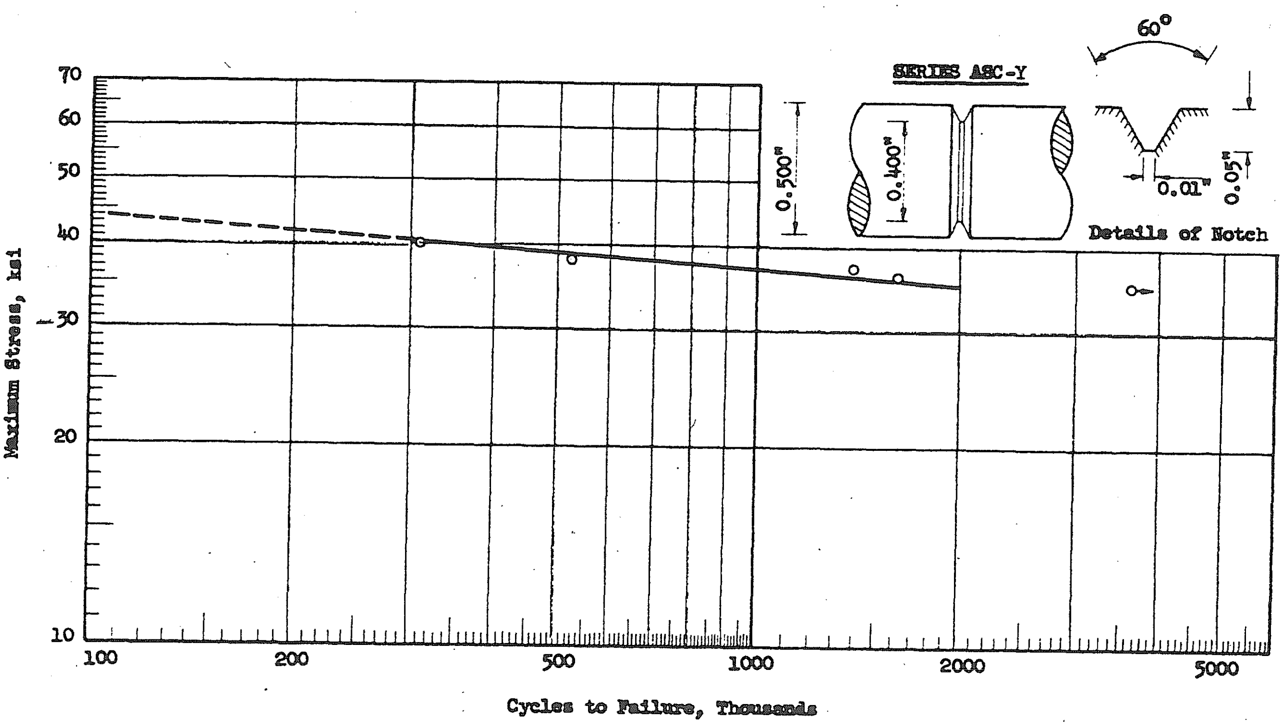



FIG. 40 RESULTS OF AXIAL FATIGUE TESTS ON NOTCHED SPECIMENS OF QT STEEL, SERIES ASC-Y

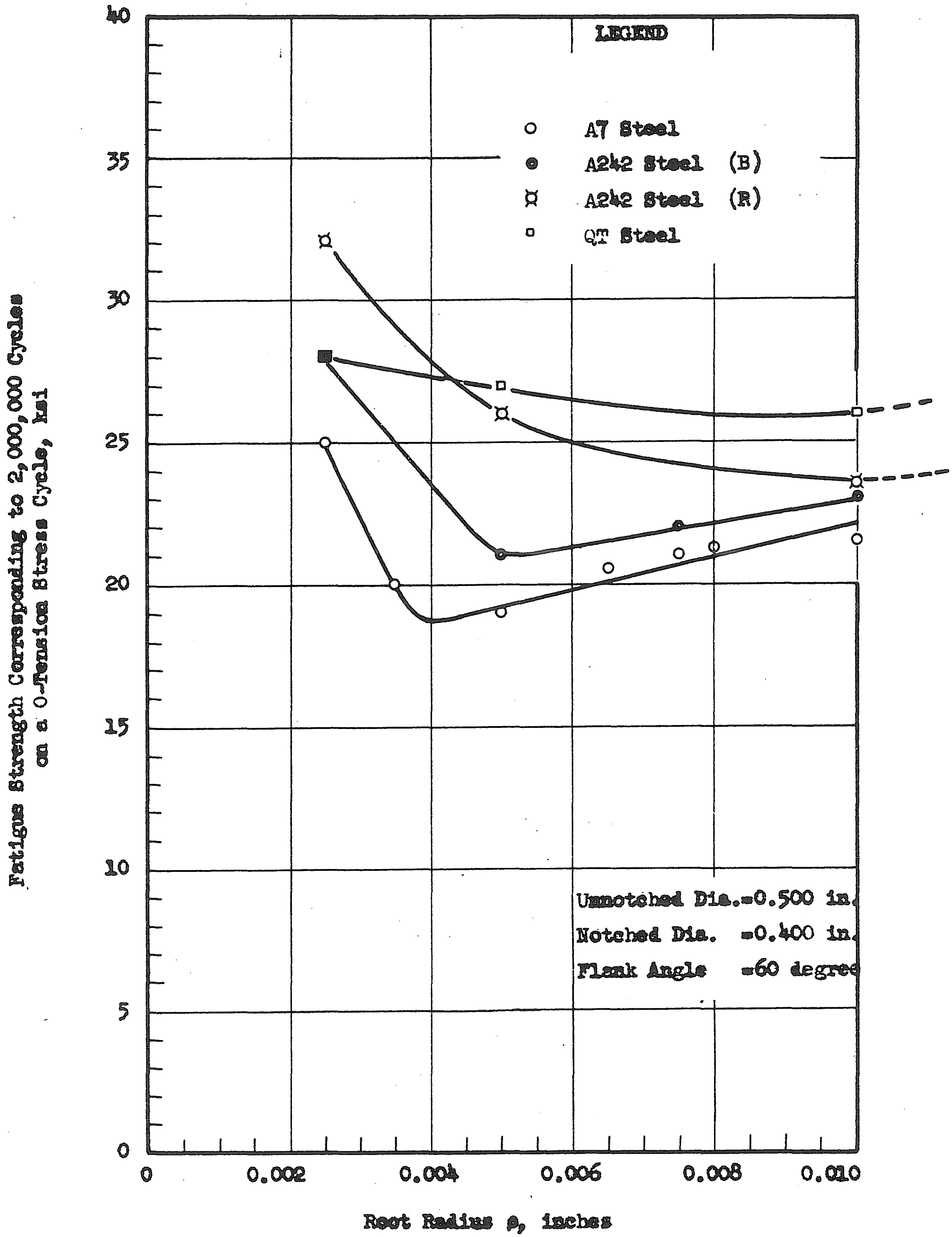



FIG. 41 SUMMARY OF RELATIONS BETWEEN FATIGUE STRENGTH AND ROOT RADIUS OF NOTCH FOR THE DIFFERENT STEELS

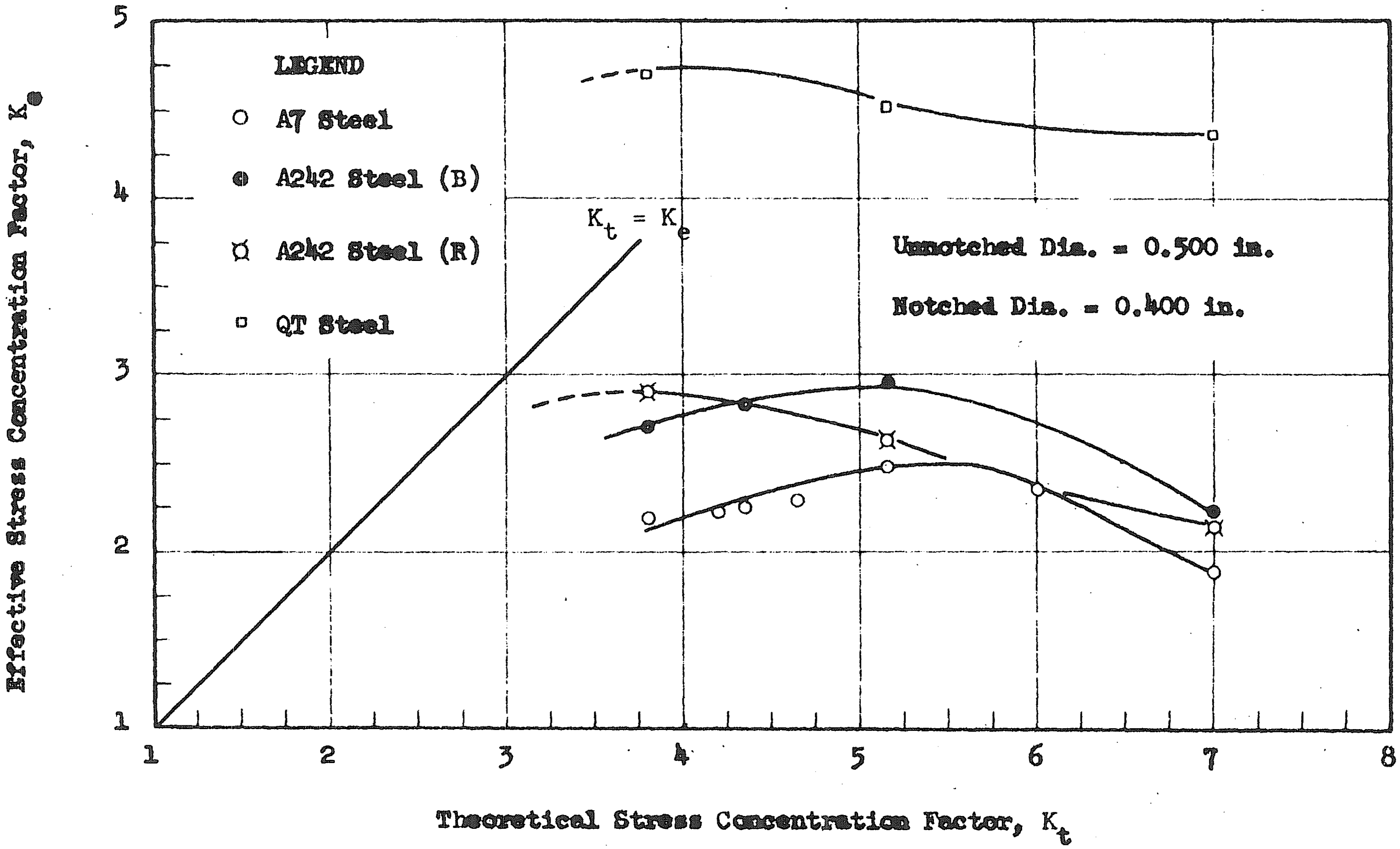



FIG. 42 SUMMARY OF RELATIONS BETWEEN THEORETICAL AND EFFECTIVE STRESS CONCENTRATION FACTORS FOR NOTCHED SPECIMENS OF THE DIFFERENT STEELS TESTED IN AXIAL FATIGUE ON A ZERO-TO-TENSION STRESS CYCLE

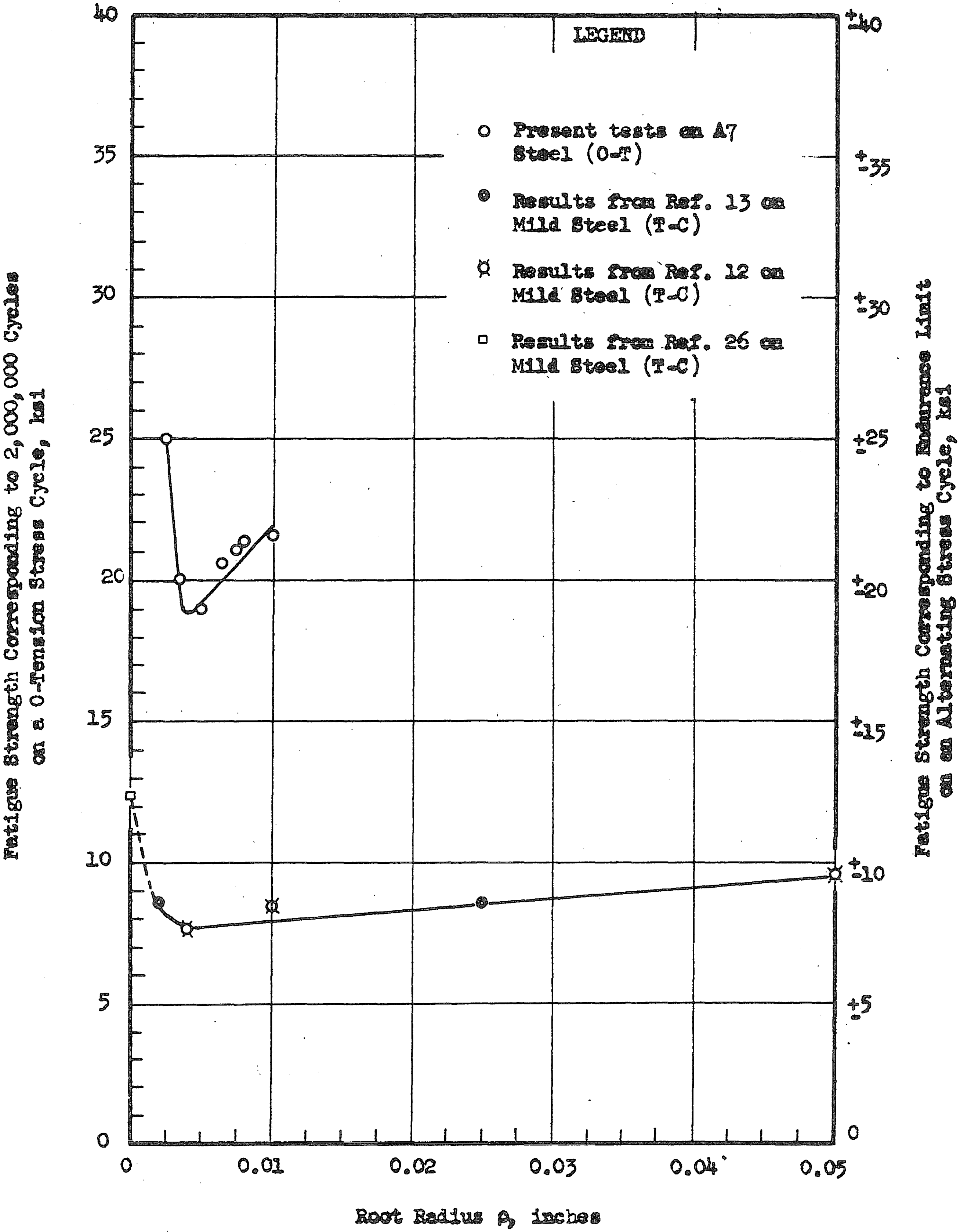



FIG. 43 COMPARISON OF RESULTS OF CURRENT TESTS ON A7 STEEL WITH SIMILAR RESULTS FROM OTHER INVESTIGATIONS

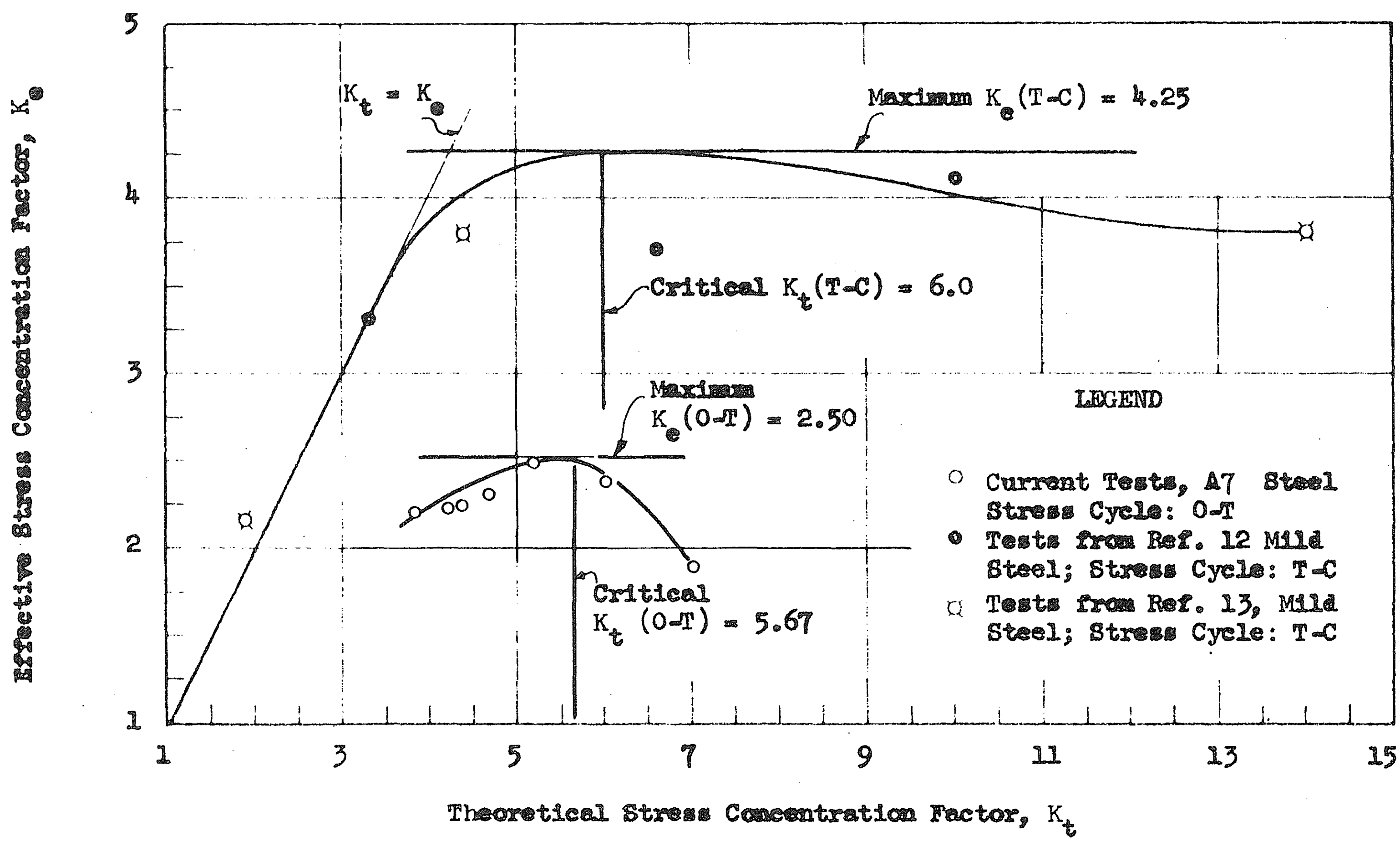



FIG. 44 COMPARISON OF RELATIONS BETWEEN THEORETICAL AND EFFECTIVE STRESS CONCENTRATIONS FOR A7 AND MILD STEEL

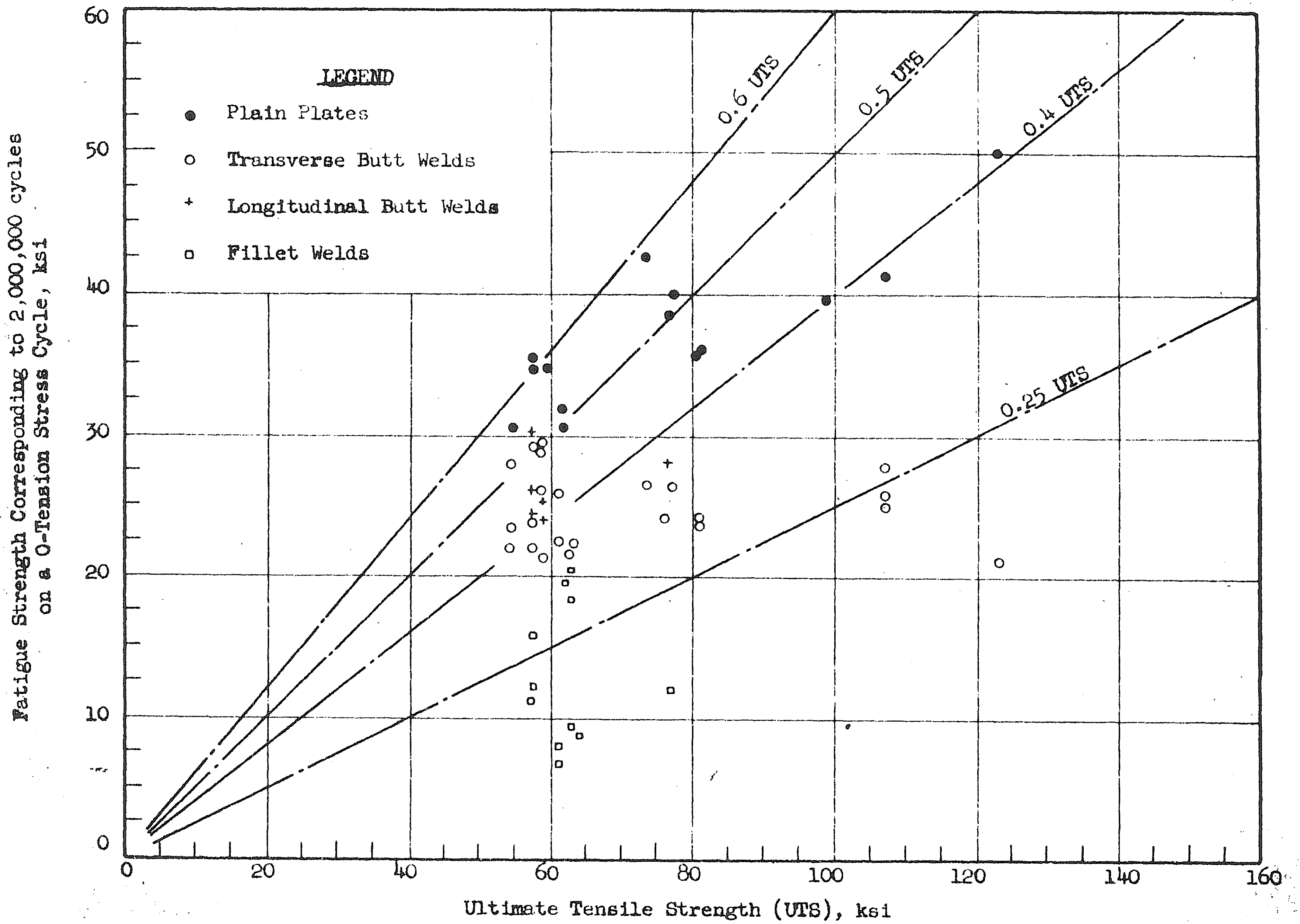



FIG. 45 RELATION BETWEEN ULTIMATE TENSILE STRENGTH AND FATIGUE STRENGTH FOR DIFFERENT TYPES OF WELDS

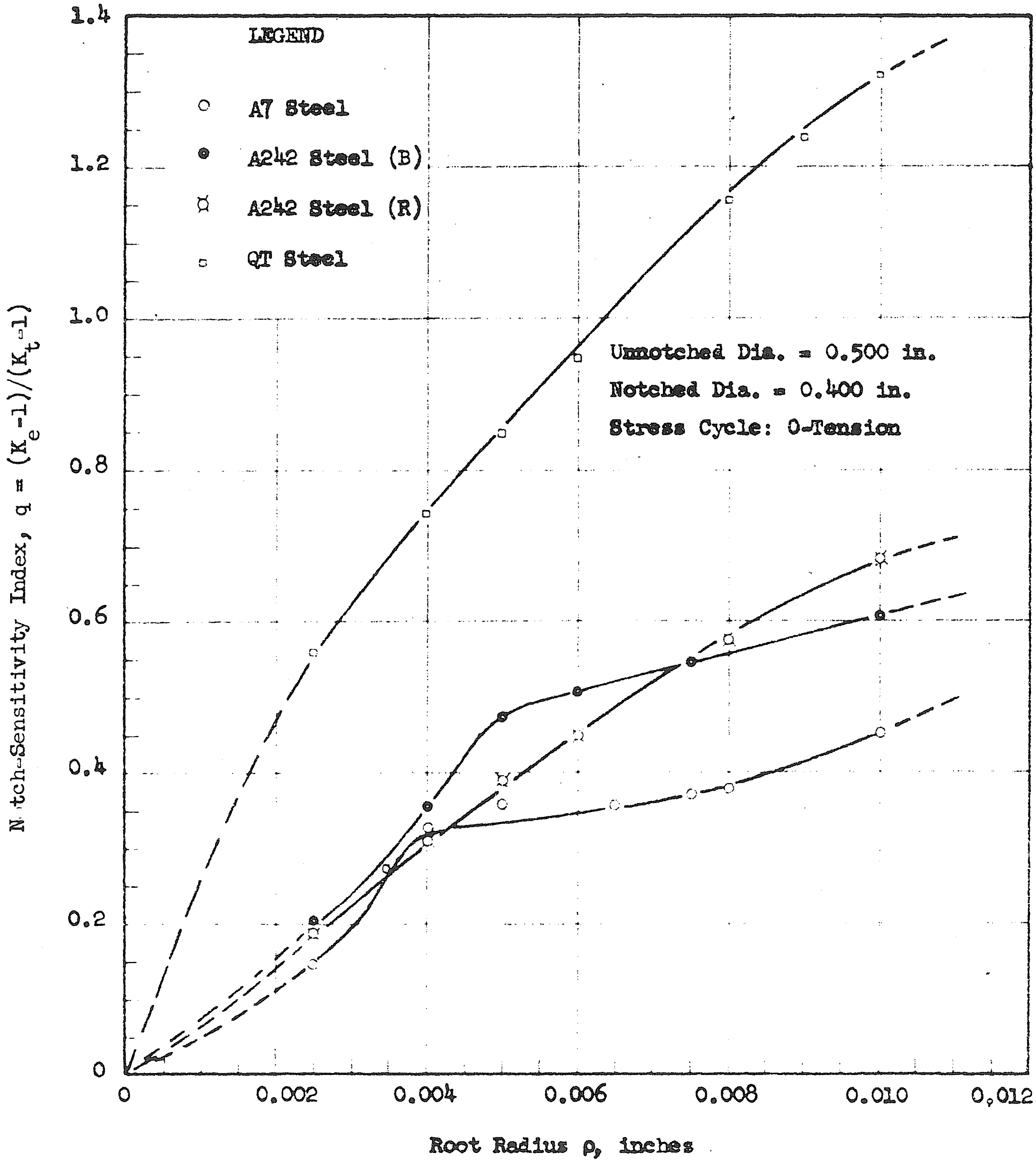
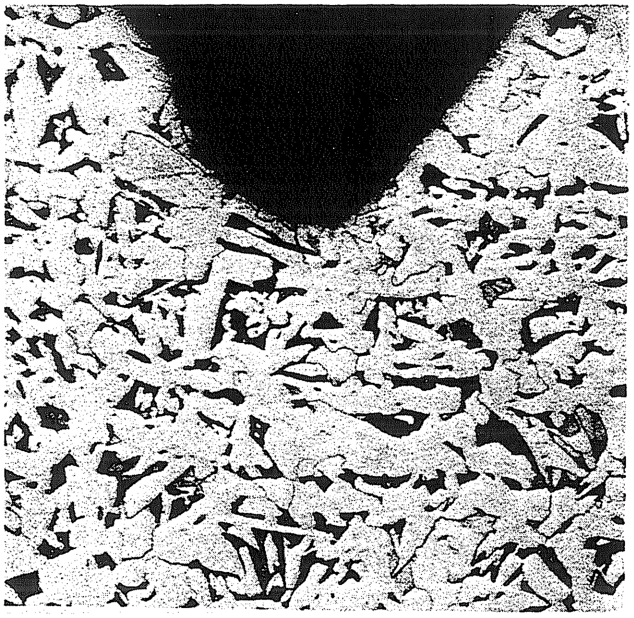
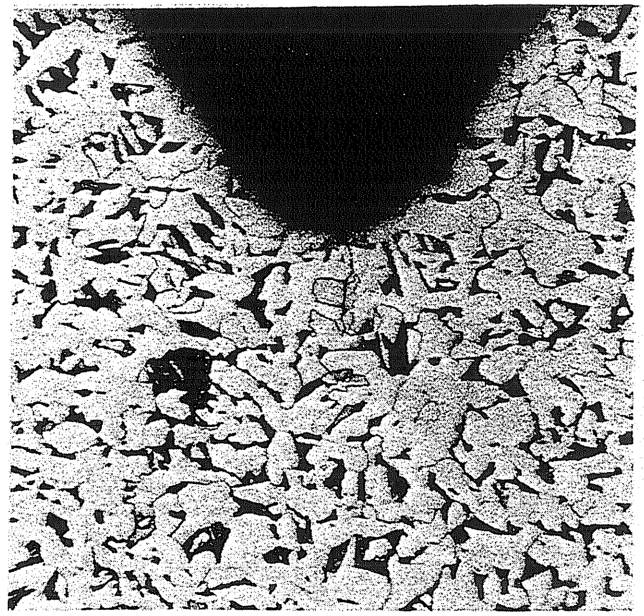



FIG. 46 SUMMARY OF VARIATION OF NOTCH-SENSITIVITY INDEX WITH ROOT RADIUS OF NOTCH FOR DIFFERENT STEELS





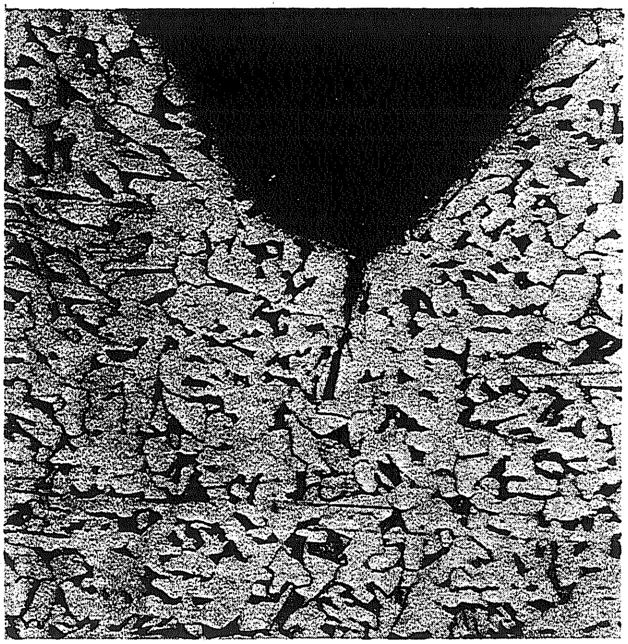
ASS-272 x150 ASS-272 x150

$\rho$ = 0.0025 in., $K_t$ = 7.00

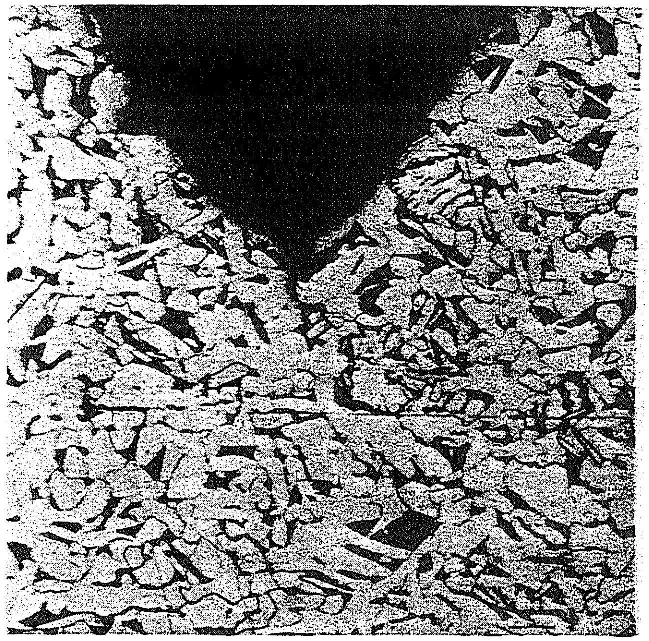
1000 to 25,000 psi; 2897,000 + cycles

ASS-272 x500 ASS-272 x500

FIG. 47 RESULTS OF MICROSCOPIC EXAMINATION, SPECIMEN ASS-272



ASS-269 x150

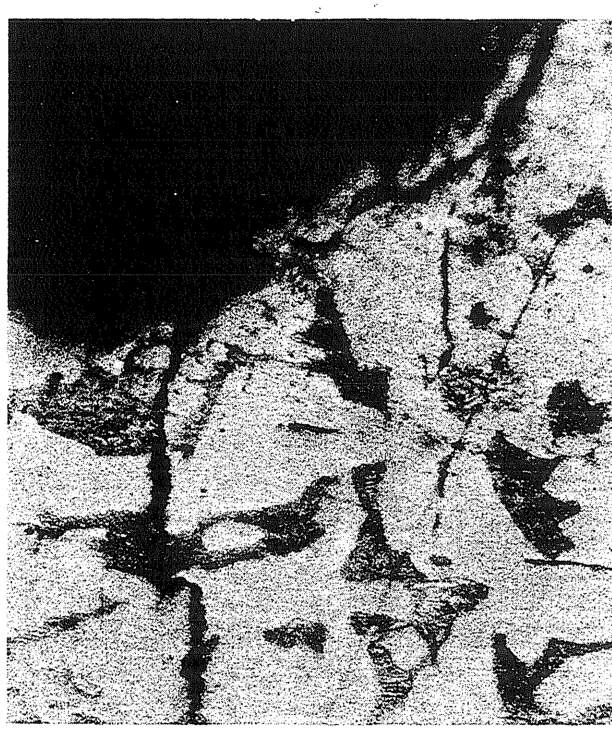


ASS-269 x150

$\rho$ = 0.0025 in., $K_t$ = 7.00
1000 to 25,000 psi; 2,849,000 + cycles

ASS-281 x500

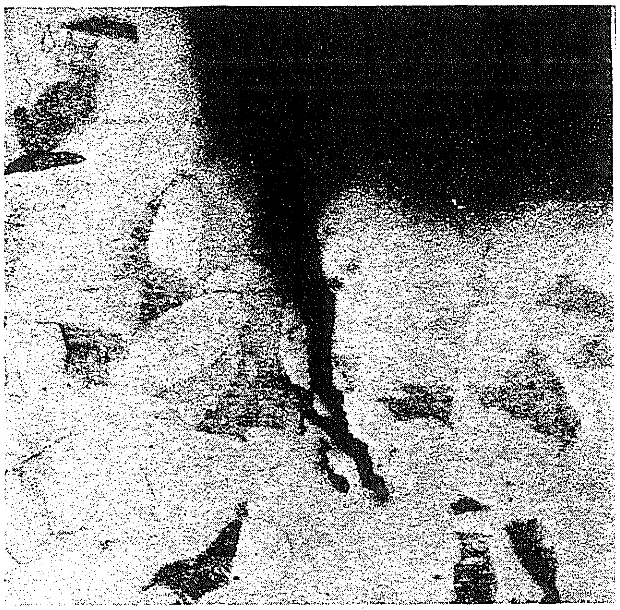
$\rho$ = 0.0035 in., $K_t$ = 6.00
1000 to 21,000 psi; 5,399,000 + cycles



ASS-280 x500

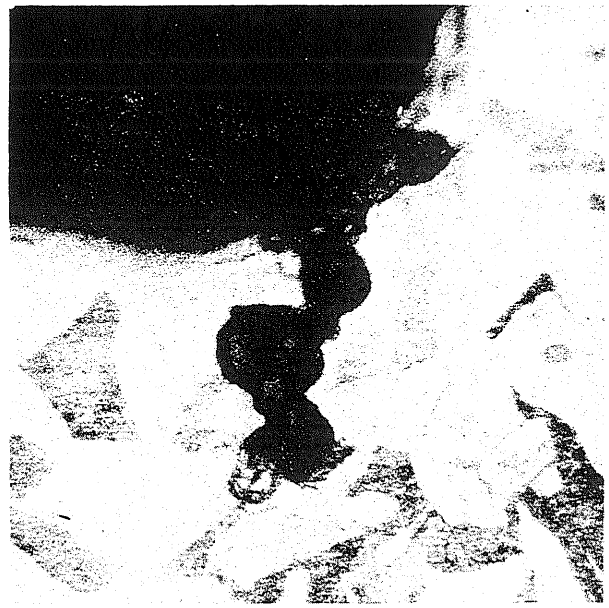
$\rho$ = 0.0035 in., $K_t$ = 6.00
100 to 20,000 psi; 3,969,000 + cycles

FIG. 48 RESULTS OF MICROSCOPIC EXAMINATION,
SPECIMENS ASS-269, 281, 280



ASS-190 x500

$\rho$ = 0.005 in., $K_t$ = 5.15
1000 to 19,000 psi; 5,357,000 + cycles



ASS-191 x500

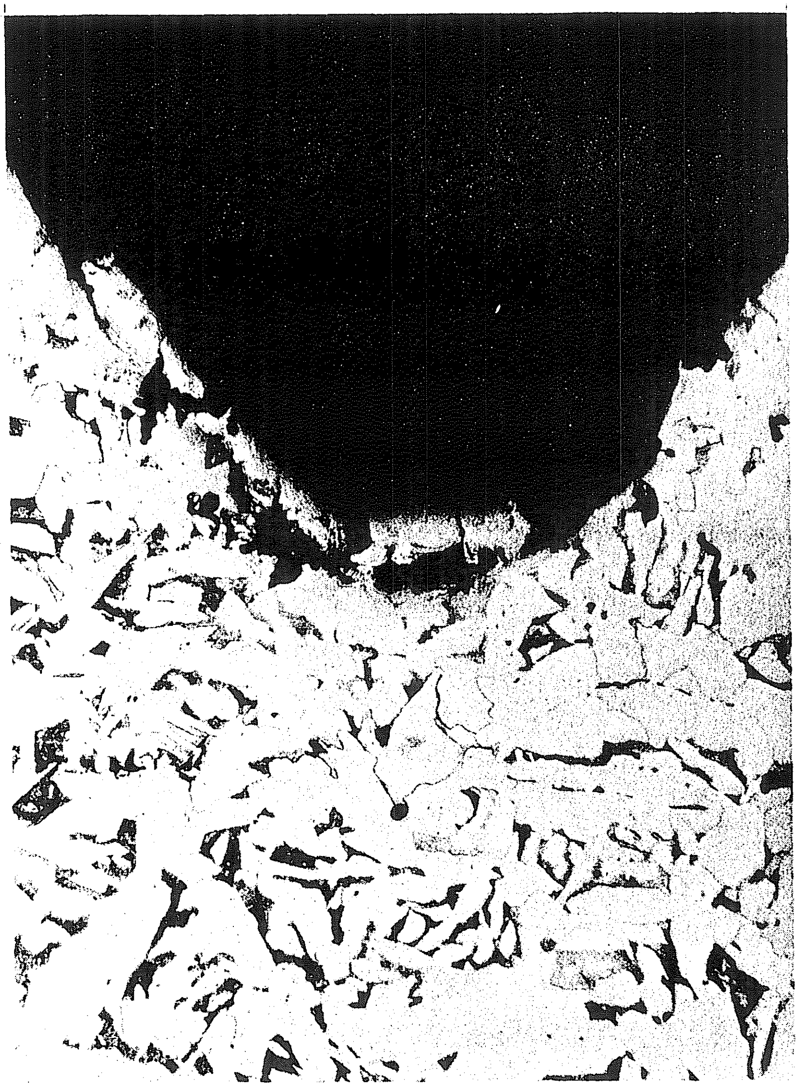
$\rho$ = 0.005 in., $K_t$ = 5.15
1000 to 19,000 psi; 5,219,000 + cycles

ASS-199 x500

ASS-199 x500

$\rho$ = 0.0065 in., $K_t$ = 4.65
1000 to 20,000 psi; 5,366,000 + cycles

FIG. 49 RESULTS OF MICROSCOPIC EXAMINATION,
SPECIMENS ASS-190, 191, 199



ASS-242 x150

$\rho$ = 0.0075 in., $K_t$ = 4.35

1000 to 21,000 psi; 5,417,000 + cycles

ASS-240 x500

$\rho$ = 0.0075 in., $K_t$ = 4.35

1000 to 20,000 psi; 6,365,000 + cycles

FIG. 50 RESULTS OF MICROSCOPIC EXAMINATION, SPECIMENS ASS-242, 240

x500 ASS-255 x500

$\rho$ = 0.010 in., $K_t$ = 3.80

1000 to 21,000 psi; 5,356,000 + cycles

ASS-254 x500

$\rho$ = 0.010 in., $K_t$ = 3.80

1000 to 21,000 psi; 5,356,000 + cycles

FIG. 51 RESULTS OF MICROSCOPIC EXAMINATION, SPECIMENS ASS-255, 254

# APPENDIX

## RESULTS OF INDIVIDUAL FATIGUE TESTS

Contained in this Appendix are the results of the individual series of tests from which the S-N diagrams presented in Figs. 9 through 40 have been conducted. The individual test results have been presented in tabular form with the series designations provided for ready identification.

TABLE A-1

RESULTS OF AXIAL FATIGUE TESTS
ON UNNOTCHED SPECIMENS OF A7 STEEL

SERIES ASS*

| Specimen | True Stress Range, psi | | Change in area, percent | Cycles to failure |
|---|---|---|---|---|
| | Minimum | Maximum | | $10^3$ |
| ASS-7 | 1,300 | 62,500 | 21.6 | 564 |
| ASS-10 | 1,200 | 61,700 | 17.4 | 277 |
| ASS-1 | 3,900 | 60,000 | 12.6 | 380 |
| ASS-8 | 1,200 | 58,600 | 19.8 | 795 |
| ASS-11 | 1,200 | 58,400 | 13.5 | 390 |
| ASS-4 | 1,100 | 56,500 | 11.4 | 400 |
| ASS-13 | 1,100 | 55,000 | 12.0 | 632 |
| ASS-6 | 1,100 | 51,800 | 7.4 | 929 |
| ASS-16 | 1,100 | 50,400 | 6.9 | 910 |
| ASS-18 | 1,100 | 49,000 | 5.4 | 1,126 |
| ASS-19 | 1,000 | 48,800 | 3.7 | 3,173 |
| ASS-12 | 1,000 | 48,800 | 4.8 | 864 |
| ASS-14 | 1,100 | 48,600 | 5.8 | 1,836+** |
| ASS-15 | 1,100 | 48,600 | 5.2 | 1,577 |
| ASS-17 | 1,000 | 48,300 | 4.8 | 2,124 |
| ASS-5 | 1,100 | 47,500 | 5.4 | 3,524+ |

*Longitudinally polished.
**Failure in threads.

TABLE A-2

RESULTS OF AXIAL FATIGUE TESTS
ON NOTCHED SPECIMENS OF A7 STEEL
SERIES ASS-V100

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-262 | 1,000 | 35,000 | 156 |
| ASS-260 | 1,000 | 35,000 | 144 |
| ASS-261 | 1,000 | 35,000 | 137 |
| ASS-257 | 1,000 | 30,000 | 558 |
| ASS-258 | 1,000 | 30,000 | 363 |
| ASS-259 | 1,000 | 30,000 | 357 |
| ASS-266 | 1,000 | 27,500 | 520 |
| ASS-265 | 1,000 | 27,500 | 452 |
| ASS-263 | 1,000 | 25,000 | 881 |
| ASS-264 | 1,000 | 25,000 | 339 |
| ASS-248 | 1,000 | 23,000 | 2,028 |
| ASS-247 | 1,000 | 23,000 | 469 |
| ASS-250 | 1,000 | 22,000 | 2,318 |
| ASS-248 | 1,000 | 22,000 | 2,086 |
| ASS-249 | 1,000 | 22,000 | 996 |
| ASS-252 | 1,000 | 22,000 | 570 |
| ASS-254 | 1,000 | 21,000 | 4,921+* |
| ASS-256 | 1,000 | 21,000 | 5,022+* |
| ASS-253 | 1,000 | 21,000 | 5,333+* |
| ASS-255 | 1,000 | 21,000 | 5,356+* |

* No failure.

TABLE A-3

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-V80

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-212 | 1,000 | 27,500 | 674 |
| ASS-213 | 1,000 | 27,500 | 594 |
| ASS-216 | 1,000 | 25,000 | 889 |
| ASS-217 | 1,000 | 25,000 | 431 |
| ASS-244 | 1,000 | 24,000 | 1,112 |
| ASS-246 | 1,000 | 24,000 | 987 |
| ASS-245 | 1,000 | 24,000 | 973 |
| ASS-214 | 1,000 | 24,000 | 705 |
| ASS-243 | 1,000 | 24,000 | 553 |
| ASS-215 | 1,000 | 24,000 | 460 |

TABLE A-4

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-V75

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-211 | 1,000 | 30,000 | 486 |
| ASS-210 | 1,000 | 30,000 | 349 |
| ASS-202 | 1,000 | 25,000 | 1,089 |
| ASS-237 | 1,000 | 25,000 | 663 |
| ASS-238 | 1,000 | 25,000 | 516 |
| ASS-203 | 1,000 | 25,000 | 323 |
| ASS-205 | 1,000 | 24,000 | 866 |
| ASS-204 | 1,000 | 24,000 | 576 |
| ASS-239 | 1,000 | 24,000 | 386 |
| ASS-206 | 1,000 | 23,000 | 1,474 |
| ASS-207 | 1,000 | 23,000 | 581 |
| ASS-208 | 1,000 | 22,000 | 1,548 |
| ASS-209 | 1,000 | 22,000 | 781 |
| ASS-242 | 1,000 | 21,000 | 5,417+* |
| ASS-241 | 1,000 | 21,000 | 3,596 |
| ASS-240 | 1,000 | 20,000 | 6,365+* |

* No failure

TABLE A-5

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-V65

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-200 | 1,000 | 30,000 | 123 |
| ASS-201 | 1,000 | 30,000 | 93 |
| ASS-194 | 1,000 | 25,000 | 165 |
| ASS-195 | 1,000 | 24,000 | 205 |
| ASS-197 | 1,000 | 22,000 | 3,531 |
| ASS-196 | 1,000 | 22,000 | 812 |
| ASS-199 | 1,000 | 20,000 | 5,366+* |
| ASS-198 | 1,000 | 20,000 | 4,000 |

* No failure

TABLE A-6

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-V50

| Specimen | Stress Range, psi | | Cycles to Failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-193 | 1,000 | 30,000 | 225 |
| ASS-192 | 1,000 | 28,000 | 613 |
| ASS-186 | 1,000 | 24,000 | 430 |
| ASS-184 | 1,000 | 24,000 | 420 |
| ASS-185 | 1,000 | 24,000 | 301 |
| ASS-187 | 1,000 | 20,000 | 1,178 |
| ASS-191 | 1,000 | 19,000 | 5,357+* |
| ASS-190 | 1,000 | 19,000 | 5,219+* |
| ASS-188 | 1,000 | 18,000 | 5,069+* |
| ASS-189 | 1,000 | 18,000 | 5,015+* |

* No failure.

TABLE A-7

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-V35

| Specimen | Stress Range, psi | | Cycles to failure |
| --- | --- | --- | --- |
| | Minimum | Maximum | $10^3$ |
| ASS-275 | 1,000 | 35,000 | 72 |
| ASS-276 | 1,000 | 30,000 | 100 |
| ASS-277 | 1,000 | 25,000 | 125 |
| ASS-281 | 1,000 | 21,000 | 5,399+* |
| ASS-280 | 1,000 | 20,000 | 3,969+* |
| ASS-279 | 1,000 | 19,000 | 3,835+* |
| ASS-278 | 1,000 | 15,000 | 3,059+* |
| ASS-278 | 1,000 | 23,000 | 483 ** |
| ASS-279 | 1,000 | 21,000 | 2,342 ** |

* No failure.
**Re-test.

TABLE A-8

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-V25

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-267 | 1,000 | 35,000 | 100 |
| ASS-273 | 1,000 | 30,000 | 418 |
| ASS-268 | 1,000 | 27,500 | 571 |
| ASS-271 | 1,000 | 26,000 | 1,561 |
| ASS-270 | 1,000 | 26,000 | 1,334 |
| ASS-272 | 1,000 | 25,000 | 2,897+* |
| ASS-269 | 1,000 | 25,000 | 2,849+* |

* No failure.

TABLE A-9

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-P50

| Specimen | Stress Range, psi | | Cycles to failure |
|---|---|---|---|
| | Minimum | Maximum | $10^3$ |
| ASS-123 | 1,000 | 32,500 | 146 |
| ASS-124 | 1,000 | 32,500 | 134 |
| ASS-125 | 1,000 | 32,500 | 98 |
| ASS-105 | 1,000 | 30,000 | 543 |
| ASS-106 | 1,000 | 30,000 | 485 |
| ASS-104 | 1,000 | 30,000 | 396 |
| ASS-107 | 1,000 | 30,000 | 168 |
| ASS-119 | 1,000 | 27,500 | 724 |
| ASS-121 | 1,000 | 27,500 | 594 |
| ASS-122 | 1,000 | 27,500 | 312 |
| ASS-120 | 1,000 | 27,500 | 296 |
| ASS-110 | 1,000 | 25,000 | 1,358 |
| ASS-108 | 1,000 | 25,000 | 835 |
| ASS-118 | 1,000 | 25,000 | 597 |
| ASS-111 | 1,000 | 25,000 | 389 |
| ASS-109 | 1,000 | 25,000 | 349 |
| ASS-115 | 1,000 | 22,000 | 2,721 |
| ASS-116 | 1,000 | 22,000 | 1,859 |
| ASS-114 | 1,000 | 22,000 | 1,417 |
| ASS-117 | 1,000 | 22,000 | 1,317 |
| ASS-113 | 1,000 | 20,000 | 3,722+* |
| ASS-112 | 1,000 | 20,000 | 3,509+* |

* No failure.

## TABLE A-10

## RESULTS OF AXIAL FATIGUE TESTS

## ON NOTCHED SPECIMENS OF A7 STEEL

### SERIES ASS-Q50

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASS-142 | 1,000 | 32,500 | 167 |
| ASS-141 | 1,000 | 32,500 | 62 |
| ASS-134 | 1,000 | 30,000 | 575 |
| ASS-137 | 1,000 | 30,000 | 402 |
| ASS-136 | 1,000 | 30,000 | 286 |
| ASS-135 | 1,000 | 30,000 | 219 |
| ASS-138 | 1,000 | 27,500 | 908 |
| ASS-140 | 1,000 | 27,500 | 443 |
| ASS-131 | 1,000 | 25,000 | 3,560+* |
| ASS-130 | 1,000 | 25,000 | 2,077 |
| ASS-132 | 1,000 | 25,000 | 1,450 |
| ASS-133 | 1,000 | 25,000 | 438 |
| ASS-127 | 1,000 | 20,000 | 6,312+* |
| ASS-129 | 1,000 | 20,000 | 5,050+* |
| ASS-144 | 1,000 | 20,000 | 5,002+* |
| ASS-126 | 1,000 | 20,000 | 3,796+* |
| ASS-131 | 1,000 | 20,000 | 3,560+* |
| ASS-143 | 1,000 | 20,000 | 2,514 |

* No failure.

TABLE A-11

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A7 STEEL

SERIES ASS-Y

| Specimen | Stress Range, psi | | Cycles to failure |
| --- | --- | --- | --- |
| | Minimum | Maximum | $10^3$ |
| ASS-180 | 1,000 | 35,000 | 117 |
| ASS-179 | 1,000 | 35,000 | 110 |
| ASS-177 | 1,000 | 27,500 | 358 |
| ASS-178 | 1,000 | 27,500 | 358 |
| ASS-218 | 1,000 | 25,000 | 1,740 |
| ASS-174 | 1,000 | 25,000 | 859 |
| ASS-219 | 1,000 | 25,000 | 697 |
| ASS-173 | 1,000 | 25,000 | 539 |
| ASS-221 | 1,000 | 24,000 | 4,155 |
| ASS-220 | 1,000 | 24,000 | 3,209 |
| ASS-231 | 1,000 | 24,000 | 2,154 |
| ASS-228 | 1,000 | 24,000 | 2,073 |
| ASS-227 | 1,000 | 24,000 | 1,504 |
| ASS-232 | 1,000 | 24,000 | 1,147 |
| ASS-224 | 1,000 | 24,000 | 921 |
| ASS-225 | 1,000 | 24,000 | 769 |
| ASS-230 | 1,000 | 23,000 | 2,832 |
| ASS-222 | 1,000 | 23,000 | 2,439 |
| ASS-223 | 1,000 | 23,000 | 2,136 |
| ASS-235 | 1,000 | 23,000 | 1,721 |
| ASS-233 | 1,000 | 23,000 | 1,461 |
| ASS-234 | 1,000 | 23,000 | 693 |
| ASS-226 | 1,000 | 23,000 | 343 |
| ASS-229 | 1,000 | 23,000 | 257 |
| ASS-175 | 1,000 | 22,500 | 4,656+* |
| ASS-182 | 1,000 | 22,500 | 4,129+* |
| ASS-183 | 1,000 | 22,500 | 3,915 |
| ASS-176 | 1,000 | 22,500 | 742 |
| ASS-236 | 1,000 | 22,000 | 6,059+* |
| ASS-181 | 1,000 | 21,000 | 4,362+* |

* No failure.

TABLE A-12

RESULTS OF AXIAL FATIGUE TESTS ON

UNNOTCHED SPECIMENS OF A242 STEEL

SERIES ASB*

| Specimen | True Stress Range, psi | | Change in area, percent | Cycles to failure $10^3$ |
|---|---|---|---|---|
| | Minimum | Maximum | | |
| ASB-76 | 1,075 | 64,600 | 7.1 | 485 |
| ASB-80 | 1,050 | 62,000 | 4.8 | 2,818+** |
| ASB-77 | 1,050 | 60,900 | 4.8 | 3,418+** |
| ASB-79 | 1,030 | 59,900 | 3.3 | 4,186+** |

*Longitudinally polished.
**No failure.

TABLE A-13

RESULTS OF AXIAL FATIGUE TESTS ON

UNNOTCHED SPECIMENS OF A242 STEEL

SERIES ASB**

| Specimen | True Stress Range, psi | | Change in area, percent | Cycles to failure |
|---|---|---|---|---|
| | Minimum | Maximum | | $10^3$ |
| ASB-70 | 1,200 | 71,500 | 16.1 | 234 |
| ASB-71 | 1,050 | 63,000 | 4.7 | 234 |
| ASB-72 | 1,075 | 59,200 | 7.1 | 782 |
| ASB-74 | 1,050 | 57,150 | 4.8 | 1,579 |
| ASB-73 | 1,000 | 54,200 | 1.6 | 4,391+* |
| ASB-75 | 1,000 | 53,400 | 0.8 | 3,399+* |

*No failure.
**Rough turned.

TABLE A-14

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASB-V100

| Specimen | Stress Range, Psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASB-94 | 1,000 | 37,000 | 218 |
| ASB-95 | 1,000 | 37,000 | 137 |
| ASB-92 | 1,000 | 35,000 | 347 |
| ASB-93 | 1,000 | 35,000 | 269 |
| ASB-82 | 1,000 | 25,000 | 4,542 |
| ASB-84 | 1,000 | 25,000 | 3,853 |
| ASB-81 | 1,000 | 25,000 | 1,653 |
| ASB-85 | 1,000 | 25,000 | 1,141 |
| ASB-86 | 1,000 | 24,000 | 3,313 |
| ASB-83 | 1,000 | 24,000 | 2,709 |
| ASB-87 | 1,000 | 23,500 | 1,260 |
| ASB-88 | 1,000 | 23,000 | 3,482 |
| ASB-89 | 1,000 | 22,000 | 2,726 |
| ASB-90 | 1,000 | 21,000 | 2,796 |
| ASB-91 | 1,000 | 20,000 | 4,959+* |

* No failure.

TABLE A-15

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASB-V75

| Specimen | Stress Range, psi | | Cycles to Failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASB-2 | 1,000 | 35,000 | 337 |
| ASB-9 | 1,000 | 35,000 | 272 |
| ASB-3 | 1,000 | 35,000 | 229 |
| ASB-10 | 1,000 | 35,000 | 154 |
| ASB-11 | 1,000 | 35,000 | 144 |
| ASB-4 | 1,000 | 30,000 | 622 |
| ASB-1 | 1,000 | 30,000 | 597 |
| ASB-14 | 1,000 | 30,000 | 388 |
| ASB-5 | 1,000 | 30,000 | 238 |
| ASB-6' | 1,000 | 26,000 | 630 |
| ASB-6 | 1,000 | 26,000 | 437 |
| ASB-13 | 1,000 | 25,000 | 1,062 |
| ASB-16 | 1,000 | 25,000 | 336 |
| ASB-15 | 1,000 | 25,000 | 857 |
| ASB-7 | 1,000 | 24,000 | 1,726 |
| ASB-12 | 1,000 | 24,000 | 1,294 |
| ASB-8 | 1,000 | 23,000 | 6,015+* |
| ASB-17 | 1,000 | 23,000 | 2,117 |
| ASB-18 | 1,000 | 23,000 | 1,019 |
| ASB-20 | 1,000 | 22,000 | 8,074+* |
| ASB-19 | 1,000 | 22,000 | 1,708 |

* No failure.

## TABLE A-16

## RESULTS OF AXIAL FATIGUE TESTS

## ON NOTCHED SPECIMENS OF A242 STEEL

## SERIES ASB-V50

| Specimen | Stress Range, psi | | Cycles to failure |
|---|---|---|---|
| | Minimum | Maximum | $10^3$ |
| ASB-63 | 1,000 | 27,000 | 936 |
| ASB-61 | 1,000 | 25,000 | 790 |
| ASB-62 | 1,000 | 23,000 | 914 |
| ASB-67 | 1,000 | 22,000 | 1,691 |
| ASB-64 | 1,000 | 22,000 | 786 |
| ASB-66 | 1,000 | 21,000 | 4,175+* |
| ASB-65 | 1,000 | 20,000 | 4,086+* |

* No failure.

TABLE A-17

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASB-V25

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASB-97 | 1,000 | 32,000 | 264 |
| ASB-33 | 1,000 | 30,000 | 1,089 |
| ASB-35 | 1,000 | 29,000 | 2,819+* |
| ASB-98 | 1,000 | 29,000 | 447 |
| ASB-34 | 1,000 | 28,000 | 3,216+* |
| ASB-28 | 1,000 | 28,000 | 2,383 |
| ASB-99 | 1,000 | 27,000 | 3,033+* |
| ASB-96 | 1,000 | 26,000 | 3,818+* |

* No failure.

TABLE A-18

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASB-Q50

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASB-55 | 1,000 | 30,000 | 181 |
| ASB-56 | 1,000 | 30,000 | 142 |
| ASB-57 | 1,000 | 27,500 | 235 |
| ASB-58 | 1,000 | 27,500 | 235 |
| ASB-51 | 1,000 | 25,000 | 448 |
| ASB-54 | 1,000 | 25,000 | 439 |
| ASB-52 | 1,000 | 25,000 | 150 |
| ASB-53 | 1,000 | 25,000 | 133 |
| ASB-59 | 1,000 | 22,500 | 414 |
| ASB-60 | 1,000 | 22,500 | 231 |
| ASB-45 | 1,000 | 20,000 | 2,032 |
| ASB-41 | 1,000 | 20,000 | 2,029 |
| ASB-42 | 1,000 | 20,000 | 923 |
| ASB-46 | 1,000 | 20,000 | 543 |
| ASB-43 | 1,000 | 20,000 | 484 |
| ASB-44 | 1,000 | 20,000 | 236 |
| ASB-50 | 1,000 | 18,000 | 3,825+* |
| ASB-49 | 1,000 | 18,000 | 3,730+* |
| ASB-47 | 1,000 | 18,000 | 3,622+* |
| ASB-48 | 1,000 | 18,000 | 2,479 |

* No failure.

TABLE A-19

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASB-Y

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASB-23 | 1,000 | 35,000 | 297 |
| ASB-26 | 1,000 | 35,000 | 171 |
| ASB-29 | 1,000 | 35,000 | 165 |
| ASB-25 | 1,000 | 35,000 | 123 |
| ASB-30 | 1,000 | 30,000 | 493 |
| ASB-69 | 1,000 | 30,000 | 351 |
| ASB-68 | 1,000 | 30,000 | 159 |
| ASB-21 | 1,000 | 25,000 | 774 |
| ASB-22 | 1,000 | 25,000 | 613 |
| ASB-24 | 1,000 | 24,000 | 3,955+* |
| ASB-27 | 1,000 | 24,000 | 2,206 |
| ASB-28 | 1,000 | 24,000 | 1,697 |

* No failure.

TABLE A-20

RESULTS OF AXIAL FATIGUE TESTS ON

UNNOTCHED SPECIMENS OF A242 STEEL

SERIES ASR* and ASR**

| Specimen | True Stress Range, psi | | Change in area, percent | Cycles to failure $10^3$ |
|---|---|---|---|---|
| | Minimum | Maximum | | |
| SERIES ASR* | | | | |
| ASR-25 | 1,050 | 68,800 | 5.5 | 4,589+*** |
| ASR-29 | 1,040 | 67,700 | 4.0 | 2,550+*** |
| SERIES ASR** | | | | |
| ASR-23 | 1,125 | 66,800 | 11.7 | 1,102 |
| ASR-21 | 1,050 | 63,500 | 5.5 | 864 |
| ASR-20 | 1,025 | 62,000 | 3.2 | 1,854 |
| ASR-24 | 1,050 | 61,500 | 4.0 | 1,344 |
| ASR-22 | 1,025 | 59,400 | 2.4 | 3,332+*** |
| ASR-19 | 1,000 | 50,800 | 1.6 | 13,177+*** |
| ASR-18 | 1,000 | 48,000 | --- | 5,081+*** |
| ASR-17 | 1,000 | 45,000 | --- | 5,184+*** |
| ASR-16 | 1,025 | 41,000 | 2.4 | 5,007+*** |

*Specimens longitudinally polished.
**Specimens rough turned.
***No failure.

TABLE A-21

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASR-V100

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASR-11 | 1,000 | 38,000 | 94 |
| ASR-12 | 1,000 | 38,000 | 81 |
| ASR-13 | 1,000 | 37,000 | 152 |
| ASR-14 | 1,000 | 37,000 | 135 |
| ASR-9 | 1,000 | 35,000 | 676 |
| ASR-10 | 1,000 | 35,000 | 409 |
| ASR-2 | 1,000 | 25,000 | 2,227 |
| ASR-1 | 1,000 | 25,000 | 688 |
| ASR-4 | 1,000 | 24,000 | 5,436+* |
| ASR-5 | 1,000 | 24,000 | 5,231+* |
| ASR-3 | 1,000 | 24,000 | 3,968 |
| ASR-6 | 1,000 | 24,000 | 1,738 |
| ASR-7 | 1,000 | 23,500 | 5,295+* |
| ASR-8 | 1,000 | 23,500 | 5,101+* |
| ASR-15 | 1,000 | 23,500 | 2,489 |

* No failure.

TABLE A-22

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASR-V50

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASR-30 | 1,000 | 30,000 | 367 |
| ASR-32 | 1,000 | 28,000 | 348 |
| ASR-33 | 1,000 | 27,000 | 891 |
| ASR-35 | 1,000 | 27,000 | 700 |
| ASR-34 | 1,000 | 26,000 | 5,264+* |
| ASR-31 | 1,000 | 26,000 | 4,039+* |

* No failure.

TABLE A-23

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF A242 STEEL

SERIES ASR-V25

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASR-37 | 1,000 | 36,000 | 418 |
| ASR-38 | 1,000 | 34,000 | 887 |
| ASR-42 | 1,000 | 33,000 | 3,619+* |
| ASR-39 | 1,000 | 33,000 | 1,549 |
| ASR-36 | 1,000 | 32,000 | 4,718+* |
| ASR-40 | 1,000 | 32,000 | 4,083+* |

* No failure.

TABLE A-24

RESULTS OF AXIAL FATIGUE TESTS ON

UNNOTCHED SPECIMENS OF QT STEEL

SERIES ASC*

| Specimen | True Stress Range, psi | | Change in area percent | Cycles to failure $10^3$ |
|---|---|---|---|---|
| | Minimum | Maximum | | |
| ASC-61 | 1,060 | 127,000 | 5.5 | 794 |
| ASC-63 | 1,000 | 122,400 | 3.1 | 2,991+** |
| ASC-62 | 1,000 | 120,400 | 2.4 | 3,386+** |
| ASC-60 | 1,000 | 116,000 | 0.8 | 7,218+** |
| ASC-59 | 1,000 | 110,000 | --- | 2,979+** |

*Specimens longitudinally polished.
**No failure.

TABLE A-25

RESULTS OF AXIAL FATIGUE TESTS ON

UNNOTCHED SPECIMENS OF QT STEEL

SERIES ASC**

| Specimen | True Stress Range, psi | | Change in area percent | Cycles to failure $10^3$ |
|---|---|---|---|---|
| | Minimum | Maximum | | |
| ASC-55 | 1,080 | 117,400 | 7.0 | 139 |
| ASC-56 | 1,030 | 107,400 | 3.2 | 263 |
| ASC-54 | 1,000 | 101,600 | 3.6 | 5,363+* |
| ASC-53 | 1,000 | 95,750 | 1.6 | 4,007+* |
| ASC-52 | 1,000 | 92,200 | 2.4 | 5,308+* |
| ASC-51 | 1,000 | 76,200 | 0.8 | 5,506+* |
| ASC-52 | 1,000 | 106,500 | --- | 3,676+*** |
| ASC-51 | 1,000 | 102,600 | --- | 5,308+*** |

*No failure.
**Specimens rough turned.
***Retested, no failure.

TABLE A-26

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-V100

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASC-108 | 1,000 | 43,000 | 157 |
| ASC-109 | 1,000 | 43,000 | 70 |
| ASC-106 | 1,000 | 40,000 | 333 |
| ASC-107 | 1,000 | 40,000 | 264 |
| ASC-71 | 1,000 | 35,000 | 5,292+* |
| ASC-74 | 1,000 | 35,000 | 1,095 |
| ASC-72 | 1,000 | 35,000 | 834 |
| ASC-73 | 1,000 | 35,000 | 597 |
| ASC-76 | 1,000 | 33,000 | 855 |
| ASC-75 | 1,000 | 33,000 | 602 |
| ASC-78 | 1,000 | 30,000 | 5,734+* |
| ASC-79 | 1,000 | 30,000 | 1,424 |
| ASC-77 | 1,000 | 30,000 | 1,372 |
| ASC-80 | 1,000 | 30,000 | 538 |
| ASC-81 | 1,000 | 27,000 | 5,024+* |
| ASC-83 | 1,000 | 27,000 | 1,863 |
| ASC-82 | 1,000 | 27,000 | 845 |
| ASC-103 | 1,000 | 25,000 | 6,019+* |
| ASC-84 | 1,000 | 25,000 | 5,122+* |
| ASC-85 | 1,000 | 25,000 | 5,011+* |

* No failure.

TABLE A-27

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-V100a*

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASC-94 | 1,000 | 35,000 | 360 |
| ASC-95 | 1,000 | 35,000 | 309 |
| ASC-87 | 1,000 | 30,000 | 729 |
| ASC-86 | 1,000 | 30,000 | 685 |
| ASC-88 | 1,000 | 27,500 | 1,583 |
| ASC-89 | 1,000 | 27,500 | 1,115 |
| ASC-91 | 1,000 | 26,000 | 1,287 |
| ASC-90 | 1,000 | 26,000 | 804 |
| ASC-93 | 1,000 | 24,000 | 5,384+** |
| ASC-92 | 1,000 | 24,000 | 1,302 |

* Heat treatment, performed after notching, consisted in heating specimens to 1650°F. and air cooling.

** No failure.

TABLE A-28

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-V100b*

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASC-97 | 1,000 | 35,000 | 263 |
| ASC-99 | 1,000 | 35,000 | 183 |
| ASC-101 | 1,000 | 30,000 | 5,122+** |
| ASC-100 | 1,000 | 30,000 | 1,855 |
| ASC-102 | 1,000 | 30,000 | 995 |
| ASC-105 | 1,000 | 28,000 | 5,012+** |
| ASC-104 | 1,000 | 28,000 | 4,210+** |
| ASC-98 | 1,000 | 27,000 | 5,010+** |
| ASC-96 | 1,000 | 25,000 | 5,020+** |

* Heat treatment, performed before notching, consisted in heating to 1650°F. and air cooling.

**No failure.

TABLE A-29

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-V50

| Specimen | Stress Range, psi Minimum | Stress Range, psi Maximum | Cycles to failure $10^3$ |
|---|---|---|---|
| ASC-47 | 1,000 | 35,000 | 453 |
| ASC-39 | 1,000 | 35,000 | 173 |
| ASC-44 | 1,000 | 32,500 | 632 |
| ASC-46 | 1,000 | 31,500 | 1,607 |
| ASC-48 | 1,000 | 31,000 | 359 |
| ASC-42 | 1,000 | 30,000 | 3,277+* |
| ASC-40 | 1,000 | 27,500 | 2,971+* |
| ASC-49 | 1,000 | 27,500 | 1,261 |
| ASC-125 | 1,000 | 27,000 | 2,958+* |
| ASC-124 | 1,000 | 25,000 | 3,942+* |
| ASC-123 | 1,000 | 20,000 | 5,413+* |

*No failure.

TABLE A-30

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-V50a*

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASC-30 | 1,000 | 35,000 | 121 |
| ASC-29 | 1,000 | 35,000 | 119 |
| ASC-26 | 1,000 | 30,000 | 256 |
| ASC-24 | 1,000 | 30,000 | 235 |
| ASC-27 | 1,000 | 30,000 | 221 |
| ASC-25 | 1,000 | 24,000 | 573 |
| ASC-32 | 1,000 | 24,000 | 415 |
| ASC-33 | 1,000 | 24,000 | 408 |
| ASC-28 | 1,000 | 22,000 | 1,067 |
| ASC-31 | 1,000 | 21,000 | 845 |
| ASC-34 | 1,000 | 21,000 | 472 |
| ASC-38 | 1,000 | 20,000 | 3,117+** |
| ASC-37 | 1,000 | 20,000 | 947 |
| ASC-35 | 1,000 | 20,000 | 610 |
| ASC-36 | 1,000 | 19,000 | 3,777+** |

* Heat treatment, performed after notching, consisted in heating specimens in 1650°F. and air cooling.

** No failure.

TABLE A-31

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-V25

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASC-112 | 1,000 | 35,000 | 825 |
| ASC-113 | 1,000 | 35,000 | 510 |
| ASC-114 | 1,000 | 33,000 | 376 |
| ASC-115 | 1,000 | 31,000 | 282 |
| ASC-111 | 1,000 | 30,000 | 2,877+* |
| ASC-116 | 1,000 | 27,000 | 864 |
| ASC-117 | 1,000 | 24,000 | 3,042+* |
| ASC-121 | 1,000 | 20,000 | 3,115+* |
| ASC-120 | 1,000 | 17,000 | 2,741+* |
| ASC-120 | 1,000 | 30,000 | 4,222+** |
| ASC-117 | 1,000 | 27,000 | 3,779+** |
| ASC-111 | 1,000 | 25,000 | 3,571+** |

* No failure.

** Retested, no failure.

TABLE A-32

RESULTS OF AXIAL FATIGUE TESTS

ON NOTCHED SPECIMENS OF QT STEEL

SERIES ASC-Y

| Specimen | Stress Range, psi | | Cycles to failure $10^3$ |
|---|---|---|---|
| | Minimum | Maximum | |
| ASC-65 | 1,000 | 40,000 | 308 |
| ASC-67 | 1,000 | 38,000 | 523 |
| ASC-66 | 1,000 | 37,000 | 1,395 |
| ASC-68 | 1,000 | 36,000 | 1,614 |
| ASC-64 | 1,000 | 35,000 | 3,618+* |

* No failure.