FINAL REPORT

ON

THE EFFECT OF CYCLIC STRESS ON THE TRANSITION TEMPERATURE OF STEEL

BY

H. E. JACQUES

Massachusetts Institute of Technology
Under Bureau of Ships Contract NObs-25391

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

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

Very truly yours,

C. Richard Soderberg

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Enclosure

PREFACE

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

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FINAL REPORT

PROJECT SR-101

on

THE EFFECT OF CYCLIC STRESS ON THE TRANSITION TEMPERATURE OF STEEL

NAVY DEPARTMENT, BUREAU OF SHIPS
Contract NObs-25391

by

H. E. Jacques

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

ABSTRACT

This report concerns an investigation to determine if prior fatigue would affect the transition temperature curves in impact of ship steels. Tests were made on two shipbuilding steels, B and W, the greater amount of work having been done on steel B.

A combination fatigue-impact specimen was designed and used. This specimen was round with a circumferential notch and could be tested in impact by sawing off the tapered ends necessary for holding in the fatigue machine.

As testing proceeded, it was found that fatigue cracks were developing at the base of the notch both above and below the endurance limit. When specimens were cyclically stressed so as to avoid fatigue cracks, the resulting transition curve showed little deviation from the original curve presumably due to the low stress of the prior fatigue.

A series of specimens of steel B were prestrained in tension prior to testing in impact with a marked shift of the transition curve resulting.

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INTRODUCTION

In recent years a number of investigations have been undertaken to deal with the problem of fractures of ocean going ships. These investigations have sought to study the nature and causes of these fractures and to develop small laboratory tests which may determine the suitability of individual heats for shipbuilding steel at the time of manufacture.

In service a ship is subjected to many different forms of stress which undoubtedly alter the properties of the structural steel. Unfortunately no comprehensive study has been made to date which undertakes to measure qualitatively and quantitatively the stresses experienced by a ship at sea.

The Bureau of Ships of the Navy Department has been greatly concerned with this problem of fracture and has sponsored this project to investigate the effect of one form of service loading on the strength characteristics, specifically the effect of cyclic stress or fatigue on the impact properties of shipbuilding steel.

After the project was under way, it was thought advisable to also determine the effect of prestraining in tension on the impact properties. These tests were incorporated in the test schedule and the results are included in this report.

This work was carried out under Bureau of Ships contract NObs-25391. It was conducted at Massachusetts Institute of Technology with Professor John M. Lessells as supervisor and Mr. Herbert E. Jacques as investigator.

EXPERIMENTAL WORK

1. Choice of Test

a) Rayflex Machine

In the early stages of this investigation it seemed desirable to cyclically stress a square specimen of Charpy size either with or without the notch. At this time the use of the Rayflex Fatigue Machine appeared promising. This machine produces bending by means of two alternating current magnets which alternately attract and repel the ends of the specimen. The frequency of the magnets is variable and is set to give resonant vibration of the specimen.

There were three disadvantages associated with the use of this machine which led to its abandonment in favor of the R. R. Moore rotating beam fatigue machine.

First, specimens had to be from 18 to 24 inches long to give a sufficient beam length. Out of each length only one Charpy specimen would be procured. This would necessitate an enormous supply of material and result in high cost of specimen preparation.

Secondly, it was impossible to produce maximum bending stresses of over 37,000 psi with a specimen of constant cross section. The remedy for this would have been to attach steel weights to the ends of the specimens so as to increase the bending moment at the test section without increasing its size.

And lastly, exceptional care would have had to be taken to insure that the specimens were as square as possible. It was observed that in the preliminary tests the specimens vibrated in an elliptical pattern rather than straight up and down. The major axis of this ellipse coincided with the longer diagonal of the cross section.

b) Round Notched Impact Specimen

It was then learned that Dr. C. H. Lorig[1] of Battelle Memorial Institute had used a round notched specimen in impact which gave results comparable to the standard V-notch Charpy specimen. It was thought possible to adapt this specimen to a rotating beam type of fatigue test in which the fatigue specimen could be machined to the impact form of specimen.

Dr. Lorig kindly supplied the specifications of his specimen and instructions for its preparation. Drawings of the impact and fatigue specimens are shown in Fig. 1. Details of the preparation of this specimen are given in the Appendix.

Since Dr. Lorig had not specified that the round notched specimen was comparable to the V-notch Charpy for medium carbon steels of shipbuilding quality, it was thought desirable to make some comparative impact tests of the specimens using such a steel.

In order to conserve the project steels, the material selected for the comparative tests was a medium carbon shipbuilding steel meeting the requirements of Navy grade 4885. Several small 3/4" plates of this material were obtained from the Boston Navy Yard. These plates were annealed before using. The results of the comparative impact tests are shown in Fig. 2.

After verification had been obtained of the suitability of the round notched impact specimen, a test schedule was prepared and the experimental work begun. The results included in this report are based entirely on the specimen shown in Fig. 2.

2. Procedure.

Specimens were stressed cyclically in an R.R. Moore Rotating Beam Fatigue Machine (Fig. 3). A detailed account of the use of this machine is given in the Appendix.

The Charpy impact tester used in these tests is shown in Fig. 4. This machine is of standard construction and has an energy capacity of 225 feet pounds and a striking velocity of 17.4 feet per second.

Specimens were held at the desired test temperatures in thermos bottles for at least 30 minutes. Not more than 5 seconds elapsed between removal of the specimen from the temperature bath and fracture.

The test temperatures were produced as follows:

a) Below 32°F, dry ice and carbon tetrachloride
b) 32°F, ice and water mixture
c) 32°F to 160°F, water
d) Above 160°F, mineral oil

3. Experimental Results - Steel B

The first and major portion of the work was done on steel B. This steel is an .18C, semi-killed, hot-rolled shipbuilding steel. This steel was received in 3/4" plate form and was tested as received. The chemical analysis and mechanical properties of this steel are given in the Appendix.

Fatigue Tests

S/N diagrams were obtained for steel B with notched and standard smooth specimens. These curves are shown in Fig. 5.

The stresses shown for the notched specimens are the nominal stresses based on the specimen diameter at the root of the notch.

For this form of notch the strength reduction factor for steel B is 1.2 (endurance limit for unnotched specimens divided by endurance limit for notched specimens; 31,000/25,800 = 1.2).

Impact Tests

A summary of all impact tests on steel B is shown in Fig. 6. The detailed results of tests on unstressed specimens of steel B are shown in Fig. 7.

Overstressing Tests

After the S/N diagram had been obtained, a series of notched fatigue specimens were subjected to a stress 15% over the notched endurance limit and a cycle ratio of 50%, i.e., half the number of cycles to produce failure at that stress.

When the notched endurance limit had been determined as 25,800 psi, a series of specimens were stressed at 29,700 psi for 105,000 cycles. These specimens were altered to impact form and tested at various temperatures. The results are shown in Fig. 8.

At this time it was observed that all the specimens exhibited a dark band about 0.02" wide on the fracture surface adjacent to the base of the notch. It was thought that these bands might represent fatigue cracks. This proved to be the case. The methods used in the detection and measurement of the cracks are described in the Appendix. The dark bands are shown in Fig. 15.

Similar dark bands both above and below the endurance limit have been reported by MacGregor and Grossman[2] although they concluded that the bands did not represent fatigue cracks.

Fatigue Crack Investigation

The original object of this investigation was to determine the effect of cyclic stress alone on the transition temperature. The contribution of a fatigue crack to transition temperature shift would be impossible to evaluate. Therefore, the next phase of the project was directed toward investigating the occurrence of fatigue cracks with the object of avoiding them.

Specimens were run for various numbers of cycles at lower stresses and then sectioned and measured as described in the Appendix.

At first it was thought necessary to explore the region on the S/N diagram down to the vicinity of the endurance limit only. The numbers of cycles were reduced to as low as 2,000 cycles. All specimens tested showed measurable cracks.

It was then evident that stresses below the endurance limit must be explored. This was done and cracks were evident until the stress was reduced to 10,000 psi, about 40% of the endurance limit. There was no evidence of cracking in two specimens run at 10,000 psi for 1.75 million cycles.

Fatigue Crack Occurrence

The data on fatigue crack occurrence and magnitude are shown in Fig. 11. Some discussion of these curves is desirable.

It can be seen that the curves for the two higher stresses are not straight and intersect, while the curves for the lower stresses are quite regular. This is thought to be an effect of testing technique. When the crack investigation was started, the object was to find a combination of stress and numbers of cycles which would not result in the occurrence of fatigue cracks. In doing this, test specimens which ran reasonably free from vibration were deemed satisfactory for this purpose. However, as the existence of fatigue cracks below the endurance limit became evident, it was seen that a previously unreported phenomenon was occurring. Therefore, in order to accumulate data which would be as accurate as possible, only those specimens which would run perfectly smoothly were used in the investigation of the lower stresses. The plot for 21,500 psi is a good example of data from vibrationless specimens.

Final Stressing

Since no fatigue crack had developed in two specimens run at

10,000 psi for 1.75 million cycles, it appeared safe that a series of specimens could be stressed at 10,000 psi for one million cycles without danger of cracking.

This was done and the specimens tested in impact. The results are shown in Fig. 9.

Prestraining in Tension

In addition to prestressing by cyclic stress, a series of notched specimens were subjected to a static tensile load before testing in impact.

A complete tension test was conducted on the notched specimen. The description of this test is included in the Appendix. The test specimens were loaded to 55,000 psi which should have resulted in a reduction of the specimen diameter at the root of the notch of one per cent or 0.004". For all the specimens prestrained in tension, this reduction in diameter was between 0.003" and 0.004".

The specimens were altered to impact form and tested at various temperatures as before. These results are shown in Fig. 10.

Cyclograph Magnetic Core Loss Machine

Some of the fatigue work on steel B was done in conjunction with a DuMont Cyclograph, an electronic machine for determining the amount of magnetic core loss. This work was performed by C. P. Moore[3], a graduate student at M.I.T.

Attempts were made to correlate Cyclograph data with the growth of the fatigue crack and shift of the transition curve due to cyclic stress. This investigation was largely unsuccessful and further discussion is unwarranted.

4. Experimental Results - Steel W

The investigation of Steel W was conducted in a manner similar to that of Steel B.

The results of impact tests on round notched specimens of Steel W are shown in Fig. 12.

The results of fatigue tests on standard smooth and notched specimens of steel W are shown in Fig. 13.

Fatigue cracks occurred in steel W as in Steel B. The occurrence of the cracks was investigated in the same way. The crack growth plot for Steel W is shown in Fig. 14.

These data indicate that specimens of Steel W would have to be prestressed at or about 10,000 psi to avoid fatigue cracks. Since this stress produced little effect on the transition temperature of Steel B, it was decided that further investigation of Steel W was not warranted.

Discussion of Results of Steel B*

Both prestressing by fatigue and prestraining by tension have shifted the transition curve upwards in temperature.

The curve of specimens stressed at 29,700 psi (curve B, Fig. 6) shows the largest shift, about 75°F. However, this curve is partially invalidated because of the presence of a fatigue crack. Whether or not the major factor in the shift is due to the prestressing alone is in doubt.

When the fatigue stress was reduced to 10,000 psi to avoid cracking, the resulting curve (curve C, Fig. 6) shows little shift, only about 10°F. Apparently this stress, which is only 40% of the endurance limit, is too low to give any definite effects.

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*It was thought unnecessary to discuss the lesser work on steel W as all the W data available agree with that of Steel B.

The curve for specimens prestrained in tension (curve D, Fig. 6) lies between the two previous ones and reveals a shift of about 30°F from the original curve A.

The maximum energies of curves B and D are appreciably lower than those of the original curve A. Curve C shows no reduction in maximum energy.

Aside from the expected ascending order of curves A, C, and B, it does not appear possible to deduce any correlation between them. Test of specimens prestrained in tension at other stresses should prove valuable. It is expected that these curves would also be in an ascending order.

One effect of the notch has been to make these specimens of a rather small test section since the behavior of the material at the root of the notch is the determining factor in these tests. Larger shifts and lower maximum energies of the transition curves might have resulted if the specimens had been prestressed or prestrained prior to notching.

The crack growth curve of Steel B (Fig. 11) presents some interesting new information. One observation is that fatigue cracks have formed at stresses well below the endurance limit. The lowest nominal stress at which a fatigue crack was found was 11,500 psi, about 45% of the endurance limit of the notched bars.

The fatigue cracks have grown with increasing numbers of cycles at all stresses investigated. As mentioned previously, the curvature and crossing of the lines of higher stress in Fig. 11 is thought to be due to the greater eccentricity of the specimens tolerated at that stage of the investigation.

The most revealing crack line is that for 21,500 psi. This stress had been chosen for investigation at high numbers of cycles because it was sufficiently far below the endurance limit, about 15%, to successfully avoid fracture due to scatter and yet high enough to experience positive effects from fatigue. One specimen was run to 83 million cycles at this stress, giving a point that shows the crack size at that stress to be steadily increasing.

It is interesting to observe that for the stresses below 23,200 psi, the crack lines indicate an approximately steady rate of growth, that is, the near parallelism of the lines indicates that the effect of variation of stress is more a variation of the point of crack occurrence and not a variation in their rate of propagation.

Reference is made to work done by H. F. Moore[4] on the propagation of fatigue cracks in railway car axles. Moore produced cracking by stressing above the endurance limits but propagated these cracks by stressing below the endurance limit. His work showed that the stress must be reduced to one half the endurance limit to avoid crack propagation. Although the present investigation is not exactly comparable it is interesting to note the agreement on about one half the conventional endurance limit as a form of "non-cracking endurance limit."

In their work on fatigue damage, Russell and Weldker[5] show damage regions for various materials, but these regions are above the endurance limit exclusively. Their criterion of damage was the inability of a specimen to run indefinitely at its original endurance limit.

The present report shows "damage" also below the endurance limit, although it is of a different nature. Nevertheless, this "damage" is very real. It appears that the effects of fatigue damage should be granted a wider range of investigation to determine the effect of fatigue on more of the physical properties of metals.

CONCLUSIONS

The present study has shown that several hitherto uninvestigated phenomena affect the characteristics of the transition curves.

It has been established that fatigue cracks develop and propagate at cyclic stresses below the endurance limit as well as above the endurance limit in both Steels B and W. Studies made of the behavior of their growth reveal a regular pattern of crack propagation extending outward to eighty-three million cycles at one stress level.

Cyclic prestressing in rotary bending, or static prestraining by tension, of specimens prior to the impact test, results in a shift of the original impact transition temperature curve toward regions of higher temperatures for Steel B.

When the fatigue prestressing is carried out at stress levels which result in crack formation, a large change in transition temperature, as well as a considerable reduction in maximum impact energy, occurs. On the other hand, prestressing at low stress levels which do not result in fatigue crack formation produces a smaller shift in the transition temperature with virtually no reduction in the maximum impact energy. Between these two limits lies the curve for specimens prestrained in static tension which indicates an intermediate transition temperature shift and an intermediate reduction in maximum impact energy.

While this investigation is obviously of an exploratory nature, it is, nevertheless, safe to conclude that the following phenomena, in their order of importance, produce a marked effect on the impact transition curves:

1. Fatigue damage accompanied by high stress concentrations associated with fatigue cracks.

2. Gross plastic deformations resulting probably in an increase of the micro (small scale) stress concentrations.

3. Fatigue damage which does not result in macro stress concentrations but which is undoubtedly associated with micro plastic deformations.

RECOMMENDATIONS

Stemming from the conclusions, the following recommendations for further investigation of the various phenomena noted above are indicated:

1. Effect of various amounts of plastic deformation (prestraining in tension) on the transition temperature. This work should include the study of notched impact specimens which have been machined out of prestrained material as well as the prestraining of originally notched specimens.

2. Effect of cyclic stress amplitude, both in direct (axial) loading as well as bending, on the rate of crack propagation.

3. The effect of cyclic stresses on the transition temperature at amplitudes below those which produce cracks. These should be carried out both in direct loading as well as bending.

From the viewpoint of fundamental investigation, such studies should be carried out on a variety of ferrous and nonferrous alloys regardless of their utility in ship construction. From a practical standpoint, ship plate materials which have been investigated in considerable detail by other research workers should be included in the program.

Consideration should also be given to the development of a technique whereby any physical changes in the plastic properties of the specimens during the process of static prestraining could be determined. Techniques such as those developed by Dr. B. J. Lazan[7], and those of Lessells and Associates, Inc.[8], could very well be applied to the study of energy losses and changes in the elastic and plastic properties of the specimens during the cyclic prestressing operation.

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1. Letter from Dr. C.H. Lorig to Prof. J. M. Lessells dated August 7, 1947.

2. MacGregor, C. W., and Grossman, N., "Some New Aspects of the Fatigue of Metals Brought out by Brittle Transition Temperature Tests," The Welding Journal Research Supplement, March 1948.

3. Moore, C. P. "Investigation of Core Losses in Low Carbon Steels,", M. S. Thesis, M.I.T., September 1948.

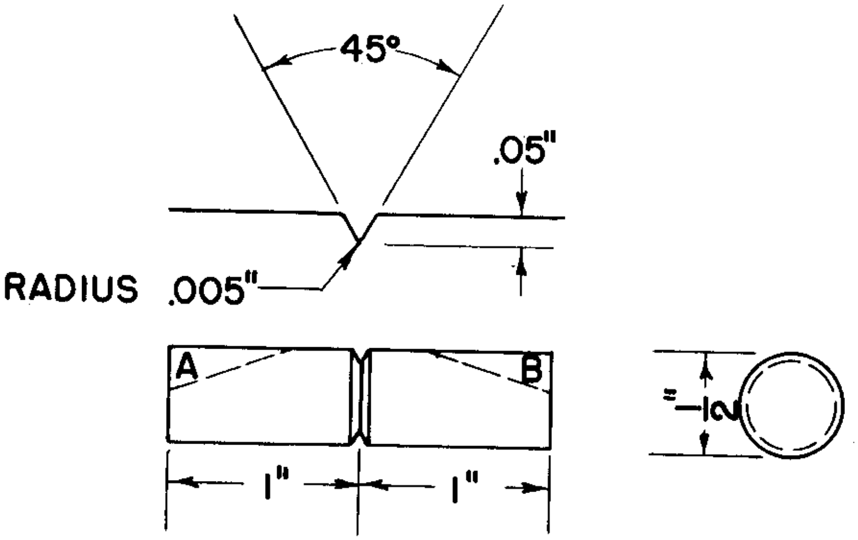
4. Moore, H. F., "A Study of Fatigue Cracks in Car Axles," Bulletin No. 165, University of Illinois Engineering Experiment Station, 1927.

5. Russell, H. W., and Welcker, W. A., "Damage and Overstress in the Fatigue of Ferrous Metals," A.S.T.M. Proceedings, Volume 36, Part II, 1936.

6. Gensamer, M., Klier, E. P., Prater, T. A., Wagner, F. C., Mack, J. O., and Fisher, J. L., "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests," U. S. Navy, NObs-31217, Serial No. SSC-9, March 19, 1947.

7. Lazan, B. J., "The Damping, Elasticity, and Fatigue Properties of Materials and Structures under Sustained Cyclic Stress," U. S. Navy, ONR Contract N6. ori-221.

8. Shepler, P. R., "Numerical Study of Factors in the Stress Concentration Theory as Applied to the Hysteresis and Fatigue of Metals," Contract N7onr-468 - Task Order 1, NR-035-153.



ROUND CHARPY TEST SPECIMEN

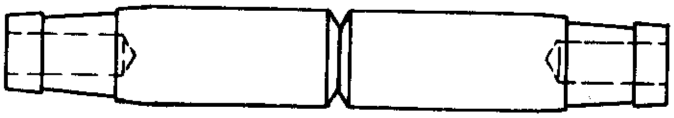


FIG. 1 R. R. MOORE NOTCHED FATIGUE SPECIMEN

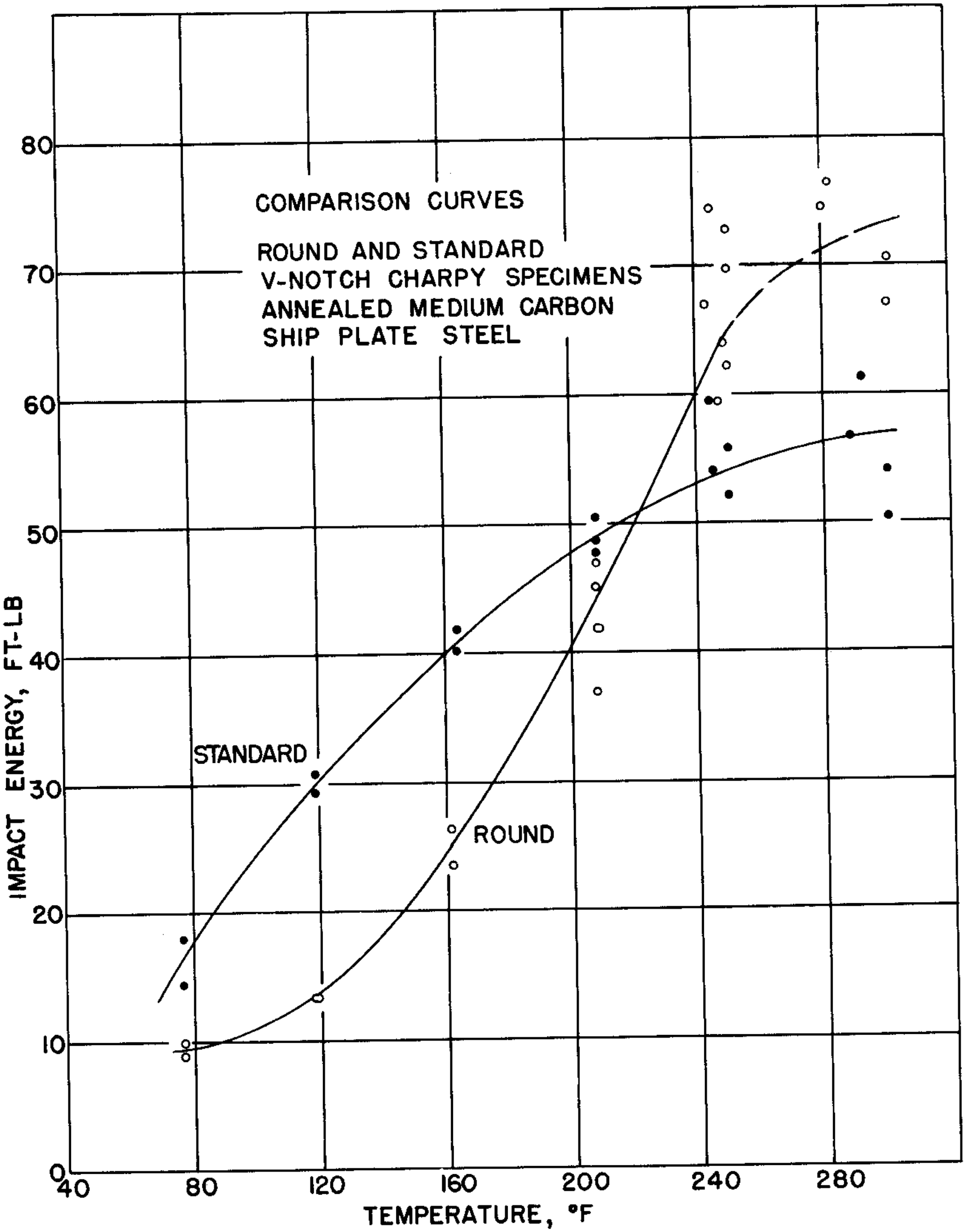

COMPARISON CURVES
ROUND AND STANDARD
V-NOTCH CHARPY SPECIMENS
ANNEALED MEDIUM CARBON
SHIP PLATE STEEL
STANDARD
ROUND
IMPACT ENERGY, FT-LB
0
10
20
30
40
50
60
70
80
40
80
120
160
200
240
280
TEMPERATURE, °F

FIG. 2

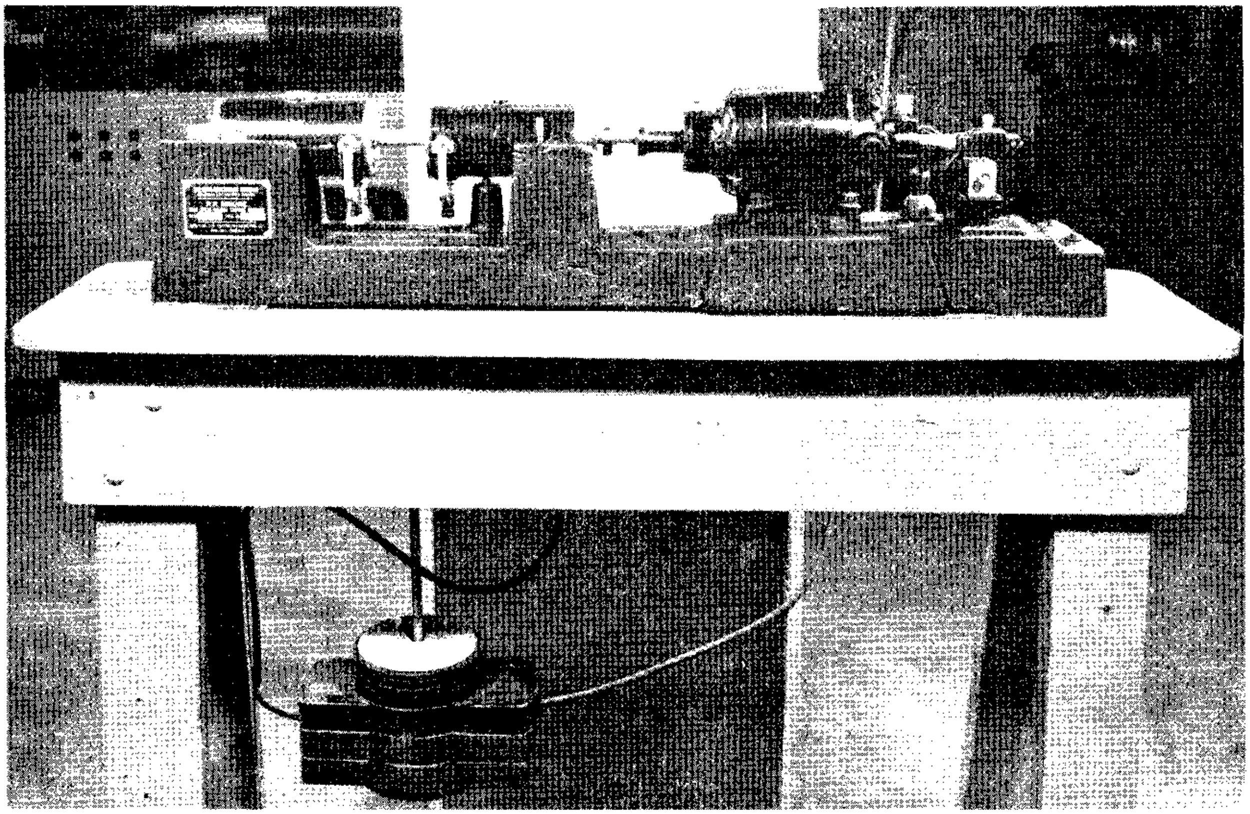


FIG. 3 - R. R. MOORE ROTATING BEAM FATIGUE MACHINE

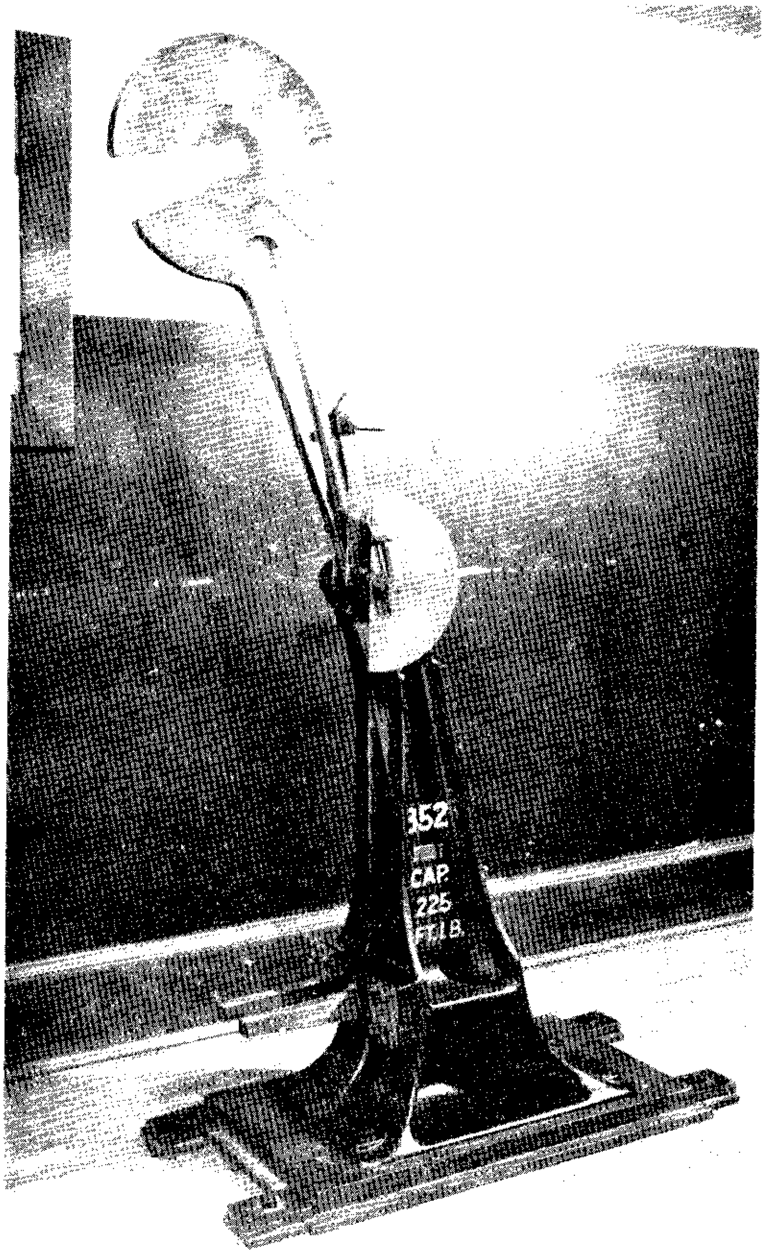


FIG. 4 - CHARPY IMPACT MACHINE

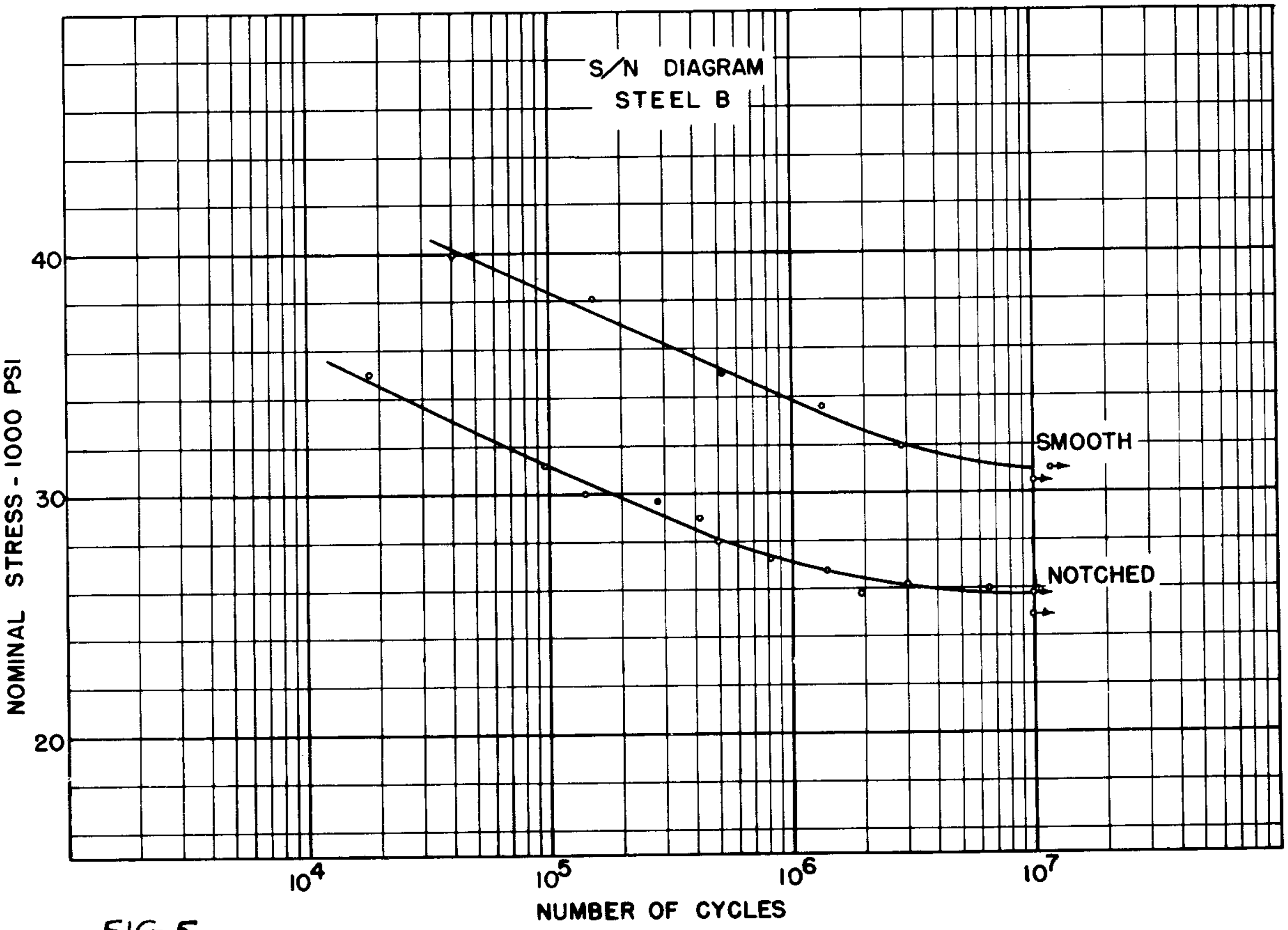

S/N DIAGRAM
STEEL B
40
30
20
NOMINAL STRESS - 1000 PSI
10^4
10^5
10^6
10^7
NUMBER OF CYCLES
SMOOTH
NOTCHED

FIG 5

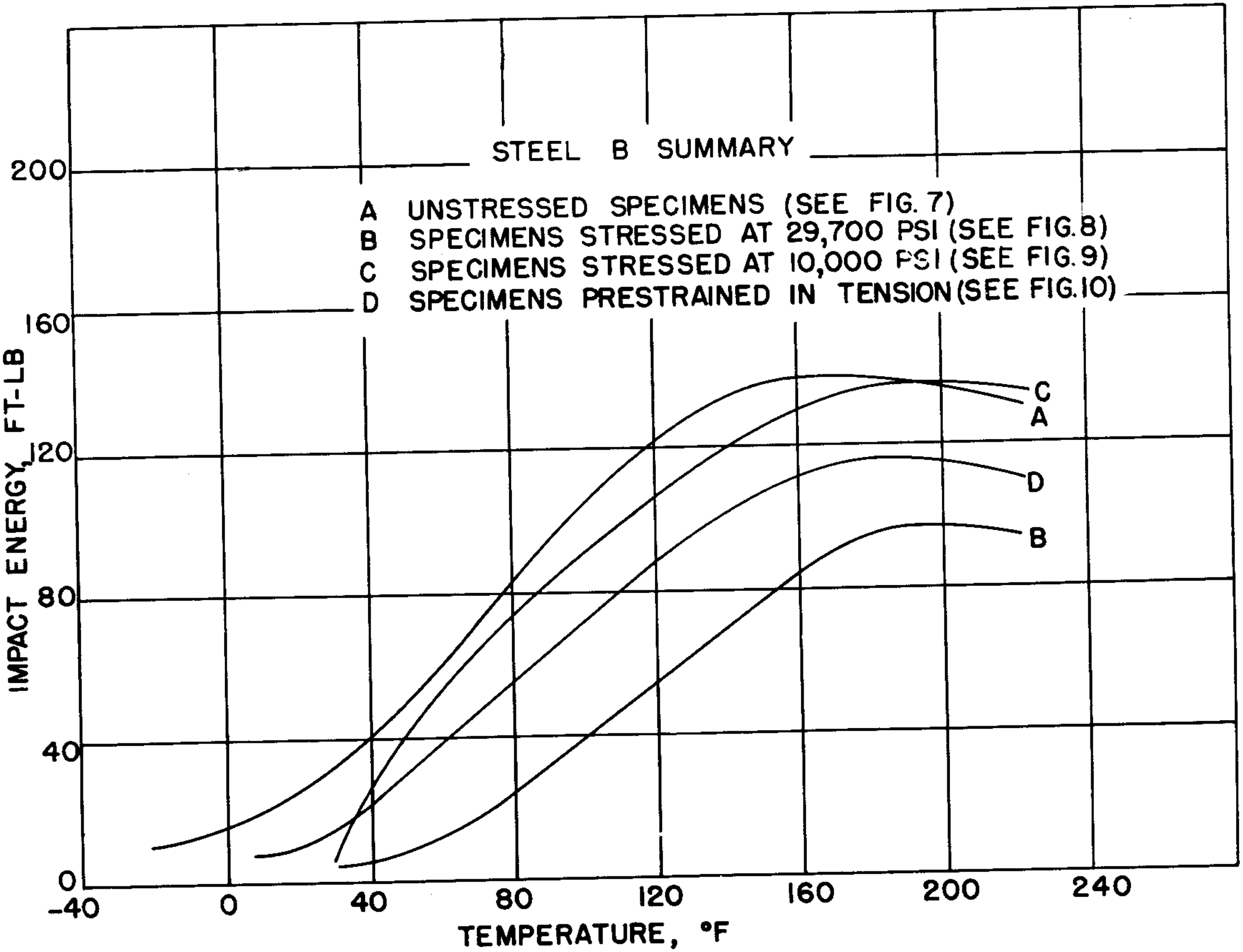
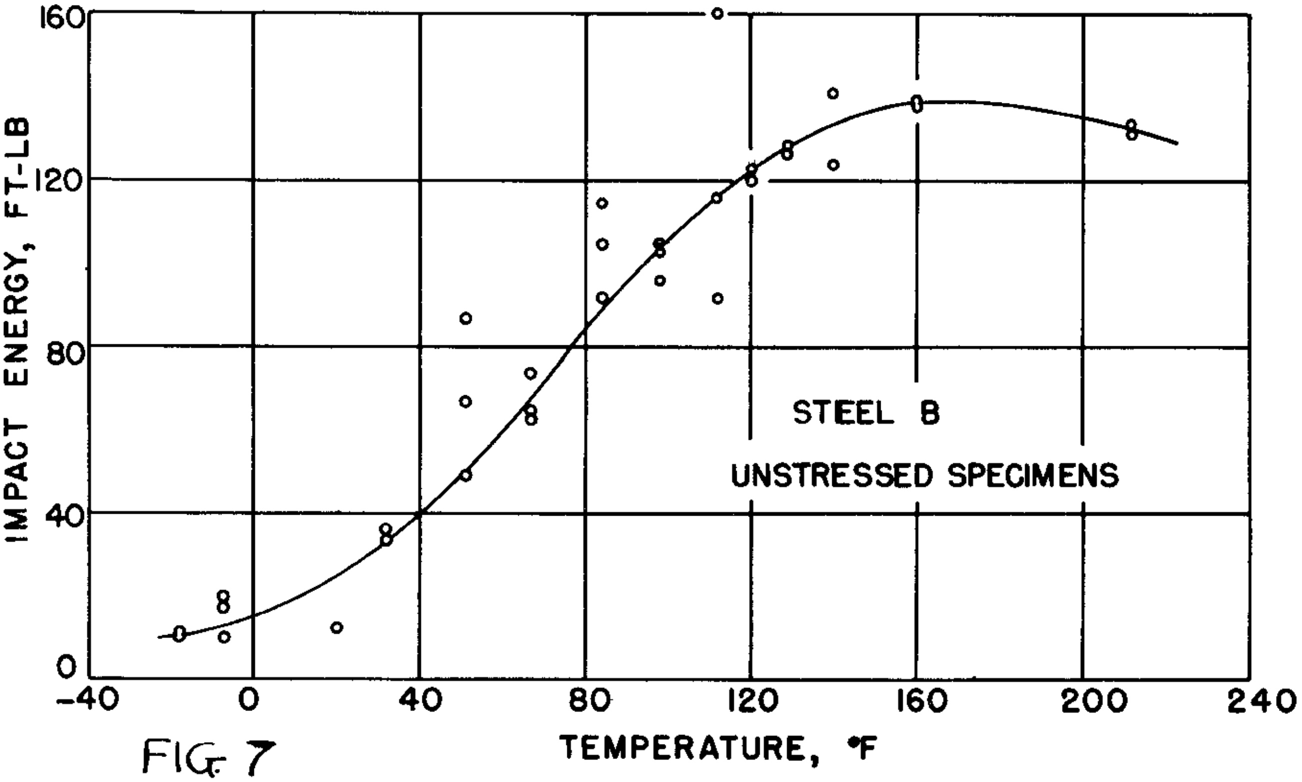
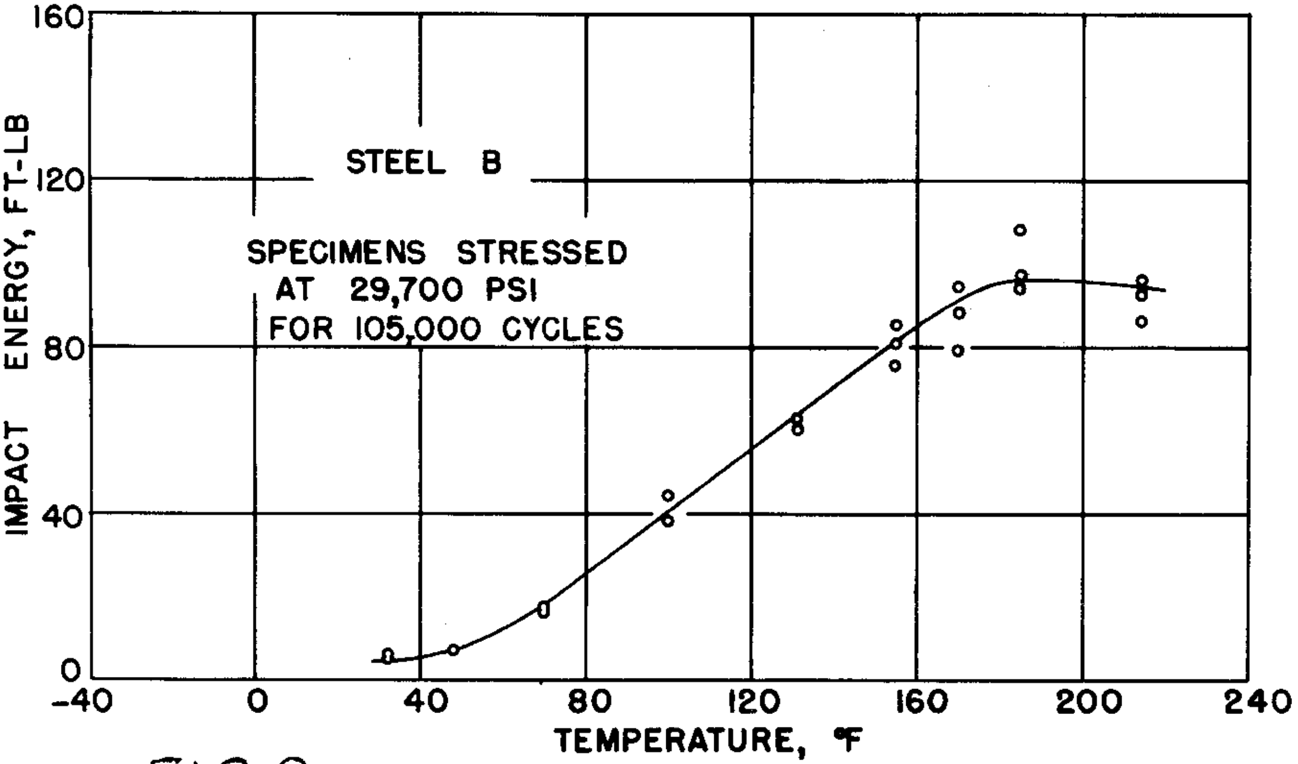

STEEL B SUMMARY
A UNSTRESSED SPECIMENS (SEE FIG. 7)
B SPECIMENS STRESSED AT 29,700 PSI (SEE FIG. 8)
C SPECIMENS STRESSED AT 10,000 PSI (SEE FIG. 9)
D SPECIMENS PRESTRAINED IN TENSION (SEE FIG. 10)
C
A
D
B
IMPACT ENERGY, FT-LB
0
40
80
120
160
200
-40
0
40
80
120
160
200
240
TEMPERATURE, °F

FIG. 6



IMPACT ENERGY, FT-LB
160
120
80
40
0
-40
0
40
80
120
160
200
240
TEMPERATURE, °F
STEEL B
UNSTRESSED SPECIMENS

FIG. 7



IMPACT ENERGY, FT-LB
160
120
80
40
0
-40
0
40
80
120
160
200
240
TEMPERATURE, °F
STEEL B
SPECIMENS STRESSED
AT 29,700 PSI
FOR 105,000 CYCLES

FIG. 8

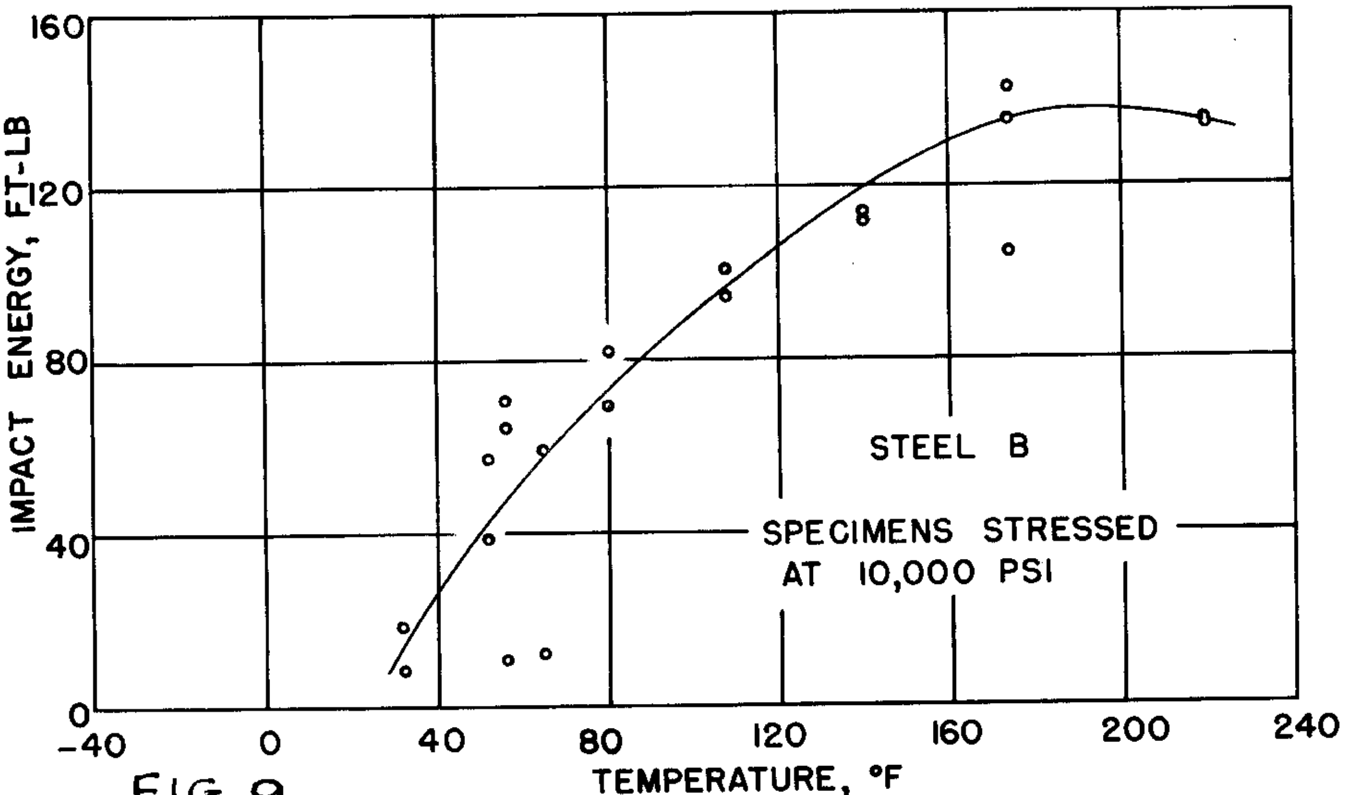

160
120
80
40
0
IMPACT ENERGY, FT-LB
-40
0
40
80
120
160
200
240
TEMPERATURE, °F
STEEL B
SPECIMENS STRESSED AT 10,000 PSI

FIG 9

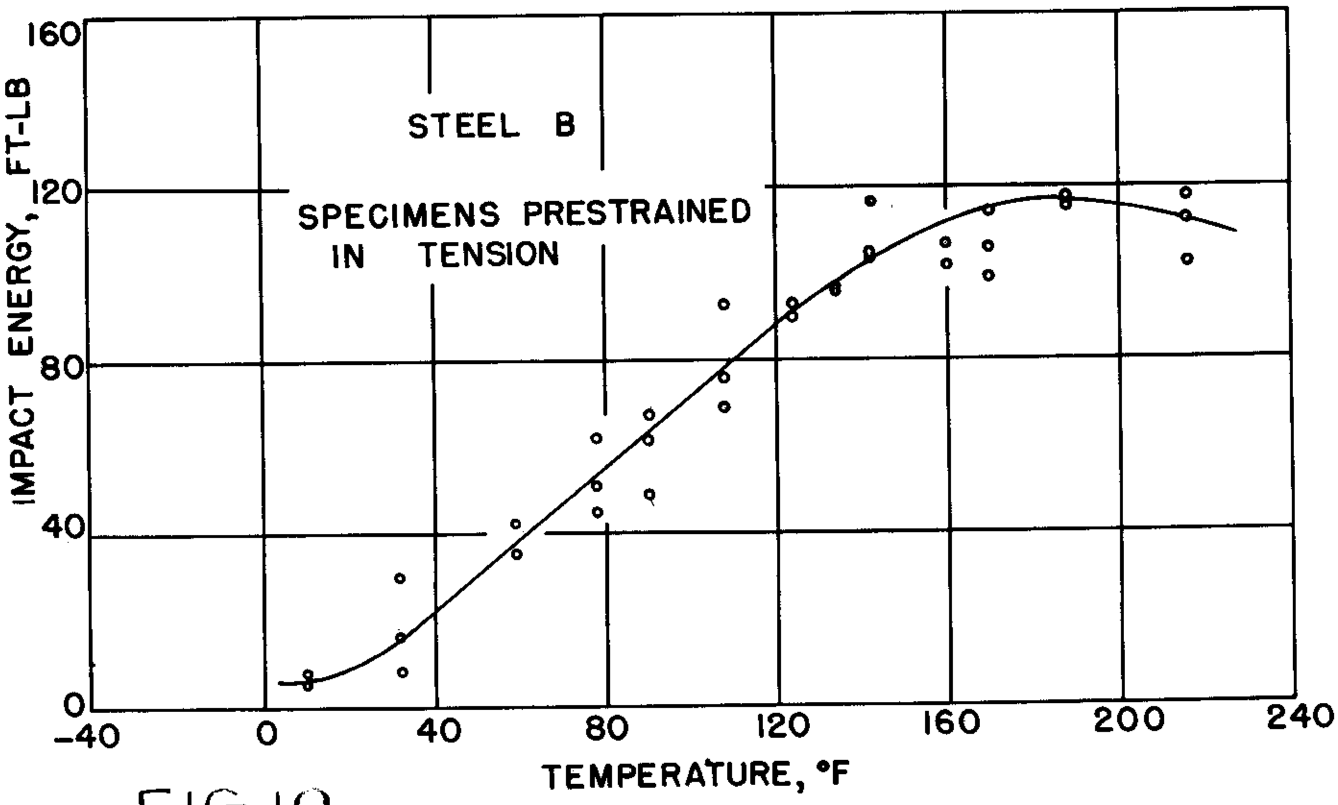

160
120
80
40
0
IMPACT ENERGY, FT-LB
-40
0
40
80
120
160
200
240
TEMPERATURE, °F
STEEL B
SPECIMENS PRESTRAINED IN TENSION

FIG. 10

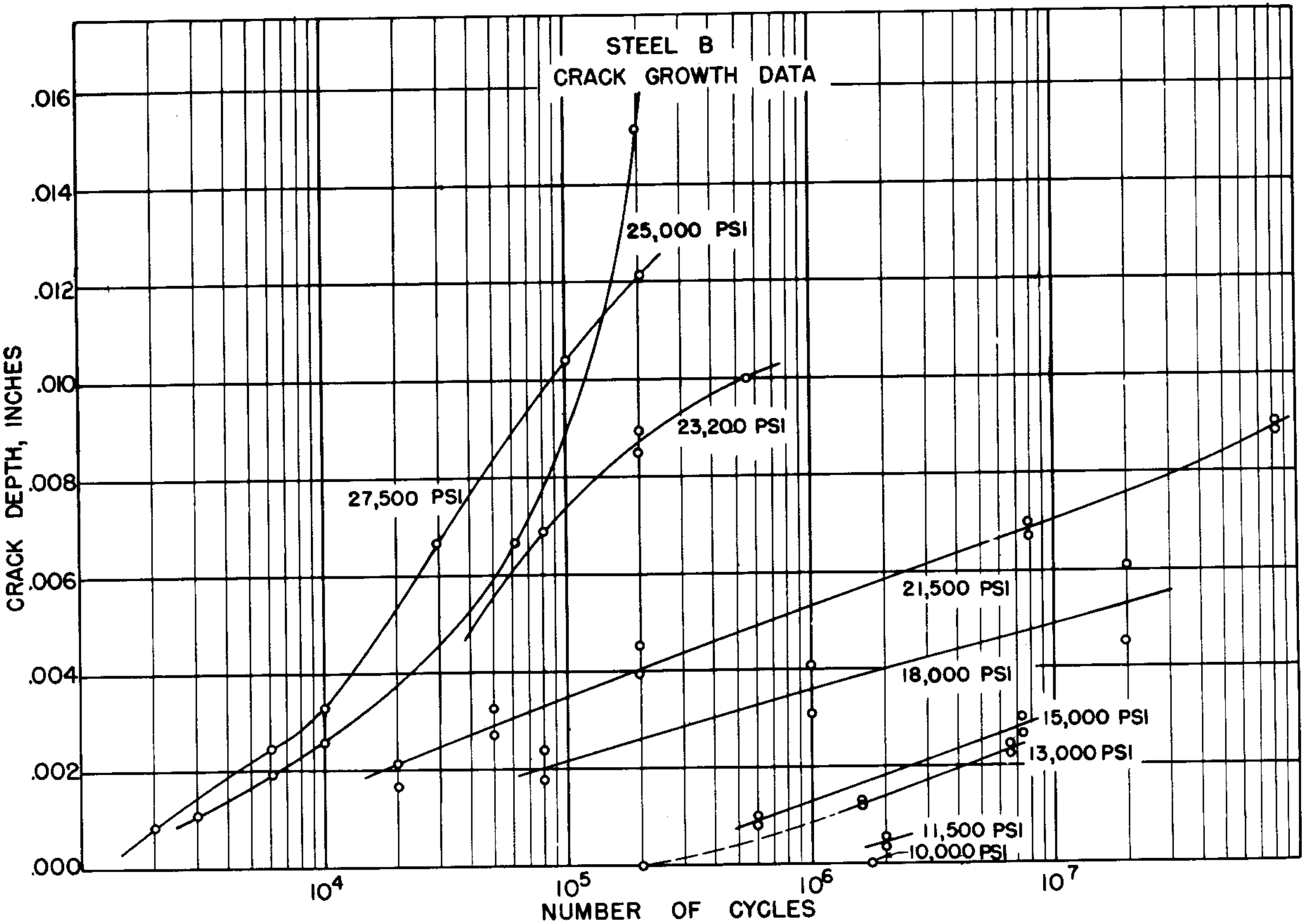

STEEL B
CRACK GROWTH DATA
CRACK DEPTH, INCHES
.016
.014
.012
.010
.008
.006
.004
.002
.000
10^4
10^5
10^6
10^7
NUMBER OF CYCLES
25,000 PSI
23,200 PSI
27,500 PSI
21,500 PSI
18,000 PSI
15,000 PSI
13,000 PSI
11,500 PSI
10,000 PSI

FIG. 11

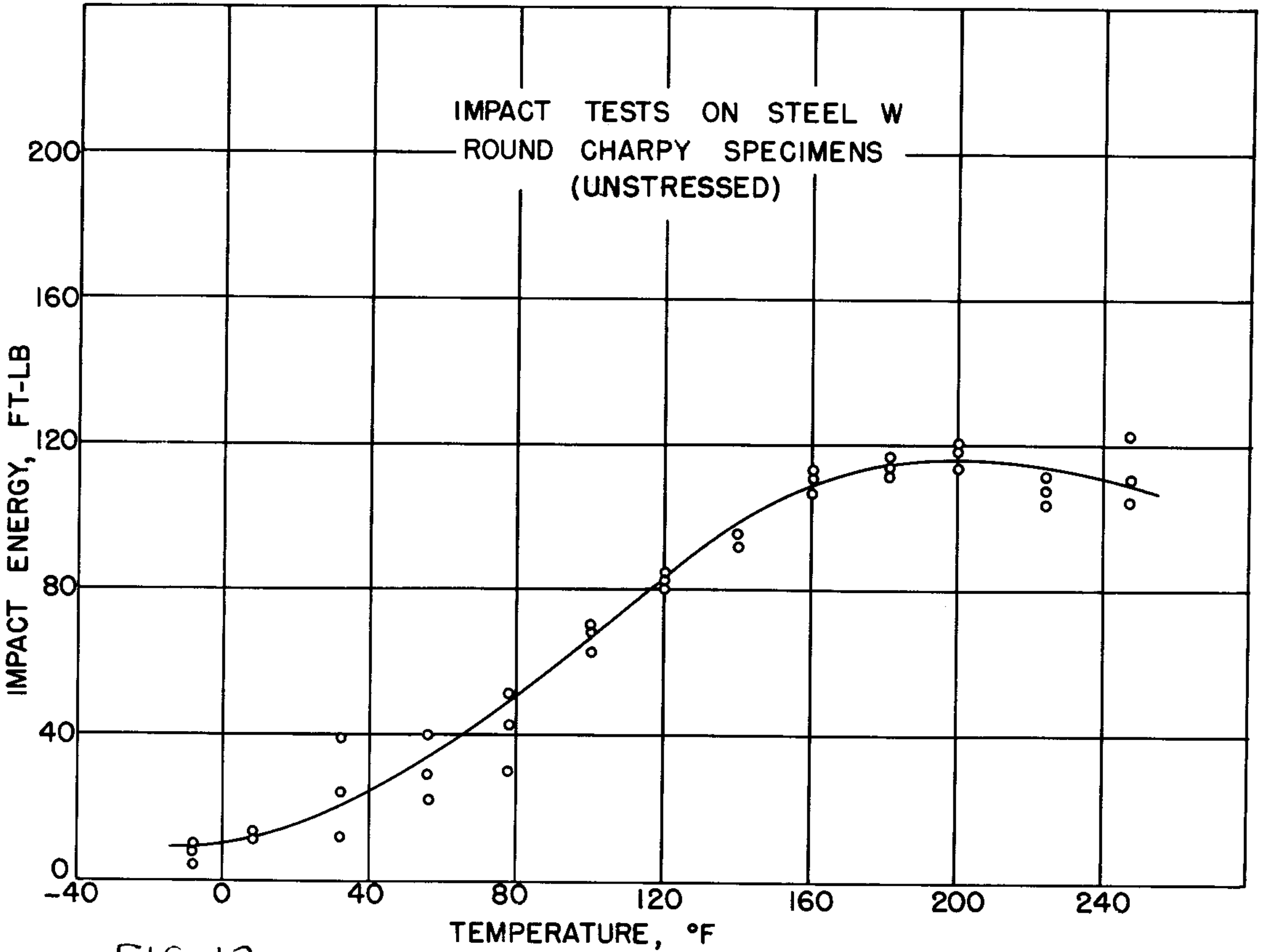

IMPACT TESTS ON STEEL W
ROUND CHARPY SPECIMENS
(UNSTRESSED)
IMPACT ENERGY, FT-LB
0
40
80
120
160
200
-40
0
40
80
120
160
200
240
TEMPERATURE, °F

FIG. 12

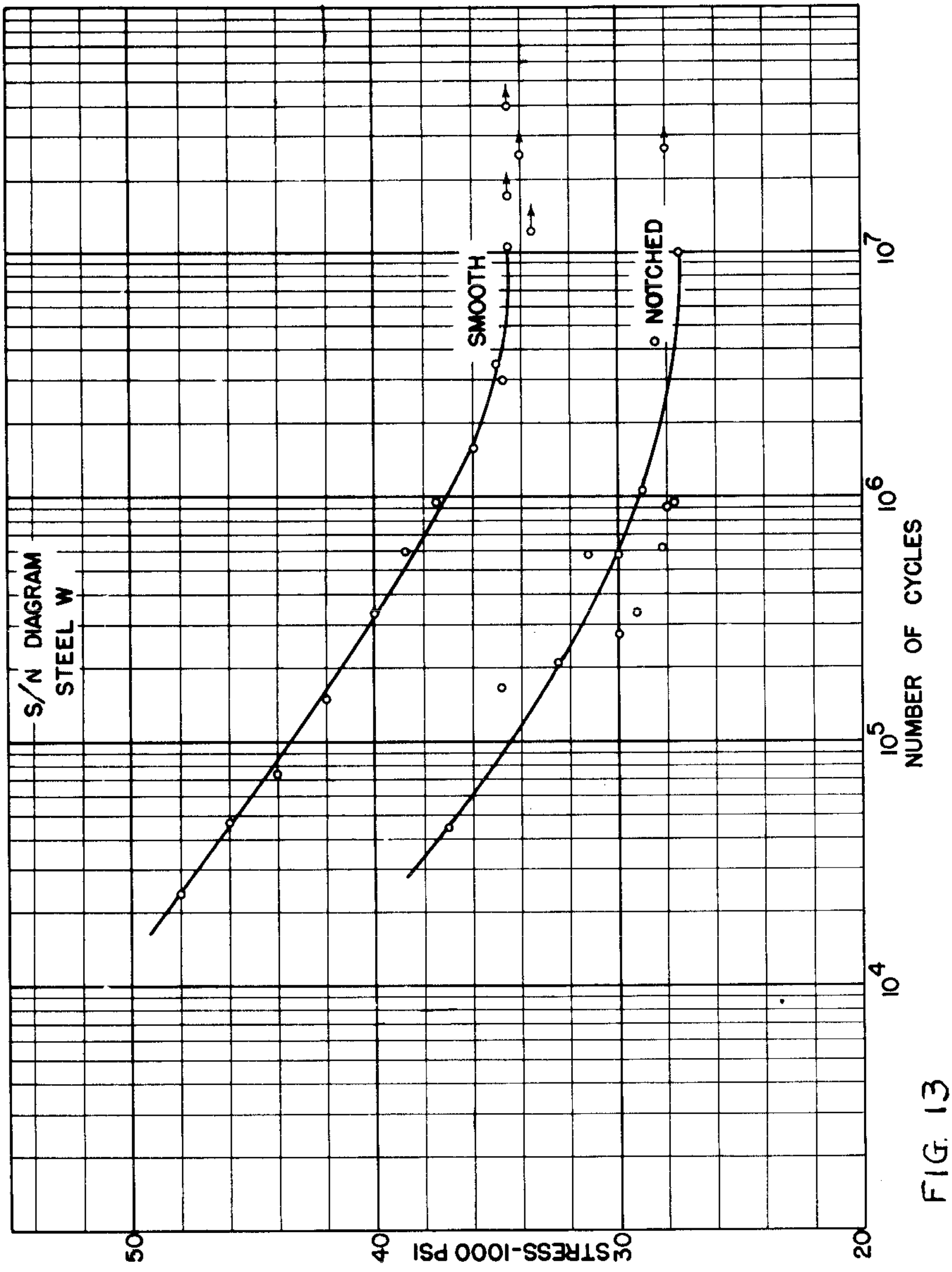

S/N DIAGRAM
STEEL W
SMOOTH
NOTCHED
50
40
30
20
STRESS-1000 PSI
10^4
10^5
10^6
10^7
NUMBER OF CYCLES

FIG. 13

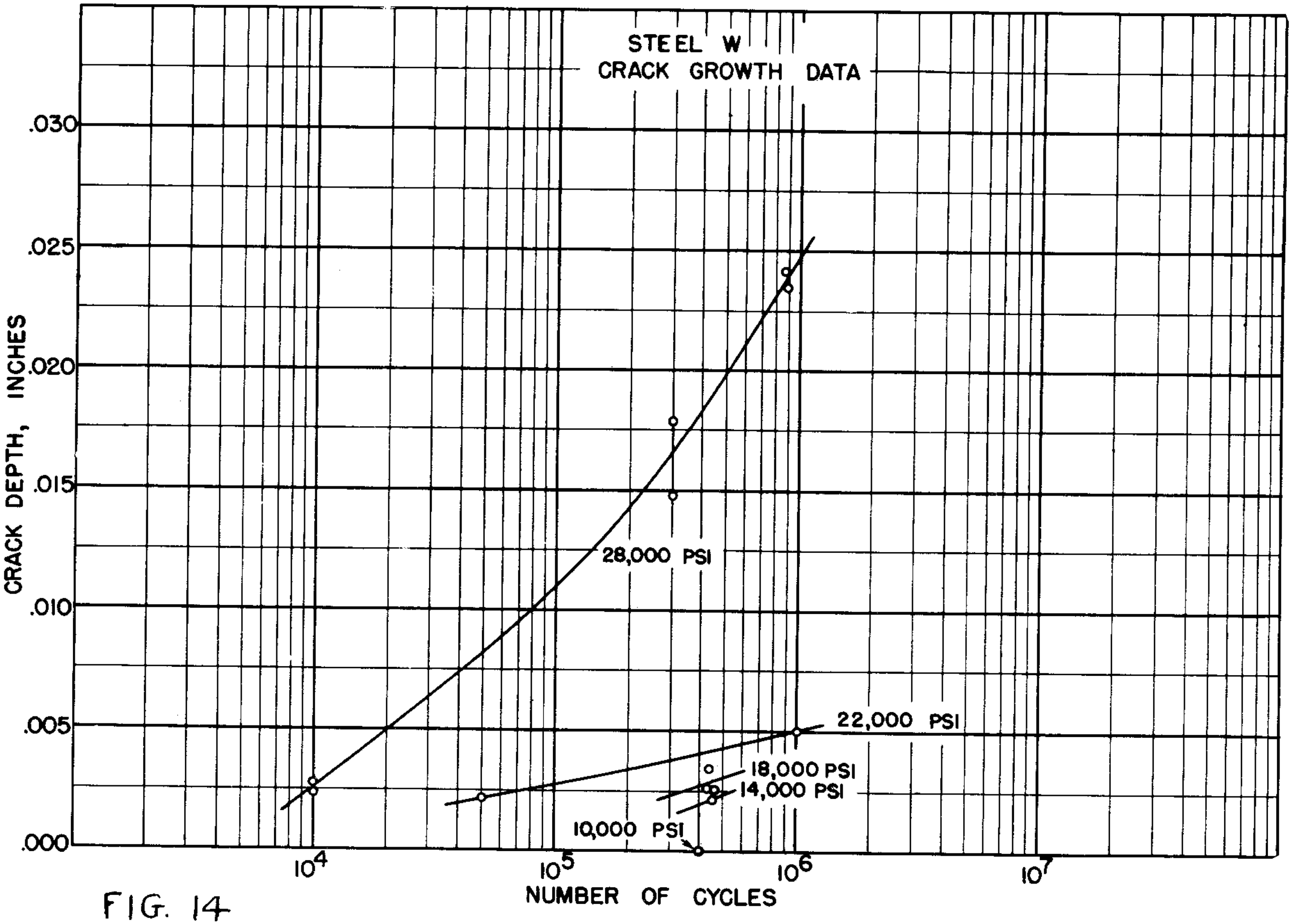
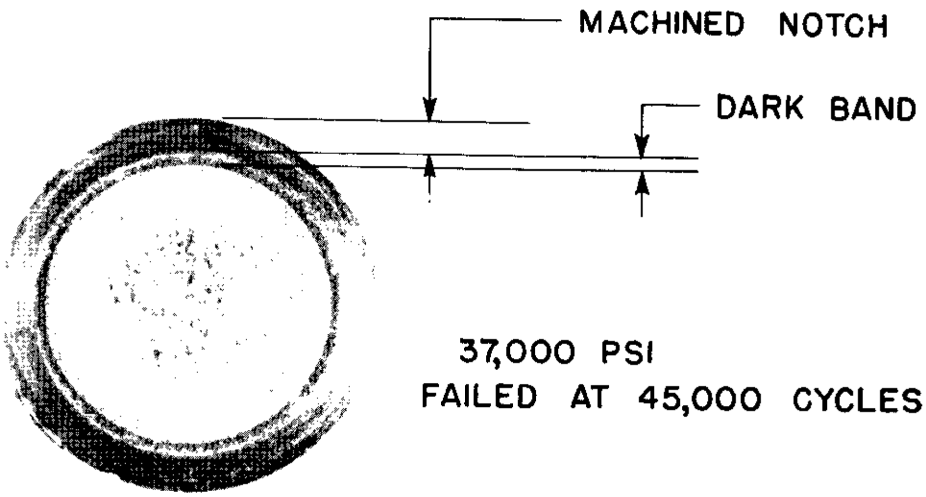

STEEL W
CRACK GROWTH DATA
CRACK DEPTH, INCHES
.030
.025
.020
.015
.010
.005
.000
28,000 PSI
22,000 PSI
18,000 PSI
14,000 PSI
10,000 PSI
10^4
10^5
10^6
10^7
NUMBER OF CYCLES

FIG. 14



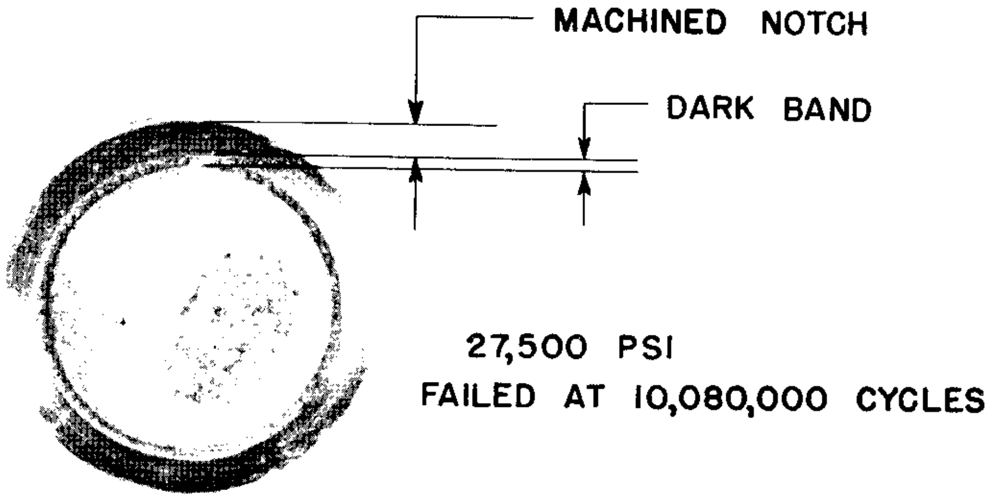


FIG. 15

DARK BANDS FOUND IN FATIGUE SPECIMENS OF STEEL W

(The above specimens failed in fatigue.)

APPENDIX A

1. CHARACTERISTICS OF STEELS B AND W

Composition

	Steel B (in %)	Steel W (in %)
C	0.18	0.21
Mn	0.73	0.52
P	0.011	0.013
S	0.030	0.010
Si	0.040	0.23
N	0.006	0.0049

Mechanical Properties

	Steel B	Steel W
Tensile Strength psi	59,600	62,540
Yield Point psi	35,800	37,230
Elongation in 8"	26.0	30.3

2. PREPARATION OF ROUND NOTCHED SPECIMENS

Both Steel B and Steel W were received in 3/4" plate form, hot rolled, with some sheared and some flame cut edges. These plates were tested as received with no additional heat treatment.

All the specimens were cut out with their length parallel to the direction of rolling and were taken from the middle of the thickness of the plate. Each specimen was marked so that the direction of the thickness of the original plate was perpendicular to the direction of the impact blow of the Charpy machine. Care was taken that no specimen test section was closer than 2 inches to a flame cut edge.

Drawings of the impact and fatigue specimen are shown in Fig. 1, (page 15). The impact specimen had to be cut away (milled) at A and B as shown to permit the broken halves to pass through the Charpy machine without jamming. However, an occasional jam was experienced.

The tapered ends and overall length of the fatigue specimen correspond to the standard specimen used in the R. R. Moore rotating beam fatigue machine.

The notch was cut in a single operation using a tungsten carbide tool. A 10" South Bend tool room lathe was employed. The specimen was held in a collet and the back gears employed to give the slowest spindle speed of about 40 rpm. As the work was revolving in reverse, it was necessary to invert the cutting tool in the tool post. The smallest feed available, 0.002" per revolution, was used. Higher spindle speeds and feeds were tried but the notch finishes obtained were not so good as the low speed finish. The work was constantly lubricated with carbon tetrachloride during notching. It was possible to hold the diameter of the specimen at the base of the notch to 0.400" plus 0.002" minus zero.

The tungsten carbide tool was first ground to a 45° angle and the tip radius was formed by hand honing with a 220 grit diamond hone. A Jones and Lamson optical comparator set for 62.5X was used for measuring the tip radius and tool angle. In this manner it was possible to produce the 45° angle within one degree and the 0.005" radius on the tip within 0.0002" on the radius.

After experience had been gained in machining these notches, it was decided to regrind the tool bit and rehone the radius after every 40 notches. In this interval, the tool angle did not change appreciably but the tip radius would be reduced about 0.0002".

3. USE OF THE R. R. MOORE FATIGUE MACHINE

One of the R. R. Moore rotating beam fatigue machines used in this work is pictured in Fig. 3, (P. 17).

The specimen is held in tapered sleeves mounted in ball bearing housings. Equal moments are applied to each housing to give a constant bending moment across the specimen. The moments are applied by a dead load to each housing through an equalizing bar.

The fiber stress experienced by a specimen in this machine is dependent on the diameter of the specimen and the dead load applied. Each specimen was measured to the nearest 0.0005" and the applied load for a given stress calculated.

It was noted that the eccentricity of specimens appeared to have an appreciable effect on the scatter of data in the fatigue tests. Eccentricity of the smooth specimens (standard R. R. Moore specimens, 0.300" diameter) usually resulted in scatter only, while eccentricity of the larger notched specimens would sometimes result in obviously premature fracture.

Quantitative standards of eccentricity were obtained in the following manner: With a specimen assembled in the fatigue machine, a dial indicator mounted on a heavy base was rested on the specimen turned by hand. In general, if the dial indicator showed a variation of more than 0.005" in reading, the specimen would vibrate severely and premature fracture or excessive scatter was expected. For best results, the eccentricity was kept below 0.002".

Test data in which this care had been taken are shown in the S/N diagrams of both steels and lines of crack growth for steel B below 23,200 psi.

The scatter of data for the S/N diagram for notched specimens of Steel W is worthy of discussion. The initial fatigue tests on round notched specimens of Steel W showed a great amount of scatter. Fractures were experienced at stresses 5000 psi below stresses where some specimens had run 12 million cycles without fracture. Since the S/N diagram for standard smooth specimens showed little scatter, the notch finish was investigated.

The same notching method which produced a smooth finish in Steel B was found to leave small circumferential ridges at the root of the notch and occasionally would tear small particles out of the bottom of the notch.

Specimens with no tears were selected for further use, the others discarded. The minute ridges in the notch were lapped off by using #30 bare copper wire and 440 grit lapping compound. The specimen to be lapped was held in a lathe collet with the spindle revolving at about 100 rpm. The wire was rotated by means of an electric drill running at about 300 rpm. The other end of the wire was gripped in a pin vise mounted in a small ball bearing. The drill and ball bearing were held by hand and with a slight tension on the wire. The rotating wire was brought to bear on the bottom of the notch for 30 seconds.

The notch finish obtained in this manner was not quite so good as that obtained in Steel B by machining alone. However, fatigue tests of lapped specimens gave usable data.

4. FATIGUE CRACK INVESTIGATION

When the dark bands on the fracture faces of the fatigue specimens were observed, it was attempted to prove that they represented fatigue cracks by means of non-destructive crack detection tests. Magnaflux, Zyglo, and penetrating dyes were all used unsuccessfully.

Presumably the Magnaflux test failed because of the disturbing effect of the notch itself. The dyes would penetrate the crack but not in a quantity sufficient to produce discoloration at the bottom of the notch after cleaning.

A destructive method of sectioning, mounting, and polishing was resorted to. This method was very successful and was used exlusively thereafter.

In this method, one end of the specimen was cut off about one-half inch away from the notch. A longitudinal cut was then made along the length of the specimen to about one-half inch on the other side of the notch. The cutting wheel was 0.030" thick. This cut was not centrally located but was sufficiently offset so that one portion of the specimen was truly a half specimen. This true half was then cut free of the remainder and mounted in a conventional bakelite base.

The specimen was polished and slightly etched. Some photographs of these sections are shown in Figs. 17 to 20.

Cracks were readily located in this manner and were plainly visible under a microscope down to a few ten thousandths of an inch in length.

The crack lengths, or actually, the depths of crack penetration, were measured by using the objective and lighting system of a Tukon tester with an eyepiece equipped with movable cross-hairs mounted on a calibrated micrometer lead screw.

In the plots of cracks growth data, it may be seen that there are either one or two points plotted for each stress and number of cycles. In both cases only one specimen was used. Originally only one side of a specimen was measured for crack penetration but later both sides were measured and plotted.

Of all these specimens there was found only one which had fatigue cracks large enough to be visible to the naked eye. This specimen was run at 29,700 psi for 250,000 cycles. Since this number of cycles is past the point necessary to produce failure at that stress, it can be assumed that failure was imminent at this point. A photograph of the entire cross section of this specimen is shown in Fig. 16.

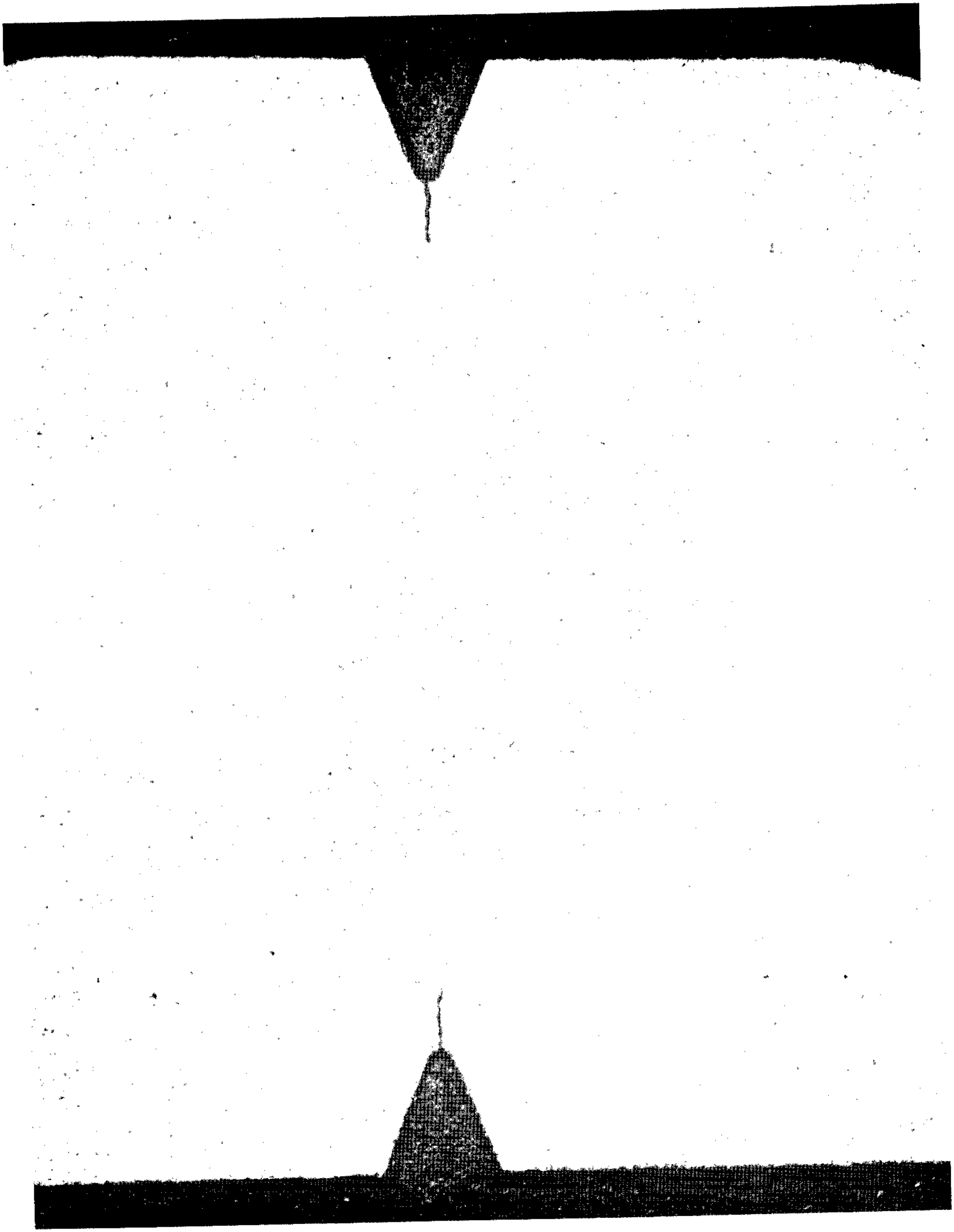


FIG. 16 - FATIGUE CRACKS IN STEEL B 29,700 psi, 250,000 CYCLES

FIG. 17 - PHOTOGRAPH OF FATIGUE CRACK IN STEEL B;
27,500 psi, 100,000 CYCLES. 270X

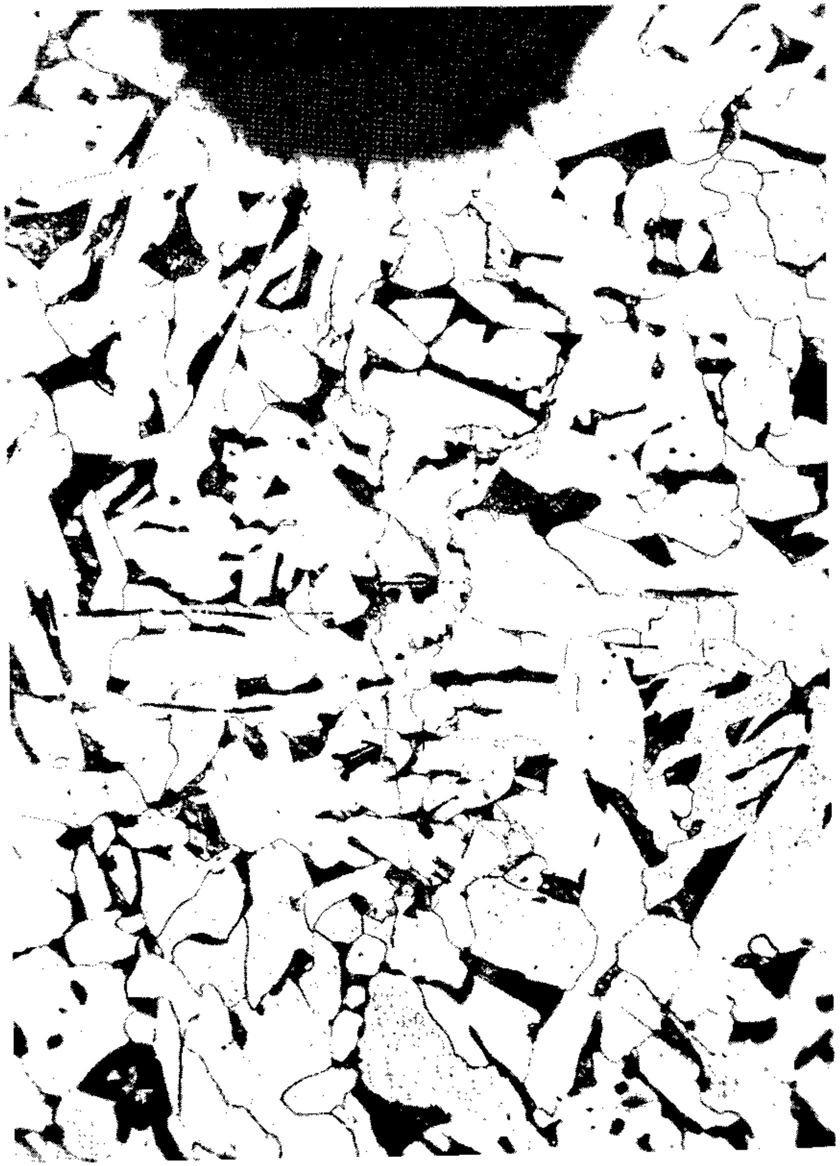
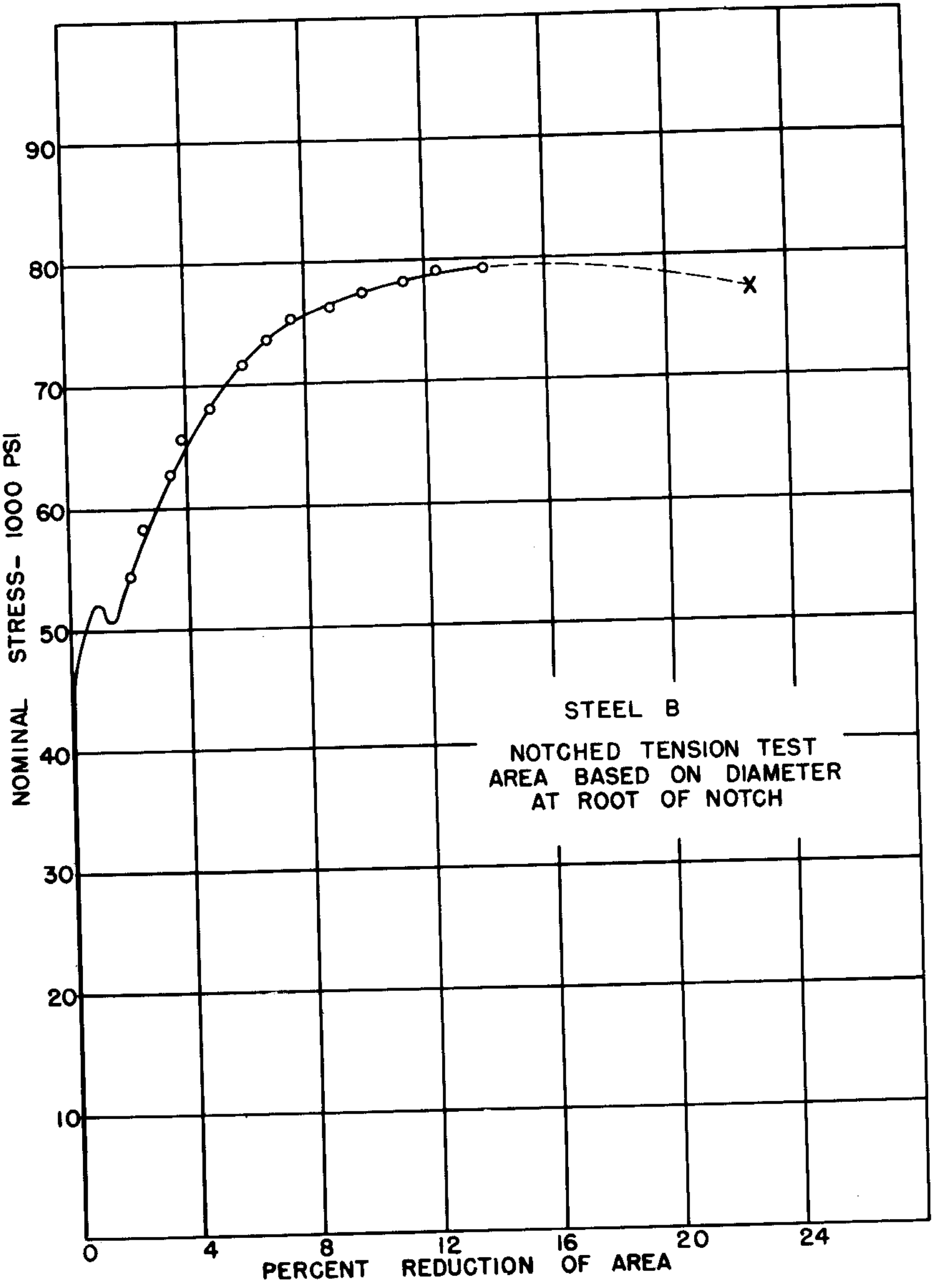


FIG. 18 - PHOTOGRAPH OF FATIGUE CRACK IN STEEL B;
25,000 psi, 200,000 CYCLES. 270X

FIG. 19 - PHOTOGRAPH OF FATIGUE CRACK IN STEEL B; 23,200 psi, 200,000 CYCLES. 270X

FIG. 20 - PHOTOGRAPH OF FATIGUE CRACK IN STEEL B 23,200 psi, 80,000 CYCLES. 270X



NOMINAL STRESS- 1000 PSI
90
80
70
60
50
40
30
20
10
0
4
8
12
16
20
24
PERCENT REDUCTION OF AREA
STEEL B
NOTCHED TENSION TEST
AREA BASED ON DIAMETER
AT ROOT OF NOTCH

FIG. 21