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DESIGN PROPERTIES OF HIGH-STRENGTH STEELS IN THE PRESENCE OF STRESS-CONCENTRATIONS

Effects of a Number of Variables on the Mechanical Properties of Aircraft High-Strength Steels

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FOREWORD

This report was prepared by Syracuse University under USAF Contract No. AF 33(616)-2362. The contract was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73605 "Design and Evaluation Data for Structural Metals" formerly RDO No. 614-13 "Design and Evaluation Data for Structural Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. A. W. Brisbane as project engineer. This work was performed in the period between March 1954 and June 1955.

ABSTRACT

This report presents a large amount of test data on a number of low-alloy steels, heat treated to strength values between 210,000 and 290,000 psi. The steels investigated were four heats of 4340 and one heat of each of the following: V-Mod. 4330, 98B40, Hy-Tuf, Super Hy-Tuf, Super TM-2 and Inco. Furthermore, the results of tests previously performed on an additional heat of 4340 (small dia. bar) are included for purposes of comparison and completeness. The tests performed were the following: a) Tension, which yielded information concerning the tensile and yield strengths as well as the ductility (reduction of area and elongation) of the steels studied. b) Notch-Tension, from which the notch strength, notch-strength ratio and information on the notch sensitivity of the steels were obtained. c) Impact, which permitted evaluation of impact characteristics of the steels at various test temperatures, as well as some information regarding the transition from impact-ductile to impact-brittle behavior. d) Fatigue and Notch-Fatigue, from which the endurance limit and the fatigue strength at various numbers of cycles were obtained for both smooth and notched specimens. e) Stress-Rupture, which permitted investigating the behavior of high-strength steels under sustained load conditions.

In addition, hardness measurements as well as metallographic studies were performed on all steels.

This report comprises first an extensive discussion of the effects of all fundamental factors investigated here. These factors are: (a) specimen position, (b) various heats of 4340 steel, (c) as-processed section size, (d) as-tested section size, (e) tempering temperature, (f) 500°F temper brittleness, (g) stress concentration, (h) directionality, (i) eccentricity, (j) loading time and (k) test temperature. This is followed by a comparison of the properties of the various steels, those of 4340 steel being used as basis.

The appendices (Supplement 1 and 2) assembles the individual data in graphical and tabular form. Various parametric representations are used to facilitate their utilization.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
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SYMBOLS USED

SYMBOL

K: Theoretical stress-concentration factor as derived by Neuber's Theory.

L: Longitudinal specimens, i.e. specimens taken along the direction of rolling.

Tr: Transverse specimens, i.e. specimens taken perpendicular to the direction of rolling.

R.L: Longitudinal specimens taken from the rim of the V-Mod. 4330 bar.

C.L: Longitudinal specimens taken from the core of the V-Mod 4330 bar.

R.T: Transverse specimens taken from the rim of the V-Mod. 4330 bar.

C.T: Transverse specimens taken from the core of the V-Mod. 4330 bar.

e: Eccentricity, i.e. the distance from the center of the specimen to the line of load application.

D: Shank diameter of notch-tension or notch-fatigue specimens.

d: Notch diameter of notch-tension or notch-fatigue specimens.

INTRODUCTION

The increasing needs of the aircraft industry for high-strength materials have recently led to the use of low-alloy steels, heat treated to 230,000 to 270,000 psi. However, steels at strength levels above 200,000 psi are subject to design restrictions, which are of little significance at lower levels, such restrictions are now recognized to be characteristic for these super-high-strength steels. The objective of the present research program is to supply the designer of aircraft with basic information for a variety of test conditions, upon which design for these steels can be based.

The tests used have been selected to allow coverage of the various areas of potential aircraft failures and they include: a) tension, b) notch-bar tension tests (concentric and eccentric), c) impact tests, d) fatigue and notch-fatigue tests, and e) stress-rupture tests.

The steels investigated were 4340 (four heats of this steel were studied), vanadium-modified 4330, 98B40, and the proprietary steels Hy-Tuf,* Super Hy-Tuf,* Super TM-2,** and Inco Ultra High-Strength Steel.***

The large volume of test data obtained in the present work leads to considerable problems in the presentation. This results from the fact that numerous variables have been considered and examination of each of these variables requires the comparison of data for up to ten steels. Since consideration of the specific data for each steel would be needlessly tedious, the discussion is concentrated on characteristic data and their trends. The specific data needed for the development of the basic principles, are presented in both, graphical and tabular form in supplements 1 and 2.

Most of the previous evidence has been discussed in a literature survey (1 to 5)**** which preceded the present experimental investigation. Therefore, the general subject of ultra-high strength steels will not be considered in this report. Only that literature will be discussed, which has a direct bearing on and which is needed for a full evaluation of the test data obtained in the present work.

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*Supplied by Crucible Steel Company of America

**Supplied by Timken Roller Bearing Company

***Supplied by the International Nickel Company, Inc.

****Numbers in parenthesis pertain to the bibliography

I. EXPERIMENTAL PROCEDURE

1. Materials

Pertinent information about the steels studied is presented in Table I. The materials were selected as being the most promising of the deep hardening, low-alloy, constructional steels for use in the ultra high-strength range. Developmental steels for this application are numerous, but the steels selected are the only ones which could be commercially obtained at the present time.

2. Test Specimens

(a) Specimen Preparation: The tensile, notch-tensile, fatigue, notch-fatigue and stress-rupture specimens used in this investigation are presented in Figure 1. Specimens were rough machined and left approximately 0.015 inch oversize on each surface and were finished to proper dimensions after heat treatment. Smooth specimens and specimens with mild notches (K = 3) were finish ground, while sharp notches (K = 5, 8 and 10) were machined by means of a properly ground high-speed steel tool.

(b) Specimen Heat Treatment: Heat treatment was performed according to the SAE - Aeronautical Material Specifications (AMS) pertinent for the specific steels. The specimens were austenitized in graphite blocks and in controlled atmosphere. They were then oil quenched and tempered at from 250° to 800°F (± 10°F), for one hour. Tempering was followed by air cooling.

(c) Specimen Orientation: The properties of all the steels were determined for the longitudinal direction. Transverse properties have also been determined in a number of instances, as they are becoming increasingly important for the following reasons:

(i) Forgings may be used under conditions where loads are applied in several directions simultaneously. Under these conditions, high stresses may occur perpendicular to the fiber direction of the forgings.

(ii) The frequency of transverse failures appears to increase as the strength of the steel increases. Consequently directionality assumes greater importance at high strength levels.

(iii) It is often desired to use rolled stock and rough shapes hand-forged from these, for prototypes, which renders the utilization of transverse properties essential.

(d) Specimen Size: The 0.3-inch-diameter specimen has been the type most commonly employed in notch-tensile investigations. However, it is to be expected that increasing the specimen size will adversely modify the notch properties. For the above reason 0.5-inch-diameter, as well as 0.3-inch-diameter specimens, were tested to evaluate the effect of size on the notch-strength characteristics of the steels. In these tests the specimen dimensions have been appropriately scaled to yield comparable theoretical stress-concentration factors.

(e) Specimen Location: The economic utilization of the steel required cutting the section into small blanks. The distribution of the specimens over the cross section of the bar introduced the problem of the effects of specimen position. The large volume of tests permitted analyzing this effect and determining its magnitude, (see Section II). Because of the indicated small magnitude of the effect no further attention was paid to the positioning of each specimen.

3. Hardenability Tests:

Hardenability tests were performed in accordance with the ASTM specifications for each of the steels investigated. A specimen was taken from the billet at random for all steels, except in the case of the V-Mod. 4330 steel, in which the specimen was located longitudinally in such a way that its center was 1-1/8 inch from the center of the billet, i.e. the location of the specimen was such that one half of it was in the rim section, while the other half was in the core section of the billet. This placement permitted the evaluation of the hardenabilities of the rim and the core of the steel in one specimen. The results indicated a slightly higher hardenability for the rim stock. As the difference was very small, the results of the two locations were averaged.

4. Chemical Analyses:

Chemical analyses, of the steels investigated, were conducted by Kimman and Wheeler of Syracuse, New York and the results are presented in Table II.

5. Metallographic Studies:

Macro-studies were made on a section, as received, (1/2 inch to 1 inch thick), cut from each steel bar investigated, to determine characteristic structures and forging histories of the steels. The sections were ground and etched with 25 percent solution of nitric acid. Photographs were taken. In addition micro-studies were made on all steels (tempered at 500°F and etched with 4 percent Nital solution) along and perpendicular to the direction of rolling, to determine fiber development, impurities and inclusions. The results of these tests are presented in Supplement 1.

6. Hardness Tests:

The main tests were preceded by preliminary hardness investigations, performed on 3/4 in. x 3/4 in. x 1 in. specimens, which were oil quenched and tempered at from 250° to 800°F. Thirty-six hardness readings were taken at the center of each specimen, and the results were used as guides in arriving at the required strength levels. Furthermore, hardness tests were performed on the notch-tensile specimens after fracture. The specimens were cut to obtain a cross-section 1/4 in. from the fracture. The resulting section was polished and four hardness readings were taken. A total of 12 specimens were tested for each steel, thus yielding a total number of 48 hardness readings.

The results indicated a maximum scatter of ± 1-1/2 Rc units from the average. Consequently only the average of these readings are shown in this report.

7. Tension Tests:

The specimens for unnotched or "smooth" tension tests shown in Figure 1(a), were used for V-Mod. 4330. However, some difficulties were encountered with transverse specimens of Super Hy-Tuf and 98B40, as many specimens broke under the head. Therefore, the stepped specimen shown in Figure 1(b) was employed with all steels, other than V-Mod. 4330.

All tensile tests were performed at room temperature on a 60,000 pound hydraulic testing machine. To insure concentricity of loading, the concentric fixture shown in Figure 2 was used.

The tensile strength, elongation, and reduction of area were obtained in the conventional manner.

The 0.2-percent-yield strength was obtained with only a limited degree of accuracy by adapting a 2-inch extensometer to the 1-inch gage specimens in the manner shown in Figure 3.

8. Concentric Notch Tension Tests:

Two different specimen diameters, namely 0.3 in., Figure 1(c), and 0.5 in., Figure 1(d), were used in the notch-tension test. The notch on these specimens was of the 60-degree, 50-percent type, in which case the 50 percent refers to the ratio of the area of the notched section to that of the cylindrical part. Three different stress-concentration factors were employed, namely K = 3, 5 and 10. The radii at the notch bottom, corresponding to these stress-concentration factors, were calculated by Neuber's theory and are presented in Table III.

An optical comparator with 62.5 diameter magnification was used to measure the notch radii and the notch diameters, before and after the test.

The concentric fixture shown in Figure 2 was used for the 0.3 inch diameter specimens, and that shown in Figure 4 was used for the 0.5 inch diameter specimens. The notch strength was obtained by dividing the maximum load by the original area of the notched section. The notch ductilitity (reduction of area at the notched section) was obtained in the conventional manner.

9. Eccentric Notch-Tension Tests:

The specimen shape used for the Eccentric Notch-Tension Test is shown in Figure 1(c). Only 0.3 inch diameter longitudinal specimens were tested. Three stress-concentrations were again used, namely K = 3, 5, and 10.

The eccentric notch test was performed by offsetting the line of load application from the specimen center to the root of the notch, a distance equal to 0.106 inches. This was achieved by using the adapter shown in Figure 5, in conjunction with the concentric fixture of Figure 2.

The eccentric notch strength and notch ductility were obtained as described for the concentric notch-tension tests.

10. Impact Tests:

Impact tests were performed on standard V-notch Charpy specimens at four temperatures; 212°F (boiling water), room temperature, -71°F (by immersion in a solution of chloroform, dry ice and carbon tetrachloride) and -150 to -166°F (in Freon No. 12 contained in a beaker immersed in liquid nitrogen). In the first and last two cases the specimens were kept in the solutions for a period of approximately 10 minutes. Care was taken to insure minimum temperature change by placing the specimen in the impact machine as quickly as possible.

11. Fatigue and Notch-Fatigue Tests:

All fatigue tests were of a rotating-beam type and were performed at room temperature.

The specimens used are shown in Figures 1(e) and 1(f). In all cases, except for 4340 steel, only longitudinal specimens were tested. In addition to smooth specimens, K = 1, one stress concentration was employed, namely K = 8.

In the case of 4340 steel, both longitudinal and transverse smooth specimens were investigated. Three stress-concentration factors (K = 3, 5 and 8) were used for the longitudinal direction. Table III shows the notch radii for the various stress-concentration factors based on Neuber's theory.

The preparation of the smooth specimens was as follows: Following heat treatment, the specimen was mechanically polished in a direction parallel to its axis by turning the specimen against a fine polishing belt moving parallel to the specimen and tightly pressed along its contour. This resulted in a smooth mirror-like surface on all specimens.

12. Stress-Rupture Tests:

The specimens used are shown in Figures 1(b) and 1(c). Only longitudinal 4340 specimens were tested, and only one stress-concentration factor, namely K = 5, in addition to smooth specimens (K = 1), was employed.

II. DEPENDENCE OF STATIC PROPERTIES OF HIGH-STRENGTH STEELS ON VARIOUS FACTORS

1. Introduction:

In Section II of this report the fundamental effects of the numerous variables disclosed by tension tests on smooth and notched bars are discussed, correlated and evaluated. Most of the static tests were performed on specimens machined from 3 to 4-1/2 inches round or square hot rolled sections from commercial, electric-furnace heats. In addition, a limited number of tests relate to small round bars, 1-1/2 inch and 3/4 inch diameter.

A number of factors were varied in the study of the tension properties of smooth and notched testbars. They included the effects of specimen location, multiple heats of 4340 steel, as-processed section size, as-tested section size, testing direction, stress concentration, eccentricity and loading time. These factors were investigated in addition to the major variable, the strength level, which extended from 210,000 psi to a maximum value of 290,000 psi.

Furthermore in phase II of this project the basic effects of hydrogen on the tensile and notch strength of 4340 steel was explored. This work is discussed in a separate report (6) and will be referred to here only as necessary.

2. Effects of Positioning of Specimens:

In order to economically utilize large sections for test specimens, it is necessary to take the specimens from different locations within the section. This raises the question of how much the variations in chemistry, grain size, fibering etc., which exist in such sections, contribute to enlarged scattering of the test data. This applies particularly to the difference in ductility, in impact strength and in notch-strength of surface and core specimens (4, 5).

The section (4 in.sq.) used for the tests on V-Mod. 4330 steel permits evaluating the effect of specimen positioning on the properties of this alloy in some detail. If an effect of location exists, it will be apparent primarily in the strength of sharply-notched specimens (K = 10) and particularly also in the transverse direction. Since these quantities were found to vary only slightly with the strength level in the range investigated here, compensation for the rather limited number of identical tests is obtained by averaging the test data for different strength levels.

The specimens were distributed over the cross-section according to Figure 6(a) and 6(b). They fall into a number of distinctly different groups regarding their position, as shown in Table IV. Two to four specimens were available for each strength level and for each of the different distances from the center.

Both individual test values and their averages are plotted in Figure 7(a) as a function of distance from the center of the bar. The results in Figure 7(a) indicate that the longitudinal notch strength was independent of specimen location. Even for the transverse notch-strength represented in Figure 7(b), the difference between the values for extreme positions was less than 10 percent.

A similar analysis for other alloys indicates even smaller effects of positioning according to Figures 8, 9, 10, and 11. Considering the rather large variations of transverse data it was decided, therefore, to abandon any distinction between variously-positioned specimens. Otherwise, another variable would have been added, which would have materially increased the volume of testing.

3. Variations in Tension Properties of Different 4340 Heats:

It is a well known fact that the properties of various heats of the same nominal composition differ considerably. Many factors contribute to these variations, but the magnitude of the effects and their true source are not yet known. Apparently no systematic study of these variations has been previously performed.

Considerable effect in this respect is generally ascribed to the variations in chemistry and hardenability. These properties are assembled for the 4340 steels in Figure 12, together with such data for an additional steel (Heat 5) which was previously studied at Syracuse University (8). In addition, Figure 12 includes the latest (Feb. 1954) standard AISI-hardenability limits. The steels differed markedly in hardenability, within the AISI scatter band, with no apparent relation to chemistry.

Conventional mechanical properties, tensile strength, yield strength, elongation and reduction of area of specimens taken from large sections (3-1/4 to 4-1/4 in.round) were available for four of these steels, and determined from longitudinal, subsize (0.28 in.dia.) specimens. These properties were found to be practically identical, according to Figure 13. The variations in carbon content and major alloying elements are apparently too small to be significant and the different hardenabilities also appear to produce no effect.

The same applies to the tensile and yield strengths in the transverse direction, which were about the same as those in the longitudinal direction, Figure 14. Regarding transverse elongation and reduction of area, heat 4 appears to be slightly superior to the other heats, and this is confirmed by the results of the notch-tensile tests discussed further below.

Two smaller sections investigated (heats 1 and 5) differed slightly regarding their (longitudinal) tension properties, as was to be expected from their somewhat different carbon contents.

4. Variations in Notch-Strength Properties of Different 4340 Heats:

The values of concentric notch strength of the different heats of 4340 are presented in Figure 15 as a function of the tempering temperature and in Figure 16 as a function of strength level.

However, the results of the notch-tensile tests on different heats can be best evaluated from the values of the notch-strength ratio, plotted vs. stress concentration and given in Figure 17 for a strength level of 230,000 psi and in Figure 18 for 270,000 psi.

Longitudinal specimens, taken from either large or small sections, yielded notch-strength ratios agreeing within rather close limits. In general, however, the values for the small sections were found to be near the upper limit of the scattering range, and, in the larger sections, heat 4 also appeared very slightly superior to the other heats.

Regarding the notch-strength ratio of transverse specimens, all large sections yielded considerably higher values than the one small section investigated. Heat 4 again exhibited the highest values.

The trend curves shown in Figures 17 and 18, have been established on the basis of all evidence procured in this study and, therefore, appear at times to be not entirely in agreement with the experimental data shown in these graphs. However, the effects of other variables to be discussed below indicate that some of these test results must be located on the fringe of the scattering range and, therefore, be given only little weight. This applies particularly to the transverse values. Attention may also be called to the fact that the transverse curves are not as accurately established as the longitudinal curves, but that the general trend of the curves for the two types of specimens (longitudinal and transverse) has been found to be rather different, at least for the heavy sections.

5. Effects of As-Processed Section Size on Static Properties:

One heat (No. 1) of the 4340 steel was investigated in two different as-processed sections, 4-1/4 inch and 1-1/2 inch round. This permits some evaluating of the changes in properties associated with progressive processing of a steel. Considerable literature on this subject exists, but it relates primarily to lower strength levels than investigated here. In addition, a very limited amount of data indicates that while some longitudinal properties improve, transverse properties may deteriorate on processing to small section sizes (5) (9), (10). The present investigation provides further evidence, in this respect.

The tensile strength of the smaller section appears to be identical with that of the larger sections, except for the lowest tempering temperatures where it is distinctly higher, see Figures 13 and 14.

The yield strength and elongation of the two as-processed section sizes, compared in both the longitudinal and transverse directions, appeared practically identical. The longitudinal reduction of area of the small section size was slightly higher than that of the larger section. On the contrary, the small section possessed distinctly lower transverse reduction of area than the larger section.

The notch-strength ratio follows the same trend as the reduction of area, see Figures 17 and 18. As already discussed these were slightly higher for the small section, when tested longitudinally but distinctly higher for the large sections, when tested transversely. Furthermore, the transverse notch-strength ratio for the small section follows a trend different from that for the large section. This will be discussed further below.

With regard to the effect of as-processed section size on the notch strength of steel, it was observed that for the sharp notches (K = 10) the data obtained at Syracuse University are in slight disagreement with the results, which are presented in Figure 73 of reference (5), of a comparable investigation at Case Institute. While the notch strength for different section sizes studied in this program, were approximately the same when tested in the longitudinal direction, the results of Case Institute show an appreciable decrease in the notch strength when the as-processed section size was increased from 3/4 to 2-3/4 inch diameter. Furthermore, the results obtained at Syracuse University were intermediate between those for the two as-processed section sizes studied at Case Institute. No explanation for these discrepancies is available at the present, and further tests on various as-processed section sizes would be needed, to establish the true effect of the as-processed section size.

6. Effects of As-Tested Section Size on Notch-Strength:

Notch-tensile tests were performed with most steels on specimens of two different sizes, 0.3 and 0.5 inch diameter respectively, in both the longitudinal and transverse directions.* Previous evidence (5) indicates that markedly higher notch-strength values are obtained with smaller rather than with larger specimens, when heat treated to high strength values. The results obtained in this investigation provide further information in this respect.

The values of notch strength for the two test specimen sizes investigated here are presented in Figure 19 as a function of tempering temperature. These results clearly reveal the reduction in notch strength with increasing (as-tested) section size on the notch strength. This effect becomes larger as the stress concentration increases and is much more pronounced in the transverse direction than it is in the longitudinal direction.

These relations are further evaluated by representing the test data in several other ways, as follows:

Figure 20 shows diagrammatically the extreme trend curves for the notch-strength ratio in dependence of the stress concentration, for two alloys, V-Mod. 4330 and 98B40, for both 0.3 and 0.5 inch diameter specimens, and in both the longitudinal and transverse directions. This graph illustrates the range of notch-strength ratios encountered in this investigation. Regarding the effect of as-tested section size the graphs show that the lower limit, i.e., the notch strength of highly-notch-sensitive steels, is considerably smaller for the large specimens than for the small specimens. This applies to both longitudinal and transverse specimens. The lowering of a particular curve, by the increase in section size for a given strength level, varies greatly with the alloy.

This effect is further illustrated for the various steels in Figures 21, 22 and 23, (see also Figures 7 and 8) where all values of transverse notch-strength ratios are plotted vs. longitudinal notch-strength ratios. For 4340 (Figure 21), Super TM-2 Inco (Figure 22) and V-Mod. 4330 (Figure 23) the data are only slightly shifted to lower values as the as-tested section size increases. In contrast, a considerable reduction in the notch strength of 98B40, Super Hy-Tuf (Figure 21) and Hy-Tuf (Figure 23) is caused by increasing the specimen size.

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*In this investigation the specimens were first rough machined from the sections, subsequently heat treated and finally finished by either grinding or machining.

Tests on larger notched 4340 specimens, having a 1.1 and 1.5 inch diameter, have recently been performed at Syracuse University (11). The results further illustrate the pronounced reduction in the notch strength introduced by an increase in the as-tested section size. It is clear from the results of this study that notch-tensile tests on 0.3 inch diameter test bars are less sensitive in disclosing differences in the properties of various aircraft steels than tests on somewhat larger test sections. Small specimens, therefore, appear of little usefulness for a comparison and evaluation of these steels.

7. General Effects of Tempering Temperature on Tensile Strength and Notch Strength:

The tensile strength of heat-treated steels containing 0.25 to 0.45 percent carbon, such as the investigated aircraft steels, generally decreases gradually with increasing tempering temperatures. The highest strength values considered to be of practical significance, between 250,000 and 300,000 psi, can be obtained by tempering at 400°F or slightly higher, depending upon the alloy. A tensile strength of about 200,000 psi is usually obtained at 800°F or slightly higher.

The notch strength usually first increases on tempering the as-quenched steel. It then passes through a maximum (or sometimes through two maxima) and finally decreases. In all instances previously studied, the notch strength of specimens, such as used here, was found to be about 1.5 times the tensile strength if the strength was 180,000 psi or lower (5).

The actual values of notch strength and notch-strength ratio in the high-strength range vary greatly, depending upon numerous factors. The effects of some of these factors were already discussed in preceding sections.

In regard to the effect of tempering temperature, or strength level, test data obtained in this study agreed with previous evidence in that the strength of sharply-notched bars revealed a pronounced increase in notch-strength ratio as the tensile strength changes from 230,000 psi to 210,000 psi. In all instances, extrapolation indicates that the notch-strength ratio of 1.5, or insensitivity to notching, would be reached at a strength of about 180,000 psi, even under the most severe testing condition (large transverse specimens), see Section V.

Therefore, steels heat-treated to a strength between 230,000 psi and 270,000 psi represent a different class of materials, as compared with those heat-treated to a strength of 180,000 psi or less, characterized by a rather different response to stress concentrations on static loading. The dividing line passes near a strength of 200,000 psi and according to previous evidence (5), may be either greater or less, depending upon the severity of loading (section size, fiber, temperature etc.).

8. 500°F Temper Brittleness and Notch Strength:

One of the objectives of this investigation was to determine whether the "500°F-Temper Brittleness" apparent in the impact strength of many heat-treated steels was also reflected in other properties. Actually, the tempering-temperature range of minimum impact strength is usually found to be between 600° and 700°F, and it is practically absent in steels with increased silicon contents such as Hy-Tuf and Super Hy-Tuf (5), (12).

The impact tests performed in this program yielded results in conformance with these previously established facts, as the alloys investigated had low silicon contents and possessed higher impact values after tempering at 400°and 500°F than at 600° and 700°F, see Section III.

The notch strength of these alloys, when plotted vs. the tempering temperature, was generally found to vary only within comparatively narrow limits in the range of tempering temperatures between 400° and 700°F. The values of the 0.3 inch diameter longitudinal specimens were usually slightly higher for the 400° and 500°F tempers than for the 600° and 700°F (and 800°F) tempers. In some instances, this difference was maintained in the notch strength of the larger and of the transverse specimens, while in others such values appeared to become lower as the tempering temperature decreased. The notch-strength ratio also did not indicate the existence of 500°F temper brittleness.

Previous tests on 4340 steel, on the other hand, revealed a rather pronounced minimum in notch strength under a variety of more severe testing conditions than employed here; namely the following: (a) on testing specimens machined from very heavy sections (5), (b) on testing at very low temperatures (8), (c) on testing specimens taken across the flash line of forgings (13) and (d) on testing hydrogen-embrittled steel (6,7). It appears, therefore, that the 500°F temper brittleness of many heat-treated steels may be insignificant under ideal testing and service conditions but that it may become rather pronounced under increasingly severe load conditions.

9. Effects of Stress Concentration on Notch Strength:

Figure 24 presents a diagrammatic summary of the effects of stress concentration on notch strength. The curves shown in this graph are rather well supported by experimental evidence, see Section V. This applies particularly to the longitudinal values, while the larger scattering of transverse values renders their trend curves slightly less definite. The transverse curves may also be affected by the as-processed section size, aforementioned. The as-tested section size had no effect on the trend of these curves, as proven by the data obtained for the two specimen sizes within a broad overlapping range.

The curves in Figure 24 illustrate that the strength of notched high-strength-steel specimens decreases as the stress concentration increases, other factors being identical. For the steels investigated here, and stress concentrations between 3 and 10, this effect may range from nil, the notch-strength ratio than being close to 1.5, up to 50 percent for notch-sensitive steels. This fact has been already established in a previous investigation on 3140 steel (5).

The large number of such curves, established in this investigation and summarized in Figure 24, clearly reveals the fact that all values of longitudinal notch-strength ratio conform to the same family of curves, irrespective of steel composition, strength level, as-processed and as-tested section size.

All curves, representing the transverse notch-strength ratio as a function of stress concentration, were also found to belong to a single family of curves, see Figure 24. However, the trend of the transverse curves is distinctly different from that of the longitudinal curves, in that the rate of decrease in notch-strength ratio, with increasing stress concentration, is noticeably lower for transverse specimens. As the test values available to date fall rather short of the value 1.5 for the notch-strength ratio of notch-insensitive steels, further tests on steels having a lower strength are required to establish more definitely the trend of these curves. However, it appears already established by the present investigation that it is more difficult to eliminate the notch sensitivity of transverse specimens by reducing stress concentrations than that of longitudinal specimens.

As previously mentioned the notch-strength ratio in the transverse direction for the small section of 4340 (heat 1) deviates slightly from the general trend, in that it possesses values of notch-strength ratio at a stress concentration, K = 3 higher than those of the family. These curves appear to belong to a family distinctly different from that established for the larger sections both longitudinally and transversely. Further tests on small sections in the transverse direction will be needed before the trend can definitely be established.

10. Notch-Strength of High-Strength Steels in the Presence of Eccentric Loads:

Although concentric-notch tests yielded valuable information relating to the behavior of constructional steels in the presence of stress raisers, and therefore are extensively used by many investigators, to date, actual service conditions to which a steel part may be subjected are not well simulated by this test. A steel part with an irregular contour is usually subjected, in service, to a number of combinations of loads which may result in a complex state of stress and strain. To simulate such service conditions the eccentric-notch test has been proposed (14), (15), but uncertainties regarding the test conditions have prevented its extensive use. It differs from the concentric-notch test in that the line of load application is offset by a certain distance from the specimen-center line. In the eccentric tests performed in this investigation the eccentricity was approximately 0.106 inches, this value being selected so that the line of load application passed close to the root of the notch.

The results of the eccentric notch-tension tests that were performed on four heats of 4340 steel are presented in Figure 25. These results clearly reveal the pronounced reduction in notch-strength due to eccentricity, to values as low as 35 to 45 percent of the concentric notch strength **under these conditions of stress.**

The curves representing the eccentric notch-strength as a function of tempering temperature appear to follow a trend similar to that for the concentric notch-strength over the entire range of tempering temperature investigated.

The effect of stress concentration appears from Figure 26 considerably different in the eccentric than in the concentric tests. Under concentric loading, notch-sensitivity appears to fade out as the stress-concentration factor decreases below a value of 3, see Figure 24. In contrast, an investigation of Figure 26 indicates that under eccentric load, even at values of $K = 3$ or lower, a pronounced notch sensitivity is still retained. In fact, the curves representing the eccentric notch-strength ratio as a function of stress concentration, follow a trend similar to that for the concentric notch-strength ratio in the transverse direction, see Figure 24.

Regarding the response of the various heats it can be concluded from Figures 25 and 26 that the eccentric strength of the mildly-notched test bars was about the same for all four heats. In contrast, sharply-notched bars yielded highest values for heats No. 1 and 4, slightly lower values for No. 3 and lowest values for heat No. 2. This is in agreement with the results of concentric notch tests, and particularly with those in the transverse direction.

11. Strength of Smooth and Notched Specimens Under Sustained Loads:

The occurrence of service failures in high-strength steels under service conditions where a load was applied for a long time raises the question whether such "sustained-load failures" can occur in any highly-stressed, high-strength-steel part or whether they are limited to steels containing (a considerable amount of) hydrogen. The tendency to sustained-load failures is well established, and in fact the most significant feature of hydrogen embrittlement (6). Considering that in all probability steels always contain a small amount of hydrogen, it was considered desirable to establish whether loads close to but distinctly lower than the ultimate, would, or would not lead to failure after extended periods of time.

A number of stress-rupture tests were performed on smooth and notched (K = 5) 4340-steel specimens (heat 1) at room temperature. The results of these tests, assembled in Figures 27 and 28 clearly reveal that properly-processed and properly-heat-treated steel retains its regular strength for loading times up to at least 500 hours. In the present tests the specimens either broke immediately on application of a load that was within the scattering range of its ultimate (tensile or notch) strength, or they carried such loads or slightly lower for 500 hours or more without fracturing. Consequently, hydrogen contents considerably higher than those normally present in these steels, before pickling and plating, are necessary for developing a tendency to sustained-load failures.

These test results are in disagreement with those of Rinebolt (16) who repeatedly observed failures at loads considerably below the ultimate, within less than 200 hours. This behavior is probably due to a certain hydrogen content in such materials. These extremely complex phenomena were studied more extensively with 4340 steels in Phase 2 of this project (6), (7).

III. DEPENDENCE OF IMPACT STRENGTH OF HIGH-STRENGTH STEELS ON VARIOUS FACTORS

1. Introduction:

In Section III of this report a few fundamental phenomena, derived from impact tests, are discussed. V-notch Charpy tests were performed on specimens machined from hot-rolled 3 to 4-1/2 inch round or square sections of all steels available for this investigation at the following test temperatures: 212°F, room temperature (75°F approx.), -71°F and -150° to -160°F.

The entire range of strength levels was subjected to impact tests for one heat (No. 1) of 4340, 98B40 and V-Mod. 4330. Two strength levels, 230,000 psi and 270,000 psi, of the other 4340 heats (Nos. 2 to 4), and one strength level of the four remaining steels were tested.

2. Effect of Positioning of Specimens:

The reported impact-strength is usually an average of two test values. In the case of V-Mod 4330 steel, however, four specimens were tested for each condition and at each temperature. Two of these were taken from the rim of the 4 inch square section, 2 ± 0.4 inch away from the center, and the other two from the core, zero to one inch from the center. The results of these tests are presented in Figure 29.

The effect of specimen location, according to Figure 29 is negligible, and well within the range of scattering. This applies particularly to longitudinal specimens, but a very slight superiority of the rim over the core appears to exist in the transverse direction.

3. Dependence of Impact Strength on Tempering Temperature:

Impact tests were performed on three steels, 4340,98B40, and V-Mod 4330 over an extended range of tempering temperatures. The impact-strength values of all these steels, and all testing temperatures exhibited, according to Figures 29 to 31, minima when tempered at a temperature somewhere between 500 and 700°F. This effect is more pronounced in the (higher) longitudinal rather than in the transverse values.

The tendence of high-strength steels to exhibit low impact strength on tempering at temperatures between 500° and 700°F has been observed in previous investigations (5) and it is now commonly referred to as the "500°F temper brittleness". However, for the steels investigated here, the minimum actually occurs at about 600°F rather than at 500°F.

Tests on the alloys, containing a silicon content higher than normal, were performed in this investigation at only one tempering temperature, see Figure 32. According to previous evidence they also exhibit a minimum impact strength which, however, is shifted to a tempering temperature above 800°F, (5).

4. Dependence of Impact Strength on Test Temperature:

In general, the impact strength of high-strength steels decreases rather gradually as the testing temperature is lowered. The impact tests performed here, on all steels and at all tempering temperatures, as well as for both longitudinal and transverse directions, revealed according to Figures 33 to 35, this "transition" from an impact-ductile to an impact-brittle over a wide range of testing temperature.

However, in agreement with previous evidence (5, 17) the shape of the impact strength vs. test temperature distinctly varies with the tempering temperature. On tempering at 400°F, the most pronounced reduction in impact strength occurred as the testing **temperature** was decreased below -70°F, while tempering at 500°, 600°, and 700°F caused the impact strength to decrease markedly if the testing temperature became lower than room temperature. In this sense the "transition temperature" appeared to be considerably lower for the 400°F temper than for the higher tempers. On tempering at 800°F, this trend was found to be reversed, the transition temperature being again displaced to lower values.

This applies equally to all three steels investigated in this respect, namely V-Mod 4330, Figure 33, 4340, Figure 34, and 98B40, Figure 35, which are comparatively low in silicon content. It appears that this is also true for most commercial low-alloy steels (5). However, it may be expected that steels with higher silicon contents exhibit a transition temperature at higher tempering temperatures than steels with normal silicon contents.

5. Impact Strength of Various 4340 Steel Heats:

Impact tests were also performed on several additional heats (Nos. 2, 3, and 4) of 4340 steels. Specimens from these heats were taken in both the longitudinal and transverse directions and tempered at two temperatures, 500° (270,000 psi) and 700°F (230,000 psi).

The results of these tests are incorporated in Figures 30 and 34. According to these graphs the impact strength of all heats was found to differ only slightly, at all test temperatures.

However, the two heats Nos. 2 and 3 generally yielded values close to the lower limit of the scattering range. They therefore, appear to be slightly inferior to heats Nos. 1 and 4. This is in agreement with their rating, in regards both to ductility in tension and to notch strength.

IV. DEPENDENCE OF FATIGUE PROPERTIES OF HIGH-STRENGTH STEELS ON VARIOUS FACTORS

1. Introduction:

In Section IV of this report the fundamental effects of a number of variables disclosed by fatigue tests are discussed, correlated and evaluated. The fatigue tests were performed on specimens machined from 3 to 4-1/2-inch-round or square sections hot-rolled from commercial, electric-furnace heats. In addition, a limited number of the tests discussed relate to specimens taken from 9/16 inch diameter bars of aircraft quality 4340 steel.

Most of the factors studied in regard to static properties were also investigated in relation to their effects on the fatigue properties of the high-strength steels. Three steels were investigated extensively. Smooth and sharply-notched ($K = 8$) specimens were taken from both the rim and core positions of the V-Mod 4330 steel section and heat-treated to a strength ranging from about 200,000 to 260,000 psi. S-N curves for this steel are presented in Figures 36 and 37. Longitudinal and transverse smooth specimens as well as longitudinal specimens, provided with notches leading to various stress concentrations, $K = 3$, 5 and 8, of one heat (No. 1) of 4340 steel heat treated to a strength ranging from 210,000 to 270,000 psi were tested. The results of these tests are shown in Figures 38 and 39. Figures 40 and 42 summarize the result of the fatigue tests on several other steels, 98B40, Hy-Tuf and Super Hy-Tuf.

2. Effect of Positioning of Specimens:

The graphs for V-Mod 4330, Figures 36 and 37, include test results for specimens taken partly from the core and partly from the rim of the 4-inch-square section. The center of the core specimens was located zero to one inch and that of the rim specimen 1-1/2 to 1-3/4 inch away from the center of the section.

According to this evidence the S-N curves of both rim and core smooth and rim and core notched specimens appear to be identical within the rather small scattering range of the tests. The positioning of the fatigue specimens, therefore, had no effect on the test data for V-Mod 4330 steel. As the result of the static tests, discussed in Section II, indicate effects of positioning of equal magnitude for all alloy steels investigated, and for sections ranging between 3-inches and 4-1/2-inches round or square, no attention has been paid to specimen location for fatigue tests on steels other than V-Mod 4330.

3. Basic Considerations Regarding the Fatigue Strength of Smooth and Notched Specimens at Various Cycles:

The fatigue tests performed in the course of this investigation related to unnotched specimens K = 1 and to specimens provided with 60-degree, 50-percent notches, having a root radius which led to a stress concentration of K = 8. In addition, stress concentrations of K = 5 and K = 3 were studied in several instances. Test data were obtained for cycles ranging from a few thousands to over 10 millions.

Furthermore, in Phase II of this project, an exploratory study of the effects of hydrogen on fatigue-strength properties of 4340 steel was undertaken. This work is discussed in a separate report (7). Part of the work on hydrogen embrittlement is particularly valuable for the following discussion. It concerns the basic data for unembrittled material and differs from the main body of data obtained in Phase I of the program in two respects, namely: (a) It was obtained on specimens taken from small-diameter rod (9/16 in. dia.), rather than from a 4-1/4-inch-diameter section, and (b) it covered the range of small numbers of cycles*, between about 10 and 10,000. The results of such tests comprise a valuable extension of the test data, obtained on Phase I of the program, as it adds to the program the two variables; as-processed section size and number of cycles.**

The combined test data for specimens, taken from both the heavy and light sections, are presented schematically in Figure 43 and they permit evaluating the dependence of fatigue and notch-fatigue strength upon the number of cycles. The values of the fatigue strength for very high numbers of cycles, i.e., of the endurance limit, will be discussed further below. The values of fatigue strength for somewhat lower numbers of cycles, i.e. 100,000, depend on all variables to nearly the same extent as the endurance limit.

However, as the number of cycles decreases below 10,000 the dependence of fatigue strength on various factors materially changes. It is

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* In order to obtain such information, the speed of revolution of the fatigue testing equipment had to be greatly reduced, to 250 cycles per minute.

** The fact that the small section comprised a different heat should not invalidate the effects of the other factors, as the fatigue strength of 4340 steel has been found to be rather consistent.

then to be expected that the fatigue strength would gradually approach the static strength under the particular condition of loading. In the present case, the fatigue tests were performed by (rotating) bending.

The bending strength, both of smooth and notched specimens of the various strength levels of 4340, generally comprises a nominal stress derived from elasticity calculations. The actual stress, at the surface of a bent specimen, becomes increasingly smaller than the nominal stress, as the specimen is progressively strained beyond its elastic limit, or for practical considerations, beyond its yield strength. In other words, the ratio of nominal to actual surface stress, or "bend factor", gradually increases in plastic bending from a minimum value of unity at the yield point, to a considerably higher value. Calculations for a cylindrical specimen have shown that a maximum value of about 1.7 should be approached by this ratio for strains exceeding approximately 5 percent (18).

Consequently, the (nominal) bending strength of a steel should exceed its tensile strength by 70 percent or more, as long as the steel is reasonably ductile. However, if the steel possessed a rather limited ductility, i.e. if it failed at a low value of strain, its bending strength may be anywhere between its tensile strength and a maximum value of 1.7 times the tensile strength.

The static bending strength, of solid cylindrical sections of these steels, is of little significance and is not definitely known because of the large deflections encountered in such tests. However, calculations and test data on hollow sections lead to a ratio of "bending modulus of rupture" to tensile strength (bend factor) in the vicinity of about 1.6 for 4340 steel, heat treated to a strength of either 180,000 or 260,000 psi (19).

In dynamic (fatigue) bending tests, the strength of the steels is found to be greatly reduced at high numbers of cycles. However, the fatigue strength rapidly increases as the numbers of cycles decreases; and for cycles of about 1,000 bending-fatigue-strength values considerably above the tensile strength have been repeatedly observed (20).

This can be taken as a confirmation of the above discussed concept, that for very small cycles the bending fatigue strength of ductile steels should approach a value equal to 1.6 to 1.7 times the tensile strength.

In regard to the bending strength of notched specimens, such as used here, the fact must be considered that their ductility may be either high or low. In the case of high ductility the static notch strength in tension has been found to be about 1.5 times the tensile strength, and their bending strength, therefore, should be of the order of 1.5 x 1.6 = 2.4 their tensile strength. In the case of less ductile notched specimens, however, the notch-strength ratio may be considerably lower than 1.5, and the bend factor may be anywhere between 1.6 (1.7) and 1.0. This means that their fatigue strength, at very low number of cycles, may be expected to be somewhere below the maximum value of 2.4 times the tensile strength and that it may be considerably less than the tensile strength, if the notch ductility of the particular steel and particular specimen shape (stress concentration) were very small.

4. Experimental S-N Curves for Smooth and Notched Specimens:

The test data obtained for smooth and notched 4340 steel specimens conform well with the above developed concept as shown in Figures 44, 45, and 46. In the case of smooth specimens, values for very low cycles are available for two strength levels, 290,000 psi and 210,000 psi (Figures 44 and 46). In both instances, the fatigue strength in bending was found to be nearly equal to the tensile strength at 1,000 cycles and to be approximately 30 percent higher at 100 cycles. The fatigue (S-N) curves, for smooth specimens, extrapolate smoothly to 1 cycle and to a value of 1.6 (to 1.7) times the tensile strength, define the static bending strength, as schematically illustrated in Figure 43.

The fatigue curves for notched specimens terminated at values of endurance limit, which, for high stress concentrations, are considerably below those of smooth specimens for a notch-ductile material (in tensile tests), such as the 210,000 psi level, see Figure 46. On the other hand, the static strength of this heat treatment was nearly 40 percent higher for the notched than for the smooth specimen (for the notch geometry used here). Its bend factor may be estimated to be as high as 1.5. The test data are again in conformance with this concept. The notch-fatigue strength was equal to the tensile strength at about 500 cycles, and 40 percent higher at 100 cycles. Between these cycles, therefore, the fatigue curves for smooth and notched specimens of the 210,000 psi level of 4340 steel intersect. The notch-fatigue S-N curve also extrapolates well to a value of about 1.5 times the notch strength or about 1.4 x 1.5 = 2.1 times the tensile strength, as schematically shown in Figure 43.

In contrast, the fatigue strength of notched specimens of the 290,000 psi level remained throughout below that for the smooth specimens, see Figure 44. This is explained by the very low ductility of such notched specimens. Because of this, the notch strength was also found to be slightly higher than the tensile strength, approximately 1.1 times. The static bending strength should be only slightly higher than the tensile strength, say 1.1 times. Therefore, the static strength of notched specimens may be estimated to be about 1.1 x 1.1 = 1.2 times the tensile strength. The test data again agree with this concept. The notch-fatigue strength of the 290,000 psi level was found to be below the tensile strength at cycles as low as 100. The S-N curve extrapolates to a value slightly higher than the tensile strength which is considerably lower than the assumed static bending strength (of smooth specimens), as illustrated in Figure 43. It is even smaller than some of the experimental values of smooth fatigue strength at low cycles.

5. Effects of Stress Concentration:

With a number of steels, fatigue tests were performed on specimens provided with a 60-degree, 50-percent notch and a sharp notch radius resulting in stress concentration K = 8. In addition tests were performed on 4340 (Heat No. 1) covering a more extended stress concentration range, namely K = 3, 5 and 8, the results of which are presented in Figure 47. Previous tests on high-strength steels relate generally to milder notches, (2). These revealed that the ratio of the endurance limits of smooth to notched specimens was generally equal to the stress concentration for mild notches, but became less than this as the stress concentration exceeded a certain limit. This notch-sensitivity effect depends upon the strength level of the steel. In general, the notch-fatigue strength of very strong steels was found to be lower than that of slightly lower strength level. These latter, therefore, showed a great reduction in endurance limit by sharp notching, and in this respect, a greater notch sensitivity than the highest strength levels.

The tests on 4340 (Heat No. 1) disclosed according to Figure 47, that the endurance limit of notched specimens varied within 30 and 50 percent of that of smooth specimens.

At all strength levels investigated, the values for K = 5 were found to be distinctly higher than either for K = 3 or for K = 8. as shown in Figure 48, while it was expected that they would decrease with increasing stress concentration. This discrepancy may be tentatively explained by the fact that the specimens for K = 3 were finished by grinding, while those for the other stress concentrations were finish-machined with a high-speed steel tool. This machining operation may be associated with burnishing which generally introduces compressive surface stresses and raises the fatigue strength. In contrast, grinding may have eliminated the protective compressive heat treating stresses and replaced them by tensile stresses. The endurance limits for K = 5 appear particularly high in that the notch effect for this stress concentration is found to be particularly small in relation to the value of stress concentration. This is in distinct contrast to the result of tests on softer steels reported by Peterson and Wahl (1936), and Moore and Jordan (1936) (16).

6. General Relations Between Tensile Strength and Endurance Limit:

According to previous concepts, the endurance limit of heat-treated steels increases first, nearly proportionally, with increasing strength (or hardness) until it reaches a maximum, at a strength of 200,000 psi or higher, and then decreases gradually with further increase in strength (2). A few tests on 4340 steel, heat treated to strength values up to 280,000 psi (22) and older evidence on some other alloy steels (2), however, have indicated that in the high-strength range of these steels the endurance limit continues to increase with strength.

The values of endurance limit for smooth specimens determined in this investigation and assembled in Figure 49 usually followed a somewhat different trend for most of the alloys investigated. At a strength of 210,000 psi the endurance limit was generally found to be between 85,000 and 100,000 psi or 40 to 50 percent of the tensile strength. It then appeared to decrease slightly with increasing strength level and to develop a minimum for strength values, between 220,000 and 240,000 psi, for the 0.4-percent-carbon alloys, and at slightly lower strength levels for the 0.3-percent-carbon steel. At still higher strengths a noticeable increase in endurance limit, and sometimes even the endurance ratio (ratio of endurance strength to tensile strength) was observed for the 0.4 percent carbon steels, while the 0.3 carbon steel passed through a maximum at a strength of about 240,000 psi, and then appeared to decrease with further increase in strength.

The endurance limit of notched specimens, of all steels investigated, increased with increasing strength, as shown in Figure 50. The endurance ratio varied for the sharpest notch, K = 8, between 0.15 and 0.25. As far as the rather limited accuracy of such values permit, they usually exhibited minimum values at an intermediate strength level, somewhere between 220,000 and 250,000 psi.

The ratio of the endurance limits of smooth and notched specimens was for all steels higher at the lowest strength, 210,000 psi, than at the higher strength levels investigated, Figure 51.

7. Effects of As-Processed Section Size on Fatigue-Strength Characteristics:

Systematic tests on the fatigue properties of specimens taken from different sections of the same steel were not performed. Thus the tests on Phase I of the program throughout relate to specimens taken from 3 to 4-1/2 inch round or square sections. However, additional low-cycle fatigue tests were made during the study of hydrogen embrittlenent (7) on specimens machined from 9/16-inch-diameter, 4340-steel bar stock, as already discussed, and these connect with, or slightly overlap, those on the heavier section, regarding the number of cycles investigated.

As illustrated in Figures 44 to 46, the data obtained for the smaller section generally appear to be slightly lower than those for the larger section. This difference was nearly nil at a strength of 210,000 psi (800°F temper) but noticeably increased with increasing strength level, particularly for notched specimens. This result may possibly be correlated with the observed low transverse strength of the smaller section. An additional factor may be the relatively low carbon content (0.38) of the smaller section.

8. Transverse Fatigue-Strength Properties:

The endurance limit in the transverse direction was determined for various strength levels of 4340 steel (Heat No. 1). As is apparent from Figure 47 (also see Figures 38 and 39), it is about 70 to 75 percent of the longitudinal endurance limit, for all three strength levels investigated. This difference is also maintained at lower cycles, down to about 100,000 cycles. However, at still lower cycles the transverse fatigue strength gradually approaches the longitudinal fatigue strength. This conforms to the fact that the tensile strength is practically the same in both directions.

Tests on notched transverse specimens were not performed in this study.

V. COMPARISON OF THE VARIOUS ALLOY STEELS

1. Introduction:

In Section V specific properties of the various steels are compared with each other, using as a base or as bases the properties of 4340 steel (Heat No. 1).

In order to facilitate such a comparison, usually each of the large number of mechanical characteristics is plotted for all steels vs. the tempering temperature in three graphs, two of these refer to one such quantity for the steels containing 0.4-percent-carbon and the third graph relates to the 0.3-percent-carbon steels.

In addition, notch-strength values of the various alloys are represented as function of the stress concentration. Again, three sets of graphs are used, each set of curves representing values of notch strength of several steels obtained under a particular testing condition (section-size and orientation), and at a constant strength level. This permits evaluation of this most significant design criterion at the various investigated strength levels, namely 210,000 ± 10,000, 230,000 ± 10,000, 250,000 ± 10,000 and 270,000 ± 10,000.

2. Composition and Hardenability:

The compositions of the steels studied have been already presented in Table II. It is observed that all heats of 4340 steel have rather closely the same composition except for the silicon content of heat No. 2 which is appreciably lower than the silicon contents of the other heats. This may account for the low hardenability exhibited by heat No. 2 of 4340, see Figure 12. It has been discussed above in detail that the properties of all four heats of 4340, available in the form of 3-1/4 to 4-1/4-inch-diameter sections, differed only slightly. Of these, Heat No. 1 was investigated more extensively than the other heats. Its properties have been used, therefore, as basis for further comparison, as they should be representative throughout for this steel.

In general, the steels investigated fall into two groups with regard to carbon content. These are the 0.4-percent-carbon group, which includes 4340, 98B40, Super Hy-Tuf, Super TM-2 and Inco steels, and the 0.3-percent-carbon group which includes V-Mod. 4330 and Hy-Tuf. Usually, the 0.4-percent-carbon steels exhibit a higher hardenability than the 0.3-percent-carbon steels, as shown in Figure 52. In the 0.4-percent-carbon group, Super Hy-Tuf, Super TM-2 and Inco exhibited maximum hardenability, showing full hardening over the length of the Jominy-test bar.

They are approached by 4340, while 98B40 possessed distinctly lower hardenability. The two steels in the 0.3-percent-carbon group had approximately the same hardenability. The hardenability curve for Hy-Tuf developed a minimum at about 1-1/2 to 2 inches from the quenched end. This trend is also exhibited by the curve for 98B40 to a lesser degree.

3. Hardness and Tensile Strength:

The hardness (Figure 53) and tensile strength (Figure 54) of the different steels are plotted as a function of the tempering temperature.

Each of the steels investigated shows a response to tempering which is characteristic and different from that for any other steel. In general, a tempering temperature of 400°F is considered the low commercial limit. In this treatment the hardness and strength are primarily dependent on the carbon content and on the tendency of the steel to retain austenite (4). This explains the variations at 400°F apparent from Figures 53 and 54.

The decrease in hardness and tensile strength with increasing tempering temperature was very different for the different steels, 98B40 responded fastest, rather closely followed by 4340. V-Mod 4330 and Super TM-2 were found to be more sluggish, in this respect, while Inco Hy-Tuf, and particularly Super Hy-Tuf showed a considerable loss in hardness and strength only if the tempering temperature exceeded 700°F.

This is explained by the secondary hardening introduced by the various alloying elements, and particularly silicon. This sluggishness is of some practical importance, as it is desirable to obtain a high strength level by tempering at a maximum temperature, in order to impart to the steel improved stability at slightly elevated temperatures.

Super Hy-Tuf exhibited a phenomenon not encountered in other alloys, namely a low transverse tensile strength over the whole investigated range of tempering temperatures. This may be correlated with the fact that this alloy generally had low transverse properties in all respects. However, Hy-Tuf also showed this directional effect on the tensile strength and this cannot be explained by or correlated with other observations.

4. Yield Strength:

The 0.2-percent yield strength of the alloys studied is shown in Figure 55 as a function of tempering temperature.

It is a general phenomenon that the yield strength of any heat-treated steel exhibits a maximum on tempering at a temperature between 500° and 700°F, depending upon the composition (4). The steels investigated here conformed to this pattern.

The absolute maximum value of yield strength was found to be highest (250,000 psi) for Super Hy-Tuf (but only in the longitudinal direction) and slightly lower and about equal (230,000 psi) for all other 0.4-percent-carbon steels, while it was considerably lower for the 0.3-percent-carbon steels. In this group, Hy-Tuf was slightly superior (210,000 psi) to V-Mod. 4330 (195,000 psi).

Super Hy-Tuf again exhibited materially lower yield strength in the transverse than in the longitudinal direction.

5. Ductility:

The elongation and reduction of the area of the steels are plotted in Figures 56, 57 and 58 vs. tempering temperature.

For any of the alloys investigated both elongation and reduction of area were found to vary only within rather narrow limits for the range of tempering temperature investigated. A general slight tendency to increase with increasing tempering temperature after passing through a minimum at 600° to 700°F has been observed, in agreement with previous data (4).

Lowest longitudinal values of both elongation and reduction of area were encountered in Super Hy-Tuf and 98B40, while the other 0.4-percent-carbon steels exhibited an elongation equal to, but a reduction of area distinctly inferior to that of 4340. In contrast, the 0.3-percent-carbon steels had both a higher elongation and a higher reduction of area than 4340.

Regarding the transverse values of these quantities, it is believed that any characteristic difference between the alloys may be overshadowed by the rather large effect of processing conditions, discussed in section II. However, attention should be called to the particularly low values encountered in Super Hy-Tuf, and possibly (but hidden by scattering) in 98B40, while Hy-Tuf was found to be superior in this respect to all other steels.

On the whole, elongation and reduction of area were thus higher, the lower the (400°F) strength and hardness of the steel.

6. Notch-Strength Ratio:

The results of notch-tensile tests are summarized in Figures 59 to 69 for the different steels. Each figure relates to one strength level. The ratio of notch-strength to tensile strength, or "notch-strength ratio" is used here as an index of notch sensitivity. Attention may be called to the fact that a notch-strength ratio of 1.5 indicates notch insensitivity of the steel condition for the particular test geometry (section size, stress concentration, and orientation.)

Figure 59 to 69 indicate, in general, that the differences between the longitudinal notch strength of the investigated steel increase, as their strength level increases. In addition, much greater differences have been observed, in the 0.5-inch-diameter specimens, than in the 0.3-inch-diameter specimens. This is also true for the transverse notch strength. Less attention is paid in this discussion to the transverse than to the longitudinal values, because of possible interference of the processing conditions. Thus the smaller test specimen appears rather insensitive and not well suited for the desired quality comparison, which is based, therefore, primarily on the longitudinal notch strength of the 0.5-inch-diameter specimens. This quantity is always shown in Figures 59 to 69 in the upper right corner of each graph.

While at any particular strength level data for all seven steels are not available, the results of the tests for a strength of 250,000 psi on four steels Figures 64 to 66, and for a strength of 270,000 psi on six steels, Figures 67 to 69, lead to the following rating of the steels. V-Mod. 4330 exhibited the highest notch strength (ratio) or lowest notch sensitivity, followed rather closely first by 4340 and then by both Super TM-2 and Inco. The other three steels were considerably inferior to these four steels and 98B40 was slightly superior to both Super Hy-Tuf and Hy-Tuf, wherever a comparison was possible.

Attention may be called to the fact that such a comparison of 0.3-inch-diameter specimens shows a notch-strength ratio for Hy-Tuf, at all strength levels, equal to that of V-Mod. 4330 and, on the average, slightly higher than that of 4340.

Furthermore, regarding transverse notch strength, (ratio) Hy-Tuf usually exhibited highest values while V-Mod. 4330 rated below 4340, by this test. This was particularly true for 0.3-inch-diameter specimens.

The relative quality of the two steels, V-Mod. 4330 and 4340, also varied with the strength level. Maximum superiority of V-Mod. 4330 over 4340 was observed at 230,000 psi while both steels differed only slightly at either 210,000 psi or 270,000 psi.

7. Impact Strength:

The results of the "Charpy" impact tests performed on the various alloys in the longitudinal direction are summarized in Figures 70 and 20 as a function of the tempering temperature and for each of the various test temperatures used.

The results clearly reveal that for all test temperatures V-Mod. 4330 possessed, over the range of tempering temperatures investigated, an impact strength higher than that exhibited by either 4340 or 98B40, and that the impact strength of 4340 was intermediate between V-Mod. 4330 and 98B40.

Although impact tests on Hy-Tuf, Super Hy-Tuf, Super TM-2 and Inco were performed for one strength level only, Figures 70 and 20 indicate that Hy-Tuf then possessed the highest and Super Hy-Tuf the lowest impact strength among all the steels investigated. Inco ranged, regarding its impact strength, slightly above V-Mod. 4330, and Super TM-2 ranged, in general, between V-Mod. 4330 and 4340.

In the transverse direction, a comparison between the impact strength of the various alloys is not possible due to the large scattering of the test data. However, the two steels, namely Hy-Tuf and Inco, that exhibited the highest impact strength in the longitudinal direction also appeared to have the highest impact strength in the transverse direction. The transverse impact strength of all the other steels and at all testing temperatures was found to differ only to an extent that did not exceed the scattering of the tests. A curve drawn through the average of all these points followed the same general trend as the curves for longitudinal specimens, Figures 72 and 73.

Regarding the effect of testing temperatures all steels showed, at all tempering temperatures, a gradual decrease in impact strength as the testing temperature was reduced. Within the accuracy of the test data the steels behaved nearly equally in regard to such a transition to a low-impact-energy condition.

8. Fatigue Strength:

The rotating-beam fatigue data for the various steels tested are summarized in Figure 74 for both smooth and sharply notched (K = 8) specimens as a function of tempering temperature.

The results indicate that in the absence of stress concentrations, 4340 steel possesses fatigue properties superior to those for 98B40 and V-Mod. 4330 steels in the tempering range from 500° to 800°F. At tempering temperatures below 500°F, however, the tests resulted in higher fatigue properties for 98B40 than for 4340 and V-Mod. 4330. V-Mod. 4330 possessed the poorest smooth-fatigue properties of all steels investigated. This is true for all tempering temperatures used except in the range between 600° and 750°F where 98B40 developed a sharp minimum.

The notch-fatigue strength of V-Mod. 4330 is superior to that of 4340 and 98B40 throughout the range of tempering temperatures investigated. The notch-fatigue strength of 98B40 was equal to or slightly lower than that of 4340 when tempered at between 500° and 700°F, but slightly higher when tempered at either 400°F or 800°F.

From the limited data that were obtained on Hy-Tuf it appears that its smooth-fatigue strength is about the same as that for V-Mod. 4330 while its notch-fatigue strength is slightly lower than that for V-Mod. 4330 when tempered at 500°F. It is also seen that the smooth-fatigue strength of Super Hy-Tuf was approximately equal to that of 4340 while the notch-fatigue strength was higher than that of 4340 when tempered at 800°F.

The results of these tests indicate a very complex dependence of the fatigue strength of super high strength steels on the heat-treating conditions. This is further emphasized by the recently-disclosed fact that minor changes in tempering, such as repetition of the tempering treatment ("double tempering") may materially improve the fatigue strength (23).

VI. GENERAL SUMMARY OF RESULTS

1. Introduction:

In Section VI the fundamental effects of the various factors, varied in this study, are summarized. These effects are considered with regard to the various mechanical properties investigated, namely the tensile, notch-tensile, impact and fatigue properties.

In addition, an attempt is made to correlate the results of the notch-tension and the V-notch Charpy tests.

2. Effects of Positioning of Specimens on Notch-Tension, Impact and Fatigue Properties:

The effects of specimen position on the mechanical properties were evaluated from notch-tension, V-notch Charpy impact and smooth-and-notch fatigue tests, particularly for V-Mod. 4330 steel. The transverse notch strength of the other steels was also considered in this respect.

The position of the specimen in the large sections investigated had a slight effect only on the transverse notch-strength, which increased as the specimen location moved from the center to the rim of the section. The magnitude of this effect was less than 10 percent for V-Mod. 4330. With the other steels comparable data were available only for a limited range of positions. While a small effect, as discussed above, was apparent, it was well within the scattering range of the test.

The effect of specimen position on impact and fatigue properties was also within the scattering range of the tests.

3. Variations of Tension, Notch-Tension, and Impact Properties in Different Heats:

Several different heats of 4340 steel, which differed considerably in hardenability, were subjected to tension, notch-tension and V-notch Charpy impact tests.

In regard to tensile and yield strength of longitudinal and transverse specimens as well as ductility in the longitudinal direction, the various heats were found to be practically identical.

Reduction of area (and elongation) in the transverse direction, as well as notch strength and impact strength in both the longitudinal and transverse directions, were on the whole highest for heat No. 4 followed by heat No. 1, while heats Nos. 2 and 3 usually exhibited lower values.

There is no correlation apparent between these properties and hardenability, as heat No. 1 possessed highest hardenability, closely followed by heats Nos. 3 and 4, while heat No. 2 possessed the lowest hardenability.

4. Effects of As-Processed Section Size on Tension, Notch-Tension, and Fatigue Properties:

The effects of as-processed section size are disclosed by a comparison of certain properties of specimens taken from a number of large (3-1/4 to 4-1/4 inch-diameter) 4340-steel sections and one small section of the same heat as one of the large sections, and one additional small 4340 section.

Their tension-test characteristics in the longitudinal direction were identical. An exception was the higher tensile strength of one of the small sections on tempering at 400°F.

The longitudinal notch strength of the small sections was, in all instances, slightly but distinctly higher than that of the large sections

The transverse notch strength and the transverse ductility in tension of the 1-1/2-inch-diameter section was 20 to 30 percent lower than the averages of the respective values for the large sections.

Regarding fatigue strength, the test results are not strictly comparable as different sections from the same heat were not investigated and as the testing conditions for the two section sizes investigated also differed slightly. In general, the smaller section appeared to be equal to the large section at a strength level of 210,000, but slightly inferior at higher strength levels.

5. Effects of As-Tested Section Size on Notch-Tensile Strength:

The notch-tension data obtained in the testing of notched 0.3 and 0.5-inch-diameter specimens indicated that increasing the as-tested section size generally results in considerably lowering the notch strength. This effect varied greatly with the steel composition.

The results also revealed that the notch-strength of 0.3-inch-diameter test bars differed less for different steels, and other variables than that of somewhat larger test sections.

6. General Effects of Tempering Temperature on Tensile, Notch-Tensile, and Impact Properties:

The tensile strength of heat-treated steels, such as the investigated aircraft steels, generally decreases with increasing tempering temperature. For the investigated 0.3 percent carbon steels, the strength decreased from values of 250,000 to 270,000 psi on tempering at 400°F to values close to 200,000 psi on tempering at 800°F. For the 0.4 percent-carbon steels the strength was between 270,000 and 300,000 psi on the tempering at 400°F and approximately 200,000 psi on tempering at 800°F.

In contrast, the notch strength generally increases at first with increasing tempering temperature, passes through a maximum (or sometimes through two maxima) and finally decreases in proportion to the tensile strength. The notch strength of a steel after tempering at 400°F was equal to or slightly higher than the tensile strength. With increasing tempering temperatures up to 800°F the notch strength approached a value close to 1.5 times the tensile strength.

The impact strength of the three steels investigated (4340, 98B40 and V-Mod. 4330) first increased on tempering in the range between 300° to 400°F, developed a minimum between 500° and 700°F and then increased on tempering above 800°F.

7. Effects of Strength Level on Endurance Limit:

The rotating beam fatigue tests performed on smooth and notched specimens machined from a number of alloys revealed that for a strength level of about 200,000 psi the endurance limit of smooth specimens was between 85,000 and 100,000 psi or 40 to 50 percent of the tensile strength depending upon the steel composition. It then appeared to develop a minimum for strength values between 220,000 and 240,000 psi for the 0.4-percent-carbon alloys, and at slightly lower strength levels for the 0.3-percent-carbon steel. At still higher strengths a noticeable increase in endurance limit was observed for the 0.4-percent-carbon steels, while the 0.3-percent-carbon steel passed through a maximum at a strength of about 240,000 psi and then appeared to decrease with further increase in strength.

The endurance limit of notched specimens, of all steels investigated, increased, in general, with increase in strength level.

8. Effects of Stress Concentration on Notch-Tensile and Notch-Fatigue Strength:

The notch-tension tests on all steels, confirmed the general relation that the strength of notched high-strength-steel specimens decreases as the stress concentration increases.

The magnitude of the stress-concentration effect depended upon the notch sensitivity which greatly varied, in this investigation, depending on other variables. If the steel was nearly notch-insensitive, it yielded a notch-strength ratio close to 1.5 for all stress concentrations (K = 3, 5 and 10), the effect of which, therefore, was nearly nil. In contrast, for highly-notch-sensitive conditions the notch-strength ratio was already low for K = 3 and it further decreased considerably with increasing stress concentration.

This effect was less pronounced in the transverse than in the longitudinal direction.

The results also indicated that all values of longitudinal notch-strength ratio when plotted against the stress concentration belong to one single family of curves, and that all values of transverse notch-strength ratio also belong to a different family irrespective of the specimen section size.

Regarding the dependence of endurance limit on stress concentration, it was found that for K = 3 and K = 8 the endurance limit of several strength levels of 4340 steel was approximately the same while it was higher for K = 5. This trend was contrary to the expected decrease in endurance limit with increase in stress concentration. This may tentatively be explained by differences in the processing of the various notches (grinding for K = 3 and machining for K = 5 and 8).

9. Effects of Eccentricity on Notch-Strength:

Eccentric tests were performed on longitudinal 4340 specimens provided with notches leading to stress-concentration factors of 3, 5 and 10. These tests showed, for all strength levels, a nearly equal decrease in notch strength, about 60 ± 5 percent, from the value of concentrically-loaded specimens.

In addition under concentric loading, the notch-sensitivity of longitudinal specimens appears to fade out as the stress-concentration factor decreases below a value of 3. In contrast, on eccentric loading, even at values of K = 3 or lower, a pronounced notch sensitivity is still retained. This is principally due to high bending stresses imposed by the eccentricity.

10. Relation Between Impact Strength and Notch Strength:

The (longitudinal) impact strength of the three completely-investigated steels, namely 4340, V-Mod. 4330 and 98B40 conforms, regarding their rating, in general, to that of the static notch strength in the longitudinal direction.

A superiority of Hy-Tuf over the other steels was also found to exist in longitudinal notch-tension tests on 0.3-inch-diameter specimens. However, increasing the as-tested section size led to much greater loss in notch-strength for this alloy than for either 4340 or for V-Mod. 4330.

Hy-Tuf was also found to possess exceptionally low transverse notch strength. For Super Hy-Tuf the impact tests yielded the same rating as the static notch test. The favorable position of Inco regarding its impact strength is not in agreement with the results of longitudinal notch-tension test, where this steel exhibited practically the same as, or lower strength than 4340. On the other hand, its transverse notch-strength was exceptionally high. The rating of Super TM-2 by the impact test was also more favorable than by the longitudinal notch-tensile test, but conformed more closely to that by the transverse notch-tension test.

The tentative conclusion that may be drawn from the above comparison is that the magnitude of the impact strength of a longitudinal specimen is also affected by the transverse properties of the material. Considerably more factual information is required in order to definitely confirm any such correlation.

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TABLE I. INFORMATION PERTINENT TO THE STEELS INVESTIGATED

Alloy	Producer	Producer's Heat No.	Designation used in Laboratory	Method of Production	Size and Shape
4340	Republic Steel Corp.	H-25407A	1	E.F. H.R.A.	4¼ in. rd. 1½ in. rd.
4340	Rotary Electric Steel Co.	24870	2	E.F. H.R.A.	4 in. rd.
4340	Rotary Electric Steel Co.	38195	3	E.F. H.R.A.	3½ in. rd.
4340	Rotary Electric Steel Co.	25735	4	E.F. H.R.A.	3¼ in. rd.
4330 V-MOD.	Republic Steel Corp.	E60473A	1	E.F. H.R.A	4 in. sq.
98B40	United States Steel Corp.	34511	1	E.F. H.R.A.	4½ in. rd.
HY-TUF	Crucible Steel Co. of America	E11079	1	E.F. H.R.A.	3 in. rd.
SUPER HY-TUF	Crucible Steel Co. of America	6-0096	1	E.F. H.R.A.	3 in. rd.
SUPER TM-2	Timken Roller Bearing Co.	AC-14480	1	E.F. H.R.A.	3 in. rd.
INCO	Bethlehem Steel Company	18E007	1	E.F. H.R.A.	4¼ in. sq.

E. F. - Electric Furnace Steel

H.R.A. - Hot Rolled, Annealed

TABLE II. COMPOSITIONS OF THE VARIOUS ALLOYS INVESTIGATED

ALLOY	PER CENT OF ALLOYING ELEMENTS									
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
4340 Heat No. 1	0.41	0.79	0.013	0.016	0.31	1.83	0.77	0.23		
4340 Heat No. 2	0.40	0.74	0.023	0.029	0.19	1.83	0.77	0.24		
4340 Heat No. 3	0.425	0.83	0.014	0.013	0.30	1.77	0.80	0.24		
4340 Heat No. 4	0.415	0.75	0.011	0.014	0.31	1.76	0.81	0.24		
98B40	0.46	0.79	0.017	0.017	0.35	0.86	0.81	0.19		
SUPER HY-TUF	0.41	1.28	0.014	0.024	1.77		1.26	0.33	0.17	
SUPER TM-2	0.41	0.72	0.012	0.014	0.61	2.08	1.15	0.44		0.14
INCO	0.39	0.74	0.014	0.014	1.54	1.83	0.83	0.38	0.07	
V-MOD. 4330	0.32	0.88	0.012	0.018	0.26	1.79	0.84	0.355	0.07	
HY-TUF	0.285	1.29	0.019	0.015	1.58	1.87	0.24	0.40		

TABLE III. STRESS-CONCENTRATION FACTORS AND CORRESPONDING NOTCH RADII FOR NOTCH-TENSILE AND NOTCH-FATIGUE SPECIMENS

TYPE OF SPECIMEN	D-IN.	d-IN.	STRESS-CONCENTRATION FACTOR K	NOTCH RADIUS r - IN.
NOTCH-TENSILE	0.3	0.212	3	0.011
			5	0.0035
			10	0.0008
	0.5	0.353	3	0.018
			5	0.006
			10	0.0013
NOTCH FATIGUE (BENDING)	0.265	0.188	3	0.007
			5	0.002
			8	0.0007

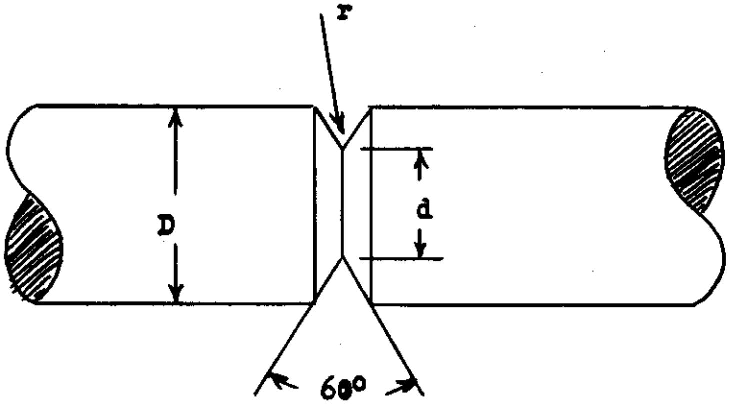
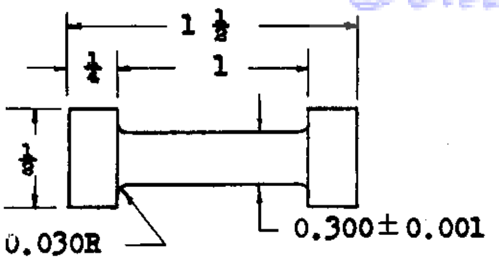


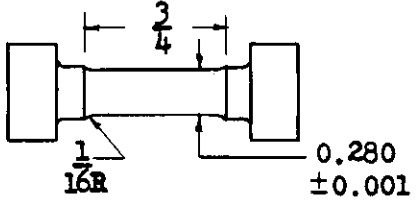
TABLE IV. POSITION OF VARIOUS SPECIMENS IN V-MOD. 4330

STEEL BAR

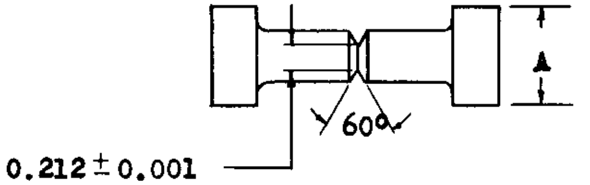
TYPE OF SPECIMEN	APPROXIMATE LOCATION FROM CENTER - IN.			
0.3 IN. DIA. LONGITUDINAL	0	3/4	1-7/64	2-13/64
0.5 IN. DIA. LONGITUDINAL	23/32	1-37/64	1-45/64	
0.3 IN. DIA. TRANSVERSE	0	3/4	1-9/16	
0.5 IN. DIA. TRANSVERSE	1/2	1-1/2		



(a) 0.3 IN.DIA. TENSILE

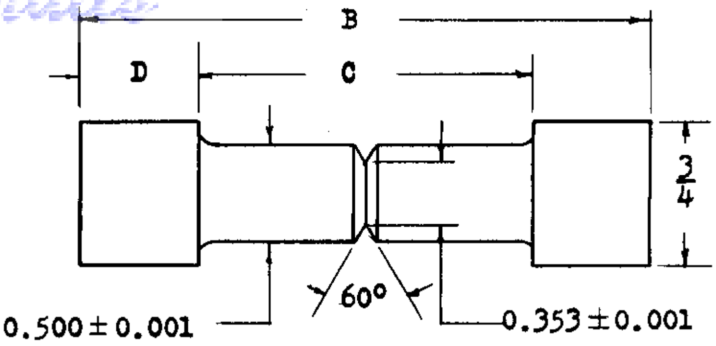


(b) 0.28 IN.DIA. TENSILE
AND STRESS RUPTURE



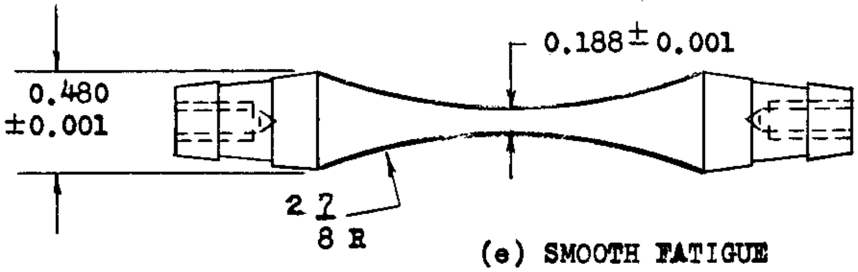
A = 1/2 CONCENTRIC AND STRESS RUPTURE
A = 13/16 ECCENTRIC

(c) 0.3 IN. DIA. NOTCH-TENSILE

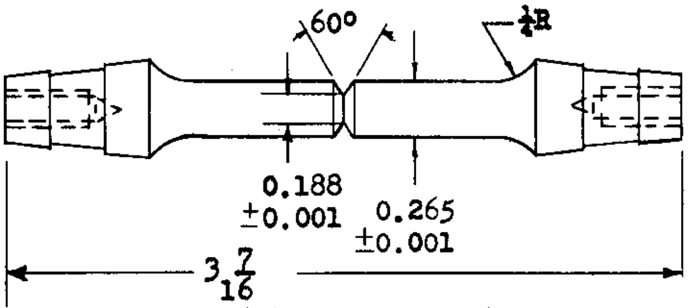


B = 3 or 2 1/8
C = 1 3/4 or 1 1/8
D = 5/8 or 1/2

(d) 0.5 IN. DIA. NOTCH-TENSILE



(e) SMOOTH FATIGUE



(f) NOTCH-FATIGUE

FIG. 1 TEST SPECIMENS USED IN THIS INVESTIGATION.

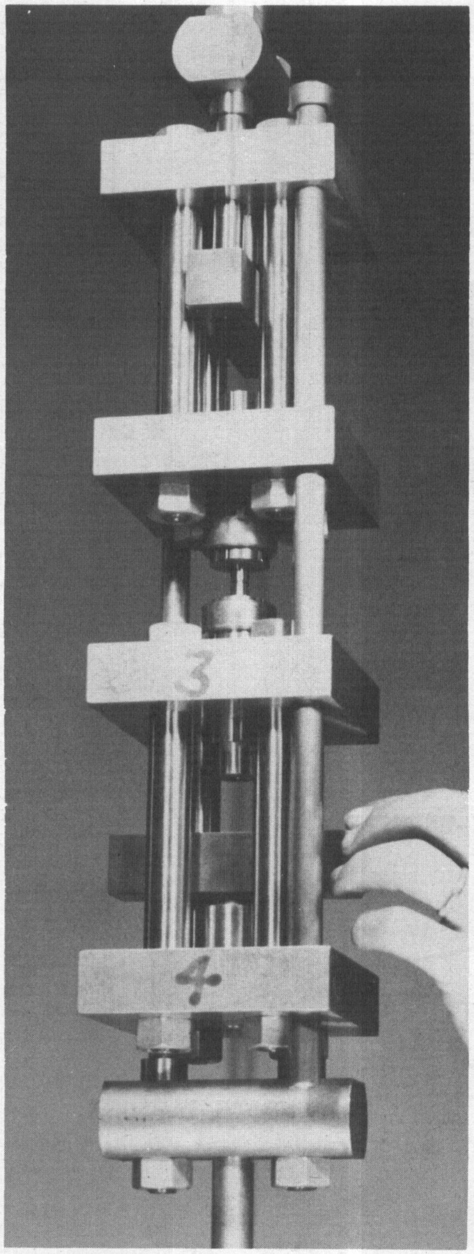


FIG. -2 FIXTURE FOR CONCENTRIC LOADING OF 0.3 IN. DIA TENSILE SPECIMENS

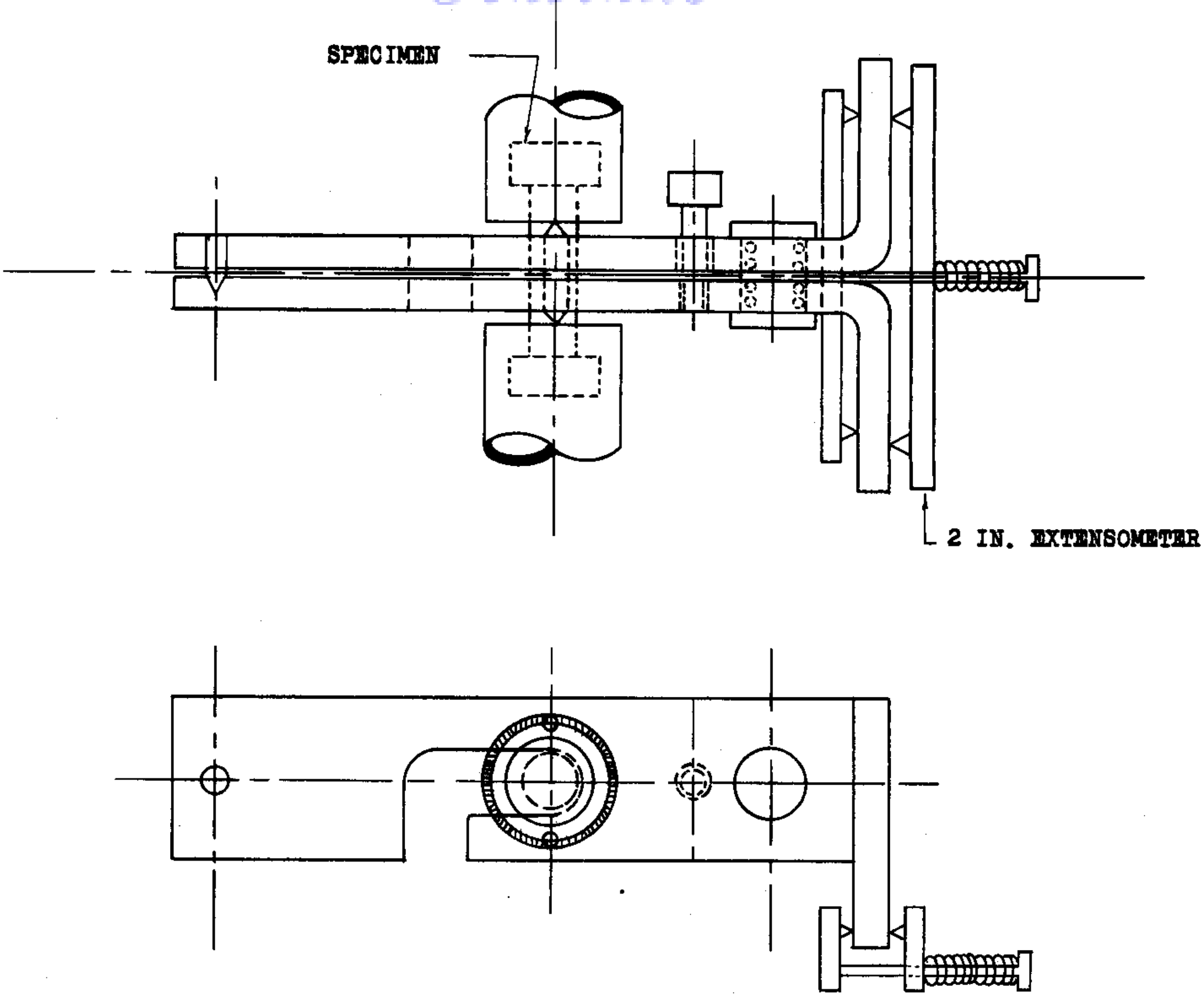


FIG. 3 ADAPTATION OF TWO-INCH EXTENSOMETER TO ONE-INCH GAGE SPECIMENS.

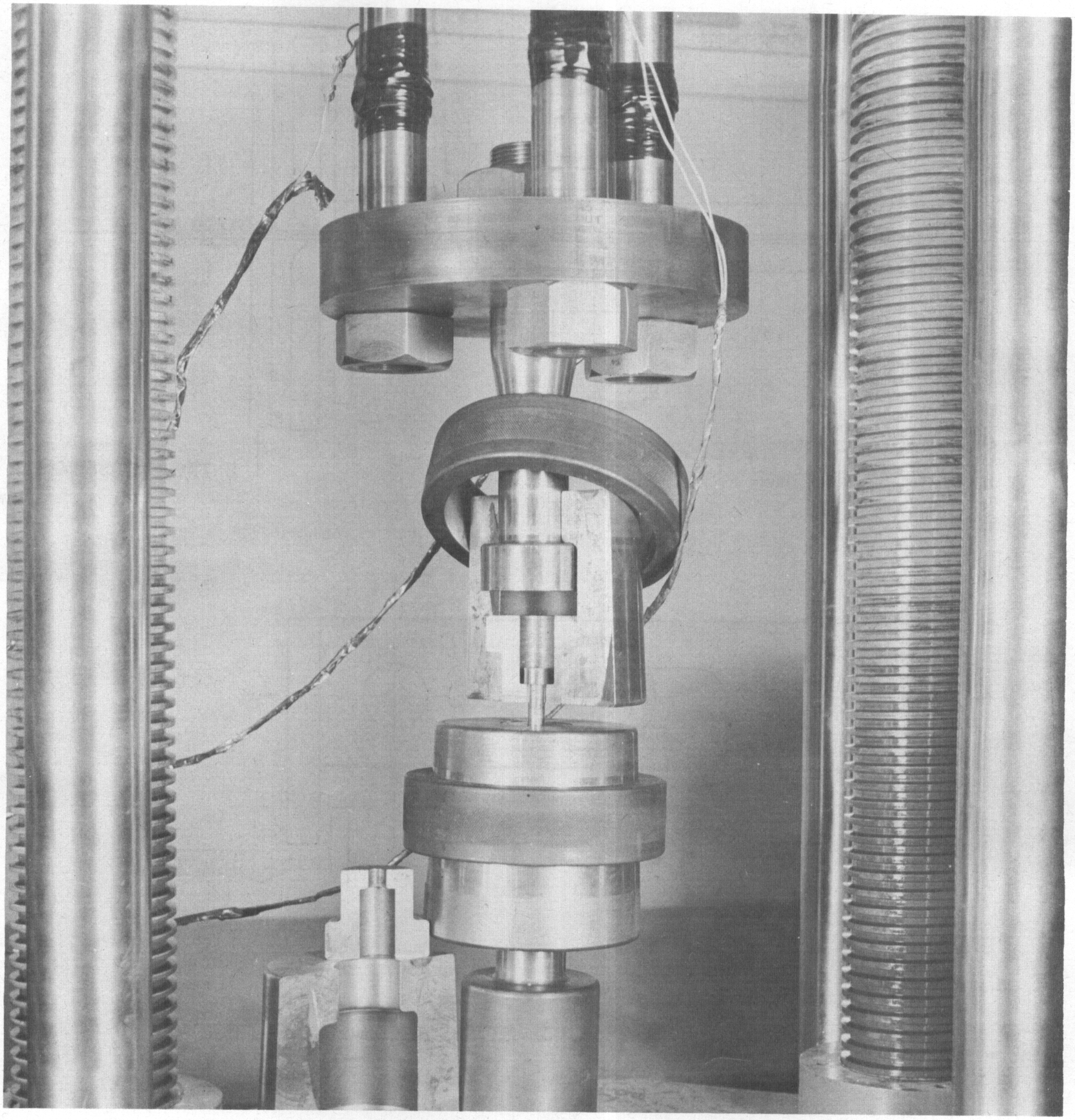


FIG . - 4 CONCENTRIC FIXTURE FOR 0.5 IN. DIA.NOTCH-TENSILE SPECIMENS

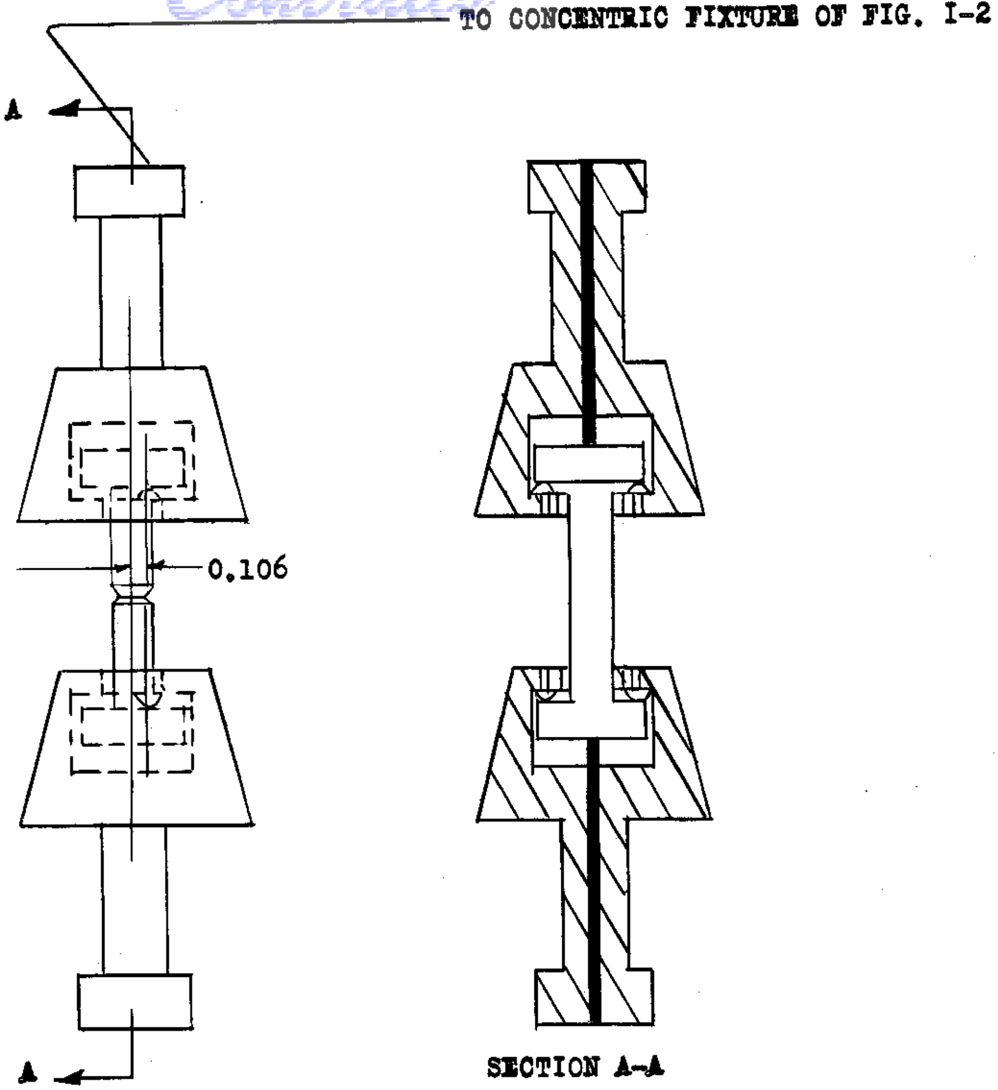
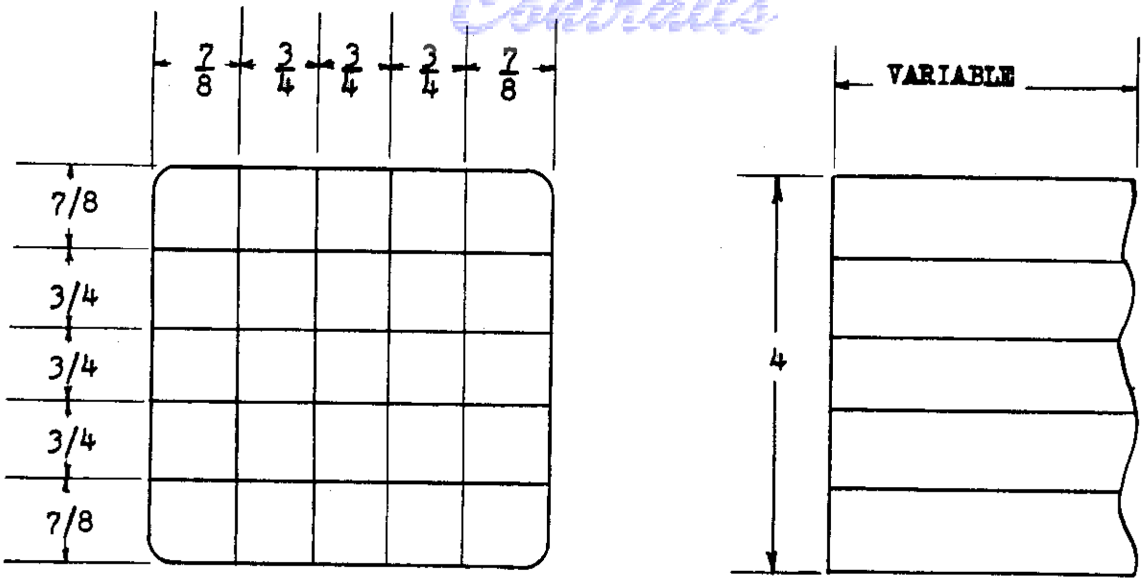
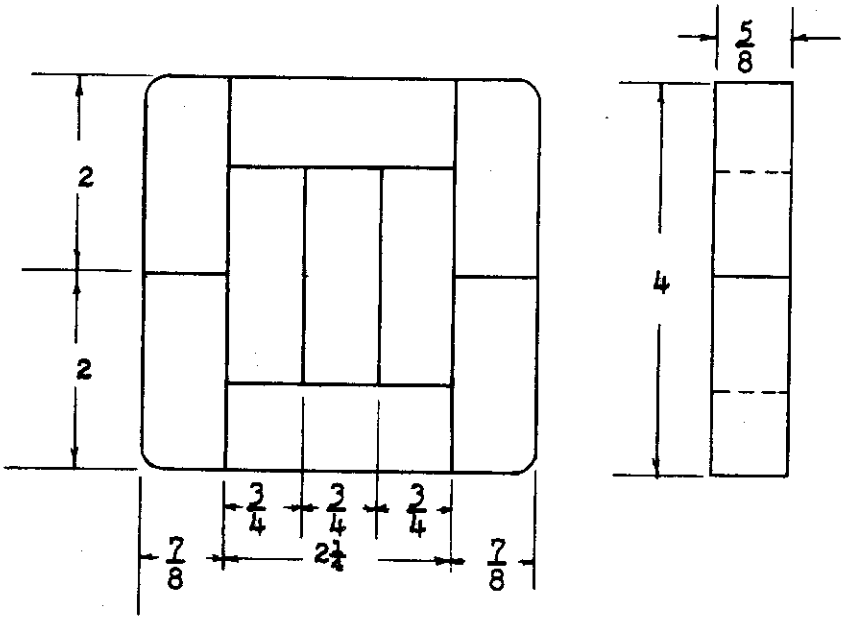


FIG. 5 FIXTURE FOR ECCENTRIC TESTING

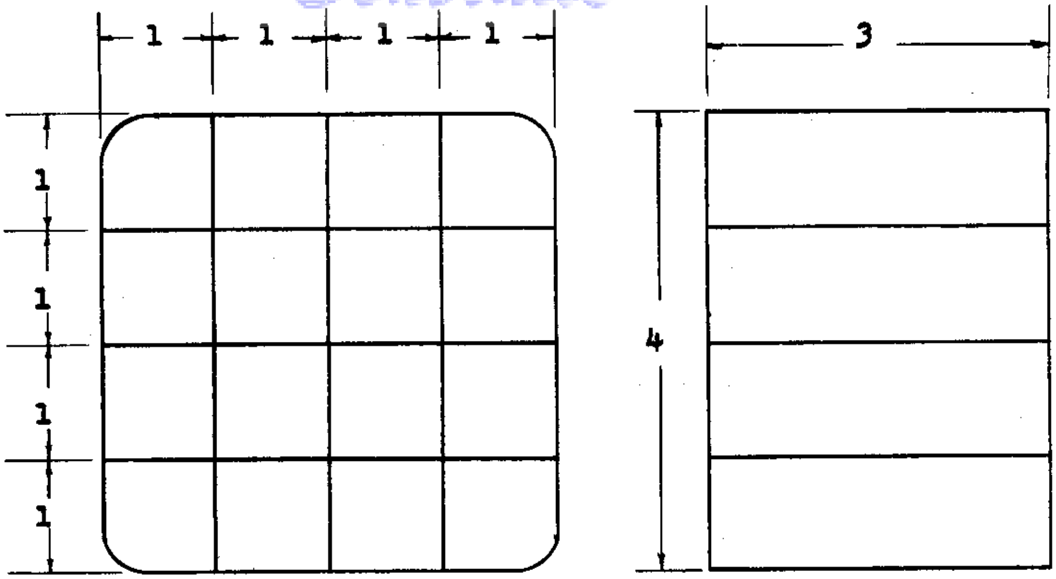


LONGITUDINAL SPECIMENS
(0.3 IN. DIA. TENSILE AND NOTCH-TENSILE, IMPACT, AND FATIGUE)

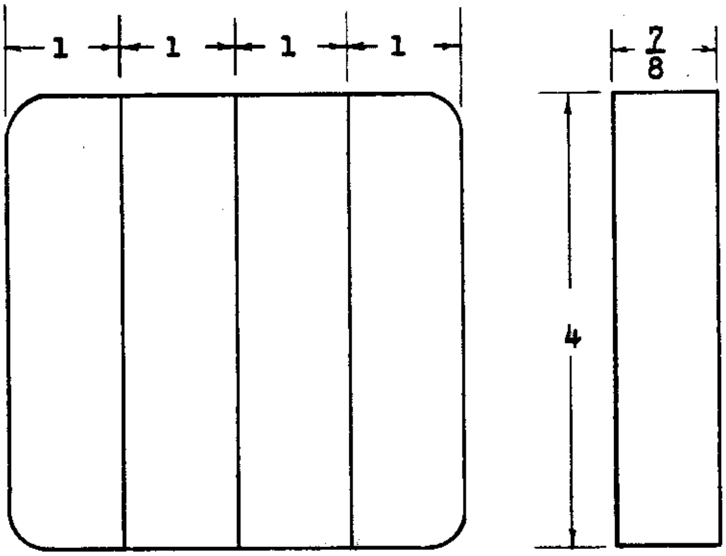


TRANSVERSE SPECIMENS
(0.3 IN. DIA. TENSILE AND NOTCH-TENSILE AND IMPACT.)

FIG. 6a POSITIONING OF LONGITUDINAL AND TRANSVERSE SPECIMENS IN V-MOD. 4330 BILLET.



LONGITUDINAL 0.5 IN. DIA. NOTCH-TENSILE SPECIMENS



TRANSVERSE 0.5 IN. DIA. NOTCH-TENSILE SPECIMENS

FIG. 6b POSITIONING OF LONGITUDINAL AND TRANSVERSE SPECIMENS IN V-MOD. 4330 BILLET.

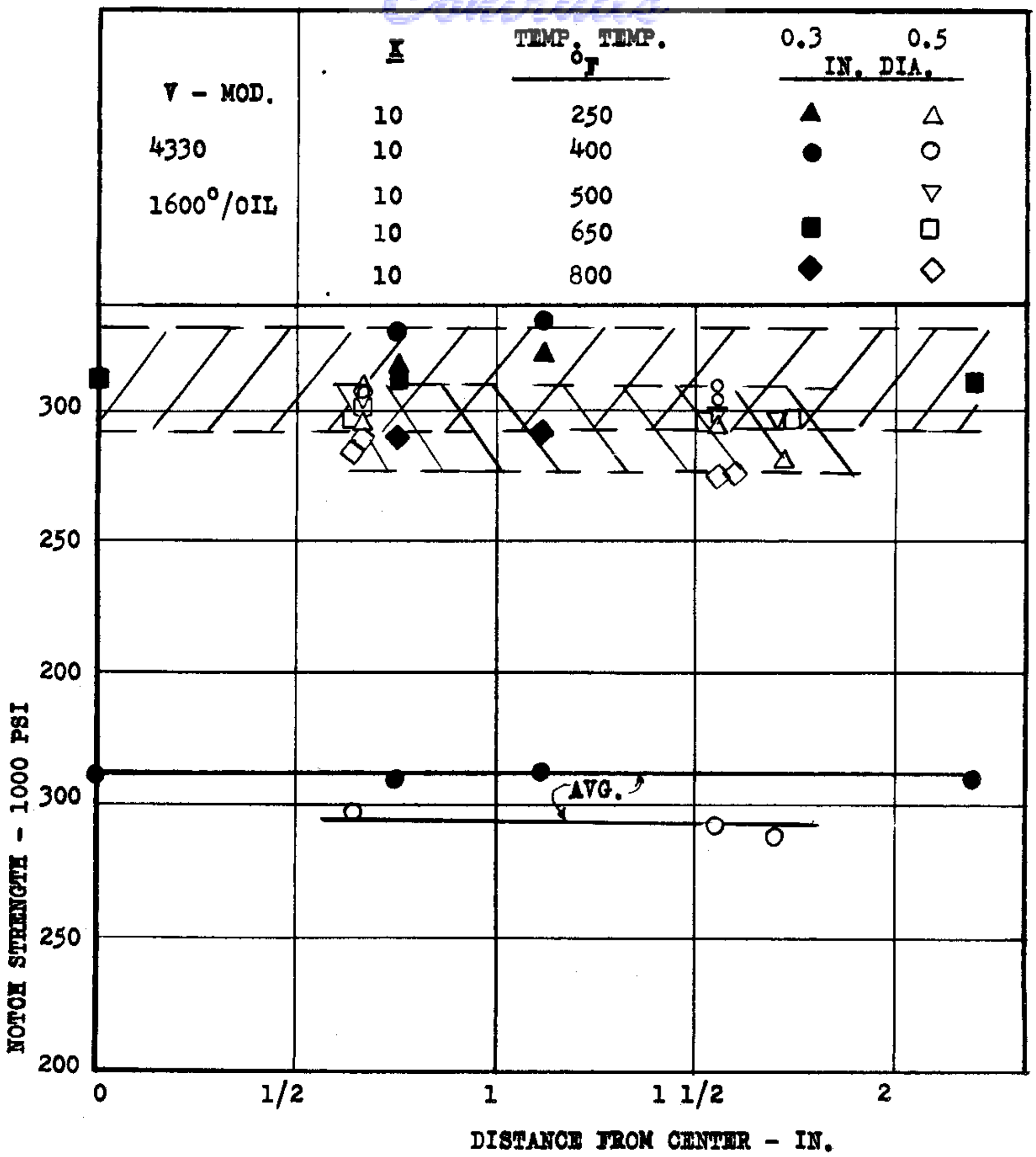


FIG. 7a NOTCH STRENGTH AS A FUNCTION OF DISTANCE FROM CENTER OF V - MOD 4330 STEEL BAR FOR SHARPLY NOTCHED LONGITUDINAL SPECIMENS.

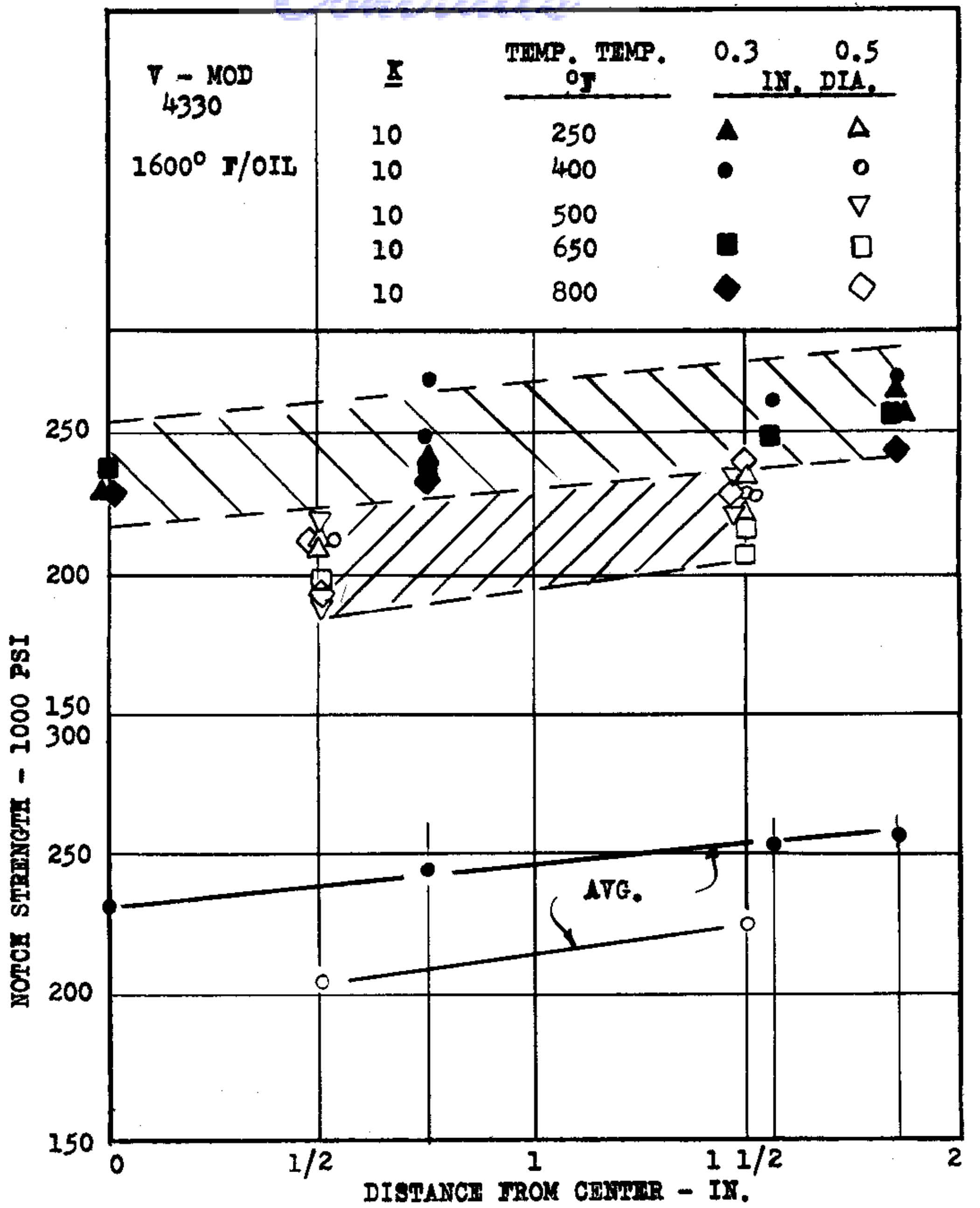


FIG. 7b NOTCH STRENGTH AS A FUNCTION OF DISTANCE FROM CENTER OF V - MOD. 4330 STEEL BAR FOR SHARPLY NOTCHED TRANSVERSE SPECIMENS.

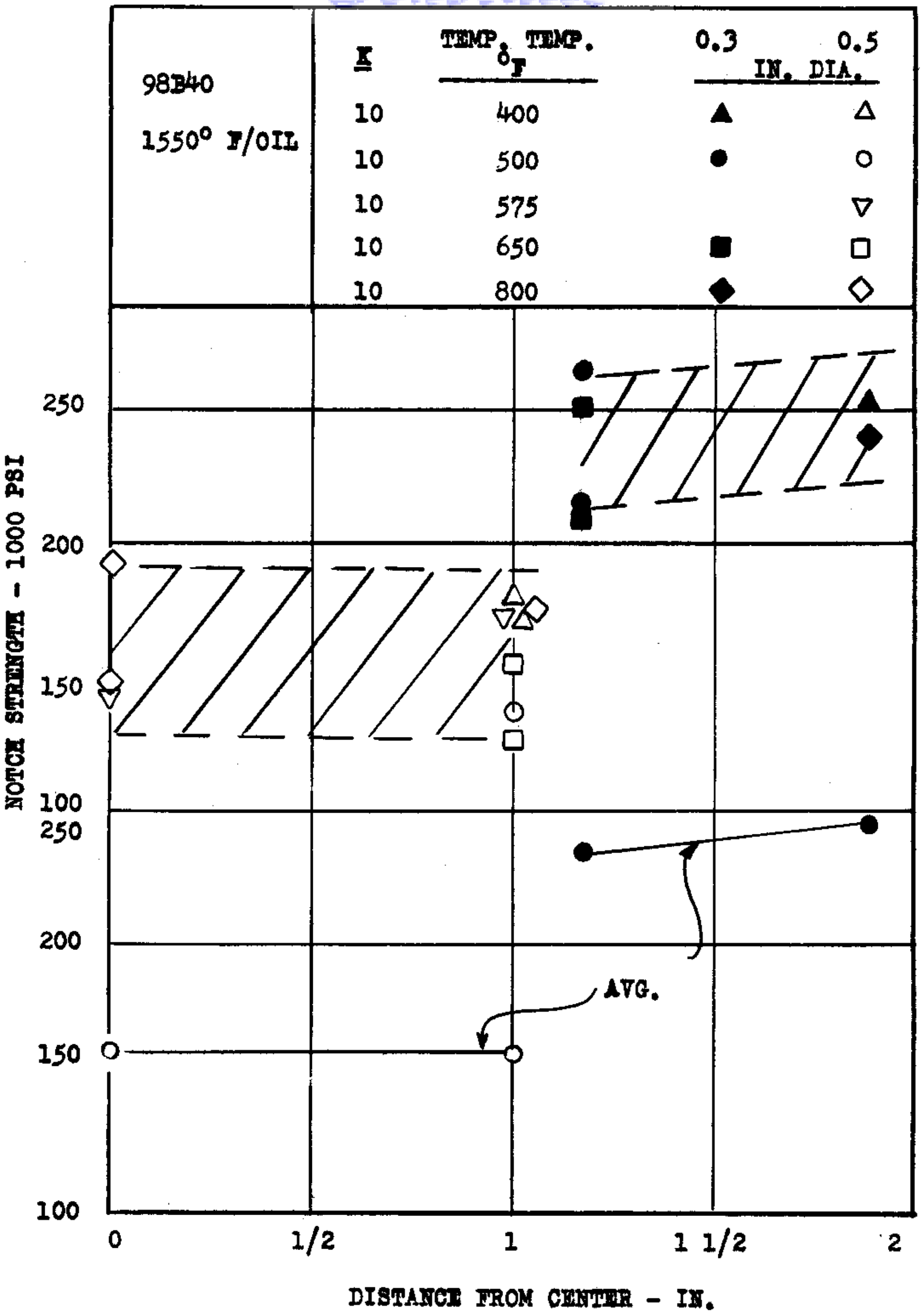


FIG. 8 NOTCH STRENGTH AS A FUNCTION OF DISTANCE FROM CENTER OF 98B40 STEEL BAR FOR SHARPLY NOTCHED TRANSVERSE SPECIMENS.

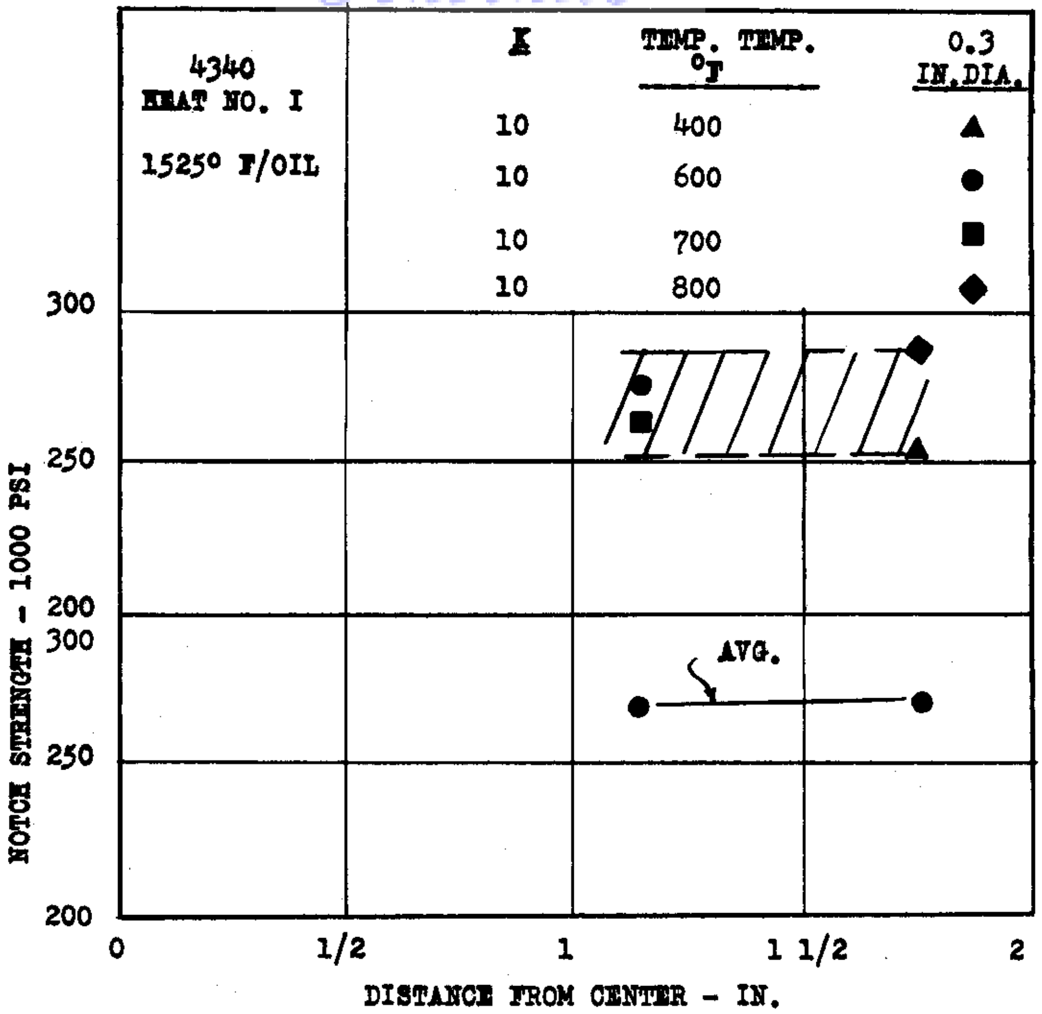


FIG. 9 NOTCH STRENGTH AS A FUNCTION OF DISTANCE FROM CENTER OF 4340 STEEL BAR (HEAT NO. I) FOR SHARPLY NOTCHED TRANSVERSE SPECIMENS.

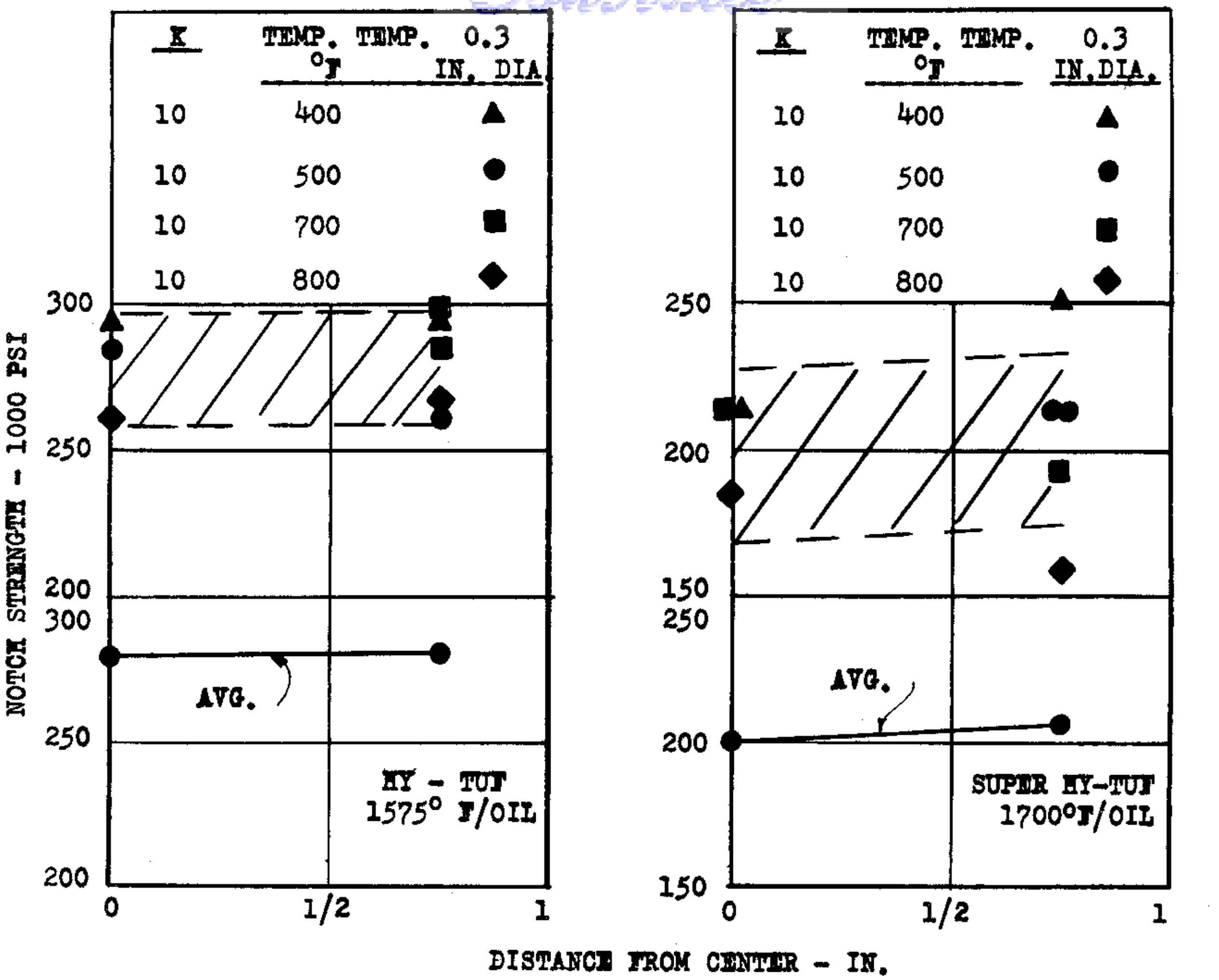


FIG. 10 NOTCH STRENGTH AS A FUNCTION OF DISTANCE FROM THE CENTER OF HY-TUF AND SUPER HY-TUF STEEL BARS FOR SHARPLY NOTCHED TRANSVERSE SPECIMENS.

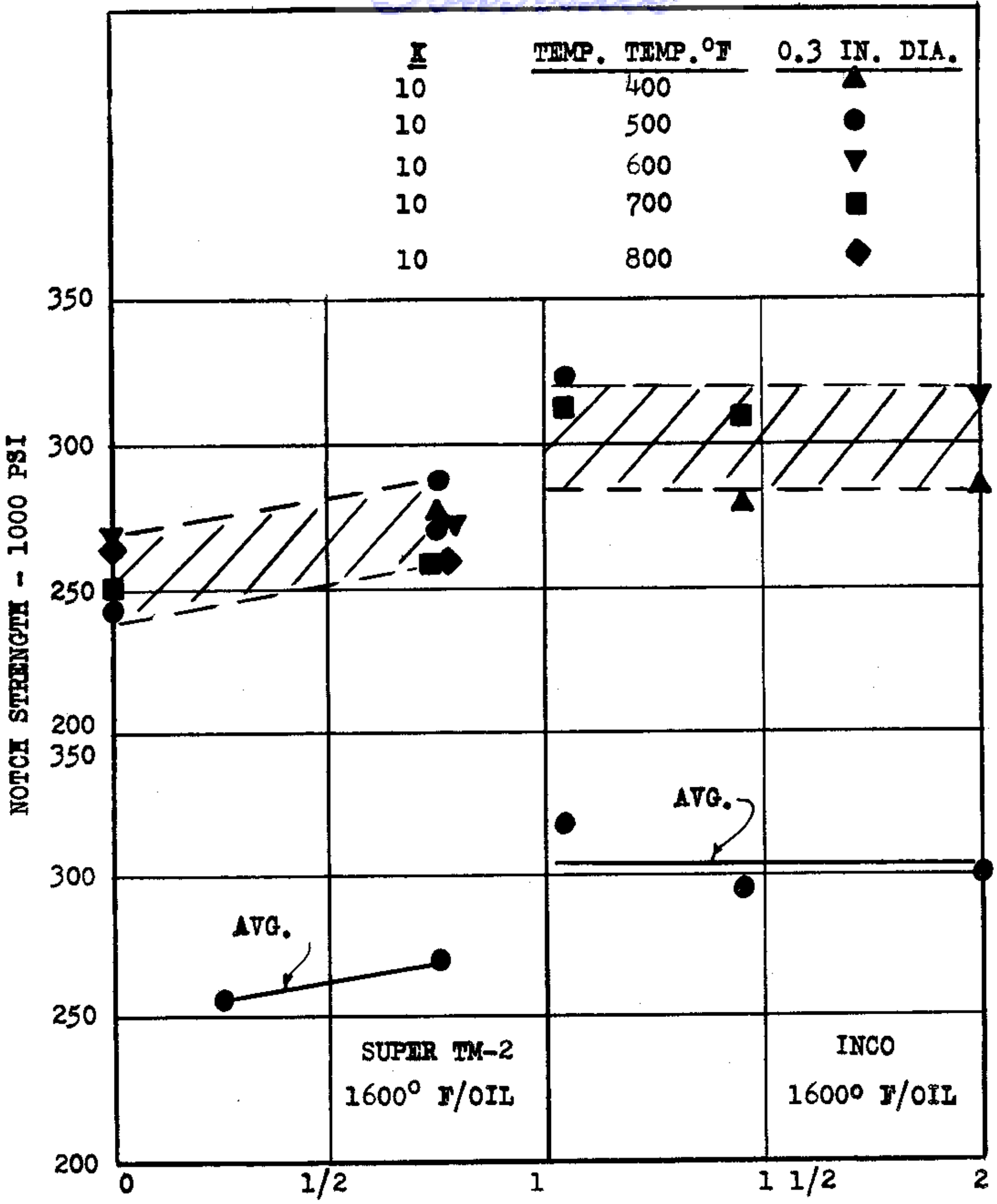


FIG. 11 NOTCH STRENGTH AS A FUNCTION OF DISTANCE FROM THE CENTER OF SUPER TM-2 AND INCO STEEL BARS FOR SHARPLY NOTCHED TRANSVERSE SPECIMENS.

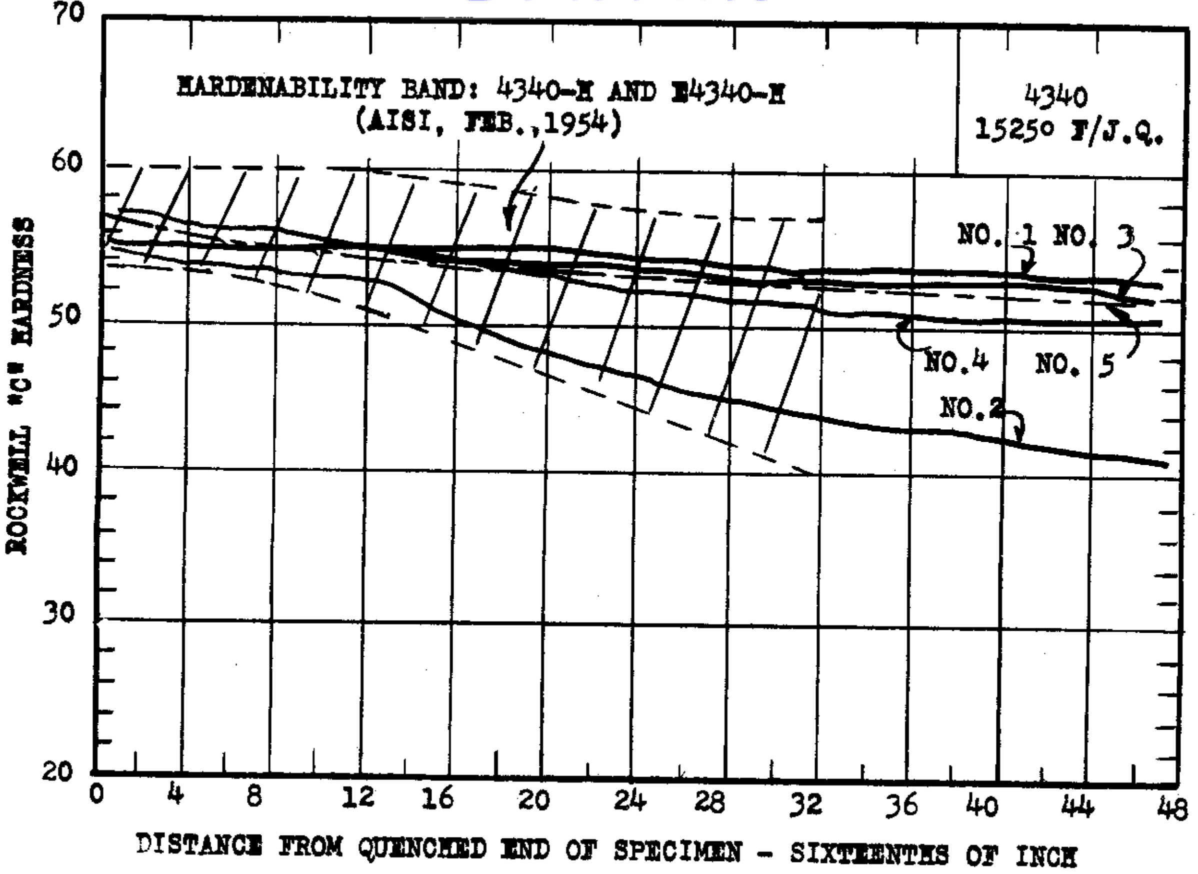


FIG. 12 JOMINY HARDENABILITY OF VARIOUS HEATS OF 4340 STEEL

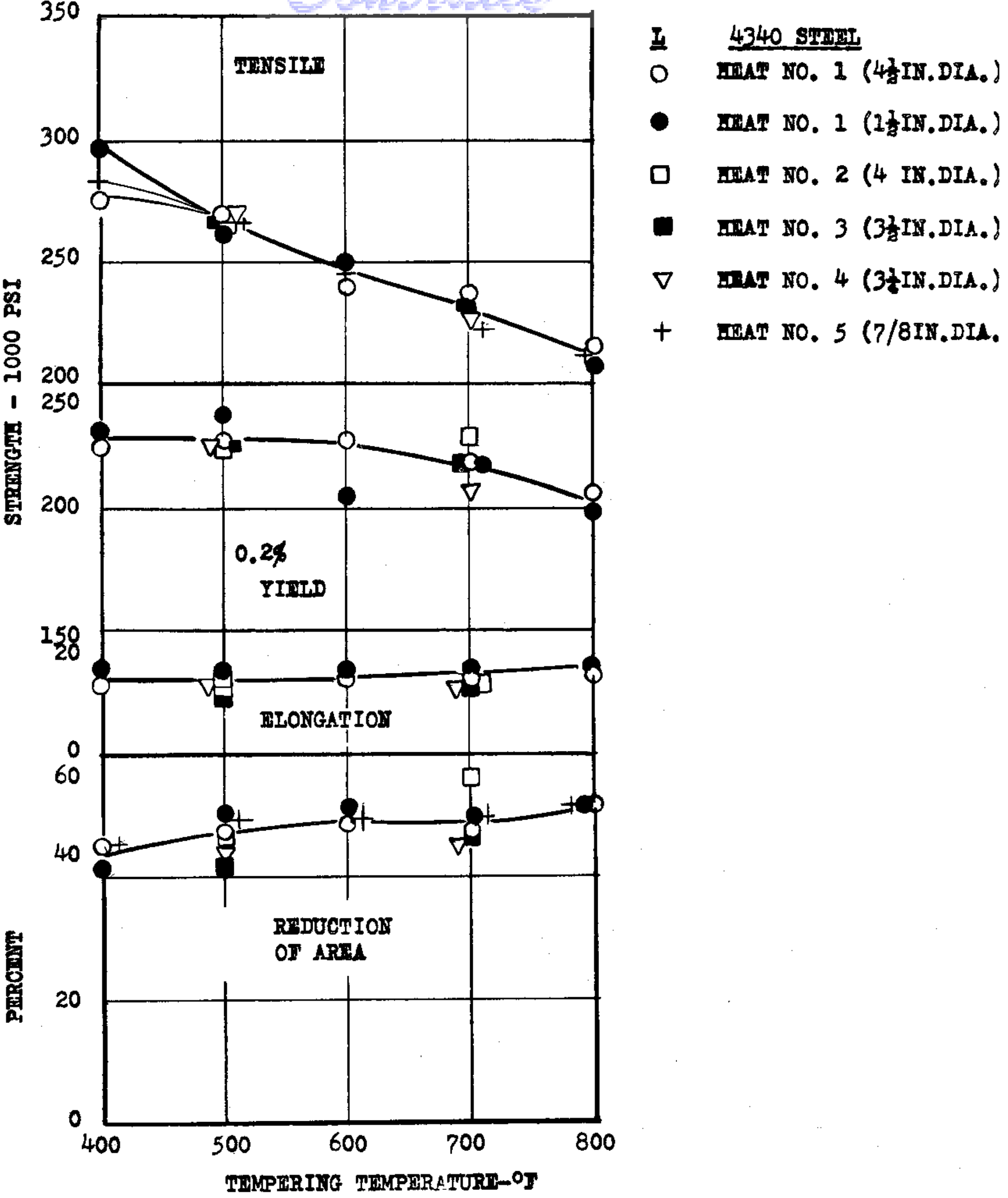


FIG. 13. EFFECT OF TEMPERING ON THE LONGITUDINAL, TENSILE STRENGTH, YIELD STRENGTH, ELONGATION, AND REDUCTION OF AREA OF 4340 STEEL.

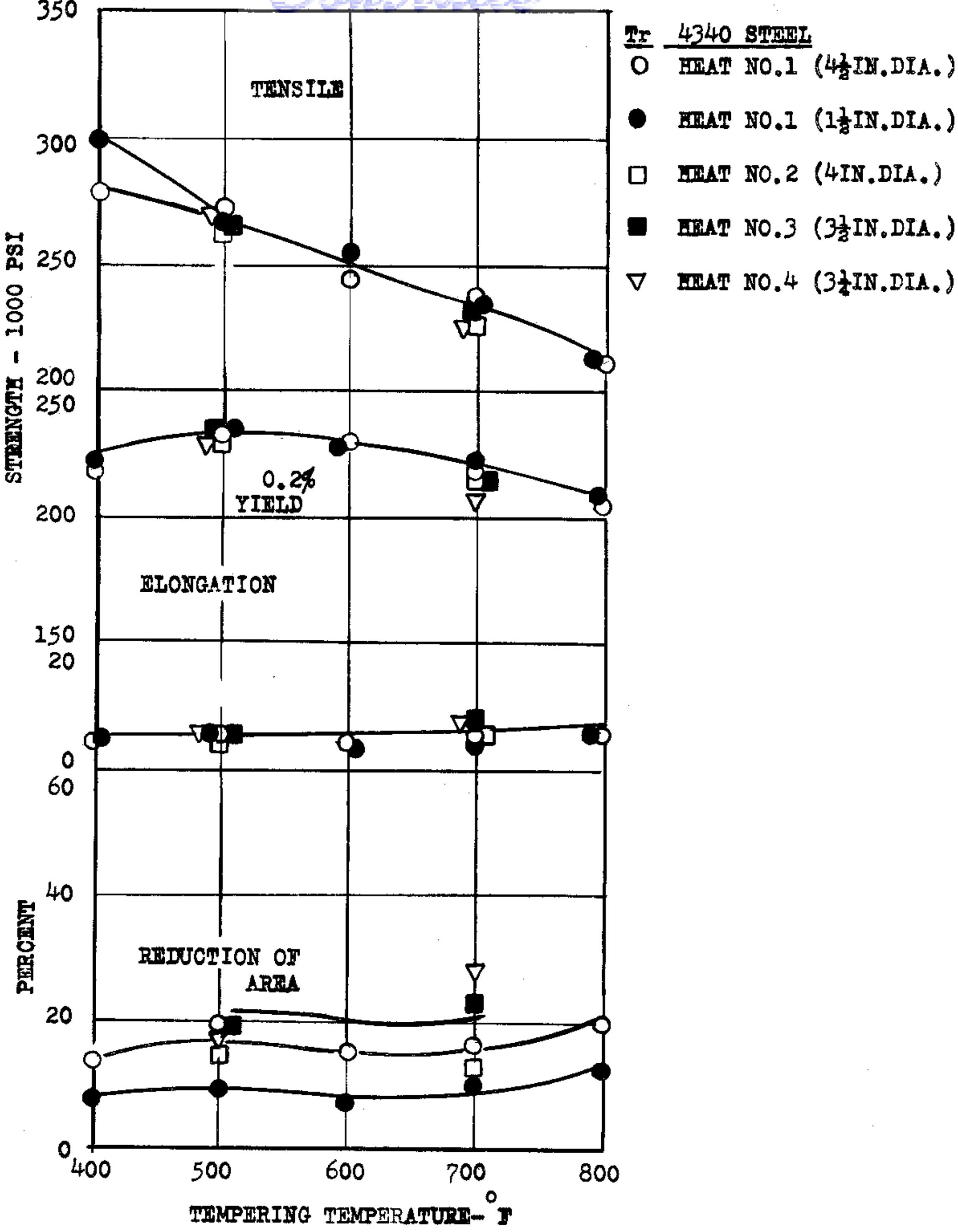


FIG. 14 EFFECT OF TEMPERING TEMPERATURE ON THE TRANSVERSE, TENSILE STRENGTH, YIELD STRENGTH, ELONGATION AND REDUCTION OF AREA OF 4340 STEEL.

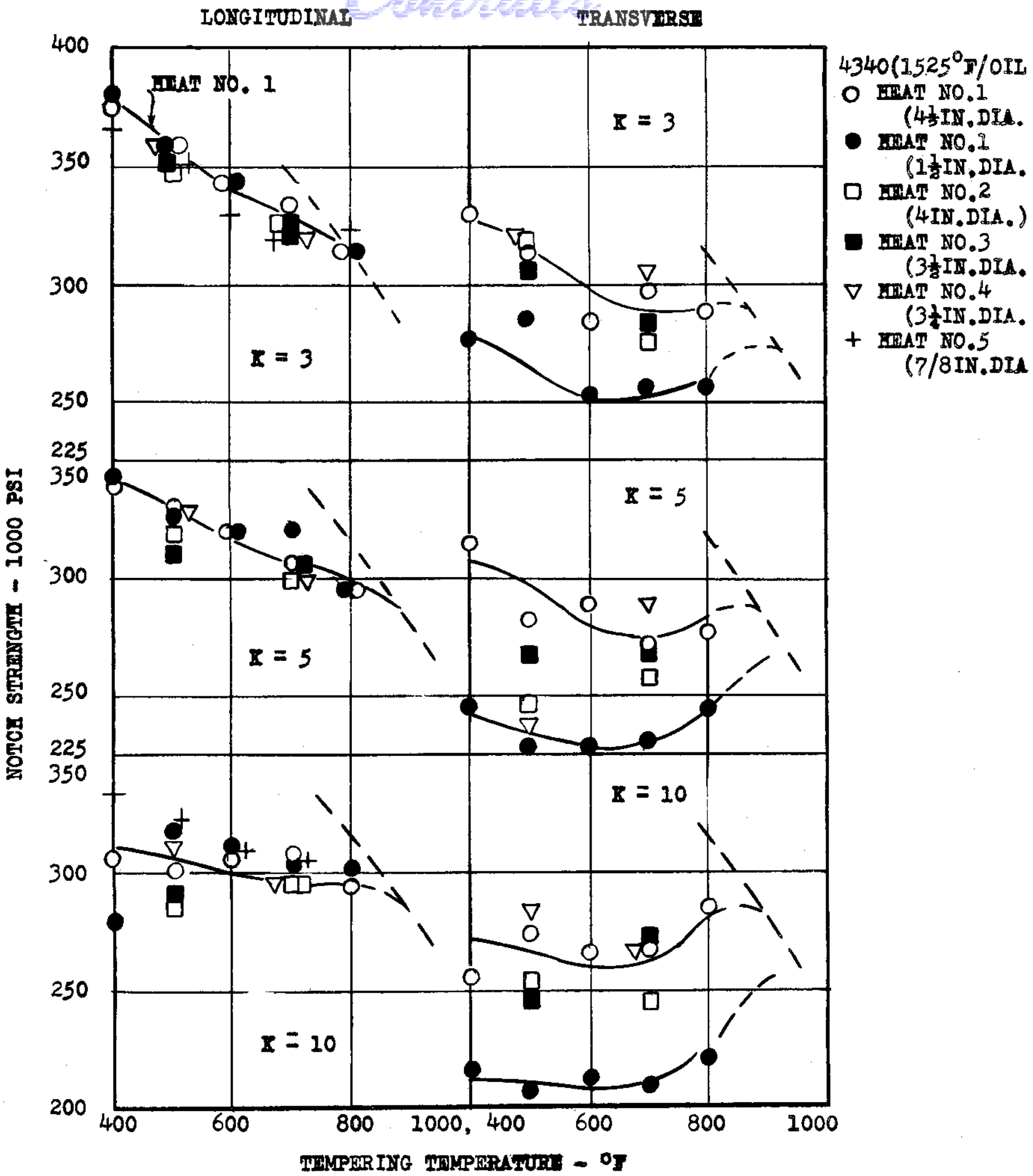


FIG. 15 NOTCH STRENGTH OF FOUR HEATS OF 4340 STEEL AS A FUNCTION OF TEMPERING TEMPERATURE FOR 0.3 IN. DIA. SPECIMENS.

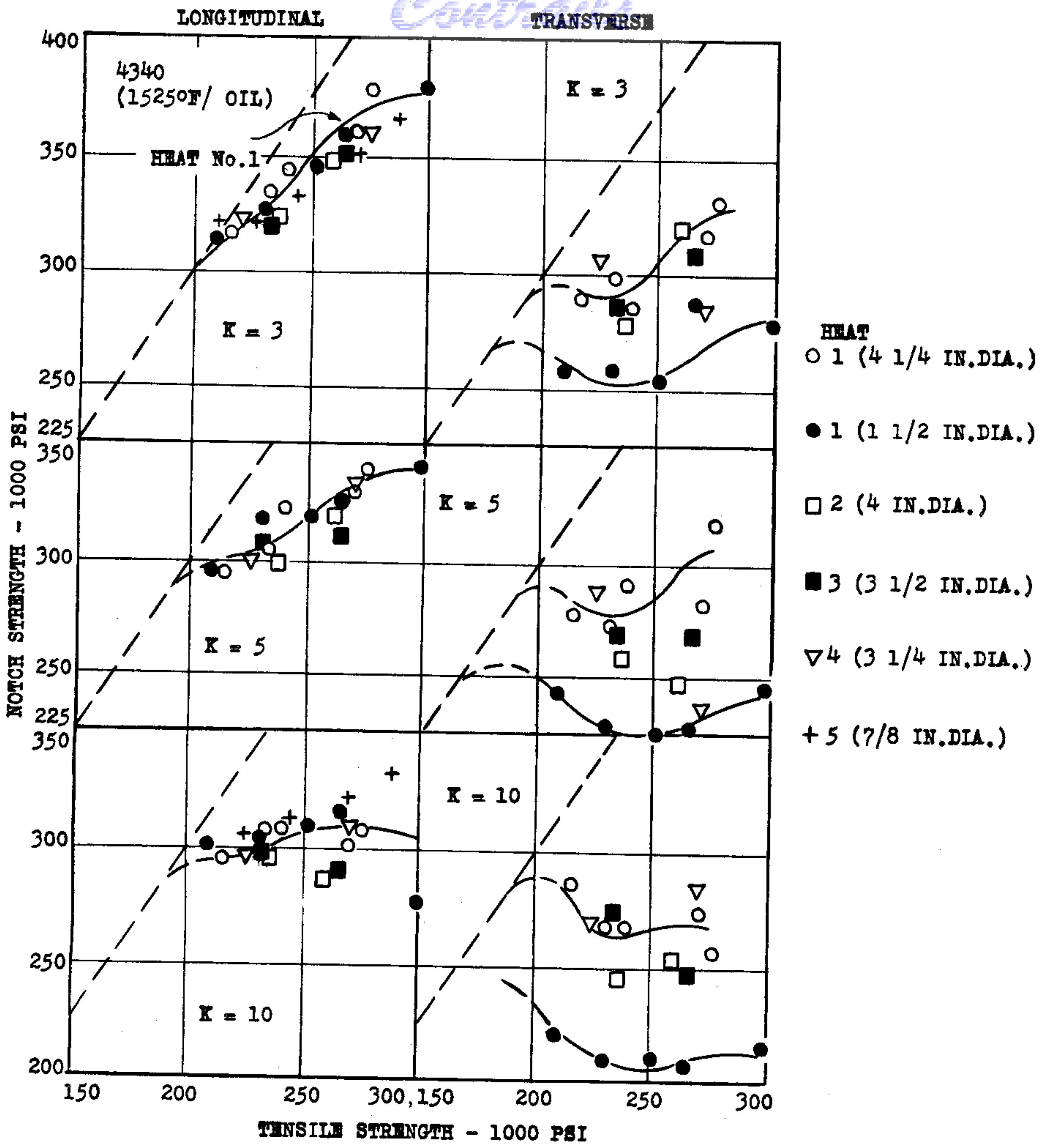


FIG. 16 NOTCH STRENGTH OF FOUR HEATS OF 4340 STEEL AS A FUNCTION OF TENSILE STRENGTH FOR 0.3 IN.DIA.SPECIMENS.

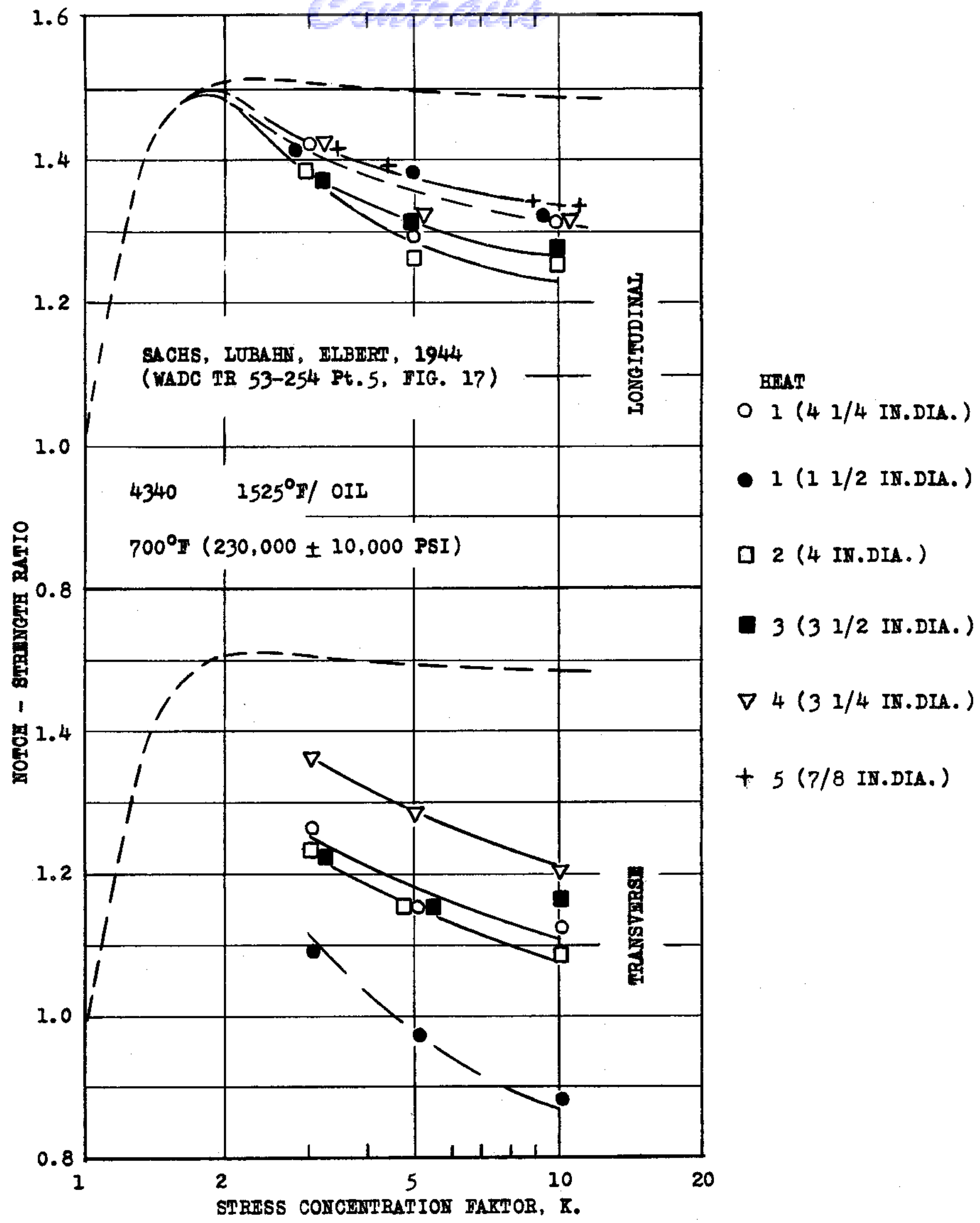


FIG. 17 VARIATION OF NOTCH-STRENGTH RATIO OF VARIOUS 4340 STEEL HEATS WITH STRESS CONCENTRATION FOR 0.3 IN.DIA.SPECIMENS.

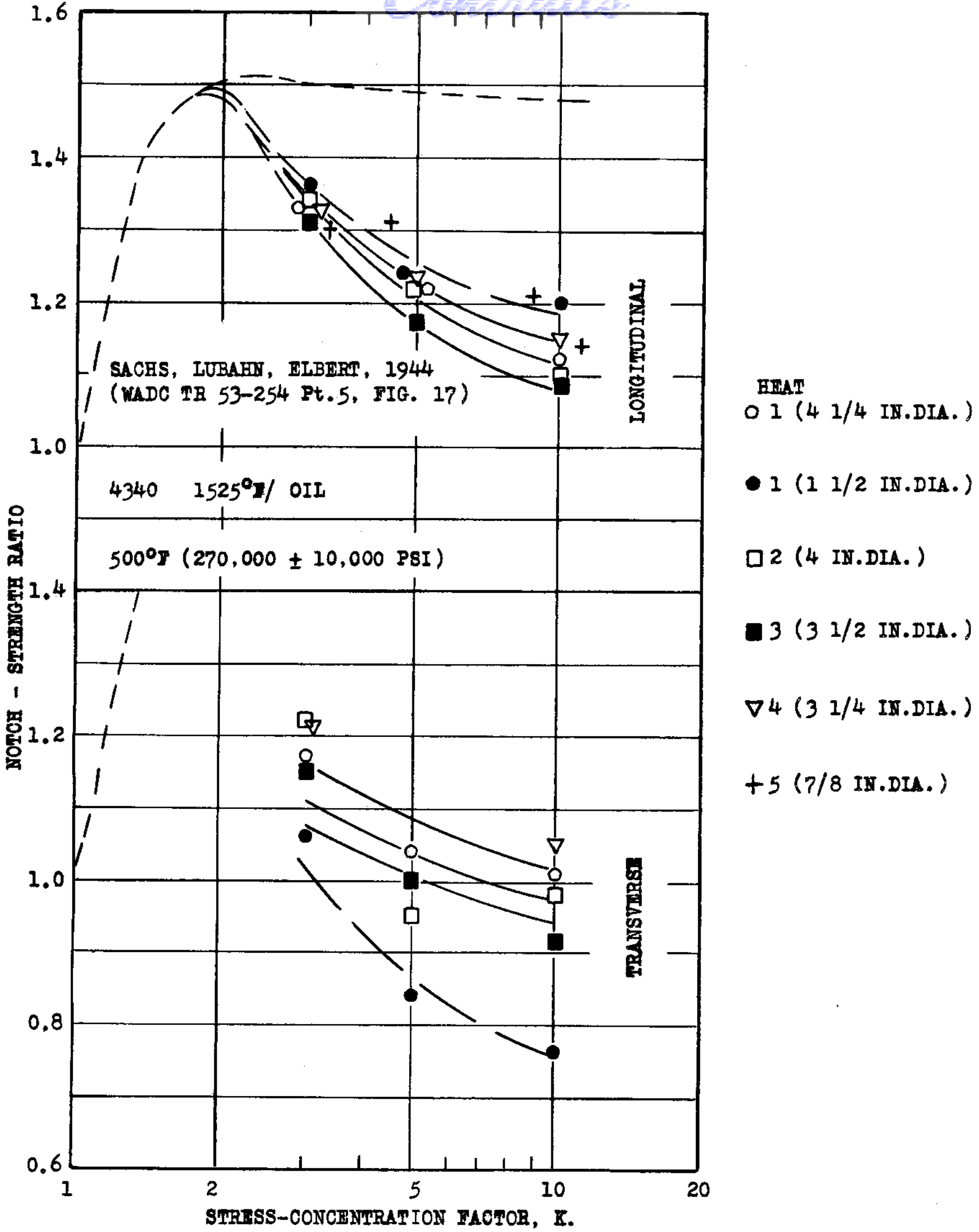


FIG. 18 VARIATION OF NOTCH-STRENGTH RATIO OF VARIOUS 4340 STEEL HEATS WITH STRESS CONCENTRATION FOR 0.3 IN.DIA.SPECIMENS.

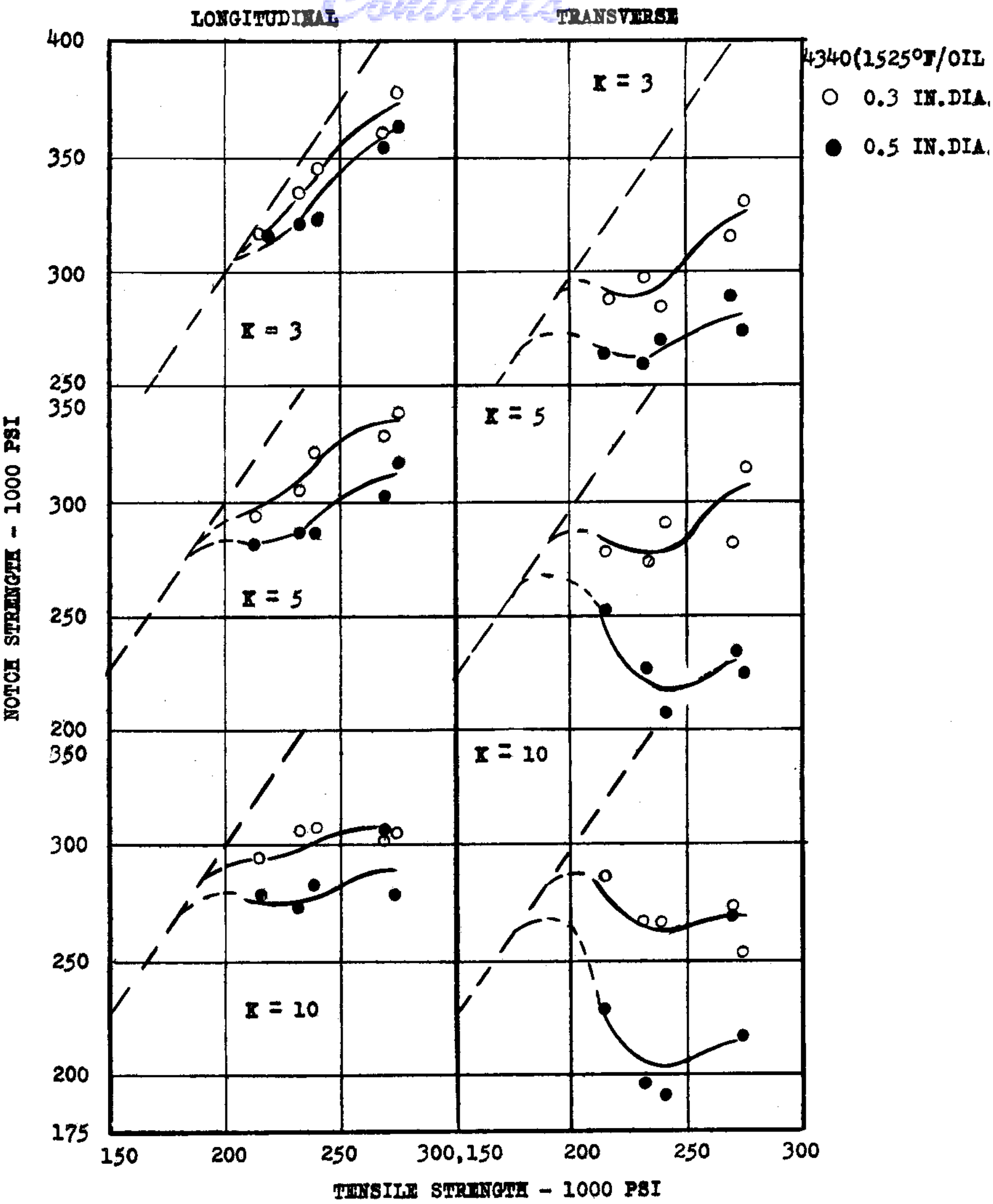


FIG. 19. NOTCH STRENGTH FOR 0.3 AND 0.5 IN. DIA. LONGITUDINAL AND TRANSVERSE SPECIMENS FROM 4340 STEEL (HEAT NO. 1)

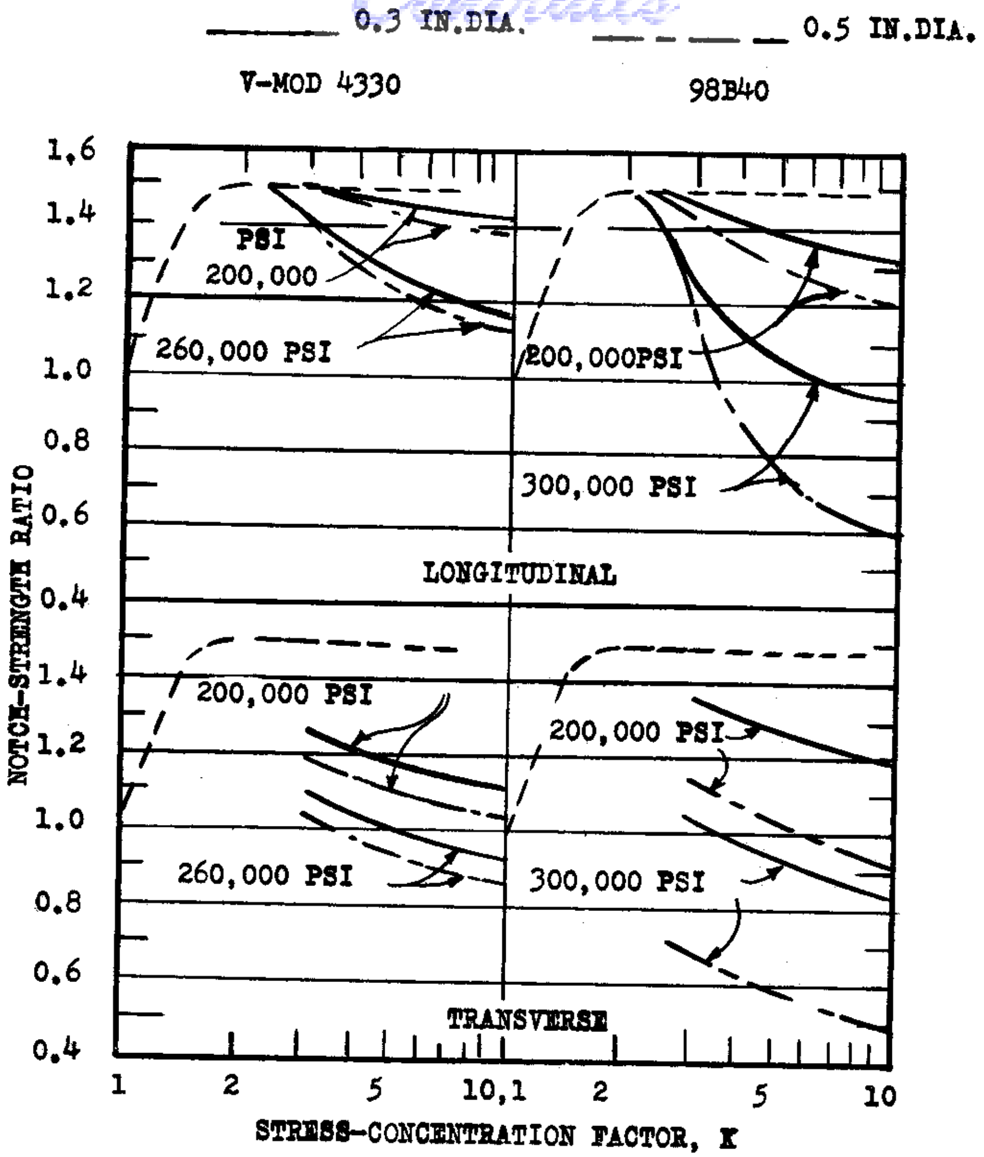


FIG. 20 EXTREME TREND CURVES FOR NOTCH-STRENGTH RATIO AS A FUNCTION OF STRESS CONCENTRATION FOR V-MOD 4330 AND SUPER HY-TUF STEELS.

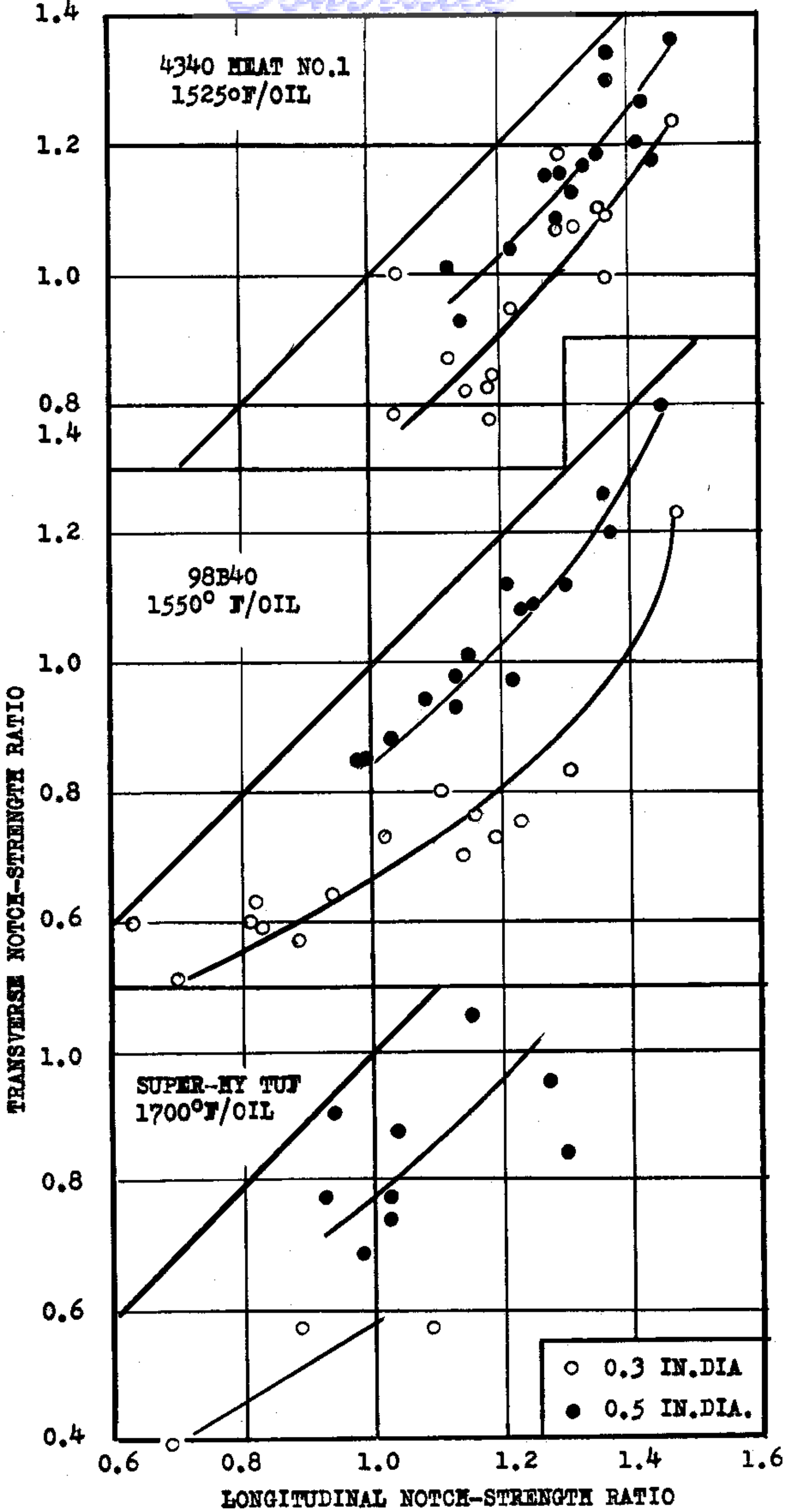


FIG. 21 TRANSVERSE NOTCH-STRENGTH RATIO AS A FUNCTION OF LONGITUDINAL NOTCH-STRENGTH FOR THREE HIGH STRENGTH STEELS.

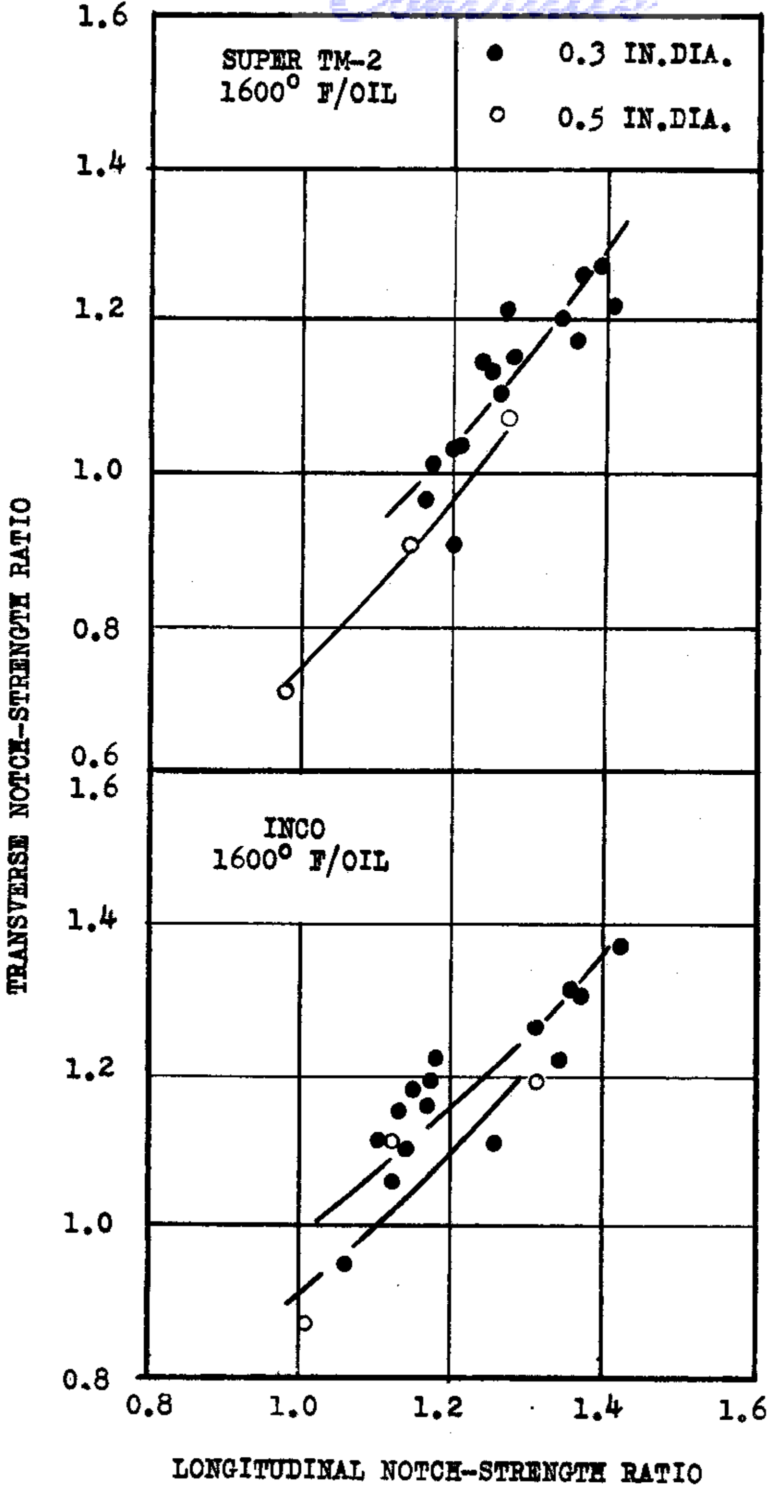


FIG. 22 TRANSVERSE NOTCH-STRENGTH RATIO AS A FUNCTION OF LONGITUDINAL NOTCH-STRENGTH RATIO FOR TWO HIGH-STRENGTH STEELS.

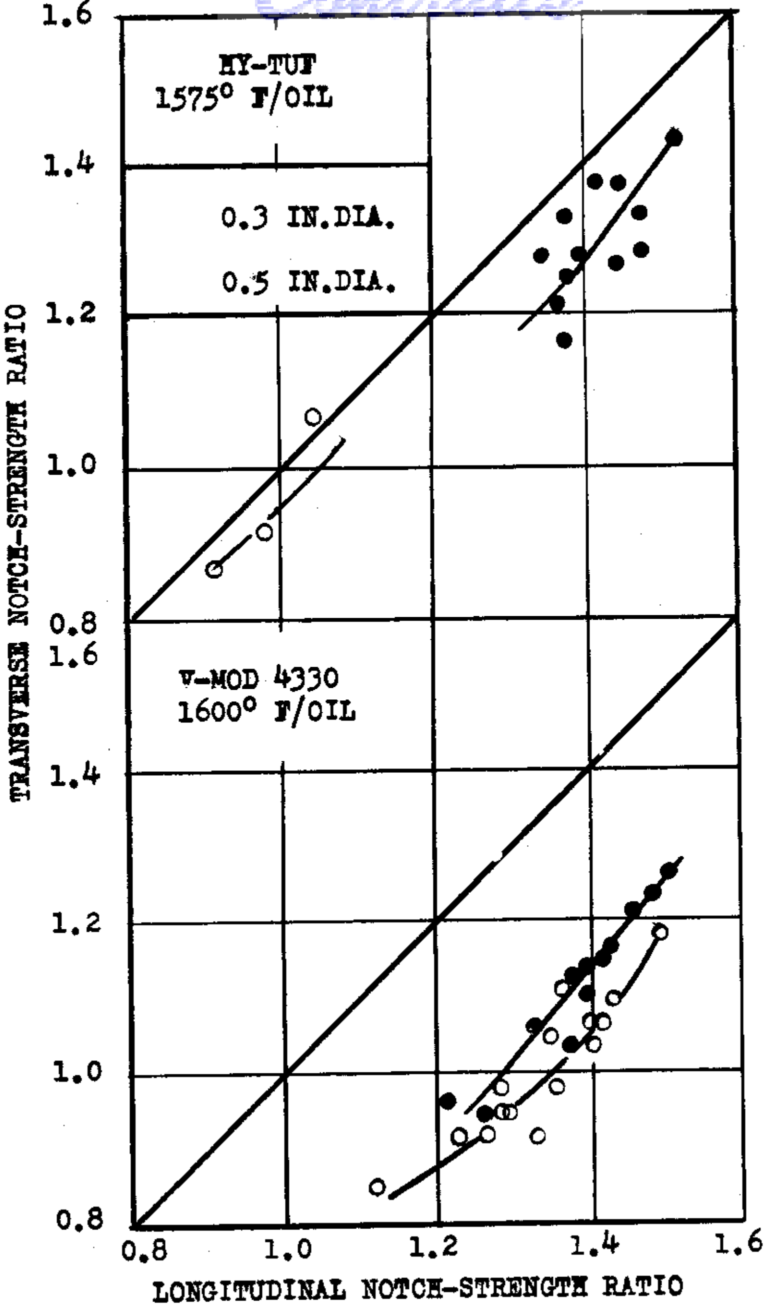


FIG. 23 TRANSVERSE NOTCH-STRENGTH RATIO AS A FUNCTION OF LONGITUDINAL NOTCH-STRENGTH RATIO FOR TWO HIGH-STRENGTH STEELS.

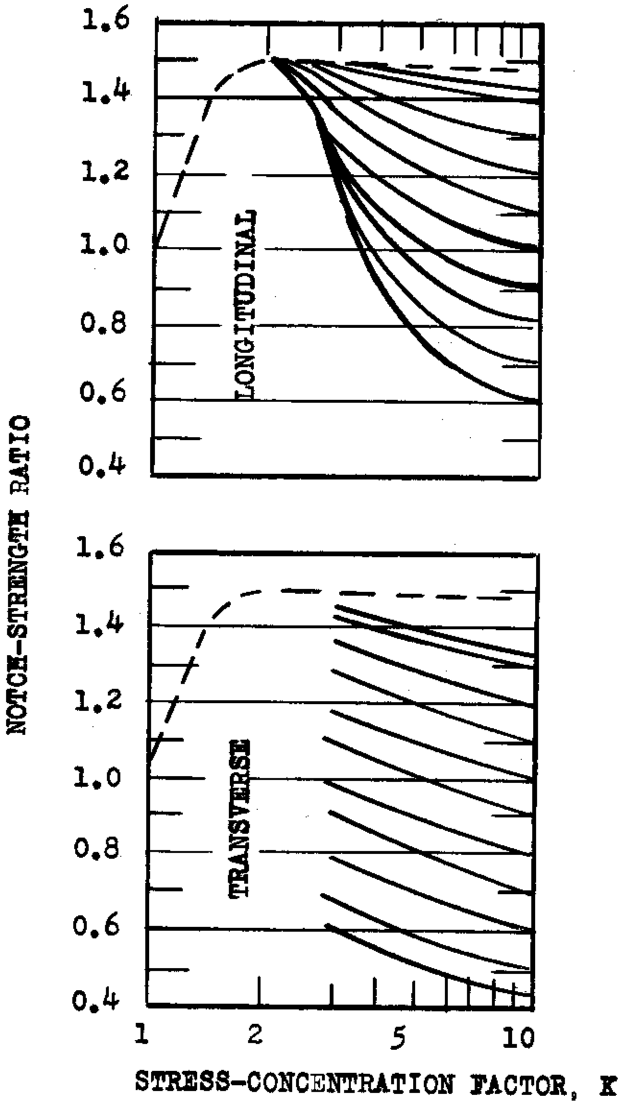


FIG. 24 DIAGRAMATIC PRESENTATION OF THE RANGE OF VARIATIONS OF NOTCH-STRENGTH RATIO OF HIGH-STRENGTH STEELS WITH STRESS CONCENTRATION.

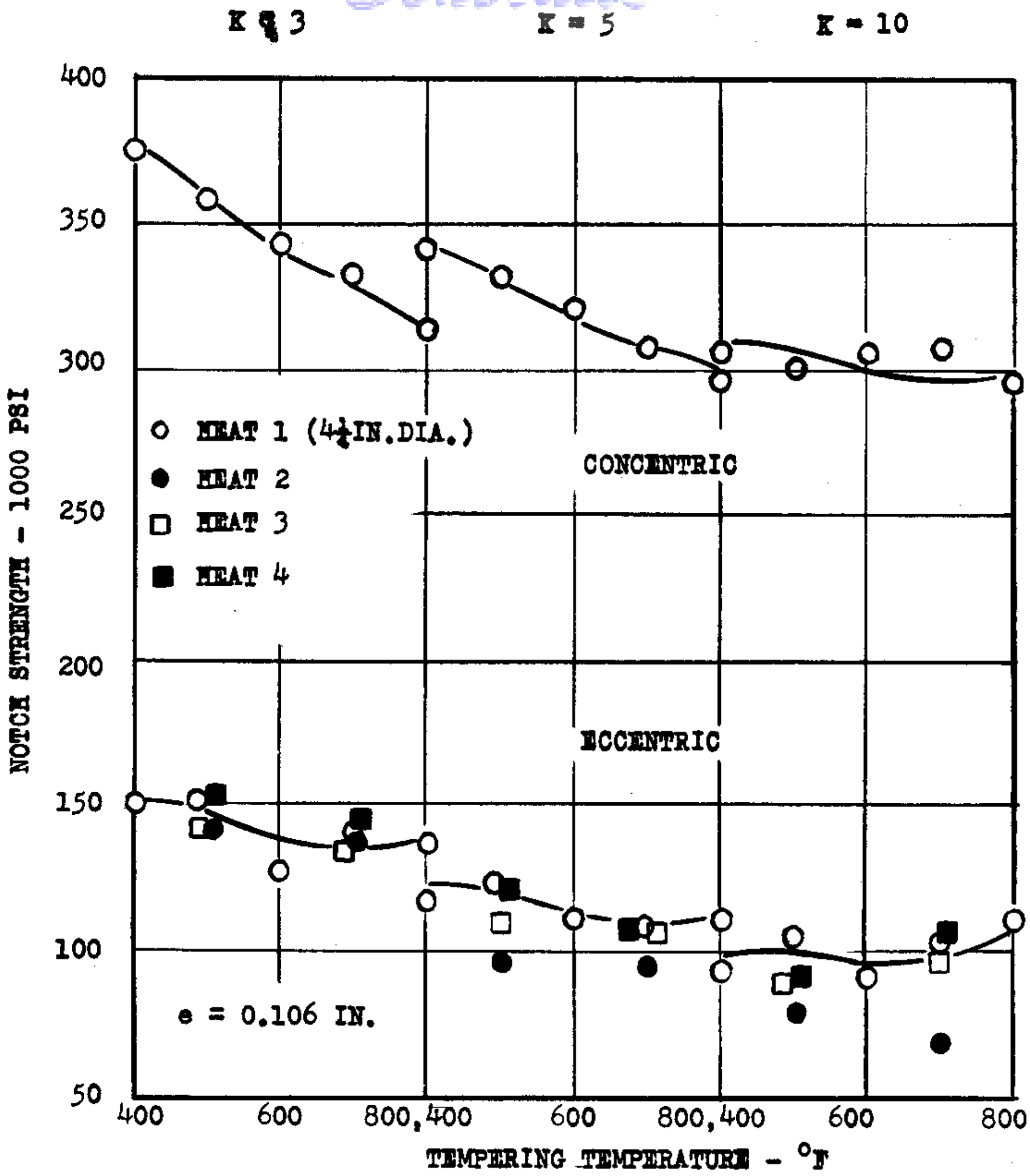


FIG. 25 CONCENTRIC AND ECCENTRIC NOTCH-STRENGTH OF FOUR HEATS OF 4340 STEEL AS A FUNCTION OF TEMPERING TEMPERATURE FOR 0.3 IN. DIA. LONGITUDINAL SPECIMENS.

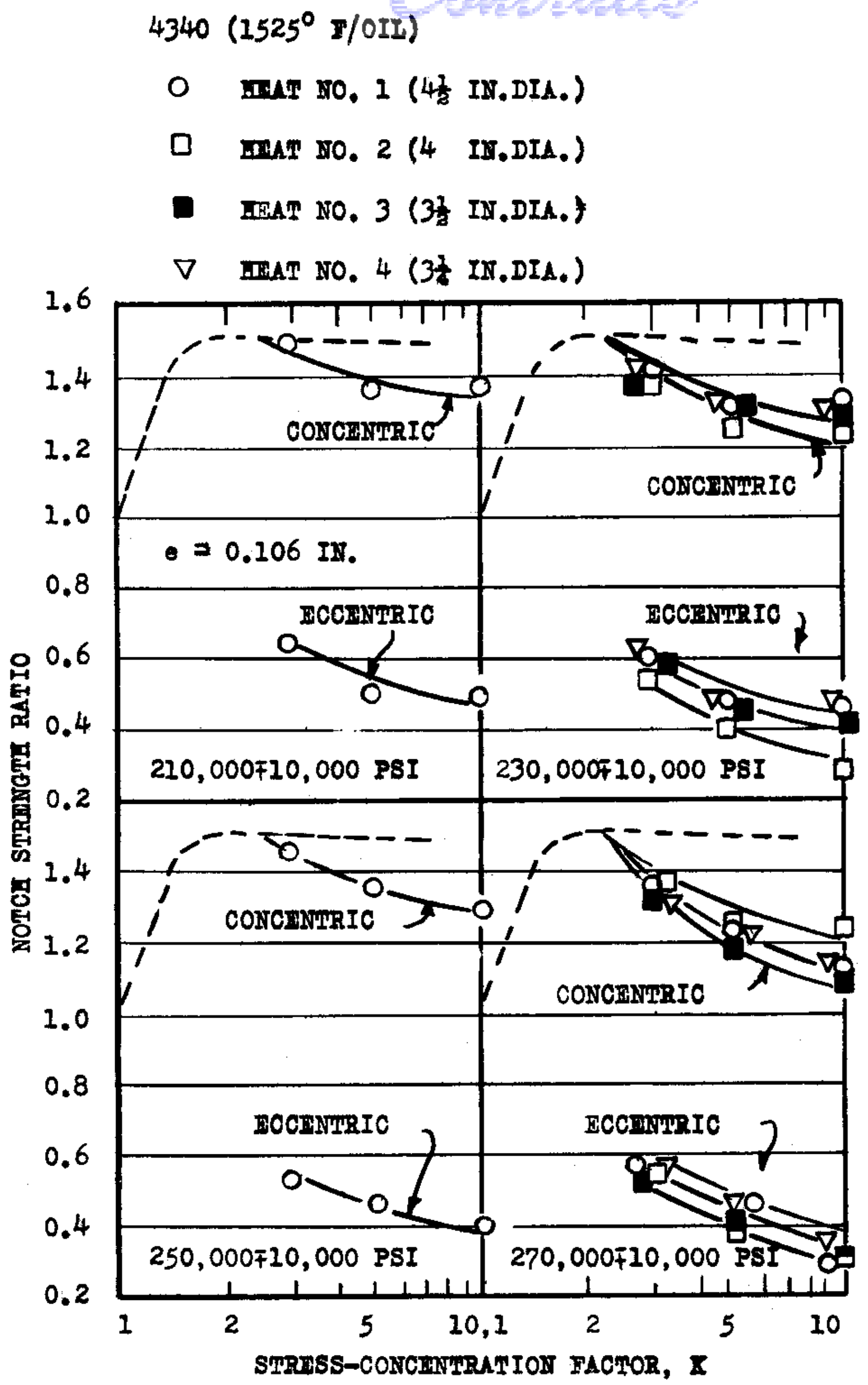


FIG. 26 VARIATION OF NOTCH-STRENGTH RATIO WITH K FOR CONCENTRIC AND ECCENTRIC 0.3 IN. DIA. SPECIMENS.

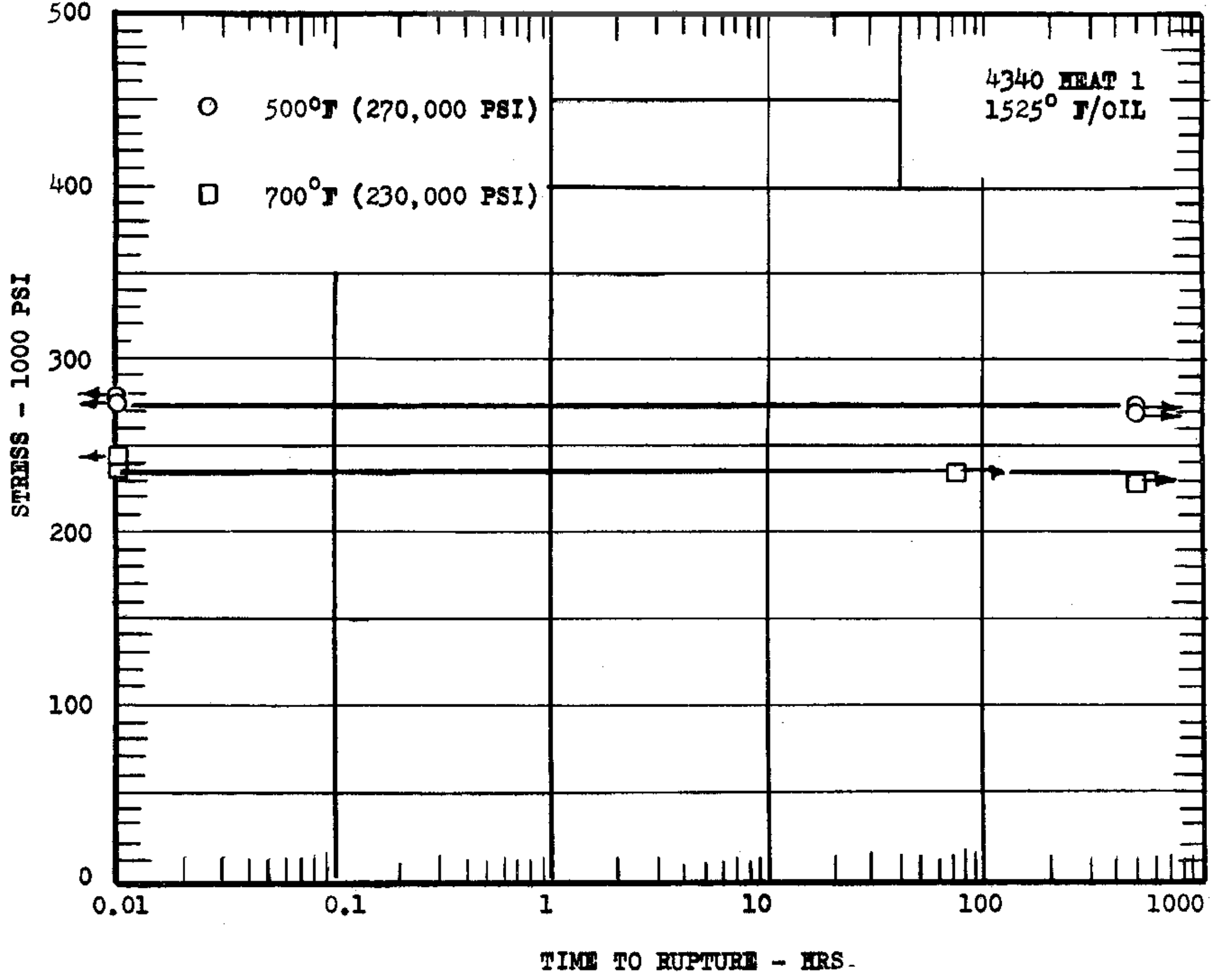


FIG. 27 STRESS-RUPTURE DIAGRAM FOR SMOOTH 4340 SPECIMENS AT TWO STRENGTH LEVELS.

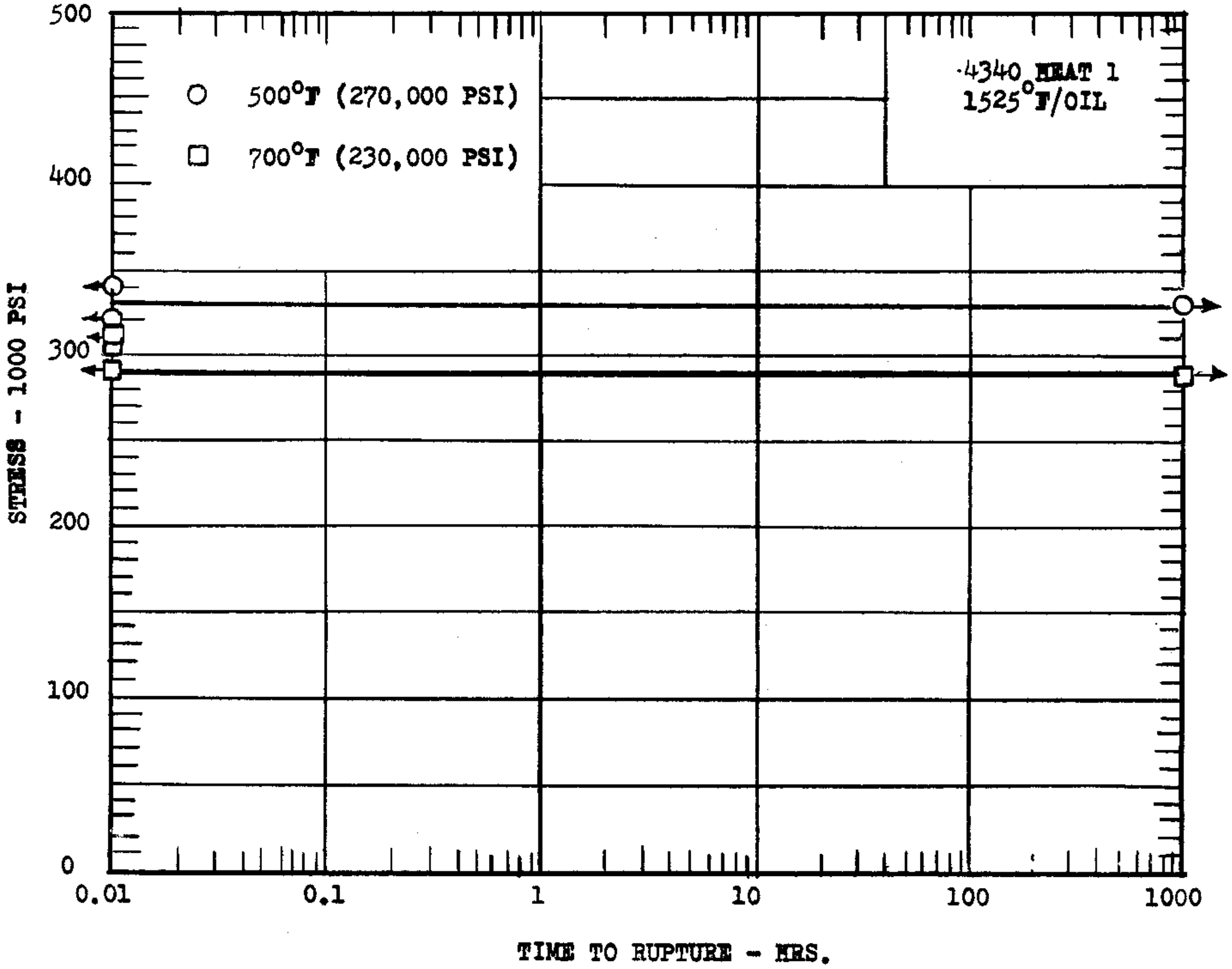


FIG. 28 STRESS-RUPTURE DIAGRAM FOR NOTCHED (K= 5) 4340 SPECIMENS AT TWO STRENGTH LEVELS.

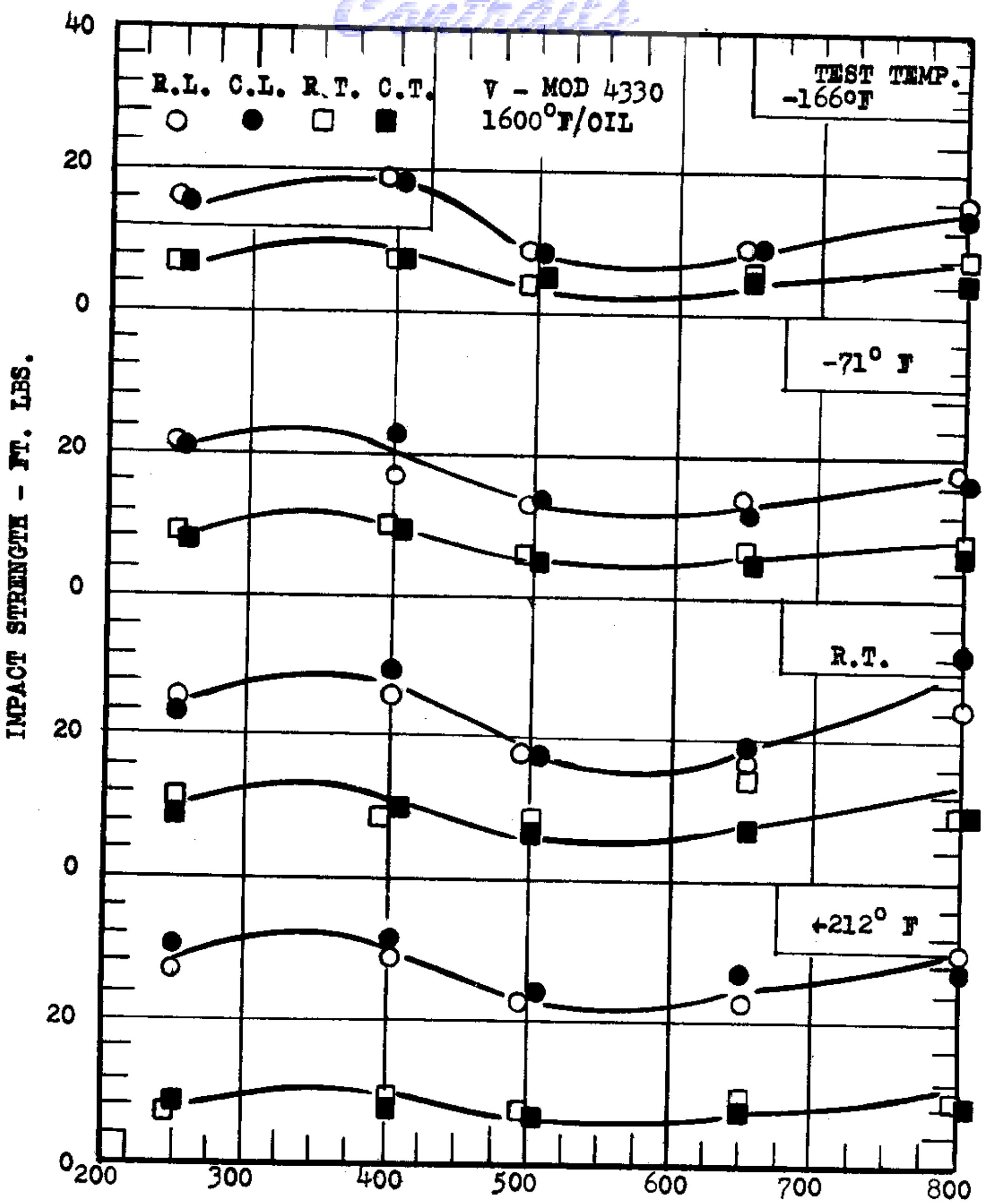


FIG. 29 VARIATION OF IMPACT STRENGTH WITH TEMPERING TEMPERATURE FOR V-MOD 4330 STEEL.

SECTION: 4IN.SQ.

SPECIMEN: STD. V-NOTCH CHARPY

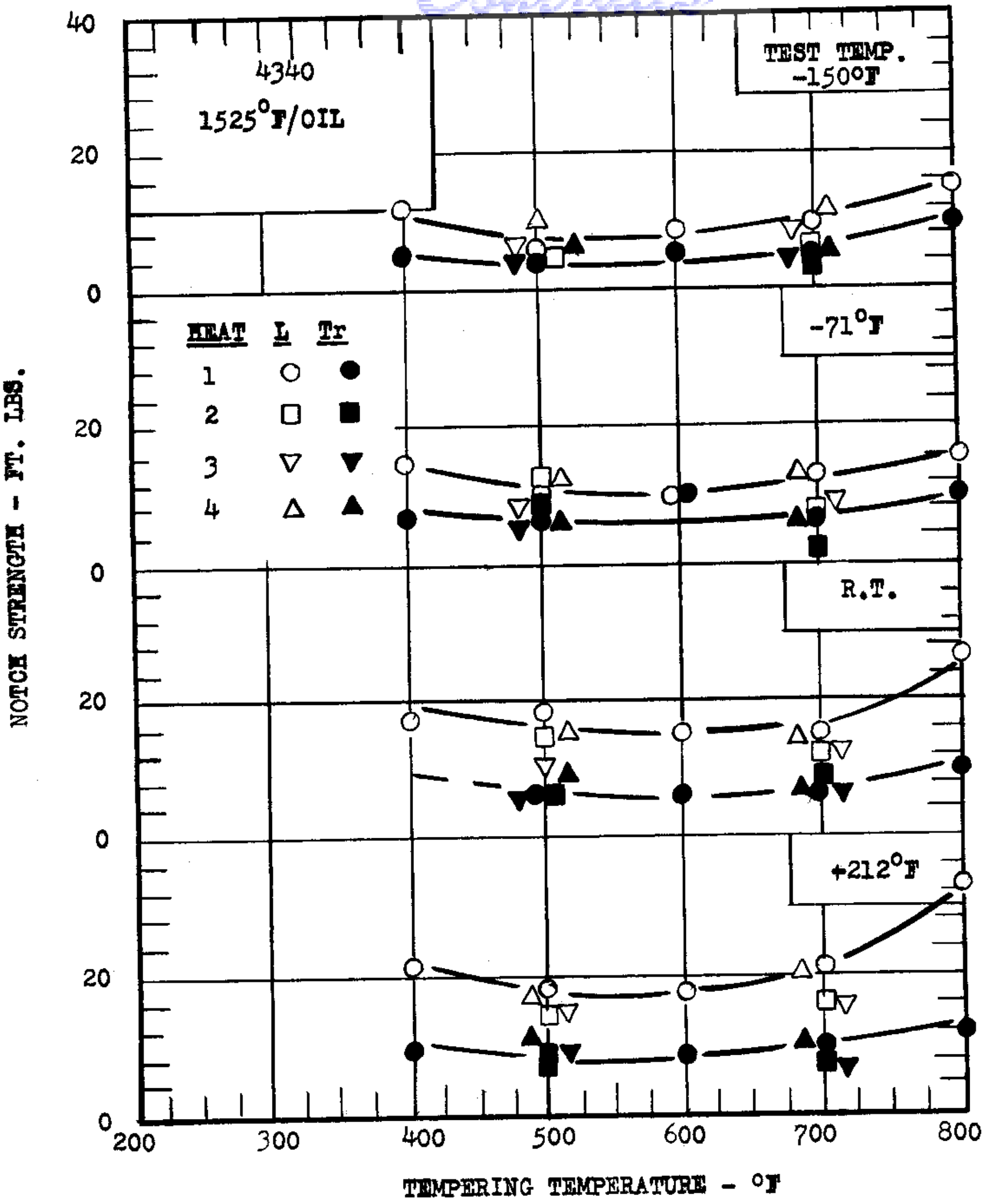


FIG. 30 VARIATION OF IMPACT STRENGTH WITH TEMPERING TEMPERATURE FOR FOUR HEATS OF 4340 STEEL.

SECTION: HEAT 1: 4¼; HEAT 2: 4; HEAT 3: 3½; HEAT 4: 3¼ IN. DIA.

SPECIMEN: STD. V-NOTCH CHARPY

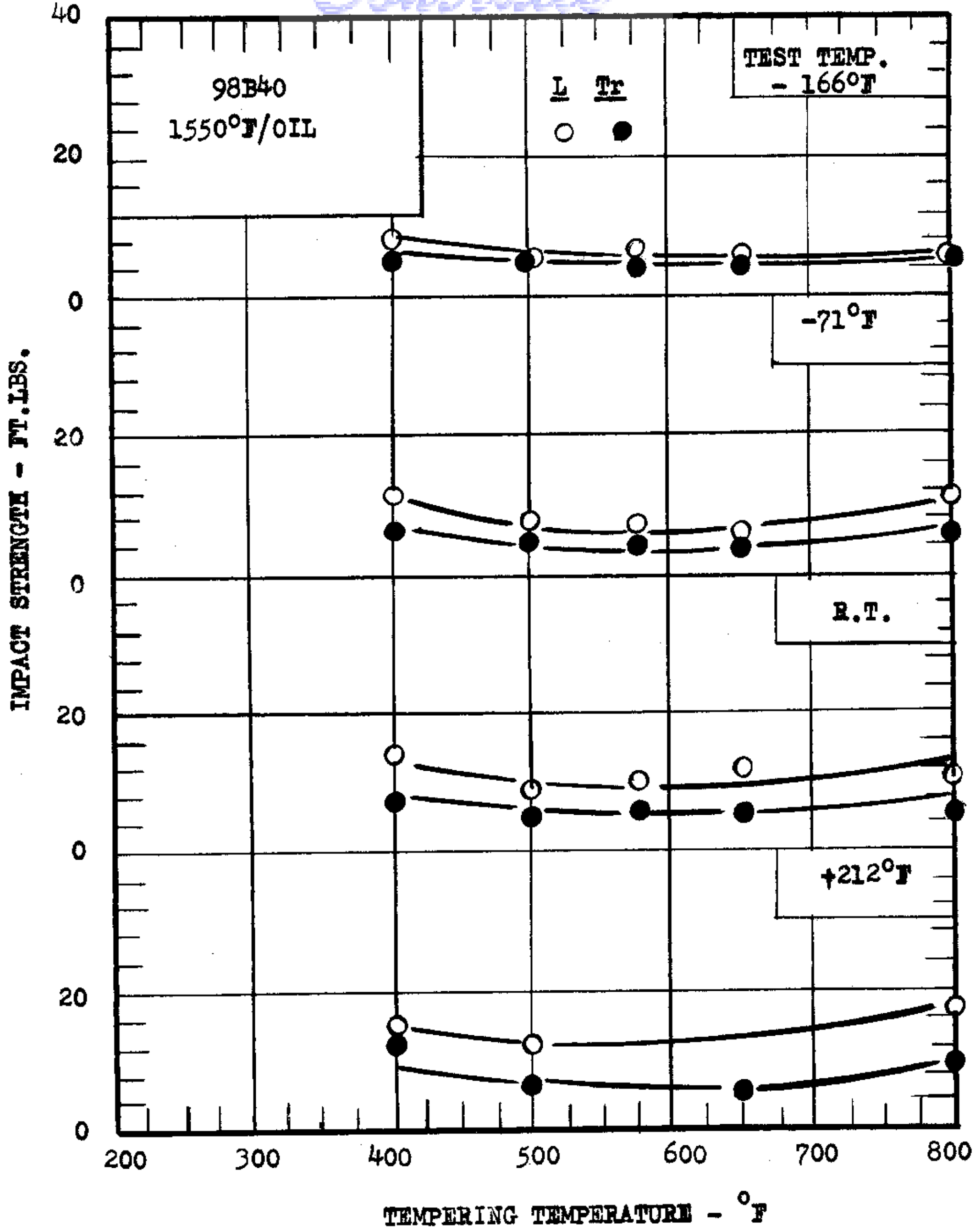


FIG. 31 VARIATION OF IMPACT STRENGTH WITH TEMPERING TEMPERATURE FOR 98B40 STEEL.

SECTION: 4½ IN.DIA.

SPECIMEN: STD. V-NOTCH CHARPY

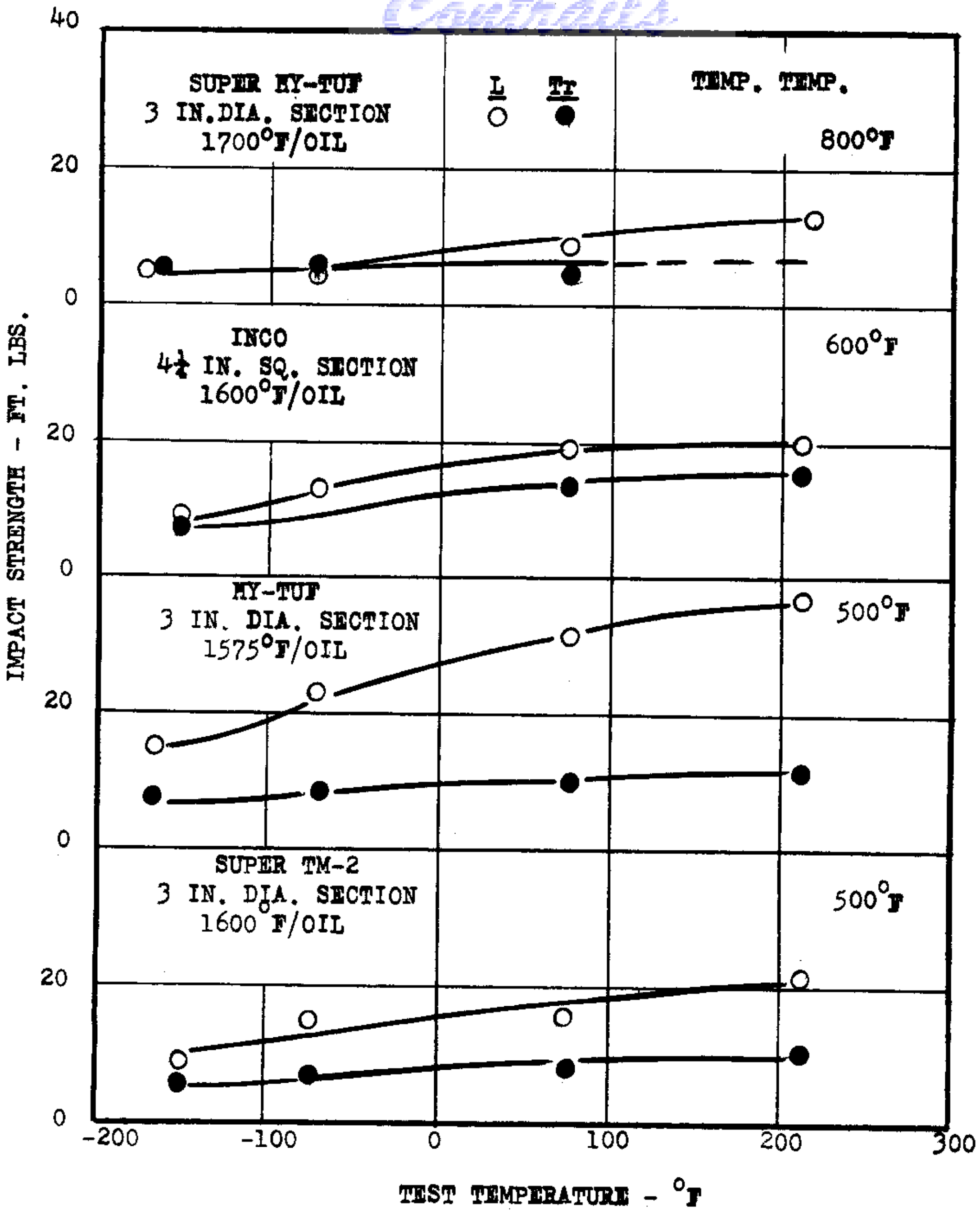


FIG. 32 VARIATION OF IMPACT STRENGTH WITH TEST TEMPERATURE FOR A NUMBER OF HIGH-STRENGTH STEELS.

SPECIMEN: STD. V-NOTCH CHARPY

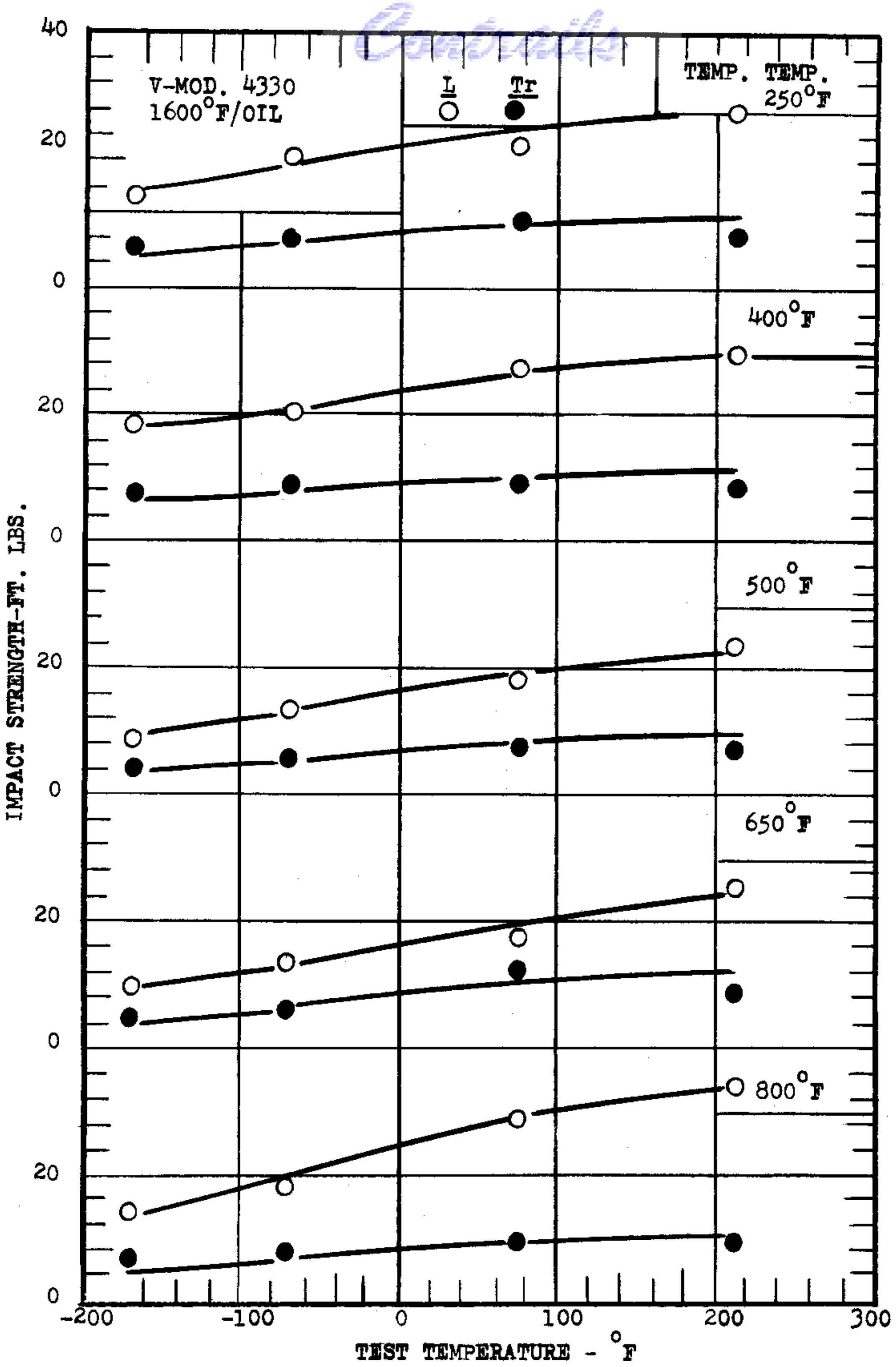


FIG. 33 VARIATION OF IMPACT STRENGTH WITH TEST TEMPERATURE FOR V-MOD. 4330 STEEL.

SECTION: 4 IN. SQ.

SPECIMEN: STD. V-NOTCH CHARPY

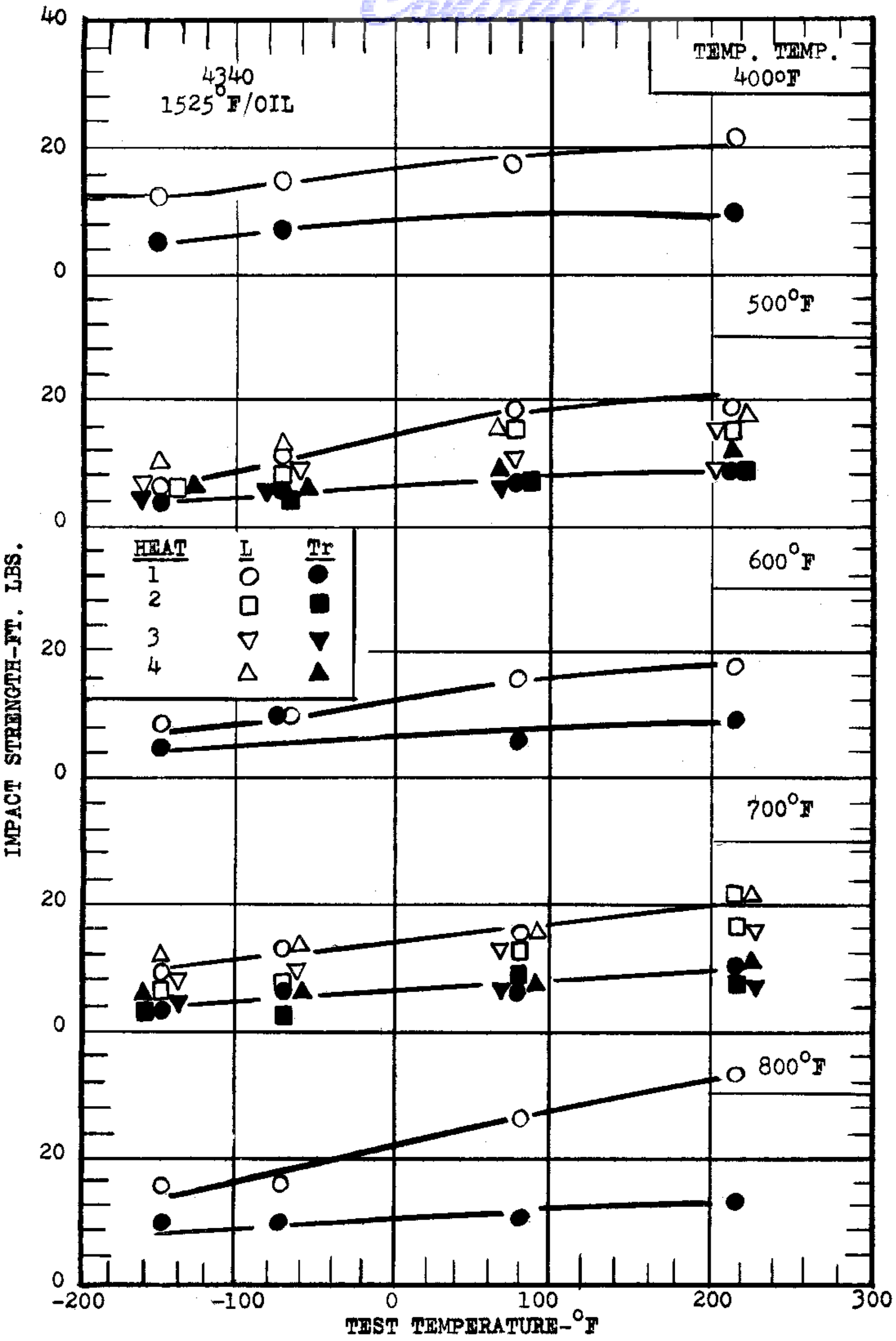


FIG. 34 VARIATION OF IMPACT STRENGTH WITH TEST TEMPERATURE FOR FOUR HEATS OF 4340 STEEL.

SECTION: HEAT 1 : 4-1/4; HEAT 2 : 4; HEAT 3 : 3-1/2; HEAT 4 : 3-1/4 IN. DIA.

SPECIMEN: STD. V-NOTCH CHARPY

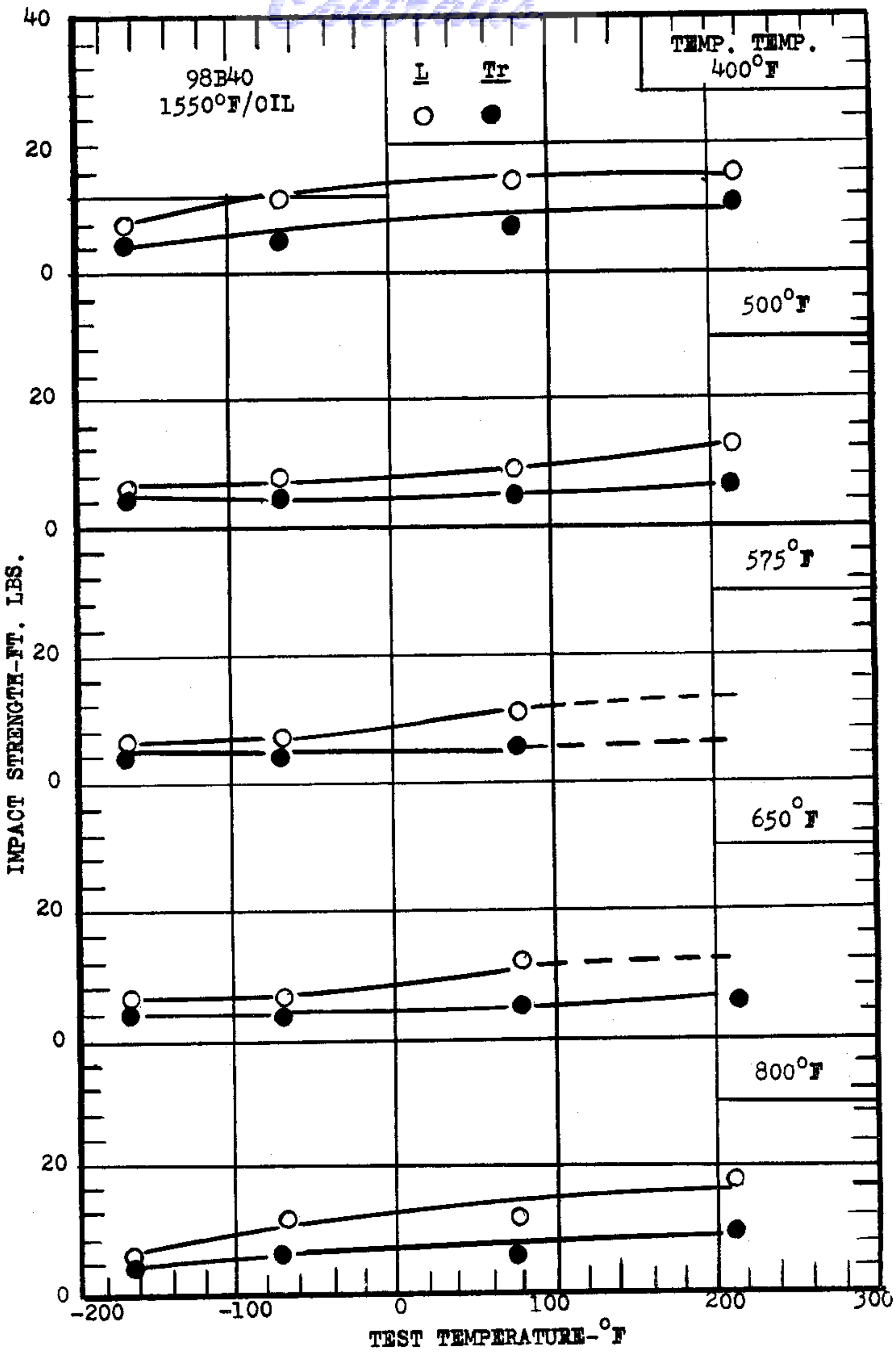


FIG. 35 VARIATION OF IMPACT STRENGTH WITH TEST TEMPERATURE FOR 98B40 STEEL

SECTION: 4-1/2 IN. DIA.

SPECIMEN: STD. V-NOTCH CHARPY

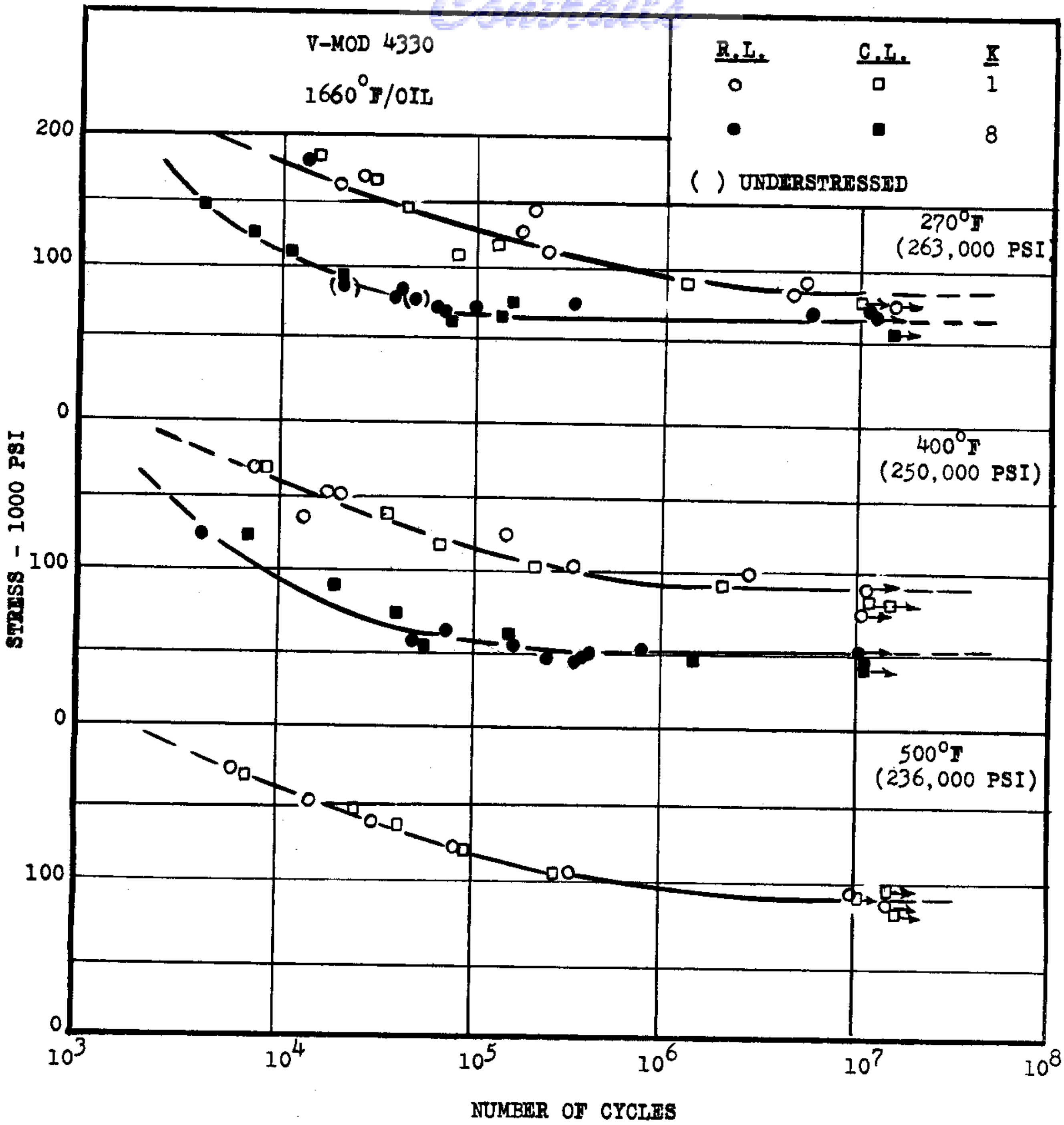


FIG. 36 S-N CURVES FOR SMOOTH AND NOTCH ROTATING BEAM FATIGUE SPECIMENS FROM V-MOD. 4330 STEEL HEAT TREATED TO 263,000, 250,000 AND 236,000 PSI.

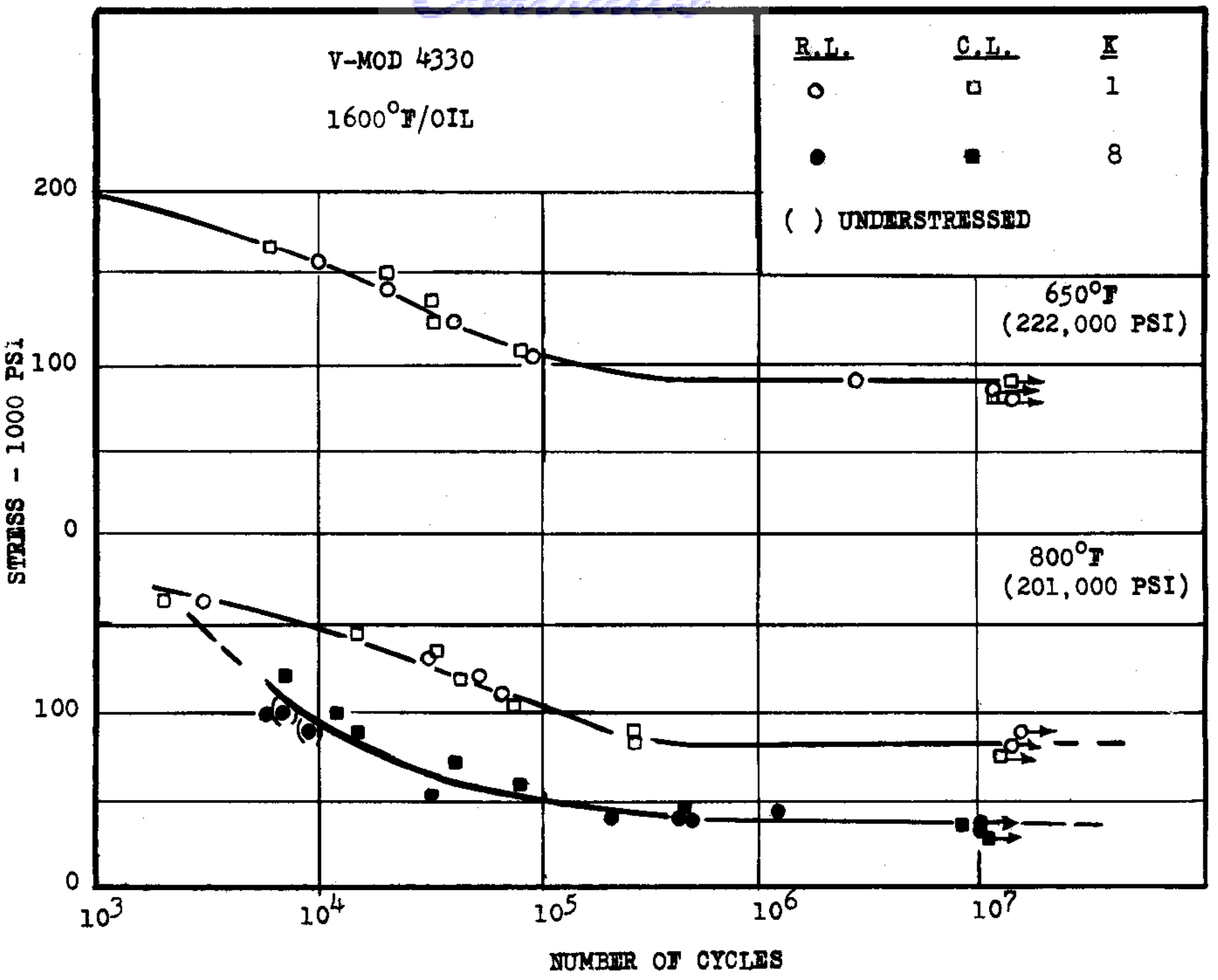


FIG. 37 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM V-MOD. 4330 STEEL HEAT TREATED TO 222,000 AND 201,000 PSI.

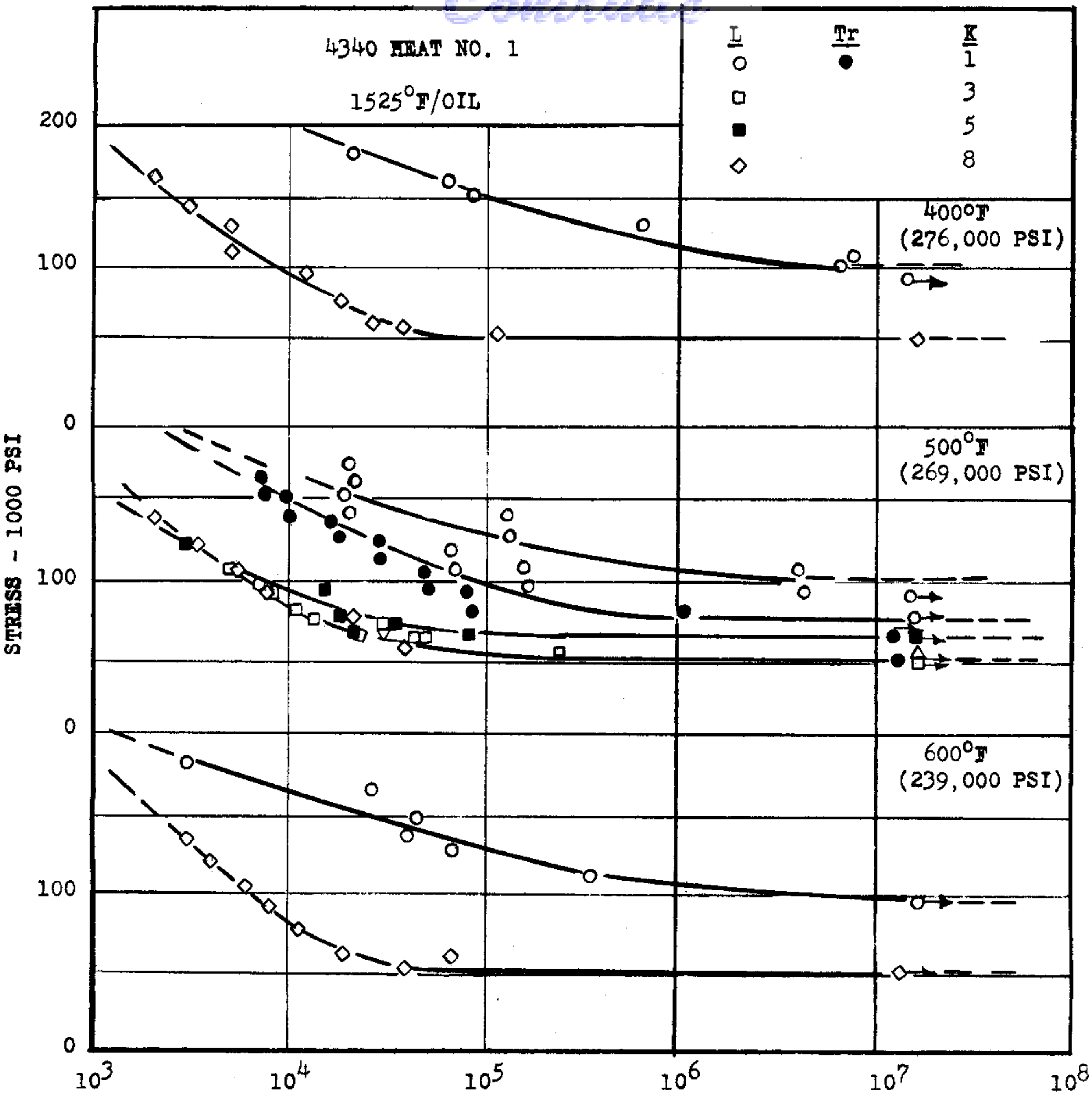


FIG. 38 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 4340 STEEL HEAT TREATED TO 276,000, 269,000 AND 239,000 PSI.

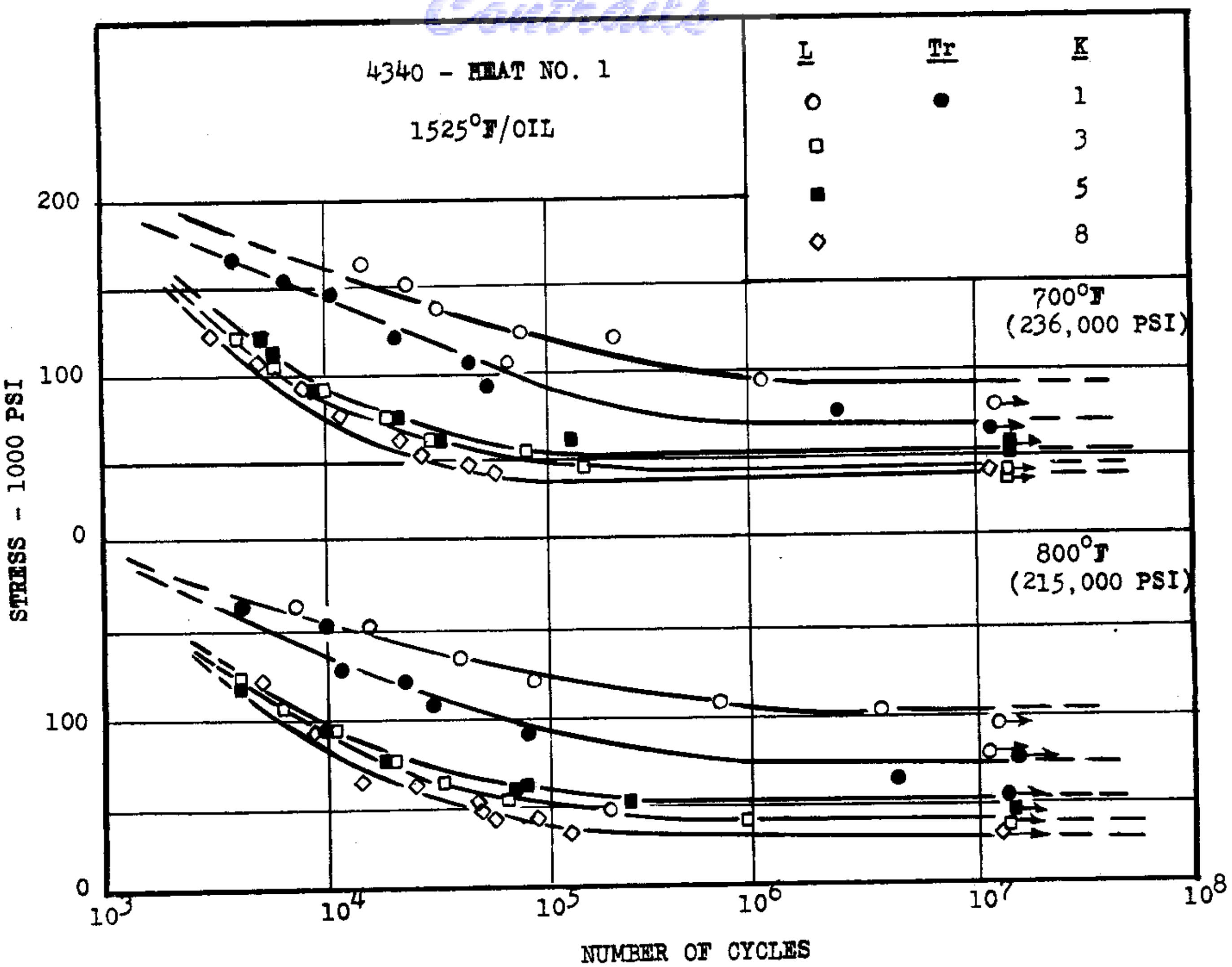


FIG. 39 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 4340 STEEL HEAT TREATED TO 236,000 AND 215,000 PSI.

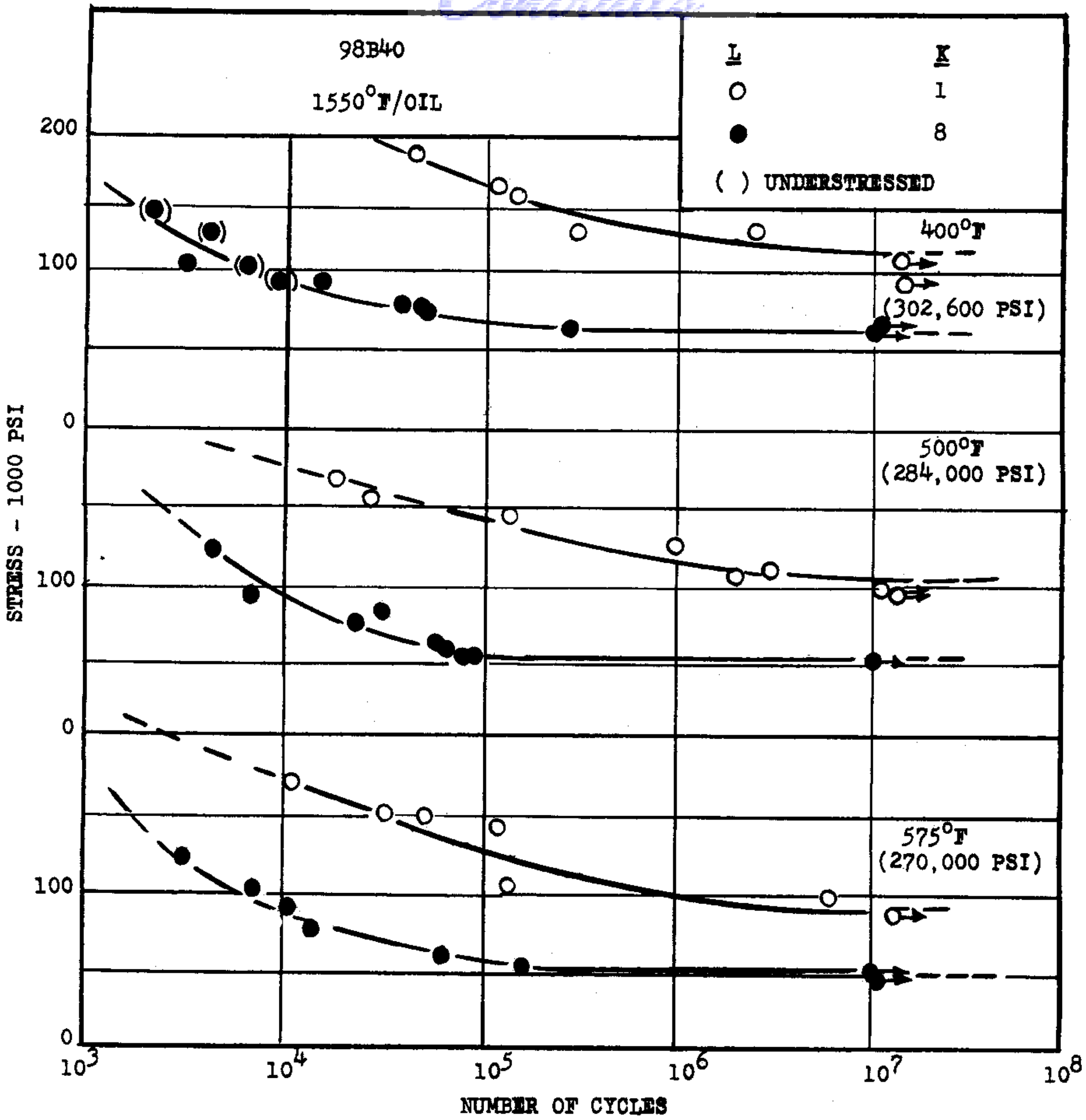


FIG. 40 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 98B40 STEEL HEAT TREATED TO 302,000, 284,000 AND 270,000 PSI.

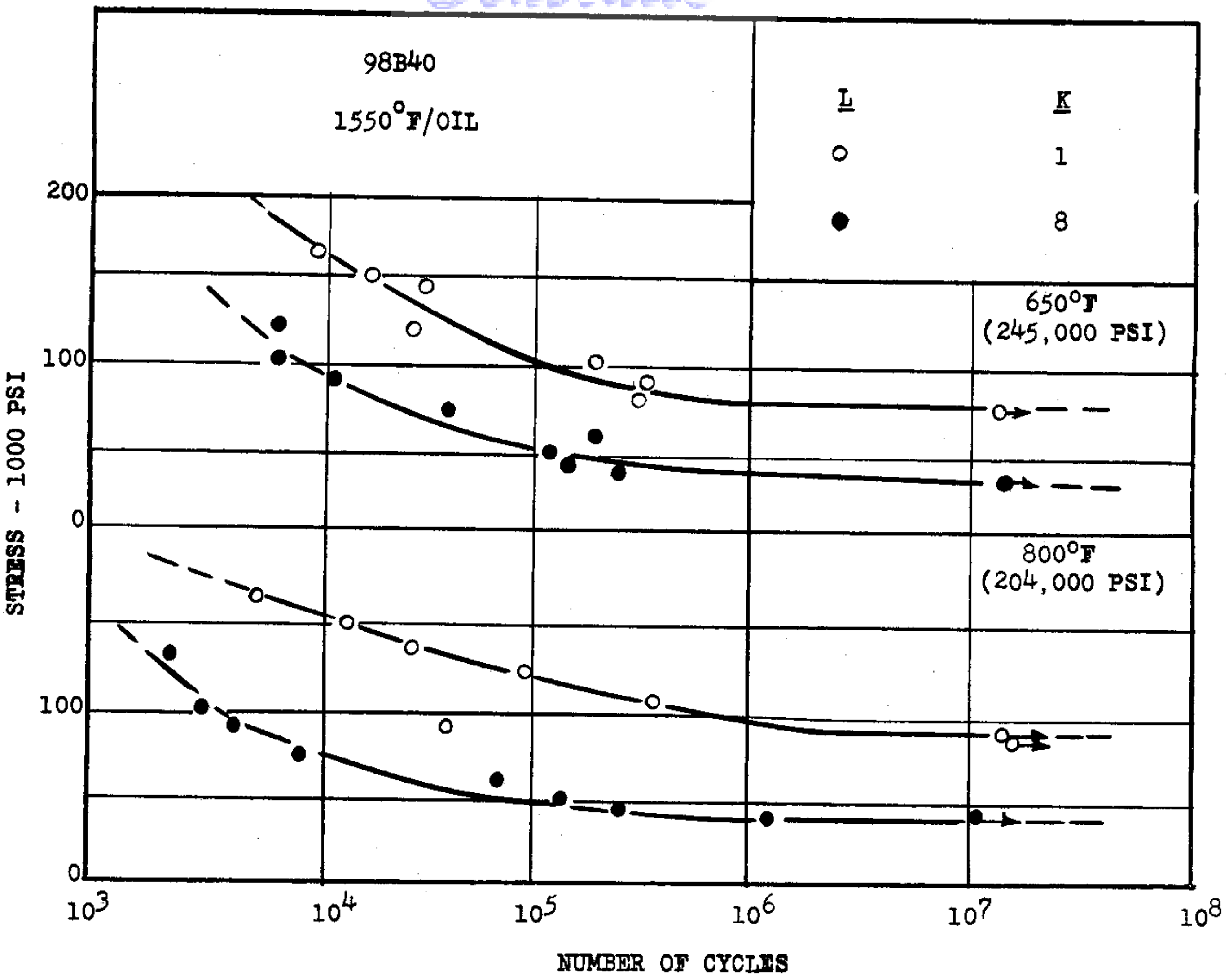


FIG. 41 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 98B40 STEEL HEAT TREATED TO 245,000 AND 204,000 PSI.

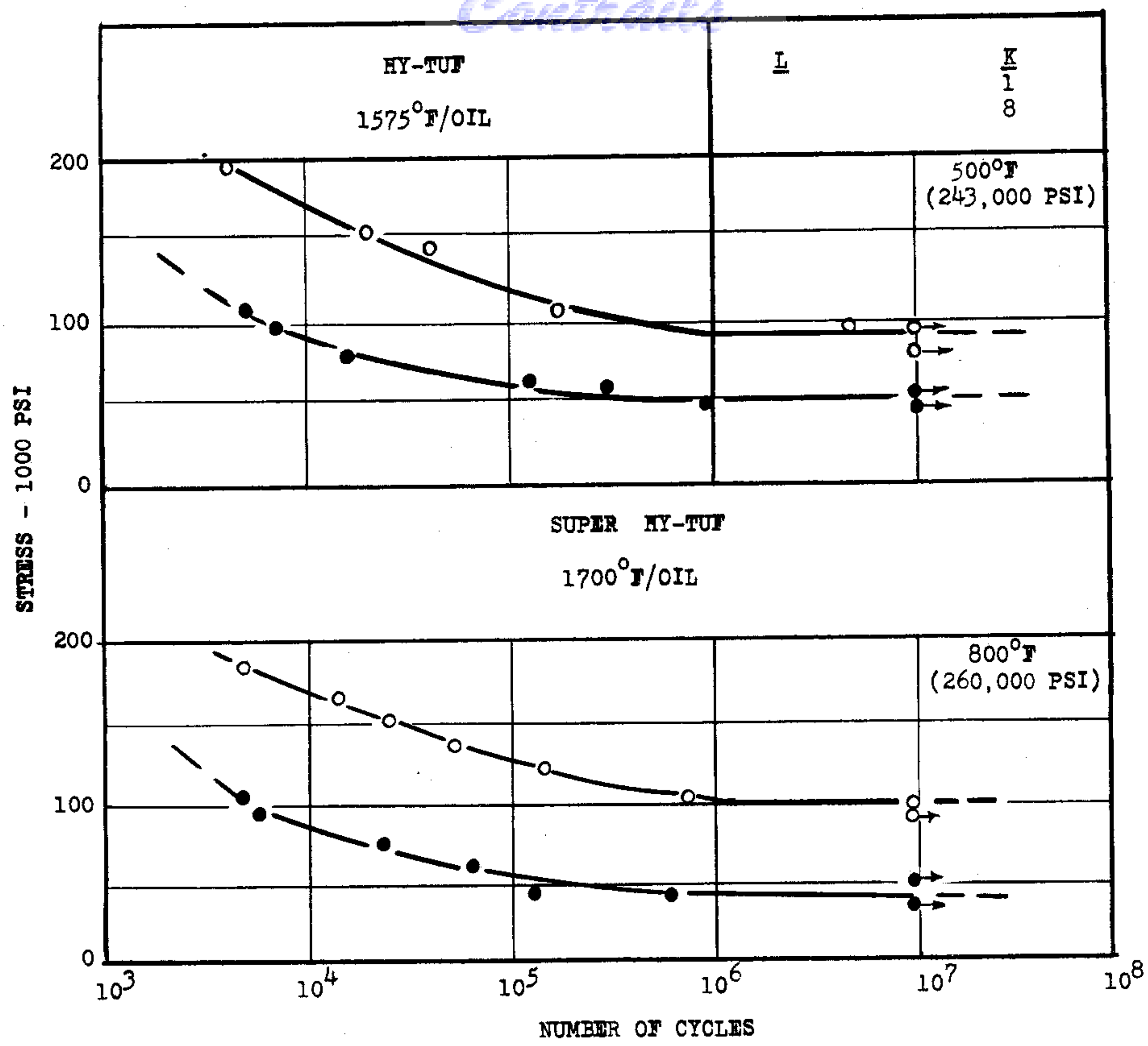


FIG. 42 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM HY-TUF HEAT TREATED TO 243,000 PSI AND SUPER HY-TUF HEAT TREATED TO 260,000 PSI.

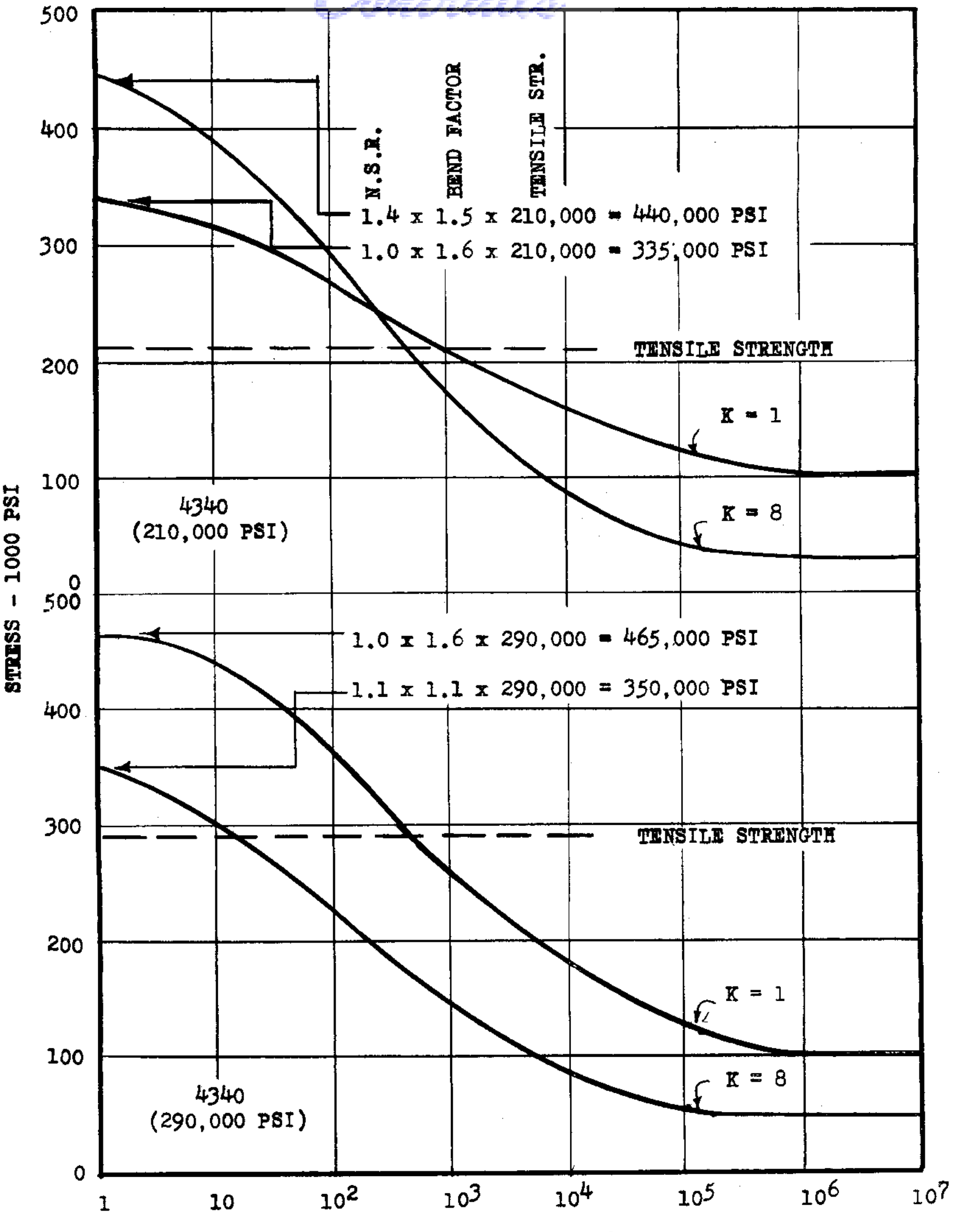


FIG. 43 S-N CURVES FOR SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 4340 STEEL.

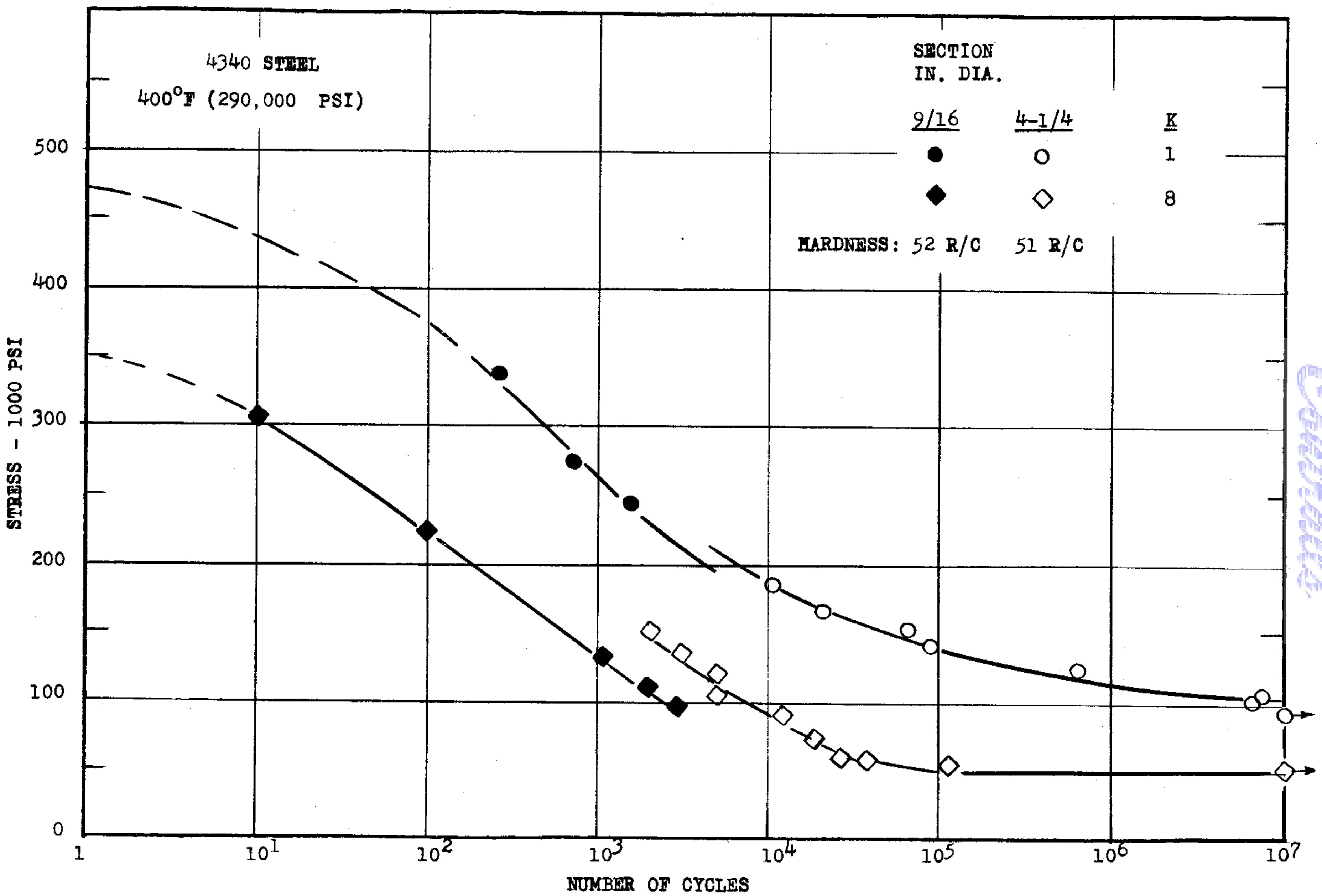


FIG. 44 S-N CURVES FOR SMOOTH & NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 4340 STEEL TEMPERED AT 400°F.

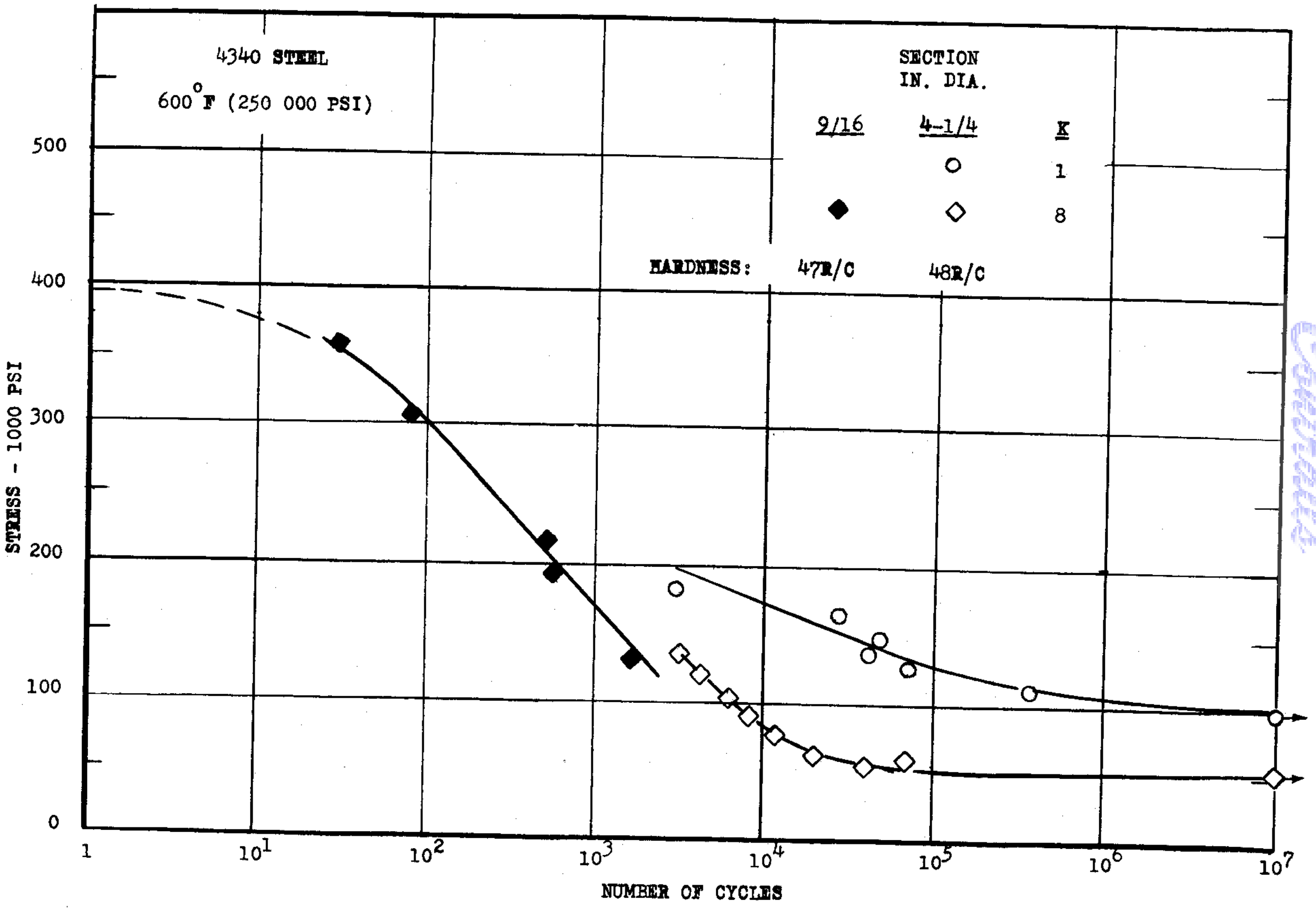


FIG. 45 S-N CURVES FOR SMOOTH & NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 4340 STEEL TEMPERED AT 600°F.

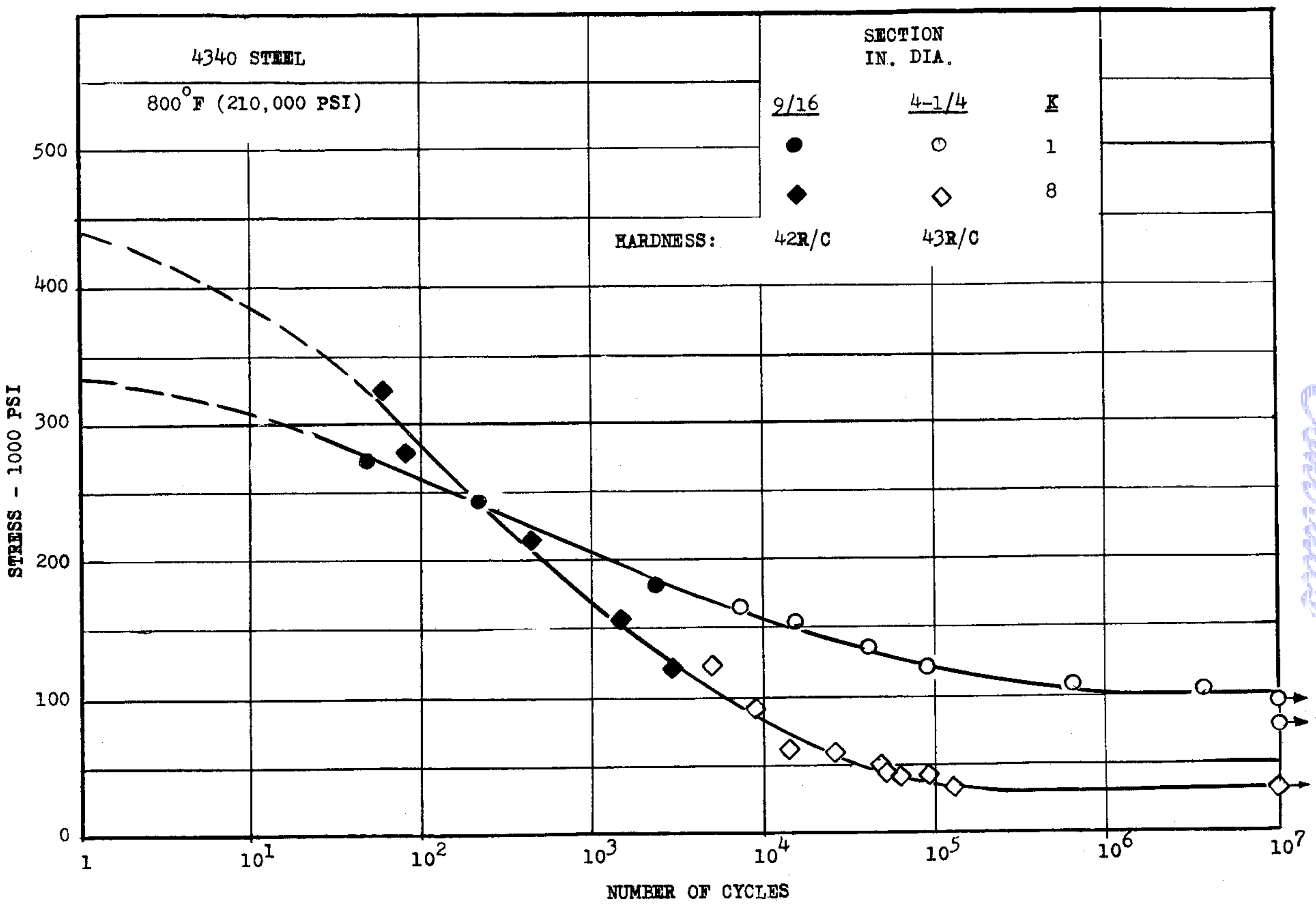


FIG. 46 S-N CURVES FOR SMOOTH & NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 4340 STEEL TEMPERED AT 800°F.

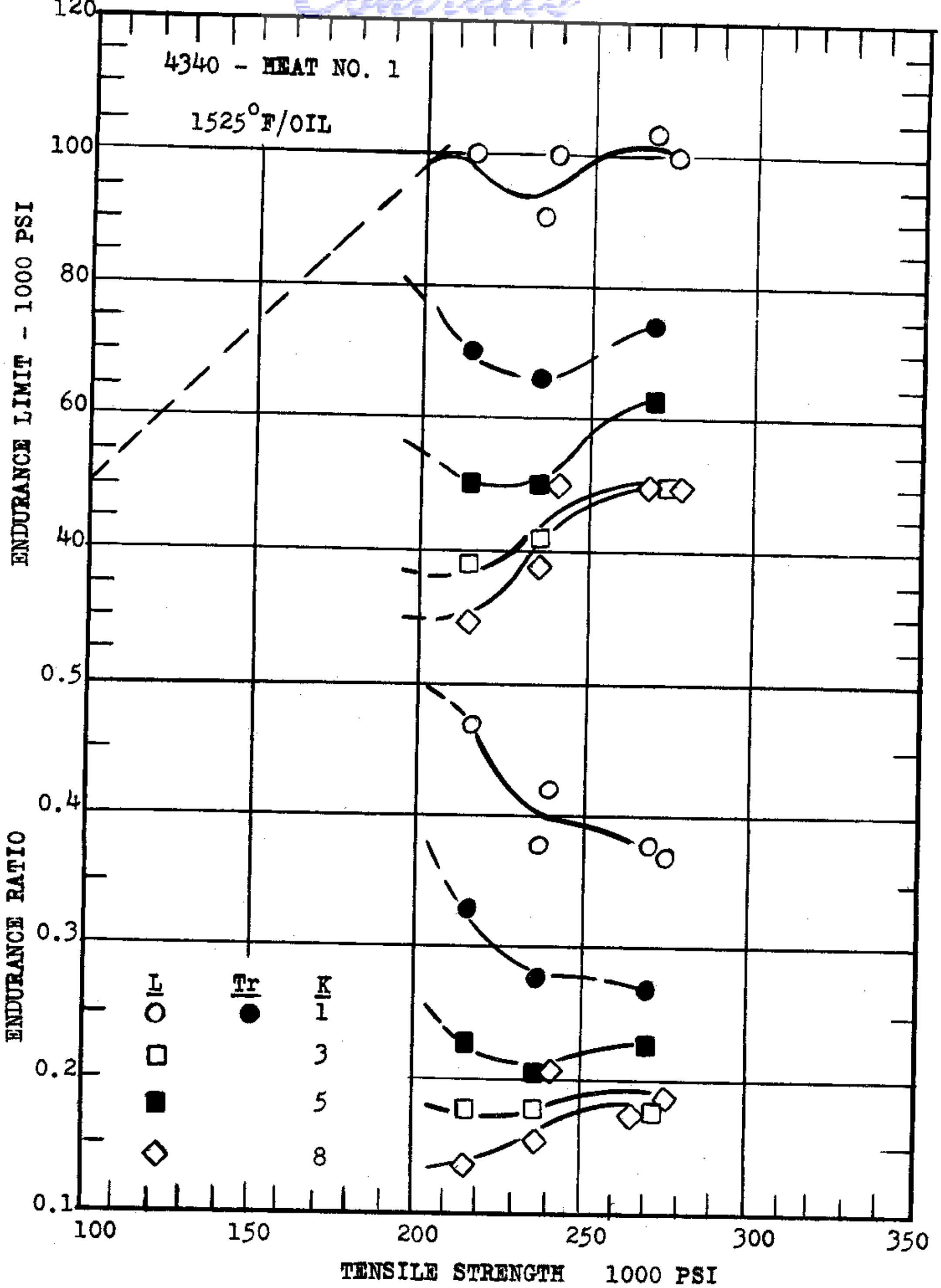
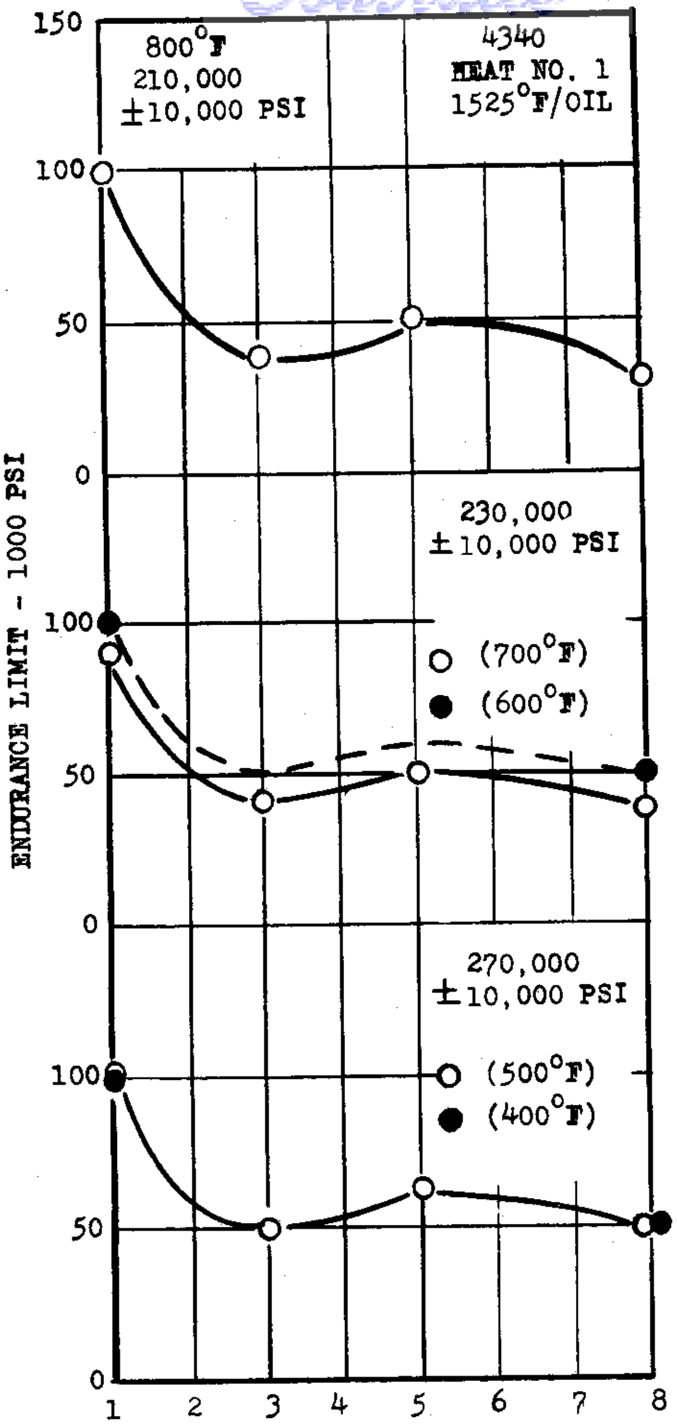


FIG. 47 VARIATION OF ENDURANCE LIMIT AND ENDURANCE RATIO WITH TENSILE STRENGTH.

SECTION: 4-1/4 IN. DIA.

SPECIMEN: ROTATING BEAM TYPE

TEST TEMP. R.T.



STRESS CONCENTRATION FACTOR, K

FIG. 48. EFFECT OF STRESS CONCENTRATION ON ENDURANCE LIMIT OF 4340 STEEL AT VARIOUS STRENGTH LEVELS.

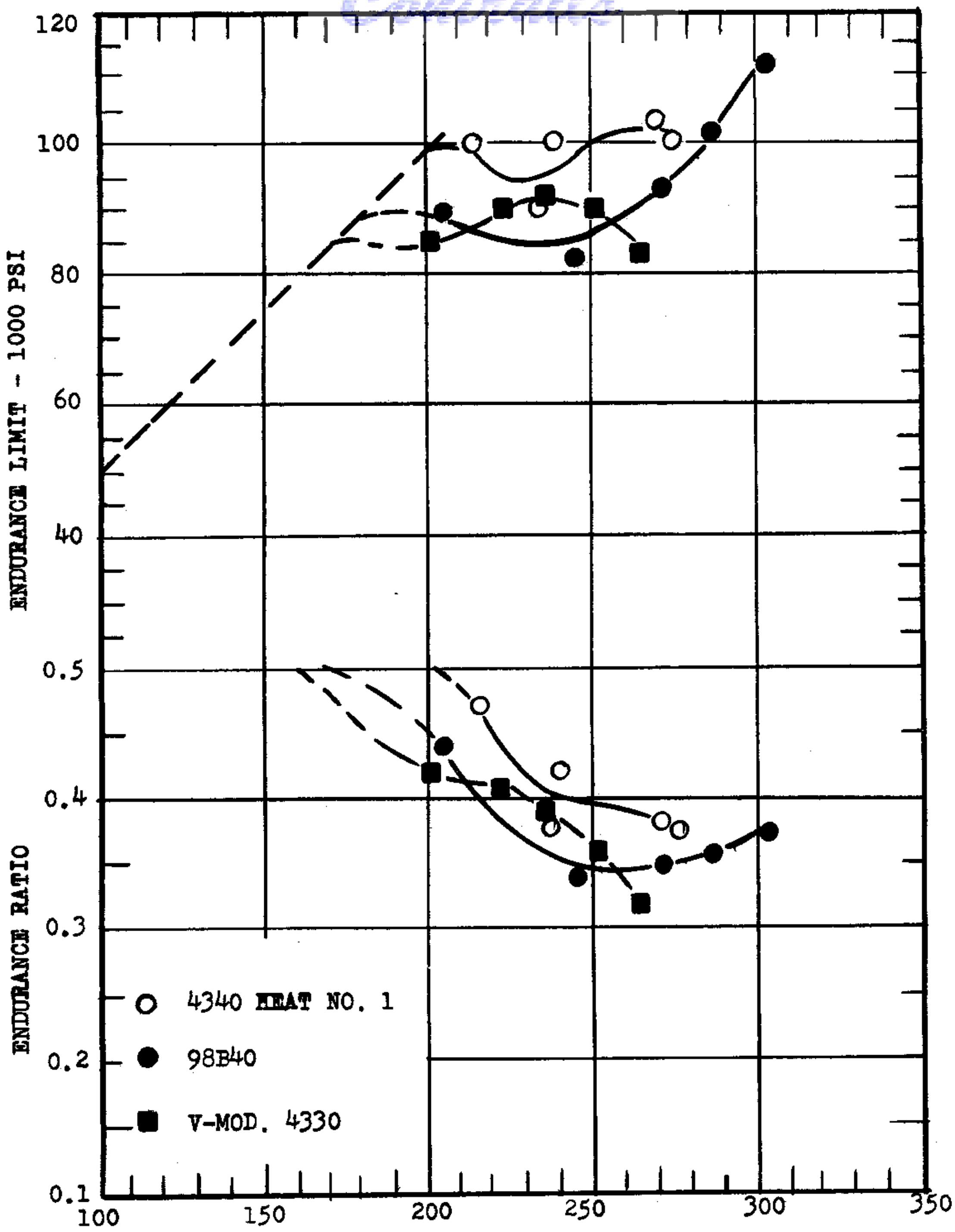


FIG. 49 VARIATION OF ENDURANCE LIMIT AND ENDURANCE RATIO WITH TENSILE STRENGTH FOR SMOOTH SPECIMENS FROM THREE HIGH-STRENGTH STEELS.

SPECIMEN: ROTATING BEAM TYPE

TEST TEMP.: R.T.

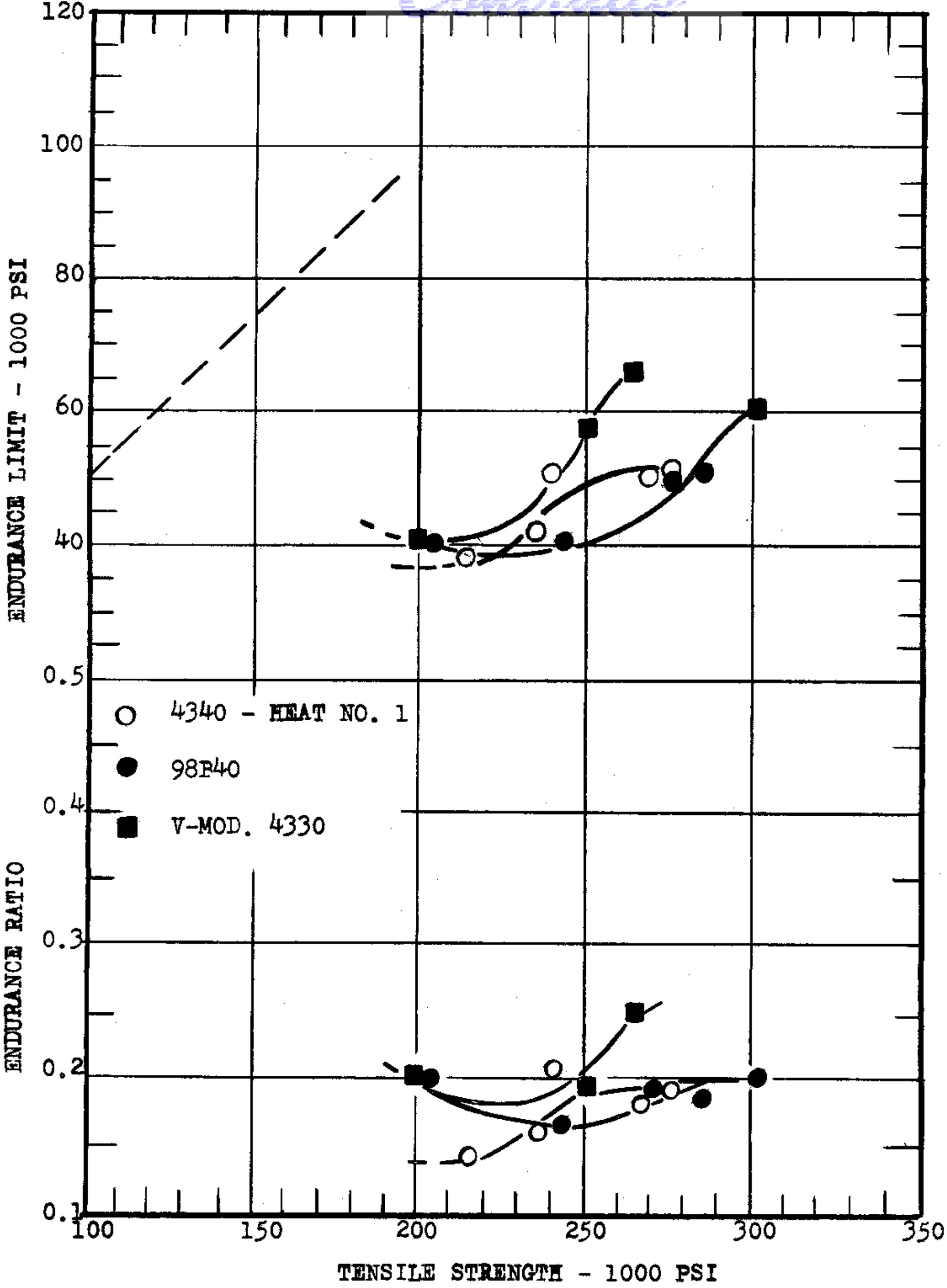


FIG. 50 VARIATION OF ENDURANCE LIMIT AND ENDURANCE RATIO WITH TENSILE STRENGTH FOR NOTCHED (K = 8) SPECIMENS FROM THREE HIGH-STRENGTH STEELS.

SPECIMEN: ROTATING BEAM TYPE.

TEST TEMP.: R.T.

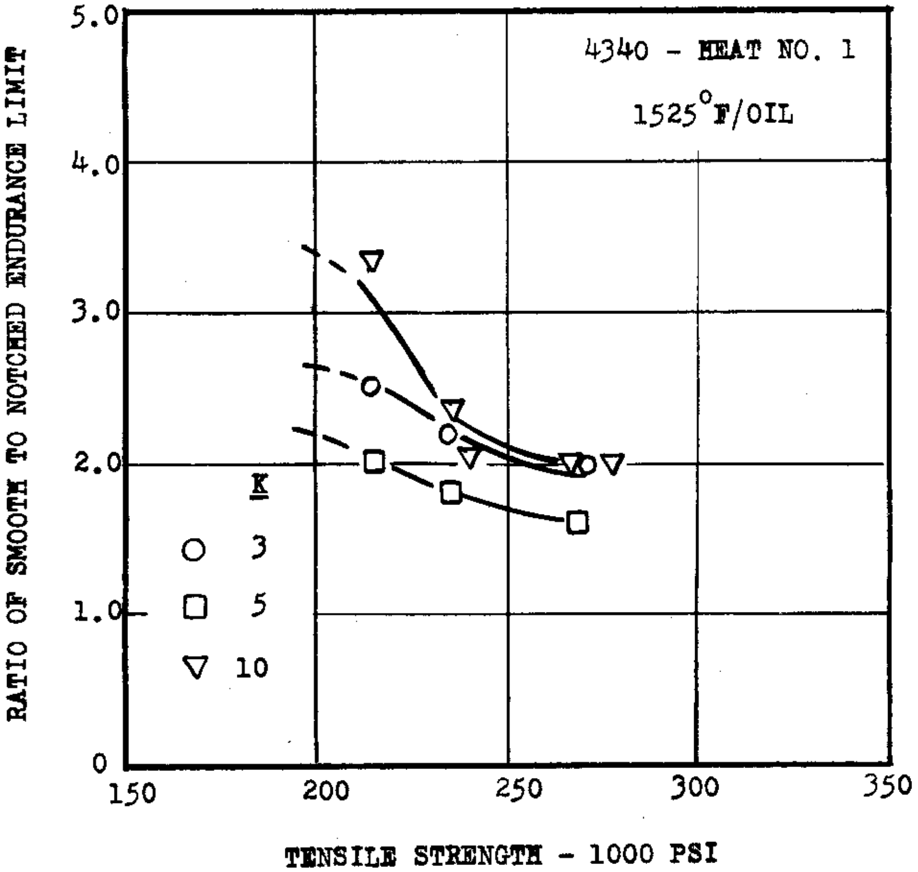


FIG. 51 EFFECT OF STRENGTH LEVEL ON RATIO OF SMOOTH TO NOTCHED ENDURANCE LIMIT.

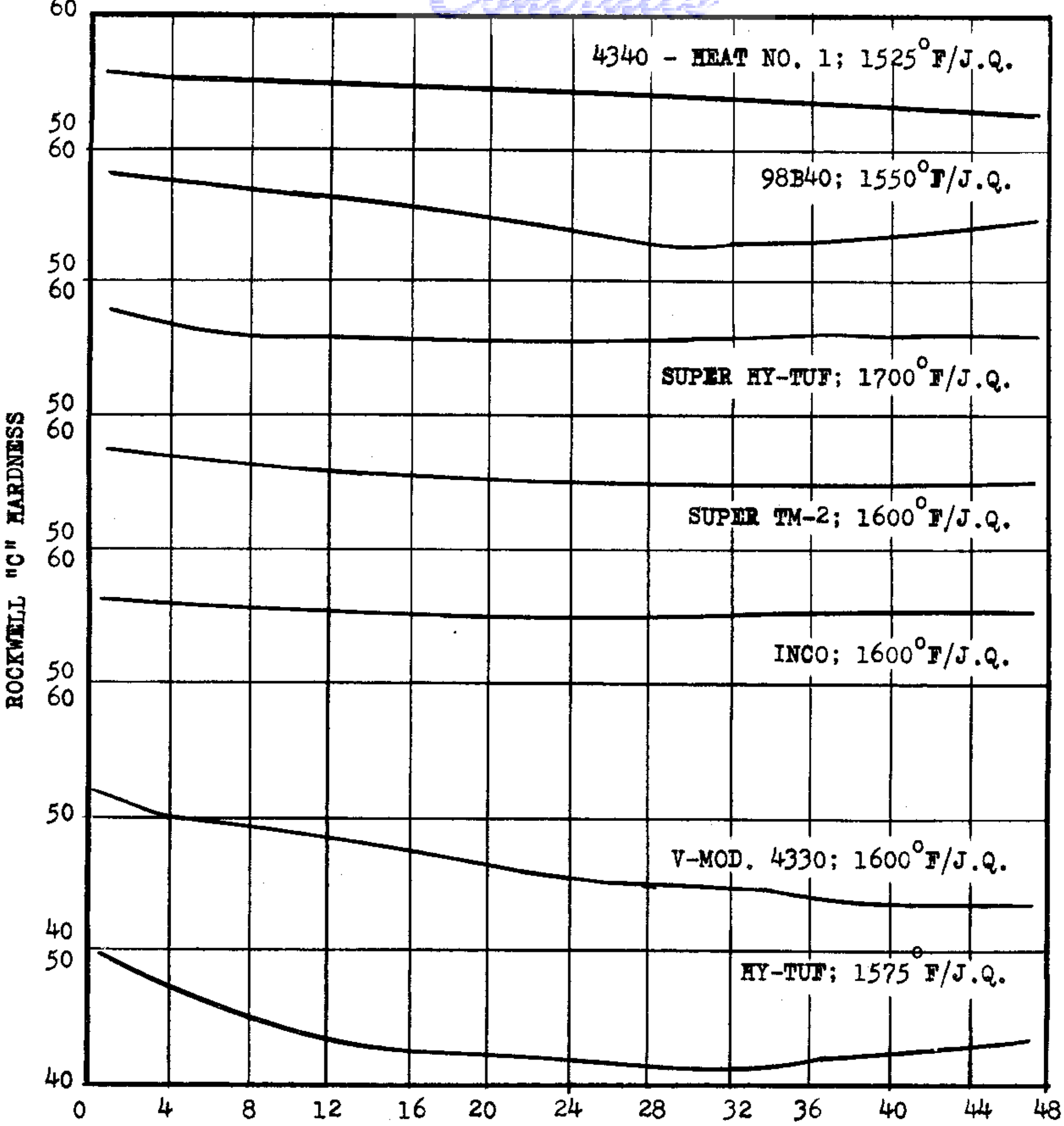


FIG. 52 JOMINY HARDENABILITY OF VARIOUS HIGH-STRENGTH STEELS.

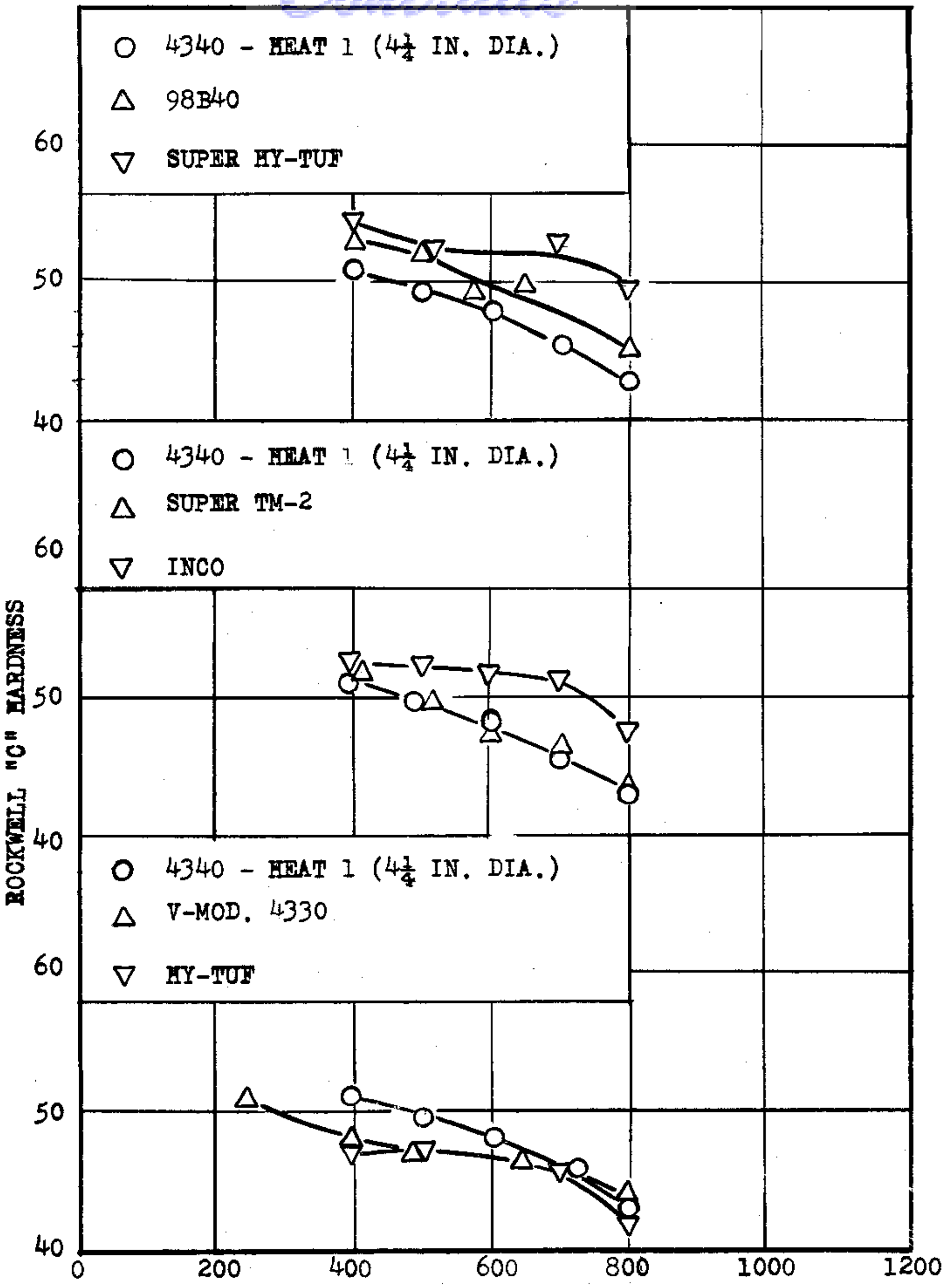


FIG. 53 HARDNESS OF 4340, 98B40, SUPER HY- TUF, SUPER TM-2, INCO, V-MOD. 4330 AND HY-TUF AS A FUNCTION OF TEMPERING TEMPERATURE.

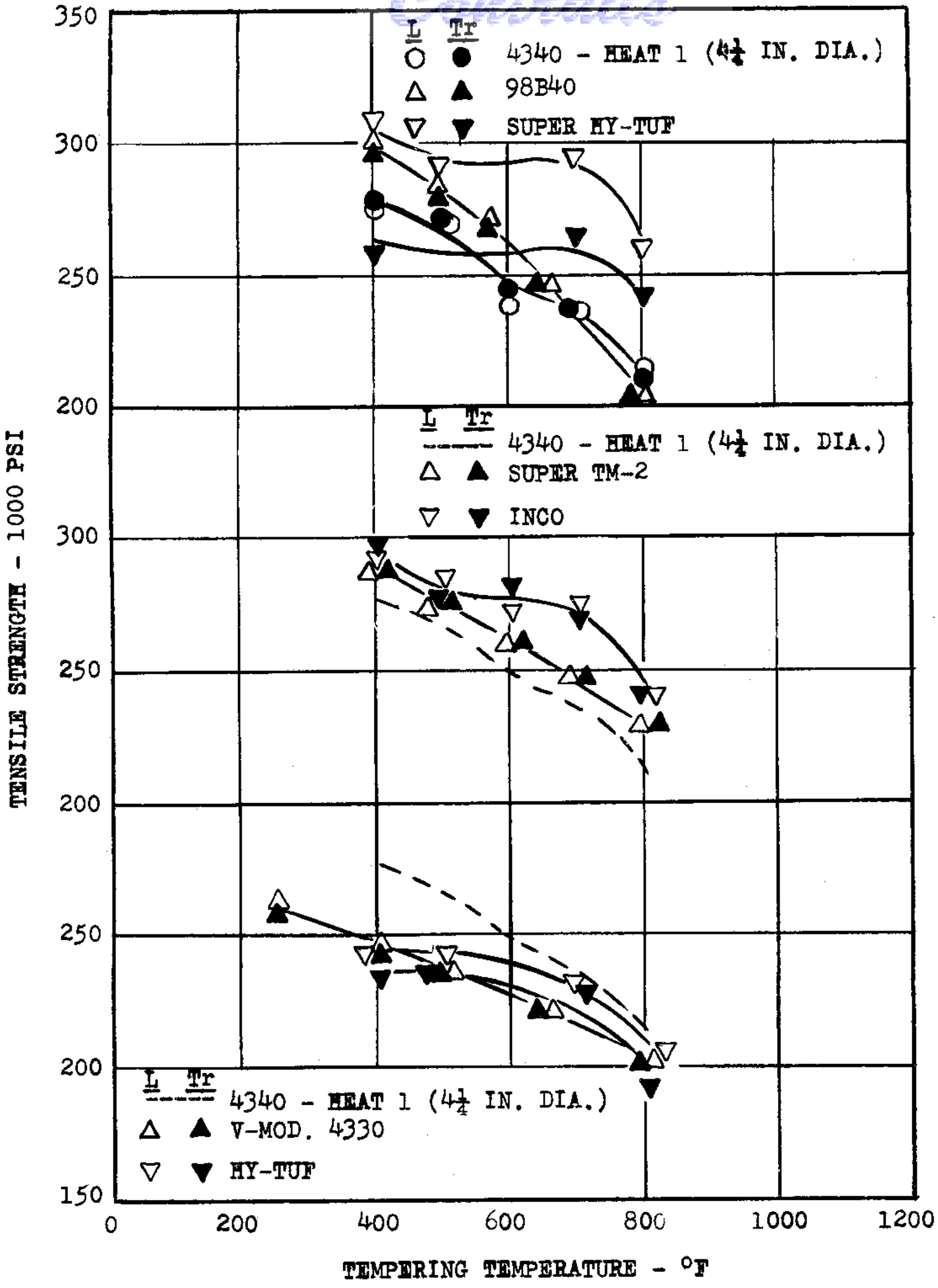


FIG. 54 TENSILE STRENGTH OF 4340, 98B40, SUPER HY-TUF, SUPER TM-2, INCO, V-MOD. 4330 AND HY-TUF AS A FUNCTION OF OF TEMPERING TEMPERATURE.

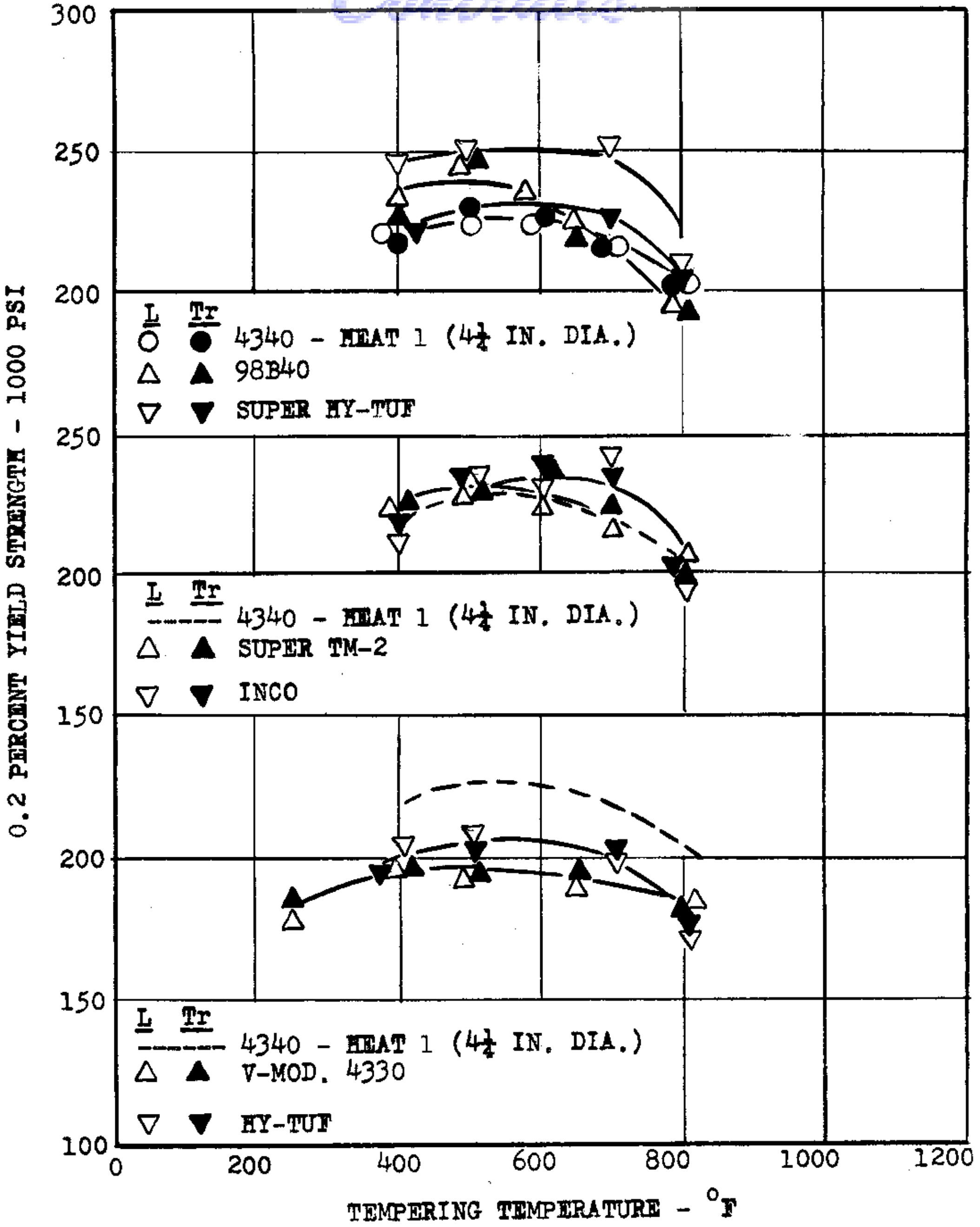


FIG. 55 YIELD STRENGTH OF 4340, 98B40, SUPER HY-TUF, SUPER TM-2, INCO, V-MOD. 4330 AND HY-TUF AS A FUNCTION OF TEMPERING TEMPERATURE.

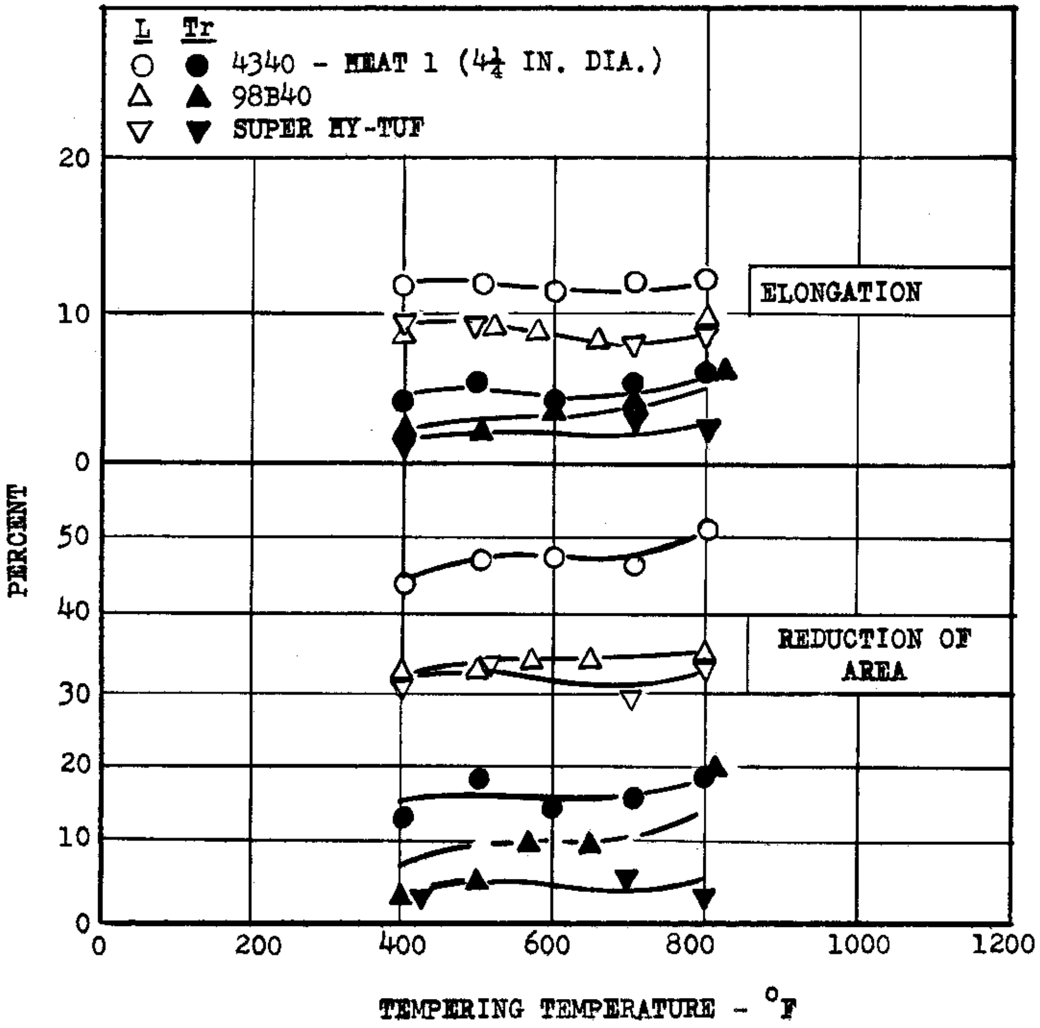


FIG. 56 EFFECT OF TEMPERING TEMPERATURE ON THE DUCTILITY OF 4340, 98B40 AND SUPER HY-TUF.

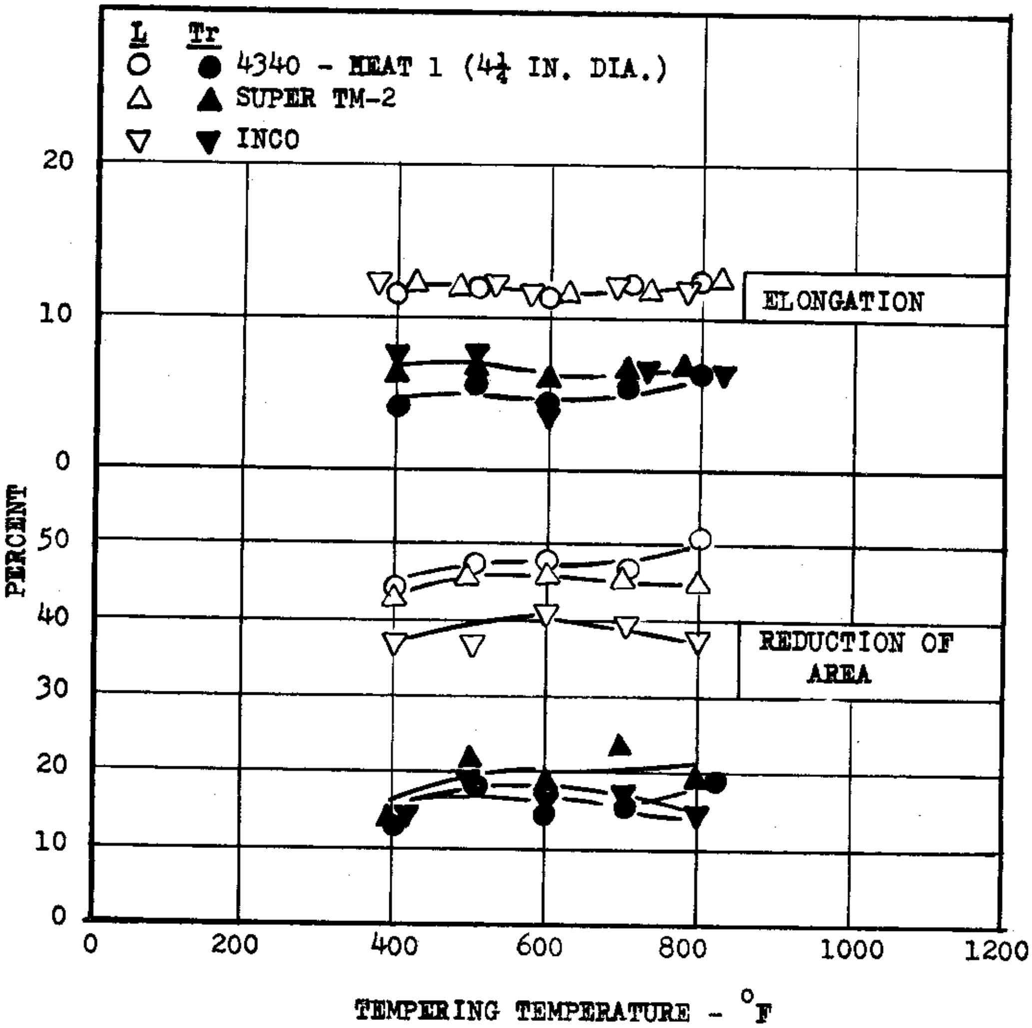


FIG. 57 EFFECT OF TEMPERING TEMPERATURE ON THE DUCTILITY OF 4340, SUPER TM-2 AND INCO.

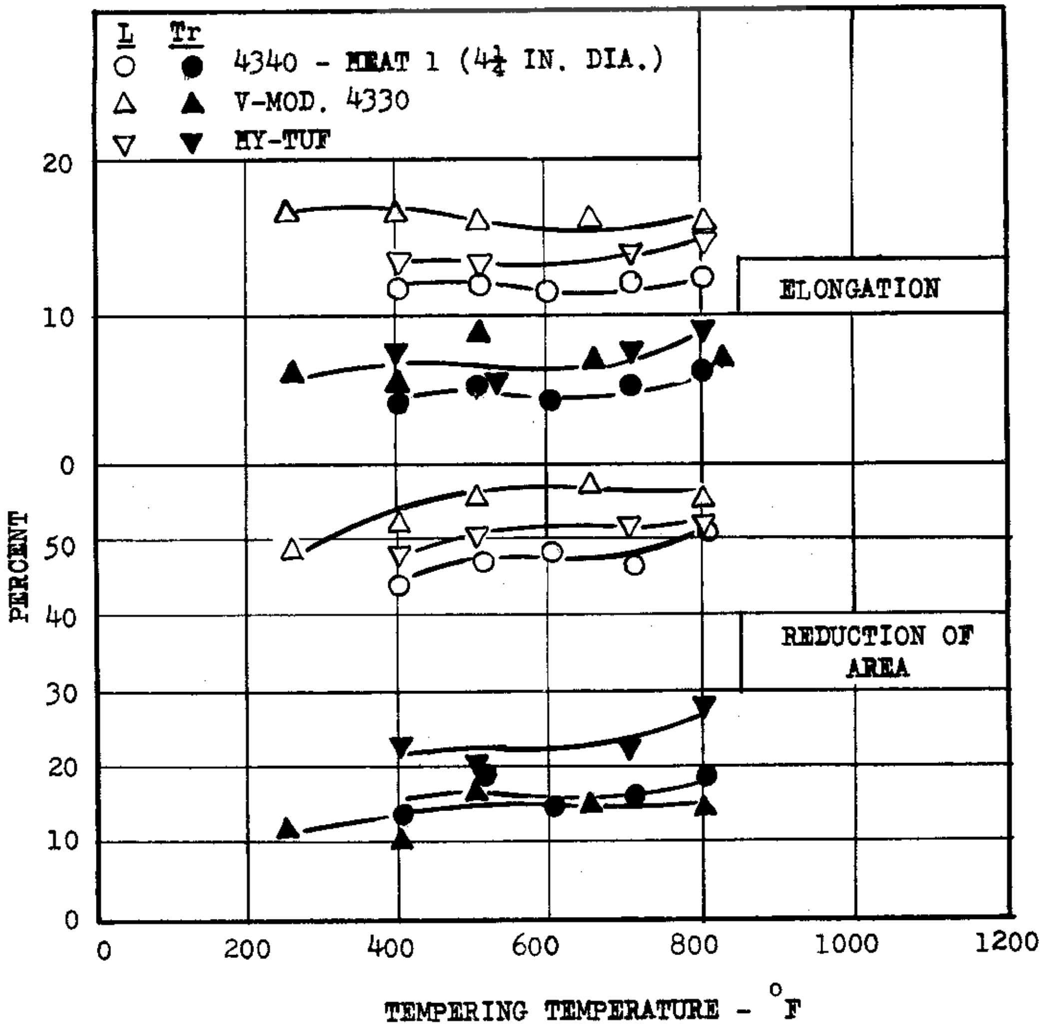


FIG. 58. EFFECT OF TEMPERING TEMPERATURE ON THE DUCTILITY OF 4340, V-MOD. 4330 AND HY-TUF.

4340 HEAT 1 (4¼ IN. DIA.)
98B40

210,000 ± 10,000 PSI

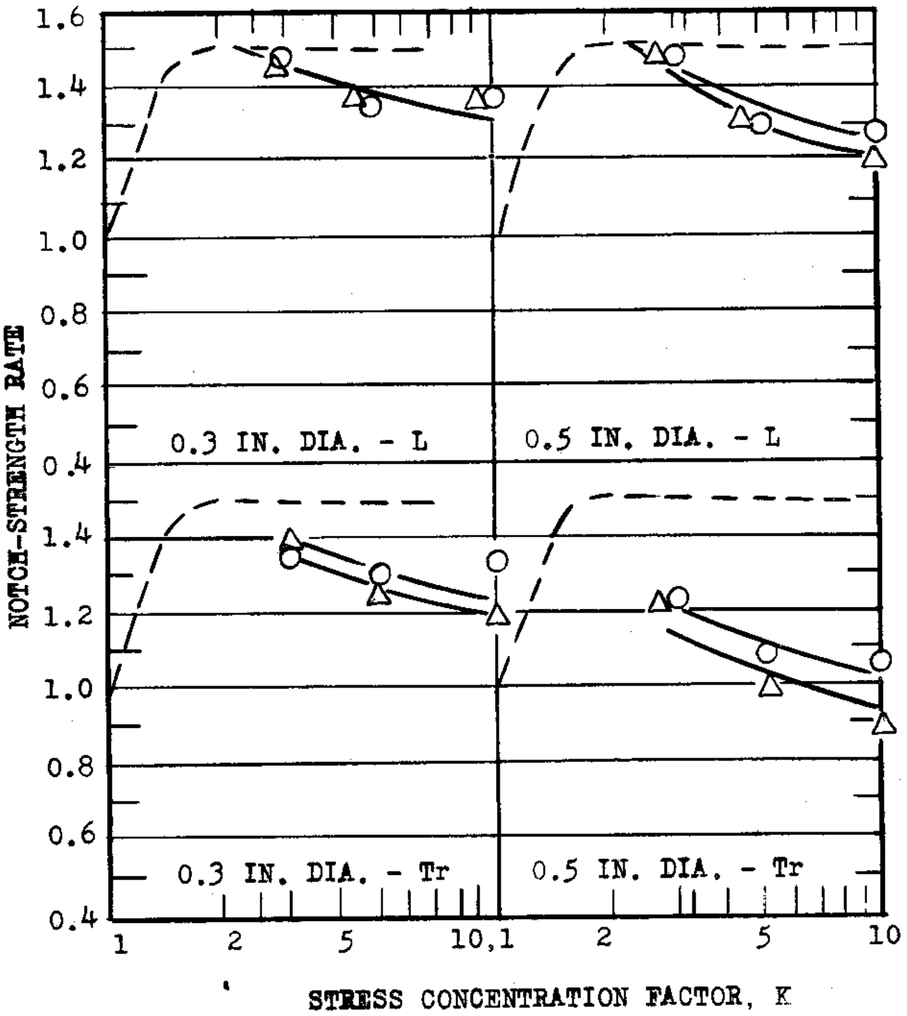


FIG. 59 EFFECT OF STRESS CONCENTRATION ON THE NOTCH STRENGTH RATIO OF 4340 AND 98B40 AT APPROX. 210,000 PSI.

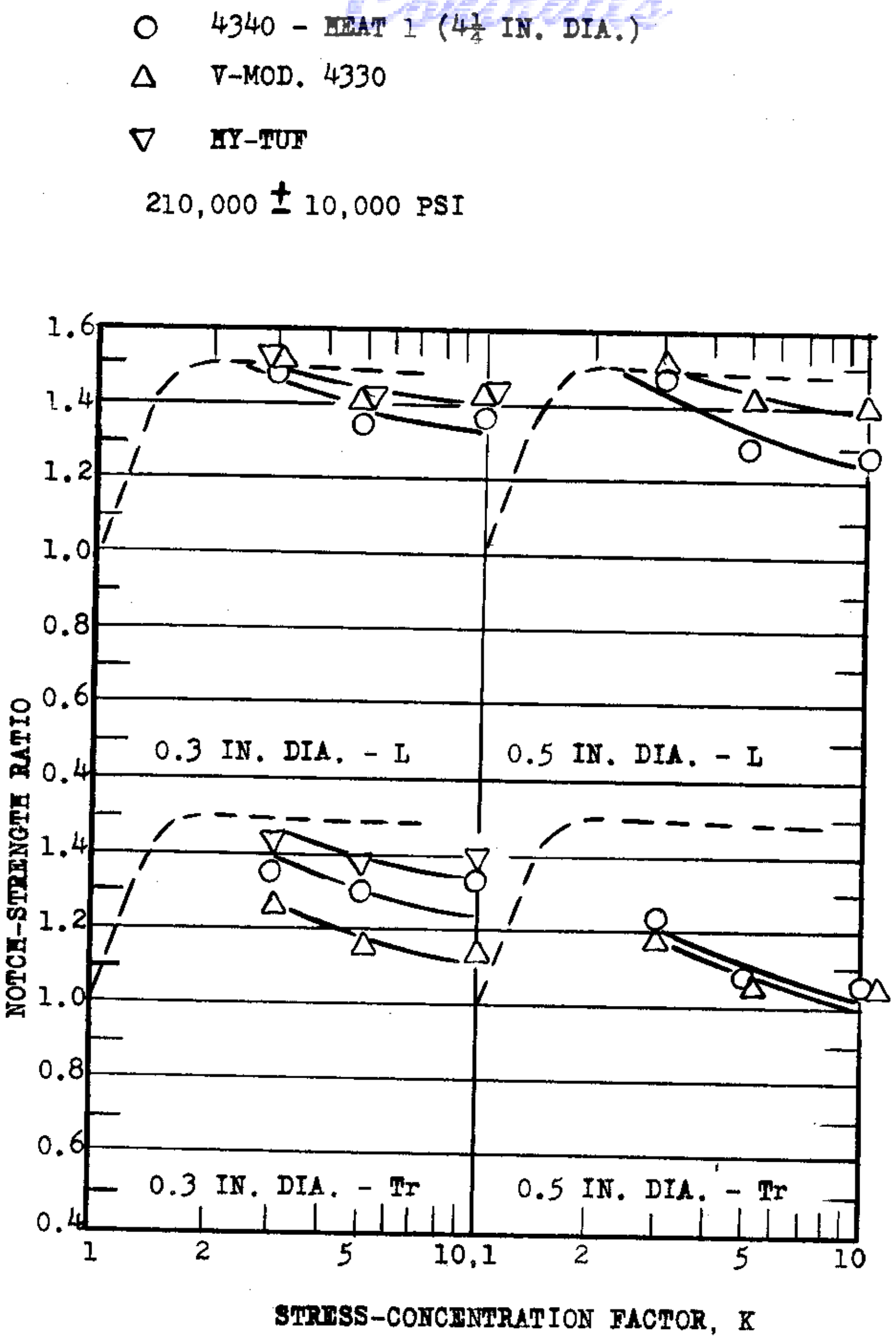


FIG. 60 **EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, V-MOD. 4330 AND HY-TUF AT APPROX. 210,000 PSI.**

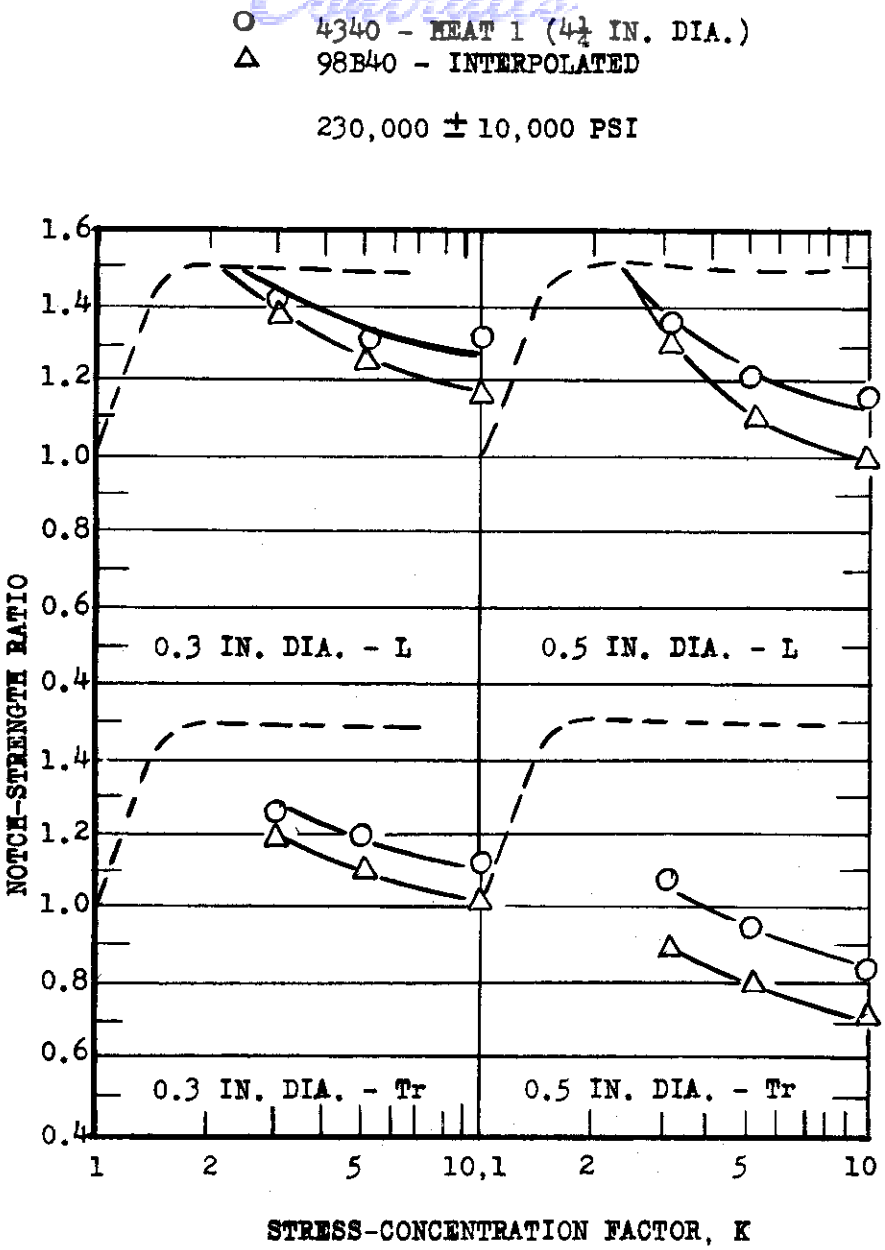


FIG. 61 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340 AND 98B40 AT APPROX. 230,000 PSI.

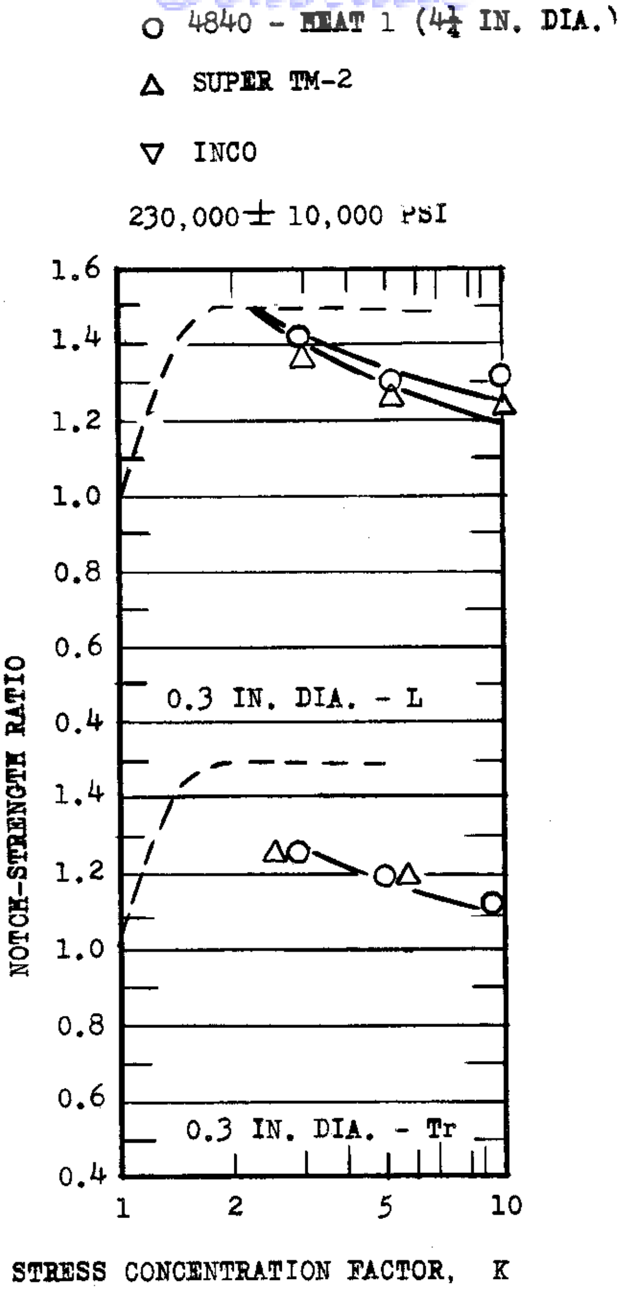


FIG. 62 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, SUPER TM-2 AND INCO AT APPROX. 230,000 PSI.

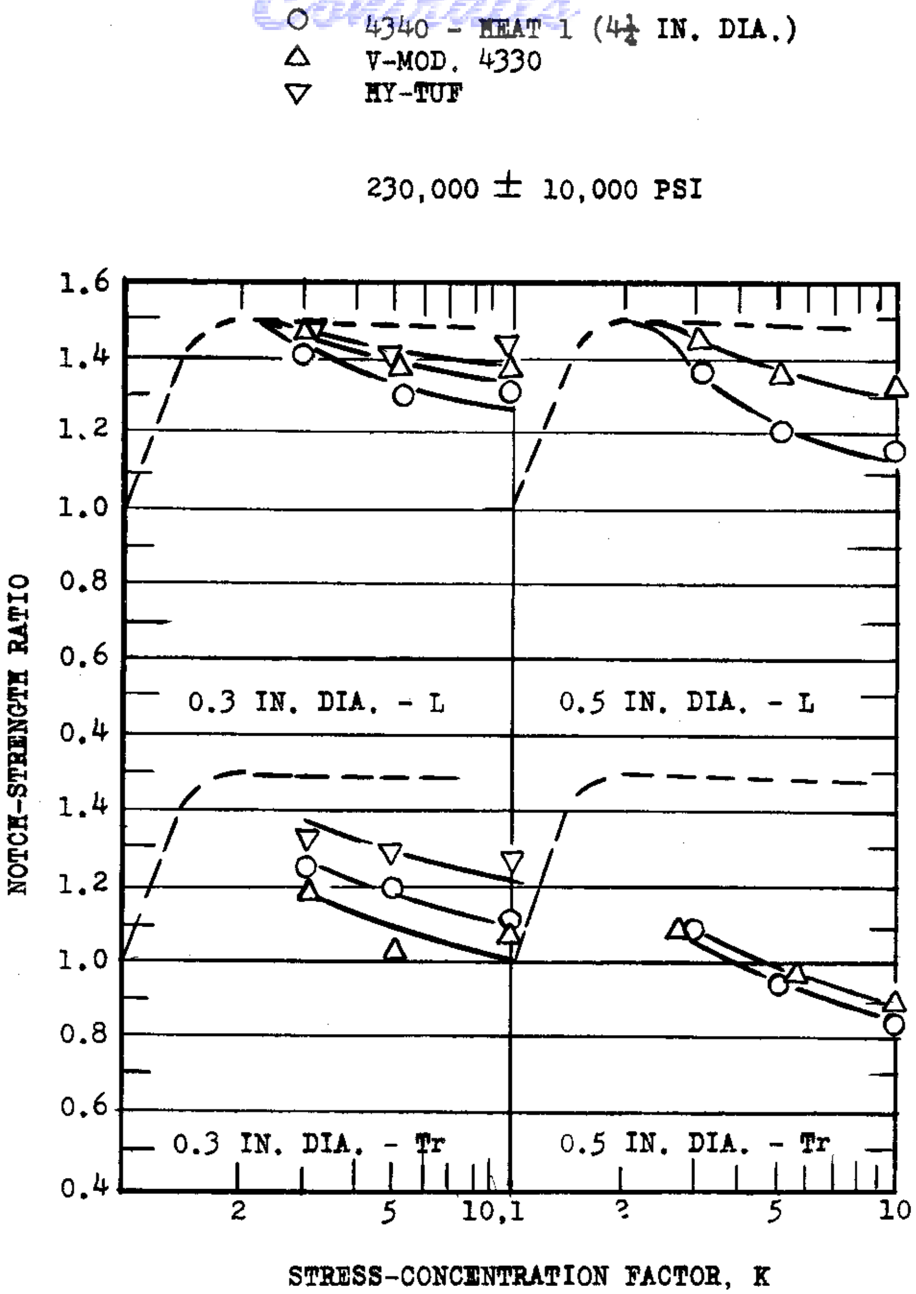


FIG. 63 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, V-MOD. 4330 AND HY-TUF AT APPROX. 230,000 PSI.

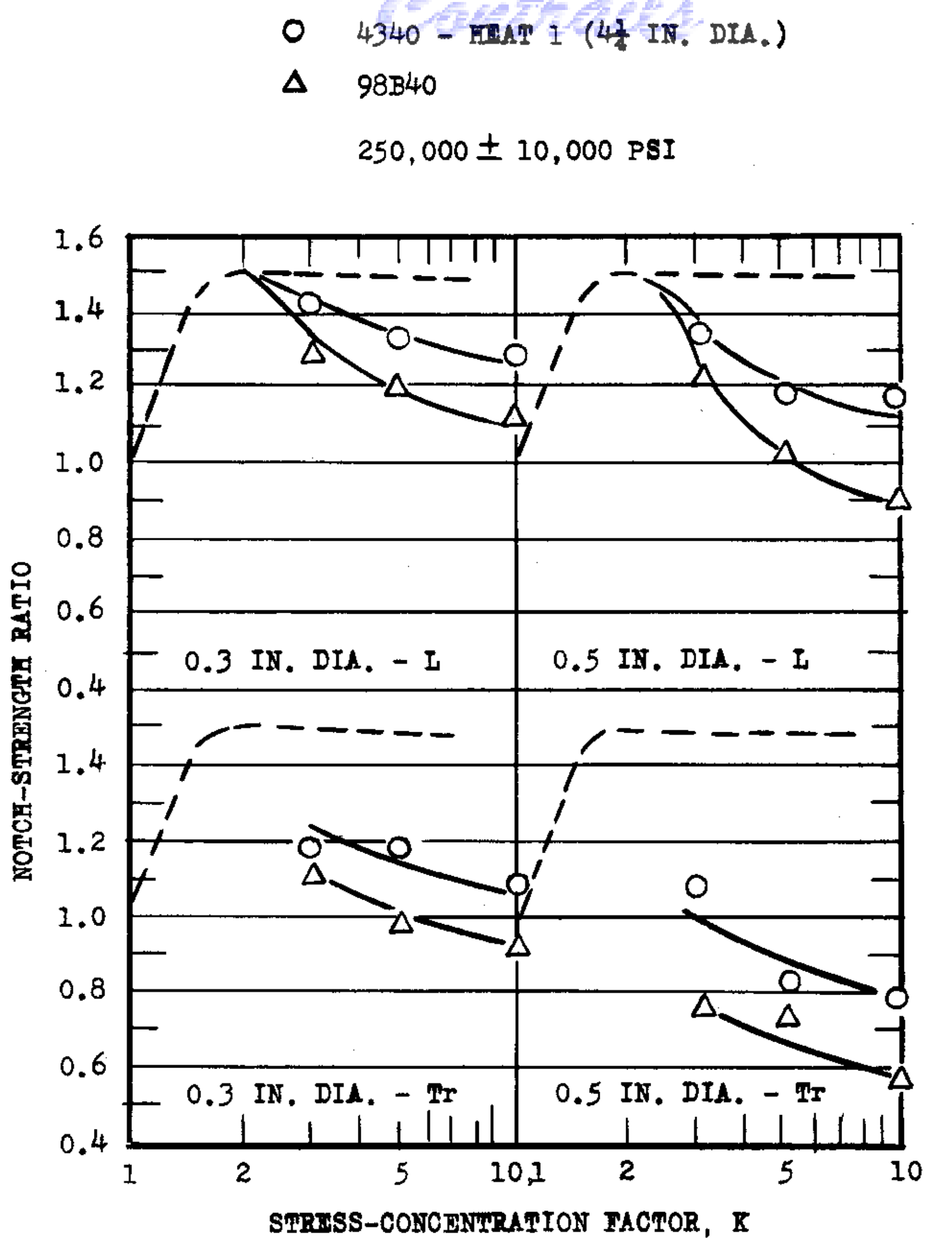


FIG. 64 EFFECT OF STRESS CONCENTRATION ON THE NOTCH STRENGTH RATIO OF 4340 AND 98B40 AT APPROX. 250,000 PSI.

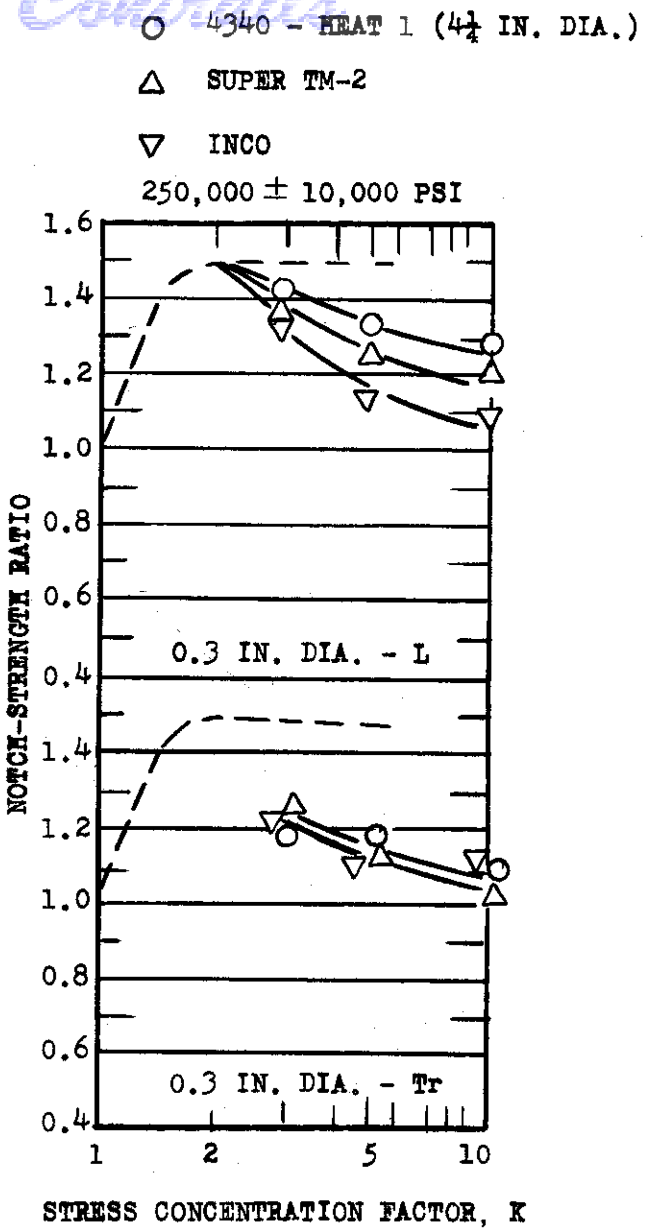


FIG. 65 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, SUPER TM-2 AND INCO AT APPROX. 250,000 PSI.

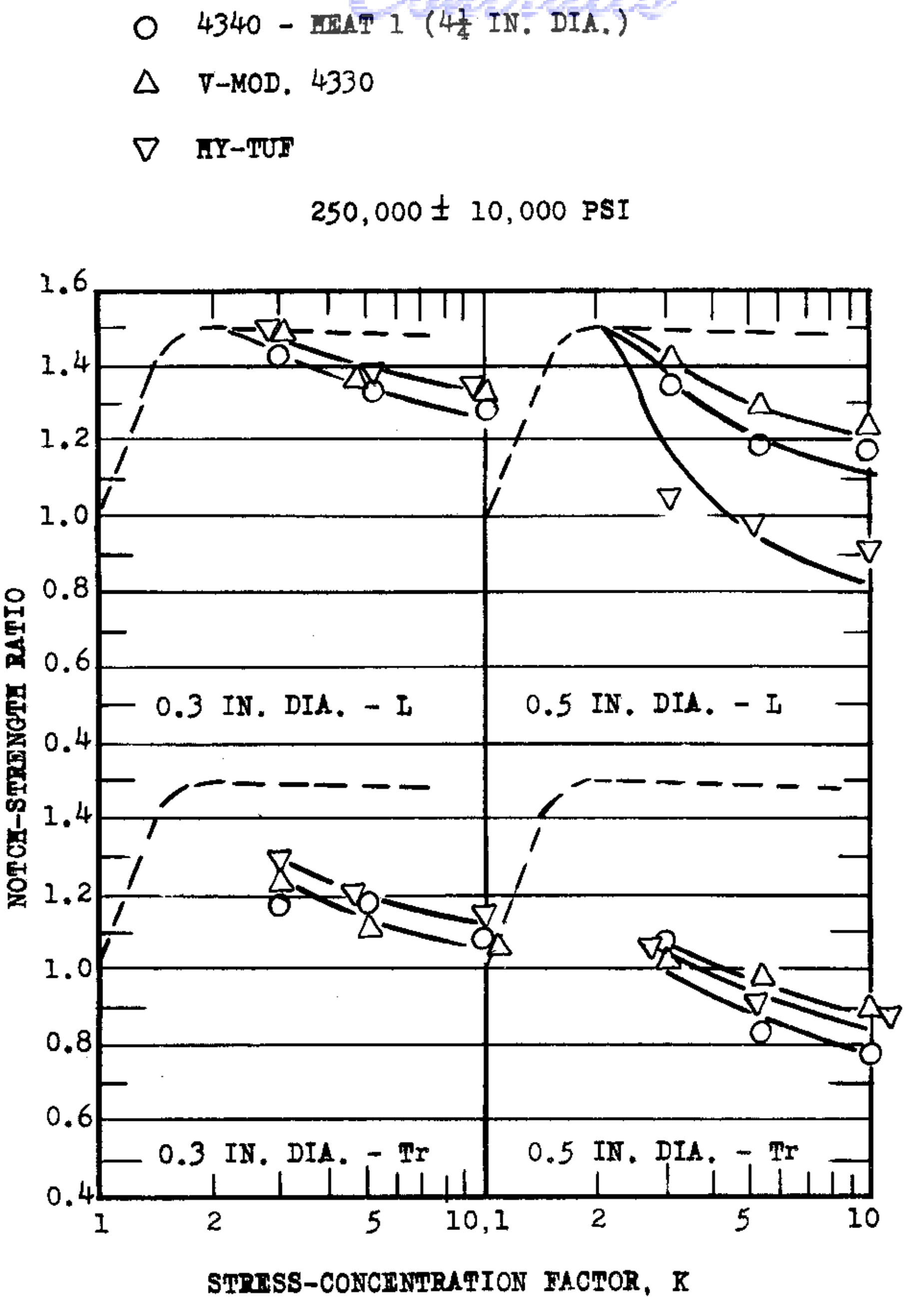


FIG. 66 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, V-MOD. 4330 AND HY-TUF AT APPROX. 250,000 PSI.

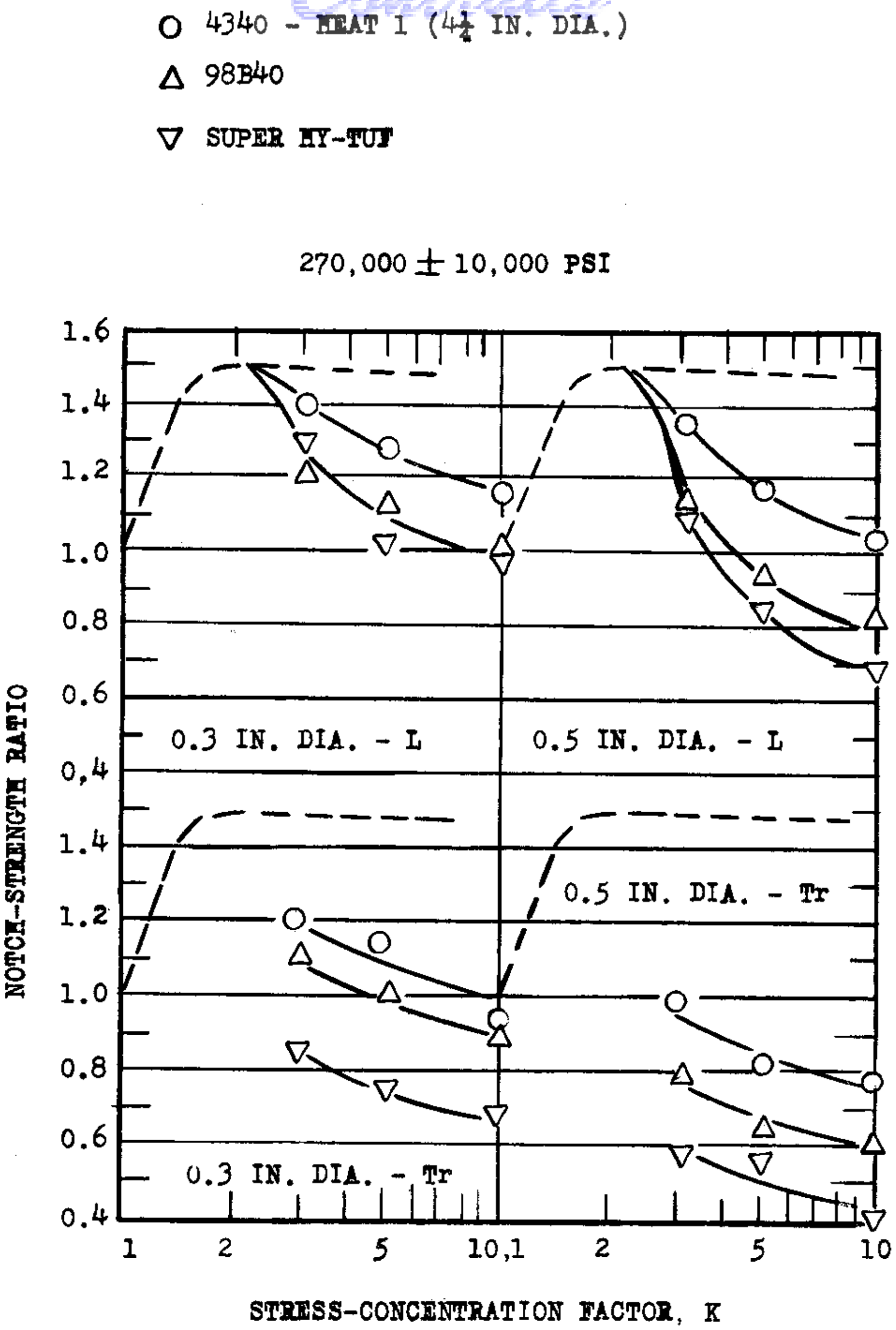


FIG. 67 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, 98B40 AND SUPER HY-TUF AT APPROX. 270,000 PSI.

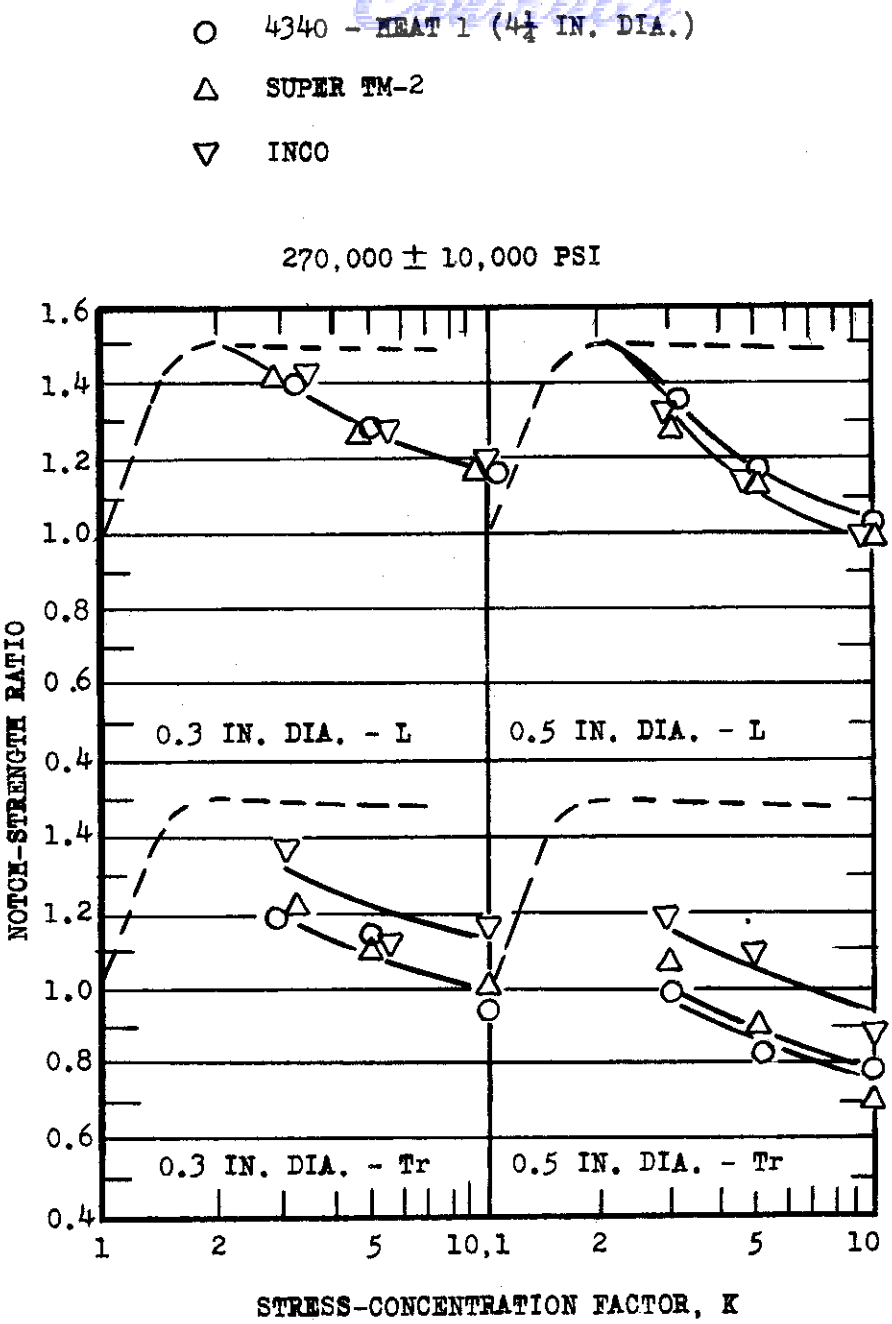


FIG. 68 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340, SUPER TM-2 AND INCO AT APPROX. 270,000 PSI.

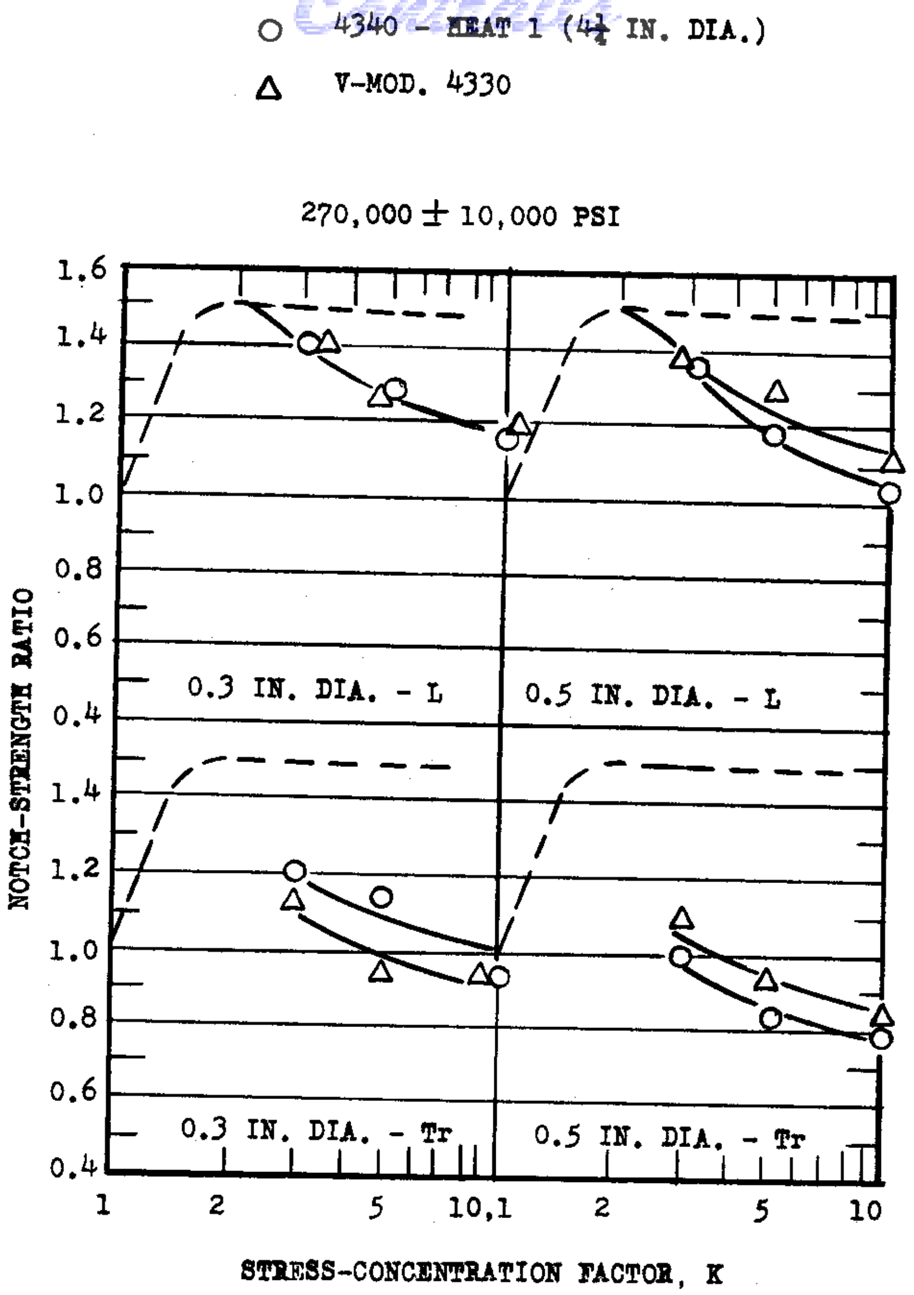


FIG. 69 EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF 4340 AND V-MOD. 4330 AT APPROX. 270,000 PSI.

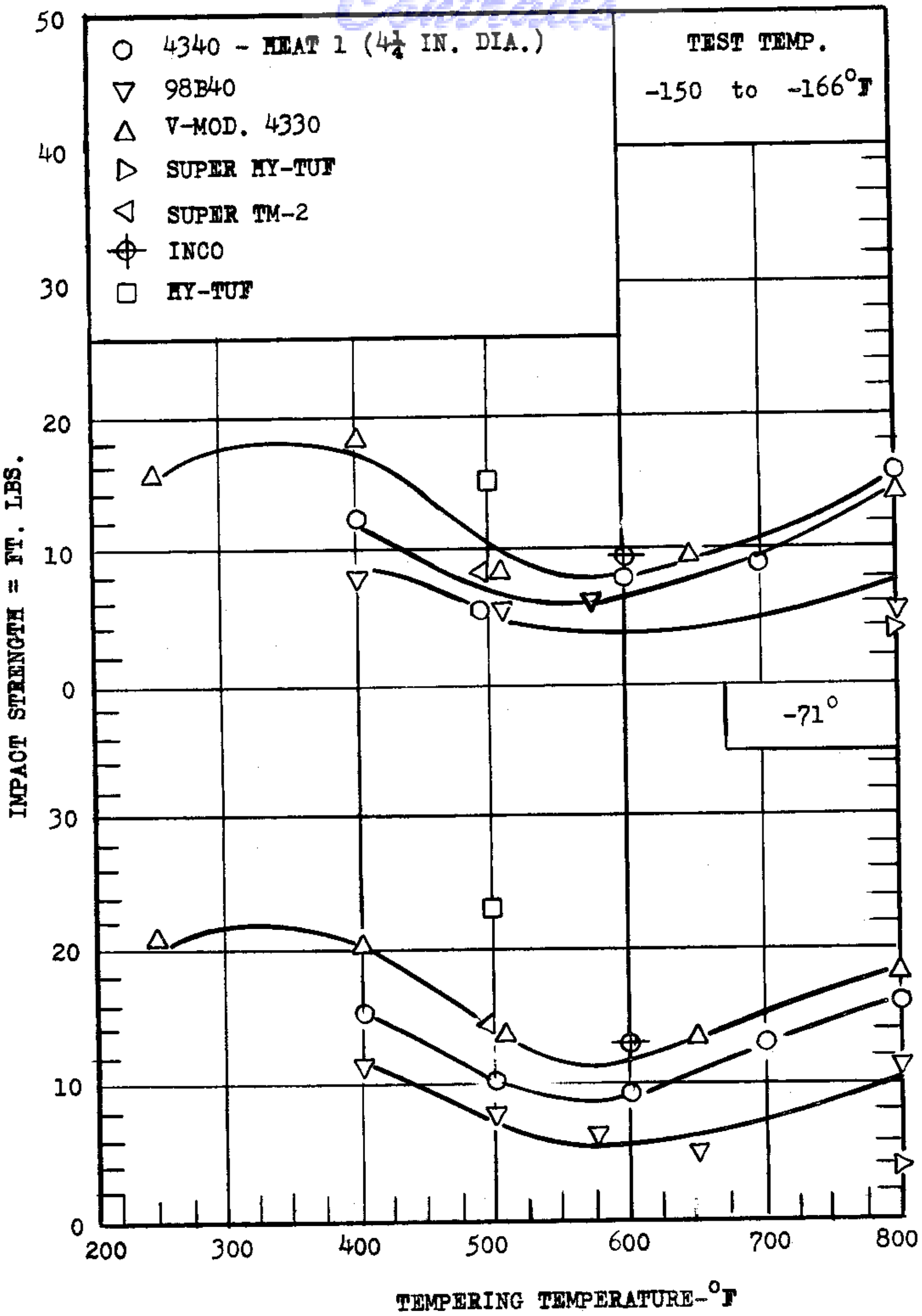


FIG. 70 VARIATION OF LONGITUDINAL IMPACT STRENGTH OF A NUMBER OF ALLOYS WITH TEMPERING TEMPERATURE.

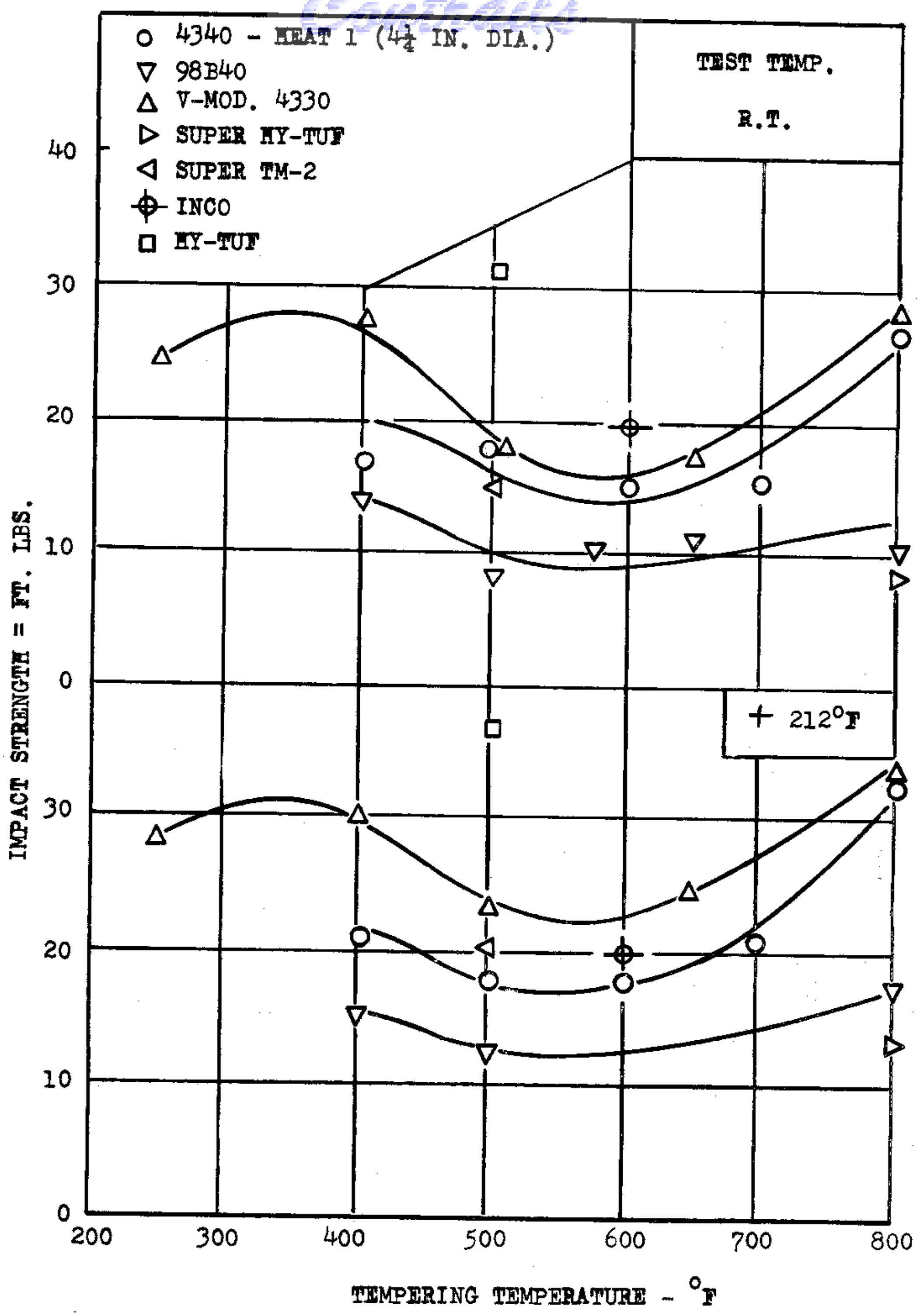


FIG. 71 VARIATION OF LONGITUDINAL IMPACT STRENGTH OF A NUMBER OF ALLOYS WITH TEMPERING TEMPERATURE.

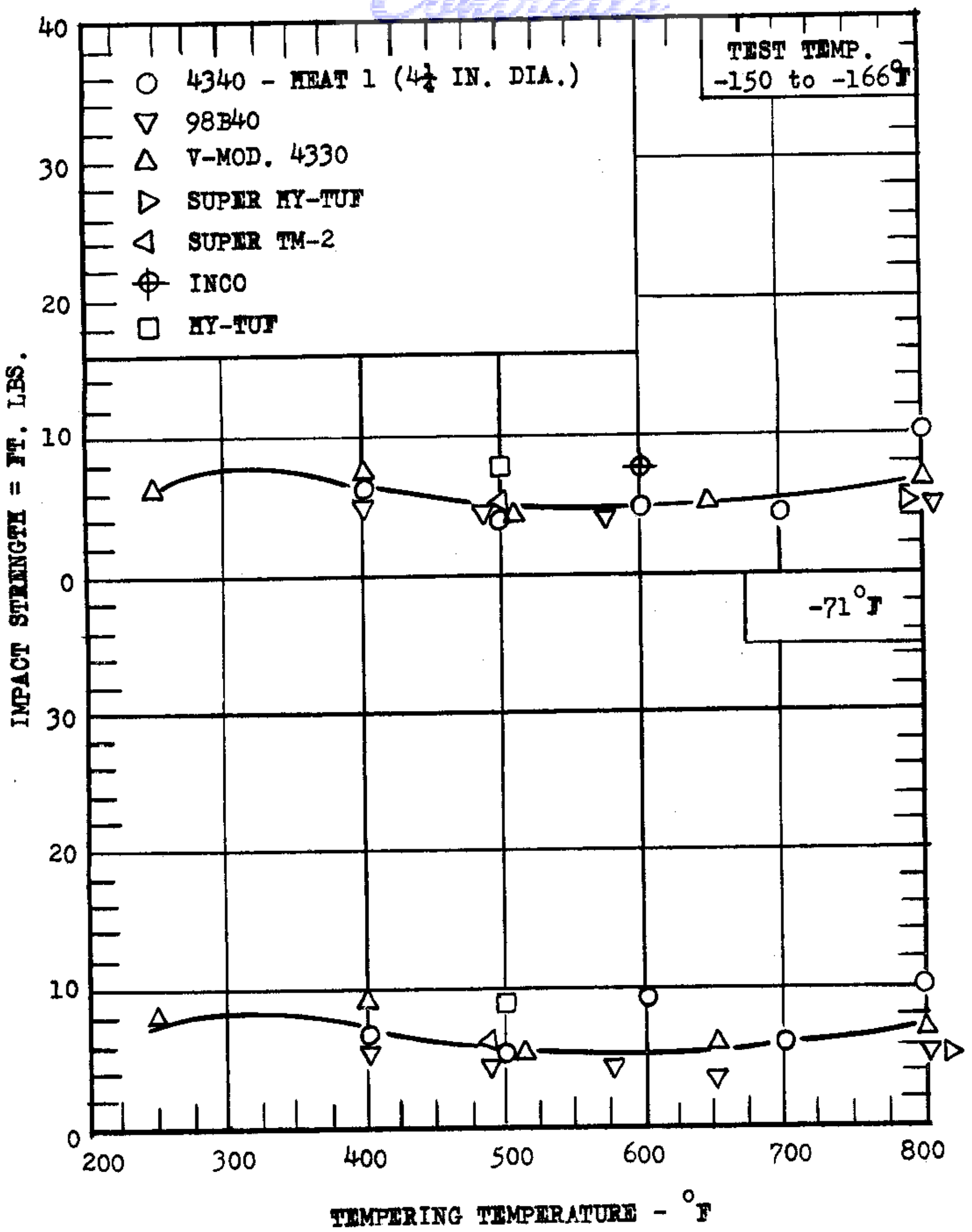


FIG. 72 VARIATION OF TRANSVERSE IMPACT STRENGTH OF A NUMBER OF ALLOYS WITH TEMPERING TEMPERATURE.

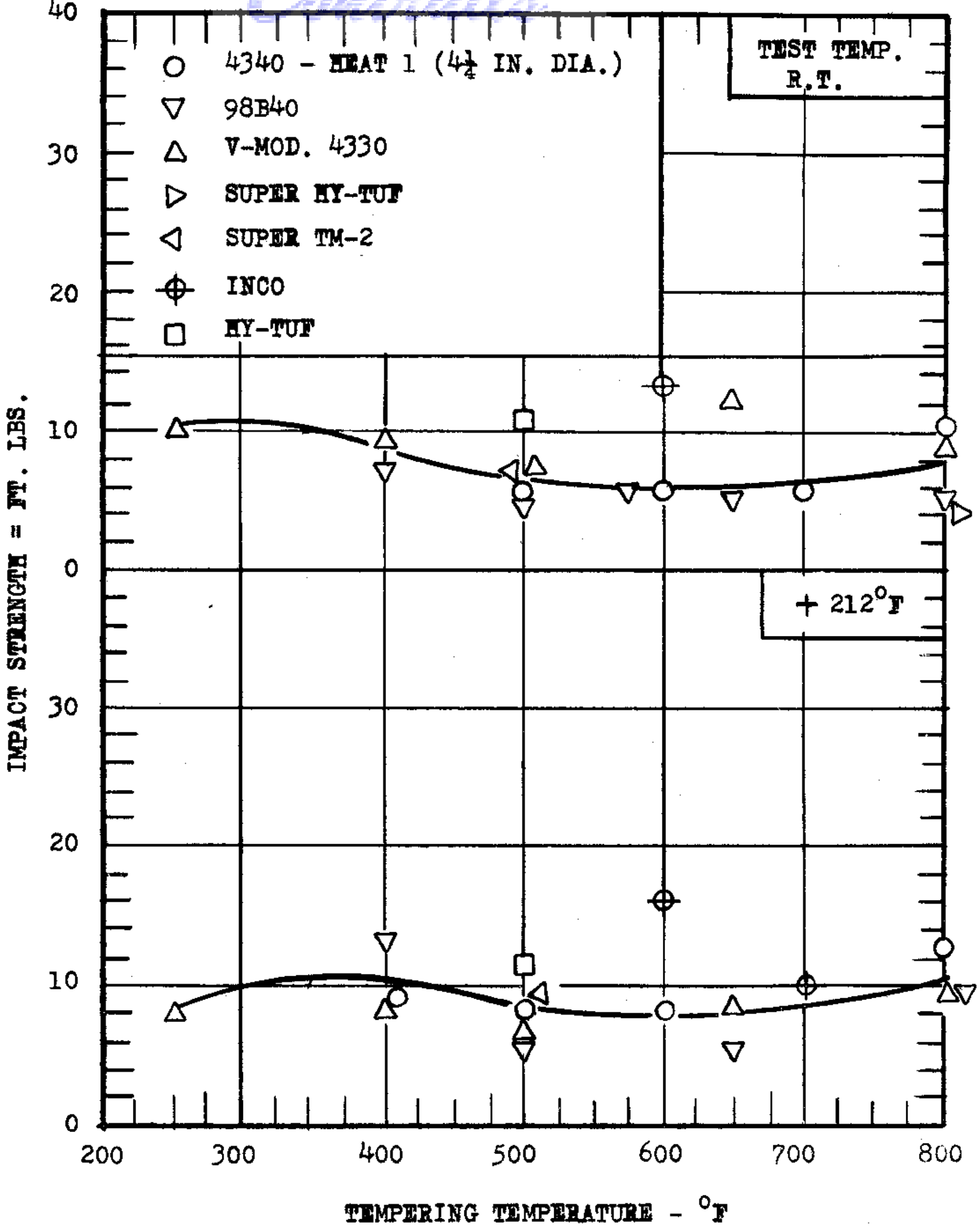


FIG. 73 VARIATION OF TRANSVERSE IMPACT STRENGTH OF A NUMBER OF ALLOYS WITH TEMPERING TEMPERATURE.

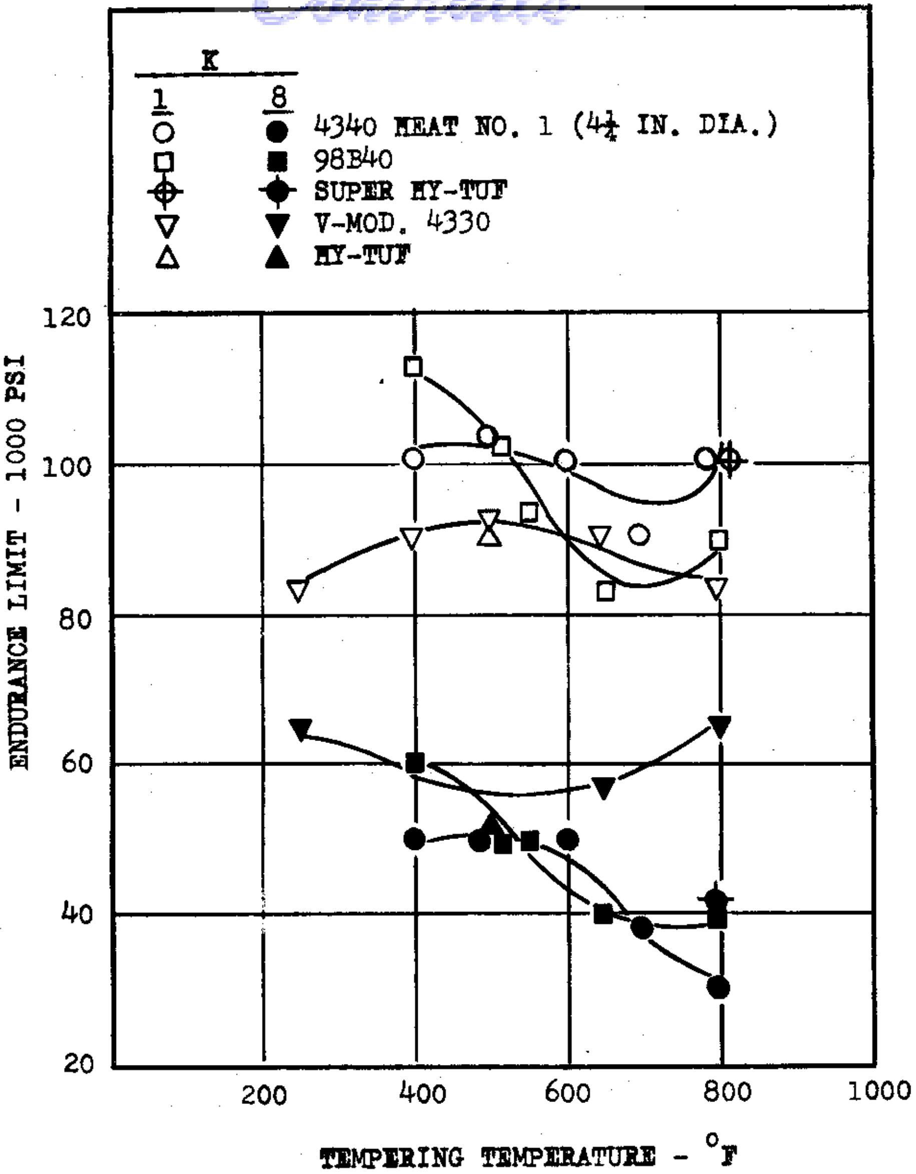


FIG. 74 EFFECT OF TEMPERING TEMPERATURE ON THE ENDURANCE LIMIT OF A NUMBER OF ALLOYS.