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TI-1508

WADC TECHNICAL REPORT 53-254
Part 4 AD 045 578

SURVEY OF LOW-ALLOY AIRCRAFT STEELS HEAT TREATED TO HIGH-STRENGTH LEVELS

Pt. 4 High-Strength Steels and Their General Static Properties

George Sachs

Syracuse University

December 1953

Statement A
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WRIGHT AIR DEVELOPMENT CENTER

20030822038

WADC TECHNICAL REPORT NO. 53-254 August 1954
Part 4

[redacted]

ERRATA-January 1955

The following corrections are applicable to WADC Technical Report 53-254, Part 4, "Survey of Low-Alloy Aircraft Steels Heat Treated to High-Strength Levels," dated August, 1954:

Page 28, Section 31, Paragraph 1, Line 12

Change the word "higher" to "lower."

Page 39, Section 42, Paragraph 4, Line 3

Delete "often heat treated."

Page 45, Lines 11, 23, and 32

Change "Figure 12 to Figure 11."

Page 90

Change "Auerbach to "Averbach."

Page 97, Figure 19

Interchange circles and triangles in composition code.

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

AF-WP-(B)-O-11 FEB 55 400

WADC TECHNICAL REPORT 53-254
Part 4

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Pt. 4 High-Strength Steels and Their General Static Properties

George Sachs

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December 1953

Materials Laboratory
Contract No. AF 33(616)-392
RDO No. 614-13

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Syracuse University, under USAF Contract No. AF 33(616)-392. The contract was initiated under Research and Development Order 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. E. Dugger acting as project engineer.

ABSTRACT

Part 4 presents a general discussion of the factors which determine the selection of high-strength steels and assembles the data available for their static-strength and design characteristics. In addition, the information available on the effects of the numerous variables encountered in making, shaping and heat treating low-alloy steels and their significance for the strength properties of aircraft parts is discussed.

The regular strength characteristics of the steels, and especially their tensile strength, yield strength, elongation and reduction of area, reveal no indication of an embrittlement of steels heat treated to strength values in excess of 200,000, in general, and of those tempered at temperatures between 500 and 750^{o}F, in particular. However, there is some indication that at very low testing temperatures steels heat treated within this tempering range also may exhibit a comparatively low ductility.

The response of static strength properties to other factors which adversely affect their performance, such as section size of slack quenching, is also limited and the practical significance of such effects is not clarified.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. E. Sorte
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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A. CONSTRUCTIONAL HEAT-TREATED STEELS AND THEIR STRENGTH LIMITATIONS

1. Definition of Constructional Heat-Treated Steels

The largest tonnage of alloy steels is of types containing 0.25 to 0.55 percent carbon (or less if to be carburized) and being heat treated by quenching and tempering for high strength and toughness. These steels are widely used in automotive and aircraft work.

The primary purpose of tempering is to impart to the steel a certain degree of ductility and toughness, in contrast to the brittleness of the condition resulting from the quenching operation. The hardened steel is also softened and reduced in strength by tempering but this effect is incidental. Experience has shown, sometimes rather painfully, that in order to insure adequate service performance the hardness and strength must not exceed certain values depending upon the particular application. In many such instances, therefore, the hardness is reduced to a safe level that is still economically bearable, while in others the use of as high a strength level as possible is attempted,

The latter applies particularly to aircraft applications. In the past, parts that were heat treated to a Brinell hardness over 400 or a strength level over 200,000 psi occasionally failed in service or testing, while a slight reduction of these values insured adequate performance. Thus, the above figures have been considered for a long time to be limitations separating a safe from an unsafe range of properties.

However, failures, in general, more frequently than not result from a combination of unfavorable and faulty circumstances, rather than from a definite limitation in the properties of a perfectly designed structure and properly processed material. Thus, regarding the application of high-strength steels, it has been recognized that various factors are very unfavorable, such as; (a) a design that introduces, (i) severe stress concentrations, and, (ii) eccentricity; (b) a heat treatment that results in, (i) deviations from a fully martensitic structure on quenching, and, (ii) excessive variations in hardness; and, (c) hydrogen embrittlement introduced by cadmium and chromium plating.

The steels to be considered here may be designated as "constructional heat-treated steels." They contain 0.25 to 0.55 percent carbon and are bordered, on the low-carbon side, by the "structural low-alloy high-strength steels", which are not (intentionally) heat-treated and which must be clearly distinguished from the much stronger heat-treated steels. On the high-carbon, and also high-alloy side, follow the "die and tool steels" which are also heat treated, but generally to higher hardnesses; and such treatment makes then suitable for their particular field of application. The constructional heat-treated steels, furthermore, compete for certain applications with "case-hardened steels". These latter steels are of low-carbon content treated in such a manner that by changes in chemical composition a hard and wear-resistant outer layer, or "case", is formed while the core remains ductile and tough.

2. General Factors Which Determine the Strength of Aircraft-Steel Parts

The properties of steels differ widely depending upon the chemical composition. The effects of the individual alloying elements are of a variety of different types (Bain). This explains the existence of the many commercially-used carbon and alloy steels. The constructional heat-treated steels used in aircraft comprise a rather homogeneous group in regard to their properties, as compared to other groups of steels.

The aircraft steels are used to impart the highest possible strength to the parts of the airplane structure. Strength limitations arise from supply and economy considerations, on the one hand, and from technical difficulties which lead to service failures, on the other hand. Of these two factors, supply and economy considerations appear to be the least important. It is doubtful whether other steels or groups of steels and other alloys possess the strength properties desired in aircraft parts, which are superior to those of heat-treated low-alloy steels. Furthermore, recent experience indicates that future development of such steels is not limited by supply or economy problems, as seemingly, neither an increase in the alloy content nor the use of scarce alloying constituents is found to improve the properties of presently available steels.

The meaning of the term "highest possible strength" for these applications is, according to general agreement, the ability of a steel part to withstand a maximum load when tested at a comparatively slow rate. This "static strength" or "load-carrying capacity" of a specific steel part depends upon two factors.

The first of these is well recognized. It is the "tensile strength" or "ultimate strength" of the part as determined, usually, on testing a cylindrical specimen which is approximately one-half inch in diameter.

The higher the strength of such a specimen when tested in tension, the higher will be the strength of the part.

This relation, however, holds true only to a certain strength value, above which the other factor becomes significant as is discussed in the subsequent article.

3. Strength Limits for Heat-Treated Steels

This other factor which determines the static strength of a steel part is still very obscure. The British use the term "body" in order to indicate that one steel composition is superior to another, or that one heat of the same steel type is superior to another, without correlation with corresponding differences in their tension properties. From all evidence available to date, it appears that all carbon and alloy steels, heat treated to an identical strength, also perform identically if their strength level is low and so long as the well-recognized embrittlement temperature ranges are avoided. Which strength value exactly comprises this limit is unknown, but it is probably in the vicinity of 150,000 psi. As the strength of the steel increases beyond this value, an effect of composition is apparent. The steels then become increasingly sensitive to certain factors as these cause a decrease rather than an increase in the static strength of a part. Besides chemical composition, there exist many such factors, the recognized effects of which will be discussed below in detail.

It may be only mentioned here, that these factors have limited, in the past, the strength of the steels in certain applications, such as bolts, to about 150,000 psi, and in main structural applications to slightly over 200,000 psi. These values are far from the maximum strength of heat-treated steels obtainable in tension specimens which is approximately 350,000 psi. However, in order to obtain this maximum strength value special precautions must be taken in preparing and executing the tensile test. On the other hand, strength values to about 300,000 psi can be obtained readily on fully hardened and tempered specimens of many heat-treated steels.

4. General Value of Different Test Methods for Evaluating Service Performance

To determine the service performance of a steel, as well as of parts made from this steel, the tensile test is used universally. The most important single mechanical quantity reported from this test is the tensile strength. Other characteristics of the tensile test are of little general significance for either design purposes or the evaluation of the service performance of a part.

Hardness tests of various types are used partly as substitutes for the tensile test and partly for controlling and analysing the uniformity of heat-treating procedures. Their main characteristics are the facts that they are non-destructive and much more easily performed than other tests. Their principal disadvantages are the scattering of the test data and the lack of accessability to the critical test region in many instances. These shortcomings have frequently led to the passing of faulty parts through inspection.

Tensile and hardness tests serve to establish the design strength at which a part is being used. However, it is clear, to date, that they fail to indicate whether a part is susceptible to service failures in the presence of stress concentrations and other factors conducive to embrittlement of the steel. Additional tests, therefore, usually supplement tension and hardness tests, for this purpose. Besides the well-established impact tests two other test methods are gradually assuming increased significance, namely the notch-bar tension test and the sustained-load test.

The notch-bar-impact tests undoubtedly reveal certain characteristics of a steel which are important for the service of a part and which are completely hidden in regular tensile tests. These relate primarily to the sensitivity of a steel to the presence of stress concentrations. Large variations in impact strength occur with changes in certain variables, and very low impact values undoubtedly indicate a high sensitivity of the steel to factors which are liable to impair the strength of an intricate steel part. Recent developments of steel compositions suitable for high-strength aircraft and other applications have been based predominantly on studies of conditions which resulted in particularly high impact values.

The recently introduced notch-bar-tensile tests appear to yield much the same basic information as the impact test. The notch-tensile data, however, are reported as nominal breaking-stress values in the presence of a specific stress concentration, instead of the less direct energy absorption values obtained in the impact test. These data are, therefore, available in more readily usuable form than are the impact data in estimating the breaking loads of a structure.

The great difficulties resulting from hydrogen embrittlement have recently brought about a considerable interest in the "sustained-load" tests. In these tests, loads substantially below the tensile strength are applied for an extended period of time, in much the same manner as in stress-rupture tests at elevated temperatures. Notched tension specimens or other shapes containing stress concentrations appear to be more suitable for such investigations than cylindrical tension specimens.

Various other test methods and the characteristics determined in such tests are of considerable interest for a general understanding of the complex phenomena which determine the strength properties of high-strength steels. Results of such tests are also required for corresponding specific applications of parts, such as, in torsion or shear.

B. TESTING OF HIGH STRENGTH STEELS FOR HARDNESS AND IN TENSION

5. General Classification of Mechanical Test Methods

The two most common "mechanical tests" are various types of hardness tests and the tensile test. On testing high-strength steels by these test methods certain phenomena are encountered which are not common to softer metals. For this reason, the execution of various hardness tests and of the tensile test will be discussed in this chapter, with particular consideration of the testing of high-strength steels.

These test methods belong to the group of "static tests." In such tests the load is gradually applied and raised at a rate which avoids impact and acceleration effects and which permits registering or recording the load at any time. The test may be non-destructive and limit the load to a value which leaves the part or test specimen substantially undamaged. More frequently, static tests are carried through to destruction of the specimen and the breaking loads and deformations under such conditions are the most significant "mechanical properties" or "strength characteristics" of the metal.

Of the many possible static tests only those will be discussed and their results reported in this part of the report which are either non-destructive, such as hardness tests, or which are performed on comparatively uniformly-shaped testbars. These include tension tests, compression tests, bending tests, shear tests, and torsion tests.

Several other static tests use sections of irregular contour, in order to determine the effects of stress concentrations resulting from section changes. This applies particularly to notch-bar tests to which a separate part of the report is devoted. Notch-bar bend tests are usually not performed statically but by means of suddenly applied loading, or "impact". Such "impact tests" and their results will also be discussed in a separate part of the report. Still another part of the report has been devoted to "repeated" or "fatigue" testing in which specimens or parts are repeatedly strained between certain load limits until failure occurs.

"Sustained-load tests" are basically static tests, but the load is then held for some time at certain values, rather than raised continuously. Such tests on high-strength steel are only significant in connection with hydrogen embrittlement, which has also been discussed in a separate part of the report.

6. Types of Hardness Tests

The most common mechanical tests for metallic materials are hardness tests of the indentation type. These tests consist of pressing a hard body into the metal piece to be tested by applying a given load, determining some dimension of the resulting permanent indentation, and ascribing to the body a hardness value, or "hardness number", depending upon the type of indenting, the load, and the dimensions of the indentation.

There are, in general, three methods of such indentation-hardness testing commonly used for high-strength steels, as follows:

a) The Brinell test,

b) The Rockwell "C" -hardness test, and,

c) The Vickers-Pyramid-hardness test.

7. Brinell Hardness

In the Brinell test the indenter usually consists of a hardened steel ball, and, in the case of high-strength steels, a load of $P = 3000$ kg (67.20 lbs.) is applied for 30 seconds on a ball of $D = 10$ mm (0.394 in.). The hardness value (BHN) is defined as the ratio of load to the curved area of indentation $\left[A = 1/2\, \pi D^2 \left(1 - \sqrt{1 - d^2/D^2}\right)\right]$. This value, P/A, is obtained from the measured diameter of the indentation, d, by means of special tables and the BHN has the dimension kg/sq.mm.

The use of a hardened steel ball is limited to hardnesses below 600 BHN, and it is important to realize that even at lower hardnesses the elastic deformation of the steel ball affects the hardness reading. Consequently, the use of a cemented-carbide ball yields a higher Brinell hardness than will a steel ball, and the use of a diamond ball a still higher value. These differences increase as the hardness increases, Fig. 1 (Tabor).

The large diameter of the ball also limits its use to comparatively extended pieces, both in respect to thickness and lateral dimensions. Smaller balls can be used, with the load being adjusted proportionally to the square of the diameter, e.g., for a 1 mm. ball, the load is: $1/10^2 \times 3000$ kg $= 30$ kg.

Because of the rather tedious execution of the Brinell test, the Vickers-hardness test and particularly the Rockwell-hardness tests are used much more extensively.

8.. Vickers Hardness

In the Vickers-hardness test or diamond pyramid hardness test, a diamond indenter is used, which is in the form of a square pyramid, the opposite faces of which make an angle of 136^o with one another. The lengths of the diagonals of the indentation are measured, and from their mean value, d, the hardness number, "VPN" or "DPH" is determined as the ratio of load, P, to surface area of indentation, d^2. Because of the pyramidal shape of the indenter, the load is of no effect on the hardness value, and it may range between one and 120 kg, depending upon the hardness and size of the specimen.

The VPN is practically identical with the BHN for values up to about 400. Then the VPN becomes increasingly larger than the BHN as the hardness increases because of the small elastic distortion of the diamond pyramid as compared to that of the steel ball, see Fig. 1.

9. Rockwell "C" Hardness

For the various Rockwell-hardness tests, different indenters and load procedures are used. For through-hardened steels of high hardness, generally, the Rockwell"C" test procedure is used. Hereby, a conical diamond indenter with a spherical tip is first subjected to a load of 10 kg, subsequently to a load of 140 kg, and finally again to a load of 10 kg. From the difference in depth of indentation between the first and second application of the smaller load an arbitrary hardness number, "Rc", is obtained by means of a dial. For high-strength steels the Rockwell "C" hardness is approximately one-tenth of both the Brinell hardness, and the Vickers hardness, Fig. 2 (American Society for Metals).

10. Preparation of Laboratory Test Specimens for Tension Testing

The tensile test is generally acknowledged to be the most complete and significant mechanical test. Various characteristics of the tensile test are frequently the only ones listed in specifications for metallic materials and this also applies to the heat-treated low-alloy steels. While it is now known that tensile test data are not sufficient for evaluating high-strength steels in regard to their service performance, the tensile test still retains its paramount importance as an acceptance test and the test results retain their significance as basic values for the designer.

In the following chapters, the basic tension properties of heat-treated low-alloy steels will be discussed as they have been determined by laboratory tests. This generally implies that small-size specimens are machined from comparatively small sections, and, in most instances, from bar stock not over 1-1/2 inches in diameter.

It is common practice in such investigations to heat treat the specimen rather than the bar stock. This practice then consists of first rough-machining the specimen, followed by heat treating and frequently completed by a grinding operation. This also serves to remove decarburized (or carburized) surface layers. As a rule, approximately 0.005 inch on each surface or 0.010 inch in diameter is allowed for this operation. Where this operation was omitted some doubt may have arisen as to a possible favorable, or unfavorable, effect of the surface condition.

On the other hand, a limited amount of evidence indicates that heat treating the section first and then completely machining the specimen is an alternative method of specimen preparation that yields much the same results in tensile tests as the more common one described above. This, however, is not necessarily true for other types of tests.

11. Testing of Specimens from Large Sections in Tension

The above discussion applies only to small section sizes while for larger sections the properties of test bars machined from heat-treated parts may be considerably inferior to those heat-treated after machining. The limiting section size, in this respect, depends greatly upon the alloy composition which in turn determines the hardenability.

On the other hand, specimens from heavy sections heat treated after machining appear to possess much the same properties as those machined from bar stock, provided that these specimens were taken in the direction parallel to the fiber of the metal structure. This "longitudinal direction" in the case of barstock, tube, etc., is that of the part axis. In the case of forgings it may be necessary to determine this direction of metal flow from the macro-structure rather than from the external part dimension. The results of tests on longitudinal specimens from heavy sections, heat treated after machining, are included in the data reported in the subsequent sections, wherever available. The properties in directions other than the longitudinal, and particularly those in the "transverse directions" are generally inferior, and these will be discussed later in detail.

12. Size and Shape of Tension Specimens

In the standard tensile test in A.S.A., a specimen is used having preferably a cylindrical length of slightly more than the "gage length" of two inches and a diameter of 0.505 in., or a cross-section of 0.200 in., and connected to heads of larger diameter. The heads may be plain (cylindrical), threaded, or of the button type. For regular testing of heat-treated low-alloy steels, any such specimen is satisfactory, as a rule. However, when accurate results on steels having extremely high strength levels are desired, the button-head type specimen is superior to the other types, particularly if the button head is machined carefully to be square, i.e., so that its bearing faces make an angle of 90° with the specimen axis. Also, special attention must be paid to the problem of concentric application of the load. Otherwise, if the tensile strength of a steel exceeds 250,000 psi, irregular failures at the shoulders or in the threads may be obtained at low values of load and strain. Furthermore, if a damaged steel condition is encountered, irregular and low test data may also occur at much lower strength levels.

Subsize tension specimens are frequently used in the investigation and testing of high-strength steels for various reasons. Thus, the length required for normal specimens is not available in the transverse directions of forgings and bar stock. Also, small specimens permit determining local variations in strength. The subsize specimen is made, preferably, geometrically similar to the normal specimen, i.e., with a gage length equal to about four times the diameter.

13. Tension Characteristics

The characteristics of the tensile test are as follows:[1]

a) The "yield strength" is usually defined as the stress required to obtain a permanent strain of 0.2%. It is determined graphically from a load-versus-extension diagram by drawing a line 0.2% apart from the elastic portion of this diagram to intersection with its curved or plastic portion.

Other definitions of yield strength or equivalent values are as follows:

i) Instead of using 0.2% permanent strain, it is occasionally found that 0.1%, 0.5%, or 1% are more convenient. In such cases, the preference strain should be reported, e.g., "yield strength (0.1%)".

ii) Softer steels frequently exhibit a sudden permanent extension on loading that exceeds 0.2%. The stress value is then designated as "yield point", rather than as yield strength. This phenomenon, however, is not encountered in testing high-strength steels.

b) The "tensile strength" or "ultimate tensile strength" is

1/ Stress and strength values referred to below are "conventional stresses" defined as loads divided by the initial cross section of the cylindrical specimen.

defined as the maximum load divided by the initial cross section or as the maximum value of conventional stress encountered in the test.

c) The "elongation" is determined from the increase in gage length, after execution of the test, by dividing by the gage length. It is given in percent and, in American practice, usually refers to a gage length of 2 in. or 4 diameters.

d) The "reduction of area" is determined from the measured diameter of the tested specimen at the point of failure. It is the difference in cross sections between the initial and final values, divided by the initial cross section. It is also usually given in percent. The reduction of area is generally recognized as a criterion of ductility.

Other, special characteristics of the tensile test may be used for basic investigations, as discussed further below.

C. GENERAL PHENOMENA OF HEAT TREATING CONSTRUCTIONAL STEELS

14. Some General Structural Relations Determining the Properties of Constructional Alloy Steels

The properties of constructional alloy steels, as well as, of several other steel types, are determined by a metallographic structural transformation. At sufficiently high temperatures all steels considered here assume basically a "homogeneous structure" consisting of a solid solution of the various alloying elements in the face-centered cubic modification of iron. This solid-solution phase is called "austenite" and the process of "homogenizing" a heat-treated steel before quenching is, therefore, also called "austenitizing".

In commercial work, the austenitizing of a low-alloy steel containing certain alloying elements may be incomplete, however, because of the "sluggishness" of these elements to go into solid solution. This fact which has been known for a long time for high-alloy steels has been recognized only in recent years for low-alloy steels.

On cooling, the austenite tends to decompose into another modification of iron and into carbides. The stable low-temperature or "annealed" condition of the so-called "ferritic" steels consists of a mixture of nearly carbon-free iron crystallized in the body-centered cubic lattice, or "ferrite", and various iron and alloy carbides.

However, on rapid cooling or "quenching" of a heat-treatable steel the regular transformation into ferrite and carbide may be entirely suppressed until a comparatively low temperature, the "martensite point", is reached. Below this temperature, which varies with the steel but which is roughly 500°F, austenite transforms the more completely the lower the temperature. The transformation product is an unstable, tetragonally-distorted ferrite, called martensite. At room temperature this martensitic transformation of a constructional alloy steel is usually more than 95 percent, and up to over 99 percent, complete, the remainder being untransformed austenite.

Part of this "retained austenite", but not all of it, can be further transformed by cooling to very low temperatures, by "freezing" or "refrigerating" comprised of dipping into liquid nitrogen immediately after quenching.

Tempering at temperatures in the vicinity of 400°to 500°F decomposes the retained austenite into a structure different from but very similar in properties to martensite. This structure is one of the many different "intermediate transformation products".

Tempering at any temperature above room temperature also causes distinct changes of the properties due to a change of the tetragonal martensite into a mixture of cubic ferrite and not clearly defined carbides of varying composition. Such "tempered martensite" is the basic structure of heat-treated steels. In general, the heat treating aims at 100 percent tempered martensite. For any given alloy steel, the tempered martensite usually becomes softer, less strong, and more ductile as the tempering temperature and tempering time increase. However, many, still largely unknown phenomena render this relation very complex, even for carbon steels.

Quenching,at a rate which is less than a critical speed within certain critical temperatures (considerably above room temperature),results in mixtures of martensite or tempered martensite and intermediate transformation products. It is now known that such "slack-quenched" steels of high strength exhibit mechanical properties distinctly inferior to those of tempered martensite,the only other constituent of which is either retained or tempered austenite.

15. Hardenability and Its Determination

The dissipation of heat through a metallic body requires a certain time that increases with increasing section size and depends upon certain thermal properties of the metal. As a consequence, the rate of cooling, under given quenching conditions, decreases with increasing section size and, for the various element of a given section, with increasing distance from the surface.

The response of a steel to the cooling rate in regard to transforming into martensite depends upon its composition. "Full hardening", resulting in 100 percent martensite plus austenite of any particular steel, can be obtained by quenching in a given quenching medium up to a certain critical section size. The cooling of the center fibers of this section just reaches the critical cooling rate which must be exceeded to avoid slack-quenching. Either this critical cooling rate or the maximum section size which fully hardens can be taken as a measure for the property of the steel which is called "hardenability".

It is general practice to determine whether full hardening has been obtained as well as the degree of slack-quenching by means of Rockwell "C" hardness values.

To determine the "hardenability" of a steel, in earlier practices, round bars having different diameters were quenched and hardness traverses taken. When a certain section size was exceeded the center hardness was found to be distinctly lower than the surface hardness. The maximum diameter which still exhibited a uniformly high hardness then was a measure of the hardenability.

In recent years the much less tedious "Jominy End-Quench Test" of measuring hardenability has been generally adopted (Boegehold 1944). It consists of cooling the end of a one-inch round bar with water and measuring the surface hardness at regular distances from the water-cooled end. The test bar should be "normalized" before finish machining by heating to 150°F above the upper critical (transformation) point, Ac_3, and holding it for 30 minutes. Subsequently, it should be heated for austenitizing for 20 minutes, to about 100°F above the Ac_3 point in a protective atmosphere. The bar is then mounted in a fixture so that a column of water is directed against its bottom face for a period of at least 10 minutes and under closely controlled conditions. Two flats, 0.015 in. deep and 180 degrees apart, are then ground along the sides of the round bar. Rockwell "C" hardness readings are finally made over this length at 1/16 in. intervals and plotted to yield the hardenability of the steel. For practical purposes, a "hardenability band" is given for each steel, which shows the range, bordered by maximum and minimum values of hardenability now specified for each steel, see Fig. 3 and Fig. 4.

It is generally assumed that rounds and other sections assume the same hardness as positions (sixteenths) of the Jominy bar which cool at the same rate. This relation has been determined for both oil-quenched and water-quenched rounds having diameters up to 4 inches, Fig. 5 (Boegehold 1944). Rectangular sections cool down slower than round bars and the equivalent diameter of the round bar depends not only upon the ratio of width to thickness of the flat bar but also upon its section size, Fig. 6 (British Standards Institution).

16. Hardenability of Aircraft Steels

Heat-treated steels are rated primarily according to their hardenability. In general, hardenability increases with increasing alloy content, and consequently also with the price of the steel. Small parts are generally made in less highly-alloyed steels than large parts. The larger the section, the fewer the steel compositions which compete in regard to hardenability.

Heat-treatable steels can be supplied either by composition or hardenability limits. The composition limits must be kept narrower to insure desired hardenability and, therefore, it is now general practice to specify hardenability in connection with larger chemical variations. Hardenability bands for the most important of such "H-steels", including tentatively standardized steels, marked by the prefix "TS", have now been established, Fig. 3 and Fig. 4.

Constructional aircraft steels are of two types. For heavy sections high-hardenability steels are used. The most common of these is 4340 steel. The hardenability band of this steel indicates that the as-quenched hardness is retained to about ten-sixteenths (inch) from the as-quenched end, Fig. 3a. This corresponds to a maximum diameter of close to two inches that will fully harden on oil-quenching, see Fig. 5. Other high-hardenability steels differ slightly from 4340 steel in this respect, see Fig. 3.

For comparatively light sections a variety of steels are used. These possess hardenability bands which indicate full hardening to not deeper than four-sixteenths, Fig. 4. The corresponding diameters of rounds are about 1/2 -inch on oil-quenching and one-inch on water-quenching.

17. Conventional-Heat-Treating Procedure

The properties of constructional aircraft steels depend upon the following two phenomena:

a) Plastic Deformation: The steels can be readily shaped by mechanical working at elevated temperatures to a practically unlimited extent. Mechanical working at room temperature, on the other hand, is very limited and applicable only to certain small parts and to the straightening of parts.

b) Heat Treatments: The steels assume high strength after "heat treating" which consists of the following steps:

1. Heating to, or "austenitizing" at, a temperature, about 100°F above the so-called "upper critical temperature" at which the steel consists predominantly of a solid solution of all alloying elements, or is austenitic.

2. Rapid cooling, "quenching", or "hardening", in water or oil, during which process the austenite persists until a certain temperature is reached. Below this temperature the austenite transforms into very hard (untempered) martensite.

3. Heating to, "tempering" at, or "drawing back" to a certain temperature for a certain time, to obtain tempered martensite with more uniform properties and a desired degree of ductility.

In the subsequent articles the hardness and tension characteristics of aircraft steels heat treated to tempered martensite will be discussed. Variations in these properties are partly introduced by the variations in chemical composition of which those of carbon content are by far the most important.

Further variations and certain features of particular alloys are explained by the fact that the condition of tempered (and untempered) martensite is an ideal condition which is actually attained only in exceptional cases. However, it appears that certain deviations from tempered martensite are of little significance for the properties of properly heat-treated constructional steels in small sections, such as those of tension specimens.

This applies particularly to the retained austenite present in many of the low-alloy steels used in aircraft after oil-quenching, as discussed in more detail in a later article.

The properties of low-alloy aircraft steels after quenching in oil or water and subsequent tempering conform in many respects to a general pattern. This is also true for other heat-treated steels, including those with higher and lower carbon contents. On the other hand, high-alloy steels may or may not be susceptible to heat treating and exhibit properties which follow relations similar to those of carbon and low-alloy steels, depending upon their compsoition.

18. As-Quenched Hardness of Aircraft Steels

The maximum value of hardness attainable on quenching to martensite depends almost entirely upon the carbon content, Fig. 7 (Burns, Moore, Archer 1938). Aircraft steels, however, frequently retain on oil-quenching a small amount of austenite which leads to a distinct reduction in hardness, as compared to the ideal values for a given carbon content.

This deficiency, however, must not be confused with that resulting from insufficiently rapid quenching. It appears, that in the automobile industry such "slack-quenching" is admissible and that a hardness as low as 10 percent below the ideal values is considered as normal (Boegehold 1944). However, steel parts for automotive purposes are usually designed to withstand fatigue loads and this limits their hardness to a value of about 30 Rockwell "C", or their tensile strength to about 150,000 psi. If tempered to such low values the as-quenched hardness of a steel is of little significance, as is discussed in detail in a subsequent article.

It has been, on the other hand, also recognized, but only rather recently, that a complete, or 100 percent, tempered-martensite structure is the most desirable for certain practical applications, including armor plate and aircraft usage. Therefore, the as-quenched hardness of these steels should not deviate from the ideal curve by an amount exceeding that explainable by retained austenite.

19. Relation Between Tensile Strength and Hardness of High-Strength Steels

The tensile strength of as-quenched, constructional steels is of little interest, because of the brittleness frequently encountered in untempered martensite. Because of this brittleness accurate determinations of the tensile strength are very difficult, and, even if all precautions are taken, widely scattering and low values are frequently encountered.

On the other hand, tempering at temperatures and times which only slightly or not at all affect the hardness may produce a comparatively high degree of ductility in such steels and make it possible to determine their tensile strength.

The tensile strength of such ductile material is also primarily a function of the carbon content and, therefore, in turn a function of the hardness. In fact, the relation between strength and hardness is rather universal, and it is generally considered to be unique for the entire range of constructional steels in the condition of tempered martensite. This relation has been established repeatedly and in general agreement for a range extending to a hardness of 42 Rockwell "C" and a strength of 200,000 psi, Fig. 8, see also Fig. 2.

The data available, in this respect, for higher values of hardness and strength, however, differ considerably. The relation reported for 4340 steel, heat treated to strength values between 240,000 and 300,000 psi, Fig. 9 (Lockheed Aircraft; Menasco) is located between those determined for various steels by other investigators. This relation for 4340 steel between the tensile strength, F_{tu}, in psi, and the Rockwell C hardness Rc, is almost linear between Rc = 48 and 57 and it can be expressed by the equation: $F_{tu} = 240,000 + 9000\,(Rc - 48)$.

20. Effects of Tempering at Very Low Temperatures

Tempering at increasing temperatures - for a constant period of time - causes a gradual change in all properties of constructional steels. These changes are qualitatively very similar for these steels but may vary considerably in magnitude and in the rate of change in different temperature ranges, Fig. 10.

Little attention has been paid to the changes occurring on tempering a quenched steel at temperatures below and including 350°F. To date, the lowest tempering temperature suggested for constructional steels is 400°F. It appears, that the principal effect at still lower temperatures is that due to a decrease in ductility with decreasing tempering temperature. Generally, the reduction of area becomes smaller and, in many instances, this change, is very sudden, see Fig. 11.

Large increases in impact strength are generally observed, while the strength of the steel usually changes only slightly on tempering up to a temperature of 300°F, provided that the steel was not severely and adversely affected by the as-quenched brittleness.

Another type of steels, namely die steels for cold-working purposes, is frequently tempered at temperatures as low as 300°F. The term "stress-relieving" commonly applied to such a treatment implies that its effects are primarily caused by a reduction of the high residual stresses introduced by quenching in water or oil. However, no proof has yet been offered that the suggested relation exists.

The general pattern of the change from the brittle to the ductile condition on tempering a steel is not well established. Thus, the results of laboratory investigation on small sections indicate a sudden increase in ductility as the tempering temperature is slightly raised while collected data of plant tests imply that this transition occurs more gradually.

The effect of steel composition on this phenomenon is also substantially unknown. It appears that some compositions, such as chromium steels and chromium-molybdenum steels are more susceptible to the as-quenched embrittlement, than nickel steels or manganese steels Fig. 10 (Sachs, Lubahn, Ebert, 1943).

The embrittlement increases, furthermore, with increasing carbon content and it is usually not encountered after quenching of steels containing up to 0.3 percent carbon. However, recent tests on steels containing less than 0.2 percent carbon also revealed the occurrence of this embrittlement after both water and oil quenching, see Fig. 11 (Carnegie Institute).

Tempering eliminates the brittleness at a temperature which increases as the carbon content, and consequently also the as-quenched hardness, of the steel increases. The steels mentioned above, containing less than 0.2 percent carbon, were found to become ductile after tempering at 212°F for a short time, and even on storing at room temperature. Steels, containing 0.7 to 0.8 percent carbon may require tempering to 800°F before they exhibit a reduction of area exceeding a few percent and a consistently-high tensile strength.

21. Tensile-Strength Limits

For practical purposes, the maximum value of tensile strength to which a particular steel can be heat treated is related to its condition after quenching and tempering at a temperature of 400°F or higher. After this treatment the hardness of the steel may be as much as 10 percent lower than that of the as-quenched condition. As for any ductile steel condition, hardness and strength are closely related. The maximum strength which is obtainable with a constructional steel depends primarily upon its carbon content.

Strength values over 200,000 psi, corresponding to Rockwell "C" values in excess of 40, can be produced in any steel which contains more than 0.15 percent carbon. Considering the commercial variations in carbon content such a steel would be classified as a 0.20 percent-carbon steel. Recent investigations revealed that such steels are distinctly more ductile than 4340 steel at the same hardness level, and that they possess superior impact and fatigue properties. German investigations indicate that attempts were made to use such steels which are usually classified as case-hardening steels also as heat-treated steels (Pomp, Krisch 1942). However, it appears that the hardenability of the lower-carbon steels does not quite reach the desired values. In addition, interest in steels, heat-treated to a minimum strength of 200,000 psi, or a strength range of 200,000 to 220,000 psi is fading, as the use of distinctly higher strength ranges has already successfully passed the experimental stage.

Steels are now used, which are heat treated to a strength of 220,000 to 240,000 psi and to a very limited extent, to a strength of 240,000 to 260,000 psi. According to the minimum carbon rule these steels require a nominal carbon content of 0.30 percent. Again, it is believed that their ductility and other important strength characteristics are superior to those of 4340 steel, if heat treated to the same strength. In this strength range 4340 steel must be tempered at temperatures between 500°and 750°F, see Fig. 10a. With the exception of the recently developed, silicon-containing steels, however, see Fig. 10, this tempering-temperature range is generally considered as undesirable because of the resulting exceptionally low impact values.

Steels, heat treated to a minimum strength of 260,000 psi, can be obtained only with a nominal carbon content of 0.40 percent, resulting in an average, or nominal, strength of close to 300,000 psi. 4340 steel heat treated to a strength of 260,000 to 280,000 psi, is now (1953) being tried out for its suitability for aircraft use. Several other steels have been proposed which may challenge 4340 steel in this strength range.

It is not clear to date, whether with increased carbon contents still higher strength levels can be obtained, in the order of a minimum strength of 300,000 psi or higher. The upper limit of tensile strength that has been obtained in heat-treated steels is in the vicinity of 350,000 psi and it corresponds to a Rockwell "C" hardness of approximately 60, see Fig. 9. Such values have been observed in fully-hardened and tempered steels of a variety of compositions, containing at least 0.4 percent carbon, if particular care was taken to apply the tension load concentrically, see Fig. 10a.

22. Changes of Yield Strength and Shape of the Stress-Strain Curve on Tempering

Another phenomenon associated with these low tempering temperatures is the relative small change, and sometimes the slight increase, of yield strength with increasing tempering temperature. This effect continues up to a tempering temperature of 400 to 600°F depending upon the steel composition, see Fig. 10.

The significance of this effect is much greater than the small actual changes indicate, as the yield-strength ratio rapidly increases on tempering from a possible minimum value of 0.75 to values as high as 0.95.

The increase in yield-strength ratio is closely correlated with the general shape of the load-extension or stress-strain curve of heat-treated steels, Fig. 12. At low tempering temperatures, including the as-quenched condition, the stress-strain diagram of a steel is smoothly curved and exhibits only a very limited range of true elasticity. Already at comparatively low stresses, variously designated as "limit of elasticity","proportionality limit", "proof stress", "yield strength", etc. distinct deviations from both elasticity and proportionality between stresses and strains become evident. As the tempering temperature increases both the elastic and plastic branches of the stress-strain curve gradually straighten out and at a certain temperature a distinct knee appears.

At this tempering temperature the yield-strength ratio reaches a maximum value. In constructional steels this is usually associated with a tensile strength between 250,000 and 200,000 psi.

As the tempering temperature increases further, the yield strength again decreases at a rate slightly higher than that of the simultaneous decrease in tensile strength. The yield-strength ratio decreases correspondingly. This, in turn, is associated with a relative increase in the slope of the plastic branch of the stress-strain curve, or increase in the so-called "strain-hardening capacity" of the steel.

The above-discussed changes in yield-strength ratio depend primarily upon the tempering temperature. Increasing tempering time also has an effect similar to that of an increase in tempering temperature, see Fig. 11. The actual value of yield strength, which depends upon the hardness affects the change in yield-strength ratio only to a minor extent.

On the other hand, the method of quenching, as well as a cold treatment subsequent to quenching, slightly but distinctly, affect the change in yield strength at low tempering temperatures. This will be discussed in detail in subsequent articles.

23. Effects of Tempering on Tensile Strength and Hardness

The tensile strength and the hardness of a fully-hardened, constructional, heat-treated, carbon or low-alloy steel generally decreases with increasing tempering temperature. The basic curves for carbon steels show a rather gradual, continuous sloping down of the curves, representing these properties as functions of the tempering temperature, Fig. 13 (Bain). The addition of most alloying elements results in curves above those of the carbon steel, or in other words, it renders the reduction of strength and hardness due to tempering smaller.

There exist basically two different effects of this nature. A few elements, particularly nickel, raise the entire curve resulting in values of strength and hardness which deviate from those of a carbon steel with equal carbon content more,the higher the tempering temperature. This effect is attributed to the existence of a low-temperature solid solution of iron and nickel which is more resistant to softening on tempering than pure ferritic iron.

Most elements, however, result in the phenomenon that tensile strength and hardness change only slightly within certain ranges of tempering temperature. As a result the curves representing these quantities as functions of the tempering temperature exhibit more or less pronounced humps. For steels, containing only one alloying element besides carbon this hump usually is more localized and, therefore, appears more definite than in the more complex aircraft steels. This temporary arrest of the tempering effect is called "secondary hardening" and it is generally attributed to a precipitation of alloyed carbides, or "special" carbides, in contrast to the precipitation of carbon and formation of iron carbide, or "cementite", in carbon steel which starts at the lowest tempering temperature and progresses as this temperature increases. This explanation does not hold true for such an effect of silicon which does not form a carbide, but, which, however, retards the formation of iron carbide (Allten, Payson, 1953). The secondary-hardening effect usually overshadows that of solid-solution hardening over most of the range of tempering temperature, but it may be associated with rapid softening at high temperatures. In some high-alloy steels secondary hardening may lead to a hardness slightly in excess of that of the as-quenched martensite, and considerably in excess of that of a combination of martensite plus retained austenite present after quenching.

Certain elements which are important for the properties of aircraft steels appear to have an insignificant effect on their response to tempering. This applies particularly to aluminum which plays a great role in steel making and in determining "steel quality".

In general, the quenching method also affects the relations between strength, hardness, and tempering time only to an insignificant extent, provided that the resulting product is tempered martensite.

24. Elongation of Heat-Treated Steels

The elongation of heat-treated steels varies only to a small degree over a rather wide range of tempering temperatures.

At very low tempering temperatures the elongation may be affected by the previously-discussed as-quenched brittleness and will then be very low if the reduction of area is also very low. Otherwise, the elongation generally exceeds a value of 10 percent after quenching and tempering at very low temperatures.

In the range of tempering temperatures between 400° and 600°F, frequently a flat minimum of elongation is observed. This is particularly true for steels with a low carbon content for which the elongation is not affected by the reduction of area because of the generally high values of this quantity.

This also explains why the elongation of steels of a particular series slightly increases with decreasing carbon content, see particularly Fig. 17.

As the tempering temperature increases above 600°F, the elongation also increases, first very slowly and then at an accelerated rate.

In the range of strength values of less than 240,000 psi, the elongation of various steels, heat treated to tempered martensite, is generally considered to be a rather definite function of the hardness or tensile strength of the steel. However, in the high-strength range such a relation does not exist.

25. Reduction of Area of High-Strength Steels

The reduction of area is usually considered to be a manifestation of the ductility or forming ability of a metal and it is frequently used to measure ductility. However, considering heat-treated steels, and particularly those possessing a strength above 200,000 psi, the significance of reduction of area is not clear. Most confusing, in this respect, probably are the conflicting facts that in certain instances changes in reduction of area sensitively and accurately indicate any embrittling effect and are a measure of its magnitude, while in other instances they either entirely fail to do so, or even suggest a reverse conclusion, or else exaggerate and greatly distort an effect.

One such effect of the last-mentioned type is the repeatedly-discussed, rapid recovery from extremely low to rather high values of the reduction of area on tempering for many steels, Fig. 11. The large amount of evidence accumulated particularly by the automobile industry, unfortunately, does not well cover this range of very low tempering temperatures.

However, it appears that such plant data show a considerably more gradual initial increase in reduction of area with increasing tempering temperature than those obtained in more closely controlled specific series of laboratory tests. Factors which may explain this discrepancy are the frequently smaller section sizes used for laboratory tests, on the one hand, and the considerable degree of slack-quenching considered admissible in non-aircraft applications (Boegehold 1944), on the other hand.

Undoubtedly, the above-mentioned rapid increase in reduction of area with increasing tempering temperature coincides with a general increase in the ductility of the steel. However, no attempt has been made, to date, to ascribe any definite significance to this phenomenon.

It is also clear that the performance of a steel changes more radically at somewhat higher tempering temperatures and particularly in the range between 300 and 800°F, Figs. 14 and 15. At these temperatures the reduction of area of practically all low-alloy steels gradually increases by a small amount. This in no way indicates that a variety of complex reactions simultaneously occur in the steels which greatly affect service performance and also certain test characteristics, such as impact strength.

For these reasons, little attention has been paid to variations of reduction of area with the tempering temperature or the tensile strength. On the other hand, undoubtedly, many other effects are best judged by such changes in reduction of area, as will be shown in the discussion of specific phenomena in subsequent articles.

The complexity of this problem is further illustrated by the results of some tests on spring-steel wire (Siebel, Panknin 1952). These data showed that high values of reduction of area, in excess of 45 percent, did not insure freedom from breakage and cracking and non-uniform deformation in torsion tests. The ductility (shear strain) of such wire on twisting was found to vary between 10 and 140 percent. Conversely, some wire which possessed a high ductility in torsion appeared rather brittle in tension.

D. EFFECTS OF ALLOYING ELEMENTS ON AIRCRAFT STEELS

26. General Discussion of Alloying Effects in Aircraft Steels

The properties of heat-treated steels depend upon their composition in a very complicated manner (Bain). The major function of alloying elements in carbon and low-alloy steels is to strengthen the steel. This may relate to a variety of applications which involve different strength characteristics of a steel. In constructional low-alloy steels used in aircraft, high strength and hardness, associated with a considerable degree of ductility and toughness, are necessary. These are required particularly for static loads at temperatures near and below room temperature. The desired properties are developed by heat treatment. In this chapter, therefore, the effects of different alloying elements will be discussed only in this respect.

Only a few of the alloying elements impart unique properties to iron, which are of particular interest for high-strength steels. This applies primarily to carbon and aluminum.

The principal function of all other alloying elements is to increase the hardenability. Additions of most of these also result in increased strength and hardness at a given tempering temperature.

An exception in this respect is boron which increases hardenability, but does not affect the response of the steel to tempering. On the contrary, silicon imparts to a steel a resistance to softening on tempering, while its usefulness for increasing hardenability is minor.

The trend of development is towards very complex steels. It has been found that adding a considerable number of alloying elements to iron causes effects which are frequently superior to those obtained by alloying only a few. While these differences are not significant for steels heat treated to moderate strength levels, they assume increased importance as the strength level of the steel is raised.

27. Carbon Content, Maximum Hardness, and Quenching Procedure

The carbon content of a steel to be heat treated to high strength values is one of its most important factors. In very small austenitized and radically quenched sections which transform fully to martensite the hardness of the steel is determined by its carbon content, see Fig. 7. The alloy content is of little significance in this respect.

These ideal hardness values are not always reached under commercial conditions of heat treating constructional low-alloy steels. Frequently, the as-quenched hardness of a steel quenched as severely as it is commercially feasible exhibits a hardness which may be as much as 5 Rockwell "C" units lower than that considered to be the maximum hardness corresponding to its carbon content. This deficiency is primarily explained by the following two phenomena.

On the one hand, many alloy steels contain after quenching a certain amount of austenite. This phase is much softer than martensite and the mixture of martensite and "retained austenite" is correspondingly less hard than the fully-martensitic structure. The amount of austenite depends upon the alloy, the quenching method, and the quenching temperature. The last two named factors explain that the as-quenched hardness of certain alloys, particularly of alloys containing considerable amounts of nickel or manganese, may vary considerably.

On the other hand, a radical quench of many alloys, and particularly of alloys containing about 0.4 percent carbon, frequently leads to cracking and excessive distortion. In commercial heat treating of aircraft parts, therefore, the basic heat-treating procedure may be modified. This modification primarily aims at a considerable reduction of the cooling rate in the range of the martensitic transformation. If such delayed or interrupted quenching is properly performed, cracking and distortion may be considerably reduced, while the martensitic transformation of the steel is not materially affected.

However, the resulting structure may be tempered rather than as-quenched martensite. Very slow cooling through the range of the martensitic transformation is equivalent to heating the martensite, obtained by quenching to room temperature, to slightly elevated temperatures.

Both the presence of a small amount of austenite and a slight tempering appear to affect the properties of heat-treated steels only to an insignificant extent. This is certainly true for steels heat treated to a strength not over 200,000 psi by tempering at temperatures of 800^{o}F or higher. At these temperatures, the austenite decomposes to a structure very similar in properties to tempered martensite. The tempering effect of quenching is then overshadowed by the much larger tempering effect at higher temperature.

The effect of retained austenite on the properties of high-strength steels in not entirely clarified. Such steels may be tempered at temperatures as low as 400^{o}F where the austenite remains unchanged. However, "refrigerating" or "freezing" the part by dipping into liquid nitrogen, i.e., cooling to about minus 300^{o}F, immediately after quenching transforms part of this austenite into martensite. This treatment, and the effects of retained austenite in general, have attracted much attention in recent investigations (Cohen 1949; French 1949; Troiano 1949). However, it now appears that the effects of retained austenite on the properties of high-strength steels are nearly negligible, as discussed in detail in a subsequent article.

28. Effect of Carbon Content on Tensile Strength

The carbon content affects the tensile strength of a heat-treated steel in much the same manner as the hardness, as has been discussed above.

Regarding the tensile strength of the as-quenched materials, however, complications arise from the fact that the steel becomes brittle if its hardness exceeds a certain limit. Therefore, a definite relation between tensile strength and hardness of heat-treated constructional steels can be established only to a strength value of approximately 300,000 psi, corresponding to a Rockwell "C" hardness of about 55, see Fig. 8 and Fig. 9, and a Brinell hardness of about 600. The actual limit seems to depend considerably upon the chemistry of the steel. Little is known, in this respect, as tensile tests on such hard steels are performed only occasionally, and, also, because the strength and ductility are then affected by details of the testing procedure. However, some tests have shown that chromium steels are clearly more susceptible to embrittlement with increasing carbon content, Fig. 14, than nickel steels, Fig. 15 (International Nickel).

The relative effect of carbon on the tensile strength is also maintained on tempering the steel. The higher the carbon content of a particular steel type or series, the greater is also the tensile strength after any particular tempering treatment. In the 0.40 percent-carbon steels admissible variations in carbon content between 0.35 and 0.45 percent account for ± 5 percent variation in tensile strength for a given heat treatment, Fig. 16 (International Nickel). The effect of carbon, in this respect, becomes more pronounced as the carbon content is reduced, in agreement with the trend of the hardness, see Fig. 7.

29. Effect of Carbon Content on Various Mechanical Properties of Heat-Treated Steels

The common concept that the yield strength is simply a function of the tensile strength or hardness is quite misleading. Such a simple relation may apply to steels heat treated to a strength below 200,000 psi. For any given tensile strength above this limit, however, the yield strength has been found to be distinctly lower the lower the carbon content of the steel, Fig. 17 (International Nickel). This is in conformance with the fact that the ratio of yield strength to tensile strength of any steel in the as-quenched condition is rather low, less than 75 percent. The "yield-strength ratio" then increases rapidly on tempering to a maximum value of about 0.95, see Fig. 10.

The elongation of heat-treated steels is not greatly affected by either the carbon content or any other variable. Within a wide range of strength the elongation of heat-treated steels differs only by a few percent, and it becomes distinctly higher only if the strength decreases below about 180,000 psi. For any given carbon content a shallow minimum in the values of elongation occurs at a low tempering temperature, see Fig. 10. With increasing carbon content the elongation at the higher strength levels decreases slightly, see Fig. 17.

The reduction of area, on the other hand, appears to depend to a marked extent upon the carbon content. For any given strength the reduction of area is lower the higher the carbon content and above a certain strength value, which is about 250,000 psi or higher, the steel changes suddenly from a condition of high ductility to one of very low ductility as the carbon content exceeds a certain value. The significance of this sudden embrittlement, with either increasing carbon content for a given strength or increasing strength for a given carbon content is obscure. The performance of heat-treated steels, in general, becomes gradually different as the strength level increases, but without exhibiting any definite and sudden change at very high strength.

The effect of carbon content on mechanical properties other than hardness and tension characteristics will be discussed in detail in the appropriate articles following.

However, it may be mentioned here that the impact strength of heat-treated steels frequently exhibits a pronounced minimum at a tempering temperature of about 600°F if tempered for a short time (1/2 to 2 hours). For this reason, tempering in the range of temperatures between 500°F and 750°F has been considered as conducive to brittleness. This may not apply to steels high in silicon, as discussed in the next article. On the other hand, recent developments of steels with a low silicon content appear to indicate that such steels tempered at temperatures as low as 400° to 500°F are superior in their performance to other steels which must be tempered at slightly higher temperatures to assume the same hardness and strength. The carbon content plays an important role in this respect, as a strength of 230,000 psi can be obtained with 0.30 percent-carbon steels after tempering at 400° to 450°F. Such steels combine the favorable effects of a low carbon content and of a low tempering temperature. The property of the steel which benefits from these factors is not well recognized, but it appears to be associated with ductility, and it reflects itself in such characteristics as notch sensitivity on either static, impact, or fatigue loading.

30. Effects of Nickel, Chromium, Molybdenum, and Vanadium on Heat-Treated Steels

The primary function of metallic alloying elements in heat-treated steels is to increase the hardenability. The hardenability of carbon steels is insufficient for any but the very smallest section sizes used in aircraft. Nickel, chromium, and molybdenum are the most important elements which improve hardenability in relation to the quantity added.

As far as steels possessing a comparatively low hardenability are concerned, it appears that the various alloying elements are interchangeable. It is clear, however, that very high hardenability can be obtained either with chromium-nickel additions, or, more economically, with combinations of molybdenum, nickel, and chromium, or with more complex steels, containing vanadium, silicon, or boron.

Nickel can be replaced by other elements, as far as hardenability is concerned. However, nickel-free steels are known to possess inferior impact resistance at low temperatures. Some tests also indicate that this is associated with comparatively low values of reduction of area at low tempering temperatures (International Nickel).

Another element important because of its hardenability effect is manganese. A certain amount of manganese is contained in any steel because of its "scavenger" action in eliminating undersirable effects of sulphur impurities. Manganese additions above this minimum increase hardenability. However, manganese steels are generally considered inferior to other steels having equal hardenability but, apparently, greater toughness and ductility. On the other hand, a high manganese content is a normal characteristic of high-hardenability steels, see Table 1. The manganese-molybdenum steels which find much use as ordinance materials are deep-hardenable, but are not advocated for use at very high-strength levels.

Vanadium additions to steels to be used at very high-strength levels are becoming increasingly popular. This element seemingly functions, principally, as an austenite grain-size refiner.

The effects of silicon and boron are rather different than those of the other elements and will be separately discussed in subsequent articles.

Most alloying elements also affect the response of a heat-treated steel to tempering. Addition of an element usually increases the hardness and tensile strength after tempering within a certain temperature range. This range varies with the alloying addition, as already discussed in a preceding article. Several such effects may be apparent in complex steels, each to be ascribed to a particular element. In addition, carbon, and the impurities nitrogen, sulphur, and oxygen are suspected to be sources for variations of certain properties, particularly of impact strength.

31. Effects of Silicon on High-Strength Steels

The effects of silicon on the mechanical properties of heat-treated steels are of an entirely different nature than those of carbon (Allten, Payson 1953). The as-quenched hardness (and tensile strength) of a fully-martensitic steel, such as a carbon steel, refrigerated after quenching, is practically the same for any silicon content between the commercial minimum and over two percent, Fig. 18. However, if the silicon dilute steel retains a certain amount of austenite, such as the nickel steels, the hardness of the steels high in silicon is found to be slightly higher than those low in silicon, probably because the silicon inhibits the retention of austenite, Fig. 19. For the same reason the hardness of the silicon-rich steel is the same in the oil-quenched and water-quenched conditions, while that of a normal nickel steel is higher after oil-quenching than after water-quenching due to the contents of retained austenite.

As the steels are tempered above about 300°F, the silicon content imparts to both carbon and alloy steels a resistance to the softening effect of tempering. As a consequence, steels with a high silicon content (1.5 to 2.5 percent) when tempered at temperatures ranging from 400° to 600°F exhibit a nearly constant hardness (and tensile strength). These are considerably higher than those of low-silicon steels of otherwise identical composition, and more so the higher the tempering temperature, see Fig. 18 and Fig. 19.

It may also be mentioned here that the impact strength is similarly affected by silicon content. In most alloy steels tempering at temperatures between 500° and 700°F is avoided because of the low impact strength observed after such treatments. Steels, high in silicon, however, exhibit a corresponding embrittlement only after tempering at 650°F or higher.

While a high silicon content is disliked by steel producers, the increase of the tempering temperature and the associated reduction of the tempering effects has made recently developed steels, high in silicon, attractive for aircraft purposes. One such steel, containing 0.3 percent carbon, is finding application for steel parts, heat treated to strength values between 220,000 and 260,000 psi (Payson, Nehrenberg 1948).

Several, otherwise similar steels, containing 0.4 percent carbon, have been proposed for parts, to be heat treated to a strength between 260,000 and 300,000 psi (Crucible Steel; International Nickel).

The nature of the effect of silicon on tempering is not clarified. Many alloy steels exhibit a similar effect called "secondary hardening" and attributed to a precipitation reaction of unknown character. Investigations on steels of various silicon content lead to the concept that silicon retards the formation of sorbite during tempering (Allten, Payson 1953).

32. Effects of Boron on Aircraft Steels

Boron is used in heat-treated steels only for one purpose, namely to increase hardenability and, by virtue of this effect, to replace other alloying elements (Knowlton 1953).

At present, such a substitution in the aircraft field appears most promising for alloy steels having a comparatively low hardenability. For the two principal aircraft steels in this group, 4130 and 4140, containing 1.00 percent chromium and 0.20 molybdenum, boron-bearing steels have been proposed which contain only 0.30 percent nickel, 0.12 percent molybdenum and 0.25 (80B30) and 0.40 (81B40) chromium respectively. The hardenability and tension characteristics of these steels are equivalent to those of the 4100 series. However, sufficient experience with the boron steels has not been accumulated, to date, which permits evaluating whether or not they will be truly equivalent to 4130 and 4140 steels for high-strength applications.

This applies even more strongly to the 86B45 steel, containing 0.55 percent nickel, 0.65 percent chromium and 0.12 percent molybdenum which is proposed as a substitute for 4340 steel, containing 1.75 percent nickel, 0.80 percent chromium and 0.25 percent molybdenum. The boron addition in combination with the increased carbon content raises the hardenability of 8645 steel to a level comparable to that of 4340, Fig. 20. On the other hand, at the present time, quality considerations point towards the desirability of a reduced, rather than an increased carbon content in high-hardenability steels. In addition, the hardenability standards for 86B45 imply that even in the range of small section sizes, corresponding to a few sixteenths, this steel responds to a loss in hardness with increasing section, see Fig. 20, contrary to 4340 and other boron-free steels.

No attempts have been made to actually increase the hardenability of these aircraft steels by boron additions above that of 4340 steel.

A systematic study of the substitution effects of boron has been carried out in Germany for both heat-treatable and case hardening steels (Scherer, Bungardt, Kunze 1952). In constructional low-alloy steels it was found that less than 0.005 percent boron can replace either chromium or manganese up to 0.5 percent or molybdenum up to 0.15 percent. In case-hardening steels up to a total of 0.7 percent of nickel plus chromium plus manganese can be saved by boron treatment.

Boron, however, has no effect on the tension characteristics of a steel at different tempering temperatures. This is in distinct contrast to the effects of another element that increases hardenability and explains the fact that lower tempering temperatures must be used for boron steels than for boron-free steels to obtain equivalent properties.

For the same reason, boron-treated steels are softer in the annealed and normalized conditions than other alloy steels of equal hardenability.

33. Effects of Aluminum Additions to Heat-Treated Steels

The effects of aluminum on steels, in general, and on constructional low-alloy steels, in particular, are entirely different from those of any other element. Aluminum in very small amounts is always added to a low-alloy steel as "scavenger" or "deoxidizer" to prevent gas evolution and the associated non-uniformity of chemical composition, or "segregation". The resulting "killed steel" may be rather low in "cleanliness", or be "dirty", because of the presence of manganese sulphide inclusions. For this reason, aluminum additions are usually kept to the minimum which is necessary for the killing action. The amount of aluminum which exceeds that used up in the killing enters into solid solution with either the ferrite or austenite.

The addition of small amounts of aluminum also makes a steel "fine grained", while a steel low in aluminum is "coarse grained". These terms, if applied to heat-treated steels, refer to their grain structure at high austenitizing temperatures such as encountered on carburizing. A coarse-grained steel then becomes susceptible to large uniform or non-uniform ("duplex") grain growth while a fine-grained steel retains its normal structure. Such overheating also affects the properties of these steels differently, as a coarse grain is usually associated with brittleness. However, after proper heat treating, the structure and properties of a fine-grained (grain size ASTM 7 to 8) and a coarse grained (grain size ASTM 3 to 4) low-alloy steel were found to be practically identical, Fig. 21 (Swinden, Bolsover 1936).

Larger variations in aluminum content were also observed to be of negligible influence on the tension characteristics of a low-alloy steel

(Schrader, Wiester, Siepmann 1950).

On the contrary, differences in aluminum content account for part of the large variations reported for the impact strength of otherwise idenical steels. According to some test results, the impact strength of a heat-treated steel, in general, and after tempering at temperatures between 400°and 800°F, in particular, considerably increases if the aluminum addition is raised up to a certain limiting value. This only recently established effect now appears very important. Variations in aluminum content may explain the large variations usually encountered in impact tests and also in service performance for different heats of the same steel composition. Small laboratory heats repeatedly have been found to possess particularly low impact strength, possibly because of the small amount of aluminum used in their manufacture and retained in the solid steel (Sachs, Sangdahl, Brown 1950; Armour Institute).

34. Review of Development of High-Strength Aircraft Steels

Until a short time ago high-strength steel parts used in aircraft construction were made primarily in one steel composition, the 0.40 percent carbon, nickel-chromium-molybdenum steel 4340, Table I. This steel possesses sufficient hardenability to yield a fully martensitic structure on oil-quenching in section thicknesses up to three inches. It is being heat treated up to a tensile strength of 180,000 to 200,000 psi and has given, in general, satisfactory service. However, when heat treated to slightly higher strength levels difficulties in production and service were encountered.

These lead to the development of a number of steels competitive or partly superior to 4340 steel, Table I. There are three distinctly different stages or aims of this development.

One group of partly already known and partly new steels aim at a strength level of 220,000 to 240,000 psi. Apparently, 4340 steel is not considered a desirable steel for these applications because of its low impact strength. Other steels, all characterized by a carbon content of 0.25 to 0.3 percent, are favored for this strength range over 4340 steel. Such steels include a "modified 4330 steel", containing vanadium, and several proprietary steels. Of these steels, the manganese-silicon-nickel-molybdenum steel "Hy-Tuf", as well as the modified 4330 steel (also known as AMS-6427 steel), have already been successfully applied to landing-gear and other parts.

A second, more recent development is that of steels, heat treated to a strength of 260,000 to 300,000 psi. This strength range requires that the nominal carbon content of the steels be (at least) 0.40 percent. When tempered at about 400°F, 4340 steel fulfills this requirement and it is the first steel proposed for this high strength and is being tried out for landing-gear parts at present (1953). Several other steels have been suggested as competitive to 4340 steel, heat treated to such high tensile strengths.

Finally attempts are being made to substitute for 4340 steel for a number of applications with steels replacing part of the critical alloying elements with boron. The steels suggested for this purpose are 86B45 and 98B40.

A variety of steels are used in aircraft for smaller parts, heat treated to high strength. Among such steels are 4130, 4140 and 8740. Boron steels, particularly 80B30, and 81B40 have been suggested as substitutes for such steels (Imhoff, Poynter 1953; Knowlton 1953).

In the following articles data are presented for the hardness, tension characteristics and impact strength of these steels when quenched in small test sections and tempered at different temperatures, for short periods of time (1/2 to 2 hours).

35. British High-Strength Steels

British specifications provide "for automobile and general engineering purposes" the following alloy steels for use as "billets, bars and light forgings up to 6 inch ruling section"; heat treated to a minimum tensile strength of 224,000 psi (100 tons per sq. in.), Table II (British Standards Institution). This strength is obtained in all these steels in bar diameters up to their ruling section by oil-quenching (or air-quenching the highest alloyed steels up to 2-1/2 in. - dia.bars) from the appropriate temperatures and tempering at 400°F.

36. Mechanical Properties of 4340 Steel

The preferred steel for parts is 4340 steel, heat treated to a strength up to 200,000 to 220,000 psi. To obtain this strength it is quenched from 1500°F and tempered at a temperature close to 800°F, see Fig. 10a.

For the higher strength level of 220,000 to 240,000 the 4340 steel has not been admitted. Other steels, namely modified 4330 steel, see Fig. 10b and Hy-Tuf, see Fig. 10c are used to a limited extent in this strength range, apparently with full success. The restriction imposed on the 4340 steel is partly explained by the frequency of failures encountered on parts that were found to be stronger than the specifications permitted and partly by the comparatively low values of certain properties determined for this steel when tempered to the above strength.

On the other hand, it appears that 4340 steel if properly processed can be used at much higher strength levels than was believed possible in the past.

In order to obtain a strength of 260,000 to 280,000 psi, the heat treating of 4340 steel must take consideration of the variations in chemical composition allowed by the specifications. The following procedure has been suggested for this purpose (Lockheed Aircraft):

a) Normalize at 1600° ± 25°F for one hour per inch thickness of largest section of part, after reaching temperature. For heating in an air furnace about 2/3 of the time at temperature, for heating in a salt bath about 1/6 of the time at temperature is allowed to reach the soaking temperature.

b) Austenitize at 1500° ± 25°F for the same time as given in (a),

c) Quench in oil,

d) Determine the Rockwell "C" hardness of the as-quenched specimens or from the Jominy-hardenability curve,

e) Temper for four hours per inch thickness at the following temperature: If Rc = 56 or less at 400°F, if Rc = 57 to 58 at 450°F, and if Rc = 59 or above at 500°F,

f) Stabilize retained austenite at 250° ± 10°F for a minimum of 24 hr.

E. TENSION CHARACTERISTICS OF HEAT-TREATED STEELS IN LARGE SECTIONS

37. Summary of Variations Encountered in Large Sections of Heat-Treated Steels

The basic strength data are reported in the preceding sections for designing of aircraft parts and heat treating these parts. However, they are derived from the testing of sections which, in many instances, are considerably smaller than the actual parts. When it becomes desirable to evaluate the strength properties of such larger sections their testing presents a complicated problem, for a variety of reasons.

Even the testing of sections as small as 1-1/2 to 2 inch diameter round may yield different results depending upon the location of the specimen. These can be taken either in such a way that their axis is identical with that of the bar and contains material from the "core" or it can be taken close to the surface. As the section size increases additional specimens at various locations between surface and core can be tested. Frequently, uniform sections of moderate size are evaluated by means of specimens positioned halfway between surface and core or, in the case of rounds, at "one-half radius". Depending upon the testbar location the test results may vary considerably.

In addition to such longitudinal specimens heavy sections also permit taking testbars in other directions. The properties derived from such tests are generally inferior to those obtained from longitudinal tests. Furthermore, the definitions of longitudinal and other directions in complex shapes may require a special analysis.

Tests on large sections can be executed by two different procedures. The one method comprises preparing small specimens from the annealed or normalized parts followed by heat treating. It provides the inherent properties of the material as affected by specimen location and direction. The results of tests at corresponding locations and in equivalent directions may depend considerably upon the particular part tested. Most pronounced, in this respect, is the effect of the "as-processed section size". The magnitude of this effect may vary greatly, depending upon such factors as ingot size and details of its breakdown and processing to the final shape.

The other test procedure consists of sectioning the previously heat-treated part and machining specimens from it. It serves to determine the actual properties of a part which may considerably depend upon its "as-quenched section size" or "ruling section". The effects of location and direction and the "mass effect" of the as-quenched section size are superimposed on each other.

The most important change in mechanical properties caused by an increase in the size of the quenched part is that referred to as "slack-quenching", mentioned repeatedly in preceding articles.

Furthermore, test data generally also depend upon the "as-tested section size". Very little is known about this effect for high-strength steels. However, as far as tensile strength and yield strength are concerned, tests on full-size parts of uniform section appear to yield the same values as small test sections. In other respects, however, the effect of the as-tested section size may be large.

38. Effect of Specimen Location on Tension Characteristics of Heat-Treated Steels

The tension characteristics of a cast steel ingot may vary greatly depending upon the location of the specimen in the ingot. These variations are caused by segregations of certain elements of the steel as well as by porosities and inclusions which favor certain portions of the ingot.

Hot working and cold working the cast ingot by either forging or rolling improves the properties of the steel, in general, and particularly those of the portions of the ingot which were highly deficient in the cast condition. It is commonly believed that if the reduction of the ingot, measured by the change in section size from that of the ingot to that of the product, is large the properties of the product, after proper heat treating, have become uniform. This conclusion is probably based on the fact that the small bars which generally serve to evaluate the properties of a steel are found to possess properties which are very consistent along the length of the bar and also over the cross section of the bar.

This also applies to the high-strength steels. It appears that the properties of longitudinal specimens taken as closely as possible to the surface will substantially be the same as those of specimens which contain the material of the center, or "core", of the bar, if the section is sufficiently small. Conversely, in somewhat larger sections a distinct difference between surface and core may be observed, Fig. 22 (Pomp, Krisch 1942). This difference is usually limited to such properties as reduction of area and impact strength which depend upon the ductility of the steel. On the other hand, the tensile strength, yield strength and hardness of steels are generally not affected by the specimen location.

In this connection, the results of an investigation on a very large forging (Ammareller 1950), approximately 32 inches in diameter, made in a 0.37C - 1.1Mn - 0.28 Mo steel and heat treated to 100,000 psi, may be of interest. In these tests, nearly constant values of tensile strength and yield strength were obtained at all positions and in all three directions; the longitudinal, the radial, and the circumferential. The reduction of area in the longitudinal direction also varied only between about 55 percent near the surface to minimum values near 45 percent at locations intermediate between core and surface. However, very large variations in this quantity were observed in the other two directions, between over 50 percent and under 20 percent. The lowest values again occurred some distance apart from the center of the forging. The impact strength corresponded roughly to the reduction of area. Its minimum value in the longitudinal direction was slightly over 50 percent of the maximum value near the surface, while the maximum values in the other directions were between 70 and 90 percent, and the minimum values as low as 10 percent of the maximum value in the longitudinal direction.

39. Definitions of Directionality and Transverse Directions

Furthermore, in any worked section on "wrought"material, the ductility of transverse specimens is found to be considerably lower than that of similarly located longitudinal specimens, see Fig. 22. This effect is called "directionality", or "fiber".

The longitudinal direction of sections other than rounds is that of their greatest extension during working, for example, the rolling direction of sheet, plate, square and rectangular sections. The transverse directions are basically of two types, the "short-transverse" direction being that in the minimum dimension of the product and the "long-transverse" direction being perpendicular to both the longitudinal and short-transverse directions. In the case of rounds, squares, hexagons, etc., the short- and long-transverse directions are the radial and circumferential directions, and these must possess identical properties by reasons of symmetry. Similarly, in the case of an upset disk, the longitudinal and long-transverse directions are the radial and circumferential directions, and these must possess identical properties.

Special consideration must be given to these directions in complex forgings. In many instances, the longitudinal direction is identical to the "fiber" of the part consisting of elongated crystals and inclusions and made visible by etching.

The properties in the long-transverse direction are usually intermediate between those of the other two principal directions. This also applies to any other direction. Directions within the plane formed by the longitudinal and short-transverse direction are also designated by the angle which they form with the longitudinal direction.

40. Transverse Properties of Heat-Treated Steel Bars

The difference between the properties in the transverse and longitudinal directions of a steel depends upon a variety of factors.

It greatly increases with the hardness or strength level of the steel, Fig. 22 and Fig. 23 (Pomp, Krisch 1942; Sachs, Lubahn, Ebert, Aul 1945; Benkoe 1949; Menasco). The reduction of area of longitudinal specimens only decreases by a rather small amount as the strength increases and it remains quite high even at extremely high strength values. On the contrary, at the same time the ductility of transverse specimens decreases rapidly to assume very small values at very high strength levels.

Very little evidence is available regarding the dependence of transverse properties upon other chemical, metallurgical, and processing factors. In addition, such effects may be overshadowed by the large differences which are found to occur in the same type of product if manufactured by different companies or perhaps even if manufactured by the same company at different times, see Fig. 22. This is in agreement with observations on other metals, such as aluminum alloys. It indicates that transverse properties are greatly affected by some unrecognized factors in ingot-forging, -rolling, and, -heating practices. Considering the great practical significance of this problem for the application of heavy forgings, it appears highly desirable that definite data on this subject be secured.

The chemical composition of the steel is probably a minor factor for the transverse properties. Data available for steels as different as 2340 steel, see Fig. 23, and 4340 steel, see Fig. 24, reveal substantially the same general behavior. Furthermore, some tests on 6 in. dia. bars in the slack-quenched condition also yielded nearly identical test results, in this respect, for 4340 and 98B40 steel, see Fig. 25 and Fig. 26.

General, but scattered information suggests that the transverse properties depend upon the location of the specimen. Wherever specimens have been taken at different distances apart from the surface those closest to the surface generally exhibit superior ductility. One such example are the slack-quenched 6 in. dia. bars, mentioned above.

The effect of (as-processed) section size can be deduced from several investigations on bars of different diameters produced by the same manufacturer, Fig. 22 (Pomp, Krisch 1942) and Fig. 23 (Sachs, Lubahn, Ebert, Aul 1945). In these instances, the smaller of two bars investigated exhibited higher values of reduction of area in the core. This result disagrees with the common concept that extreme elongating may greatly weaken the transverse cohesion, such as exemplified by the laminating or even bursting of some such products.

41. Miscellaneous Directionality Effects

The properties of steels change progressively as the testing direction moves from the longitudinal to a transverse direction. The results of a few tests on specimens cut from a heavy forging under 45 degrees to the fiber direction are in agreement with this concept, see Fig. 24 (Cleveland Pneumatic Tool). The 45-deg. specimens yielded a reduction of area between that of longitudinal and transverse specimens in a 2-3/4 in. dia. bar at various strength levels.

The ductility of 2340 steel tubes in the circumferential direction, determined by means of bursting tests using internal pressure, was also found to be rather low and to follow the same trend with respect to its dependence upon the strength level as the transverse ductility of bar stock, see Fig. 23 (Sachs, Lubahn 1943). The circumferential direction is basically a long-transverse direction. The very low ductility values observed, however, are partly explained by the testing technique which presumably lowers the ductility. On the other hand, the tensile strength is not materially affected by the method of its determination if the tube is thin walled.

The low ductility of 45-deg. specimens at high strength levels also explains, in part, the low ductility of flashwelded parts. In this process, the hot portions of the two parts in contact mushroom under the applied pressure while their surfaces weld together. Upsetting tests on a solid length of bar showed that the resulting change in the fiber direction, Fig. 27, caused a considerable decrease in the ductility in the longitudinal direction, in much the same manner as changing the specimen direction (Menasco). In addition, overheating of the upset section was found to result in extremely low ductility values.

42. General Remarks on Effects of Section Size and Cooling Rate

In the preceding chapters of this report, the properties of small-size test bars with a predominantly tempered-martensite structure were discussed. These specimens were usually heat treated close to the finished size, but occasionally also specimens were included in the discussion that had been machined from larger, fully-hardened sections and presumably exhibited the same properties as small test bars.

In this chapter, however, the effects of the as-quenched section size will be discussed under the assumption that the material, before quenching, possessed identical properties in all section sizes. Such tests on sections machined from a uniform oversize section apparently are not available. As a rule, the different section sizes investigated were processed to this size. Consequently, any of the effects discussed may be distorted by the effects of the as-processed section size and of the specimen location as described in the preceding chapter.

The effects of section size are basically effects of cooling rate. The hardnesses resulting from cooling a steel at different rates are commonly derived from a Jominy hardenability test. Each distance of this test bar from the quenched end corresponds to a different cooling rate and consequently also to certain fibers of water- and oil-quenched rounds, see Fig. 3 (Boegehold 1941). However, whether this simple concept also applies to high-strength constructional steels and entirely explains their properties in different section sizes is not yet clarified.

The common concept of a deep-hardening steel, such as the steels used for major aircraft application, is that of a steel the properties of which in sections up to a limiting size are often heat treated substantially the same as those of much faster cooled test bars. As far as all tension characteristics and hardness are concerned, this was found to be true in a number of instances such as for an 0.3C - .25 Ni - 0.75 Cr - 0.50 Mo steel, Fig. 28 (Swinden, Bolsover 1936) and for the high-strength steel, Hy-Tuf, Fig. 29 (Payson, Nehrenberg 1948).

43. Effects of As-Quenched Section Size on Properties of High-Strength Steels

The small differences in the properties for different section sizes appear insignificant and are usually neglected. The slight increase in tensile strength and yield strength with increasing section size may be attributed to a corresponding reduction in austenite content. Apparently, no other tension characteristics respond to this variation.

It may be pointed out, however, that recent tests clearly revealed that a given hardness and strength, at the commercially maximum level, may be associated with a pronounced decrease in either notch-tensile strength (Sachs, Sangdahl, Brown 1950) or notch-impact strength (Troiano, Klingler 1952) when the section size increases beyond a certain value which is considerably below that at which a decrease in hardness or tensile strength is noticed. This applies particularly to chromium and manganese steels, while nickel steels were found to be less affected by the section size, in this respect.

If the section size increases beyond a critical value, the hardness, tensile strength and yield strength decrease. Different heats of the same steel type may respond quite differently to such slack-quenching depending upon their hardenability, see Fig. 29 (Payson, Nehrenberg 1948). In very large sections of such a steel type, therefore, the tension properties may vary from part to part within wide limits.

Other tension characteristics, particularly reduction of area as well as impact strength, do not respond in a simple manner to an increase in section size. It appears that small deficiencies in tensile strength and hardness may be associated with considerable decreases in reduction of area and impact strength. On the other hand, a considerable loss in tensile strength usually causes reduction of area and impact strength to increase.

These effects of section size are most pronounced in the as-quenched and other very hard conditions. As the tempering temperature is increased, the deviations of the properties of slack-quenched material from those of tempered martensite become smaller, see Fig. 26.

Depending upon the hardenability of the steel, the effect of slack-quenching becomes apparent at a certain section size and progresses as the section size increases, Fig. 30 (Pomp, Krisch 1942), see also Fig. 29. Tensile strength and yield strength appear to decrease nearly in proportion to the difference between actual bar diameter and the critical bar diameter at which slack-quenching is first apparent. At the same time, reduction in area and impact strength may either decrease or remain nearly constant and increase only if the loss in strength becomes quite large. The elongation generally responds only slightly to slack-quenching.

Attempts have been made to evaluate the response of the mechanical properties of a steel to slack-quenching by determining the properties of transverse slices of modified Jominy hardenability specimens (Carnegie Institute). The data obtained by this procedure, to date, relates to steels possessing comparatively low hardenability and the variations in strength properties observed, therefore, were large and complex and cannot be clearly evaluated. The data discussed above for test bars of various diameters are also deficient in that they generally cover only incompletely the range in which the effects of slack-quenching become first noticeable and which is of primary interest for aircraft applications of high-strength steels.

44. Properties at Different Locations of Slack-Quenched High-Strength Steel Bars

The properties of a slack-quenched steel bar may differ considerably depending upon the location from which the test bar is taken. Basically, these variations may be caused by two factors; namely, the different cooling rate on the one hand, and the inherently different properties of the different fibers of a large section on the other hand. These latter variations in mechanical properties with the distance of the tested, identically treated, section from the surface (or center) of the bar were discussed in a preceding article. In this respect, only such properties as reduction of area and impact energy were found to be affected, while tensile strength, yield strength, and hardness of any fiber of a large section were found to respond in nearly the same manner to a given heat-treating procedure.

Variations in these properties: tensile strength, yield strength, and hardness, consequently illustrate clearly the effects of slack-quenching on the distribution of the mechanical properties in a large section. According to expectation, these quantities are usually found to increase as the distance of the test bar from the center of the heat-treated bar increases, in relation to the cooling rate of this fiber. However, various investigations on large sections heat treated to high strength values by oil quenching and tempering revealed that these differences in strength and hardness may vary greatly. The conventional typical behavior is illustrated by a series of bars of different diameters of which the strength and hardness is lower and varies more the larger the cross section, Fig. 31 (Iron Steel Institute). The tension characteristics of a particular large size will then be found to vary greatly over the cross section, such as in the case of 4 in. dia. bars of modified 4330 steel quenched and tempered at 700°and 1150°F respectively, Fig. 32 (Dirkes, Bowman, Horne 1952).

On the other hand, as already mentioned in the preceding article, it has been repeatedly observed that the strengths of surface and core specimens of a large section may be at nearly the same, low level. This has been found to be true also for 6 in. dia. bars of 4340 steel, Fig. 25, and 86B45 steel, Fig. 26 (Armour Institute).

The decrease in the values of reduction of area from the surface to the core observed in these tests may be attributed to differences in the inherent properties of the material, rather than considered to be an effect of slack-quenching. This also applies, to a more pronounced extent, to the reduction of area in the transverse direction, see Fig. 25 and Fig. 26. However, these effects may be overshadowed by an increase in reduction of area in those instances where the strength of the core is considerably below that of the surface, see Fig. 32.

45. Differences Between Slack-Quenched Material and Tempered Martensite

Comparing the changes in mechanical properties caused by slack-quenching with those of tempering a steel, the following can be deduced from the data presented in the preceding articles.

A loss in strength by slack-quenching (without or with tempering at low temperatures) is also accompanied by a corresponding loss in yield strength, while the decrease in strength caused by tempering only slightly affects the yield strength. The yield-strength ratio of slack-quenched material, therefore, remains always rather low and it is, particularly in the range of 150,000 psi to 200,000, usually considerably lower than that of steels which were quenched and tempered to equal strength.

The reduction of area of slack-quenched material also responds to a progressive decrease in strength considerably less than that of a steel tempered to increasingly higher temperatures. In addition, it appears that low values of reduction of area may be associated with steels of certain compositions and slack-quenched under certain conditions. However, little is known about these factors which may produce such conditions of low ductility. This also applies to the impact strength.

Tempering of slack-quenched material at increasingly higher temperatures produces effects similar to those observed in fully-hardened test bars in the different properties. However, at low and intermediate tempering temperatures the response of the slack-quenched material to tempering is very slow, and in regard to the yield strength, it may be even opposite to that occurring in tempered martensite, see Fig. 25 and Fig. 26. As a consequence, for steels possessing a tensile strength up to a value as high as 200,000 psi, the effects of slack-quenching may have become rather small. At still lower strength levels it may appear to have faded out except for the fact that the yield-strength ratio always remains lower than that of tempered martensite, in proportion to the slack-quenching effect present before tempering.

F. EFFECTS OF HEAT-TREATING VARIABLES ON TENSION CHARACTERISTICS OF HEAT-TREATED STEELS

46. Summary of Heat-Treating Variables

In the preceding chapters, the tension characteristics of steels heat treated to the basic structural condition of tempered martensite were discussed in detail. In summarizing the results of tests on tempered martensites, it can be stated that under closely controlled testing conditions the variations in test results are primarily explained by variations in the chemistry and in the processing of the steel. It appears that these effects overshadow those of small variations in preparing and heat treating the specimens.

On the other hand, heat treating of large sections and heat treatments different from conventional quenching and tempering may produce properties which greatly differ from those of tempered martensite. Particular attention is now focused on the condition of slack-quenching which is always present if the section size of a steel exceeds a certain limit given by its hardenability. In addition, proper quenching of an intricate part is difficult and practical experience indicates that such parts frequently contain slack-quenched areas at locations where the circulation of the quenching medium was hindered. In this chapter particularly, the results of systematic tests will be described aimed at a rational explanation of the effects of slack-quenching.

In addition, data on the comparatively small effects of variations in heat treating will be presented in this chapter. These are of various types and their nature and full significance is frequently obscure. Systematic investigations performed in the last decade, however, revealed that such effects may be of particular importance for high-hardenability steels, heat treated to very high strength values. Among these variables are the temperature of normalizing which usually precedes the austenitizing, the temperature (and time) of austenitizing, and the quenching medium or quenching rate.

The tests discussed in the following articles relate again to small-size, regular tension specimens. Subsize specimens have been frequently used in studies of this nature in order to insure the extreme conditions of heat treating desired.

47. Effects of Normalizing and Austenitizing Temperatures on Tension Characteristics of Heat-Treated Steels

Low-alloy steels generally contain carbides of alloying elements. These carbides vary greatly in size depending upon whether the steel is heat treated, normalized (air cooled), or annealed (furnace cooled). While the carbides are of a submolecular size in steels quenched and tempered at very low temperatures, they increase in size with the tempering temperature. In normalized steels the size of the carbides depends upon the hardenability of the steels but it is always smaller than in annealed steels. Particularly large carbide particles are the globules found in steels after a "spheroidizing" anneal which serves to produce maximum softness for purposes of machining or forming.

The solution of the carbides during the austenitizing treatment requires some time which is greater as the particle size of the carbides increases. This explains the observation that a high-hardenability steel, such as 4340 steel, requires in the annealed condition several hours of heating at the austenitizing temperature in order to attain its normal tension characteristics and, particularly, impact strength on quenching and tempering, Fig. 33 (Welchner, Rowland, Ubben 1944). It is general practice, therefore, to normalize a low-alloy steel before its actual heat treating. As a result, the temperature and time of either normalizing or austenitizing have been considered negligible factors in the past, provided that excessive grain coarsening or decarburization were avoided.

Recent investigations, however, revealed that the temperatures of both normalizing and austenitizing may markedly affect the properties of heat-treated steels, Fig. 34 (Eilender, Arend, Neuhaus 1952). It was particularly observed that the hardenability of the investigated manganese-chromium-vanadium steel increased as the temperature of normalizing was raised, while an increase in the austenitizing temperature produced slightly higher as-quenched strength and hardness.

The structure of a steel prior to quenching also affects its response to hardening (Welchner, Rowland, Ubben, 1944). Full hardenability by the Jominy method is obtained with either 4140 steel or 4340 steel, if hot-rolled, normalized, or hardened, within a very short time on heating to 1525°F, while annealed material requires more than one hour and spheroidized material more than four hours at this temperature. If 40 minutes are allowed for austenitizing, the minimum hardening temperature for the normalized condition is 1500°F, while the annealed condition is still incompletely hardened at 1600°F.

48. Differences in Tension Characteristics of Oil-Quenched and Water-Quenched Steels

On quenching a steel at cooling rates which result in a fully-hardened condition a certain amount of austenite, up to about 10 percent, may not be transformed into martensite. This tendency to retain austenite at room temperature depends upon the chemical composition of the steel (French 1949; Cohen 1949). It increases particularly with increasing amounts of both carbon and nickel in the steel.

More austenite, if any, is formed after quenching in oil than after more radical quenching in water, or water containing certain compounds which favor rapid cooling due to suppressing vapor formation, such as a salt solution ("brine") or caustic-soda solution.

As a consequence, the tensile strength, yield strength and hardness of oil-quenched specimens of certain steels, such as nickel-chromium steels, are usually observed to be considerably lower than those of water-quenched specimens, Fig. 12 (Carnegie Institute).

These steels are more brittle after water-quenching than after oil-quenching, and a slight difference in ductility (reduction of area) has then been found to be retained also after tempering at low temperatures.

On the other hand, if a steel has little tendency to retain austenite, such as 5140 steel, it has been observed that the water-quenched and oil-quenched conditions possess equal strength, Fig. 35 (International Nickel). Some observations on this steel also indicate that the reduction of area of the more radically quenched specimens may then be slightly superior to that of oil-quenched specimens.

Furthermore, the yield strength of oil-quenched material has been frequently observed to be particularly low, as compared to that obtained after water-quenching, see Fig. 12 and Fig. 35.

Various effects are superimposed to yield the general trends of property changes caused by tempering if oil-quenched and water-quenched specimens are compared to each other.

Apparently, the first such effect is an increase of the yield strength of oil-quenched material to a level which corresponds to that of the tensile strength. If little austenite was present, such as in 5140 steel, the yield strength values of both the oil-quenched and water-quenched conditions then become identical, see Fig. 35. Otherwise, their difference then conforms to that resulting from retained austenite, see Fig. 12. This increase in yield strength clearly occurs at very low tempering temperature and short tempering times which are insufficient to decompose austenite. On the contrary, if the tempering temperature exceeds about 450°F the austenite transforms and, as a consequence, all properties of the steels after both oil-quenching and water-quenching approach equal values, see Fig. 35. The experimental evidence in this respect is rather incomplete, but the phenomena connected with the cold treatment of such steels as discussed in the subsequent article can be considered as a confirmation of the above conclusions.

The differences in the reduction of area of steels after water-quenching and oil-quenching, respectively, are usually very small and are frequently obscured by the scattering in these values. Thus, in general, differences in austenite content appear to affect reduction in area only to an insignificant extent. On the other hand, the different quenching methods may account for some differences in reduction of area, see Fig. 35, which cannot be explained at present. Variations in elongation due to the phenomena discussed above are generally of no significance.

49. The Effects of Austenite Decomposition by Refrigerating on the Tension Characteristics of Heat-Treated Steels

Another possibility to study the effects of differences in austenite content arises from the fact that the martensitic transformation becomes more complete as the quenching temperature decreases (Cohen 1949). Therefore, use is being made of cooling steels to very low temperatures, in particular to those of liquid air or nitrogen, or about -300°F, to reduce the austenite content of tool steels and occasionally also of constructional high-strength steels. The effect of such "cold treatment", "freezing", or "refrigerating" is greater the earlier this treatment follows quenching, and repetitions of it are also effective, but with rapidly diminishing returns.

As is to be expected, refrigerating was found to have practically no effect on the properties of a steel which presumably contains no or very little austenite after quenching. Such a condition apparently prevails in a water-quenched, low-carbon, nickel-chromium-molybdenum-vanadium steel, Fig. 36 (Carnegie Institute).

Refrigerating of oil-quenched steels which contain retained austenite produces effects very similar to, and possibly identical with, the differences between oil-quenched and water-quenched specimens, discussed in the preceding article. Therefore, as is to be expected, refrigerating was found to increase the tensile strength slightly and the yield strength considerably more if a steel retained austenite, such as a nickel steel (Castleman, Averbach, Cohen 1952) or a 4340 steel, Fig. 37 (Menasco). Other effects, such as a slight decrease in reduction of area and impact strength are also possible (French 1949; Bailey, Harris 1950; Sachs, Sangdahl, Brown 1950).

The different tempering effects observed on oil-quenching steels with or without a subsequent cold treatment respectively are also identical with those discussed above for oil-quenched and water-quenched specimens respectively. The tensile strength and yield strength of a steel which retains austenite, such as 4340 steel, gradually approach each other as the tempering temperature increases, see Fig. 10a. In this process the yield strength of oil-quenched specimens may first slightly increase or remain practically constant over a considerable range of tempering temperatures.

In this particular steel, 4340, the effect of refrigerating on the tensile strength was found to be retained, to a considerable portion, on tempering to temperatures between 400° 500°F up to very long tempering times, Fig. 38 (Menasco). During this treatment, the tensile strength of both conditions decreased by nearly 5 percent. The same applied to the yield strength of the non-refrigerated specimens. On the contrary, the yield strength of refrigerated specimens first increased slightly or remained constant, and only after a long tempering time it assumed the downward trend which represents the regular tempering effect.

In these investigations the effects of retained austenite on the reduction of area and elongation were found to be practically nil.

50. Tension Characteristics of Tempered Martensite-Austenite Mixtures

It has been disclosed by the experimentation discussed in the preceding article that small amounts of transformation products resulting from tempering retained austenite were found to be of only slight significance on the properties of steels containing predominantly tempered martensite.

This conclusion has been confirmed by more systematic tests in which mixtures of tempered martensite and tempered austenite in various proportions were produced by the following procedure. The steel was quenched into a medium held at a temperature between room temperature and the martensite point, at which the martensitic transformation begins. The quenching temperature may range from that of liquid nitrogen (-320°F) to over 500°F. Subsequently, the specimens were transferred to the tempering bath in which the decomposition of the austenite (into intermediate transformation products) was carried to completion. This method enabled transforming a given steel into mixtures ranging from substantially 100 percent tempered martensite (1 percent tempered austenite) to 10 percent tempered martensite and 90 percent tempered austenite.

The tension characteristics of such mixtures, containing up to 40 percent tempered austenite, were found to be much the same as those of a steel of which the as-quenched strength was reduced and the reduction of area increased in proportion to the content of tempered austenite,

Fig. 39 (Bailey, Harris 1952). This is explained, but only in part, by the fact that tempered austenite, or austempered steel, is generally softer than tempered martensite.

More elaborate tests of the same nature, in which transverse specimens were tested, showed, furthermore, that the relation between reduction of area and tensile strength was only slightly affected if the content of tempered austenite did not exceed 40 percent, Fig. 40 (Carnegie Institute).

The yield strength of such mixtures, however, appeared to be distinctly below that of tempered martensite of equal strength, see Fig. 39.

Specimens which contained predominantly tempered austenite exhibited properties, in these tests, which were quite different from those of a tempered martensite of equal strength. It may be particularly noted that the reduction of area of these mixtures rich in tempered austenite exceeded those of tempered martensite if their strength (and hardness) was high, or in the vicinity of 200, 000 psi, see Fig. 39 and Fig. 40. On the contrary, at low strength levels the ductility of specimens high in tempered austenite was found to be considerably below that of tempered martensite.

The elongation of tempered martensite, in the range of high strength values, appears to be adversely affected by the presence of tempered austenite in amounts up to 40 percent, see Fig. 39.

51. Tension Characteristics of Austempered and Patented Steels

The tempered austenite obtained on isothermal decomposition at different temperatures after preceding quenching to considerably lower temperatures appears to differ from that resulting from "austempering" at the same temperature without preceding quenching and creation of martensite. This conclusion can be derived from the fact that all tension characteristics of austempered material were found to be distinctly different from those of a mixture containing 90 percent tempered austenite and 10 percent tempered martensite, see Fig. 39 (Bailey, Harris 1952).

The tension characteristics of austempered steels are considerably different from those of tempered martensites, according to tests on a high-carbon steel, Fig. 41 (Gensamer, Pearsall, Smith 1940). These revealed particularly that the reduction of area may be very low if the steel is austempered within certain temperature ranges, while a comparatively high ductility is associated with very high strength levels. Very large variations in the reduction of area at various austempering temperatures were also observed in a nickel steel, see Fig. 39 (Bailey, Harris 1952).

Partly austempered steels are probably the starting material for lead-patented wire. Testing of patented, undrawn wire disclosed that it usually possesses a low ductility, Fig. 42 (Godfrey 1942). The hot drawing of the wire after leaving the lead bath results not only in a progressively increasing tensile strength, but also in progressively increasing reduction of area and bending quality. The nature of this phenomenon has not yet been clarified.

Such wire in 1065 and 1075 steels, heat treated to strength values between 280,000 and 300,000 psi, has been found to possess higher ductility in bending and torsion than the same wire, conventionally heat treated to the same strength as the undrawn patented wire and subsequently drawn in the same manner as the patented wire (Walzel, Mitsche 1936). The tensile strength of such wire was also considerably lower than that of the patented wire.

52. Tension Characteristics of Tempered Slack-Quenched Steels

Systematic investigations on mixed structures of steels are primarily aimed at an evaluation of the properties of slack-quenched steel products. However, the results of the systematic tests on mixtures of tempered martensite and tempered austenite, discussed in a preceding article, are of little significance for the properties of slack-quenched steels. The structure of slack-quenched steel parts contains one or more intermediate transformation products, such as ferrite, pearlite, feathery or acicular structures (bainite), in addition to (tempered) martensite. These intermediate structures are formed first and they are much softer than the martensite present after quenching. This process is quite different from that used to obtain mixutres of tempered martensite and tempered austenite which were heated at the same temperature and which are comparatively close to each other in strength and hardness. It is not surprising, therefore, that tests on such materials failed to throw any light on the embrittlement phenomena occasionally observed in slack-quenched steel products.

53. Tension Characteristics of Mixtures of Austempered Products and Martensite

A few systematic tests were made to obtain mixtures of the same type as those found in slack-quenched material by quenching a specimen first into high-temperature bath, holding in the bath for different times and then quenching in the regular manner. The resulting structure contains varying amounts of intermediate transformation products within a matrix of martensite. Investigations on a 5140 steel, austempered for various time periods at 860°F, subsequently oil-quenched and finally tempered at 300°F (to relieve quenching stresses) revealed that extremely brittle conditions were obtained if the content in intermediate transformation products ranged from an extremely small amount to about 50 percent (Sachs, Ebert, Brown 1948). Because of this brittleness it was not possible to perform tension tests on such material. Tempering at 900°F relieved the embrittlement and produced tension properties which approached those of tempered martensite. Tests on notched tension bars more accurately established the embrittlement, which had been also observed in earlier impact tests on similarly-treated specimens of several steels.

Additional test data are available for 4340 steel which was quenched into a lead bath and held for 5-1/2 minutes at 800°F before quenching in oil (AISI). This treatment developed 50 percent of the intermediate transformation product (formed at 800°F) and 50 percent martensite. After tempering at 500°F the tensile strength of this mixture was about 10 percent and the yield strength about 20 percent lower than those of tempered martensite, but these differences gradually decreased as the tempering temperature increased. Similar observations were also made on 8630 steel.

In this connection, the results of some tests on quenching a manganese-chromium steel of comparatively low hardenability in various media may be referred to, Fig. 43 (Schrader, Wiester, Siepmann 1950). Water-quenching presumably resulted in tempered martensite, while oil-quenching and air-quenching produced a slack-quenched condition of varying degree. These tests revealed that such material which after quenching is found to be less strong than martensite may be considerably more susceptible to secondary hardening. This may result in a higher tensile strength, yield strength, and hardness of the oil-quenched than of the water-quenched specimens after tempering at certain temperatures. The entire trend of the property changes on tempering of these conditions was found to be very complex and cannot be definitely explained, at present.

G. DEPENDENCE OF THE TENSION CHARACTERISTICS OF HIGH-STRENGTH STEELS ON THE TESTING TEMPERATURE

54. General Summary of Effects of Testing Temperature on High-Strength Steels

The basic mechanical properties of a metal are determined by means of tests at room temperature which may be anywhere between 60° and 100°F, or 80 ± 20°F. Within these limits the variations of temperature are of no significance for the properties of steels, in general, and high-strength steels, in particular. From the data reported in the subsequent articles it can be seen that the tension characteristics of high-strength steel remain practically constant, i.e. change within, say, less than ± 3 percent, if the temperature of testing varies by approximately ± 50°F.

On the other hand, if the temperature at which a part is used differs from room temperature by a greater amount, the effects of temperature may have to be considered. This applies particularly to elevated temperature, as the strength of most metals, including the high-strength steels, decreases as the temperature increases. This effect is gradual and it is the only effect of moderate elevated temperatures to be considered for the design of high-strength steel parts.

However, if the temperature of usage exceeds a certain limit depending upon composition and heat treating of the steel, it becomes susceptible to another effect, namely that of the duration of load application. Below this temperature limit a steel possesses a strength that is practically constant for different rates of loading. Therefore, failure does not occur if the loads remain a few percent below the tensile strength. In contrast, at high temperatures, regular static tests yield values considerably higher than loads which lead to failure after a long time.

Temperatures materially below room temperature appear to be of little significance for the performance of heat-treated steel parts. While it is true that the ductility of a steel generally becomes smaller as the testing temperature decreases, this effect is rather gradual even for steels, heat treated to a very high strength. No failures have been reported which could be associated with an effect of low temperature and, particularly, heat-treated steels appear to be entirely free from the low-temperature, notch and impact sensitivity which is prevalent in many annealed steels.

Peculiar effects may result from cold working a high-strength steel, in respect to its low-temperature ductility. These seem to throw some light on the source of the low impact strength at room temperature.

55. Effects of Elevated Temperatures on Tension Characteristics of High-Strength Steels

The tension characteristics of most heat-treated steels are adversely affected if the temperature of application is higher than room temperature. In this respect, two effects must be distinguished; namely, first a temporary, or "ambient", effect and second a permanent effect. The ambient effect consists of a lower strength when testing is conducted at elevated temperatures but recovery of the original properties when testing is again conducted at room temperature. A permanent decrease in strength, on the other hand, may occur when the steel is subjected to temperatures above or slightly below its initial tempering temperature for a considerable period of time. The presence of this additional tempering effect explains the observation that a steel, heat treated to a high strength level, may become inferior to a steel having a lower strength if used or tested at a too high temperature. This is of significance for the future application of high-strength steels as temperatures close to or above their initial tempering temperature will be occasionally encountered.

The limited amount of test data available on the short-time tensile characteristics of high-strength steels indicates that 4340, 4130, and 4140 steels belong to those steels which are already adversely affected by a slight increase of the testing temperature above room temperature, Fig. 44 (Smith, Seens, Dulis 1950; Trapp 1952; North American; Syracuse University) and Fig. 45 (North American). On the other hand, more complex steels similar to those now being proposed and already used in aircraft are known to nearly retain their room-temperature properties at elevated temperatures up to about 800^{o}F, Fig. 46. Certain alloying elements, such as silicon, also impart to a steel the property of retaining its strength on tempering in this temperature range, and this phenomenon is probably also related to the resistance of a steel at elevated temperatures.

The changes in the various tension characteristics of a steel, such as 4340 steel, on raising the testing temperature follow a complex pattern, see Fig. 44. The simple behavior which is encountered in pure metals comprises a decrease in tensile strength and yield strength and a simultaneous increase in elongation and reduction of area with increasing testing temperature. The changes in the properties of a heat-treated steel frequently differ from this trend in that the reduction in area decreases within a certain temperature range and that the tensile strength simultaneously exhibits a bump. These are superimposed to the general pattern and they are explained by precipitations of certain phases which occur simultaneously with or after cold-working. The knowledge of these phenomena is very incomplete.

56. Creep and Stress-Rupture Strength of High-Strength Steels

The tensile strength of heat-treated steels at and below room temperature is practically independent of the rate of loading. Loads within 10 percent of the tensile strength, therefore, can be and have been applied to these steels without occurrence of rupturing.

However, if such loads close to the short-time strength are applied at temperatures above a certain limit, failure will occur at a time that increases as the load stress decreases, Fig. 47, or in other words, the strength of the steel is lower the longer the time-to-failure. Under such conditions the strength of a material is designated "stress-rupture strength". While most aircraft steels become susceptible to this pronounced time effect at rather low elevated temperatures, some specially-developed low-alloy steels for high-temperature applications may exhibit a very small effect of time-to-failure on the strength up to a temperature of about 700°F, see Fig. 46 and Fig. 47.

However, as the temperature is raised above this limit the stress-rupture strength for long times-to-failure becomes increasingly lower than that for short times. Also, the effect of composition becomes then rather pronounced, Fig. 48 (Smith, Seens, Dulis 1950).

At such temperatures any steel gradually deforms, or "creeps", until it fails, at a rate that increases with increasing load (and temperature) and also varies with time. Common aircraft steels, heat treated to high strength values, exhibit pronounced creep already at 600°F, Fig. 49 (North American).

57. Tension Characteristics of High-Strength Steels at Low Temperatures

Hardness, tensile strength and yield strength of a ferritic steel generally increase as the testing temperature decreases. The magnitude of each of these effects decreases with increasing strength level and it is not noticeably different for different steel compositions, Fig. 50 and Fig. 51 (Johnson, Oberg 1933; Krisch, Haupt 1939; Krisch 1942; Wiester 1943; Zambrow, Fontana 1949; Spretnak, Fontana, Brooks 1951; Johnson, Shinn 1952).

The yield strength of a steel generally increases with decreasing temperature at a faster rate than the tensile strength. This leads, for an annealed or normalized steel, frequently to a brittle condition on testing in tension at a certain, very low temperature at which the tensile strength decreases suddenly to a much lower value.

On the contrary, tests on a 0.4 percent-carbon manganese steel, heat treated to strength values up to 300,000 psi, indicate that the tensile strength of constructional steels continues to increase down to temperatures as low as minus 320°F, Fig. 52 (Ripling 1950, 1951; Ripling, Baldwin 1951).

The reduction of area of steels, in general, and probably including all heat-treated steels, decreases at a slow rate with decreasing temperature down to a certain limiting temperature and it then becomes rather small within a narrow temperature range. However, the tests on the above-discussed manganese steel showed that such embrittlement occurs at temperatures above minus 200°F only if the steel was heat treated between 500° and 700°F, see Fig. 52. As a consequence, within a certain range of testing temperatures, specimens which were tempered at 500° to 700°F exhibited considerably lower ductility than those tempered at 400°F, Fig. 53. The general decrease in reduction of area with decreasing testing temperature also appears to depend upon the chemical composition of the steel. It has been found to be smaller for nickel-containing than for nickel-free steels.

These phenomena comprise an analogy to the dependence of impact strength at room temperature upon tempering temperature which will be discussed in detail in another part of this report. The significance of these effects is not clarified. It may be mentioned, however, that no serious failures are known to have occurred in high-strength steels as a consequence of service at low temperature, in contrast to frequent failures of this nature encountered in annealed and normalized carbon steels.

58. Effect of Straining on the Ductility of High-Strength Steels at Low Temperatures

The peculiar condition of steels which have been tempered at temperatures between 500° and 700°F is further illuminated by their unusual response to cold-working. If a metal with a stable structure is cold-worked, it loses part of its ductility and the reduction of area in tension, for example, decreases in proportion to the amount of cold-working by prestretching. This also applies to the ductility of the metal at low temperature which, however, decreases due to straining at room temperature by an amount that becomes smaller as the temperature and ductility at this temperature decrease.

Steels, however, may or may not conform to this pattern (Sachs 1948). A heat-treated low-alloy steel, such as a manganese steel, if tempered at a temperature of 800°F or higher and subsequently stretched and finally tested at minus 320°F, has been found to behave normally in that its ductility decreases in proportion to the amount of prestretching, Fig. 54 (Ripling, 1950, 1951; Ripling, Baldwin, 1951). On the contrary, the same steel if tempered at a temperature between 500° and 700°F behaved entirely differently in that its very small ductility at the low temperatures first increases with prestraining until it reaches a rather high value. Subsequently, when the amount of prestretching exceeded a certain value, about 25 percent, the normal trend is reestablished as the ductility then again decreases.

Prestraining in compression caused similar but more complex effects than those observed on prestraining in tension.

It appears from the results of these tests that cold-working of steels, tempered within the critical temperature range of 500° to 700°F, produces a change of the steel structure which is associated with an increase in ductility. This phenomenon exhibits a distinct parallelity to the changes in ductility of patented wire during its progressive drawing, see Fig. 42.

H. MISCELLANEOUS STATIC STRENGTH CHARACTERISTICS OF HIGH-STRENGTH STEELS

59. Compression Characteristics of High-Strength Steels

A very limited amount of data is available for the strength characteristics of high-strength steels determined by static tests other than tension tests. These include compression tests, torsion tests, shear tests, and bearing tests.

Compression tests serve primarily to determine the yield strength of a steel in this type of loading. Such tests have shown that the compressive yield strength of steels is generally nearly 10 percent higher than the tensile yield strength. This has been also found to apply to heat-treated steels, such as 4340 steel, up to very high strength levels, Fig. 55 (AISI; Lockheed Aircraft).

The stress-strain curves of heat-treated steels determined by compression tests are very similar to those in tension. This can be also deduced from the above-discussed fact that the yield-strength values in both types of loading follow much the same trend. However, embrittlement occurs under compression at considerably higher hardness than under tension. Consequently, compression tests permit evaluation of the effects of low tempering temperatures on the inherent stress-strain characteristics of a very hard steel. The results of such tests on a 1075 steel illustrate the gradual changes in the stress-strain characteristics of a high-carbon steel, Fig. 56 (Read, Markus, McCaughey 1948). Tempering temperatures between 500^{o} and 700^{o}F resulted in the curves which exhibit a sharply-defined yield strength and a very flat plastic branch, or minimum strain-hardening.

60. Effects of Superimposed Hydrostatic Pressure on Tension Characteristics of High-Strength Steels

The ductility of a steel can be also raised by superimposing compression in all directions to tension. Such tests require a high-pressure chamber with provisions to pull a small-size specimen in tension. For very hard steels the tension specimen must be smoothly contoured to avoid failure at section changes.

Tests on a high-carbon steel, heat treated to hardnesses up to 63 Rockwell "C", yielded the following results which are probably of general significance for high-strength steels (Bridgman 1945, 1946, 1948). The tensile yield strength, defined as the deviation from hydrostatic pressure, was practically independent of the magnitude of pressure. However, the tension stress required to produce a larger strain of given magnitude became larger as the hydrostatic pressure increased. The fracture stress increased in proportion to the ductility.

The ductility, or reduction of area, was larger the higher the hydrostatic pressure, Fig. 57. However, in order to obtain a measurable ductility for very hard steels the pressure had to exceed a certain minimum value. In the case of the specimens having a hardness of 63 Rc, even very high pressures produced only a very small and inconsistent ductility.

Specimens which were strained by a given amount were found to be strain-hardened to the same extent, independent of the superimposed pressure. However, if this pressure was high their ductility was considerably greater than that of specimens strained in regular tension.

61. Shear-Strength Characteristics of High-Strength Steels

The mechanical characteristics of steels subjected to shear stresses can be determined by torsion tests on solid test bars. These yield both the yield strength and ultimate strength of the material in torsion or shear, the stress calculations being based on the elastic formulae.

The ultimate torsion strength of 4340 and 8630 steels, heat treated to a tensile strength between 180,000 and 280,000 psi, has been found to be very close to 65 percent of their tensile strength over the entire range, Fig. 58 (AISI).

This ratio was not noticeably affected by the presence of 50 percent intermediate transformation products.

The yield strength in torsion of tempered martensite appears, according to these investigations, to remain substantially 55 percent of the tensile-strength over the entire range of strength values, Fig. 58. However, the presence of a large quantity of intermediate transformation products greatly reduces the torsion yield strength at high strength levels, in much the same manner as the tensile yield strength.

Another method of determining the (ultimate) shear strength consists of shearing or cutting a pin at two points a certain distance apart. The ultimate strength derived from this double-shear test is then the maximum load divided by twice the cross section of the pin. A few such tests on 4340 steel, heat treated to 290,000 and 330,000 psi, yielded a ratio of shear strength to tensile strength close to 0.60 (Lockheed Aircraft), which is slightly lower than that reported for steels having lower strength.

Torsion tests (twist tests) on tool steels using impact loading indicate that their ductility usually exhibits a maximum value when tempered at 350° 400°F (Luerssen, Greene 1933, 1935; Greene, Stout 1940).

62. Bearing Properties of High-Strength Steels

The bearing properties of a flat piece of metal are determined by providing a strip with a hole having a diameter D and a certain distance, e, from the narrow edge, inserting a hard pin into the hole and pulling the pin through the metal, see Fig. 59. The bearing stress is defined as the load divided by the projected area of the bearing face which is the product of hole diameter and specimen thickness. The bearing yield strength is defined as the bearing stress at which the permanent set, i.e. the distance which the pin has plastically moved into the metal, is equal to 2 percent of the hole diameter. The ultimate bearing strength is the maximum value of bearing stress. Both yield strength, and ultimate strength increase with the edge distance, e, or the ratio e/D.

For comparatively large edge distances, such as $e/D = 2$, the bearing-strength properties of heat-treated steels have been determined to be considerably higher than their tensile strength, Fig. 59 (AISI, Lockheed Aircraft). The ultimate bearing strength of 4340 steel approached a value of 1.7 times that of the tensile strength as the tensile strength exceeded 200,000 psi, while this ratio increased as the tensile strength decreased. At the same time the ratio of bearing-yield strength to tensile strength remained nearly constant at 1.4

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Reports and unpublished data were made available by the following organizations:

AISI (American Iron and Steel Institute), New York, New York
Work performed by Battelle Memorial Institute

Armour Research Foundation of Illinois Institute of Technology, Chicago, Illinois
Work sponsored by Office of Naval Research and by Wright Air Development Center

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The International Nickel Company, Inc. Work performed by G. Sachs, Syracuse University and by L. J. Klingler and A. R. Troiano, Case Institute	New York, New York
Lockheed Aircraft Corporation	Burbank, California
Office of Naval Research See, Armour Research Foundation and Case Institute	Washington, D. C.
Menasco Manufacturing Company	Burbank, California
North American Aviation, Inc.	Los Angeles, California
Republic Steel Corporation	Cleveland, Ohio
Syracuse University Work sponsored by Bureau of Aeronautics, see also, Cleveland Pneumatic Tool Company and International Nickel	Syracuse, New York
The Timken Roller Bearing Company, Steel and Tube Division	Canton, Ohio
United States Steel Corporation	Pittsburgh, Pennsylvania
Wright Air Development Center, Air Research and Development Command, United States Air Force See, Armour Research Foundation, Carnegie Institute and Case Institute	Wright-Patterson Air Force Base, Ohio

TABLE I

AMERICAN HIGH-STRENGTH AIRCRAFT STEELS

AISI (SAE) No. Or trade name	AMS No.	C	Mn	Si	Ni	Cr	Mo	V
I. Standard								
4340		.38-.43	.60-.85		1.65-2.0	.70-.90	.20-.30	
4340 H		.37-.45	.60-.95		1.5- 2.0	.65-.95	.20-.30	
4130	6370 D	.28-.33	.40-.60		----	.80-1.10	.15-.25	
4130 H		.27-.34	.35-.65		-----	.80-1.15	.15-.25	
4140	6382 D	.38-.43	.75-1.0		----	.80-1.0	.15-.25	
4140 H		.37-.45	.70-1.05		----	.80-1.15	.15-.25	
8630	6280 C	.28-.33	.70-.90		.40-.70	.40-.60	.15-.25	
8630 H		.27-.34	.60-.95		.35-.75	.35-.65	.15-.25	
8740	6322 D	.38-.43	.75-1.0		.40-.70	.40-.60	.20-.30	
8740 H	16324 A	.37-.45	.70-1.05		.35-.75	.35-.65	.20-.30	
9840	6342 B	.38-.43	.70-.90		.85-1.15	.70-.90	.20-.30	
6150	6448 B	.48-.53	.70-.90		-----	.80-1.10	.15 Min.	
6150 H		.46-.54	.60-.95	.20-.35	----	.80-1.15	.15 Min.	
52100	6440 D	.95-1.1	.25-.45		----	1.3-1.6	----	
II. New Developments (a) to 240,000 psi								
(4330 mod.)	6427	.28-.33	.80-1.00		1.65-2.00	.75-.95	.35-.50	.05-.10
Hy-Tuf	6418 A	.23-.28	1.20-1.50	1.30-1.70	1.65-2.00	----	.35-.45	
TM-2		.25-.30	.60-.80	.50-.70	1.85-2.20	1.00-1.35	.35-.50	
(b) To 270,000 psi (approx.)								
Super Hy-Tuf (Typical)		.40	1.35	1.90	----	1.35	.30	.20
Inco (.07 AL) Min.		.40 .47	.65-.90	1.45-1.80	1.65-2.00	.70-.95	.30-.45	0.05
III. Boron Steels (.0005 Min, B) (Substitutes)								
80B30		.27-.34	.55-.80		.20-.40	.15-.35	.08-.15	
(TS) 81B40		.38-.43	.75-1.0		.20-.40	.35-.55	.08-.15	
(TS) 81B40 H	6321	.37-.45	.70-1.05		.20-.40	.30-.60	.08-.15	
(TS) 86B45		.43-.48	.75-1.0		.40-.70	.55-.75	.08-.15	
(TS) 86B45 H		.42-.50	.70-1.05		.35-.75	.50-.80	.08-.15	
98B40	6422 A	.38-.43	.70-.90		.85-1.15	.70-.90	.20-.30	

TABLE II

BRITISH HIGH-STRENGTH AIRCRAFT STEELS

Steel Type	No.	Composition - Percent				Max. Bar. Dia.*
		C	Ni	Cr	Mo	
1-1/2 Ni-Cr-Mo	En 24	0.35/0.45	1.3/1.8	0.0/1.4	0.20/0.35	1-1/8
2-1/2 Ni-Cr-Mo	En 25	0.27/0.35	2.3/2.8	0.5/0.8	0.40/0.70	2-1/2
2-1/2 Ni-Cr-Mo	En 26	0.36/0.44	2.3/2.8	0.5/0.8	0.40/0.70	4
3-Cr-Mo	En 29	0.15/0.35	---	2.5/3.5	0.30/0.70	2-1/2
4-1/4 Ni-Cr	En 30A	0.26/0.34	3.9/4.3	1.1/1.4	----	6(2-1/2)
4-1/4 Ni-Cr-Mo	En 30B	0.26/0.34	3.9/4.3	1.1/1.4	0.2/0.40	6(2-1/2)

*Maximum diameter which can be heat treated to 224,000 psi (100 + Si) when oil quenched (in parenthesis when air quenched)

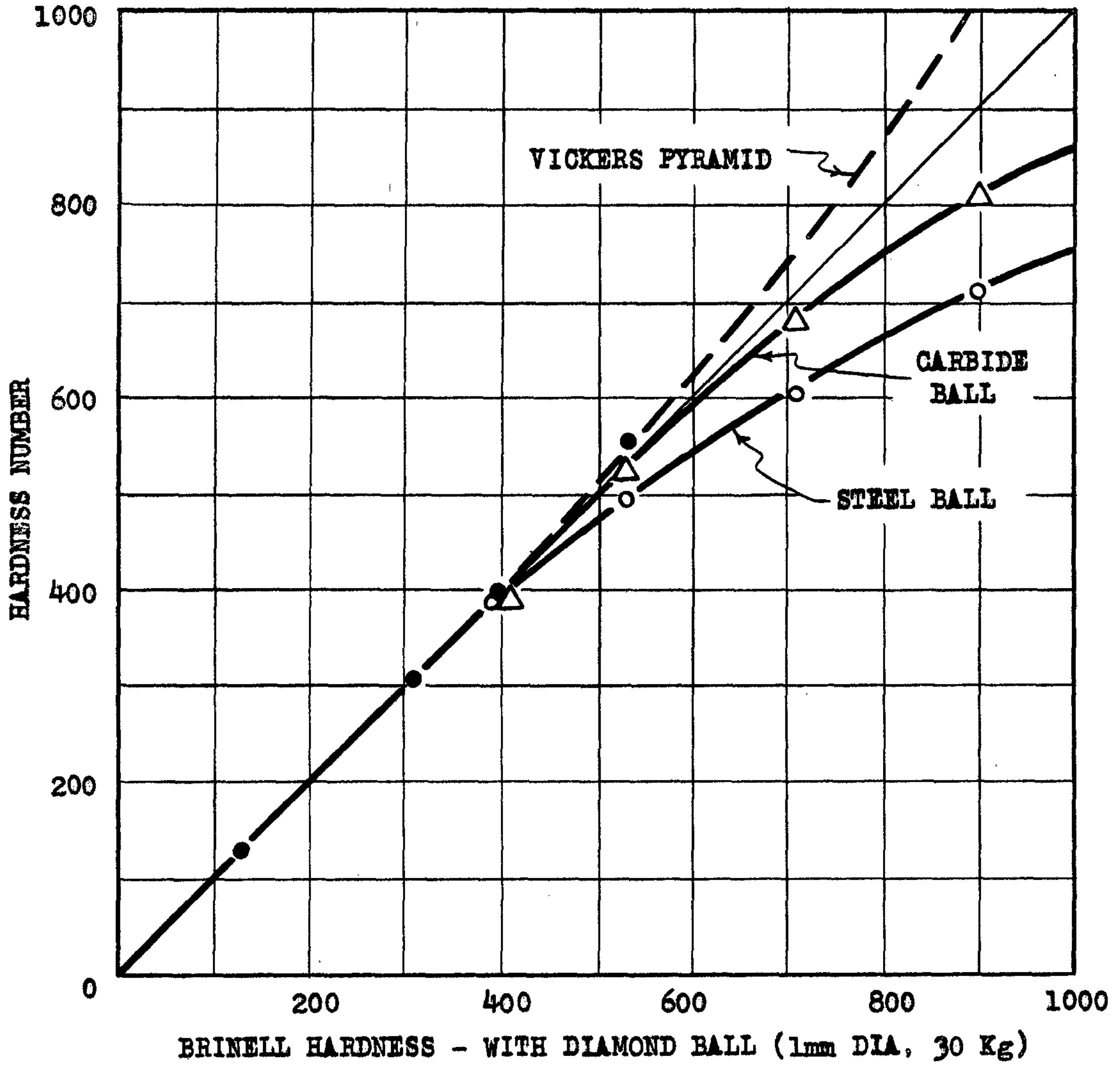


FIG. 1 EFFECT OF BALL MATERIAL ON BRINELL HARDNESS READING.

TABOR

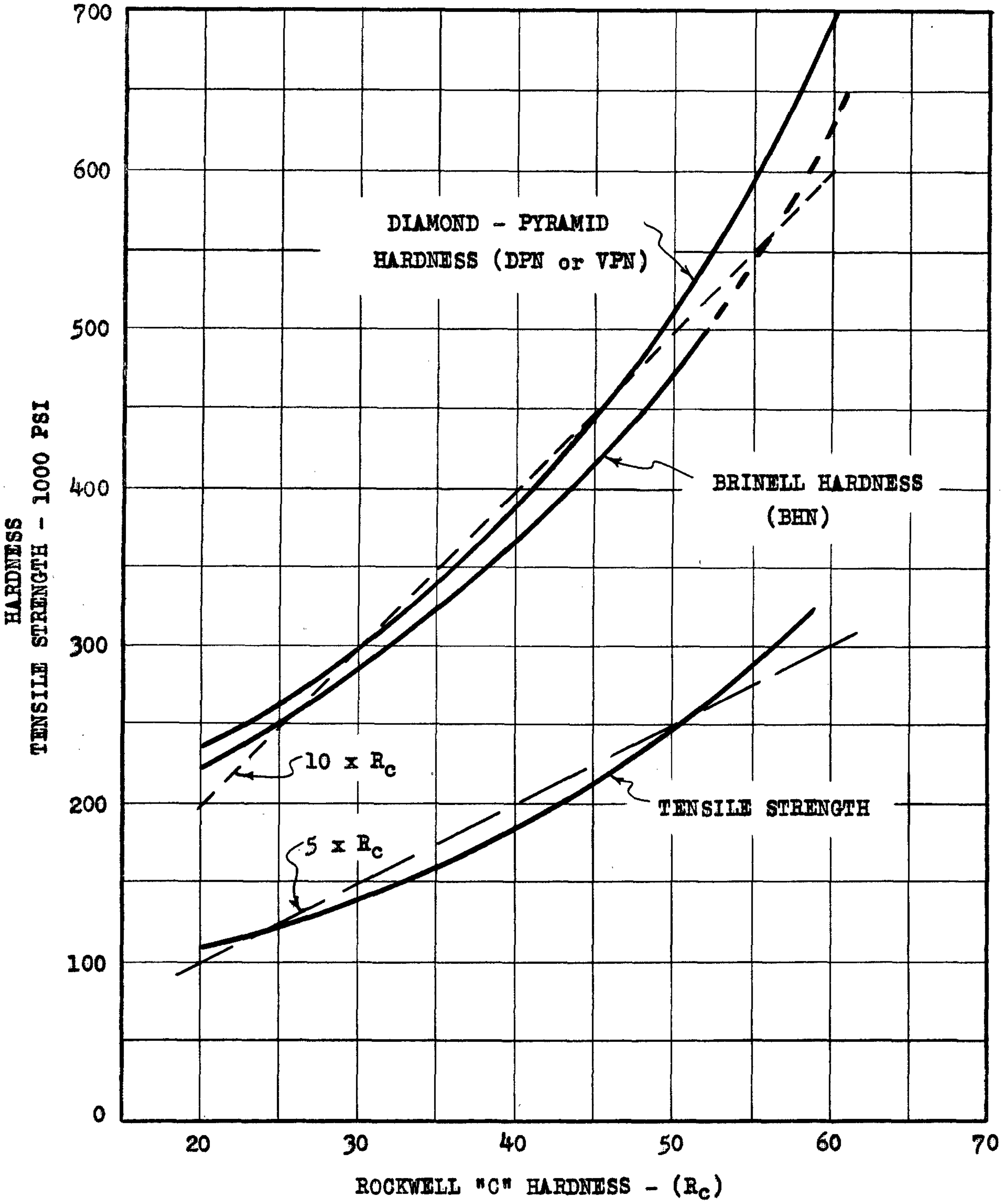


FIG. 2 HARDNESS CONVERSION CHART FOR STEELS.
(AMERICAN SOCIETY FOR METALS)

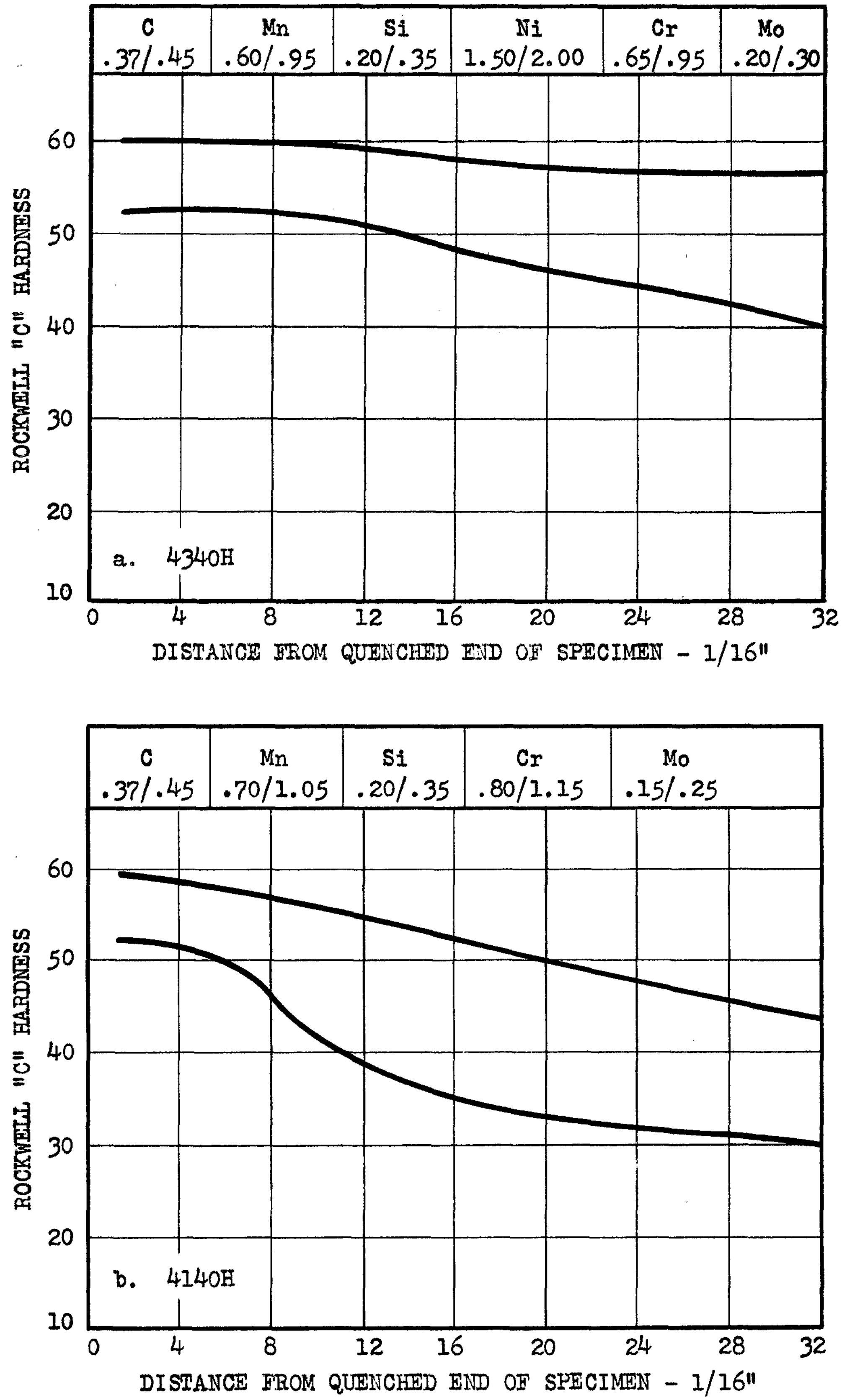


FIG. 3a-b HARDENABILITY BANDS FOR SOME STANDARD AIRCRAFT STEELS. (AISI)

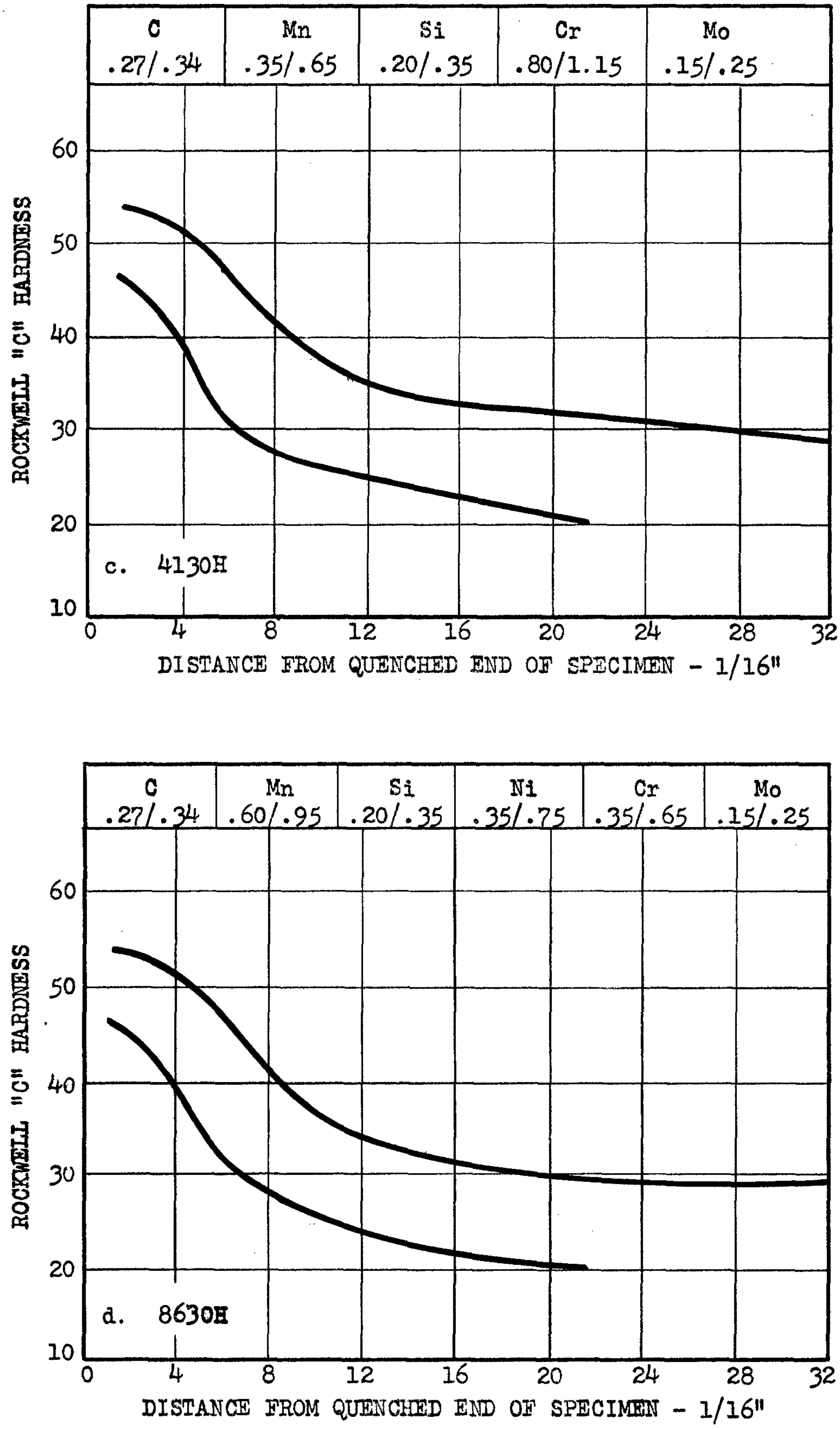
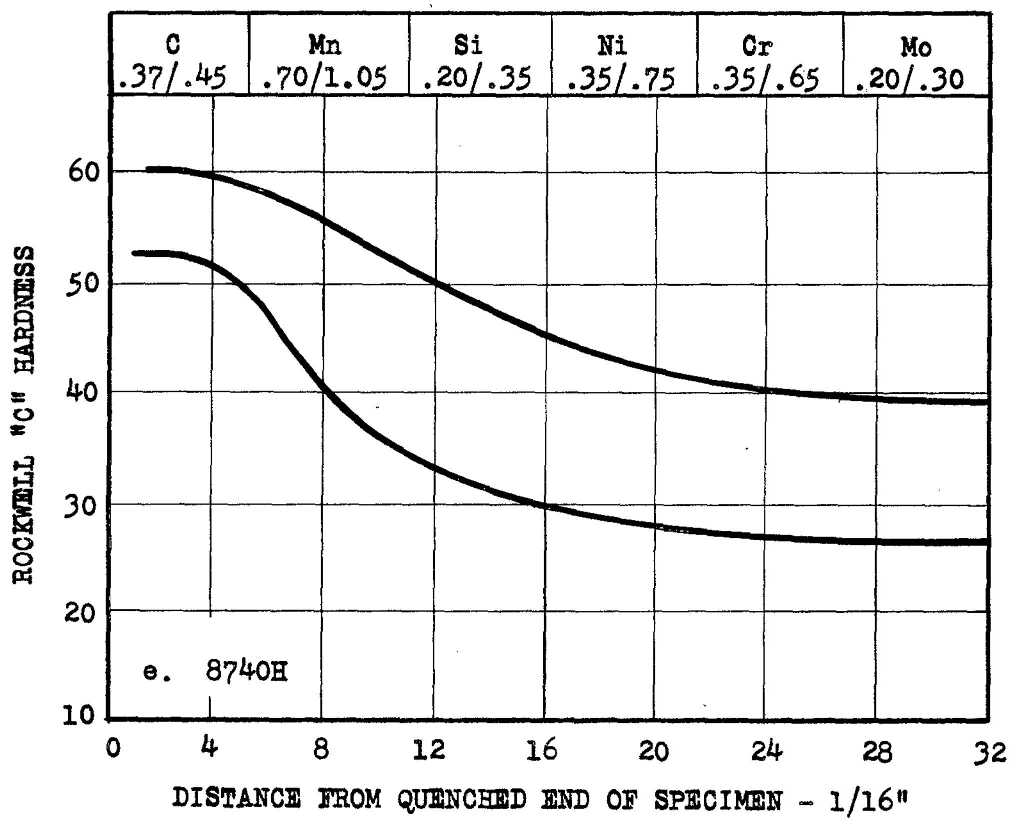
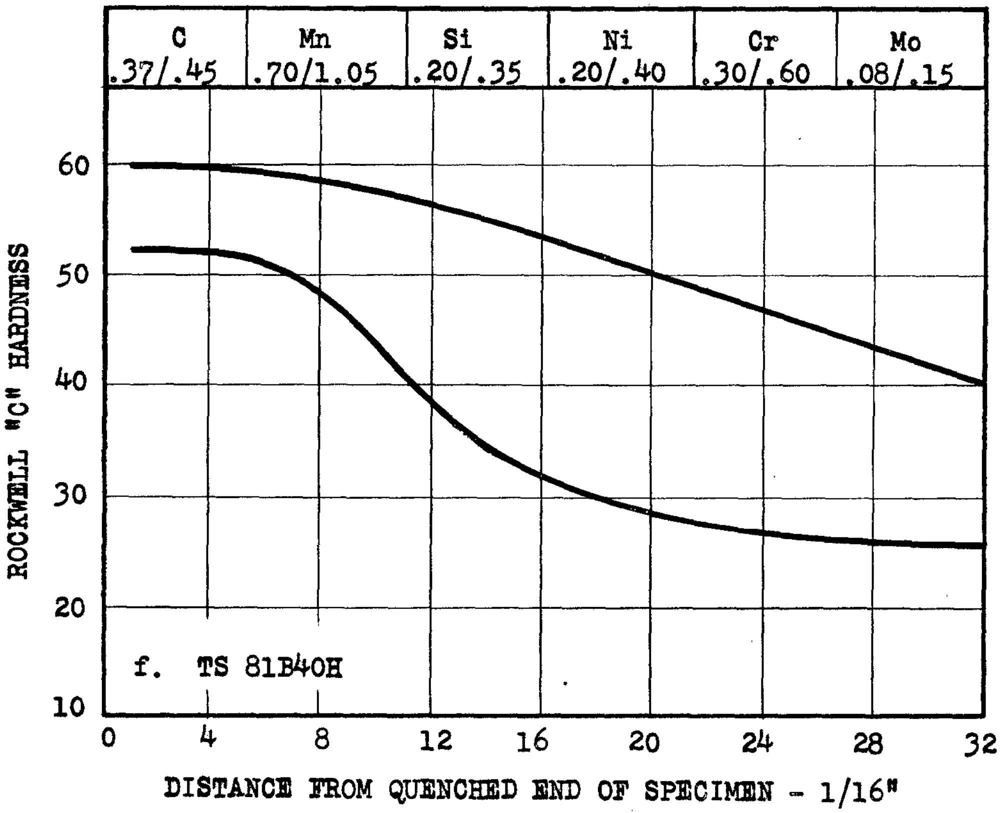


FIG. 3c-d HARDENABILITY BANDS FOR SOME
STANDARD AIRCRAFT STEELS.
(AISI)



C	Mn	Si	Ni	Cr	Mo
.37/.45	.70/1.05	.20/.35	.35/.75	.35/.65	.20/.30



C	Mn	Si	Ni	Cr	Mo
.37/.45	.70/1.05	.20/.35	.20/.40	.30/.60	.08/.15

FIG. 3e-f HARDENABILITY BANDS FOR SOME
STANDARD AIRCRAFT STEELS.
(AISI)

C	Mn	Si	Ni	Cr	Mo
.42/.50	.70/1.05	.20/.35	.35/.75	.50/.80	.08/.15

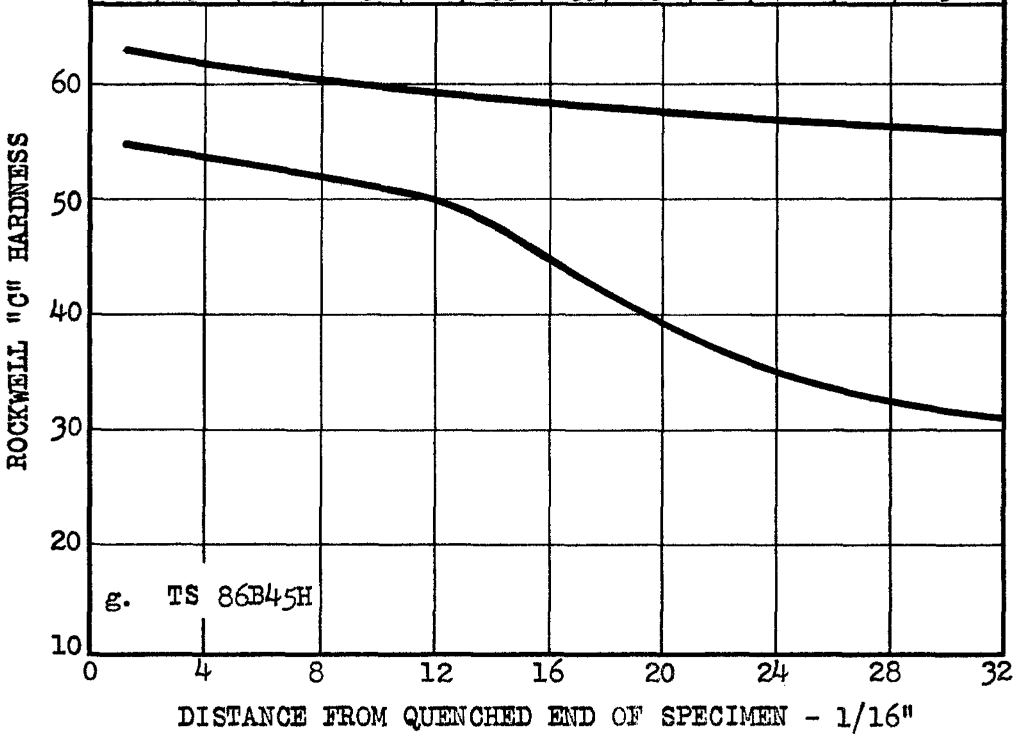


FIG. 3-g HARDENABILITY BANDS FOR SOME STANDARD AIRCRAFT STEELS.
(AISI)

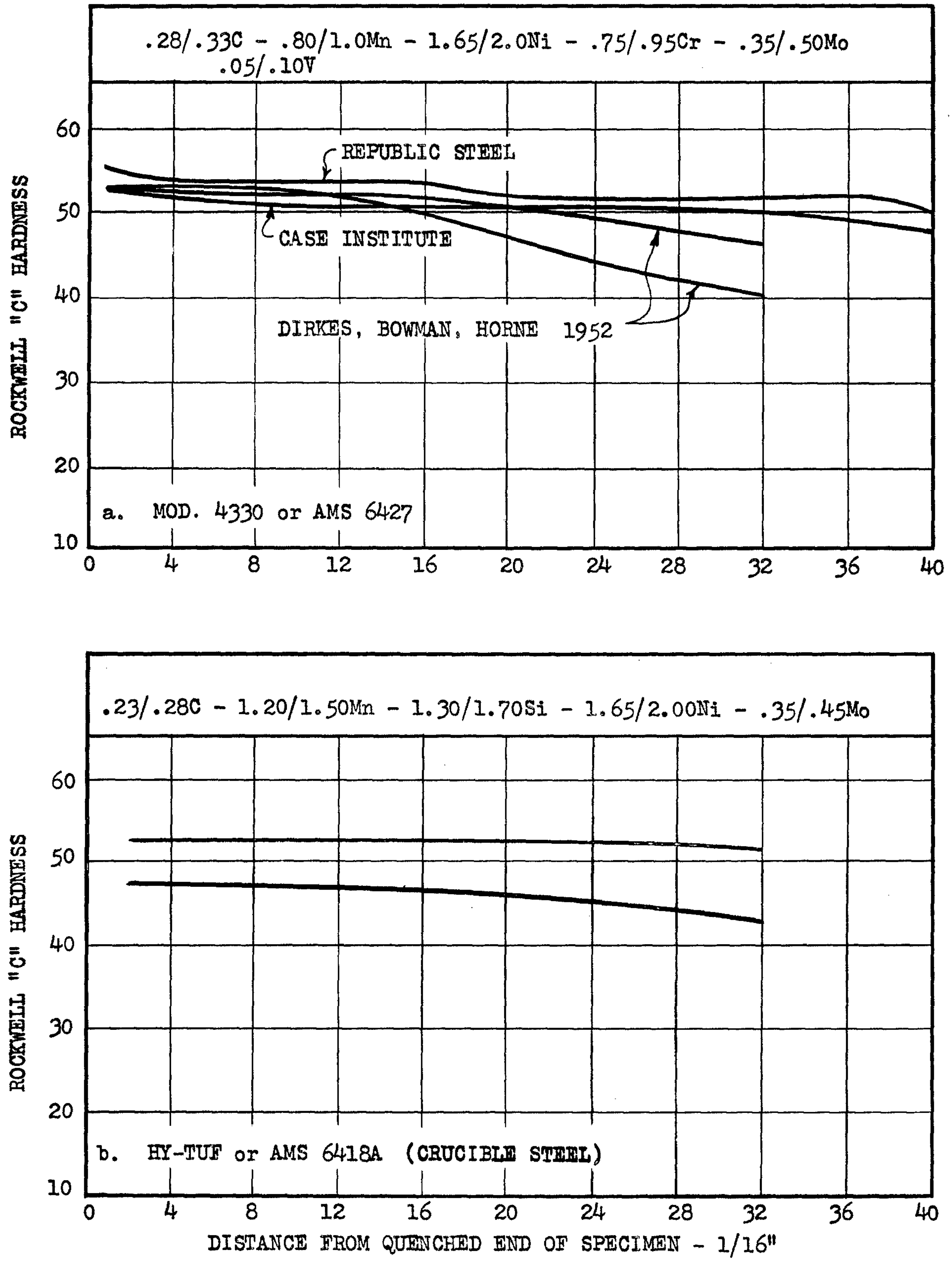


FIG. 4a-b SOME HARDENABILITY DATA FOR RECENTLY DEVELOPED AIRCRAFT STEELS.

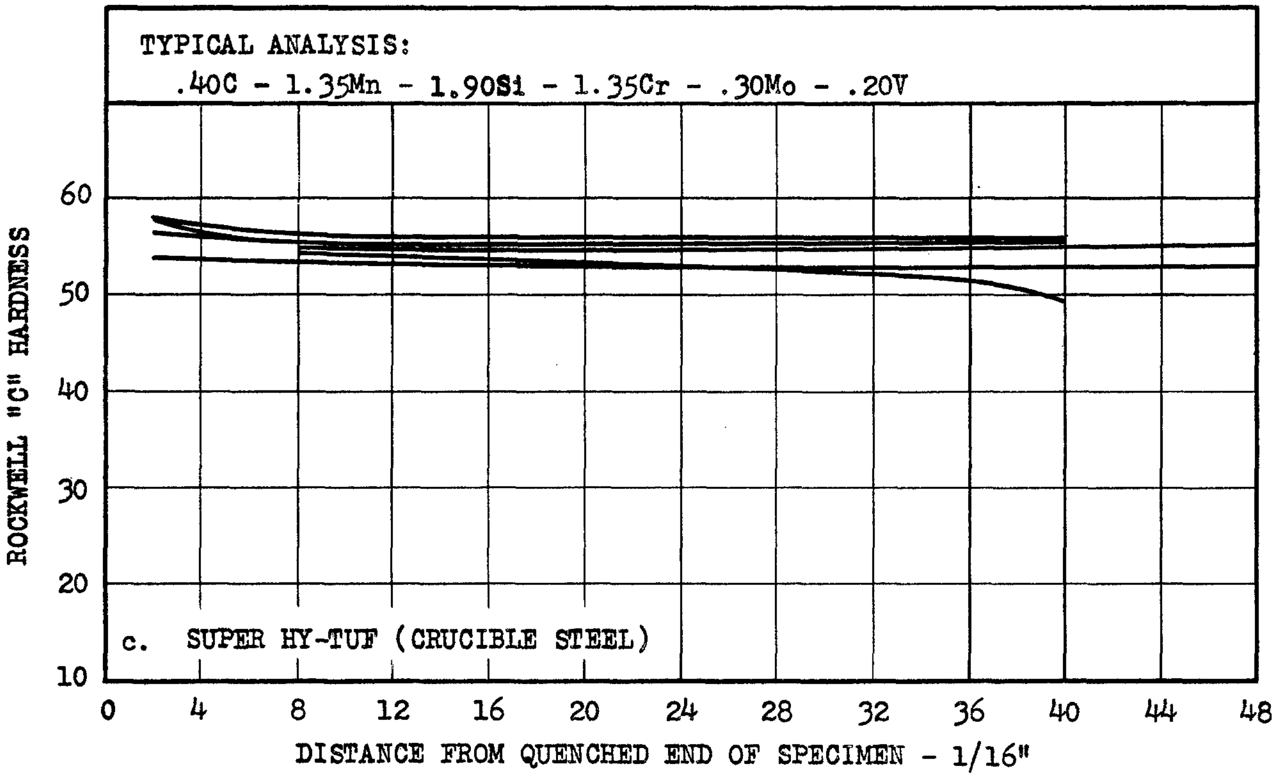


FIG. 4c SOME HARDENABILITY DATA FOR RECENTLY DEVELOPED AIRCRAFT STEELS.

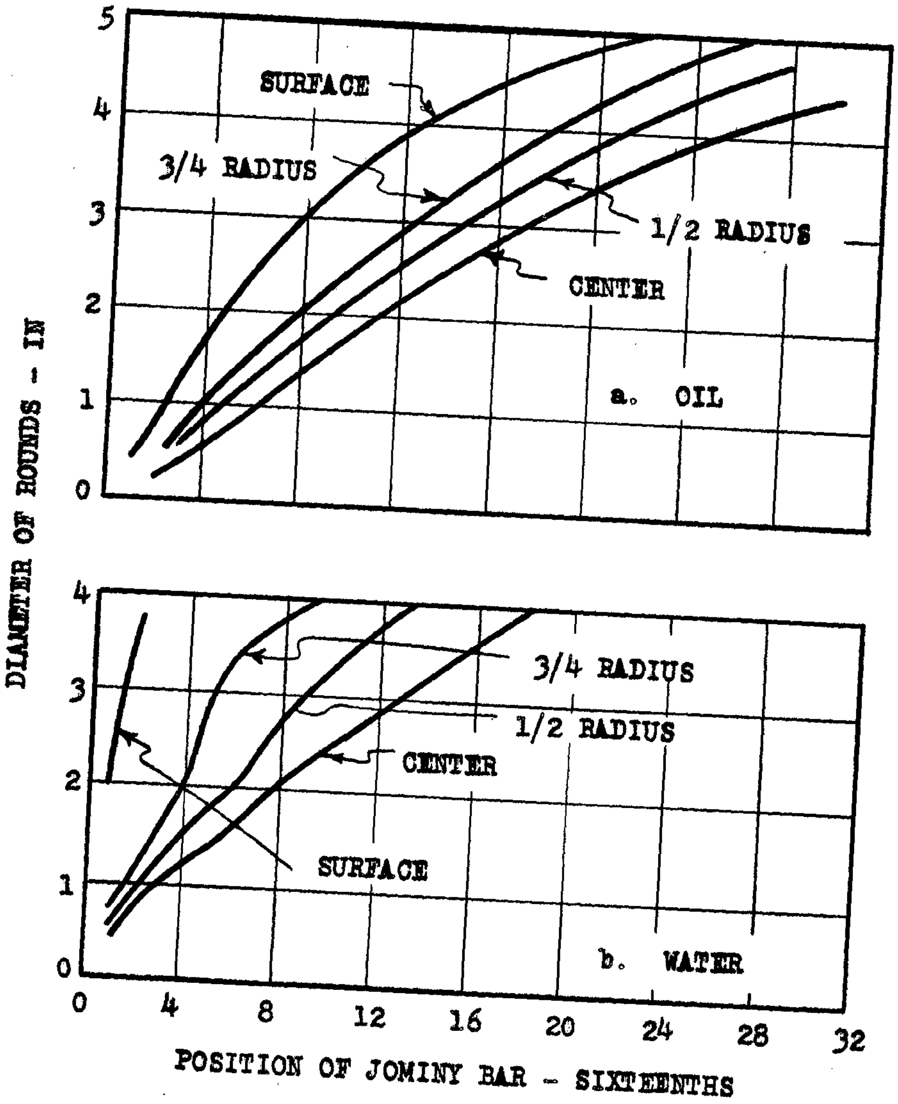


FIG. 5 CORRELATION OF IDENTICAL COOLING RATES IN JOMINY TESTS AND QUENCHED ROUNDS.

(BOEGEHOLD 1944)

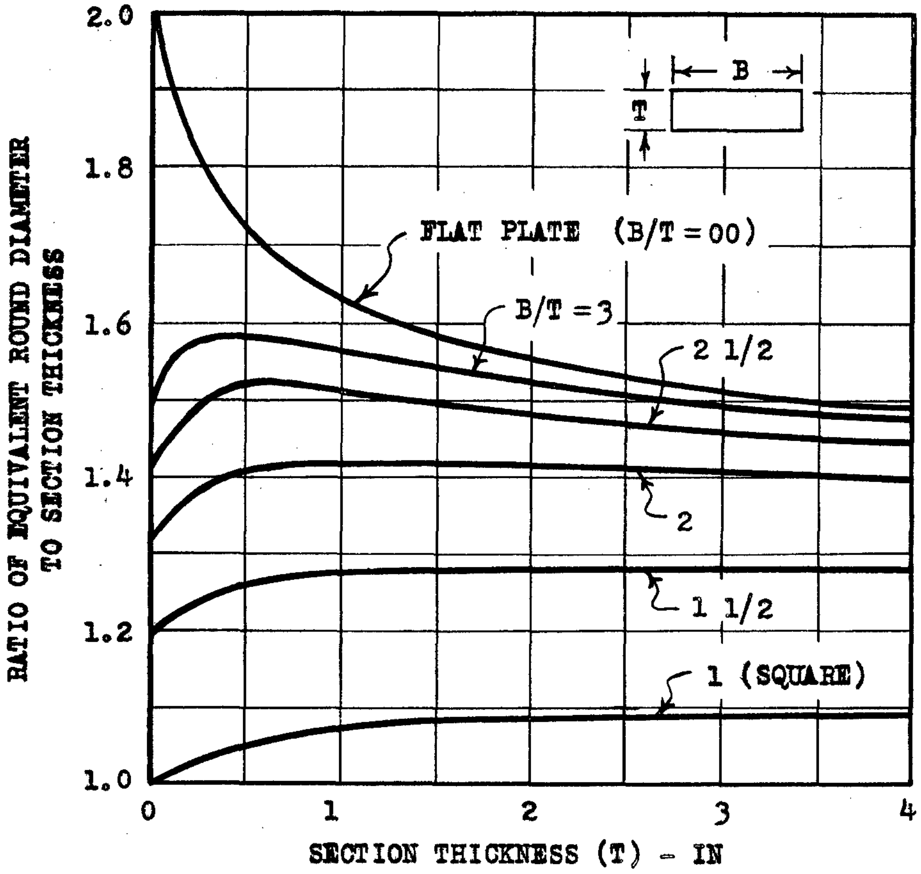


FIG. 6 CHART FOR CALCULATING EQUIVALENT DIAMETER OF ROUNDS FOR OIL QUENCHED RECTANGULAR SECTIONS.

(BRITISH STANDARDS INSTITUTION)

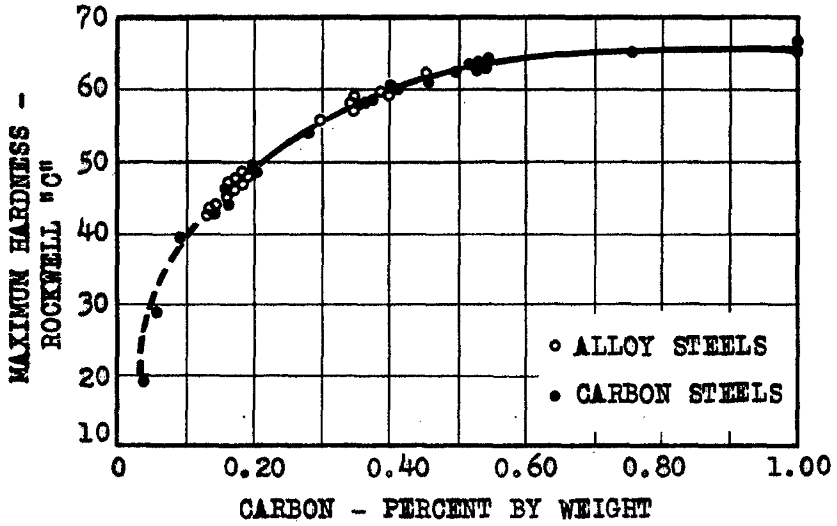


FIG. 7 IDEAL RELATION BETWEEN AS-QUENCHED HARDNESS AND CARBON CONTENT.

(BURNS, MOORE, ARCHER 1938)

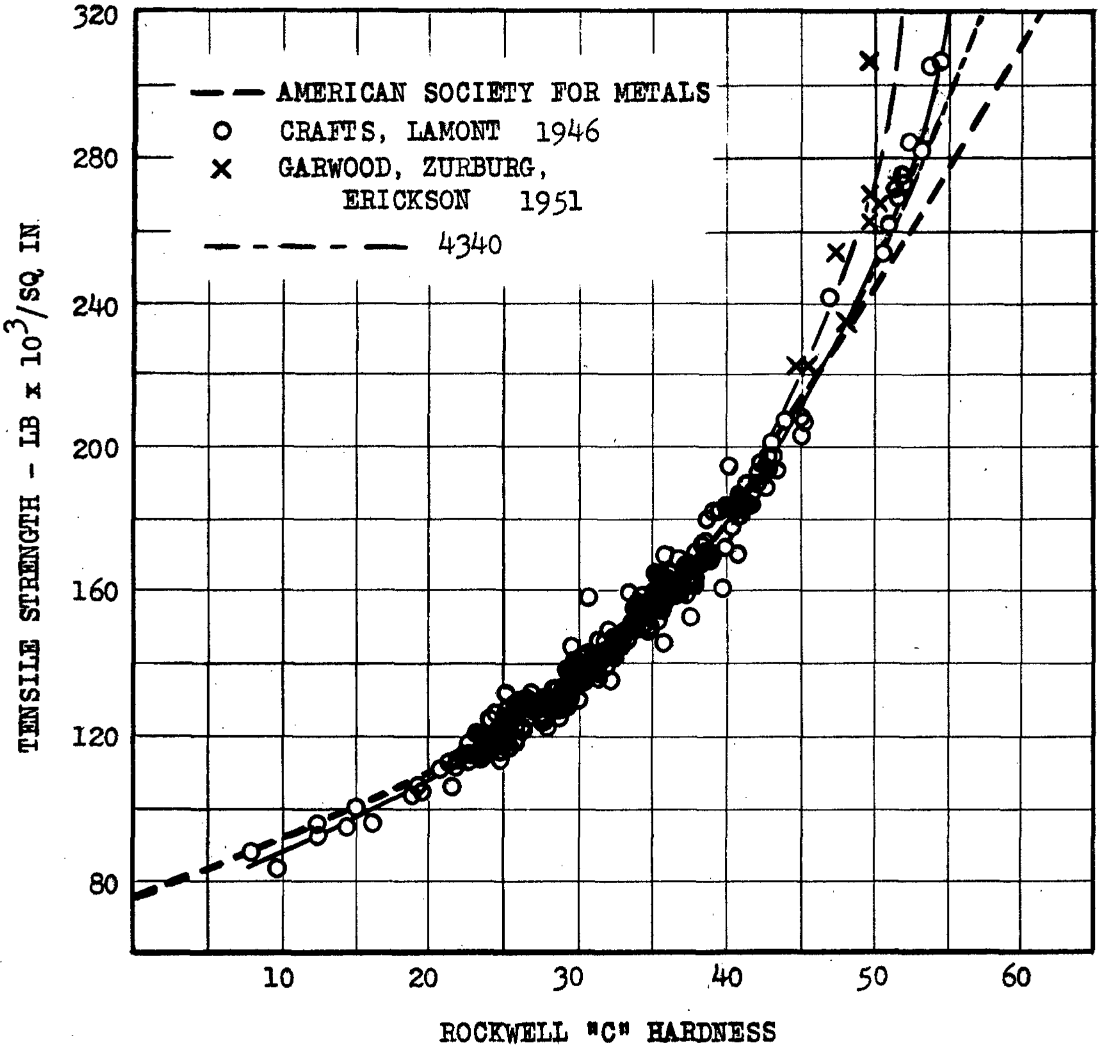


FIG. 8 RELATION BETWEEN TENSILE STRENGTH AND ROCKWELL "C" HARDNESS FOR HEAT-TREATED ALLOY STEELS.

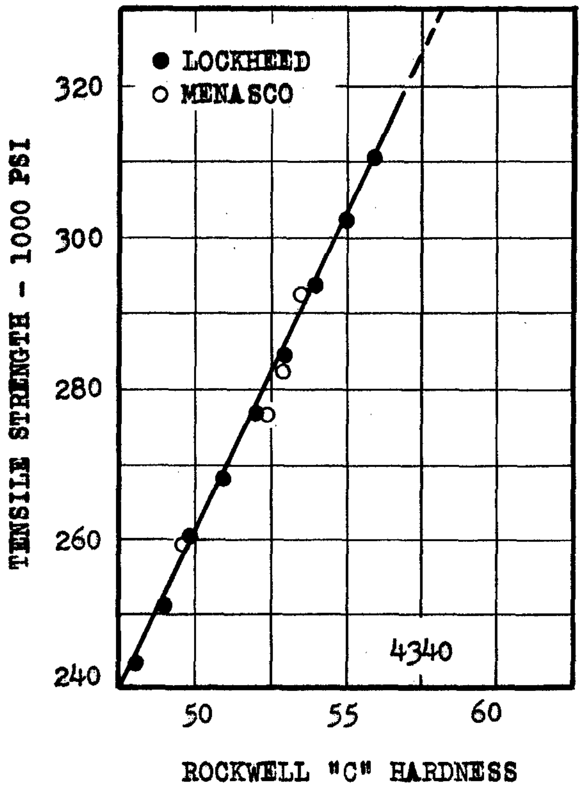


FIG. 9 RELATION BETWEEN TENSILE STRENGTH AND ROCKWELL "C" HARDNESS FOR 4340 STEEL HEAT-TREATED TO VERY HIGH TENSILE STRENGTH.

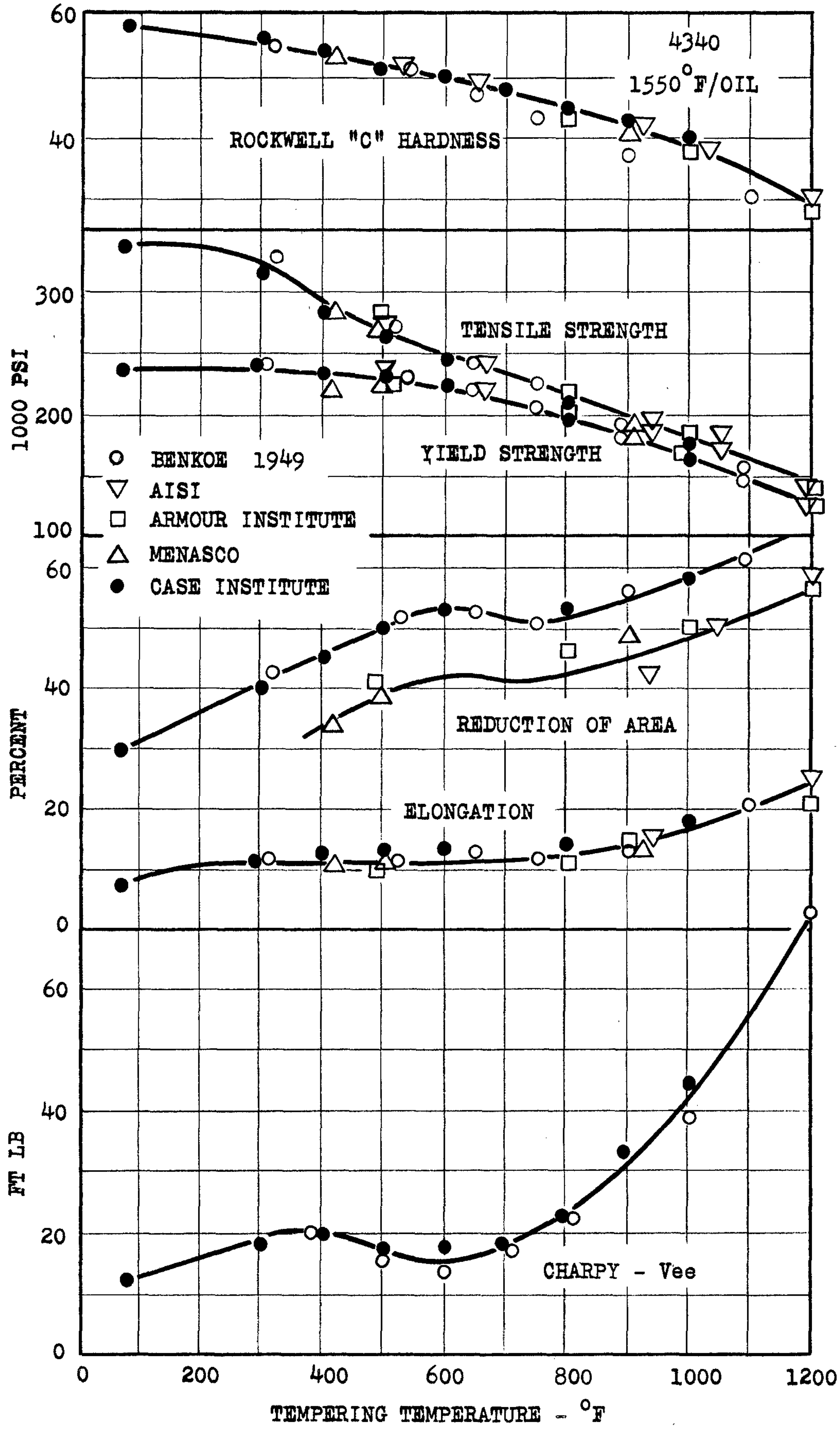


FIG. 10-a EFFECT OF TEMPERING TEMPERATURE ON TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

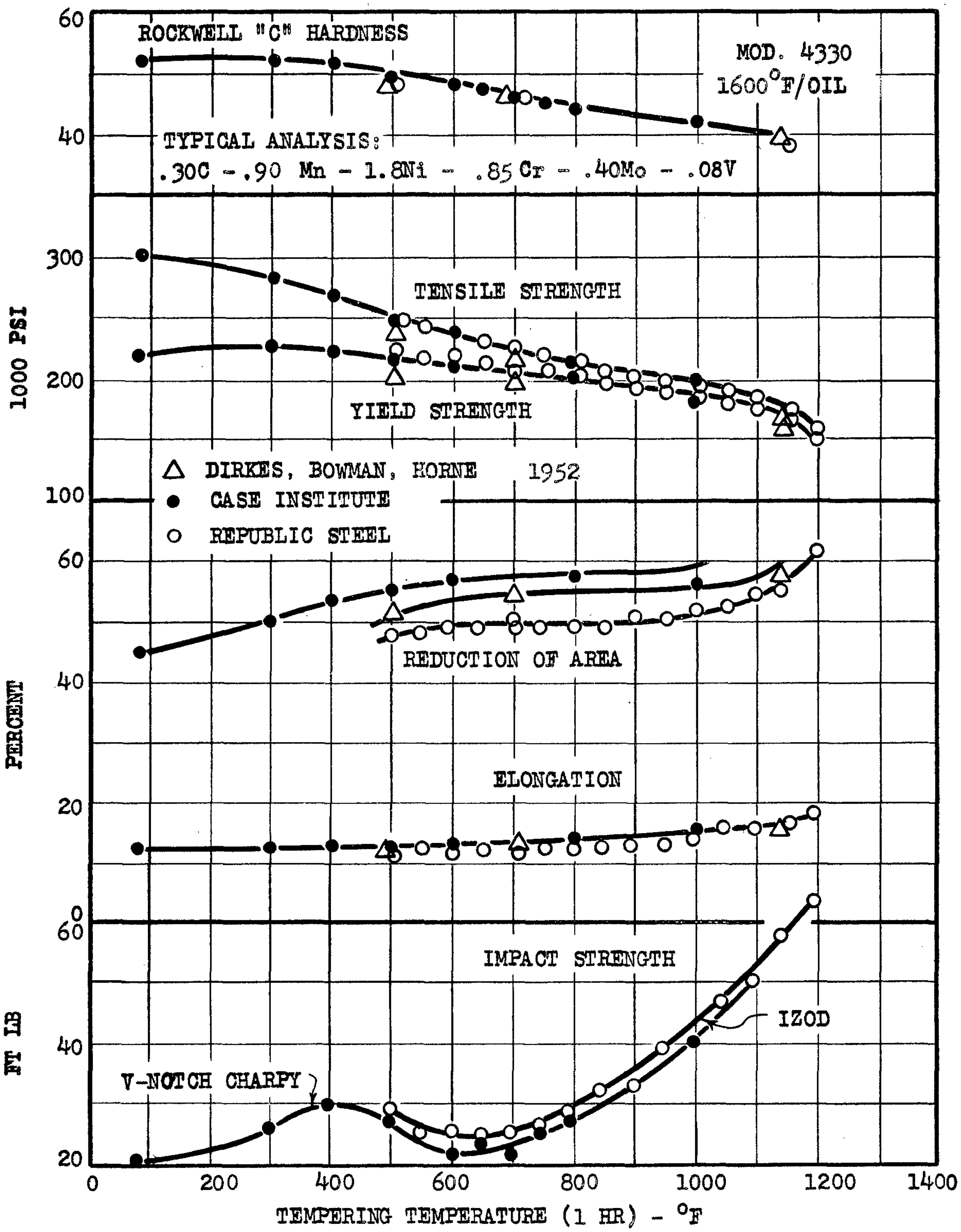


FIG. 10-b EFFECT OF TEMPERING TEMPERATURE ON THE TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

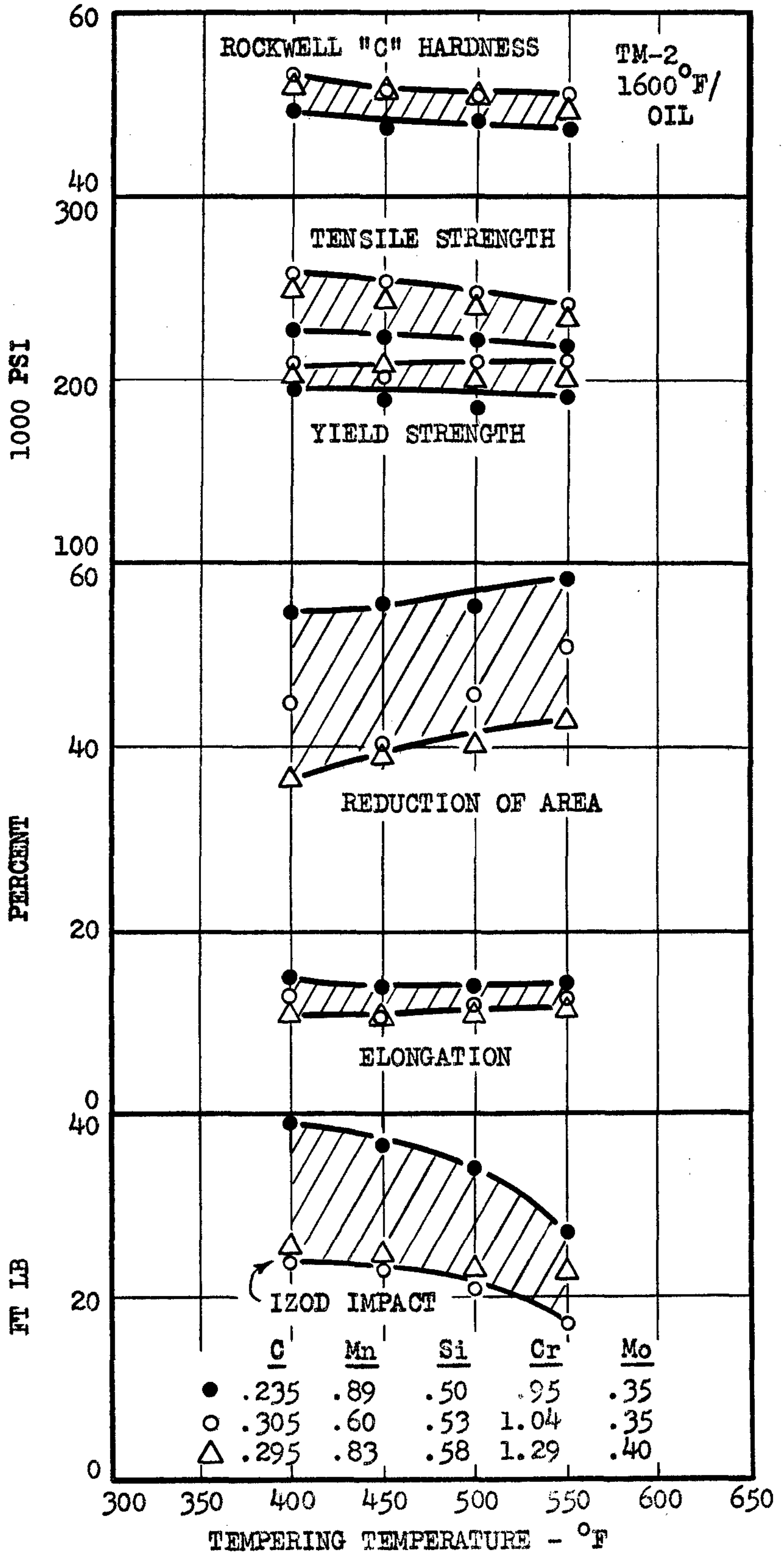


FIG. 10-c EFFECT OF TEMPERING TEMPERATURE ON THE TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

(TIMKEN)

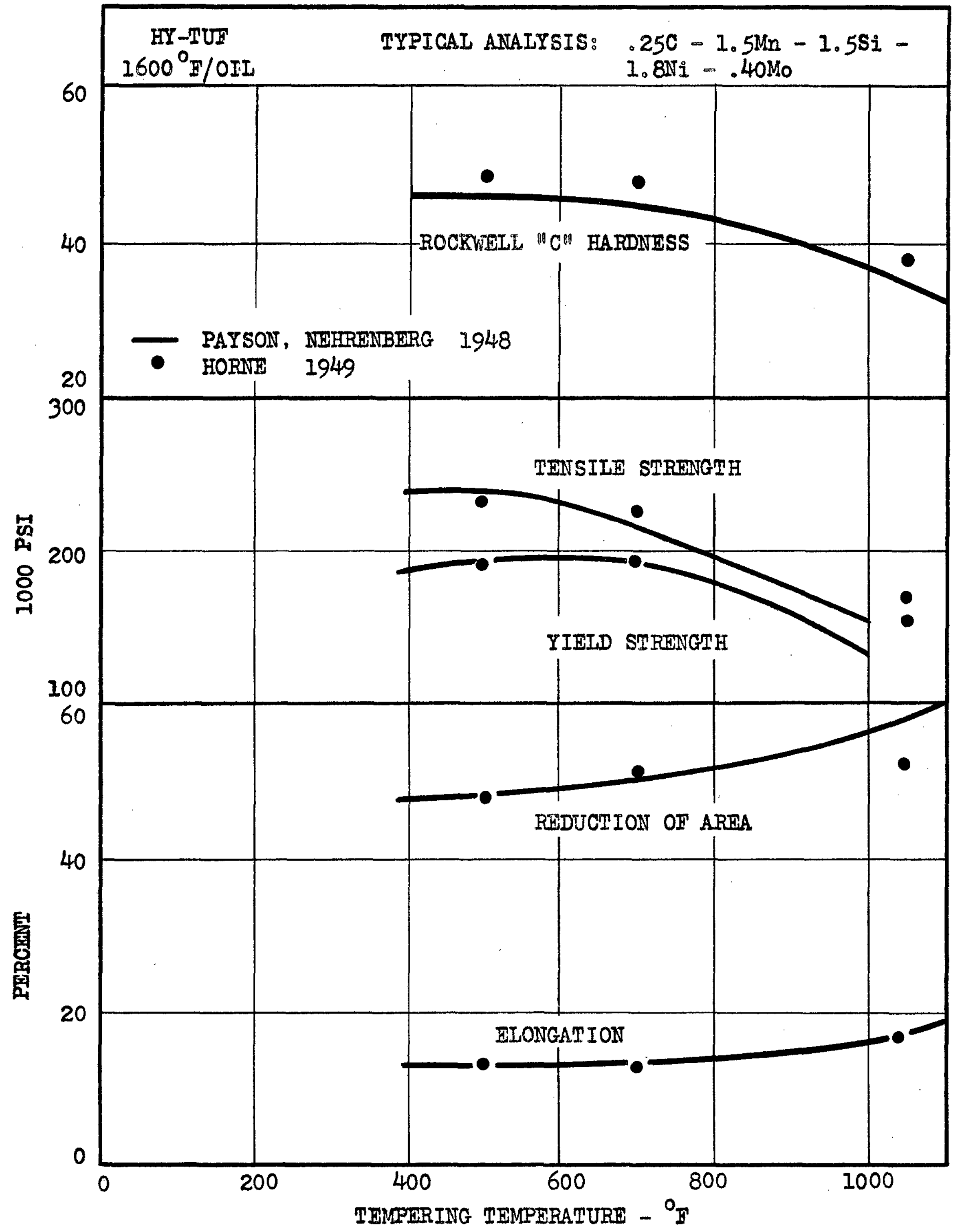


FIG. 10-d EFFECT OF TEMPERING TEMPERATURE ON THE TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

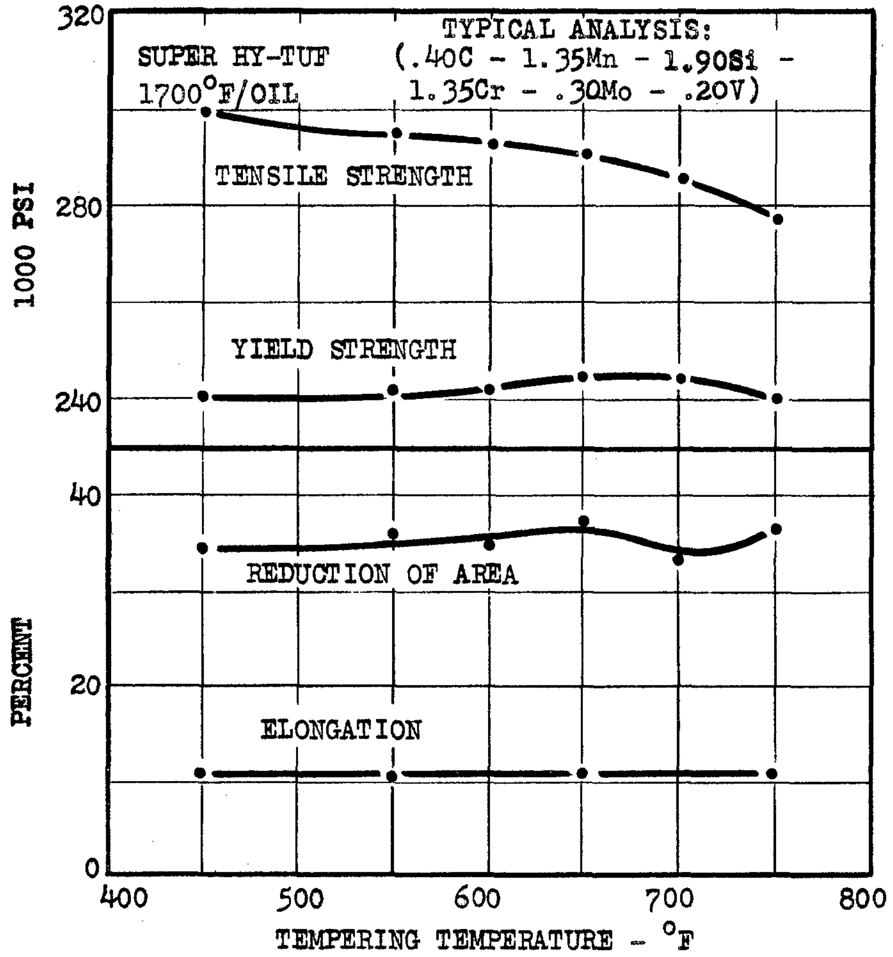


FIG. 10-e EFFECT OF TEMPERING TEMPERATURE ON THE TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

(CRUCIBLE STEEL)

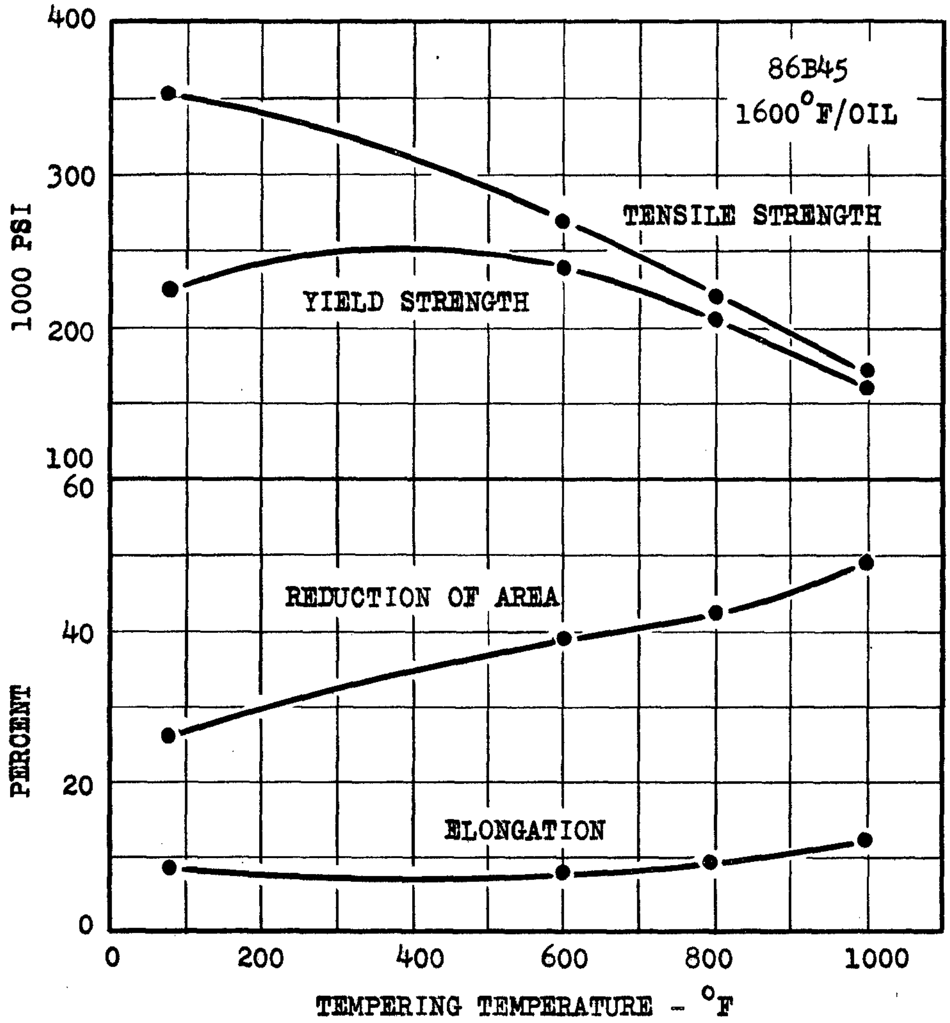


FIG. 10-f EFFECT OF TEMPERING TEMPERATURE ON THE TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

(IMHOFF, POYNTER 1953)

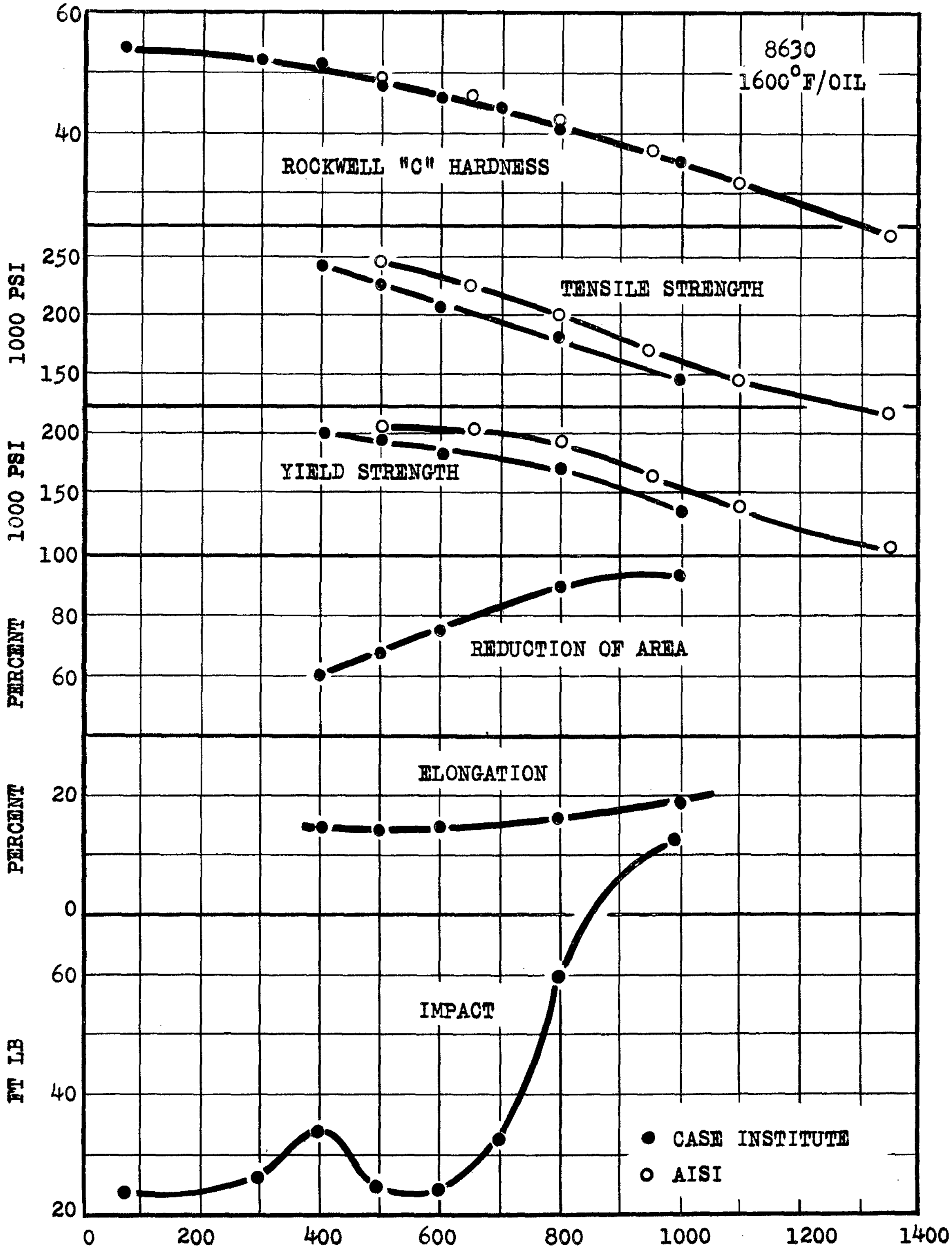


FIG. 10-g EFFECT OF TEMPERING TEMPERATURE ON THE TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

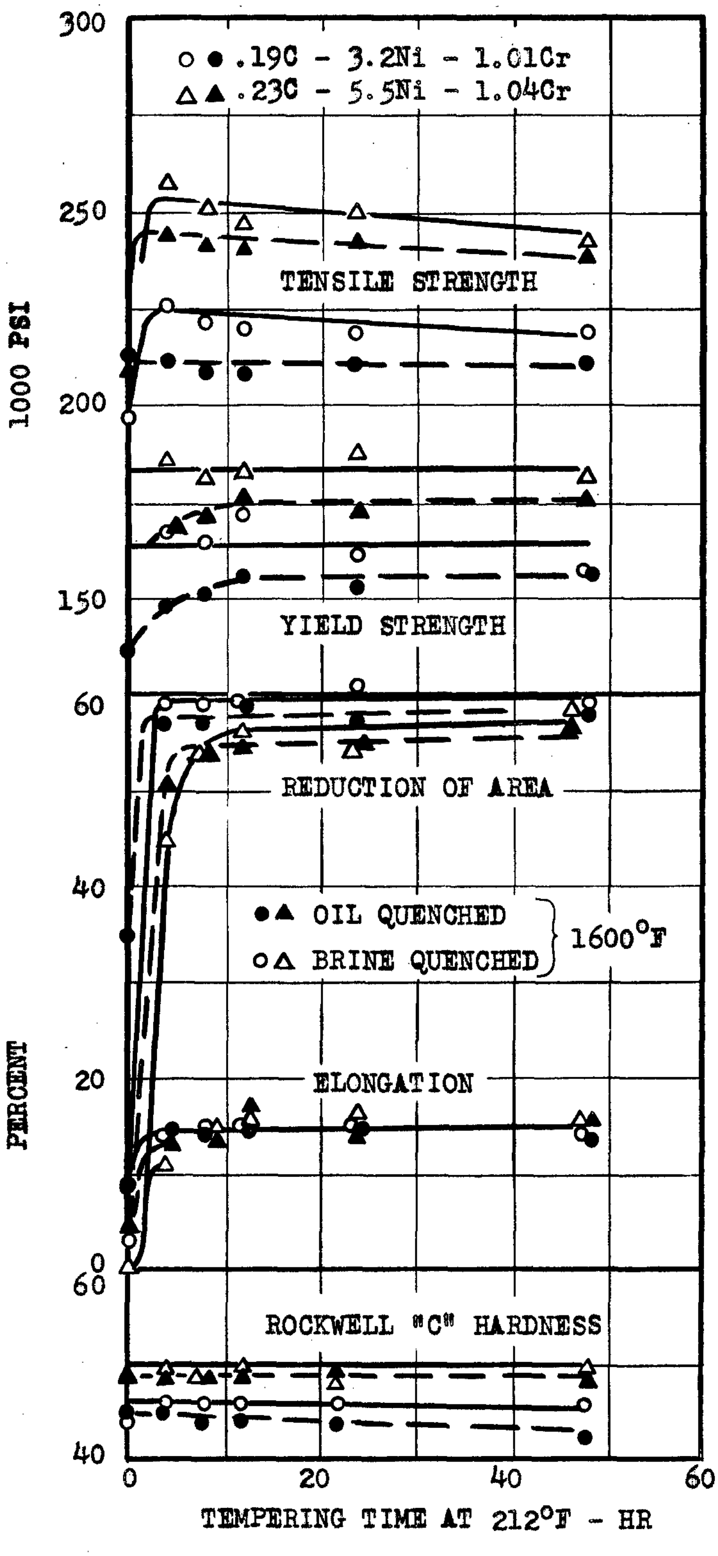


FIG. 11 EFFECT OF QUENCHING MEDIUM ON TENSION CHARACTERISTICS OF TWO NICKEL-CONTAINING LOW-ALLOY STEELS.

(DATA BY CARNEGIE INSTITUTE)

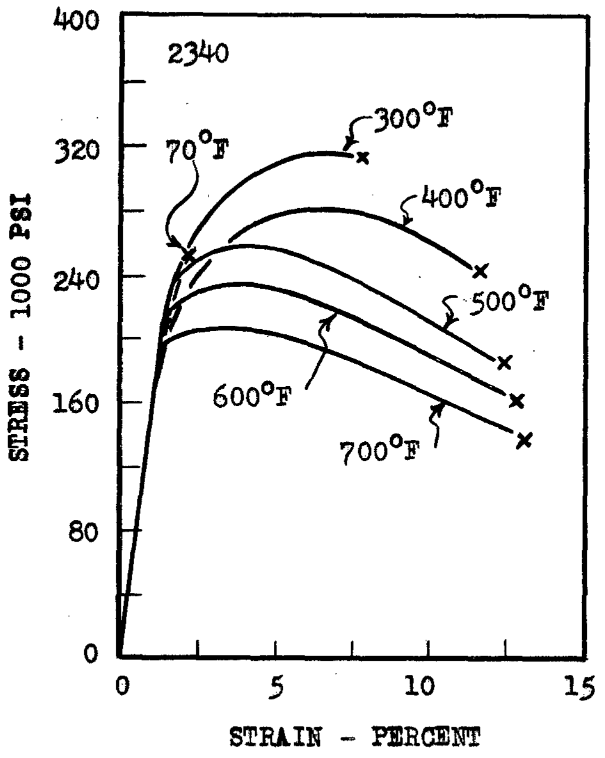


FIG. 12 TYPICAL, CONVENTIONAL STRESS-STRAIN CURVES FOR A LOW-ALLOY STEEL, HEAT-TREATED TO VARIOUS HIGH STRENGTH LEVELS.

(CASTLEMAN, AUERBACH, COHEN 1952)

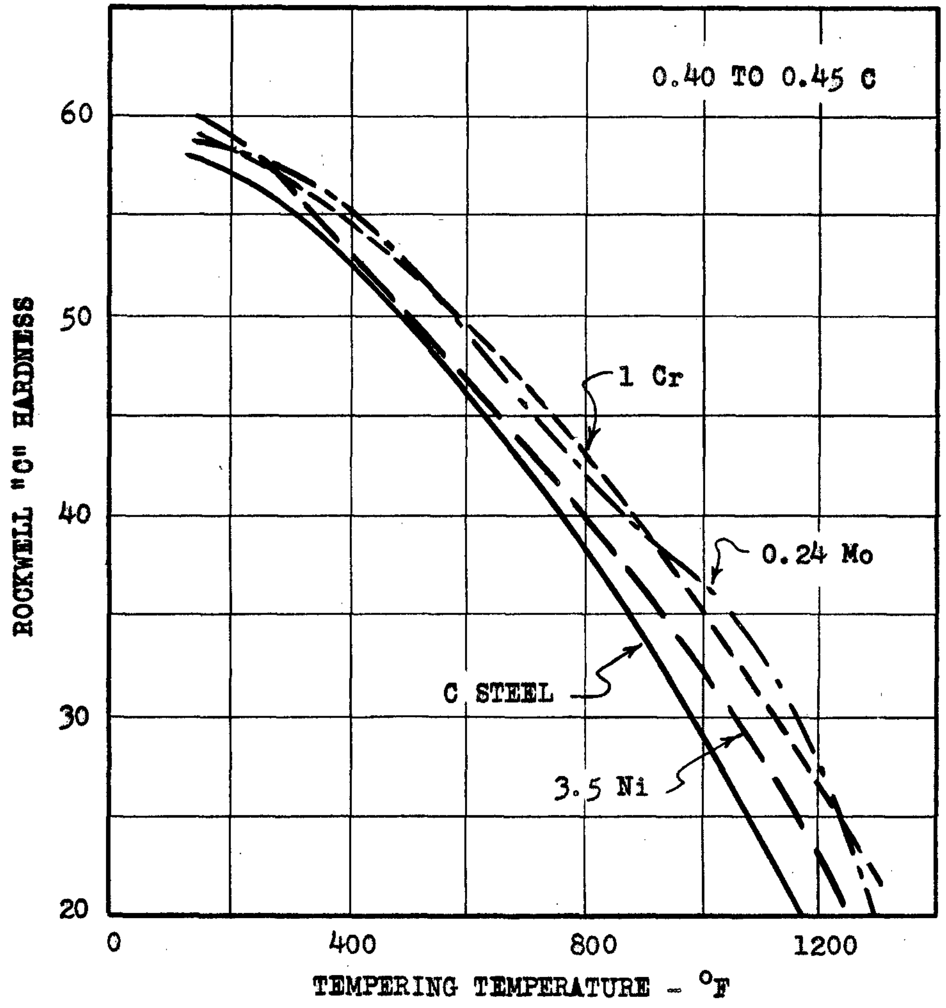


FIG. 13 EFFECT OF SOME ALLOYING ADDITIONS ON HARDNESS OF HEAT-TREATED, 0.4-CARBON STEELS.

(BAIN)

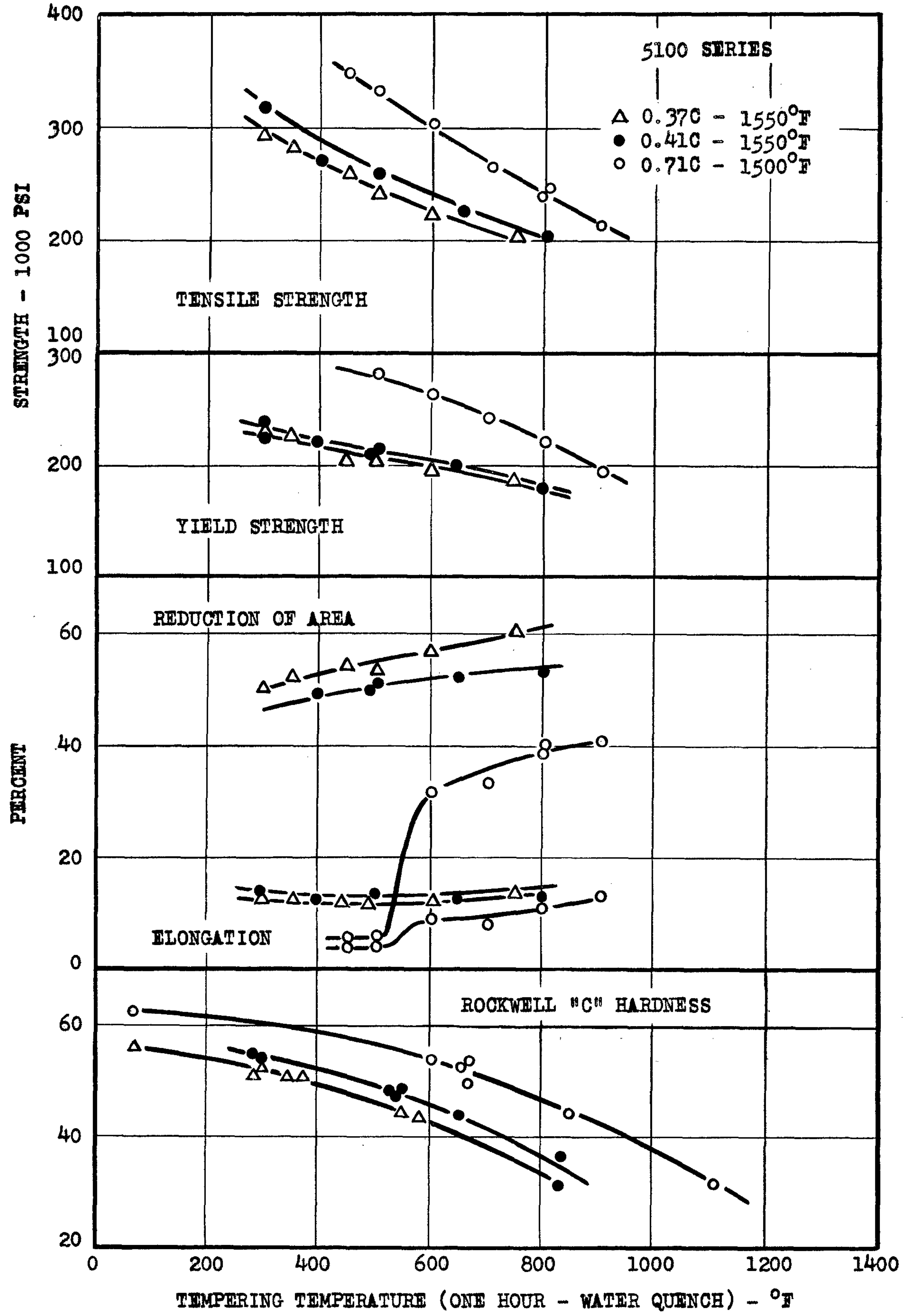


FIG. 14 EFFECT OF TEMPERING TEMPERATURE ON TENSION CHARACTERISTICS OF BRINE-AND-CAUSTIC-SODA-QUENCHED 5100 STEELS.

(DATA BY INTERNATIONAL NICKEL)

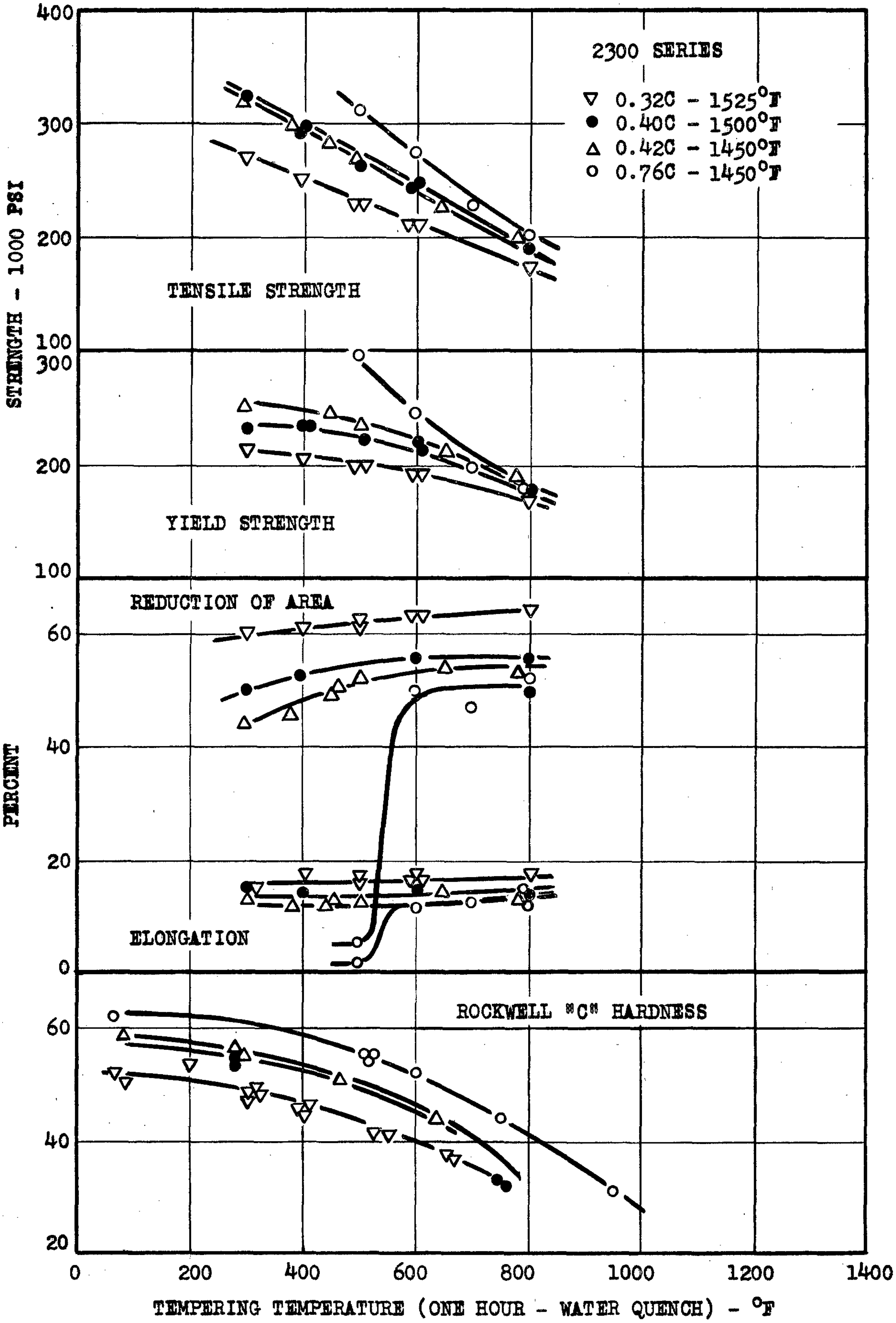


FIG. 15 EFFECT OF TEMPERING TEMPERATURE ON TENSION CHARACTERISTICS OF BRINE-AND-CAUSTIC-SODA-QUENCHED 2300 STEELS.

(DATA BY INTERNATIONAL NICKEL)

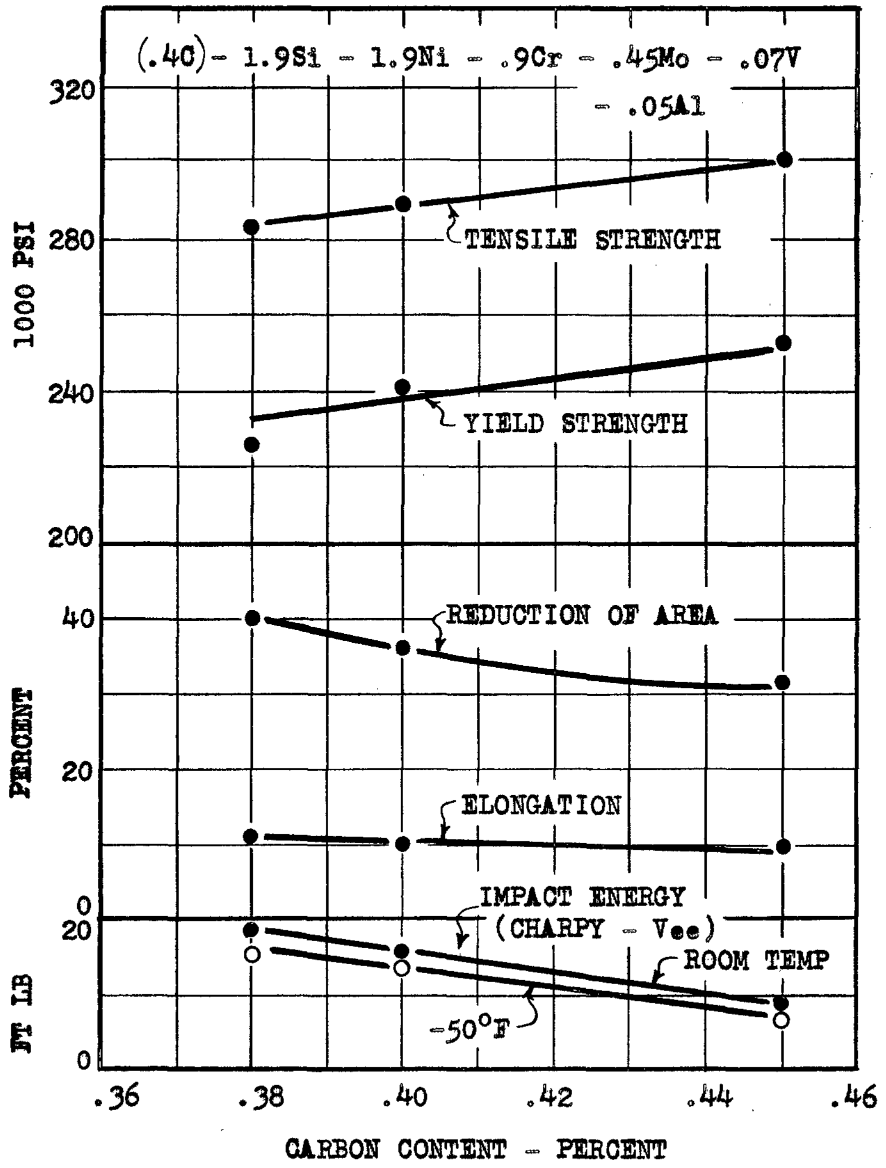


FIG. 16 EFFECT OF CARBON CONTENT ON PROPERTIES OF AN ULTRA-HIGH-STRENGTH STEEL.

(DATA BY INTERNATIONAL NICKEL)

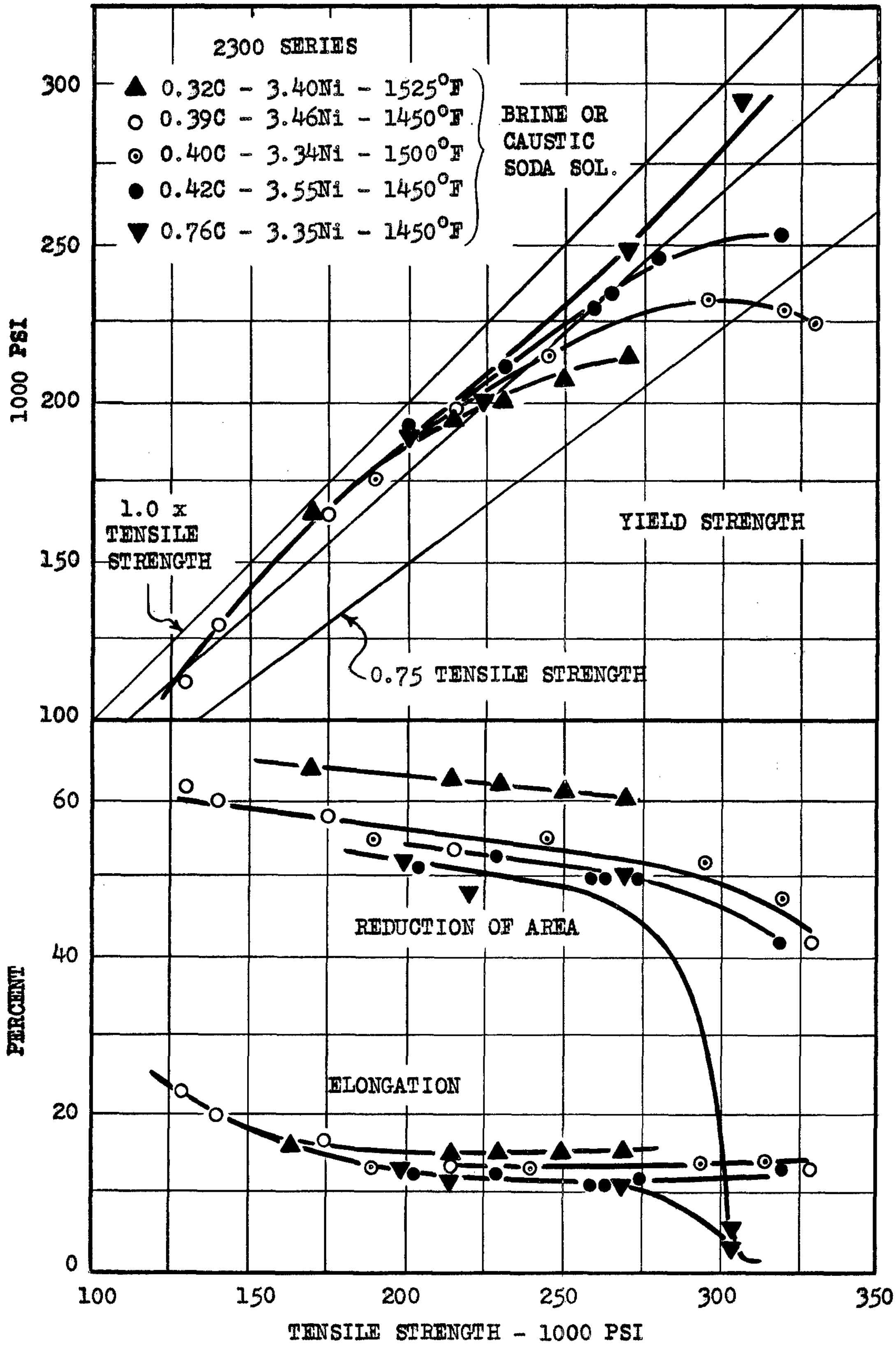


FIG. 17 EFFECT OF CARBON CONTENT ON RELATION BETWEEN YIELD STRENGTH, REDUCTION OF AREA, ELONGATION AND TENSILE STRENGTH OF 2300 STEELS.

(DATA BY INTERNATIONAL NICKEL)

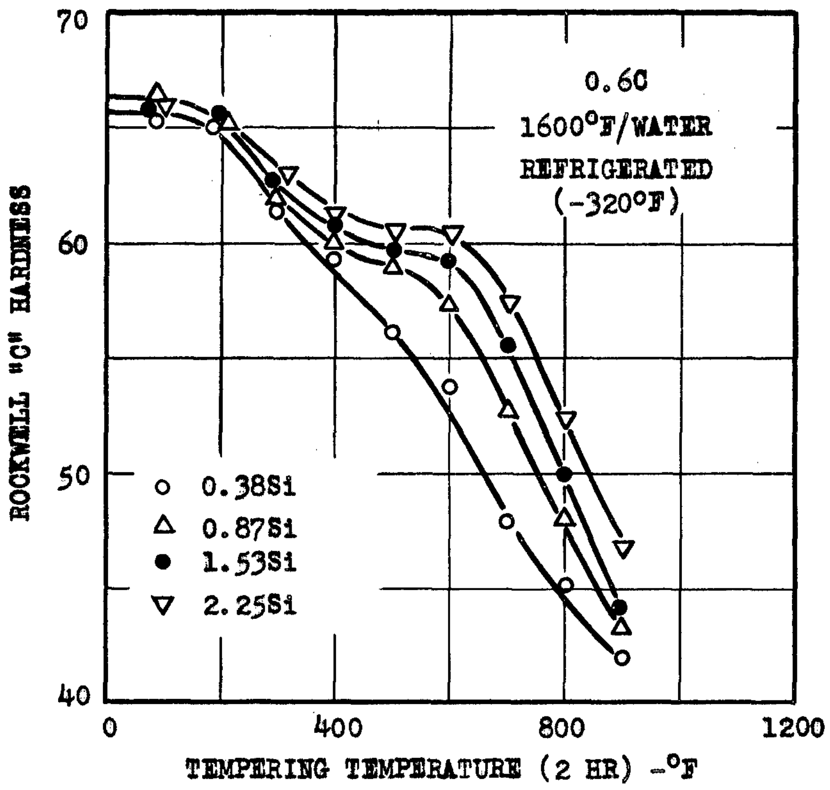


FIG. 18 EFFECT OF SILICON CONTENT ON HARDNESS OF HEAT-TREATED 0.6 PERCENT CARBON STEELS.

(ALLTEN, PAYSON 1953)

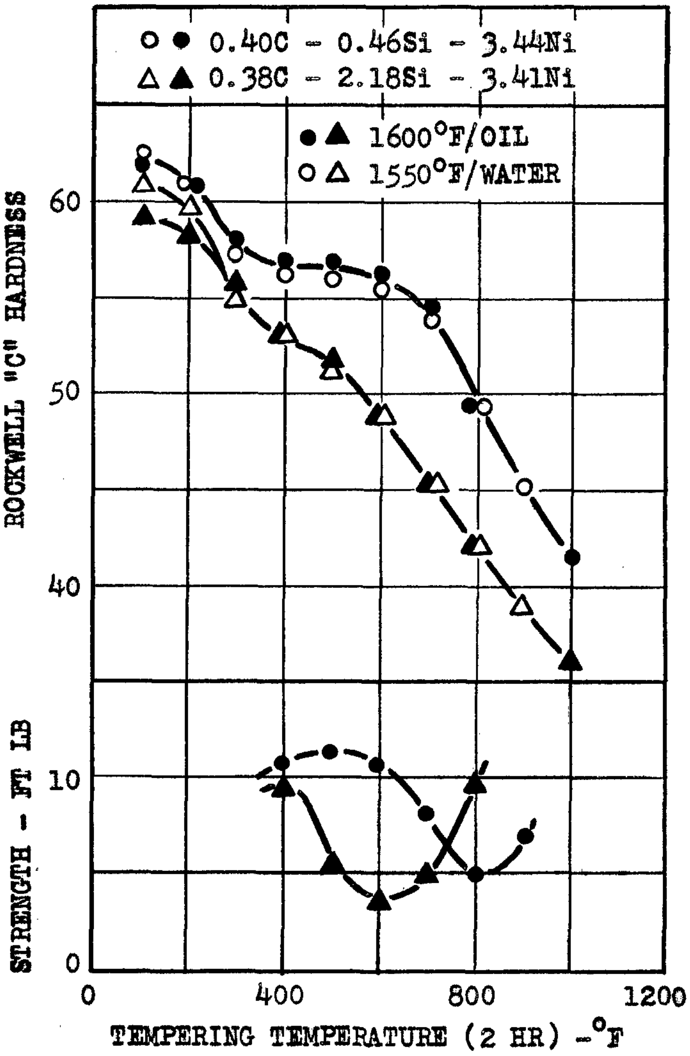


FIG. 19 EFFECT OF SILICON CONTENT ON HARDNESS AND IMPACT STRENGTH OF 3%-NICKEL STEELS, REFRIGERATED AFTER QUENCHING.

(ALLTEN, PAYSON 1953)

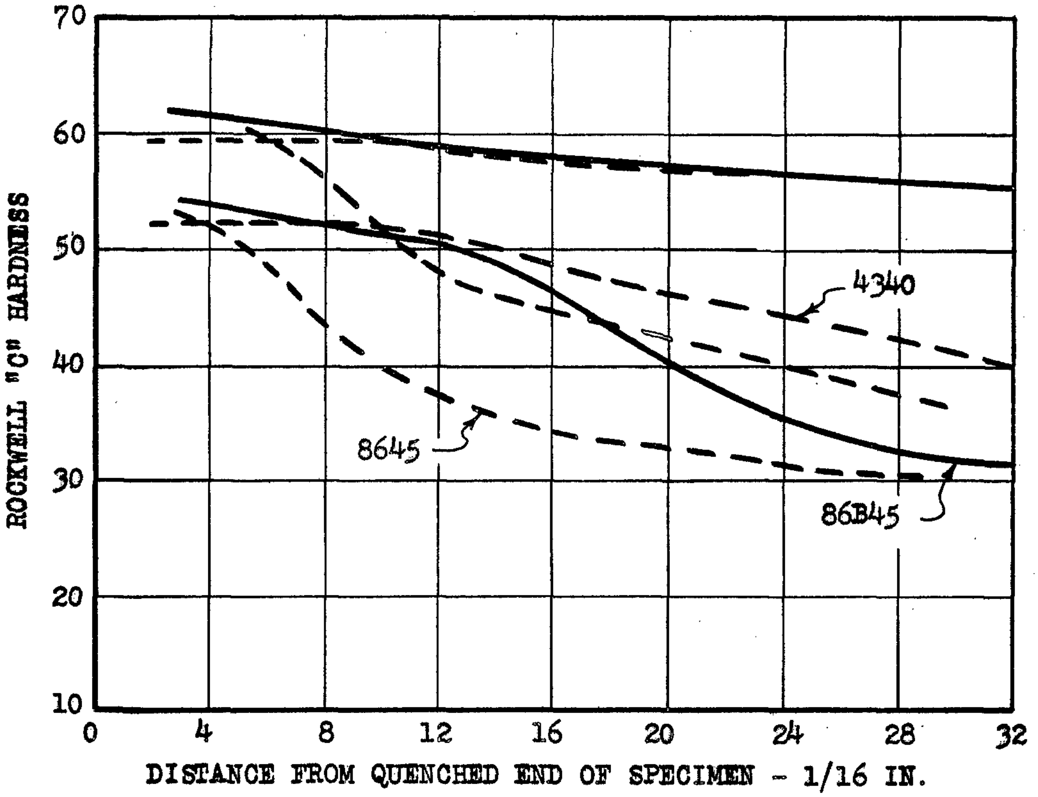


FIG. 20 COMPARISON OF HARDENABILITY CURVES FOR 8645, 86B45 AND 4340 STEELS.

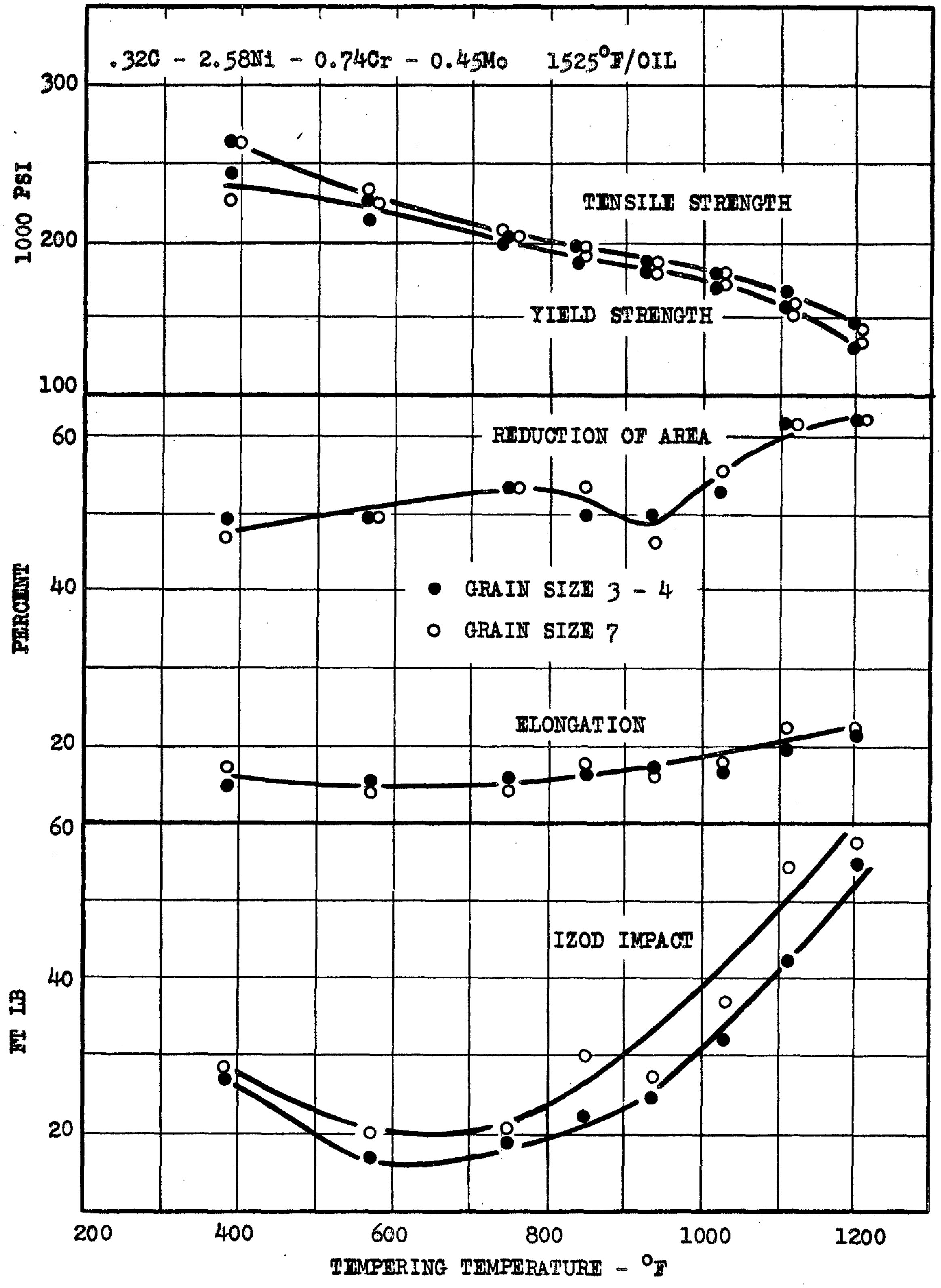


FIG. 21 EFFECT OF INHERENT GRAIN SIZE ON TENSION CHARACTERISTICS OF A CHROMIUM-NICKEL-MOLYBDENUM STEEL AT DIFFERENT TEMPERING TEMPERATURES.

(DATA BY SWINDEN, BOLSOVER 1936)

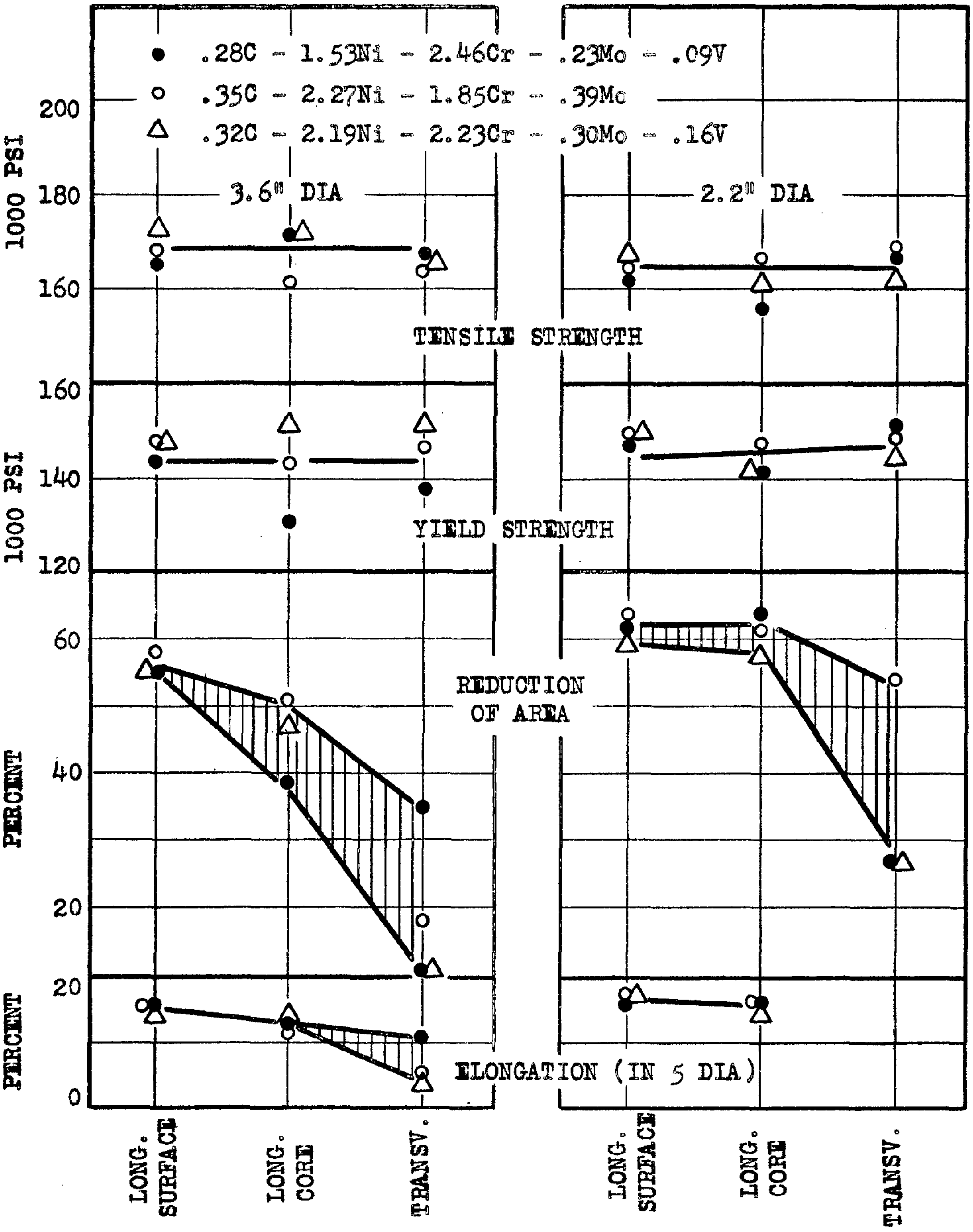


FIG. 22 EFFECT OF POSITION AND DIRECTION OF TEST BAR ON TENSION CHARACTERISTICS OF THREE DEEP-HARDENING LOW-ALLOY STEELS.

(DATA BY POMP, KRISCH 1942)

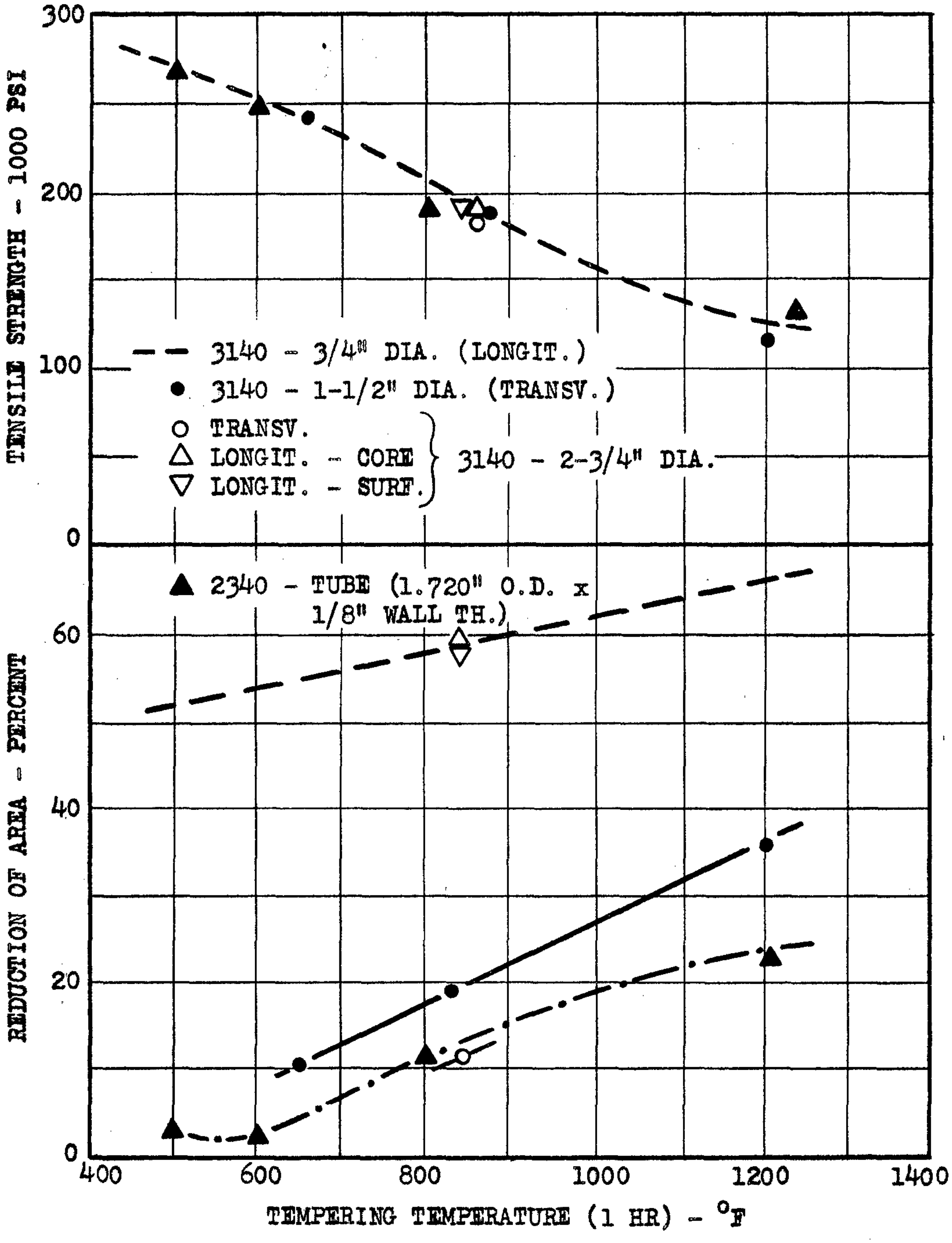


FIG. 23 EFFECT OF TEMPERING TEMPERATURE ON TRANSVERSE STRENGTH AND DUCTILITY OF SPECIMENS TAKEN FROM LOW-ALLOY STEEL BARS AND TUBE, AND SUBSEQUENTLY HEAT-TREATED.

(SACHS, LUBAHN 1943,
SACHS, LUBAHN, EBERT, AUL 1945)

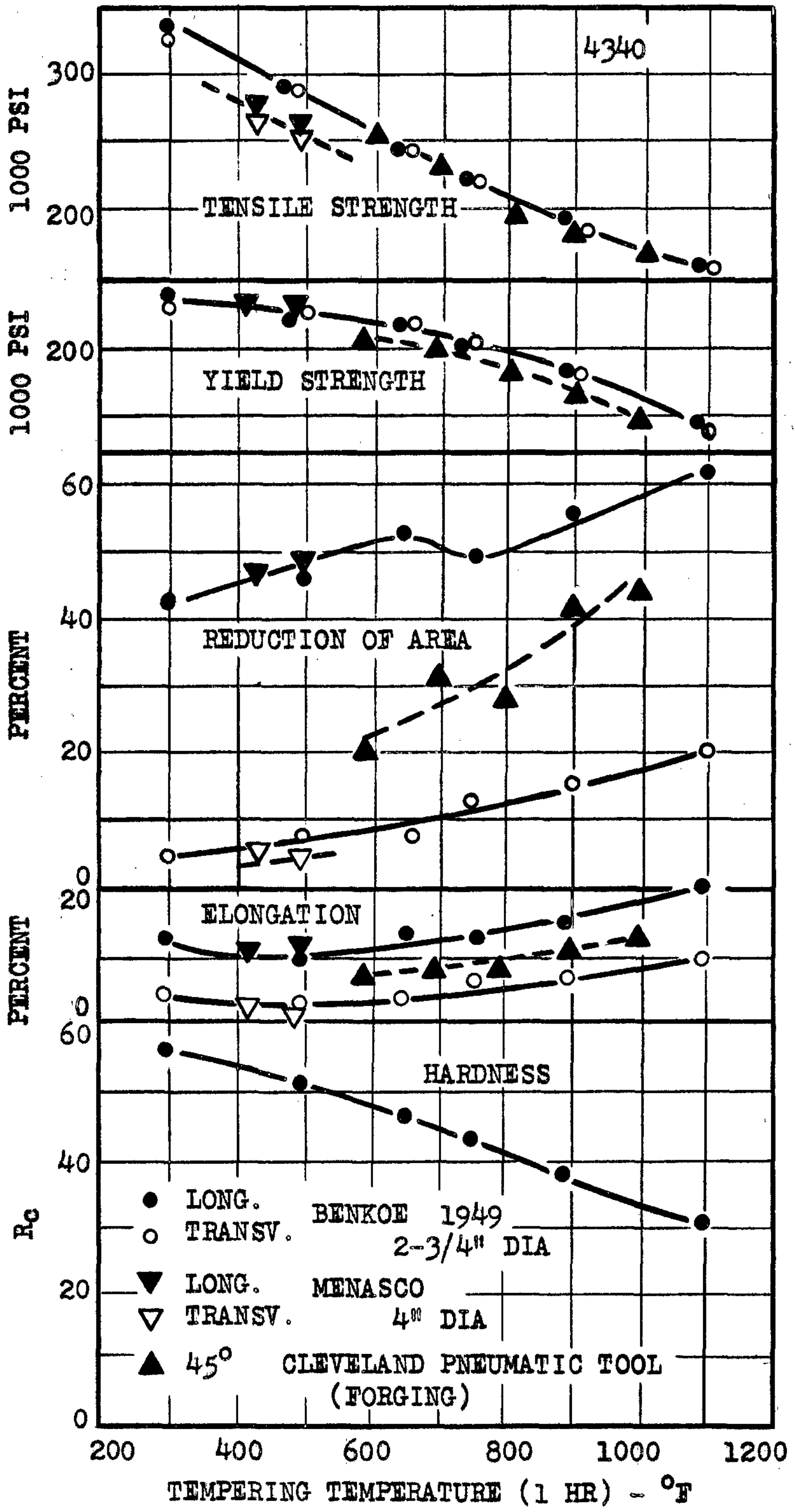


FIG. 24 EFFECT OF TEMPERING TEMPERATURE ON TENSION CHARACTERISTICS OF SPECIMENS TAKEN IN DIFFERENT DIRECTIONS FROM 4340 STEEL SECTIONS.

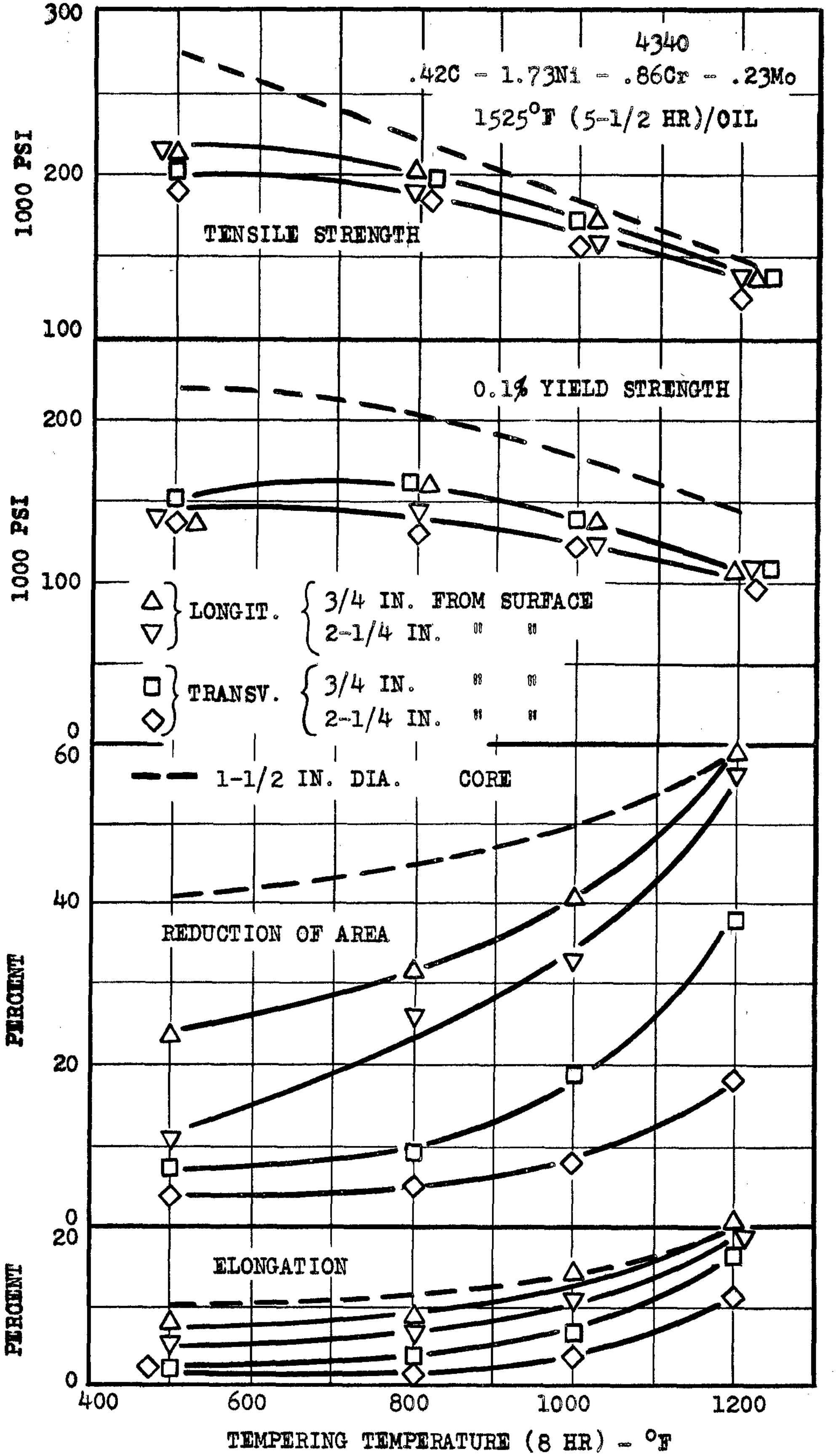


FIG. 25 TENSION CHARACTERISTICS OF A HEAT-TREATED 6 IN. SQUARE 4340 STEEL BILLET.

(DATA BY ARMOUR INSTITUTE)

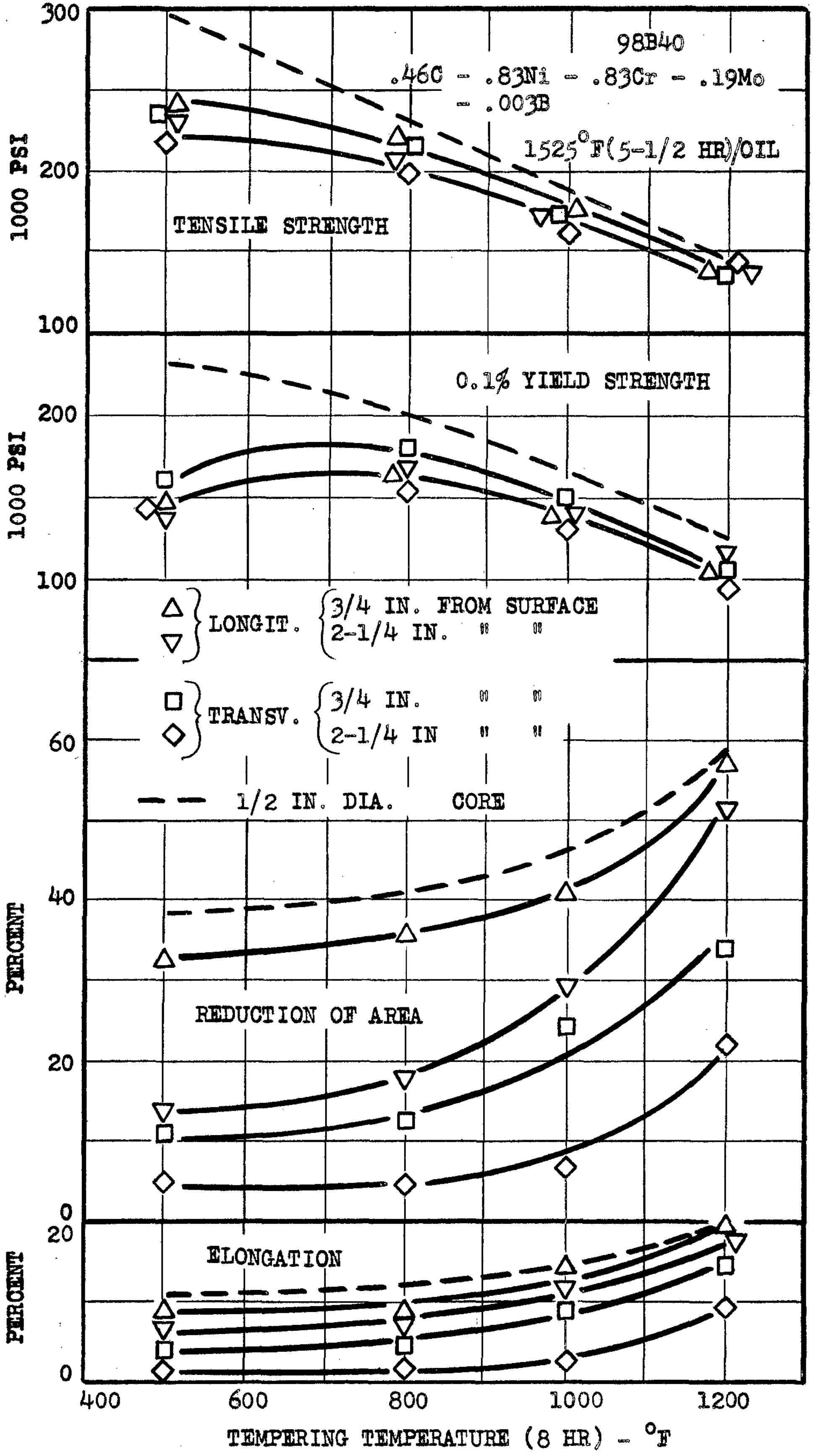


FIG. 26 TENSION CHARACTERISTICS OF A HEAT-TREATED 6 IN. SQUARE 98B40 STEEL BILLET.

(DATA BY ARMOUR INSTITUTE)

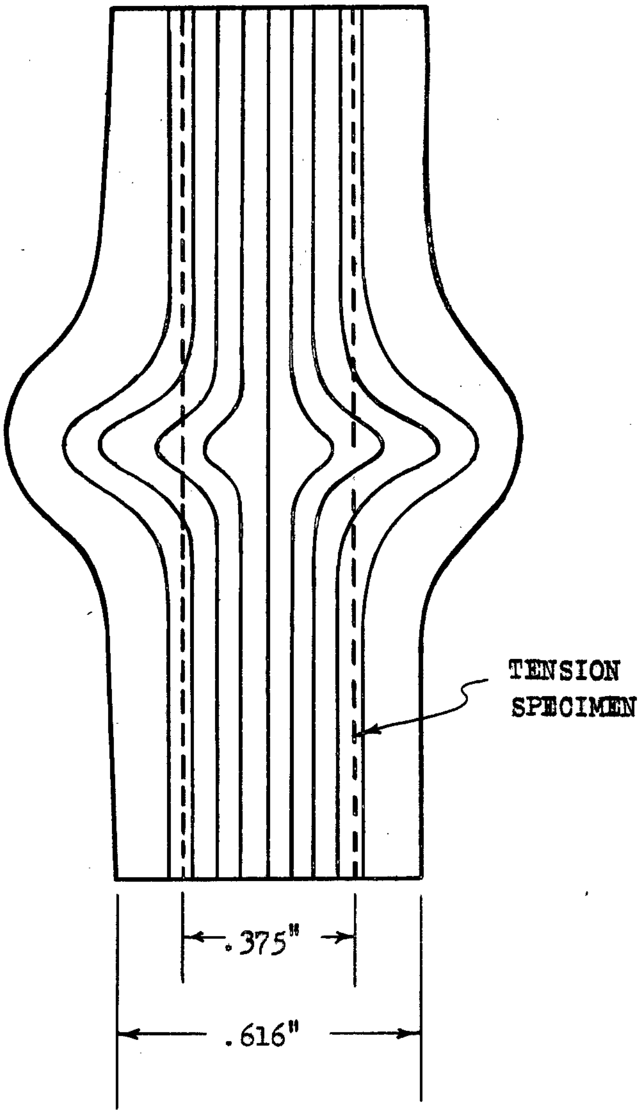


FIG. 27 FLOW PATTERN OF A HOT UPSET SPECIMEN USED FOR A TENSILE TEST TO DEMONSTRATE EFFECT OF FIBER ON STRENGTH OF FLASHWELDED PART.

(MENASCO)

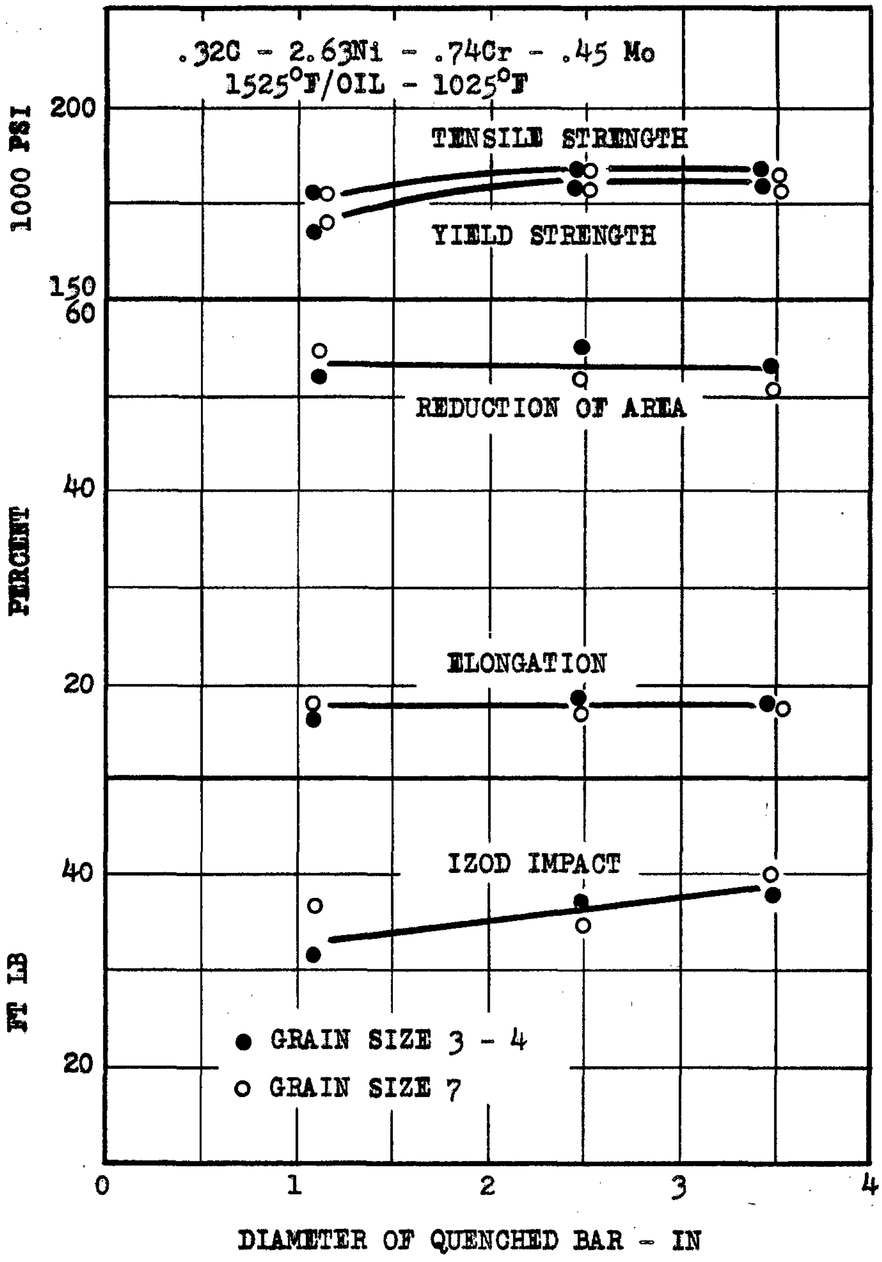


FIG. 28 EFFECT OF AS-QUENCHED SECTION SIZE AND AUSTENITIC GRAIN SIZE ON TENSION CHARACTERISTICS OF A DEEP-HARDENING NICKEL-CHROMIUM-MOLYBDENUM STEEL.

(DATA BY SWINDEN, BOLSOVER 1936)

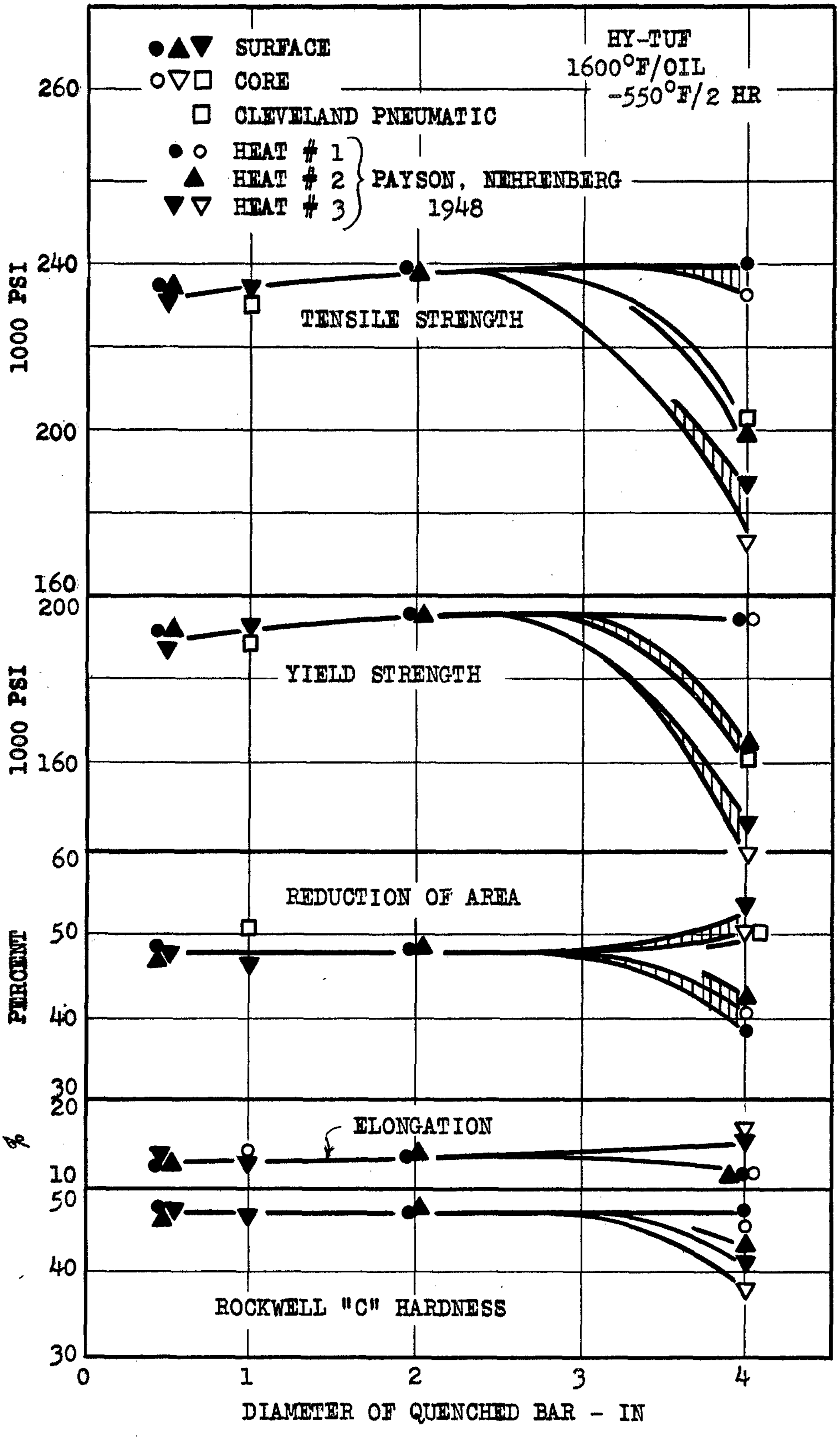


FIG. 29 EFFECT OF AS-QUENCHED SECTION SIZE ON TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL (HY-TUF).

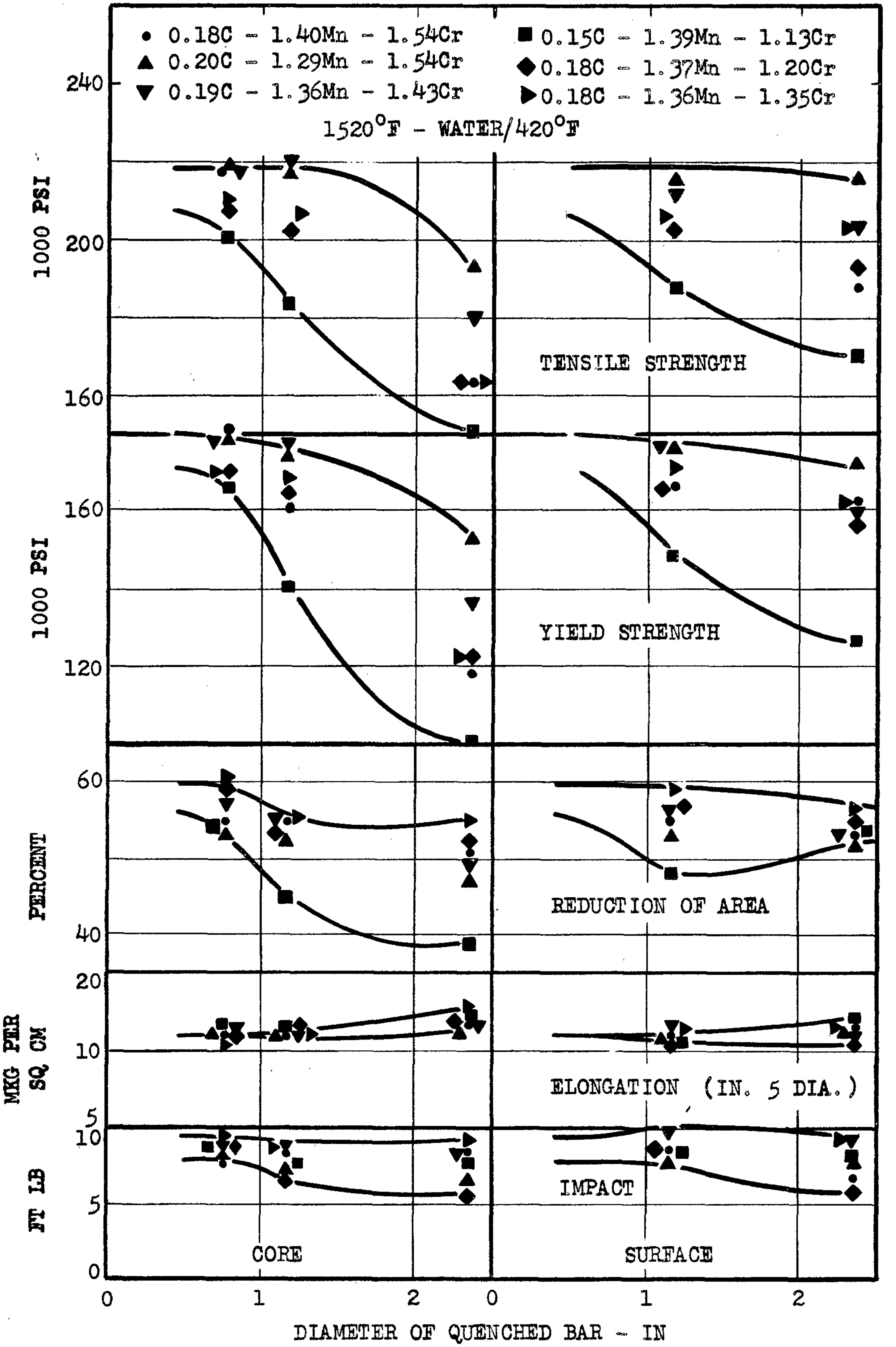


FIG. 30 EFFECT OF AS-QUENCHED SECTION SIZE ON TENSION CHARACTERISTICS OF SIX HEATS OF A LOW-ALLOY STEEL FROM DIFFERENT PRODUCERS.

(DATA BY POMP, KRISCH 1942)

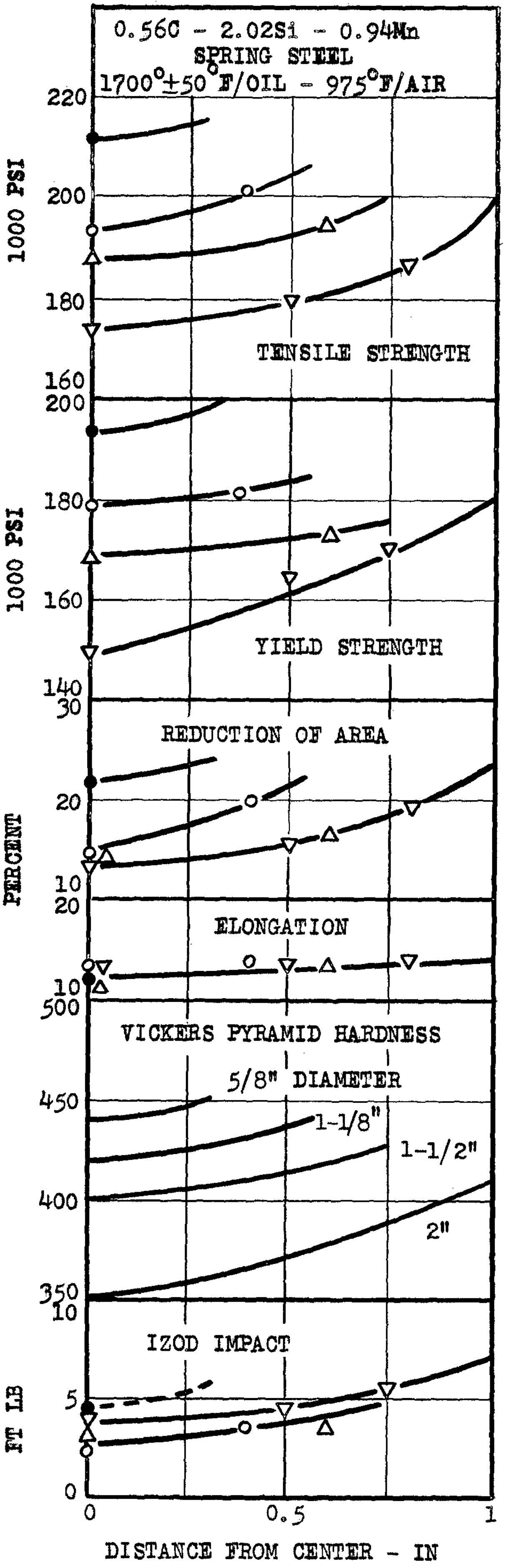


FIG. 31 EFFECT OF AS-QUENCHED SECTION SIZE ON MECHANICAL PROPERTIES OF A LOW-ALLOY STEEL.

(DATA BY IRON, STEEL INST.)

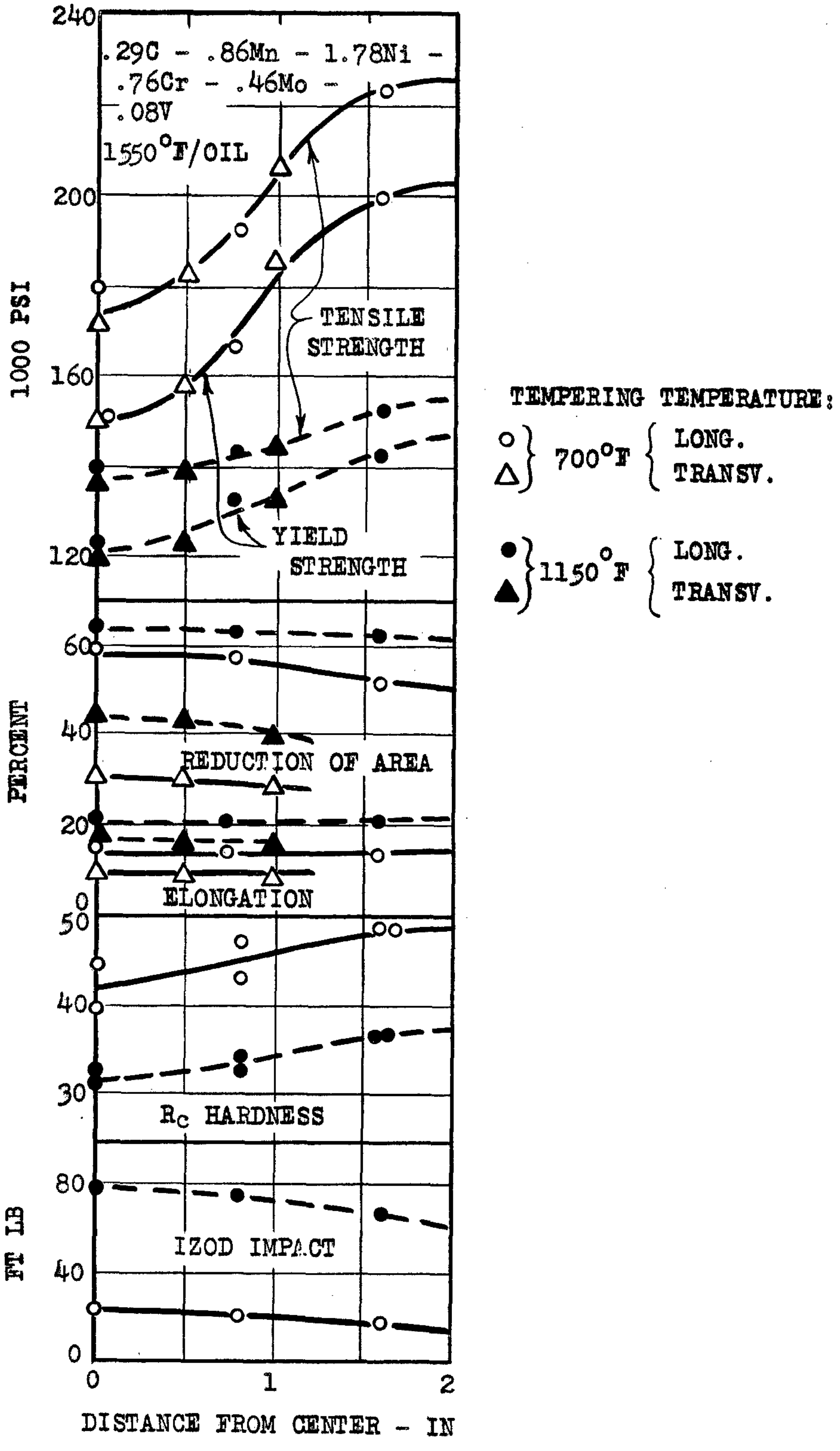


FIG. 32 MECHANICAL PROPERTIES OF HEAT-TREATED 4 IN. DIA. LOW-ALLOY STEEL BARS IN VARIOUS DIRECTIONS AND POSITIONS.

(DATA BY DIRKES, BOWMAN, HORNE 1952)

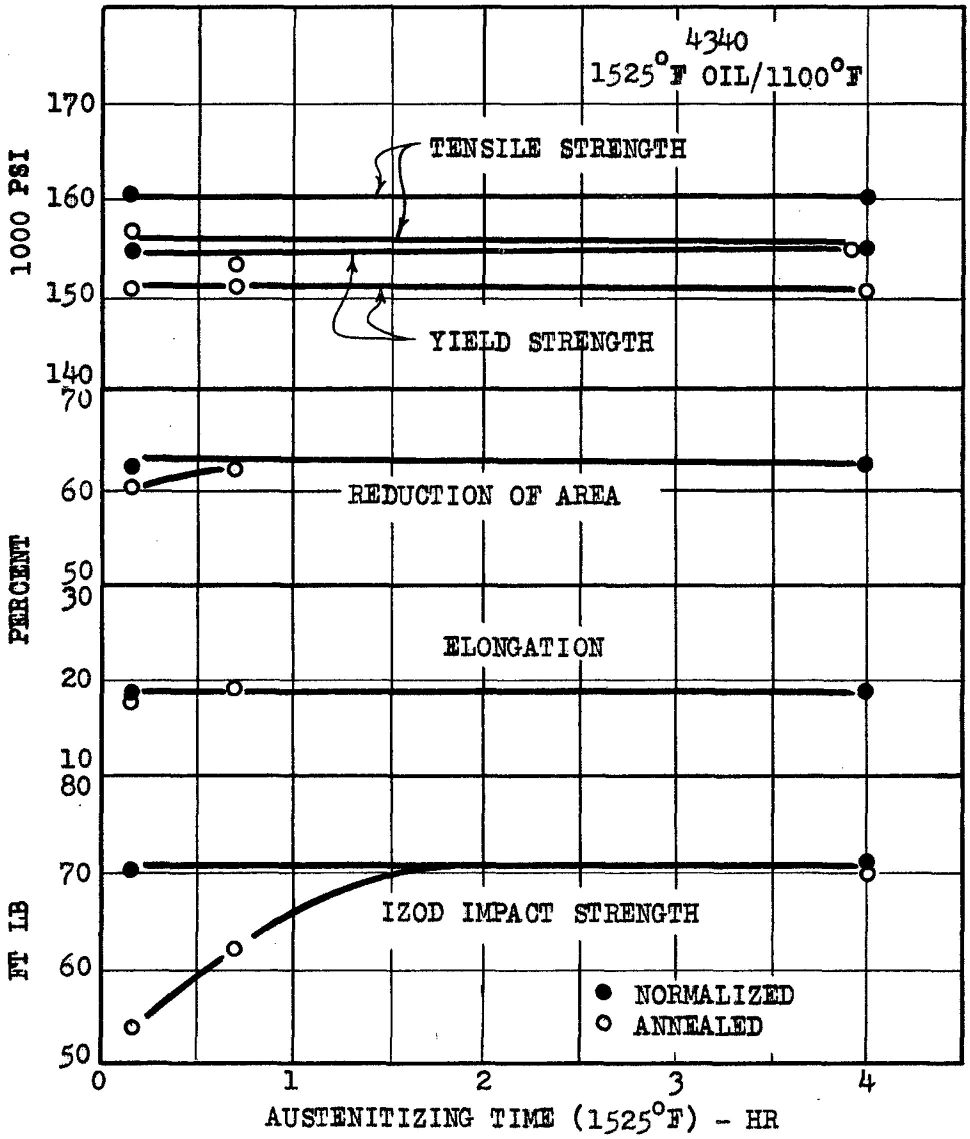


FIG. 33 EFFECTS OF TREATMENT PRIOR TO FINAL HEAT-TREATING ON MECHANICAL PROPERTIES OF 4340 STEEL.

(DATA BY WELCHNER, ROWLAND, UBBEN 1944)

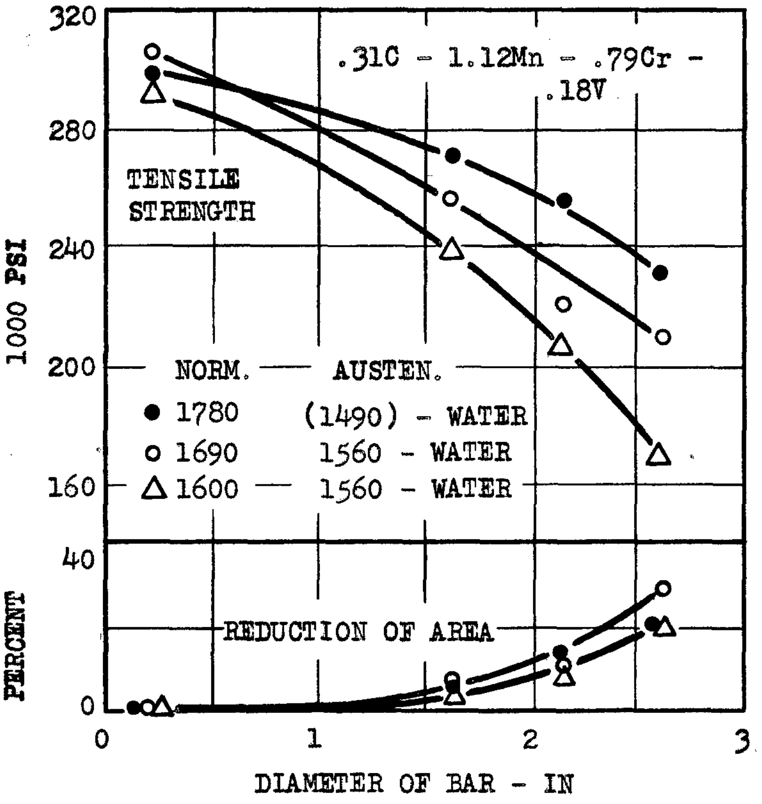


FIG. 34 EFFECTS OF NORMALIZING AND AUSTENITIZING TEMPERATURES ON TENSILE STRENGTH AND REDUCTION OF AREA OF A LOW-ALLOY STEEL.

(EILENDER, AREND, NEUHAUS 1952)

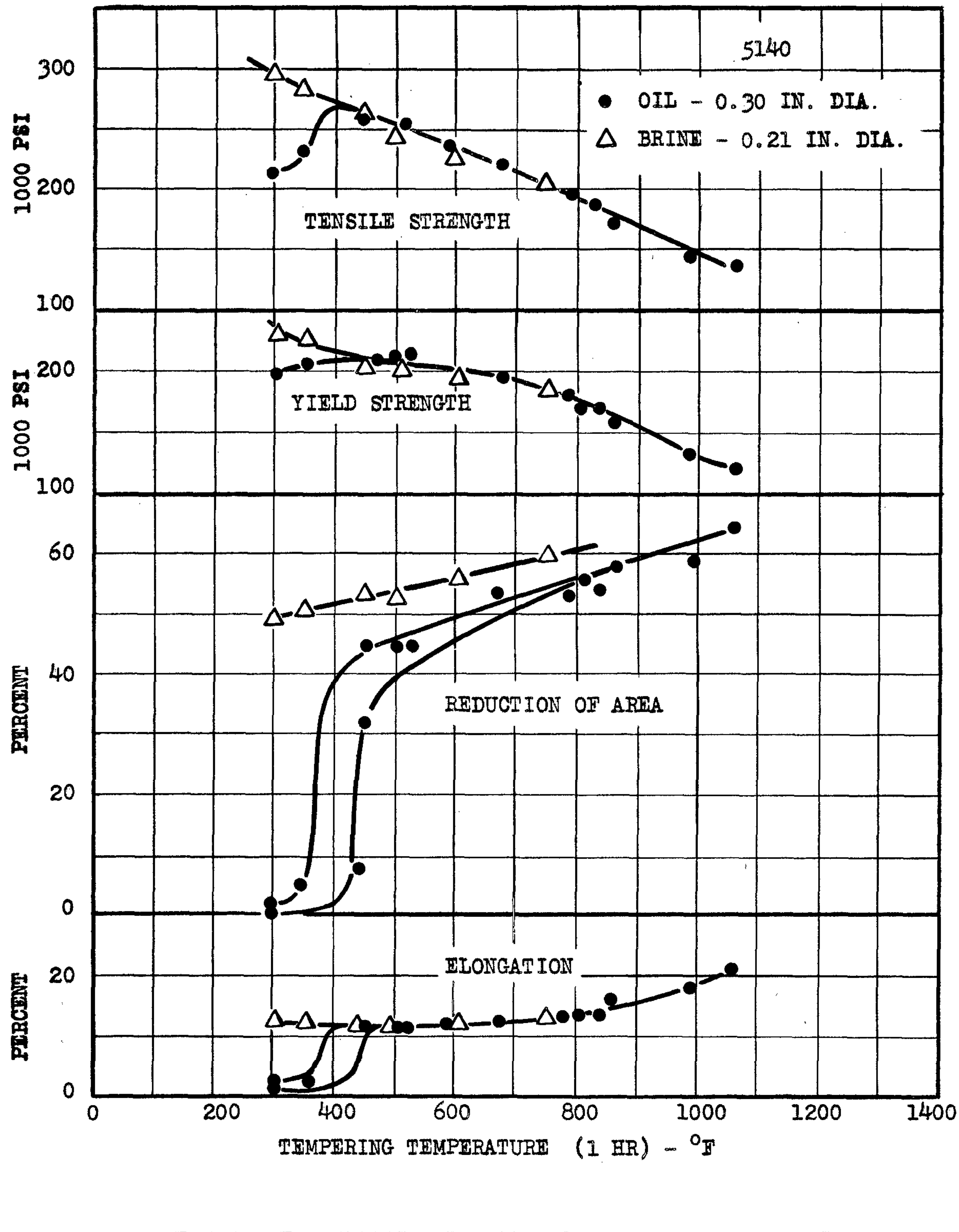


FIG. 35 EFFECT OF HEAT-TREATING PROCEEDURE ON TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

(DATA BY INTERNATIONAL NICKEL)

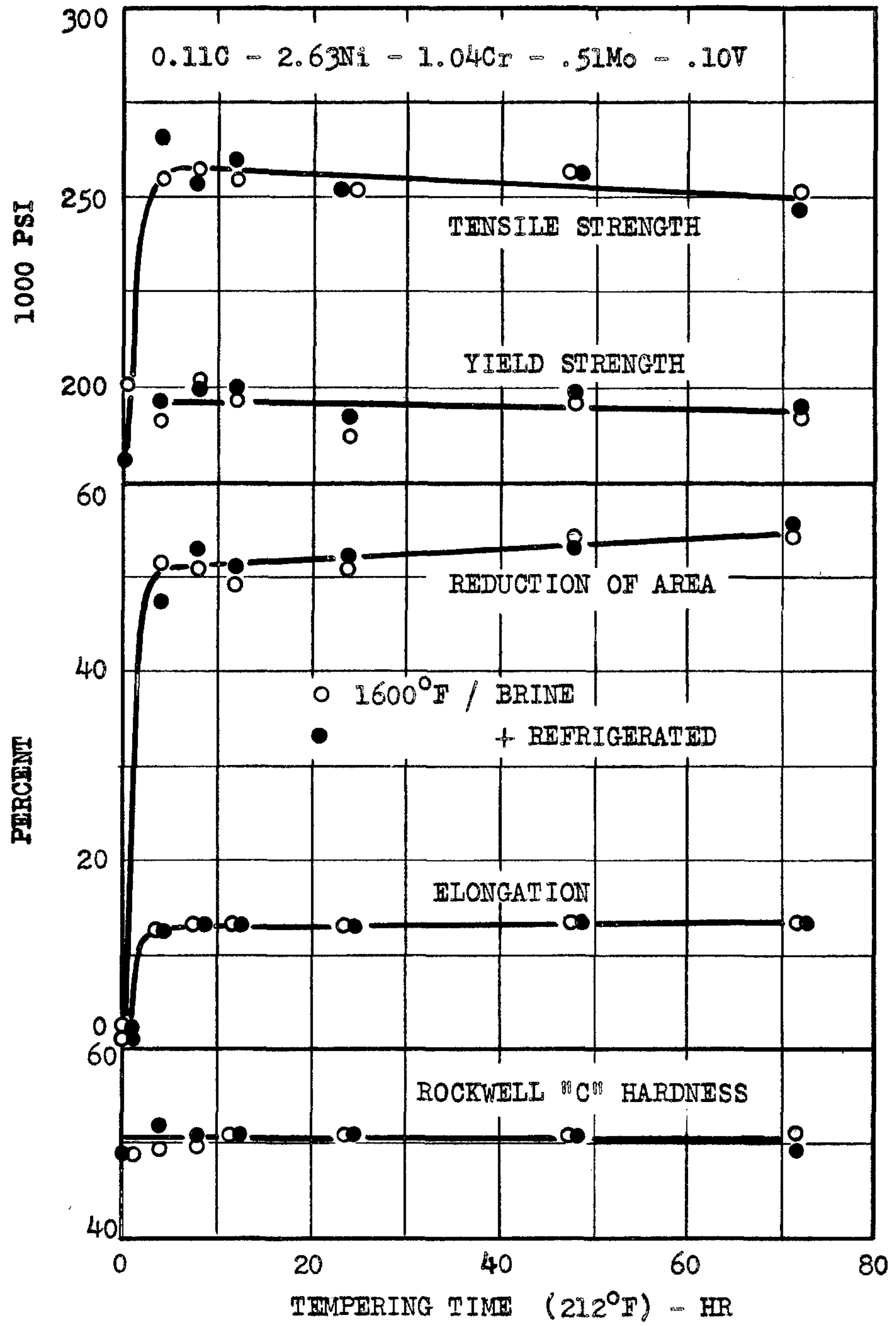


FIG. 36 EFFECT OF TEMPERING AT 212°F AND REFRIGERATING ON TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

(DATA BY CARNEGIE INSTITUTE)

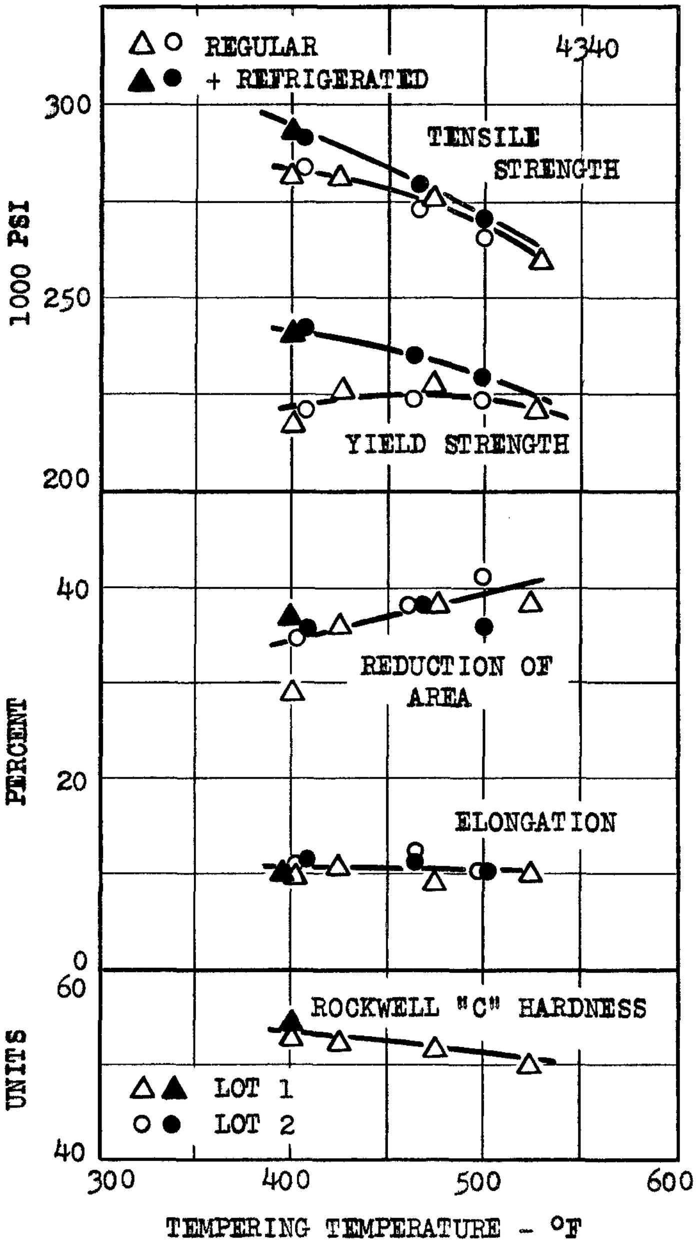


FIG. 37 EFFECT OF REFRIGERATING ON PROPERTIES OF 4340 STEEL.

(DATA BY MENASCO)

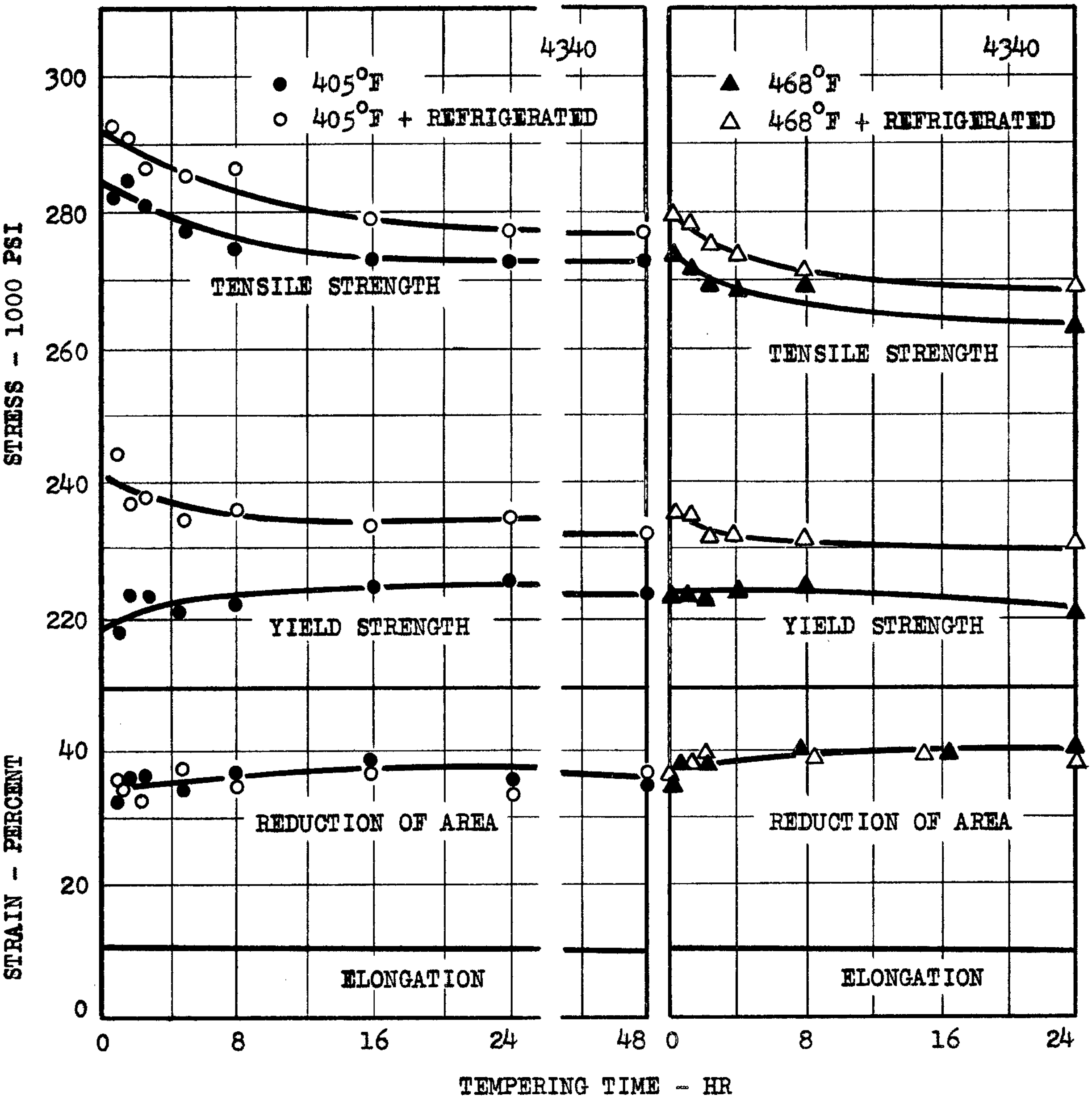


FIG. 38 EFFECTS OF TEMPERING TIME AND REFRIGERATING ON TENSION CHARACTERISTICS OF 4340 STEEL.

(DATA BY MENASCO)

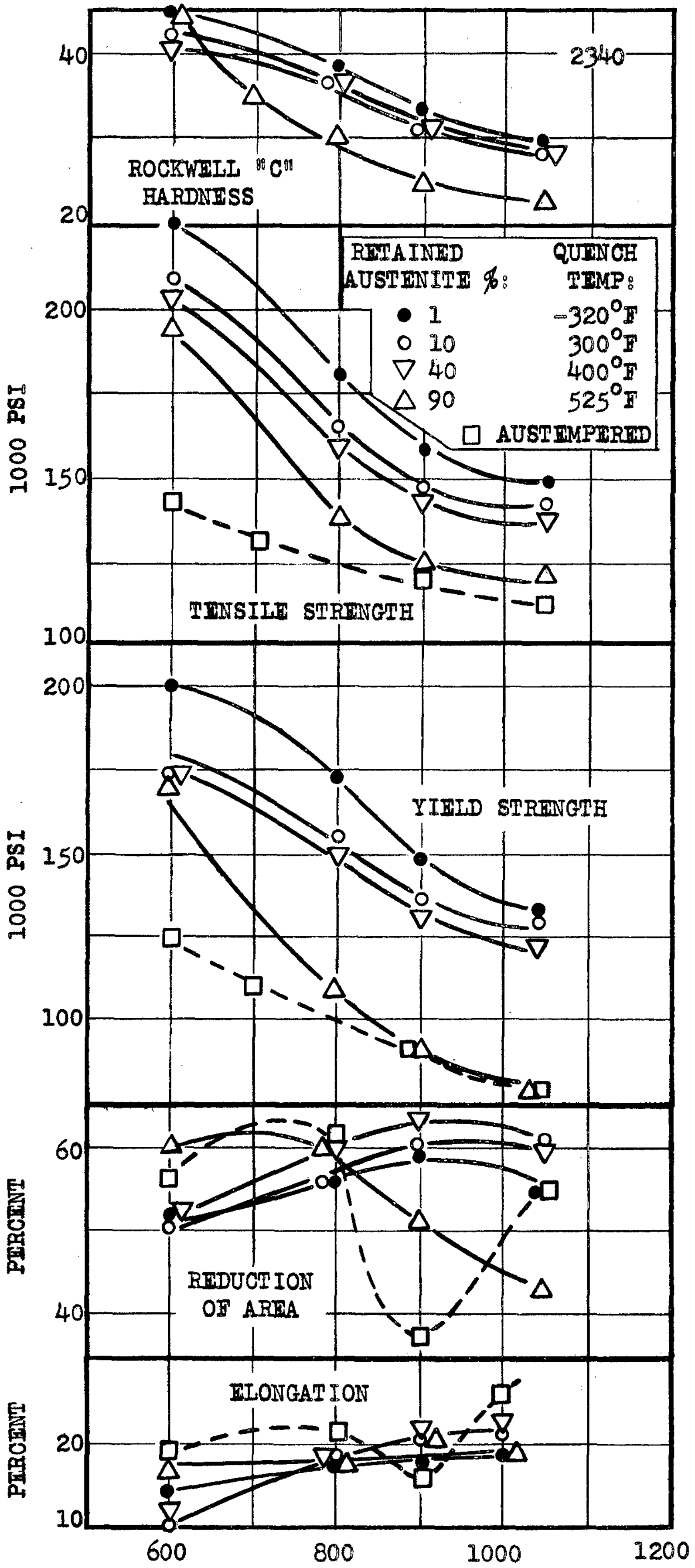


FIG. 39 EFFECT OF RETAINED AUSTENITE ON TENSION CHARACTERISTICS OF A LOW-ALLOY STEEL.

(DATA BY BAILEY, HARRIS 1952)

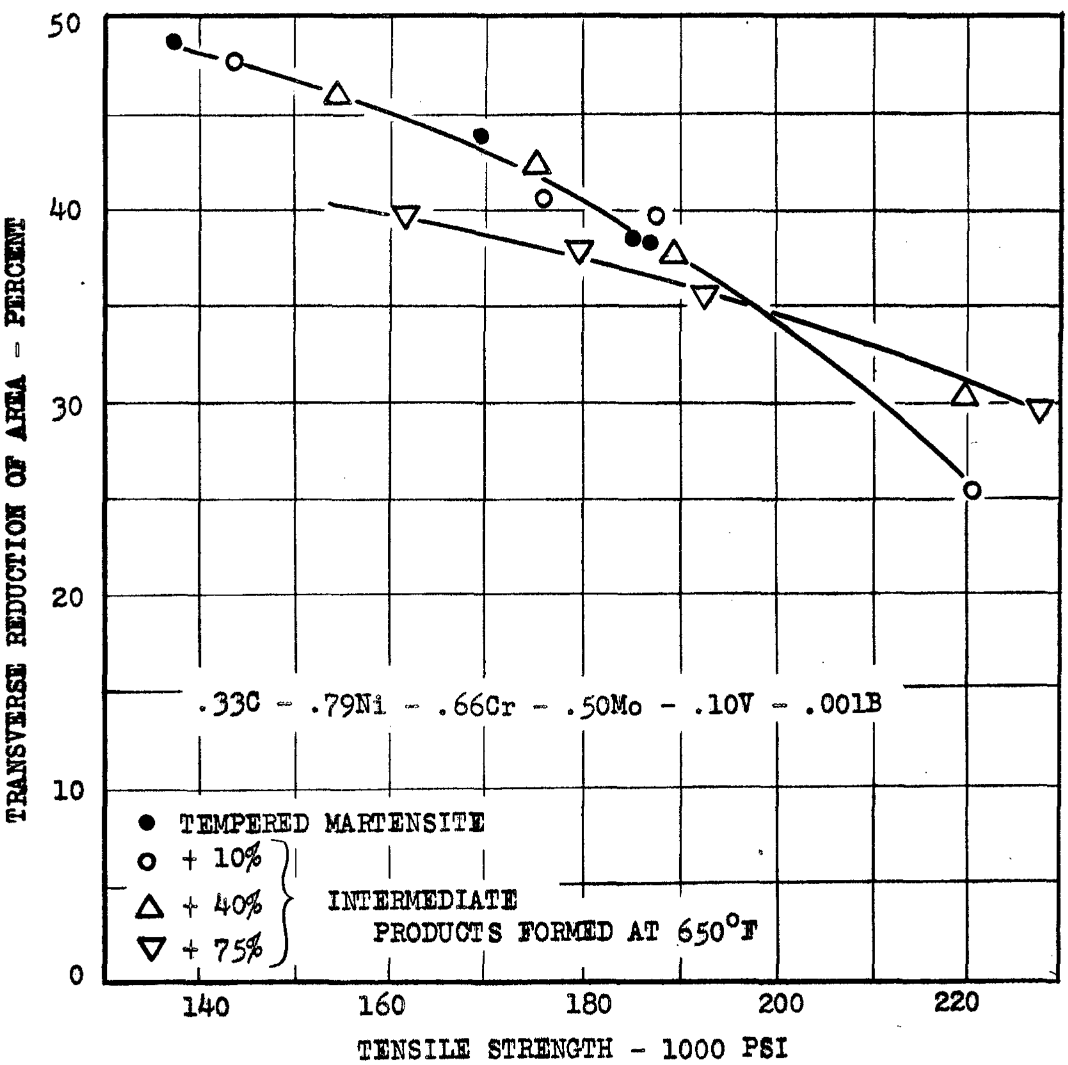


FIG. 40 REDUCTION OF AREA OF TRANSVERSE SPECIMENS vs. TENSILE STRENGTH FOR A LOW-ALLOY STEEL HEAT-TREATED TO VARIOUS COMBINATIONS OF TEMPERED MARTENSITE AND TEMPERED AUSTENITE.

(CARNEGIE INSTITUTE)

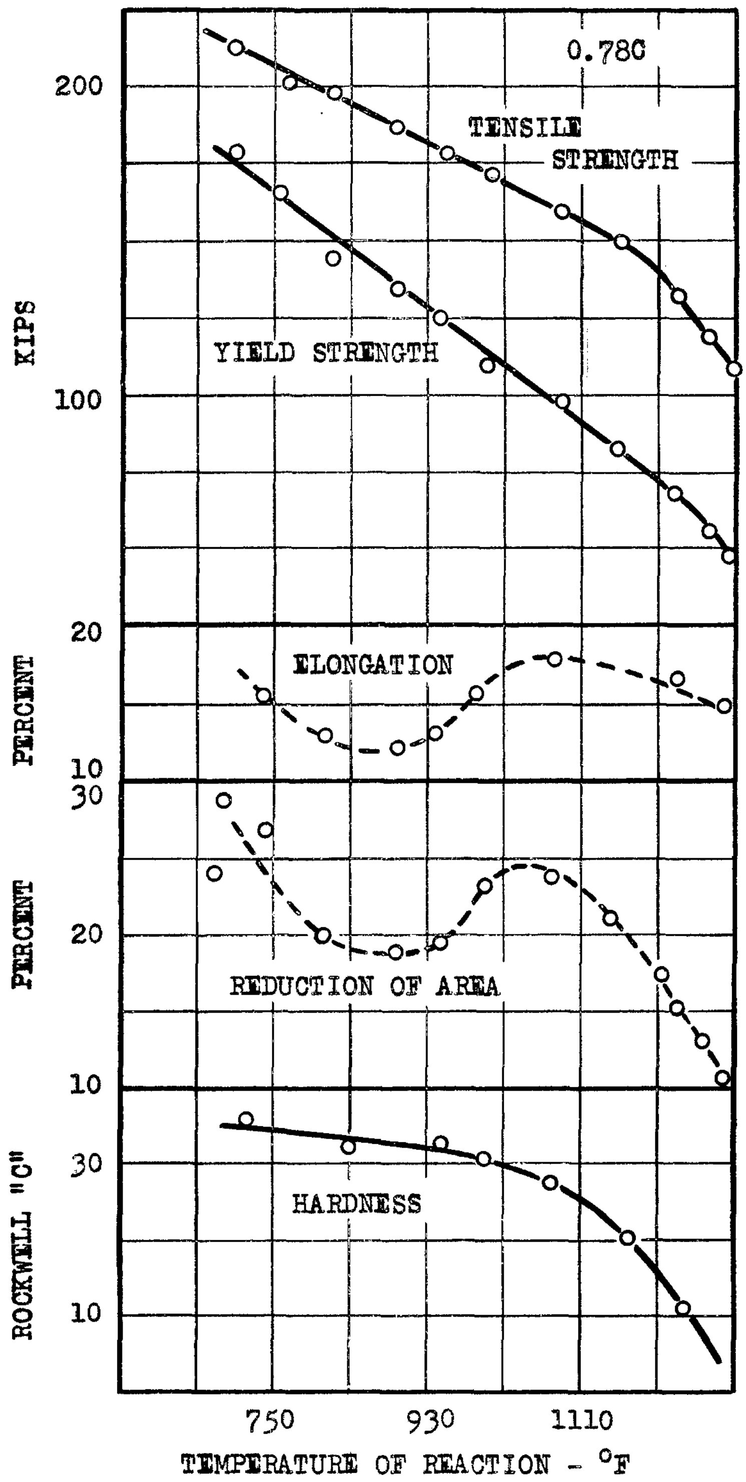


FIG. 41 TENSION CHARACTERISTICS OF A HIGH-CARBON STEEL AUSTEMPERED AT DIFFERENT TEMPERATURES.

(GENSAMER, PEARSALL, SMITH 1940)

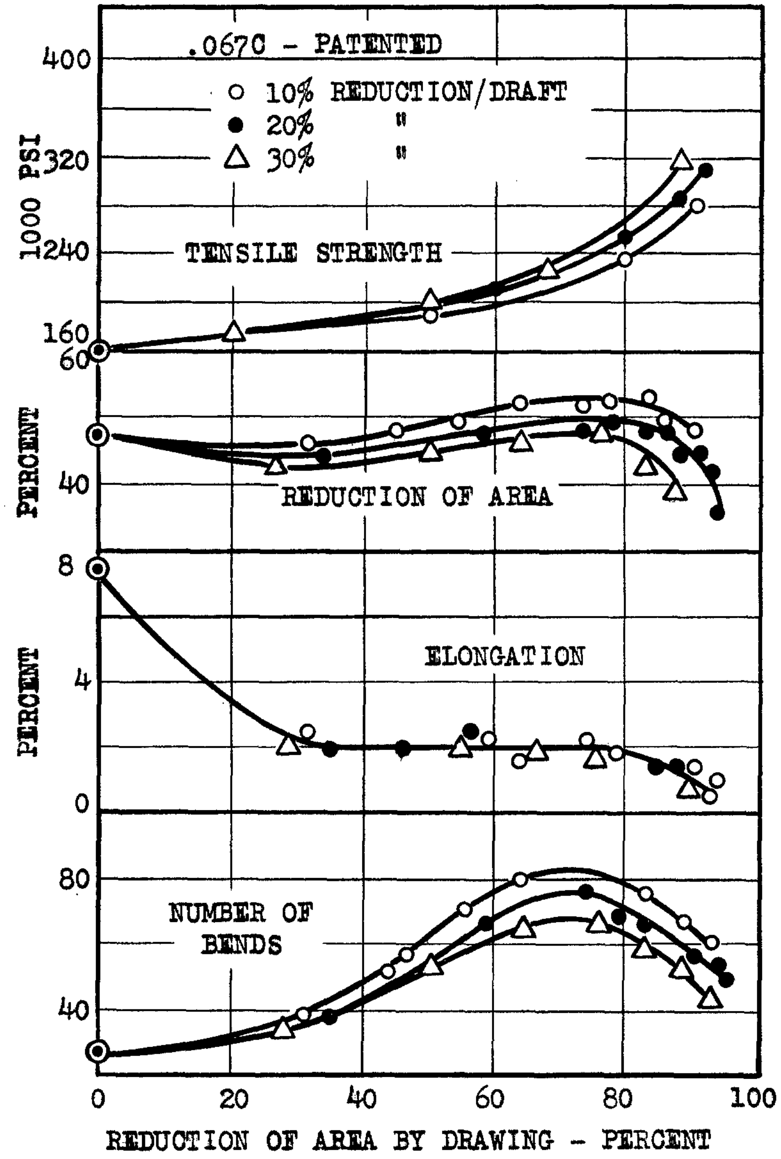


FIG. 42 EFFECT OF DRAWING ON PATENTED STEEL WIRE. (GODFREY 1942)

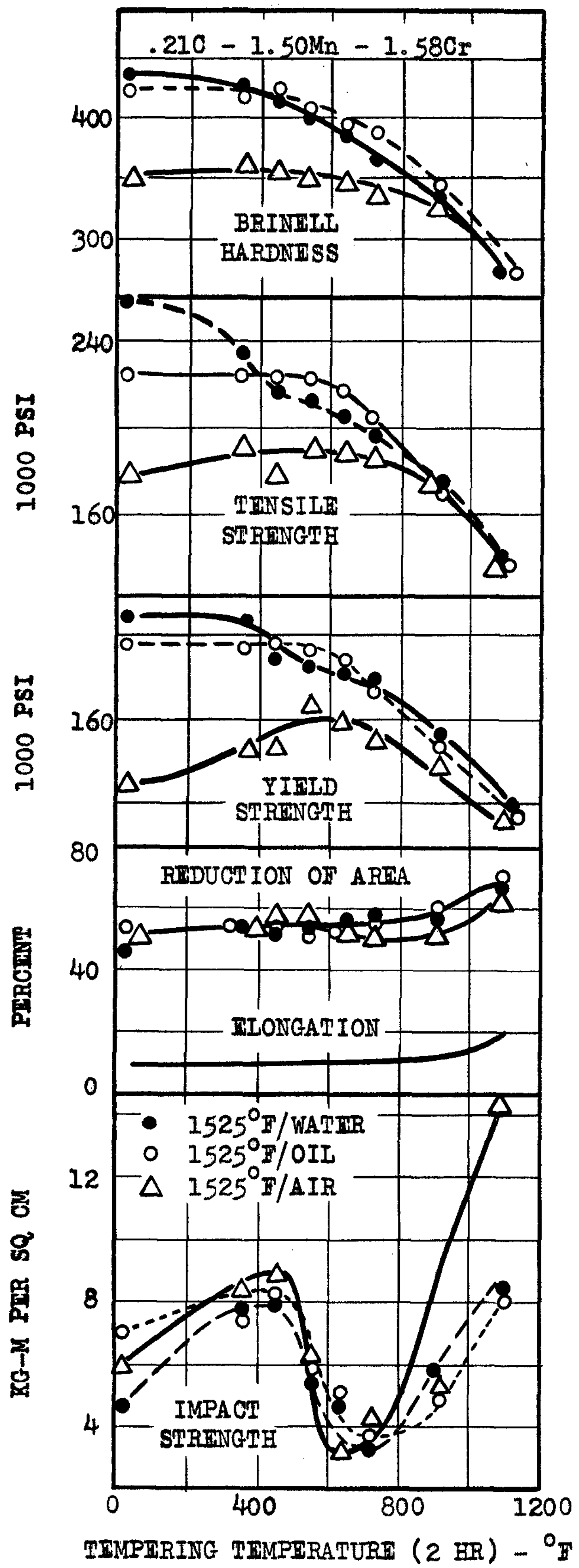


FIG. 43 EFFECT OF QUENCHING PROCEDURE ON MECHANICAL PROPERTIES OF A LOW-ALLOY STEEL. (SCHRADER, WIESTER, SIEPMANN 1950)

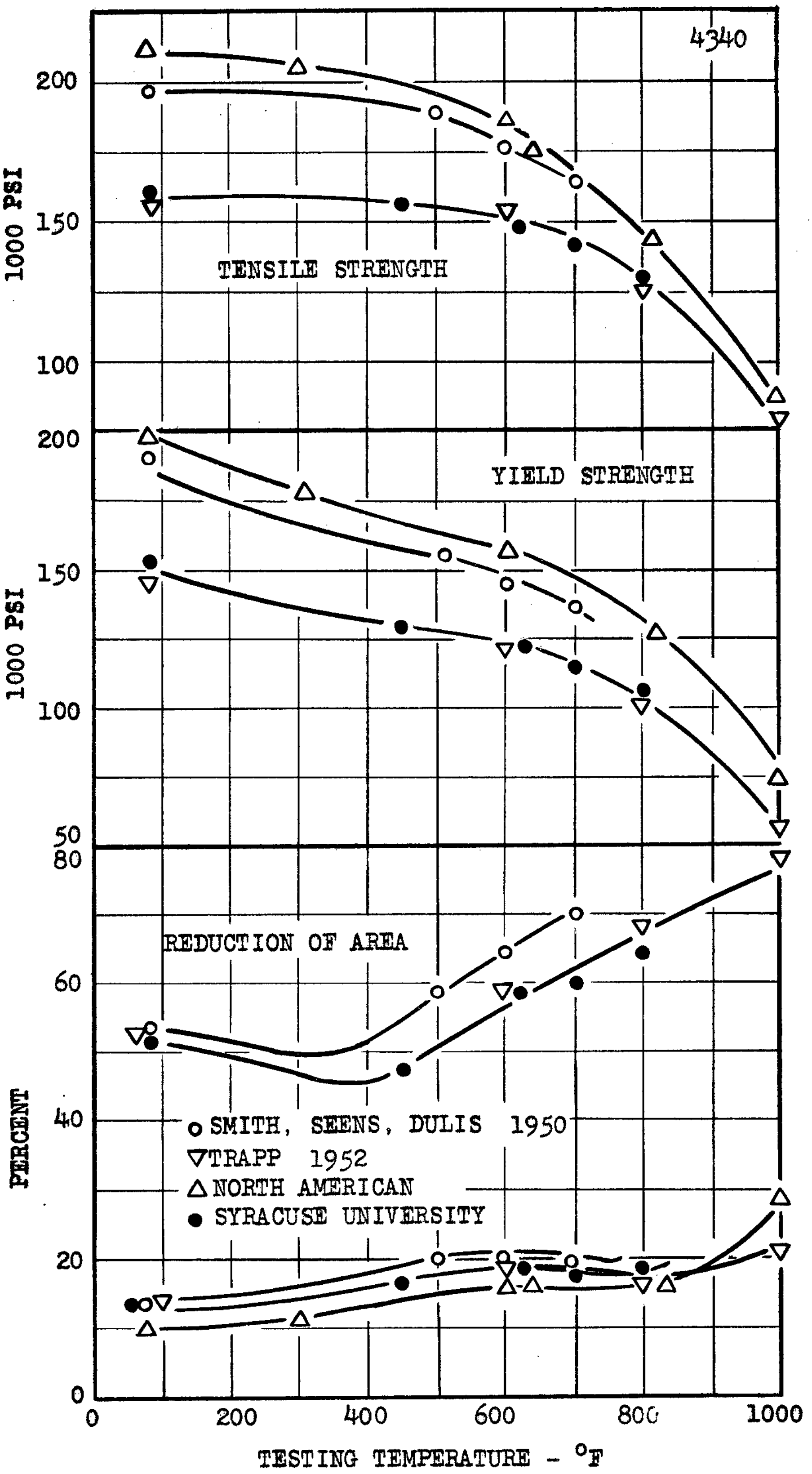


FIG. 44 SHORT-TIME TENSION CHARACTERISTICS OF 4340 STEEL AT ELEVATED TEMPERATURES.

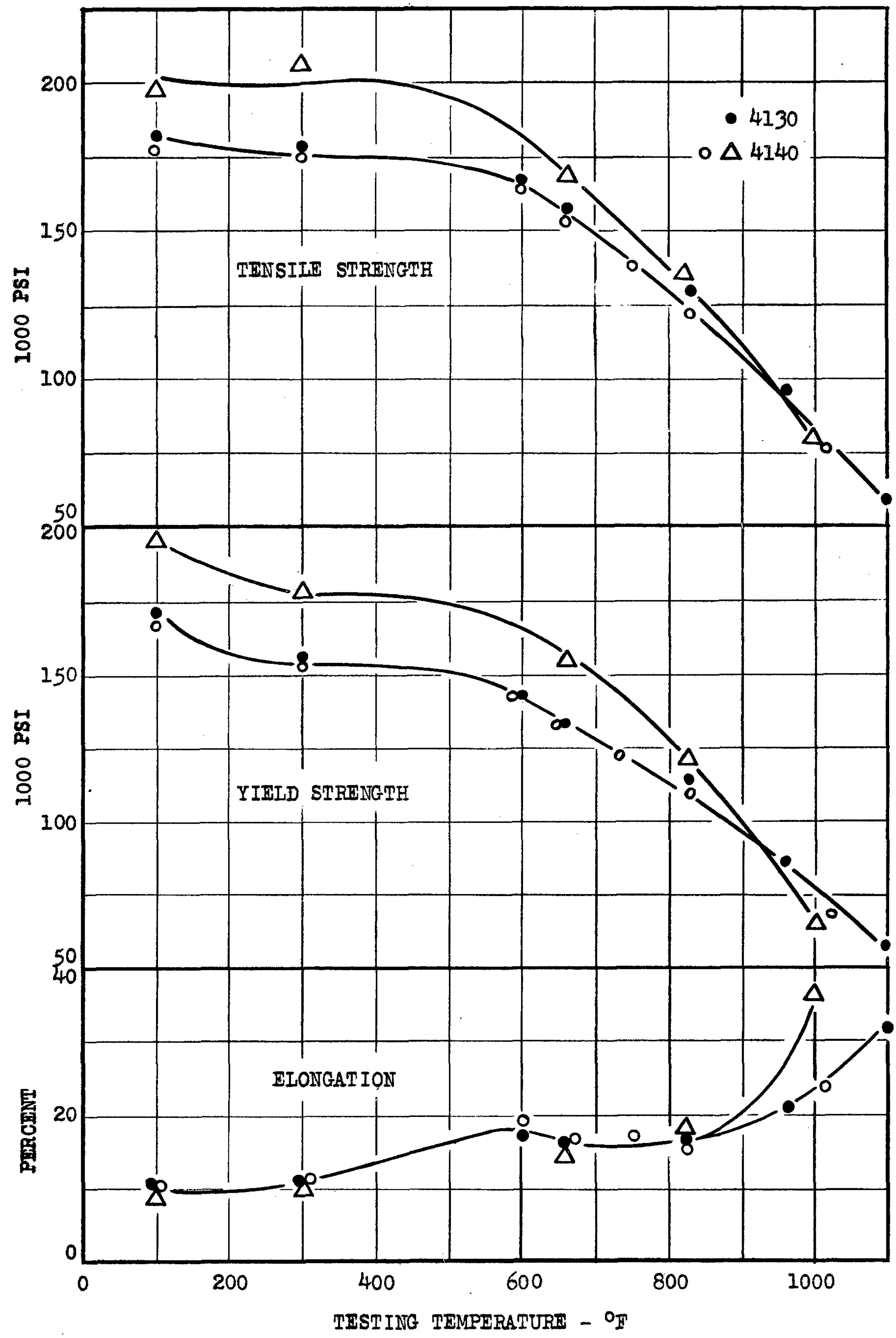


FIG. 45 SHORT-TIME TENSION CHARACTERISTICS OF 4130 AND 4140 STEEL AT ELEVATED TEMPERATURES.

(DATA BY NORTH AMERICAN)

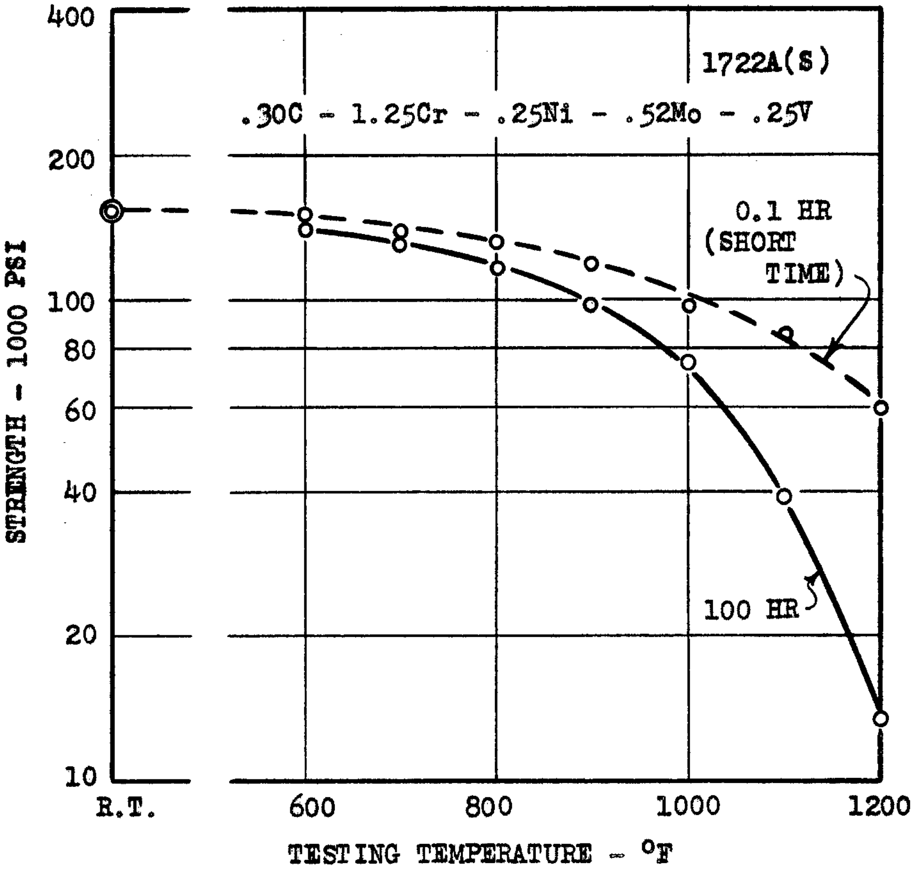


FIG. 46 STRESS-RUPTURE STRENGTH OF A LOW-ALLOY STEEL FOR HIGH-TEMPERATURE APPLICATIONS.

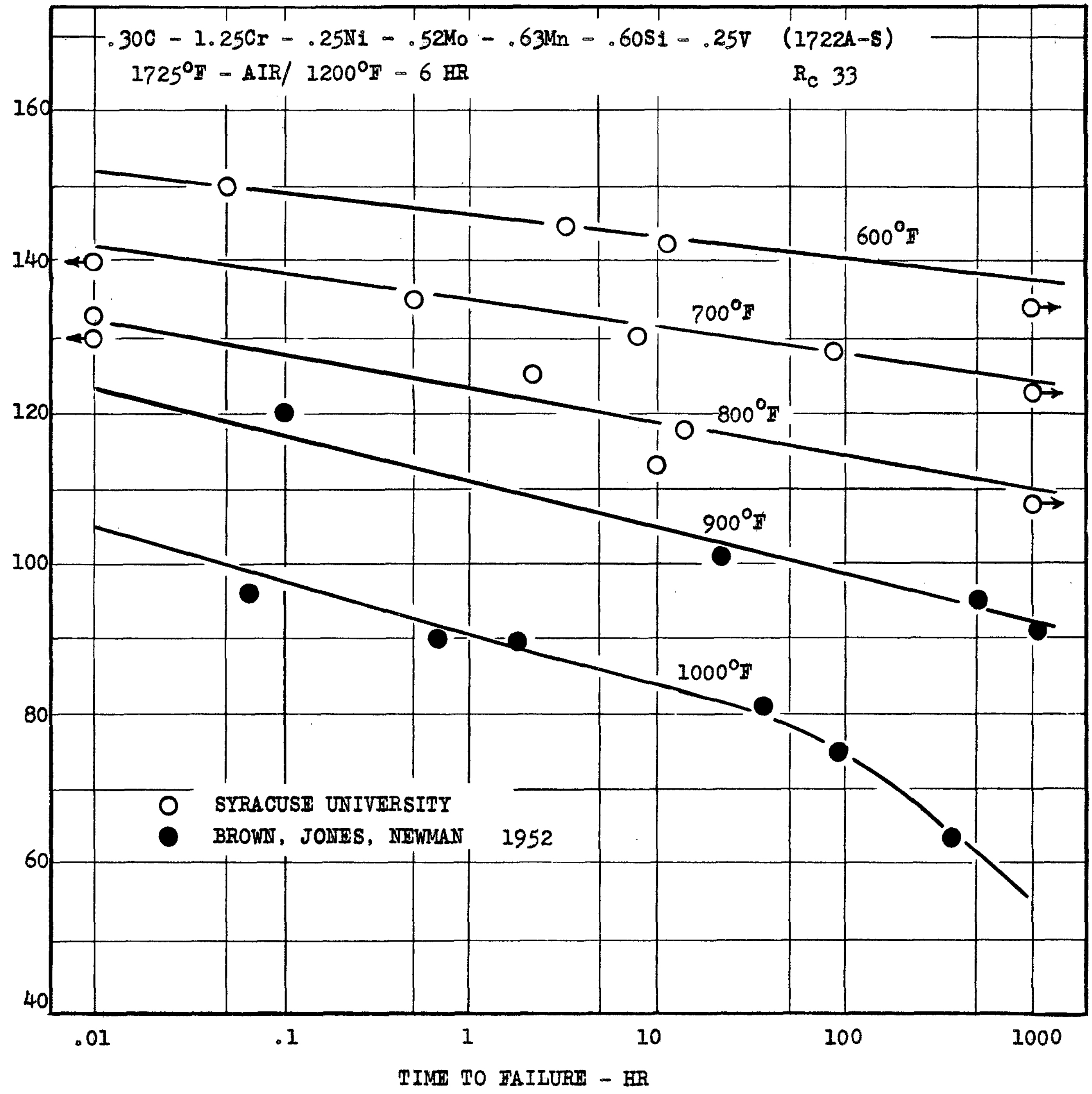


FIG. 47 RESULTS OF STRESS-RUPTURE TESTS ON A LOW-ALLOY STEEL FOR HIGH-TEMPERATURE APPLICATIONS.

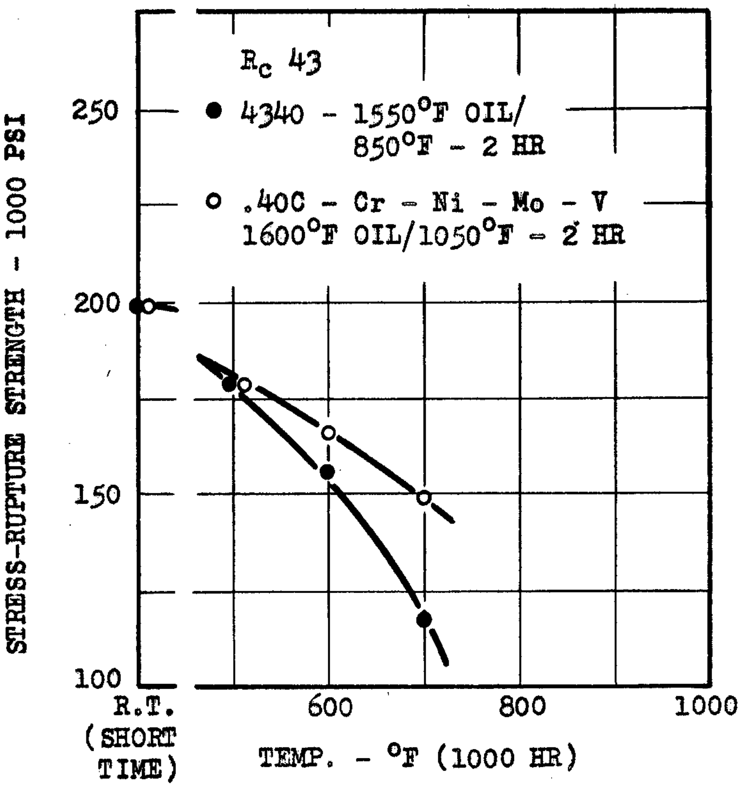


FIG. 48 STRESS-RUPTURE STRENGTH (1000 HR) OF HEAT-TREATED LOW-ALLOY STEELS.

(SMITH, SEENS, DULLIS 1950)

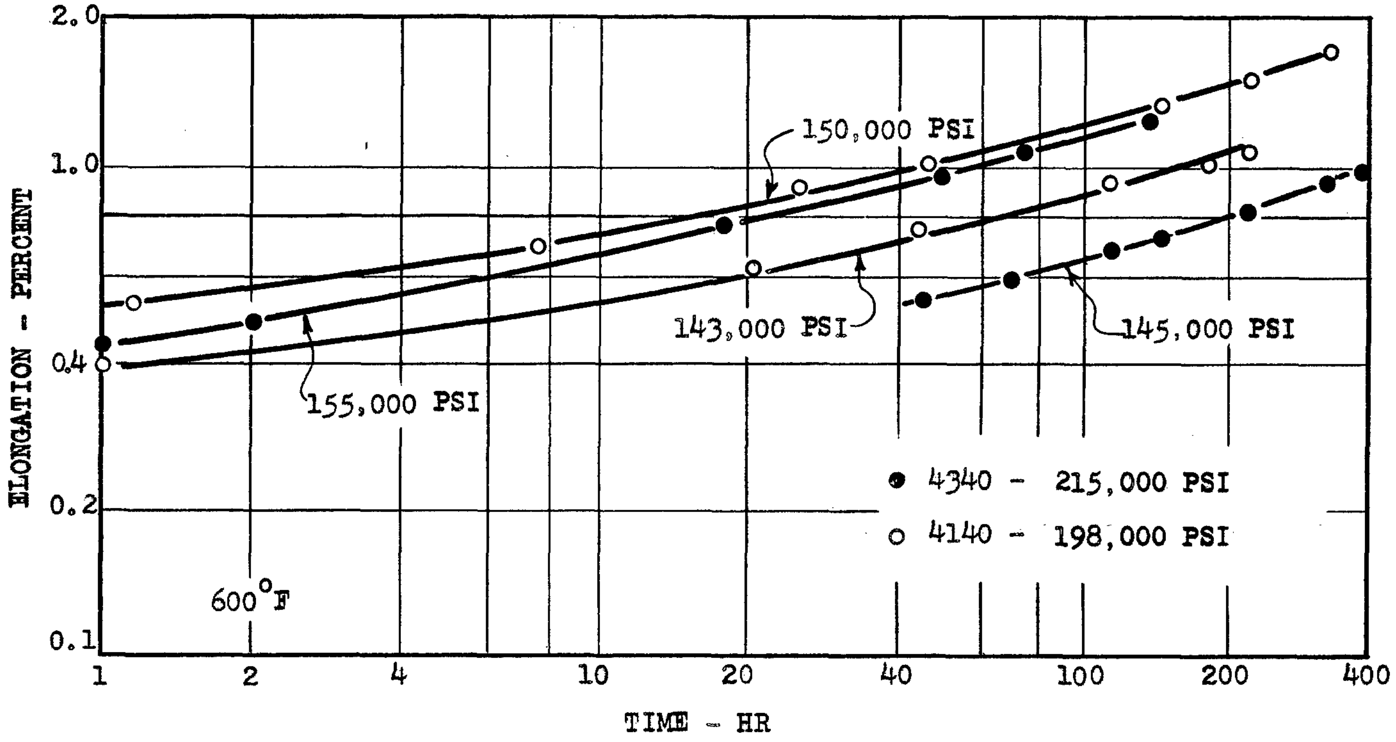


FIG. 49 CREEP CURVES FOR 4340 AND 4140 STEELS.

(NORTH AMERICAN)

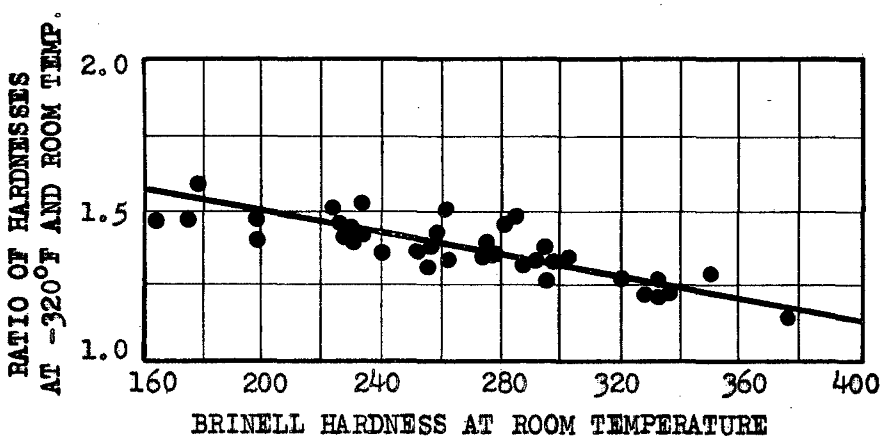


FIG. 50 INCREASE IN HARDNESS OF LOW-ALLOY STEELS WITH DECREASING TEMPERATURE.

(KRISCH, HAUPT 1939)

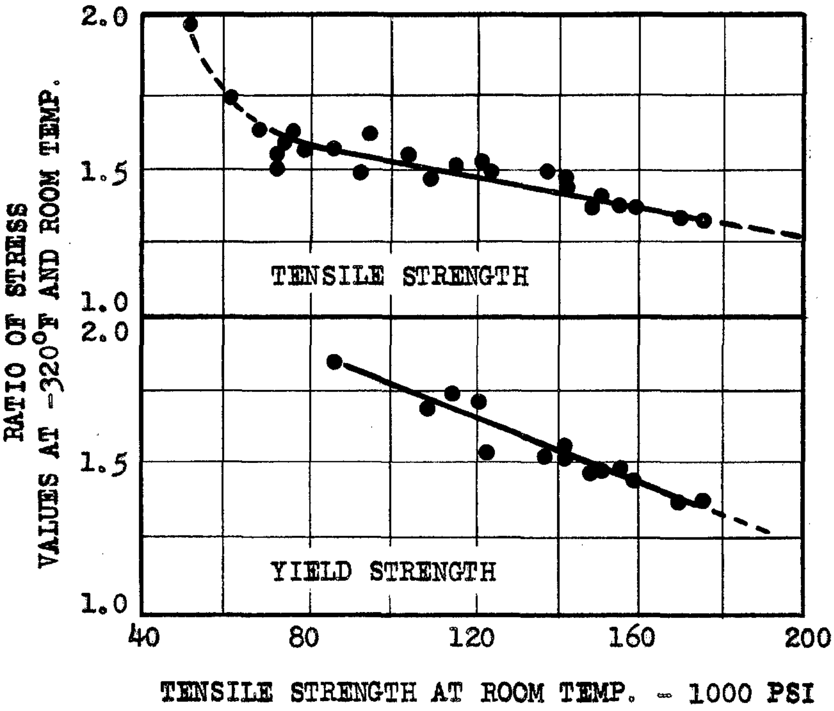


FIG. 51 INCREASE IN TENSILE AND YIELD STRENGTHS OF LOW-ALLOY STEELS WITH DECREASING TEMPERATURE.

(KRISCH, HAUPT 1939)

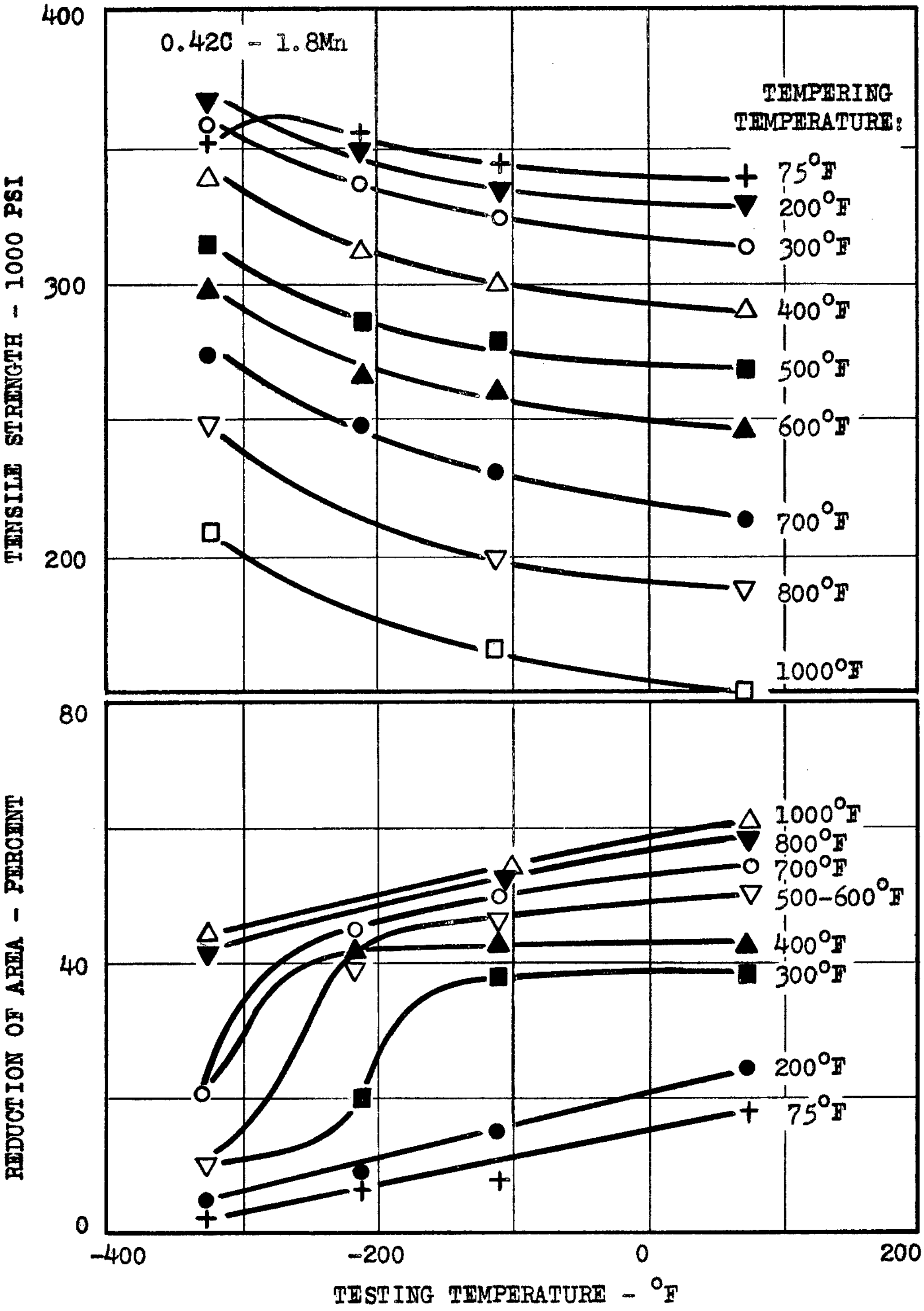


FIG. 52 EFFECT OF TESTING TEMPERATURE ON TENSILE STRENGTH AND REDUCTION OF AREA OF A HEAT-TREATED LOW-ALLOY STEEL (1340).

(RIPLING 1950)

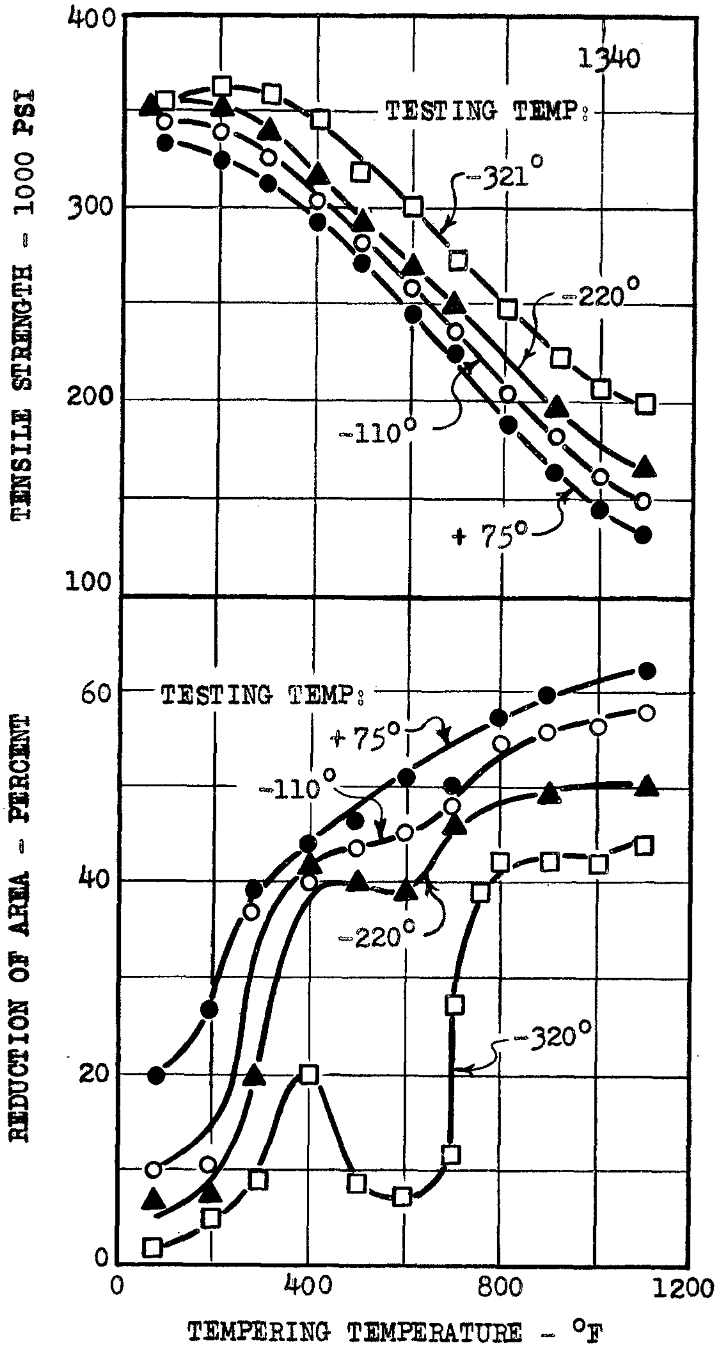


FIG. 53 DEVELOPMENT OF BRITTLE RANGE IN LOW-TEMPERATURE TENSILE TESTS ON A HEAT-TREATED LOW-ALLOY STEEL.

(RIPLING 1950)

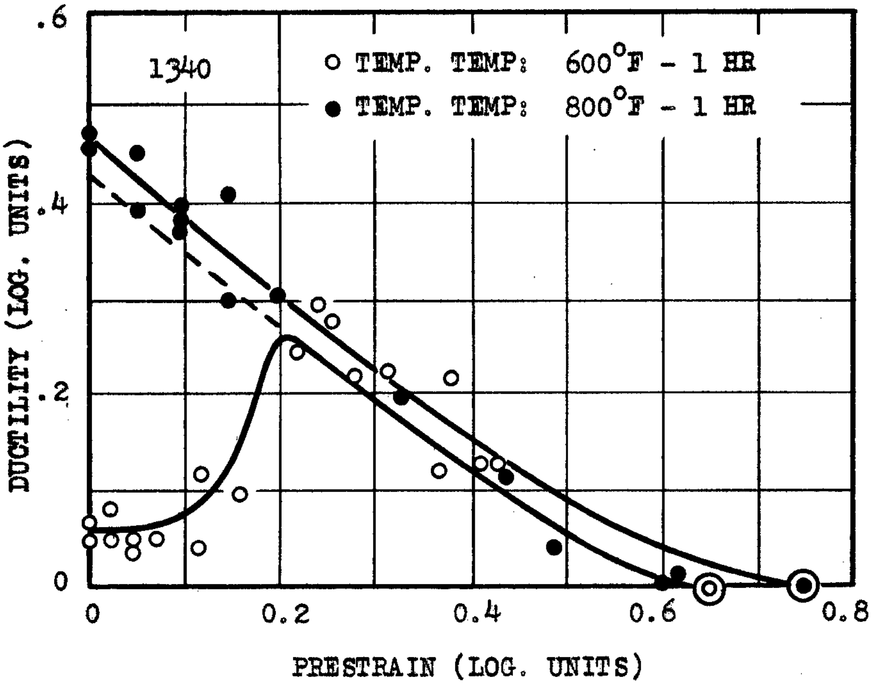


FIG. 54 EFFECT OF TEMPERING TEMPERATURE ON THE RELATION BETWEEN PRESTRAINING AT ROOM TEMPERATURE AND DUCTILITY AT -320°F.

(RIPLING 1950)

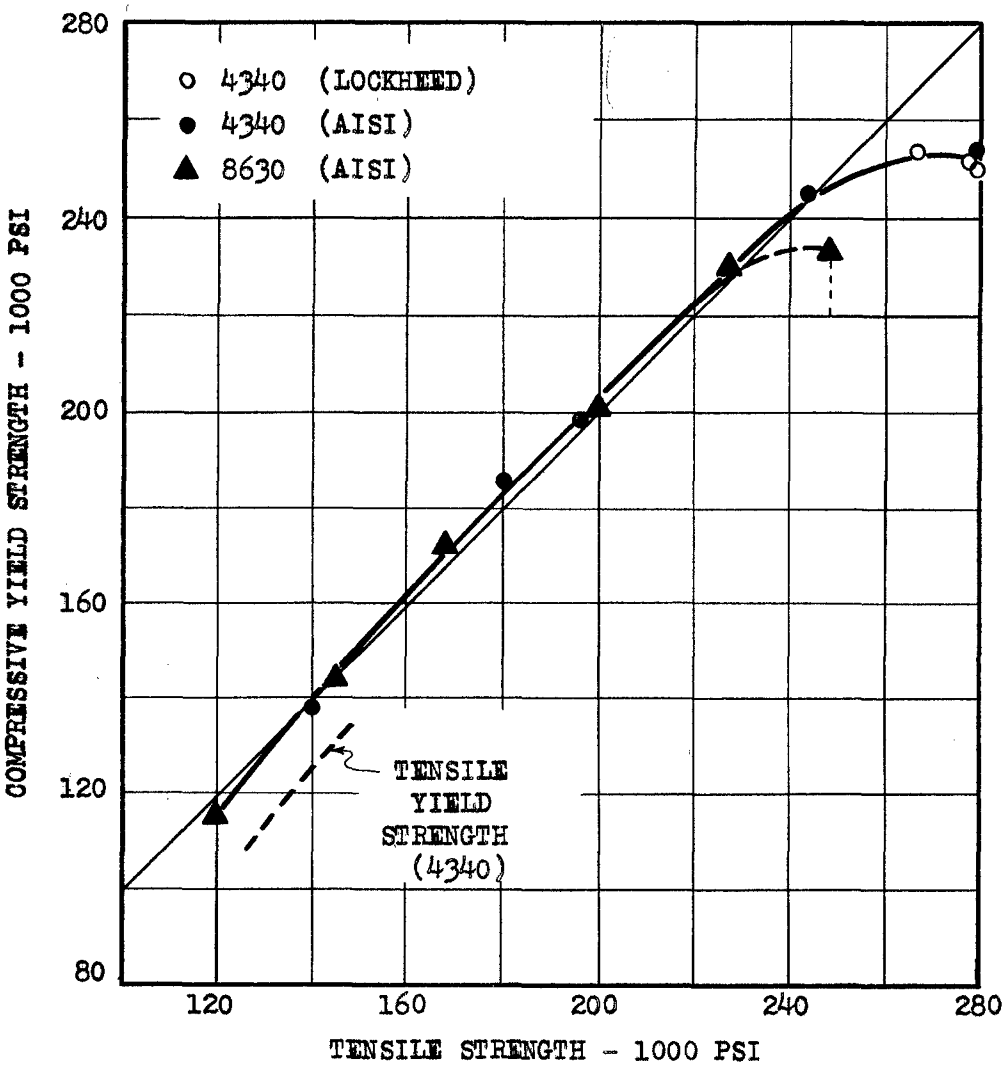


FIG. 55 COMPRESSIVE YIELD STRENGTH OF HEAT-TREATED AIRCRAFT STEELS.

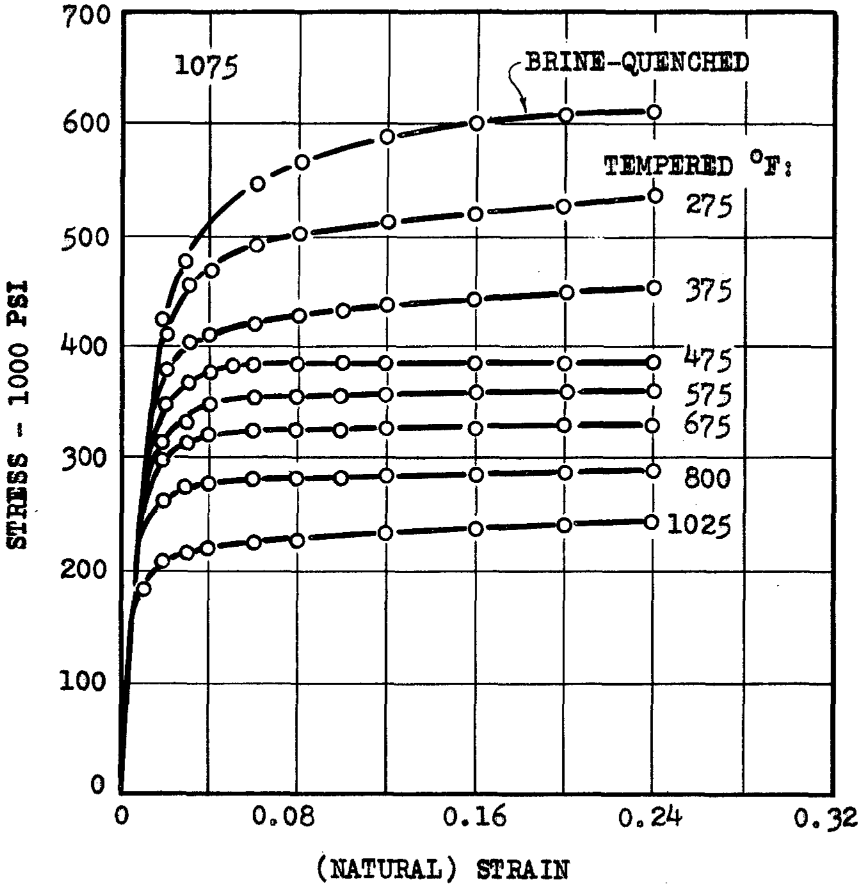


FIG. 56 COMPRESSION TEST DATA FOR 0.75% CARBON ALLOY STEEL.
(MARKUS, MC CAUGHEY 1948)

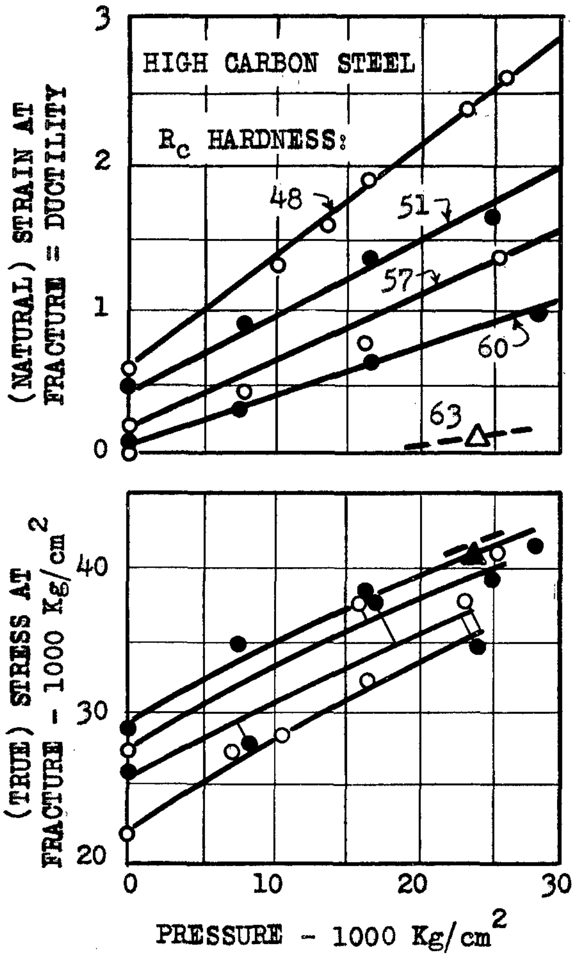


FIG. 57 EFFECT OF HYDROSTATIC PRESSURE ON DUCTILITY AND FRACTURE STRESS OF A CARBON STEEL.

(ACC. TO TESTS BY BRIDGEMAN 1945, 1946)

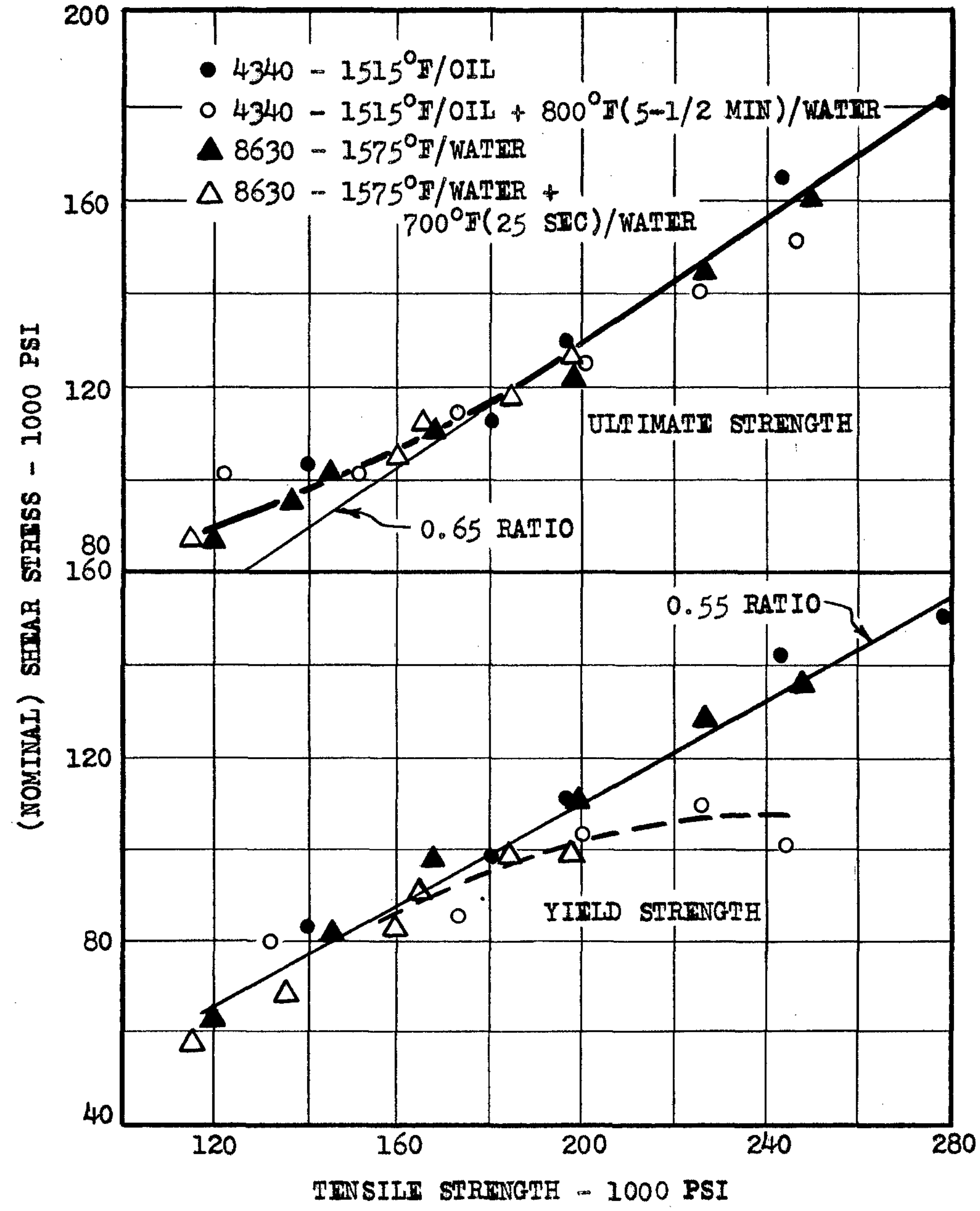


FIG. 58 TORSION CHARACTERISTICS OF TEMPERED-MARTENSITIC AND SLACK-QUENCHED HEAT-TREATED AIRCRAFT STEELS.

(AISI)

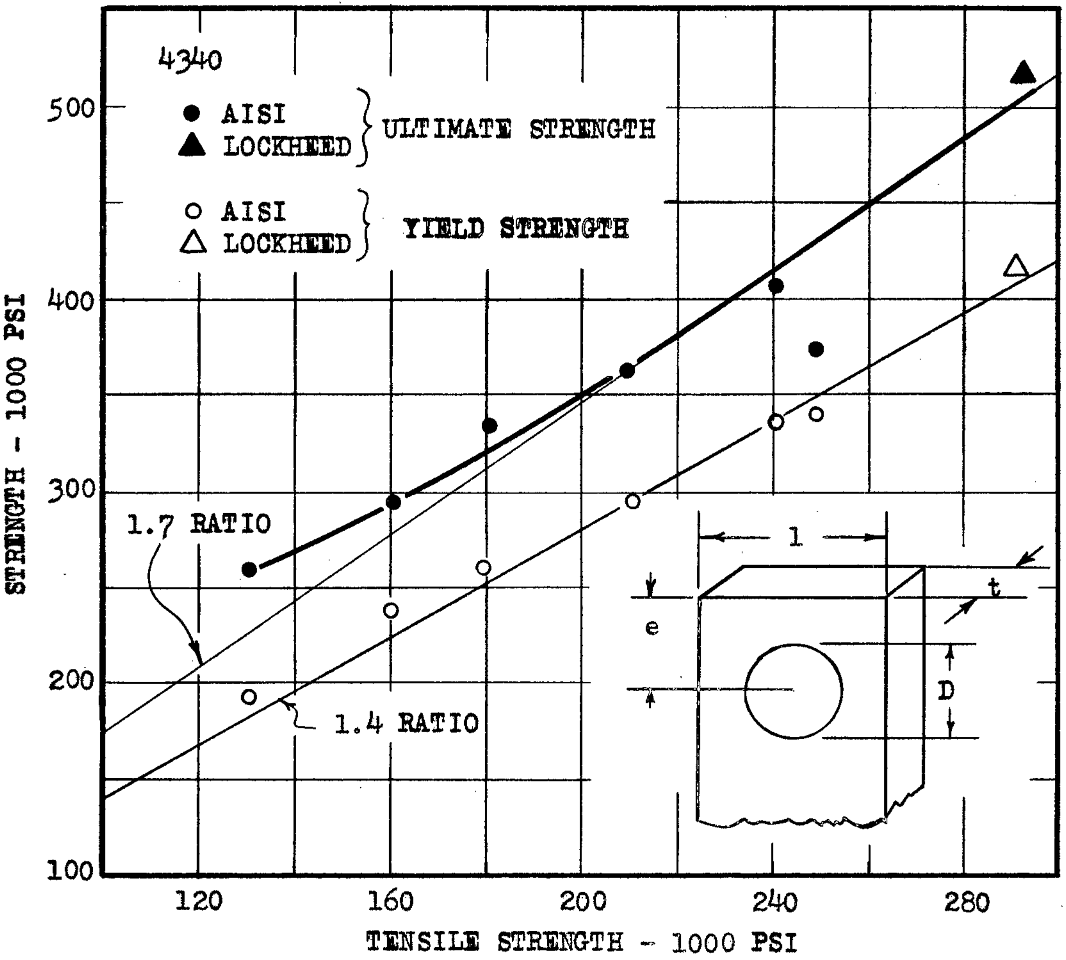


FIG. 59 BEARING STRENGTH (e/D = 2.0) OF HEAT-TREATED AIRCRAFT STEELS.