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PROGRESS REPORT

ON

CORRELATION OF LABORATORY TESTS WITH FULL SCALE SHIP PLATE FRACTURE TESTS: ANALYSIS OF TRUE - STRESS TRUE - STRAIN DATA ON PROJECT STEELS

BY

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PENNSYLVANIA STATE COLLEGE
Under Bureau of Ships Contract NObs - 31217

Transmitted through
NATIONAL RESEARCH COUNCIL'S

COMMITTEE ON SHIP STEEL
Advisory to

SHIP STRUCTURE COMMITTEE
under

Bureau of Ships, Navy Department
Contract NObs - 50148

Division of Engineering and Industrial Research
National Research Council
Washington, D. C.
June 21, 1950

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OF THE
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

June 21, 1950

Chief, Bureau of Ships
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Dear Sir:

Attached is Report Serial No. SSC-19 entitled "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests: Analysis of True-Stress True-Strain Data on Project Steels." This report has been submitted by the contractor as a Progress Report of the work done on Research Project SR-96 under Contract NObs-31217 between the Bureau of Ships, Navy Department and Pennsylvania State College.

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

Very truly yours,

Robert F. Mehl
R. F. Mehl, Chairman
Committee on Ship Steel

RFM:mh
Enclosure

PREFACE

The Navy Department through the Bureau of Ships is distributing this report for the SHIP STRUCTURE COMMITTEE to those agencies and individuals who were actively associated with the research work. This report represents results of part of the research program conducted under the Ship Structure Committee's directive "to investigate the design and methods of construction of welded steel merchant vessels."

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PROGRESS REPORT

Navy Bureau of Ships Contract NObs-31217

Project SR-96

CORRELATION OF LABORATORY TESTS WITH FULL SCALE SHIP PLATE FRACTURE TESTS:

ANALYSIS OF TRUE-STRESS TRUE-STRAIN DATA ON PROJECT STEELS

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Abstract

The results of a study of the flow and fracture strengths of the project steels are considered in this report. It appears that the flow- and fracture- strength concept of failure proposed by Ludwik (15) is not adequate to account for the results obtained.

The flow properties of the steels have been studied as a function of temperature and prestrain. The test results have been found to be adequately described by the expression

$$\sigma = \sigma_0 \delta^n$$

in which σ and δ are respectively true stress and natural strain, while σ_0 and n are constants. σ_0 has been found to vary regularly with temperature while n has been found to undergo a transition for most of the steels at sufficiently low temperatures. Both σ_0 and n appear to have fundamental significance and should ultimately be correlated in some manner with the engineering properties of the steels.

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Navy Contract NObs-31217

Research Project SR-96

CORRELATION OF LABORATORY TESTS WITH FULL SCALE SHIP PLATE FRACTURE TESTS:

ANALYSIS OF TRUE-STRESS TRUE-STRAIN DATA OF PROJECT STEELS.

In the initial organization of the project on which this is a partial report, an examination of the fundamental aspects of flow and fracture in ship plate steel was anticipated. The first report on this phase of the problem was recently submitted as a Progress Report (1). The present report is concerned with those data obtained for static tension tests at various temperatures.

INTRODUCTION

Structural steels in the normal tensile test are materials possessing very high ductility. It has been generally accepted until recently that the measure of ductility in the tensile test yields a satisfactory quantitative index of the ductility of the metal to be expected in structures. The shortcomings of this test have been positively revealed and much work has been expended in the development and examination of suitable specifications tests in its place, (2 to 14).

The testing procedures which have been advanced to supplant the tension test are throughout tests on notched bars, thus bars in which the stress system leading to failure is highly complex as compared to that obtaining in the tension test. The complexity of the stress system need not in itself offer insuperable problems if this stress system were known, but, in general, it is not known, so that from a fundamental point of view the experimental results obtained with these tests must await quantitative treatment.

The problem underlying this research stems from the fact that steel can fail by both cleavage and shear mechanisms. When a structure fails by a cleavage mechanism, the energy required to propagate the failure is contained in the structure as elastic energy. The crack once started propagates rapidly and is highly destructive. The transition from one type of failure to the other is dependent on many factors of which, for a steel of a given metallurgical structure, the three most important are section size, temperature and strain rate.

In the tensile test this transition from one type failure to the other is not usually obtained because of experimental difficulties. Hower, at sufficiently low testing temperatures (in the temperature range of liquid air) it is possible to obtain such a transition. Due to experimental circumstances it is possible to modify this transition temperature until for suitable section size and notch acuity the transition temperature may be elevated to room temperature or above.

Attempts have been made to explain the transition phenomenon in steels by the use of two strength properties known as flow and fracture strengths, (15). These two strength properties are assumed to depend in different ways on the testing conditions as indicated in Fig. 1 for strain and temperature. By a variation in strain the flow and fracture curves are elevated but at different rates which depend on the temperature of testing. As a consequence, in the case indicated, the specimen tested at the lower temperature fractures at the lower strain value and there is an evident reduction in the ductility of the test material. Hollomon and Zener (16) have discussed this point at considerable length while excellent reviews of pertinent data and analyses of the concept have been presented by Hollomon (17), Gensamer, et al (18) (19) and by Siegel and Brick (20).

It will be noted that the stress-strain diagrams presented in Fig. 1 are not the usual normal type of stress-strain diagrams. Rather they are diagrams in which true stress and natural strain are plotted. This manner of plotting is advantageous in that it reveals the rate of change of strain with stress, and passes into a form that can readily be handled by analytical methods. This treatment of the data does not, however, predict the strain at failure. The mathematical expressions used in conjunction with the true stress - natural strain relationships are presented in Appendix B. It is sufficient to point out that the relationship which is used here is $\sigma = \sigma_o \delta^n$, a generalized parabola, in which σ_o and n are constants. σ_o is the stress at a strain of 1 and n is the strain hardening exponent. $n = \delta$ at the maximum load and thus indicates the strain at which instability is to be expected. Thus it is a measure of general ductility and has been indicated as increasing for steels to the lowest temperatures at which it could be evaluated, (21) (22) as interpreted by Siegel and Brick (20). The above equation has certain shortcomings, but at present it appears to be a suitable analytical relationship whereby the flow properties of a metal may be considered. A major shortcoming in this approach is that no indication is given of the fracture point.

The concept of flow strength is fairly obvious. The concept of fracture strength, however, is not. This latter point may be further complicated by the existence of two types of fracture. There is not general agreement that two kinds of fracture exist (15) (17) (23) despite the fact that for shear failure, energy absorption is invariably high, while for cleavage failure it may be entirely negligible. A confusing item, further, is the occasion of high ductility accompanying cleavage fracture, (10) (24). Parker, et al., (25) and Davidenkov (26) and Freedman (27) support the argument for two types of fracture, Parker, et al., arguing from the crystallography of the two types of failure, while Davidenkov (26) and Freedman (27) argue from the point of view of normal and shear stress failures which in turn may be interpreted in terms of crystallography. On this question it is generally maintained that cleavage failure takes place on the (100) planes of ferrite while shear failure demands the operation of slip systems, and, thus it is contended, ultimately failure on slip planes. Probably it is not possible to prove this contention unequivocally for the shear failure.

In the following pages the experimentation which has been conducted on the tension test to reveal the effects of temperature, strain aging and notch severity on the flow properties and transition temperatures of certain project steels is reported. Data concerning fracture strengths, fracture initiation, and fracture strength as modified by stress concentration are also reviewed.

A series of binary ferrite alloys containing Ni, Cr, Co, Mo, Si and Mn were studied by means of a modified slow-bend test and a non-standard impact test. These results are reported in Appendix A.

The staff which has contributed to this work is as follows:

John R. Low, Jr.	Technical Representative
M. Gensamer	Technical Advisor
E. P. Klier	Investigator

J. Q. Mack	Investigator
F. C. Wagner	Investigator
M. A. Bishop	Research Assistant
Selma Krause	Drafting
Mina Moessen	Technical Labor
P. Vonada	Technical Labor
H. Colyer	Technical Labor

Steels

Steels A, Br, Bn, C, Dr, Dn, E, H, and N have been studied in some measure. The mill data and complete chemistry of these steels have been given previously (2). Abridged analyses are given in Table I.

TESTING PROCEDURE

Tensile specimens unless otherwise specified have been loaded in the rolling direction. The dimensions of these specimens are given in Fig. 2.

The specimens tested at other than room temperature were tested in a liquid bath. Water was used for testing in the neighborhood of +50°C (122°F); dry ice and acetone at -70°C (-94°F); isopentane cooled by liquid nitrogen at -145°C (-229°F); and liquid air at -188°C (-310°F). The testing set-up is presented in Fig. 3. The liquid container is diagrammed in Fig. 4 for the test at -145°C (-229°F). For tests at the other temperatures the insert into which the liquid nitrogen was poured to obtain this temperature was removed. The specimen was held at temperature for 10 minutes before testing.

For notched bar testing the specimen was inserted in the grips and cooled and held for 10 minutes. The load to fracture was then applied. Diameter measurements of the test section were obtained before and after testing.

When load-strain measurements required for the construction of true stress-true strain curves were made, the test was conducted at a constant cross head movement of 0.01 inches per minute. This produced an appreciable variation in the strain rate once the maximum load was passed, but since stress-strain data after this point are not used, except for the fracture strain, it was not necessary to adjust the test procedure for this variation in strain rate.

The strain measurements at room temperature were obtained with pointed micrometers as well as with the strain gage used at the other temperatures. This strain gage is shown in Fig. 5. An engineering drawing of the gage is presented in Fig. 6. The construction presented was found most suitable for the elimination of thermal effects in the scissors section of the gage. The circulating water maintained this section at a near constant value so that diameter measurements could be made on the bar irrespectively of the thermal gradient in the immersed portion of the gage.

The minimum diameter of the test bar was found by systematic hunting. Wear of the guides was checked periodically and compensations were made accordingly.

REPRESENTATION OF TEST DATA

The true stress-true strain curves for all of the tests where obtained have been presented. The numerical data resulting from the analytical treatment of these data have been tabulated and are also plotted.

The remaining data have been presented in the form of graphs, when appropriate, and have been tabulated, while certain photographs and photomicrographs are included. Some use is made of idealized curves for the purposes of discussion.

THE SCOPE OF THE TESTING PROGRAM

The tests which have been conducted are as follows:

1. The fracture strength of Steel E at -188°C (310°F) for several states of triaxial tension was determined. The different stress systems were obtained using notched bars.

2. The fracture strengths of the project steels were obtained for a mildly notched bar.

3. A series of tests was run to determine the effect of pre-strain at 25°C (77°F) on the fracture strength at -188°C (-310°F) for the project steels.

4. Tests were run on Steel C to determine the effect of prestrain at -70°C (-94°F) on the fracture strength at -188°C (-310°F).

5. The development of a crack in the center section of a necked down tensile bar was studied metallographically.

6. The true stress-true strain curves for the steels, with limited exceptions, were determined from ≠50°C (122°F) to -188°C (-310°F) for virgin plate specimens.

7. The true stress-true strain curves for the steels were determined from ≠25°C (77°F) to -188°C (-310°F) for virgin plate specimens loaded in the cross-rolling direction.

8. The true stress-true strain curves for the steels, with limited exceptions, were determined from ≠50°C (122°F) to -188°C (-310°F) after the following treatments:

a. Prestrained 2% at 25°C (77°F), held at Room Temperature for 1 month.

b. Prestrained 5% at 25°C (77°F), held at Room Temperature for 1 month.

c. Prestrained 10% at 25°C (77°F), held at Room Temperature for 1 month.

9. An approximate transition curve for a mildly notched tensile bar was determined for available steels.

EXPERIMENTAL RESULTS

TESTS 1 AND 2: - FRACTURE STRENGTH OF NOTCHED BARS

Preliminary tests revealed that certain of the project steels were appreciably ductile in the tension test conducted at liquid air temperature. Since lower temperatures, to suppress this plastic flow, were not accessible for this testing program, it was decided that mildly notched bars might be used to suppress plastic flow.

The suppression of plastic flow was desirable in order that the fracture strength of the unstrained material might be measured. The measurement of the fracture strength was desirable to allow an analysis of the concept of fracture and flow strengths. For the determination of the fracture strength two possible procedures could be used; namely, the notch could be such that the stress system was completely known, or a series of notches of various known stress concentrations could be used. From these latter test results the fracture strength could be determined by extrapolation. The first procedure, unassisted by the second, requires the evaluation of the effects of a given triaxial stress system and is probably unreliable. The second procedure, if used extensively, would require a great deal of experimental effort. It was decided, therefore, that one of the steels be used to explore the notch effect, and this steel preferably be one which failed brittlely in pure tension at liquid air temperature. Steel

E closely approximates this behavior and so was used in the evaluation of the effect of notch acuity on the fracture strength at liquid air temperature.

The results of testing are given in Table II and are plotted in Figs. 7 and 8. The data in Fig. 7 are nominal fracture strength versus stress concentration while the data in Fig. 8 are maximum calculated stress versus stress concentration.

The curves break at a stress concentration factor of approximately 2.0 but below this point represent straight line relationships. Since the bar used to determine fracture strengths for the remaining steels had a stress concentration factor of about 1.2 the nominal fracture strength for this bar could be used as the fracture strength for the unnotched bar.

The results of fracture strength measurements on the remaining steels are presented in Table III. The results obtained on unnotched bars, when these bars failed at very low strain values, are also included for comparison. These two values are probably in satisfactory agreement, but it is apparent that the fracture strength determinations are liable to scatter. Because of this scatter, further analysis of these fracture strength values does not appear to be warranted.

TESTS 3 AND 4: - PRESTRAIN ON FRACTURE STRENGTH

The determination of the fracture strength for the unstrained bar is not sufficient for the determination of the fracture strength curve. The fracture strength curve is a function of the strain and cannot be determined by any direct procedure. It can be determined by the imposition of strain at one temperature after which the test bar is cooled to a range of brittle failure and broken. By this means a fracture strength curve modified by a given thermal effect may be obtained. Several tests of this type were conducted for prestrains imposed at 25°C (77°F) and at -70°C (-94°F).* Some pertinent data for the steels are tabulated in Table IV. The data are plotted in Figs. 9 to 13.

Two important phenomena are pointed out. The first of these, which has recently been discussed by Sachs (28), is the variation of the total strain to fracture at -188°C (-310°F) as a function of the prestrain. The data are inconsistent but they tend to support the view advanced by Sachs that the prestrain at higher temperatures makes the steels more ductile at -188°C (-310°F). Fig. 14, after Sachs, (28), illustrates the supposed relationship between prestrain and added strain at -188°C (-310°F). The data obtained here are not sufficient for further discussion of this point.

The second point of interest centers on the relationship between fractures strength and strain. These data are relatively consistent in indicating an elevation of the fracture strength at approximately 40,000 psi per .3 units of natural strain. Teh consequence of this is emphasized in Fig. 9 where the flow curves for Steel C are plotted along with the fracture strength curve obtained for this steel. Between 0.1 and 0.35 natural strain, the flow curves appear to be parallel or to converge toward higher strain. Through the same increment of strain, these curves seem to be parallel to or to diverge from the fracture strength curve. From this it follows that if the temperature effect on the strength curve determined here, if lowered the appropriate amount to pass through the fracture point of the flow curves, must lie on or below the flow curve. The fracture strength curve then could have no meaning.

On the assumption that the fracture strength at different strain levels is differently affected by the temperature, an exponent similar to the strain

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* For testing procedure see Appendix C.

hardening exponent may be obtained. Such values as could be determined with some accuracy are tabulated in Table V. By assuming this exponent as being constant on extrapolation to the temperature for the flow curves at room temperature, the fracture strength curve lies above the flow curve. But as will be shown in a subsequent section, the value is still too large to allow for a real fracture strength curve at -145°C (-229°F) for certain of the steels. It seems reasonable to conclude that the fracture strength concept of failure is not valid.

TEST 5: - FAILURE IN THE TENSION BAR

The manner in which the standard round tensile bar fails has been satisfactorily determined for the fully ductile mode of failure (25) (29). It is known that after necking down, the stress condition in the center of the bar is such that a crack opens and is propagated radially. As this happens, the cross-section of the test bar is reduced and the load required to continue the test drops. For very ductile materials, for example, copper, this phase of the test can be easily followed, but such is not the case for steels. Seemingly in steels the crack once formed is propagated so rapidly that the load cannot be released in order to prevent complete failure of the bar. Several tests were conducted to further clarify certain aspects of this phase of the tensile test in steels.

Several test bars of Steel C were pulled to beyond the maximum load and before breaking were taken from the tensile machine. These specimens were sectioned by grinding on a plane parallel to the axis of the test bar. At predetermined locations along the diameter, the surfaces were polished and examined metallographically. Pertinent results are presented in the photomicrographs in Figs. 16 to 20. In these photomicrographs, location A corresponds to a plane .012 inches from the centerline of the test bar, location B to a plane .007 inches from the centerline, and location C to a plane .002 inches from the centerline. Certain test data are tabulated in Table VI.

The testing procedure may be clarified by referring to the idealized stress-strain diagram presented in Fig. 15.

This is a load-extension diagram and offers nothing new up to the point designated (a). Between points (a) and (b) the load is indicated as dropping sharply. At (b) it is supposed that the section fails completely. All specimens which are discussed here were loaded into the interval (a) (b) and the test was then stopped. As is evident from Table VI, some dexterity is required in unloading the specimen in order to prevent its total failure when the test is conducted to this stage.

All specimens examined were sectioned such that the final plane of examination was 0.002 inch from the center line of the specimen as determined on the necked-down portion of the test bar. This plane of examination may, of course, be slightly displaced from the original center-line of the specimen because of irregularities in the straining in the necked-down region.

One item which will be of concern at a subsequent point may be introduced briefly here; namely, the existence of total failure at the point (b) on the diagram. This point probably does not have a true physical significance insofar as the fracturing process is concerned, but probably is the point beyond which the weighing mechanism no longer approximately follows the load on the specimen. It indirectly indicates the limiting rate of travel of the load indicating device. Because of this the fracture load cannot be defined.

The several photomicrographs indicate that the crack development in the tensile bar is comparable to that in copper in the tensile test. It differs from crack development in copper in that once it is initiated it develops rapidly and leads to failure of the entire section. This, as has been recognized, takes place by the formation of a radial crack sensibly normal to the specimen axis and this crack extends over an appreciable portion of the section. After this is accomplished, the remaining section shears off. The final fracture is the familiar cupcone fracture.

Parker, et al., (25) have argued that the failure in the center of the test section is a shear failure rather than a cleavage failure. That this contention is correct is corroborated by the evidences of plastic flow adjacent to and in the path of the crack, cf. Figs. 17 and 20. In Fig. 20 this phenomenon is emphasized by the marked strain zone which has developed ahead of the advancing crack point. This structure was found at a slightly greater distance from the center-line of the specimen than was required to reveal the crack.

Finally, the crack does not start at some isolated point and then develop over the critical section. Rather as indicated in Fig. 18 cracking may be initiated at several points in the test section, and as indicated in Fig. 19 these cracks may grow and join. These cracks may extend over an appreciable number of grains and frequently are at an acute angle to the axis of the test bar. In some instances it appears that certain regions of the section are sheared off on a line parallel to the axis of the test bar.

TESTS 6, 7, AND 8: -- TENSILE TEST RESULTS

The data have been presented in Figures 29 to 197 and in Tables VII-A to VII-N. The various data are discussed separately. In the presentation of data, specimens transverse to the rolling direction are designated by (T).

(1) <u>The variations in reduction in area vs. temperature (Figures 21 to 28):</u> For the virgin plate Steel A, the transition range seemingly lies between -188 and -120°C. There are not sufficient data to allow a separation of the transition ranges - if such should exist - for the various levels of prestrain.

The maximum ductility is indicated for the specimens parallel to the rolling direction and which had suffered no prestrain. The minimum ductility is indicated for the transverse specimens and for those longitudinal specimens which had suffered 2% prestrain. The maximum decrease in ductility amounts to about 15-20% at temperatures above the transition range.

At liquid air temperatures the specimens which suffered prestrain are less ductile than those which had not. This is contrary to what might have been expected from the results reported under Test 2, but are in line with the data obtained for impact testing (2), where the transition temperature was found to lie at higher temperatures with increasing prestrain. This apparent correlation is obviously of very limited value.

For Steel Br the transition range extends from less than -188 to about -120°C. Again there appears to be little possibility of specifying any but the one transition range for all of the data. The results for the transverse tests are somewhat erratic, but for the most part indicate a reduction in the maximum ductility of about 20%. The prestrained bars are less ductile at -188°C than are the virgin plate bars.

For Steel Bn the transition range extends from -188 to about -145°C. The effects of prestrain are comparable to those observed for Steel Br.

At -188°C Steel Bn is less ductile than Steel Br, while there is no segregation of test values for prestrained and unstrained bars. It is of particular interest to point out that this steel is highly ductile at -150°C. Further, in the range of high ductility, the maximum reduction in ductility due to change in orientation of the test bar amounts to about 10%.

For Steel C the transition range extends from -188 to about -145°C. At -145 to -150°C the steel is fully ductile. The maximum decrease in ductility above the transition range is about 10% of the virgin plate value.

For Steel Dr the transition range extends from below -188°C to above -150°C. There is no apparent modification of this transition range as a consequence of prestrain. The ductility is little affected by orientation and prestrain, with the maximum reduction in ductility above the transition range amounting to between 5 and 10% of the virgin plate value.

For Steel Dn -188°C lies about in the middle of the transition range as at this point the reduction in area value is reduced to about 50% of the maximum. The transverse ductility is about 5 to 10% less than the longitudinal ductility. The effects of prestraining are not apparent for this steel.

The transition range for Steel E extends from about -188 to about -120°C. The transverse ductility is about 15% less than the longitudinal ductility while the maximum effect due to prestraining is a 10% reduction in ductility.

Steel H is appreciably ductile at -188°C but not so much so as Steel Dn. The transition range extends from less than -188°C to about -150°C.

Steel N is just into the upper portion of the transition range at -188°C. No plot is shown for Steel N due to the limited data, which appear in Table VII-N.

(2) The natural strain at fracture (ϵ F) vs. temperature (Figures 29 to 36): This quantity varies in the same manner as does the reduction in area.

(3) The tensile strength vs. temperature (Figures 37 to 44): The steels were made up to have 60,000 to 70,000 psi tensile strengths. This quantity when determined as a function of temperature is modified by two factors, namely, the strengthening resulting from decreased temperature of testing and the decrease in strain hardening which arises in the transition range. These factors being of opposite sign can seriously modify the experimental values of the tensile strength under certain conditions.

For Steel A the tensile strength for the unstrained longitudinal specimens is a minimum for the test bars examined. The tensile strength increases at first slowly and then more rapidly with decreasing temperature. It is about doubled at -188°C., but the major contribution to this increased tensile strength occurs between -70 and -188°C. The tensile strength increases regularly with prestrain and is elevated about 20% by a prestrain of 10%.

For Steel Br the results are nearly identical with those obtained for Steel A. The tensile strength vs. temperature curves, however, are displaced to slightly lower load values.

For Steel Bn the results for 0% prestrain, like those for Steel Br, are in close agreement with comparable values for Steel A. The behavior for prestrained bars is different for testing at -188°C. At this lowest temperature of testing the tensile strength of the 10% prestrained bars is less than that for the 5 and 2% prestrained bars. Thus the average tensile strengths for the 2, 5, 10 and 0% prestrained bars are 147,500; 137,500; 127,500 and 127,500 psi, respectively. Thus the strongest steel is that prestrained 2% while the weakest are those prestrained 0 and 10%.

The results for Steel C are in close agreement with the results obtained for Steel A.

The results for Steel Dr are in close agreement with the results obtained for Steel A.

For Steel Dn the strengthening effects for decreasing temperature of testing are less than was observed for Steel Dr. Further, the effects of prestraining are not marked, as the imposition of 10% prestrain elevates the tensile strength by less than 10% at 25 and 50°C. Prestraining possibly is more effective in elevating the tensile strength at -188°C, although the increase at this temperature is not so pronounced as for Steel Dr.

For Steel E the increase in the tensile strength due to prestraining is analogous to the behavior of Steel Bn. Thus at -188°C the tensile strengths of the 0 and 10% prestrained bars are equal and less than the tensile strength for the 2 and 5% prestrained bars.

The tensile strength for Steel H increases with decreasing temperature in analogy to that for Steel A at 0% prestrain.

(4) The lower yield strength vs. temperature (Figures 45 to 52): The lower yield strength data may be placed in two groups for presentation. The first of these groups includes Steels A, Br, C, Dr, and E. For this group of steels there is a pronounced elevation of the lower yield strength with increasing prestrain at all temperatures investigated. The percentage increase in the yield strength with prestrain drops with decreasing temperature. At 25°C for a prestrain of 10% the yield strength is about double that at 0% prestrain. At -188°C the increase is by a factor of $\frac{1}{2}$

as the numerical increase in the yield strength remains nearly constant irrespective of testing temperature.

For the unstrained steel the yield strength is increased by about 25% as the temperature is lowered from +50 to -70°C. The yield strength is increased by a factor of 300% when the temperature is lowered from 50 to -188°C. For the steel prestrained 10% the yield strength is increased by about 200% as the temperature is lowered from + 50 to -188°C.

For the second group of steels represented by Steel Bn and possibly Steel Dn, the effect of prestrain on the yield strength is markedly dependent on the temperature of testing. Thus for Steel Bn the yield strength at 25°C is raised by 100% for a prestrain of 10%. At -188°C., however, the analogous increase is only 10%.

(5) <u>The fracture strength vs. temperature (Figures 53 to 60):</u> The fracture strength is dependent on two factors which are of opposite sign, namely the strengthening effect arising from decreased temperature and secondly, the weakening effect due to decreased strain hardening because of failure at lower strain values. Since this latter factor does not become operative until the transition zone is entered, it might be expected that the fracture strength would increase until the transition zone was reached and would then behave erratically. The data do not cover the transition zone sufficiently to indicate the behavior of the fracture strength through this zone, but seemingly the fracture strength may in some instances drop sharply in this temperature interval.

The fracture strength for the prestrained bars is not markedly different from that of the unstrained bars at -70°C and higher. At -188°C, on the other hand, the prestraining causes a pronounced scatter in the fracture strength values. The scatter seemingly is not consistent.

(6) The strength coefficient vs. temperature (Figures 61 to 68): The value of the strength coefficient has been found to depend on the carbon content (30), tests being conducted at 25°C. This is corroborated by the data obtained here. The strength coefficient as might be expected is dependent on the temperature of testing and it appears that, at the different temperatures between -188° and +50°C, one of the major factors in determining its numerical value is the carbon content.

The strength coefficient is increased by from 80 to 90% as the temperature is lowered from +50 to -188°C. The strength coefficient does not appear to be consistently modified by prestrain over the temperature interval in which it was measured.

(7) The strain hardening exponent vs. temperature (Figures 69 to 76): The strain hardening exponent ranges between .20 and .25 for all of the steels at 25°C. for the unstrained test bars. This relative magnitude is obtained at -70°C for all of the steels, but there is some evidence that the magnitude of the exponent is slightly lowered for some of the steels at -70°C. At -188°C all of the steels but Steel N show a reduced strain hardening exponent. It is evident, therefore, that the strain hardening exponent undergoes a transition from a high value to some lower value. The exact character of this transition is of much interest, but only limited data are available pertaining to it.

It appears that the transition in the strain hardening exponent does not coincide with the transition in ductility. This is emphasized from a consideration of Figure 69 for Steel A. This steel possesses nearly full ductility at -150°C. At this temperature, however, the steel has seemingly passed through the transition in the strain hardening exponent. On the other hand, between -150 and -188°C this steel passes nearly through the transition in ductility but in this interval there is no comparable decrease in n. The minimum value of n for this steel is about 0.15.

Prestraining seriously modifies the strain hardening exponent as is evident from the curves, Figure 69. This situation would be expected since prestraining causes no alteration in the strength coefficient.

Results analogous to those obtained for Steel A are obtained for Steels Br, Bn, and Dn. For these steels an apparently real low level is defined for the strain hardening exponent.

For Steels C, Dr, E, and H, no attempt can be made to establish a low level range for the strain hardening exponent.

Scatter is observed for the values of the strain hardening exponent. This scatter does not appear to be large in the regions away from the transition range for this quantity. A reasonable notion of the degree of scatter cannot be given on the basis of the number of data which are presented. These data are difficult to obtain, however, because of the tendency of the steels to break at very low strain levels. Strains of greater than 0.1 are required if satisfactory values for n are to be obtained. Of the steels available only a few could be satisfactorily handled at -188°C.

(8) <u>The fracture appearance vs. temperature</u>: Much emphasis has been placed on fracture appearance as an aid in evaluating brittle and ductile behavior (3)(4)(5)(6)(7)(8)(10)(11)(12). On the other hand, it has been pointed out that fracture appearance may not be an adequate criterion of brittle behavior (24)(27). It is not surprising then that ductility does

not correlate with fracture appearance in these tests. Thus for none of the steels studied here has the transition range in ductility been observed at higher than about -145°C. The transition temperature on the basis of fracture appearance however lies at -70°C for some of the steels. The fracture data are summarized in Table VIII and probable transition temperature ranges are presented in Table IX.

TEST 9: - NOTCHED-BAR TRANSITION RANGE

The test results are presented in Figure 200. It is evident that all of the steels tested are somewhat embrittled by the mild notch used. The transition range is in general raised by about 30°C. For this test bar the steels are sensibly brittle at -188°C. There is no apparent correlation between the transition temperature determined for this test bar with the transition temperatures observed in the impact and notched bar specification tests. Considering the complexity of these latter tests this was not unexpected.

DISCUSSION

The tensile testing of the project steels was carried out with the expectation that possible fundamental material quantities might be revealed. These quantities, because they are fundamental, must affect the behavior of the metal in any kind of test. The direction and possible magnitude of this effect could possibly be derived from the data on tension testing. The question arises: has any aspect of the tension results reported here been suggestive of the operation of a fundamental quantity? To answer this question it is necessary to discuss the aspects of the tension test which have been recorded and to examine any irregularity which might exist.

The data to be considered first are those obtained for reduction in area and true strain vs. temperature. These data define the transition from ductile to brittle behavior with reduction in temperature. The fact that this transition occurs is in itself not a fundamental aspect of the test, as might appear at first sight. Thus the steels do not become truly brittle below the lower limits of the transition range in this test, for it is possible to displace the transition range to still lower temperatures by the use of a smaller specimen or by testing in torsion or compression, etc.; and it is possible to displace the transition range to higher temperatures by a variety of means. The transition range as revealed by strain measurements does not reveal the action of any fundamental quantity. This actually might be enlarged to say that any quantity which is modified by the transition range other than to become inaccessible to measurement cannot readily reveal any effect due to the operation of fundamental quantities.

The tensile strength of the steels is not discontinuous in the transition range. This quantity is poorly defined for use as required here, for it does not refer to materials at the same state of testing. Thus at 25°C the steel is ductile and suffers much plastic strain prior to fracture. At -188°C, on the other hand, the steel may fracture well before the point corresponding to maximum load at 25°C is reached. In the meantime because of the decrease in temperature the steel is appreciably strengthened. Thus two quantities of opposite sign modify the tensile strength.

The fracture stress vs. temperature curves reveal a marked transition range discontinuity. This quantity, however, suffers from the same uncertainty that was introduced against the tensile strength. Further, the problem of the definition of fracture stress arises. As has been seen earlier the fracturing process is complicated. For this reason it has been necessary to define the fracture stress considered here as that maximum nominal true stress on the section just prior to internal crack initiation.

The lower yield strength vs. temperature curves show no discontinuity through the transition range, although from the results of Joffé (31) it might be argued that this quantity would be discontinuous at the lowest temperature in the transition range. This quantity, however, is inaccessible to measurement below this point.

The strength coefficient (σ_o) varies with temperature in much the same way as does the lower yield strength and this suggests a relationship between the two. That a relationship does exist is supported by the numerical variation of these two quantities with temperature as revealed in Figures 198 and 199. The close parallelism of the two lines is hardly fortuitous.

No discontinuity with temperature is found for the strength coefficient.

The strain hardening exponent remains to be discussed. The magnitude of this quantity is intimately associated with that of the strength coefficient which has been discussed above. This follows from the fact that both quantities appear as variables in the equation

$$\sigma = \sigma_o \delta^n$$

Since this equation is developed for the plastic state, σ_o and n cannot be determined below the transition range, or specifically at temperatures where there is no plastic flow. In the upper portion of the transition range in the tensile test there is still appreciable ductility and σ_0 and n can be determined. As has already been indicated above, the σ_0 vs. temperature curves suffer no discontinuity through the transition range. This is not the case for the strain hardening exponent. For Steels C and E the strain hardening exponent is drastically lowered at -150°C . For all steels but Steel N the strain hardening exponent is lowered at the minimum temperatures at which it has been determined. This is at variance with the observation of Siegel and Brick (20) who have concluded that n should increase with decreasing temperature. For the steels tested this behavior of n might be associated with the transition from ductile to brittle behavior which is most marked in the range from -145 to -188°C. Close examinations of the data for n and the data for reduction in area as affected by the testing temperature reveals, however, that these two phenomena are not directly interrelated. Thus for Steel C at -150°C the reduction in area is 60.5% while the value of n has dropped to 0.106 while at -145°C the two values are 43.6% and .163, respectively. For Steel E tested at -150°C the reduction in area value is 47.8%, that of n is 0.134. At -145°C these values are 48.8% and 0.117, respectively. Thus for these two steels the value of n has dropped or passed through a transition at a temperature in the upper portion or above the transition range in ductility.

There are not sufficient data to treat this point extensively, but seemingly a curve such as has been drawn for Steel A, (Figure 69), under the proper experimental circumstances would typify the behavior of n vs. temperature for all of the steels. To be more specific the value of n is lowered through a brief temperature interval which may or may not coincide with the transition range as measured in the static tension test. Seemingly the minimum value for n is characteristic for the steel - for some of the steels tested here this decrease amounts to about 50%.

The strain hardening exponent seemingly is a fundamental factor in plastic work - hardening or at least approximates thereto. The experimental circumstance that loss of ductility in the tensile test intrudes prior to the transition in n limits the determination of the relationship between n and temperature. This situation could be circumvented by the use of other test procedures in more satisfactory determinations of and n.

The variation of n with temperature as revealed in the above lends some support to Gensamer's treatment (23) of plastic strain in terms of the strain hardening exponent n, a velocity coefficient η and the stress gradient. The variation of n with temperature as shown above also refutes the Siegel and Brick (20) argument against Gensamer's concept. Much more work is required, however, before an attempt at a quantitative treatment of this concept is possible. This additional work must first of all lead to a physically sound concept of fracture.

SUMMARY AND CONCLUSIONS

In the presentation of the experimental results it has been observed that the breaking of a test bar as indicated by the stress at fracture is modified by the notch acuity. This modification is not regular, but seemingly undergoes a sharp alteration as the notch acuity is increased. These observations were made on a steel which was sensibly brittle at the testing temperature of $-188^{\circ}C$.

The fracture strength as originally porposed by Ludwik (15) has been investigated and has been found to be elevated such that the fracture strength curve at -188°C is about parallel to the flow curve at 25°C. If this curve is displaced by a given stress value to pass through the fracture point it lies on the flow curve. It cannot then have the meaning suggested by Ludwik.

If it is assumed, however, that the fracture strength is displaced differently at different strain levels a relationship between σ_f and δ_f can be established. This relationship is assumed to have the same functional form as the relationship between σ and δ, and so leads to an n_{σ_f} in place of a strain-hardening exponent. If n_{σ_f} is assumed to be independent of temperature a fracture strength curve is obtained which when displaced to pass through the fracture point at 25°C lies above the flow curve. This curve, however, will not lie above but actually below the flow curve at -150°C for some of the project steels. This situation is meaningless, so that it appears that the concept of fracture-amd flow-strengths is not correct.

The development of the internal crack in the fully ductile tensile bar for steel has been examined metallographically. Evidence has been advanced to sustain the argument of Parker, et al, (25) that the internal failure is a shear failure.

The tensile properties of the project steels as a function of prestrain followed by aging and as a function of temperature have been examined. Of the properties studied it has appeared that the strength coefficient and the strain hardening exponent possess fundamental meaning. For the steels studied the value of the strain hardening exponent vs. temperature appears to be an index of their behavior.

Finally the transition range for a mildly notched tensile bar has been determined. The transition range is displaced to higher temperatures for this test bar, while the steels all appear to be affected to about the same degree.

SUGGESTIONS FOR FURTHER WORK

It appears that further investigation of ship plate steels in the following directions might prove profitable.

(a) Notch sensitivity of steels is at best a poorly defined quantity and is for the most part defined qualitatively by means of the notch-impact test. Such an evaluation normally necessitates a modification of the testing temperature with recognized far-reaching consequences. It would appear that testing of notched bars in the non-ductile range as done here for Steel E might lead to valuable data.

(b) The need for further analysis of the temperature dependence of σ_0 and n is obvious. This analysis should be more intensive for the steels which have been studied here and should likewise embrace other compositions. Such testing could best be done by torsion testing or possibly by compression testing to suppress the transition range in ductility encountered in the tension test. Exploratory work (32) using the torsion test has been completed and has allowed the evaluation of a pseudo-strain-hardening exponent for Steels C and E at -188°C. The value of n so determined is approximately 0.1.

TABLE I - CHEMICAL ANALYSES OF THE STEELS

Steel	C	Mn	Ni	N_2
A	0.26	0.50	—	.004
Br	0.18	0.73	—	.005
Bn	0.18	0.73	—	.006
C	0.24	0.48	—	.009
Dr	0.22	0.55	—	.006
Dn	0.19	0.54	—	.006
E	0.20	0.33	—	.005
H	0.18	0.76	—	.004
N	0.17	0.53	3.39	.005

TABLE II - DIMENSIONS OF TEST SPECIMENS AND TEST RESULTS FOR STRESS CONCENTRATION

EFFECTS ON FRACTURE STRENGTH AT -188°C - STEEL E

Spec. No.	A	t or t'	D_f	α_K	σ_F	$\sigma_{MAX.}$
R-54	.2000	.1407	.3982	2.3	87,600	201,48
R-55	.2000	.1407		—	—	—
R-56	.2000	.0328	.3995	2.1	116,160	243,93
R-58	.2000	.0127	.3985	1.8	132,130	237,83
R-59	.2000	.0127	.3990	1.8	121,570	218,82
R-60	.2000	.0047	.3986	1.6	126,220	201,95
R-61	.2000	.0047	.3980	1.6	120,410	192,65
R-62	.2800	.0521	.5592	2.3	87,950	202,28
R-63	.2800	.0521	.5590	2.3	90,130	207,29
R-64	.2800	.0225	--	No Test		
R-66	.2800	.0113	--	No Test		
R-68	.2800	.0044	--	No Test		
R-69	.2800	.0044	--	No Test		

A - half diameter under notch - inches.

t or t' - notch depth-inches.

D_f - Root dia. after fracture - inches.

α_k - Neuber's stress concentration factor.

σ_f - Max. nominal stress on net section - psi.

$\sigma_{max.}$ - Max. stress at the base of the notch - psi.

TABLE III - FRACTURE STRENGTH DATA FOR PROJECT STEELS AT -188°C.

Steel		σ_F	δ_F
A		142,030	.008
		144,630	.006
		160,700	.007
		150,870	.005
	Ave.	149,500	.007
	† Ave*	125,775	.057
Br		143,790	.006
		129,580	.007
		121,650	.006
		128,970	.005
	Ave.	131,000	.007
	† Ave*	130,000	.08
Bn		127,930	.000
		143,910	.007
		128.150	.002
		137,770	.007
	Ave.	134,440	.004
	† Ave*	112,660	.043

Steel		σ_F	δ_F
Dr		138,140	.012
		140,020	.009
		143,300	.013
		153,420	.016
	Ave.	143,720	.012
	† Ave*	—	—
Dn		144,000	.006
		147,000	.017
		142,000	.007
		144,930	.016
		142,470	.014
		143,890	.023
		142,890	.012
	Ave.	143,880	.014
	† Ave*	—	—
E		140,230	.0073
		102,870	.0055
		125,980	.0105
		148,620	.0049
	Ave.	130,425	.0071
	† Ave*	121,720	.045
H		154,640	.012
		151,130	.012
		147,420	.014
		151,960	.012
	Ave.	151,290	.012

* Average values for unnotched bars.

† For individual values - see Tables VII A and VII E incl.

TABLE IV - THE EFFECTS OF PRESTRAIN AT 25° AND -76°C ON THE PHYSICAL PROPERTIES OF THE PROJECT STEELS AT -188°C.

Specimen	ϵ R.T.	ϵ L.A.	ϵ TOT.	σ F.	T_ϵ
A - 1	0	.063	.063	122,000	25°C
A - 2	0	.051	.051	124,000	"
A - 3	.211	.032	.243	149,000	"
A - 4	.211	—	.211	155,000	"
B - 7	.146	.118	.264	156,000	25°C
B - 8	.153	.066	.219	145,000	"
B - 9	.045	.045	.091	133,000	"
B - 10	.103	.047	.150	143,000	"
B - 11	.192	.045	.237	147,000	"
B - 12	0	.086	.086	129,000	"
D - 7	.150	.050	.200	148,000	25°C
D - 8	.187	.167	.354	165,000	"
D - 9	.050	.036	.086	133,000	"
D - 10	.114	.054	.168	142,000	"
D - 11	0	.012	.012	128,000	"
I - 1	.019	.023	.042	128,000	25°C
I - 2	.050	.010	.060	133,000	"
I - 3	.086	.003	.089	135,000	"
I - 4	.109	.008	.117	141,000	"
I - 5	.146	.019	.165	148,000	"
I - 6	.170	.012	.182	148,000	"
I - 8	.068	.022	.090	137,000	-76°C
I - 9	.121	.019	.140	145,000	"
I - 10	.193	.030	.223	153,000	"
I - 11	.021	.021	.411	168,000	"
I - 30	0	.028	.028		"
K - 7	.150	.074	.224	160,000	25°C
K - 8	.200	.117	.317	169,000	"
K - 9	.051	.180	.231	158,900	"
K - 11	0	.256	.256	151,000	"
N - 10	.041	.321	.362	163,500	25°C
N - 11	.096	.368	.464	189,000	"
N - 12	.131	.332	.464	171,400	"
N - 13	.206	.231	.437	170,950	"
N - 14	.248	.059	.307	145,000	"
R - 7	.150	.001	.151	140,000	25°C
R - 8	.331	.009	.340	161,000	"
R - 9	.045	.006	.051	126,600	"
R - 11	.282	.019	.301	149,000	"

TABLE V - SELECTED VALUES OF n_{σ^*F} FOR THE PROJECT STEELS

Steel	$n^*_{\sigma_f}$
A	.15
C (ϵ at 25°C)	.143
C (ϵ at -70°C)	.130
Average values of all steels	.16

TABLE VI - SPECIMENS TESTED AND TEST RESULTS FOR STUDY OF INTERNAL CRACK DEVELOPMENT IN DUCTILE TENSILE BAR - STEEL C.

Specimen	d_o	Yield Load	Max. Load	Load at final diameter	Ave. diameter
I-69		3660	6400	6150	0.278
-66		3710	6425	5475	0.252 - broken
-70		3960-3375	6500	5125	-- broken
-71		3740-3230	6450	5450	0.252
-65	0.357	3500-3260	6480	5050	-- broken
-64	0.357	3690-3240	6400	5180	0.242 - broken
-27	0.357	4030-3380	6330	5100	0.235
-23	0.356	3420-3480	6700	5300	-- broken
-25	0.356	3880-3360	6440	5300	-- broken
-26	0.357	3800-3380	6410	5160	0.243

TABLE VII A. - THE RESULTS OF TENSILE TESTS FOR STEEL A

Spec. No.	Spec. Type.	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
C - 5	1	—	—	25	107,800	.8630	33,000	58,540	57.8	100,530	.211	
-6	1	—	—	25	109,800	.8800	34,000	59,640	58.6	102,030	.209	
-45	1	—	—	25	121,000	.9570	35,480	60,100	61.5	—	—	1/64"R; .505" d_o
-46	1	—	—	25	120,400	.9630	37,200	60,180	61.7	—	—	1/64"R; .505" d_o
C - A	2	--	--	-188	120,000 (in fillet)	.0490	---	130,500	--	---	---	
- B	2	--	--	-188	---	--	---	---	--	---	---	Used for alignment
- 1	2	--	--	-188	122,000	.0756	116,000	131,000	6.2	---	---	
- 2	2	--	--	-188	124,000	.0510	124,000	130,000	5.1	---	---	
-25	2	--	--	-188	129,600	.0560	122,000	128,500	5.4	---	---	
-26	2	--	--	-188	127,500	.0440	117,300	126,700	5.4	---	---	
-27	2	--	--	-188	145,600	.1450	117,300	136,700	13.5	194,100	.148	σ_o & n graphically
-28	2	--	--	--	---	---	---	---	--	---	---	
-23	2	--	--	-70	132,500	.9213	47,000	71,500	60.2	121,100	.198	
-24	2	--	--	-70	132,700	.9099	48,800	72,500	59.7	125,650	.215	
-19	2	--	--	25	117,500	.9547	32,200	59,000	61.5	112,010	.214	
-20	2	--	--	25	113,500	.9443	32,100	58,500	61.1	101,350	.212	
-21	2	--	--	48	116,700	.9527	34,100	58,900	61.4	120,250	.316	
-22	2	--	--	48	121,300	.9039	34,250	62,200	59.7	108,900	.221	
C - 11	2	2%	25	-188	133,000	.0280	129,400	138,500	2.6	---	---	
- 12	2	2%	25	-188	139,100	.0790	127,800	136,500	7.7	---	---	
- 31	2	2%	25	-70	132,700	.7710	---	80,300	53.7	132,880	.184	Fracture ½" from min. dia.
- 32	2	2%	25	-70	134,200	.7950	63,800	79,500	54.8	130,650	.180	
- 29	2	2%	25	25	123,300	.8315	49,700	67,400	55.5	111,500	.183	
- 30	2	2%	25	25	116,900	.8350	---	67,400	56.8	109,100	.169	
- 13	2	2%	25	48	122,500	.8460	49,700	65,800	57.1	108,650	.180	
- 14	2	2%	25	48	121,800	.8500	49,200	64,600	57.3	108,650	.193	

TABLE VII A. - (Continued)

C - 7	2	5%	25	-188	145,900	.0080	---	148,100	0.79	---	---	
- 8	2	5%	25	-188	146,300	.0377	---	147,200	3.7	---	---	Broke in 3 piec one at min. dia
-35	2	5%	25	-70	134,000	.7500	76,500	83,900	52.8	133,400	.177	
-36	2	5%	25	-70	142,500	.7800	76,100	83,900	54.2	125,200	.131	
-33	2	5%	25	25	126,200	.8350	62,800	70,000	56.6	111,050	.160	
-34	2	5%	25	25	122,400	.7830	63,400	71,000	54.3	113,400	.177	
- 9	2	5%	25	48	119,900	.8165	61,500	67,400	55.8	108,420	.168	
-10	2	5%	25	48	119,600	.8347	61,400	66,000	56.6	105,700	.165	
C -15	2	10%	25	-188	155,700	.0740	152,800	152,800	7.1	---	---	
-16	2	10%	25	-188	142,600	.0211	153,700	153,700	2.1	---	---	
-39	2	10%	25	-70	137,000	.7070	85,900	87,700	50.4	126,060	.118	
-40	2	10%	25	-70	135,500	.7030	87,200	89,300	50.5	128,900	.122	
-37	2	10%	25	25	124,500	.7540	74,200	75,400	53.0	112,650	.141	
-38	2	10%	25	25	122,500	.7400	73,900	75,100	52.3	113,450	.148	This specimen u to calculate v of theoretical strained bar
-17	2	10%	25	48	120,300	.7543	72,400	74,700	53.0	109,850	.143	
-18	2	10%	25	48	119,100	.7458	73,000	73,900	52.6	109,000	.138	
C - 3	2	20%	25	-188	149,000	.0348	---	---	21.5	---	---	
- 4	2	20%	25	-188	155,000	.0205	---	---	21.5	---	---	
C -56	2 (T)	--	--	-188	133,300	.0170	---	---	1.7	---	---	Break at yield yield and fract time same
-55	2 (T)	--	--	-145	154,800	.5750	85,100	101,100	43.7	158,100	.158	o & n graphic
-58	2 (T)	--	--	-75	131,060	.6950	42,500	79,200	50.1	134,570	.199	
-53	2 (T)	--	--	25	123,930	.7680	27,500	68,100	53.6	117,180	.208	

TABLE VII A. - (Continued)

C -41	3	--	--	-188	142,030	.0080	---	---	0.80	---	---
-42	3	--	--	-188	144,630	.0060	---	---	0.63	---	---
-43	3	--	--	-188	160,700	.0070	---	---	0.65	---	---
-44	3	--	--	-188	150,870	.0050	---	---	0.49	---	---
-52	3	--	--	-145	122,000	.0150	---	---	1.63	---	---
-51	3	--	--	-110	145,000	.3310	96,000	112,100	28.1	---	---
-47	3	--	--	-77	---	.45	---	92,000	37.0	---	---
-48	3	--	--	-77	---	.45	---	92,400	37.0	---	---
-49	3	--	--	27	---	.46	---	72,700	38.0	---	---
-50	3	--	--	--	---	---	---	---	---	---	---

TABLE VII Br. - THE RESULTS OF TENSILE TESTS FOR STEEL Br.

Spec. No.	Spec. Type	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
B - 1	1	---	---	25	114,500	.9820	30,900	56,900	61.2	100,290	.227	
- 2	1	---	---	25	112,000	.9520	31,200	56,800	62.0	98,385	.213	
-55	1	---	---	25	121,600	1.0890	29,700	56,100	66.3	---	---	
-56	1	---	---	25	123,600	1.1170	29,750	56,200	67.2	---	---	
B - 3	2	---	---	-188	141,066	.1880	109,000	119,400	17.1	183,320	.155	Fracture 7/8" from min. dia. No R. A. at fracture
- 5	2	---	---	-188	136,500	.1220	112,000	122,000	13.9	---	---	Did not break at min. dia. Error suspected in load reading
- 6	2	---	---	-188	147,000	.1990	112,000	120,600	18.1	---	---	Error suspected in load reading
-12	2	---	---	-188	129,000	.0860	112,500	121,000	8.2	---	---	
-15	2	---	---	-188	130,900	.0940	112,800	123,000	9.0	---	---	
-22	2	---	---	-188	137,600	.1560	108,300	---	14.7	---	---	Fracture ¼" from min. dia.
-23	2	---	---	-188	140,700	.2050	110,100	---	16.7	---	---	
- 4	2	---	---	-150	151,380	.7480	80,800	92,200	52.7	131,850	.114	$_o$ & n graphically
-20	2	---	---	-70	134,300	1.0410	43,300	66,800	64.7	112,900	.194	
-21	2	---	---	-70	129,800	1.0060	41,300	67,100	63.4	115,900	.211	
-13	2	---	---	25	126,900	1.0770	29,200	57,000	66.5	99,370	.219	
-18	2	---	---	25	122,700	1,0700	30,500	57,600	65.7	102,410	.229	
-17	2	---	---	50	117,200	1.0610	28,500	54,700	65.4	98,985	.242	
-19	2	---	---	50	114,500	1.0420	29,100	54,200	64.7	95,700	.223	
B -33	2	2	25	-188	127,000	.0440	121,500	128,100	4.3	---	---	
-34	2	2	25	-188	132,000	.0960	119,500	126,500	9.2	---	---	
-31	2	2	25	-70	133,600	1.082	56,600	70,500	62.5	113,920	.170	
-32	2	2	25	-70	131,400	1.0280	55,600	70,200	64.4	112,780	.164	
-29	2	2	25	25	118,000	1.0860	44,700	59,700	64.4	98,354	.180	
-30	2	2	25	25	119,500	1.0650	44,700	59,800	65.5	96,598	.169	
-27	2	2	25	50	116,500	1.0910	---	57,400	66.4	90,556	.167	
-28	2	2	25	50	114,000	1.0470	41,900	56,800	65.0	94,722	.137	

TABLE VII Br. - (Continued)

B -41	2	5	25	-188	138,000	.0090	---	139,300	0.9	---	---
-42	2	5	25	-188	138,400	.0280	---	139,400	2.8	---	---
-39	2	5	25	-70	132,600	1.0220	66,200	74,400	64.0	114,290	.141
-40	2	5	25	-70	131,500	1.0020	64,100	72,000	63.3	114,110	.159
-37	2	5	25	25	120,000	1.0560	53,600	61,200	65.2	95,950	.155
-38	2	5	25	25	115,000	.9810	54,300	61,900	62.5	94,685	.143
-35	2	5	25	50	118,800	1.0080	57,300	62,600	63.5	96,538	.146
-36	2	5	25	50	123,800	1.0740	56,800	63,300	65.2	97,910	.151
B -49	2	10	25	-188	144,800	.0100	---	138,000	1.0	---	---
-50	2	10	25	-188	145,600	.0160	---	144,000	1.6	---	---
-47	2	10	25	-70	135,500	.9570	76,500	80,500	61.6	119,520	.140
-48	2	10	25	-70	132,500	.8990	75,700	80,000	59.3	116.250	.130
-45	2	10	25	25	120,000	.9570	66,500	67,800	61.6	99,510	.127
-46	2	10	25	25	120,800	.9800	66,200	67,400	62.4	97,185	.113
-43	2	10	25	50	112,500	.9630	64,800	65,300	61.8	95,823	.132
-44	2	10	25	50	112,000	.9520	64,000	65,200	61.5	96,485	.137
B - 9	2	4.6	25	-188	133,800	.0910	---	128,000	4.5	---	---
-10	2	10.3	25	-188	143,000	.1500	---	136,000	4.7	---	---
- 7	2	14.6	25	-188	156,000	.2640	---	139,200	11.2	---	---
- 8	2	15.3	25	-188	145,000	.2190	---	136,000	6.3	---	---
-11	2	19.2	25	-188	147,000	.2370	---	140,900	4.2	---	---
B -64	2 (T)	--	--	-188	142,900	.2010	110,000	117,200	18.2	179,990	.145
-66	2 (T)	--	--	-145	101,200	.3230	75,900	86,400	27.6	---	---
-68	2 (T)	--	--	-145	130,050	.5960	72,800	---	44.9	---	---
-65	2 (T)	--	--	-75	116,890	.7690	40,850	68,200	53.7	114,850	.200
-67	2 (T)	--	--	25	97,900	.7440	28,300	56,400	52.5	97,322	.215
B -51	3	--	--	-188	143,790	.0060	---	----	0.65	---	---
-52	3	--	--	-188	129,580	.0070	---	----	0.73	---	---
-53	3	--	--	-188	121,650	.0080	---	----	0.80	---	---
-54	3	--	--	-188	128,970	.0050	---	----	0.49	---	---

TABLE VII Br. - (Continued)

B - 57	3	---	---	-145	114,000	.0260	---	---	2.5	---	---
- 61	3	---	---	-110	143,000	.4700	---	101,000	40.4	---	---
- 60	3	---	---	-73	---	.5184	---	83,400	41.4	---	---
- 62	3	---	---	-75	---	.2679	---	84,500	24.4	---	---
- 58	3	---	---	27	---	.3970	---	67,600	33.6	---	---
- 59	3	---	---	28	---	.4714	---	68,000	38.4	---	---

TABLE VII Bn. - THE RESULTS OF TENSILE TESTS FOR STEEL Bn.

Spec. No.	Spec. Type	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
D - 1	1	—	—	25	128,000	1.1500	33,500	57,600	68.3	103,230	.236	
- 2	1	—	—	25	127,300	1.1350	33,900	57,450	67.8	104,090	.245	
-65	1	—	—	25	107,500	.9770	33,900	57,900	62.2	—	—	
-66	1	—	—	25	127,000	1.1310	33,700	57,700	67.7	—	—	
D - 3	2	—	—	-188	—	—	—	—	—	—	—	Spec. broke discarded.
- 4	2	—	—	-188	135,182	.1390	106,730	126,630	13.0	191,650	.177	
- 5	2	—	—	-188	128,900	.0730	113,500	125,000	7.1	—	—	Error suspected in load reading
- 6	2	—	—	-188	131,000	.0100	—	129,500	1.1	—	—	Error suspected in load reading
-11	2	—	—	-188	—	—	—	—	—	—	—	Specimen discarded · Liquid air depleted
-18	2	—	—	-188	120,430	.0730	107,000	123,000	7.0	—	—	Fracture ½" from Min. Diam.
-19	2	—	—	-188	126,000	.0150	—	124,200	1.5	—	—	
-54	2	—	—	-188	134,500	.1280	108,000	124,000	11.9	—	—	
-55	2	—	—	-188	158,200	.3070	113,700	130,000	28.1	—	—	
-14	2	—	—	-150	165,432	.8990	79,600	95,700	59.3	143,210	.147	
-20	2	—	—	-70	144,000	1.0880	46,100	71,000	66.3	124,700	.222	
-53	2	—	—	-70	137,200	1.0250	46,300	70,700	64.1	124,650	.225	
-12	2	—	—	25	125,500	1.1220	29,700	56,200	68.0	99,100	.227	
-13	2	—	—	25	116,500	.9680	31,900	57,700	62.0	105,260	.247	
-15	2	—	—	25	—	—	29,200	57,200	—	—	—	Not pulled for fracture study
-56	2	—	—	25	121,500	1.0790	35,000	59,000	66.0	102,510	.215	
-16	2	—	—	50	127,000	1.1820	31,500	56,300	60.4	100,300	.231	
-17	2	—	—	50	125,000	1.1680	31,800	55,800	68.9	105,750	.275	

TABLE VII Bn. - (Continued)

D -29	2	2	25	-188	153,800	.1280	—	145,500	11.9	—	—	
-30	2	2	25	-188	147,200	.0740	—	147,100	6.1	—	—	
-40	2	2	25	-70	137,200	.9420	56,200	73,000	61.0	125,940	.212	
-47	2	2	25	25	123,000	1.0700	42,000	60,400	65.7	98,088	.170	
-48	2	2	25	25	125,500	1.1130	41,800	59,950	67.2	100,300	.188	
-49	2	2	25	50	126,500	1.1270	42,800	58,500	67.6	90,770	.145	
-50	2	2	25	50	121,600	1.0880	43,500	58,700	66.3	97,590	.186	
D -33	2	5	25	-188	139,500	.0120	—	140,000	1.1	—	—	
-34	2	5	25	-188	136,600	.0300	—	137,000	3.7	—	—	
-45	2	5	25	-70	140,000	1.0130	66,300	75,300	63.7	116,640	.147	
-46	2	5	25	-70	145,000	1.0220	66,500	76,700	64.0	115,310	.133	
-35	2	5	25	25	123,000	.9940	57,500	66,200	63.0	103,260	.149	
-36	2	5	25	25	120,200	.9760	56,800	65,500	62.3	101,430	.146	
-51	2	5	25	50	123,100	1.0220	56,100	61,500	65.1	100,500	.178	
-52	2	5	25	50	123,500	1.0530	46,300	70,700	64.1	124,650	.225	
D -37	2	10	25	-188	138,200	.1170	120,500	128,500	11.0	—	—	
-38	2	10	25	-188	134,400	.0960	119,500	126,500	9.2	—	—	
-31	2	10	25	-70	143,300	.8700	81,000	85,000	58.1	121,940	.120	
-32	2	10	25	-70	143,000	.8970	78,900	82,600	59.2	124,030	.138	
-41	2	10	25	25	121,500	.9550	68,400	70,300	61.5	103,360	.131	
-42	2	10	25	25	123,200	.9680	68,000	70,000	62.0	103,050	.127	
-43	2	10	25	50	121,800	.9370	67,600	68,500	61.2	98,185	.126	
-44	2	10	25	50	122,800	.9490	67,000	68,300	61.3	101,150	.138	
D - 9	2	5.0	25		133,000	.0860	—	—	3.5	—	—	Fracture 1/8" from fillet
-10	2	11.4	25	-188	142,000	.1680	—	134,500	5.2	—	—	Min. Diam. at fr ture 3/37" off ce
- 7	2	15.0	25	-188	148,000	.2000	—	140,500	2.0	—	—	ter
- 8	2	18.7	25	-188	165,000	.3540	—	142,800	1.5	—	—	

TABLE VII Bn. - (Continued)

D - 76	2 (T)	—	—	-188	116,200	.0590	106,500	119,700	5.7	—	—
- 75	2 (T)	—	—	-145	146,000	.6350	73,000	171,600	52.2	143,650	.178
- 73	2 (T)	—	—	-75	128,160	.8870	42,500	88,500	58.8	124,170	.246
- 77	2 (T)	—	—	25	112,660	.9590	32,700	57,600	61.3	101,770	.226
D - 61	3	—	—	-188	127,930	.0000	—	—	0	—	—
- 62	3	—	—	-188	143,910	.0070	—	—	.65	—	—
- 63	3	—	—	-188	128,150	.0020	—	—	.16	—	—
- 64	3	—	—	-188	137,770	.0070	—	—	.65	—	—
- 67	3	—	—	-145	116,000	.0150	—	—	1.64	—	—
- 70	3	—	—	-76	—	.5458	—	88,800	43.	—	—
- 72	3	—	—	-76	—	.5103	—	87,400	41.2	—	—
- 68	3	—	—	27.5	—	.5382	—	71,500	42.4	—	—
- 69	3	—	—	28	—	.6152	—	71,000	47.	—	—

TABLE VII C. - THE RESULTS OF TENSILE TESTS FOR STEEL C.

Spec. No.	Spec. Type	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	$-\sigma_o$	n	Remarks
I -35	1	___	___	25	114,500	.8670	33,400	62,300	58.1	106,610	.207	
-36	1	___	___	25	119,500	.8330	35,000	66,200	56.5	111,590	.200	
-37	1	___	___	25	113,200	.8460	34,000	63,000	57.0	109,280	.215	
-80	1	___	___	25	123,500	.9250	33,550	63,400	60.3	---	---	
-81	1	___	___	25	123,500	.9030	34,100	63,400	59.4	---	---	
I -14	2	___	___	-188	135,990	.0220	---	---	2.2	---	---	
-15	2	___	___	-188	131,400	.0780	118,500	131,500	7.5	---	---	
-18	2	___	___	-188	124,600	.0680	114,200	125,300	6.6	---	---	Fracture $\frac{1}{4}$" from min. diam.
*22	2	___	___	-188	125,500	.0680	116,000	129,500	6.6	---	---	
-30	2	___	___	-188	120,000	.0280	---	132,500	2.7	---	---	
-33	2	___	___	-188	134,000	.0140	---	134,000	1.4	---	---	Suspected error in fracture load
-34	2	___	___	-188	123,000	.0170	---	133,000	1.7	---	---	Suspected error in fracture load
-67	2	___	___	-188	124,680	.0150	117,085	129,250	5.0	---	---	
-68	2	___	___	-188	---	---	---	---	--	---	---	Specimen fractured when load was unloaded
-13	2	___	___	-150	155,960	.7030	90,700	99,100	60.5	138,690	.106	
-19	2	___	___	-70	139,100	.8870	46,300	75,300	58.8	126,450	.194	
-21	2	___	___	-70	132,500	.8420	47,000	74,500	56.9	127,400	.205	
-12	2	___	___	25	129,900	.9990	31,700	60,400	63.8	106,260	.227	
-23	2	___	___	25	---	---	35,000	67,300	--	---	---	Specimen broken. Not pulled for fracture study
-25	2	___	___	25	---	---	33,800	64,700	--	---	---	

TABLE VII C. - (Continued)

I -26	2	—	—	25	---	--	33,800	64,100	--	--	--	
-27	2	—	—	25	---	--	33,800	64,300	--	--	--	
-28	2	—	—	25	124,000	.9490	33,200	63,000	61.3	110,120	.216	
-64	2	—	—	25	---	--	32,400	64,000	--	--	--	Specimen broken. pulled for fract study
-65	2	—	—	25	---	--	32,600	64,800	--	--	--	Specimen broken. pulled for fract study
-66	2	—	—	25	---	--	---	64,250	--	--	--	Specimen broken. pulled for fract study
-69	2	—	—	25	---	--	---	64,000	39.5	--	--	Not pulled for f ture study
-70	2	—	—	25	---	--	33,750	65,000	--	--	--	Specimen broken, pulled for fract study
-71	2	—	—	25	---	--	33,300	64,500	50.2	--	--	Not pulled for f ture study
I -20	2	—	—	50	120,400	.9140	32,000	62,900	59.9	113,600	.242	
-29	2	—	—	50	120,000	.9040	32,600	62,500	59.5	109,900	.220	
I -54	2	-2	25	-188	139,000	.0210	---	136,300	2.1	--	--	
-55	2	-2	25	-188	136,500	.0250	---	138,200	2.6	--	--	
-52	2	-2	25	-170	133,000	.7750	64,100	78,600	53.9	125,080	.165	
-53	2	2	25	-170	137,000	.8020	63,400	78,900	55.2	126,680	.169	
-40	2	2	25	25	124,900	.8860	49,100	66,200	58.9	111,190	.193	
-41	2	-2	25	25	122,700	.8460	49,100	66,200	57.7	107,110	.172	
-42	2	-2	25	50	122,100	.8460	51,800	66,800	57.2	108,620	.176	
-43	2	-2	25	50	121,500	.8360	50,900	56,100	56.6	109,450	.189	

TABLE VII C. - (Continued)

I -58	2	5	25	-188	---	--	---	---	--	---	--	Broke in grips
-59	2	5	25	-188	147,500	.0100	---	---	1.0	---	--	
-56	2	5	25	-70	137,900	.7570	74,600	83,300	52.9	130,500	.158	
-57	2	5	25	-70	135,200	.7290	76,800	84,400	51.6	129,180	.145	
-44	2	5	25	25	120,100	.7540	63,300	71,400	54.7	110,690	.152	
-45	2	5	25	25	127,500	.8060	63,400	71,900	56.1	105,180	.156	
-46	2	5	25	50	122,400	.8020	62,500	70,100	55.2	108,330	.152	
-47	2	5	25	50	121,000	.8020	61,400	70,300	55.2	102,580	.151	
I -62	2	10	25	-188	154,500	.0100	---	---	1.0	---	--	
-63	2	10	25	-188	154,300	.0150	---	152,500	2.6	---	--	
-60	2	10	25	-70	136,800	.6760	84,700	89,500	49.3	129,460	.122	
-61	2	10	25	-70	138,200	.6680	84,600	89,200	48.9	123,400	.101	
-48	2	10	25	25	124,800	.7320	73,800	77,200	52.6	112,650	.130	
-49	2	10	25	25	124,500	.7080	75,600	78,300	51.5	113,250	.125	
-50	2	10	25	50	126,000	.7560	74,100	76,300	53.2	110,250	.127	
-51	2	10	25	50	121,800	.7470	74,100	76,500	52.6	112,280	.133	
I - 1	2	1.9	25	-188	128,000	.0420	---	---	2.5	---	--	
- 2	2	5.0	25	-188	133,000	.0600	---	---	1.2	---	--	Fracture next
- 3	2	8.6	25	-188	135,000	.0890	---	---	0.4	---	--	fillet
- 4	2	10.9	25	-188	141,000	.1170	---	---	0.8	---	--	
- 5	2	14.6	25	-188	148,000	.1650	---	---	1.9	---	--	
- 6	2	17.0	25	-188	148,000	.1820	---	---	0.5	---	--	
I - 8	2	6.8	-70	-188	137,000	.0900	---	---				
- 9	2	12.1	-70	-188	145,000	.1400	---	---				
-10	2	19.3	-70	-188	153,000	.2230	---	---				
-11	2	39.6	-70	-188	168,000	.4110	---	---				
- 7	2	Fract.	-70	--	129,000	.8350	47,000	75,000	56.7	---	--	

TABLE VII C. - (Continued)

I -91	2 (T)	___	___	-188	125,900	.0640	115,000	124,000	6.2	---	--	Fracture 3/8" from min. diam.
-90	2 (T)	___	___	-145	137,800	.5720	76,600	91,700	43.6	145,930	.163	
-93	2 (T)	___	___	-75	122,000	.7110	43,500	73,200	50.9	127.610	,219	
-88	2 (T)	___	___	-25	109,470	.7510	31,980	62,300	52.7	107,260	,211	
I -76	3	___	___	-188	114,480	.0080	---	---	0.79	---	--	
-77	3	___	___	-188	120,190	.0080	---	---	0.63	---	--	
-78	3	___	___	-188	148,090	.0120	---	---	1.19	---	--	
-79	3	___	___	-188	150,670	.0050	---	---	0.49	---	--	
-82	3	___	___	-145	---	--	---	---	--	---	--	Specimen broken in mach.
-85	3	___	___	-145	120,000	.0150	---	---	1.63	---	--	
-84	3	___	___	-110	147,000	.4990	76,000	102,000	39.1	---	--	

TABLE VII Dr. - THE RESULTS OF TENSILE TESTS FOR STEEL Dr.

Spec. No.	Spec. Type	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
K - 1	1	___	___	25	128,000	.9090	38,100	---	--	116,720	.208	
- 2	1	___	___	25	130,000	.9200	37,606	---	--	115,500	.207	
-60	1	___	___	25	130,700	.9570	38,100	66,900	61.6	---	--	
-61	1	___	___	25	136,500	1.0160	37,750	66,400	63.7	---	--	
- 4	2	___	___	-188	149,020	.1870	180,740	122,200	16.9	---	--	
- 5	2	___	___	-188	141,000	.1150	113,000	---	10.9	---	--	
- 6	2	___	___	-188	148,000	.1690	113,500	---	15.6	---	--	
-11	2	___	___	-188	151,900	.9760	111,300	121,900	22.6	---	--	Fractured 1/8" off center
-13	2	___	___	-188	149,270	.1940	105,600	123,500	17.6	192,400	.157	
-14	2	___	___	-188	145,300	.1690	109,800	122,900	15.5	---	--	
-46	2	___	___	-188	153,900	.2310	109,800	153,900	21.5	---	--	
-47	2	___	___	-188	142,000	.1630	109,900	121,200	7.6	---	--	
- 3	2	___	___	-150	168,860	.7850	80,000	100,000	54.4	169,000	.202	
-44	2	___	___	-70	148,300	.9210	47,500	79,600	60.2	137,700	.214	
-45	2	___	___	-70	151,500	.9490	47,100	79,500	61.3	136,300	.206	
-10	2	___	___	25	135,000	1.0070	37,100	66,500	64.0	115,560	.213	
-17	2	___	___	25	129,100	.9490	38,500	67,700	61.3	115,680	.203	
-18	2	___	___	50	130,000	1.0020	36,100	66,000	63.3	113,260	.208	
-12	2	___	___	50	127,600	.9760	37,500	65,500	62.3	112,350	.205	
-20	2	2	25	-188	152,900	.2230	120,100	125,000	18.9	195,400	.157	
-23	2	2	25	-188	156,800	.2410	120,800	124,600	21.4	195,500	.157	
-21	2	2	25	-70	146,100	.8850	60,600	81,600	58.7	136,060	.192	
-22	2	2	25	-70	145,000	.8640	60,606	81,300	57.8	135,500	.192	
-52	2	2	25	25	132,300	.9650	51,700	69,900	61.9	115,430	.187	

TABLE VII Dr. - (Continued)

K -53	2	2	25	25	132,000	.9650	52,100	69,100	62.1	112,100	.170
-32	2	2	25	50	126,500	.9770	52,900	67,300	61.4	108,690	.175
-33	2	2	25	50	125,500	.9840	--	67,406	62.6	108,030	.166
-34	2	2	25	50	127,500	.9680	--	66,700	62.0	109,200	.177
-35	2	2	25	50	127,300	.9290	49,000	65,100	62.2	110,280	.200
-26	2	5	25	-188	153,500	.1800	129,100	133,300	16.4	190,250	.123
-27	2	5	25	-188	154,200	.1800	128,200	133,200	16.4	--	--
K - 9											
-24	2	5	25	-70	148,900	.8460	75,100	85,200	57.2	135,400	.158
-25	2	5	25	-70	148,000	.8510	74,250	83,600	57.3	133,590	.146
-38	2	5	25	25	132,000	.9040	66,900	72,500	59.5	106,720	.120
-39	2	5	25	25	134,100	.9210	66,300	72,606	60.1	111,390	.145
-36	2	5	25	50	129,500	.9140	65,400	70,500	59.9	106,040	.161
-37	2	5	25	50	132,300	.9210	65,000	70,000	60.2	109,400	.152
-28	2	10	25	-188	161,200	.1800	138,000	142,800	16.4	---	--
-30	2	10	25	-188	151,800	.0690	141,800	146,600	6.6	---	--
-29	2	10	25	-70	145,000	.7850	84,200	87,500	54.4	133,440	.146
-31	2	10	25	-70	145,000	.766	86,500	89,100	53.6	136,590	.146
-40	2	10	25	25	132,500	.8480	77,300	78,900	57.2	115,400	.132
-41	2	10	25	25	131,500	.8260	78,500	80,400	56.2	116,120	.122
-42	2	10	25	25	127,200	.8350	77,250	78,800	56.6	114,740	.132
-43	2	10	25	25	133,200	.8760	76,600	77,900	58.4	112,380	.123
-54	2	10	25	50	130,500	.8510	76,600	78,500	57.3	112,210	.133
-55	2	10	25	50	131,100	.8510	76,400	78,000	57.3	114,200	.138
- 7	2	15	25	-188	160,000	.2240	---	---	7.1	---	--
- 8	2	20	25	-188	169,000	.317	---	---	11.1	---	--

TABLE VII Dr. - (Continued)

K -69	2 (T)	___	___	-188	134,000	.1160	109,100	119,400	11.0	___	___	Min. Diam. 3/4" fr fracture .0901 are at d_f
-68	2 (T)	___	___	-145	152,300	.6970	74,000	92,000	50.2	151,000	.215	
-73	2 (T)	___	___	-75	142,070	.8770	43,800	76,900	58.4	132,870	.218	
-72	2 (T)	___	___	25	125,690	.9110	35,080	64,500	59.7	112,250	.219	
-56	3	___	___	-188	138,140	.0120	---	---	1.20	---	--	
-57	3	___	___	-188	140,020	.0090	---	---	.87	---	--	
-58	3	___	___	-188	143,300	.0130	---	---	1.27	---	--	
-59	3	___	___	-188	153,420	.0160	---	---	1.61	---	--	
-67	3	___	___	-145	115,000	.0260	---	---	2.50	---	--	
-65	3	___	___	-110	160,000	.5590	67,000	105,800	42.8	---	--	
-62	3	___	___	-74	---	--	---	96,400	25.2	---	--	
-63	3	___	___	-76	---	--	---	---	--	---	--	
-64	3	___	___	26	---	--	---	81,000	51.6	---	--	
-66	3	___	___	25	---	--	---	80,100	51.6	---	--	

TABLE VII Dn. - THE RESULTS OF TENSILE TESTS FOR STEEL Dn.

Spec. No.	Spec. Type	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
N - 4	1	—	—	25	128,800	1.0400	36,400	---	--	110,570	.228	
- 5	1	—	—	25	128,800	1.0500	37,300	---	--	112,300	.239	
N - 6	2	—	—	-188	169,000	.3480	109,000	119,000	29.7	---	--	
- 7	2	—	—	-188	161,000	.3100	107,000	161,000	26.5	---	--	
- 8	2	—	—	-188	159,000	.2810	108,200	122,000	24.6	---	--	
- 9	2	—	—	-188	158,000	.2810	110,000	122,000	24.6	---	--	
-16	2	—	—	-188	---	--	---	---	--	---	--	Specimen discarded
-17	2	—	—	-188	---	--	---	---	--	---	--	Specimen discarded
-18	2	—	—	-188	165,328	.4350	103,200	117,900	35.3	184,500	.157	
-25	2	—	—	-188	163,400	.3950	103,800	115,700	33.4	---	--	
-26	2	—	—	-188	167,200	.4290	105,500	119,300	34.8	---	--	
-27	2	—	—	-188	168,400	.4100	116,300	122,000	33.8	189,600	--	
-19	2	—	—	-150	165,116	.8000	84,220	98,500	55.1	159,200	.175	
-23	2	—	—	-70	145,070	.9550	49,200	76,600	61.5	134,300	.221	
-24	2	—	—	-70	140,900	1.0170	46,850	73,100	59.3	126,900	.216	
-15	2	—	—	25	133,000	1.0890	34,100	69,600	65.5	103,370	.217	
-21	2	—	—	25	132,400	1.0910	36,300	61,600	66.4	109,200	.227	
-58	2	—	—	25	128,800	1.1060	35,000	60,900	66.9	---	--	
-59	2	—	—	25	127,800	1.1020	34,800	60,230	66.7	---	--	
-20	2	—	—	50	125,000	1.0880	34,200	59,400	66.3	104,320	.221	
-22	2	—	—	50	130,000	1.0610	39,100	63,200	65.4	109,520	.212	
N -36	2	2	25	-188	158,000	.3200	---	120,000	27.4	---	--	
-37	2	2	25	-188	157,400	.3030	---	121,000	26.1	---	--	
-34	2	2	25	-70	141,500	.9900	---	75,300	62.7	120,860	.167	
-35	2	2	25	-70	146,800	.9840	---	77,500	62.6	133,220	.207	
-32	2	2	25	25	126,000	1.0580	---	62,400	65.3	102,940	.179	

TABLE VII Dn. - (Continued)

N-33	2	2	25	25	128,000	1.0760	---	62,500	65.9	104,890	.192
-30	2	2	25	50	129,200	1.0360	---	63,600	64.5	106,720	.191
-31	2	2	25	50	124,000	.9840	---	64,000	62.6	106,850	.184
N-44	2	5	25	-188	171,300	.3620	---	129,300	30.4	---	--
-45	2	5	25	-188	171,200	.3590	---	112,400	30.2	---	--
-42	2	5	25	-70	144,400	.9650	---	78,000	61.9	127,510	.178
-43	2	5	25	-70	141,700	.9840	---	77,200	62.6	125,510	.172
-40	2	5	25	25	127,500	1.0850	---	63,500	66.3	103,920	.175
-41	2	5	25	25	124,200	1.0360	---	64,000	64.6	103,800	.172
-38	2	5	25	50	120,700	1.0020	---	63,200	63.3	100,850	.160
-39	2	5	25	50	124,800	1.0130	---	64,100	63.7	102,070	.159
N-52	2	10	25	-188	169,000	.3180	---	132,800	27.2	---	--
-53	2	10	25	-188	167,400	.2940	---	133,700	25.5	---	--
-50	2	10	25	-70	140,800	.8740	---	82,900	58.2	129,040	.152
-51	2	10	25	-70	148,100	.8870	---	85,400	58.8	130,970	.143
-48	2	10	25	25	120,600	.9570	---	68,100	61.6	105,110	.147
-49	2	10	25	25	127,900	1.0000	---	67,900	63.2	105,200	.150
-46	2	10	25	50	127,800	.9630	---	68,300	61.8	106,400	.155
-47	2	10	25	50	122,200	.9340	---	68,000	60.8	106,290	.153
N-10	2	4.3	25	-188	163.500	.3620	---	127,000	27.1	---	--
-11	2	9.6	25	-188	189,200	.4640	---	134,000	30.6	---	--
-12	2	13.2	25	-188	171,400	.4640	---	135,000	28.2	---	--
-13	2	20.6	25	-188	170,950	.4370	---	143,000	20.7	---	--
-14	2	24.8	25	-188	145,000	.3070	---	145,000	5.7	---	--
N-74	2 (T)	—	—	-188	139,200	.1590	105,200	118,600	14.7	---	--
-77	2 (T)	—	—	-145	158,200	.7560	72,300	92,000	53.0	155,400	.201

TABLE VII Dn. - (Continued)

N-75	2 (T)	___	___	-75	140,650	.8580	46,500	76,700	57.6	138,520	.247
-76	2 (T)	___	___	25	123,020	.9390	37,000	62,700	60.9	107,800	.209
N - 1	3	___	___	-188	144,000	.0060	---	---	0.8	---	--
- 2	3	___	___	-188	147,000	.0170	---	---	1.6	---	--
- 3	3	___	___	-188	142,000	.0070	---	---	0.7	---	--
-54	3	___	___	-188	144,930	.0160	---	---	1.61	---	--
-55	3	___	___	-188	142,470	.0140	---	---	1.36	---	--
-56	3	___	___	-188	143,890	.0230	---	---	2.23	---	--
-57	3	___	___	-188	142,890	.0120	---	---	1.20	---	--
-68	3	___	___	-145	152,000	.1920	---	---	17.5	---	--
-72	3	___	___	-110	---	.5710	80,000	106,300	43.3	---	--
-70	3	___	___	-75	---	--	---	94,700	49.	---	--
-71	3	___	___	-76	---	--	---	93,900	50.	---	--
-69	3	___	___	27.5	---	--	---	---	--	---	--
-73	3	___	___	26	---	--	---	67,900	53.	---	--

TABLE VII E. - THE RESULTS OF TENSILE TESTS FOR STEEL E.

Spec. No.	Spec. Type	ϵ	T_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_0	n	Remarks
R - 1	1	—	—	25	116,400	.8460	32,000	63,750	57.0	111,150	.218	
- 2	1	—	—	25	114,000	.8150	30,500	63,900	55.7	108,850	.204	
-74	1	—	—	25	114,600	1.0410	27,200	55,000	64.6	---	--	
-75	1	—	—	25	113,700	.9500	27,450	56,780	61.3	---	--	
R - 4	2	—	—	-188	121,070	.0330	116,500	125,000	3.2	---	--	
- 5	2	—	—	-188	128,000	.0050	--	127,000	0.5	---	--	
- 6	2	—	—	-188	121,300	.0300	118,000	127,800	2.7	---	--	
-13	2	—	—	-188	122,330	.0620	111,300	119,500	6.0	---	--	
-14	2	—	—	-188	119,800	.0450	112,700	120,500	4.4	---	--	
-45	2	—	—	-188	121,600	.0690	109,500	115,100	6.6	---	--	Fracture 1/2" min. diameter
-48	2	—	—	-188	118,700	.0440	108,600	114,000	4.3	---	--	Fracture 1/8" min. diameter
- 3	2	—	—	-150	158,000	.6510	86,730	101,500	47.8	151,700	.134	
-44	2	—	—	-70	129,100	.9290	40,700	68,400	60.5	117,720	.209	
-46	2	—	—	-70	128,600	1.0020	40,000	65,700	63.3	116,650	.228	
-12	2	—	—	25	112,000	.9090	28,700	58,400	59.3	102,630	.226	
-16	2	—	—	25	117,000	1.0130	29,000	55,600	63.7	99,600	.229	
-10	2	—	—	50	112,000	.9650	27,600	56,500	61.9	101,100	.235	
-17	2	—	—	50	112,000	.9650	27,100	57,000	61.9	100,100	.187	
R -30	2	2	25	-188	145,800	.0040	--	145,000	0.5	---	--	
-31	2	2	25	-188	145,800	.0040	--	145,000	0.5	---	--	
-40	2	2	25	-70	133,700	.9210	55,800	71,400	60.2	117,150	.177	
-41	2	2	25	-70	132,200	.8530	55,700	72,300	57.4	119,650	.183	
-50	2	2	25	25	108,000	.8260	42,600	61,400	56.2	101,160	.181	
-51	2	2	25	25	109,800	.8530	43,000	61,500	57.4	101,240	.180	

TABLE VII E. - (Continued)

R -18	2	2	25	50	109,400	.8890	47,100	58,300	59.1	96,820	.187	
-19	2	2	25	50	110,500	.9080	46,600	58,300	59.7	95,350	.179	
-20	2	2	25	50	111,500	.9290	40,000	56,100	62.3	94,200	.196	
-21	2	2	25	50	111,100	1.0170	41,300	55,400	63.9	91,220	.181	
-34	2	5	25	-188	139,200	.0000	--	139,200	0	--	--	
-35	2	5	25	-188	139,200	.0040	--	137,500	0.5	--	--	
-36	2	5	25	-70	132,200	.8100	69,800	78,000	55.5	123,500	.164	
-37	2	5	25	-70	136,700	.9290	68,600	74,900	60.5	114,500	.143	
-24	2	5	25	25	113,800	.9390	55,000	61,500	60.9	95,660	.151	
-25	2	5	25	25	109,900	.9040	55,000	61,600	59.5	95,650	.154	
-22	2	5	25	50	111,500	.9630	52,500	58,000	61.8	92,760	.166	
-23	2	5	25	50	110,100	.9290	51,750	56,900	62.3	95,805	.202	
R -38	2	10	25	-188	124,900	.0990	--	125,500	1.1	--	--	
-39	2	10	25	-188	126,000	.0120	--	126,500	1.1	--	--	
-32	2	10	25	-70	133,800	.8440	76,500	80,300	57.0	120,800	.145	
-33	2	10	25	-70	129,600	.8170	78,600	82,800	55.8	120,700	.138	
-26	2	10	25	--	--	--	--	--	--	--	--	Specimen discarded
-27	2	10	25	25	109,000	.7940	65,300	66,500	54.8	92,014	.140	
-28	2	10	25	25	109,000	.7940	69,800	71,500	54.8	102,000	.128	
-29	2	10	25	25	113,200	.8350	69,600	71,400	56.1	100,800	.125	
-52	2	10	25	50	108,200	.8870	62,800	64,000	58.8	94,670	.139	
-53	2	10	25	50	108,400	.9040	63,500	64,500	59.5	96,270	.142	
R - 9	2	4.5	25	-188	126,600	.0510	--	--	0.56	--	--	Fracture 3/32" off center
- 7	2	15.0	25	-188	140,000	.1510	--	--	0.12	--	--	
-11	2	28.2	25	-188	149,900	.3010	--	--	1.9	--	--	
- 8	2	33.1	25	-188	161,000	.3400	--	--	0.56	--	--	

TABLE VII E. - (Continued)

R -95	2 (T)	___	___	___	---	--	---	---	--	---	--
-91	2 (T)	___	___	-145	139,000	.6680	73,600	87,800	48.8	143,800	.117
-90	2 (T)	___	___	-75	126,520	.7550	44,200	72,500	53.1	125,660	.220
-93	2 (T)	___	___	25	112,590	.8330	29,550	60,000	56.2	106,320	.232
R -70	3	___	___	-188	140,230	.0073	---	---	--	---	--
-71	3	___	___	-188	102,820	.0055	---	---	--	---	--
-72	3	___	___	-188	125,980	.0105	---	---	--	---	--
-73	3	___	___	-188	148,620	.0049	---	---	--	---	--
R -87	3	___	___	-145	111,000	.0150	---	---	1.6	---	--
-88	3	___	___	-110	141,000	.4480	81,000	100,600	36.1	---	--
-86	3	___	___	-76	---	--	---	89,800	36.	---	--
-89	3	___	___	-70	---	--	---	89,100	37.	---	--
-84	3	___	___	27.5	---	--	---	63,800	39.	---	--
-85	3	___	___	25	---	--	---	---	--	---	--

TABLE VII H. - THE RESULTS OF TENSILE TESTS FOR STEEL H.

Spec. No.	Spec. Type	ϵ	σ_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
H - 2	2	—	—	-188	144,270	.1920	109,870	119,600	17.5	186,100	.154	
- 3	2	—	—	-188	152,500	.2740	109,500	119,000	24.0	182,200	.147	
- 1	2	—	—	-150	167,580	.8750	81,290	94,400	58.3	152,830	.173	
H -19	2 (T)	—	—	-188	141,000	.1660	110,000	119,500	15.3	---	--	
-20	2 (T)	—	—	-145	154,000	.7980	73,300	88,800	55.0	145,650	.181	
-17	2 (T)	—	—	-75	137,690	.9160	43,500	73,600	60.0	125,320	.208	
-18	2 (T)	—	—	25	119,190	.9940	31,500	59,800	63.0	102,650	.206	
H - 7	3	—	—	-188	154,640	.0120	---	--	1.20	---	--	
- 8	3	—	—	-188	151,130	.0120	---	--	1.20	---	--	
- 9	3	—	—	-188	147,420	.0140	---	--	1.36	---	--	
-10	3	—	—	-188	151,960	.0120	---	--	1.20	---	--	
-16	3	—	—	-145	138,000	.1330	---	--	12.4	---	--	
-14	3	—	—	-110	155,000	.7100	71,000	97,000	51.6	---	--	

TABLE VII N. - THE RESULTS OF TENSILE TESTS FOR STEEL N.

Spec. No.	Spec. Type	ϵ	σ_ϵ	T Test	σ_F	δ_F	$\sigma_{L.Y.}$	Tensile Strength	R.A.	σ_o	n	Remarks
LK -2	2	—	—	-188	186,400	.6080	108,350	127,500	45.6	224,920	.229	
-3	2	—	—	-188	228,500	.8110	107,900	127,000	55.4	212,100	.194	
-1	2	—	—	-150	212,180	.9860	85,620	103,800	64.7	184,800	.198	

TABLE VIII. - THE FRACTURE DATA FOR TENSILE SPECIMENS TESTS 6, 7, AND 8*

Steel A.

No.	Temp. Test.	Fracture	Prestrain
C - 45	25	c - c	0
- 46	25	c - c	0
C - 25	-188	gr. (star)	0
- 26	-188	gr. (star)	0
- 24	-70	c - c	0
- 19	25	c - c	0
- 21	48	c - c	0
C - 11	-188	gr.	2
- 12	-188	gr.	2
- 31	-70	gr. (star)	2
- 32	-70	gr. (star)	2
- 29	25	c - c	2
- 30	25	c - c	2
- 13	48	c - c	2
- 14	48	c - c	2
C - 7	-188	gr.	5
- 8	-188	gr.	5
- 35	-70	gr. (star)	5
- 36	-70	gr. (star)	5
- 33	+25	c - c	5
- 34	25	c - c	5
- 9	48	c - c	5
- 10	48	c - c	5
C - 15	-188	gr.	10
- 16	-188	gr.	10
- 39	-70	gr. (star)	10
- 40	-70	gr. (star)	10
- 37	25	c - c	10
- 38	25	c - c	10
- 17	48	c - c	10
- 18	48	c - c	10

Steel Br.

No.	Temp. Test.	Fracture	Prestrain
B - 55	25	c - c	0
- 56	25	c - c	0
B - 3	-188	gr.	0
- 12	-188	gr.	0
- 15	-188	gr.	0

*c - c - Cup and Cone
gr. - Granular - cleavage
gr. (star) -Granular Star

TABLE VIII. - (Continued)

- 22	-188	gr.	0
- 20	-70	c - c	0
- 13	25	c - c	0
- 17	50	c - c	0
B - 33	-188	gr.	2
- 34	-188	gr.	2
- 31	-70	c - c	2
- 32	-70	c - c	2
- 29	25	c - c	2
- 30	25	c - c	2
- 27	48	c - c	2
- 28	48	c - c	2
B - 41	-188	gr.	5
- 42	-188	gr.	5
- 39	-70	c - c	5
- 40	-70	c - c	5
- 37	+25	c - c	5
- 38	25	c - c	5
- 35	50	c - c	5
- 36	50	c - c	5
B - 49	-188	gr.	10
- 50	-188	gr.	10
- 47	-70	c - c	10
- 48	-70	c - c	10
- 45	25	c - c	10
- 46	25	c - c	10
- 43	50	c - c	10
- 44	50	c - c	10
<u>Steel Bn.</u>			
D - 1	25	c - c	0
- 2	25	c - c	0
- 65	25	c - c	0
D - 3	-188	gr.	0
- 4	-188	gr.	0
- 11	-188	gr. (star)	0
- 18	-188	gr.	0
- 19	-188	gr. (star)	0
- 55	-188	gr.	0
- 53	-70	c - c	0
- 13	25	c - c	0
- 56	25	c - c	0
- 16	50	c - c	0

TABLE VIII. - (Continued)

D - 29	-188	gr.	2
- 30	-188	gr.	2
- 40	-70	c - c	2
- 47	25	c - c	2
- 48	+25	c - c	2
- 49	50	c - c	2
- 50	50	c - c	2
D - 33	-188	gr.	5
- 34	-188	gr.	5
- 45	-70	c - c	5
- 46	-70	c - c	5
- 35	25	c - c	5
- 36	25	c - c	5
- 51	50	c - c	5
- 52	50	c - c	5
D - 37	-188	gr.	10
- 38	-188	gr. (star)	10
- 31	-70	c - c	10
- 32	-70	c - c	10
- 41	25	c - c	10
- 42	25	c - c	10
- 43	50	c - c	10
- 44	50	c - c	10

Steel C.

I - 80	25	c - c	0
- 81	25	c - c	0
I - 14	-188	gr.	0
- 18	-188	gr.	0
- 22	-188	gr.	0
- 67	-188	gr.	0
- 68	-188	gr.	0
- 12	25	c - c	0
- 29	50	c - c	0
I - 54	-188	gr.	2
- 55	-188	gr.	2
- 52	-70	gr. (star)	2
- 53	-70	gr. (star)	2
- 40	25	c - c	2
- 41	25	c - c	2
- 42	50	c - c	2
- 43	50	c - c	2

TABLE VIII. - (Continued)

I - 59	-188	gr.	5
- 56	-70	gr. (star)	5
- 57	-70	gr. (star)	5
- 44	25	c - c	5
- 45	25	c - c	5
- 46	50	c - c	5
- 47	50	c - c	5
I - 62	-188	gr.	10
- 63	-188	gr.	10
- 60	-70	gr. (star)	10
- 61	-70	gr. (star)	10
- 48	25	c - c	10
- 49	25	c - c	10
- 50	50	c - c	10
- 51	50	c - c	10

<u>Steel Dr.</u>

K - 60	25	c - c	0
- 61	25	c - c	0
K - 11	-188	gr.	0
- 14	-188	gr.	0
- 46	-188	gr.	0
- 47	-188	gr.	0
- 44	-70	gr. (star)	0
- 17	25	c - c	0
- 12	50	c - c	0
K - 20	-188	gr.	2
- 23	-188	gr.	2
- 21	-70	gr. (star)	2
- 22	-70	gr. (star)	2
- 52	25	c - c	2
- 53	25	c - c	2
- 32	50	c - c	2
- 33	50	c - c	2
- 34	50	c - c	2
- 35	50	c - c	2
K - 26	-188	gr.	5
- 27	-188	gr.	5
- 24	-70	gr. (star)	5
- 25	-70	gr. (star)	5
- 38	25	c - c	5
- 39	25	c - c	5
- 36	50	c - c	5
- 37	50	c - c	5

TABLE VIII. - (Continued)

K - 28	-188	gr.	10
- 30	-188	gr.	10
- 29	-70	gr. (star)	10
- 31	-70	gr. (star)	10
- 40	25	c - c	10
- 41	25	c - c	10
- 42	25	c - c	10
- 43	25	c - c	10
Steel Dn.			
N - 17	-188	gr. (star)	0
- 25	-188	gr.	0
- 26	-188	gr. (star)	0
- 27	-188	gr. (star)	0
- 24	-70	c - c	0
- 15	25	c - c	0
- 58	25	c - c	0
- 59	25	c - c	0
- 22	50	c - c	0
N - 36	-188	gr.	2
- 37	-188	gr.	2
- 34	-70	c - c	2
- 35	-70	c - c	2
- 32	25	c - c	2
- 33	25	c - c	2
- 30	50	c - c	2
- 31	50	c - c	2
N - 44	-188	gr.	5
- 45	-188	gr.	5
- 42	-70	c - c	5
- 43	-70	c - c	5
- 40	25	c - c	5
- 41	25	c - c	5
- 38	50	c - c	5
- 39	50	c - c	5
N - 52	-188	gr.	10
- 53	-188	gr.	10
- 50	-70	c - c	10
- 51	-70	c - c	10
- 48	25	c - c	10
- 49	25	c - c	10
- 46	50	c - c	10
- 47	50	c - c	10

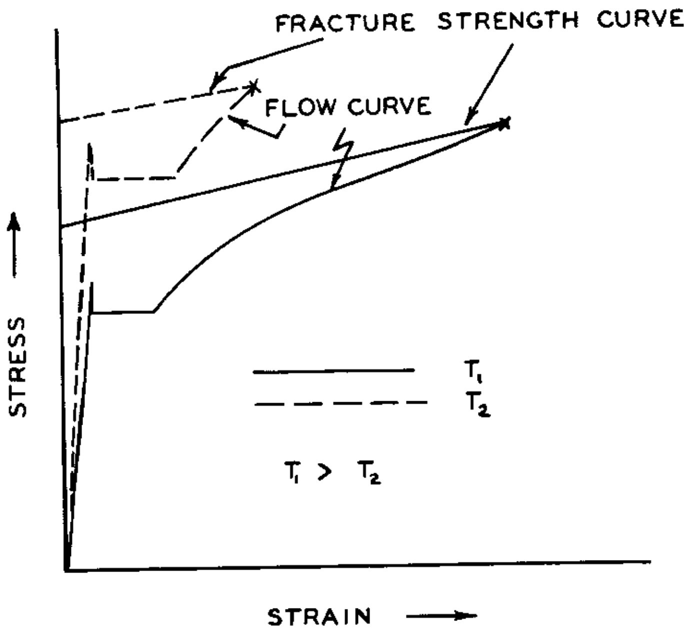
TABLE VIII. - (Continued)

Steel E.

R - 74	25	c - c	
- 75	25	c - c	
R - 13	-188	gr.	
- 14	-188	gr.	
- 48	-188	gr.	
R - 30	-188	gr.	2
- 31	-188	gr.	2
- 40	-70	c - c	2
- 41	-70	c - c	2
- 50	25	c - c	2
- 51	25	c - c	2
- 18	50	c - c	2
- 19	50	c - c	2
- 20	50	c - c	2
- 21	50	c - c	2
R - 34	-188	gr.	5
- 35	-188	gr.	5
- 36	-70	gr.	5
- 37	-70	c - c	5
- 24	25	c - c	5
- 25	25	c - c	5
- 22	50	c - c	5
- 23	50	c - c	5
R - 38	-188	gr.	10
- 39	-188	gr.	10
- 32	-70	c - c	10
- 33	-70	c - c	10
- 27	+25	c - c	10
- 28	25	c - c	10
- 29	25	c - c	10
- 52	50	c - c	10
- 53	50	c - c	10

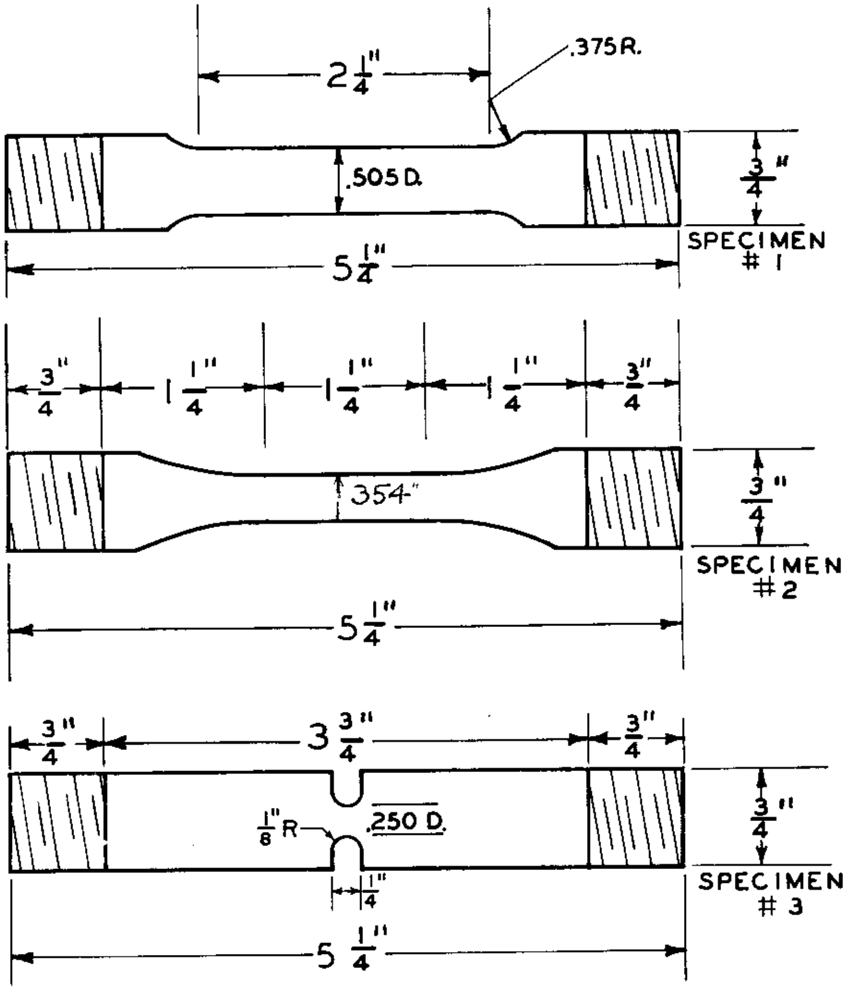
TABLE IX. - APPROXIMATE TEMPERATURES OF TRANSITION FROM FIBROUS TO GRANULAR FRACTURE FOR TENSILE SPECIMENS TESTS 6, 7, AND 8

Steel	Prestrain	Transition Temperature (T)
A	0	$-70^\circ C > T > -188^\circ C$
A	2	$25^\circ C > T > -70^\circ C$
A	5	$25^\circ C > T > -70^\circ C$
A	10	$25^\circ C > T > -70^\circ C$
Br	0	$-70^\circ C > T > -188^\circ C$
Br	2	$-70^\circ C > T > -188^\circ C$
Br	5	$-70^\circ C > T > -188^\circ C$
Br	10	$-70^\circ C > T > -188^\circ C$
Bn	0	$-70^\circ C > T > -188^\circ C$
Bn	2	$-70^\circ C > T > -188^\circ C$
Bn	5	$-70^\circ C > T > -188^\circ C$
Bn	10	$-70^\circ C > T > -188^\circ C$
C	0	$25^\circ C > T$
C	2	$25^\circ C > T > -70^\circ C$
C	5	$25^\circ C > T > -70^\circ C$
C	10	$25^\circ C > T > -70^\circ C$
Dr	0	$25^\circ C > T > -70^\circ C$
Dr	2	$25^\circ C > T > -70^\circ C$
Dr	5	$25^\circ C > T > -70^\circ C$
Dr	10	$25^\circ C > T > -70^\circ C$
Dn	0	$-70^\circ C > T > -188^\circ C$
Dn	2	$-70^\circ C > T > -188^\circ C$
Dn	5	$-70^\circ C > T > -188^\circ C$
Dn	10	$-70^\circ C > T > -188^\circ C$
E	0	———
E	2	$-70^\circ C > T > -188^\circ C$
E	5	$\approx -70^\circ C$
E	10	$-70^\circ C > T > -188^\circ C$



LUDWIK REPRESENTATION OF MECHANICAL FAILURE

FIG. 1



SPECIMENS

FIG. 2

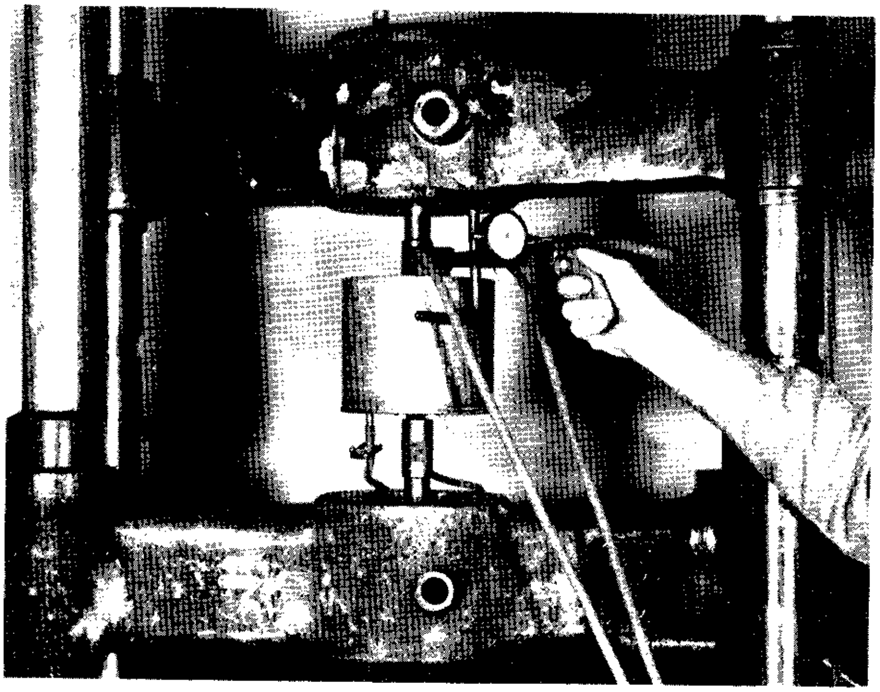


Fig. 3 - Testing Set-Up

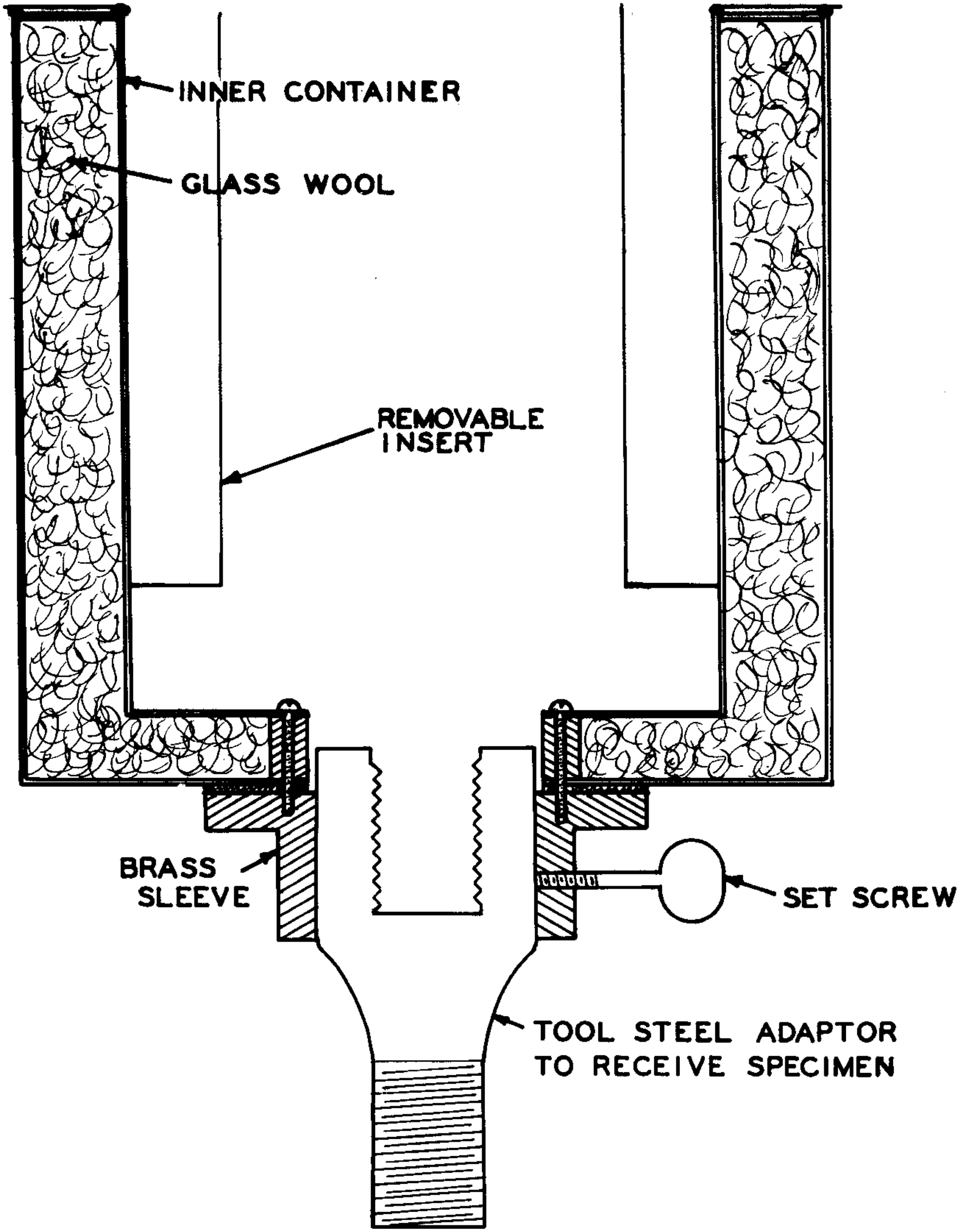


FIG. 4 FIXTURE FOR LOW TEMPERATURE TENSILE TESTS

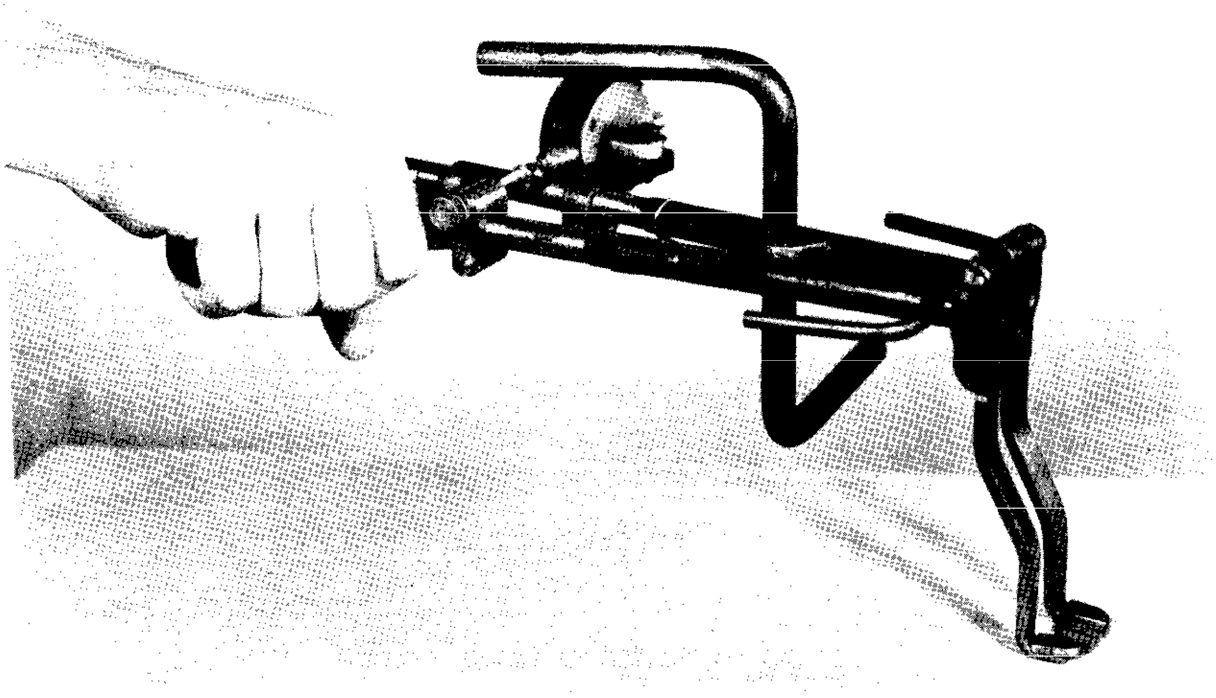


Fig. 5 - Photograph of Diameter Gage

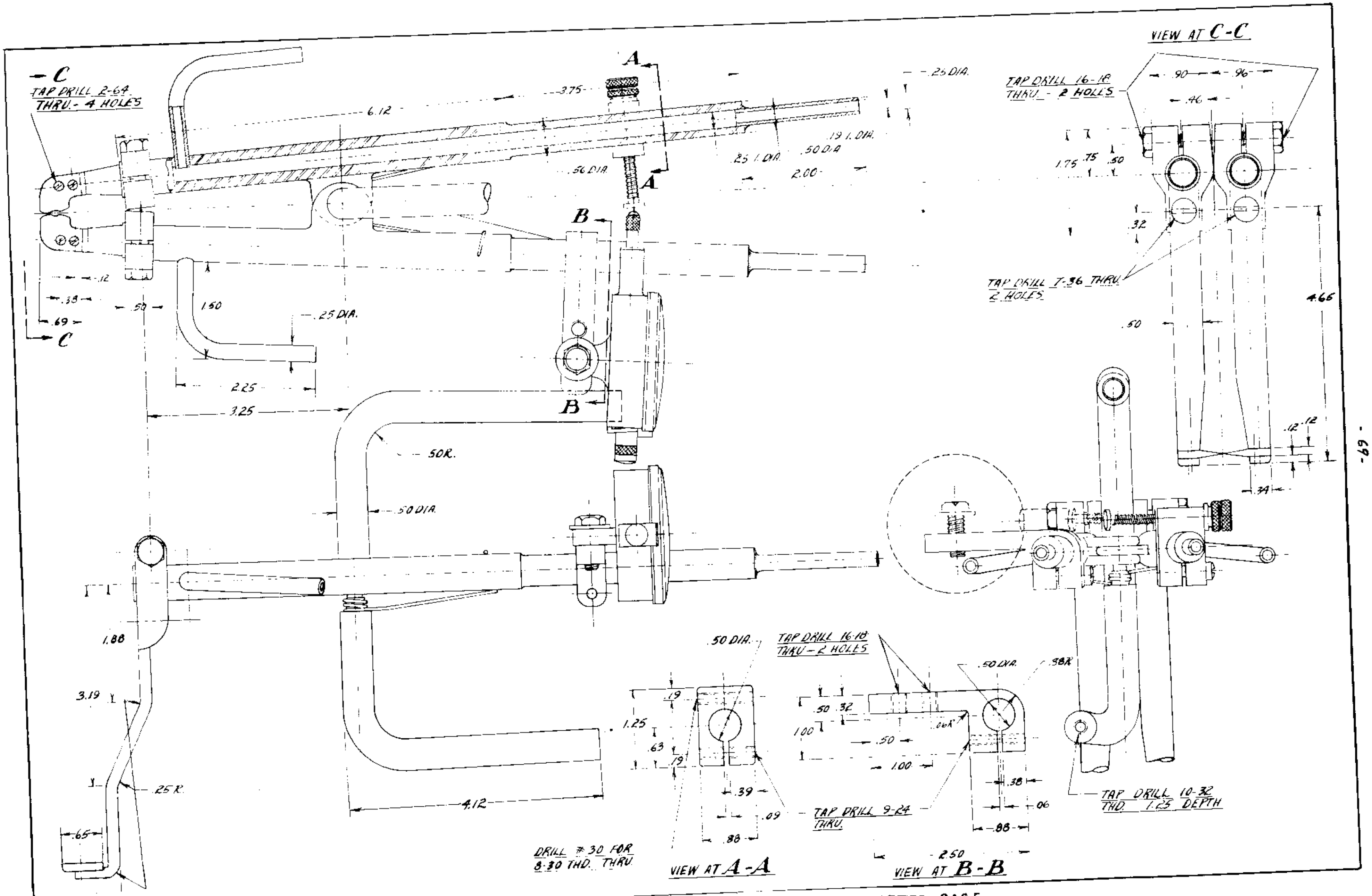


FIG. 6 LINE DRAWING OF DIAMETER GAGE.

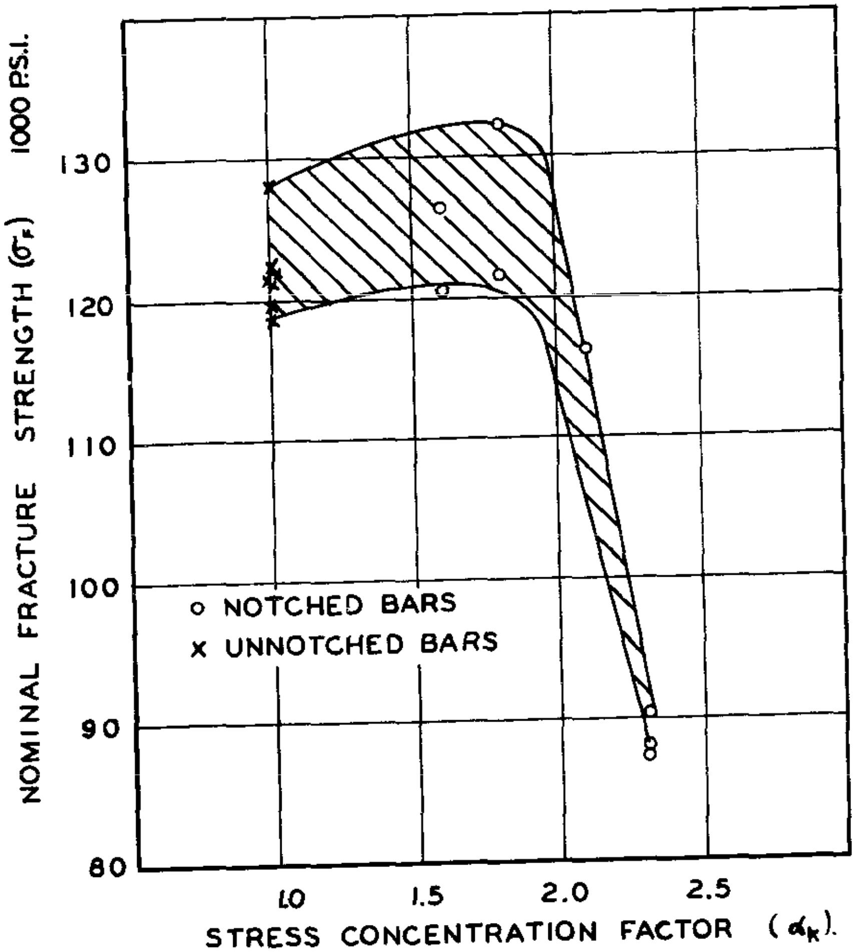
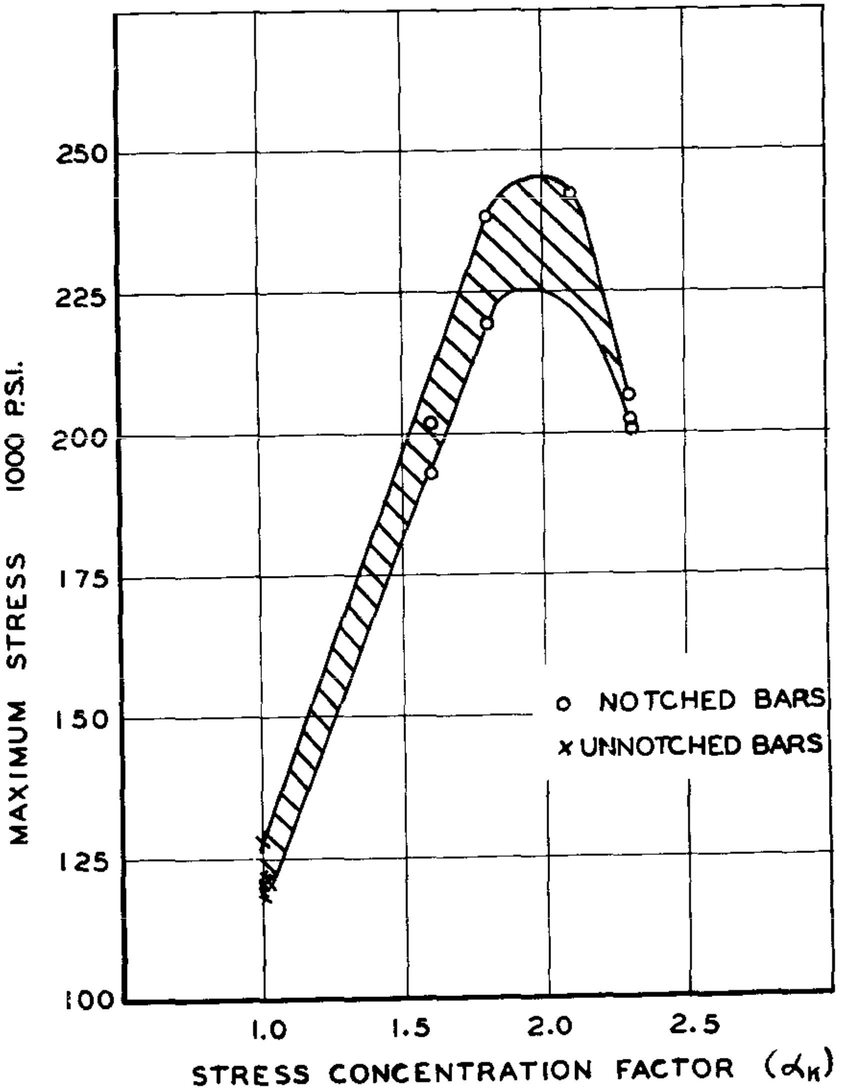


FIG. 7 FRACTURE STRENGTH OF NOTCHED BARS VERSUS STRESS CONCENTRATION FACTOR (α_k) – STEEL E
ALL FRACTURES WERE BRITTLE



MAXIMUM STRESS AT BRITTLE FRACTURE VERSUS STRESS CONCENTRATION FACTOR (α_k), STEEL E
FIG. 8

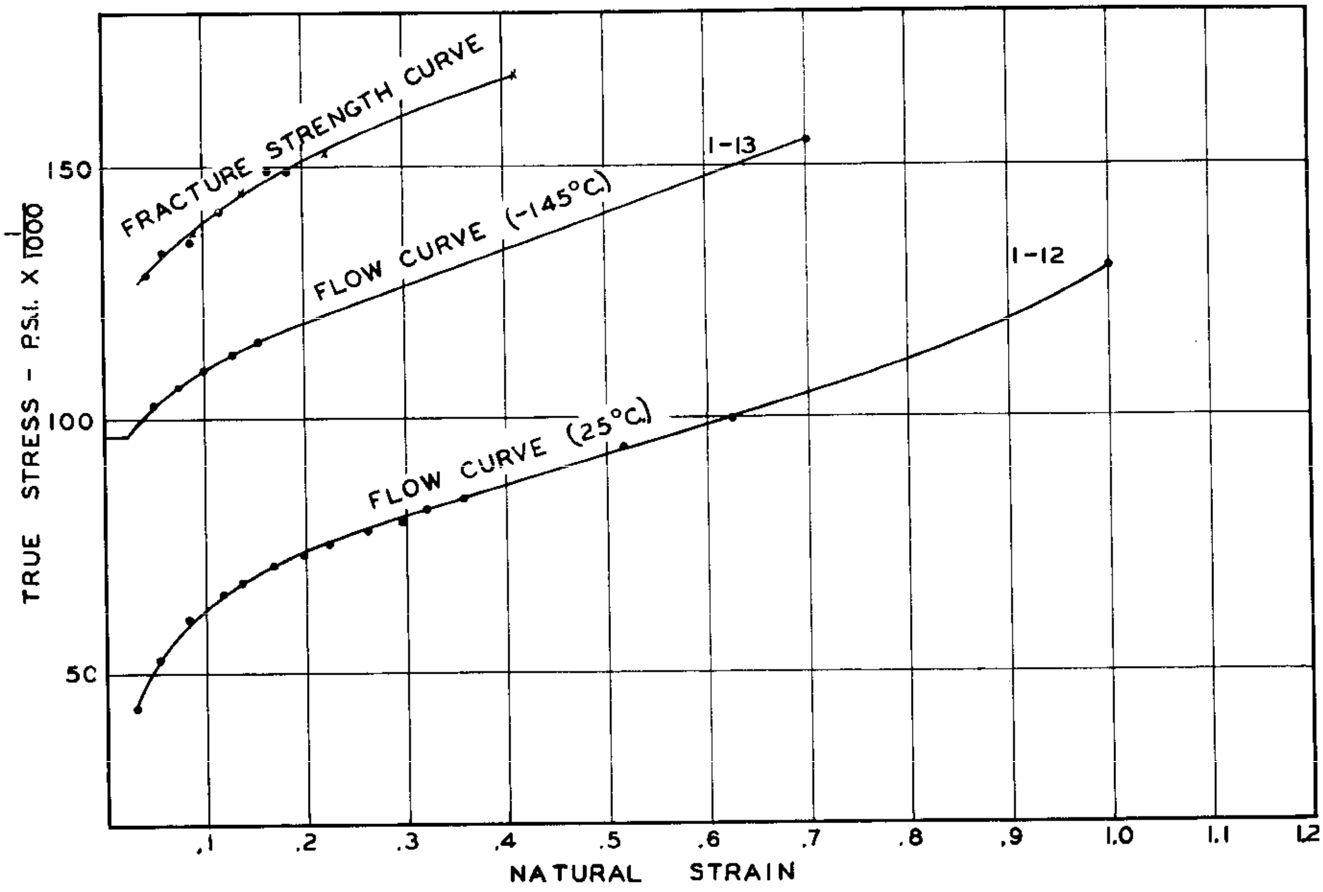


FIG. 9 SELECTED FRACTURE AND FLOW STRENGTH CURVES FOR STEEL C

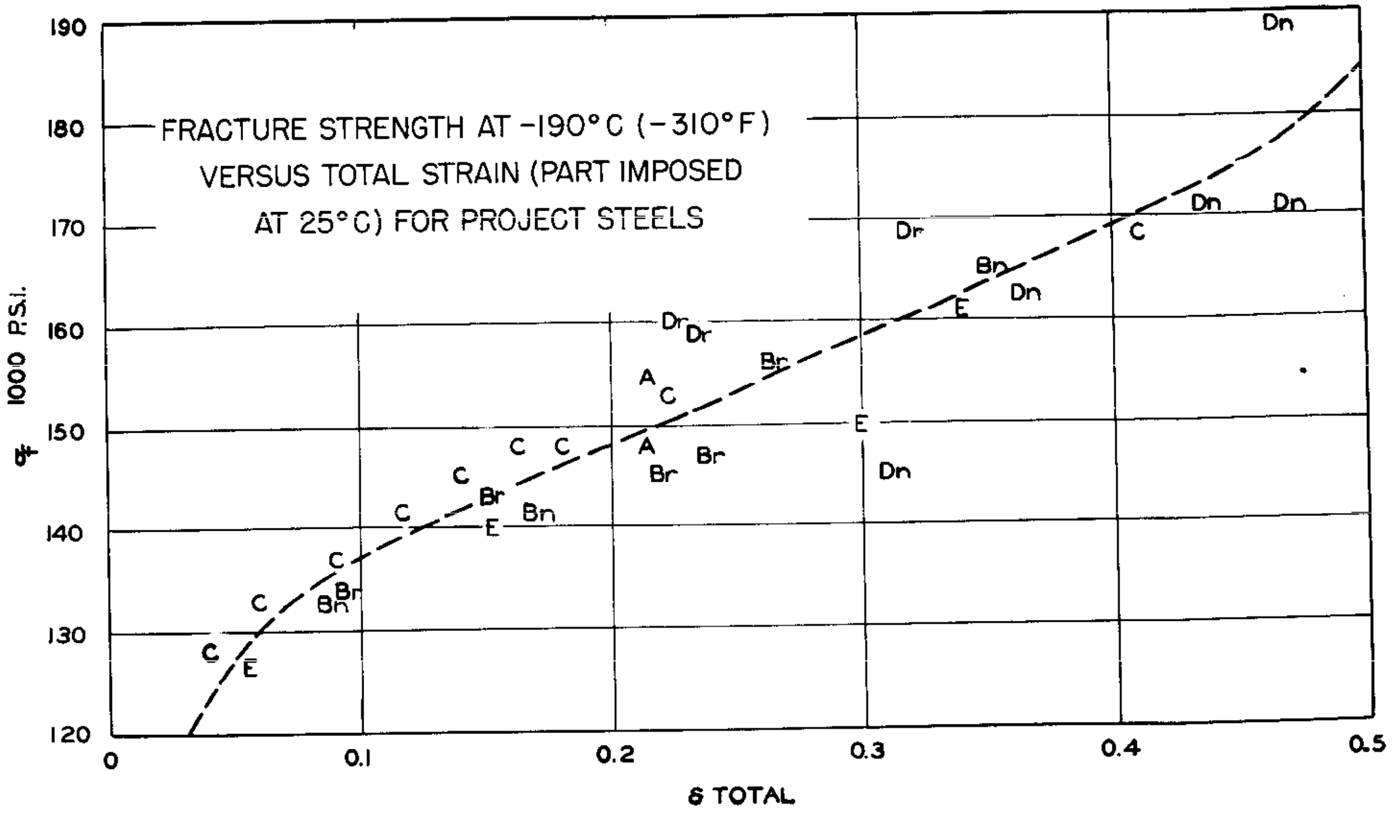
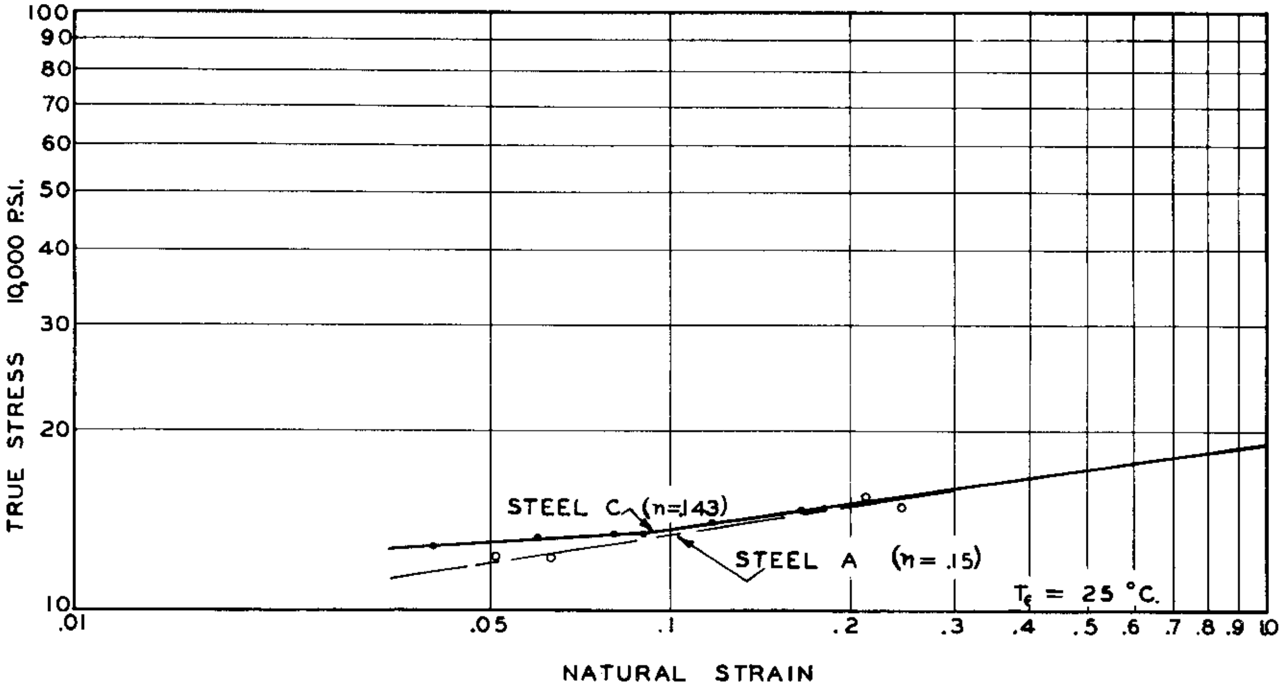
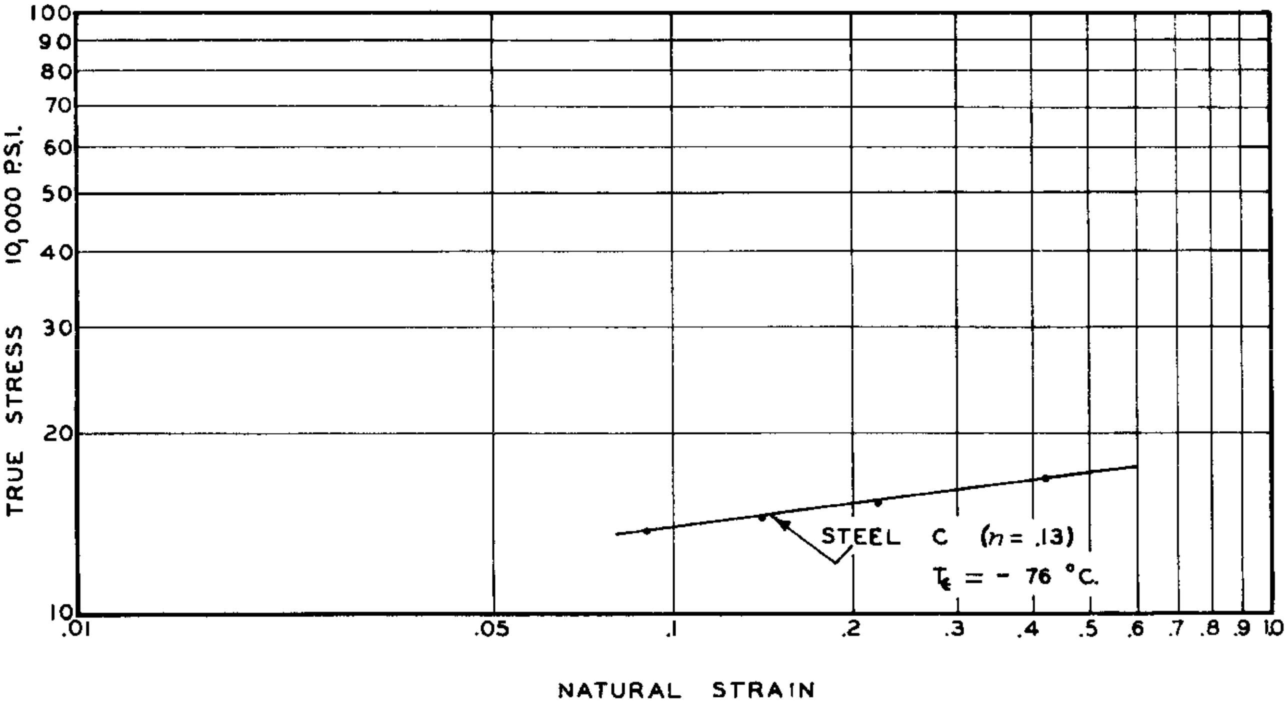


FIG 10



THE VARIATION OF FRACTURE STRENGTH AT -190°C
FOR PRESTRAIN AT 25°C — STEELS A, AND C
FIG. 11



THE VARIATION OF FRACTURE STRENGTH AT -190°C
FOR PRESTRAIN AT -76°C — STEEL C
FIG. 12

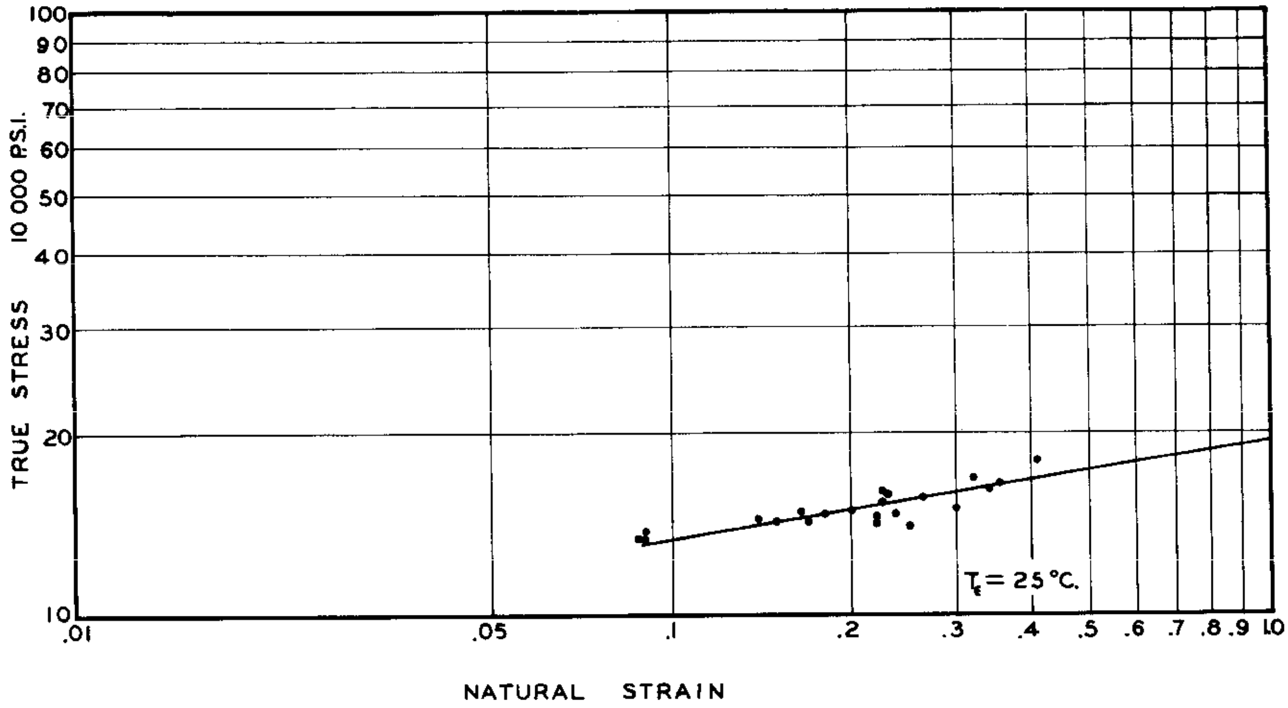
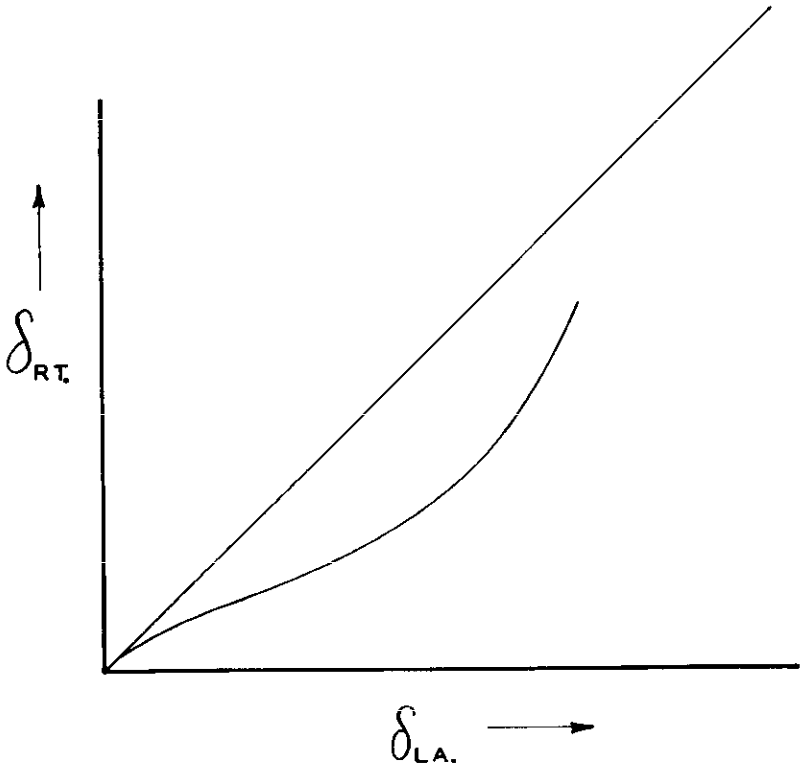
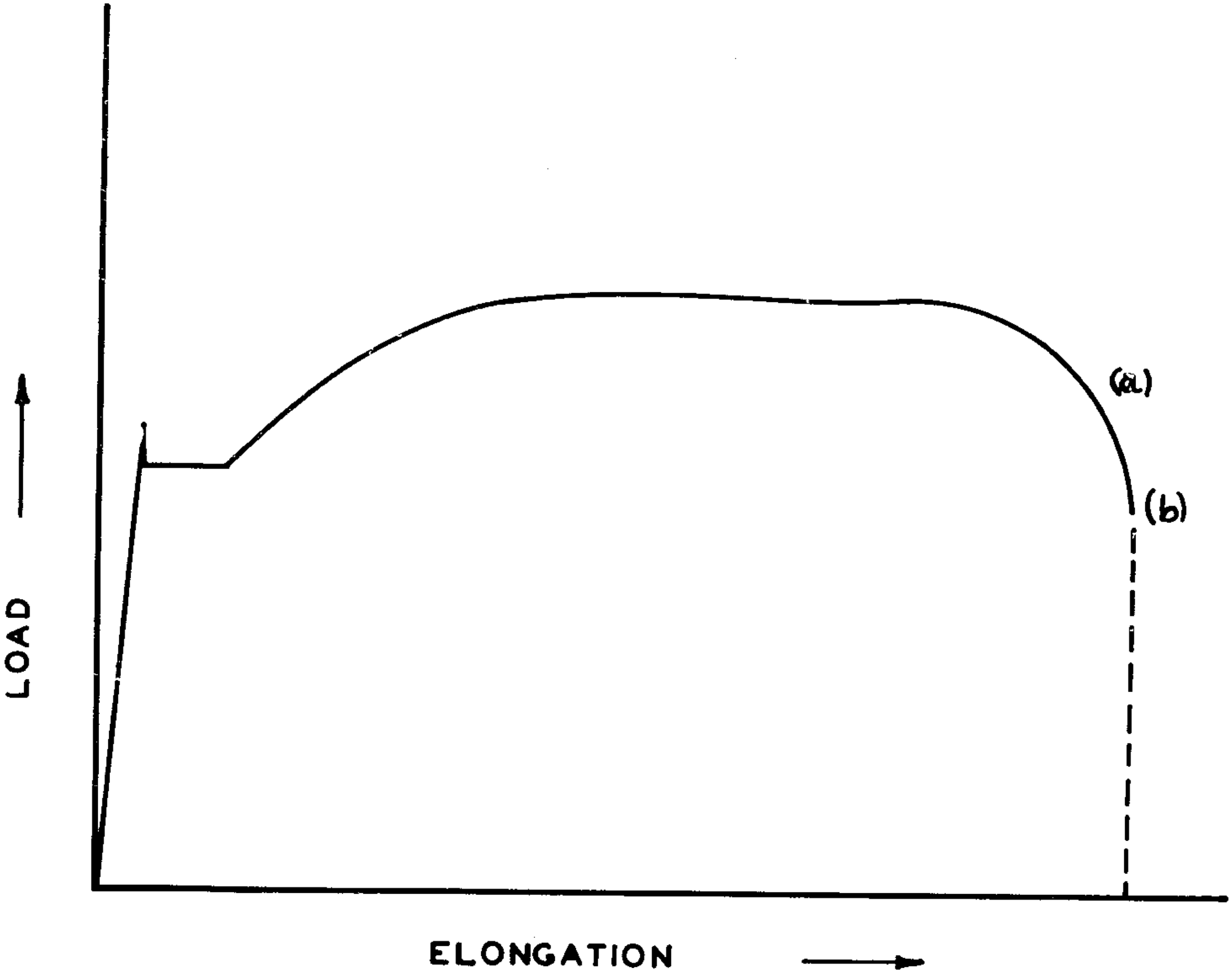


FIG. 13 THE DATA OF FIG. 10 ON Ln-Ln PLOT



EFFECT OF PRESTRAIN AT 25°C ON TOTAL STRAIN
AT −188°C. IDEALIZED AFTER SACHS (28)
FIG. 14



SCHEMATIC LOAD - ELONGATION CURVE

FIG. 15

Fig. 16 - Photomicrograph of Internal Crack in Tension Bar - Steel C. Location B. X 100.

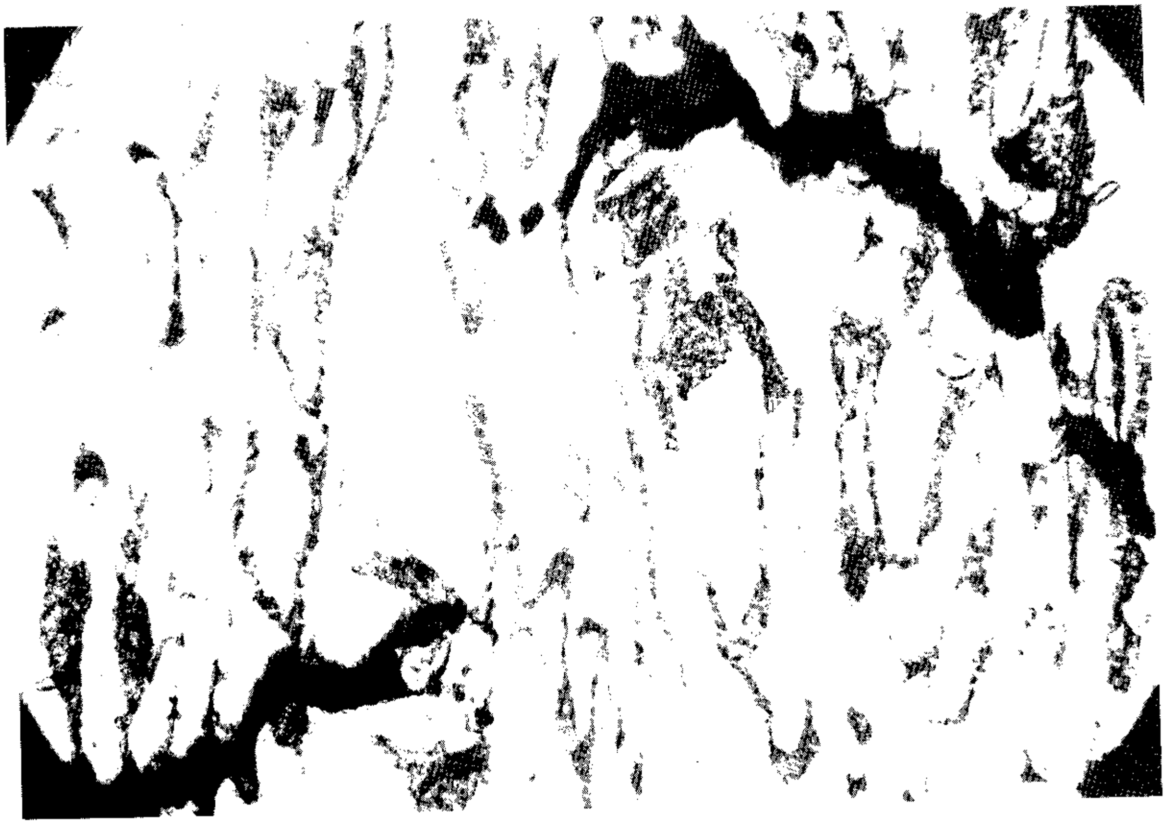


Fig. 17 - Photomicrographs of Internal Crack in Tension Bar - Steel C. Location B. X 250.

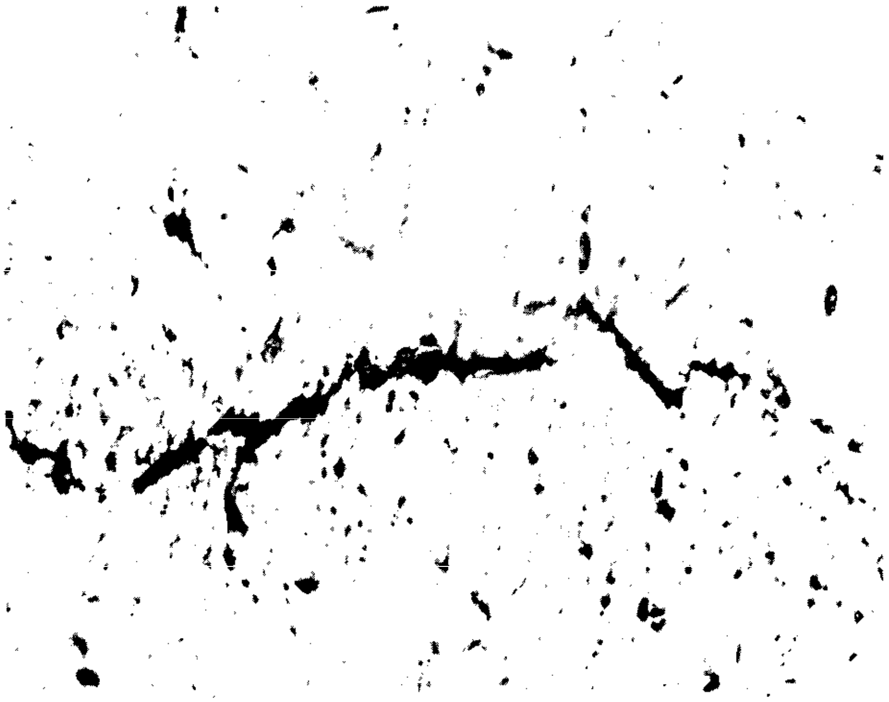


Fig. 18 - Photomicrograph of Internal Crack in Tension Bar - Steel C. Location C. X 100.

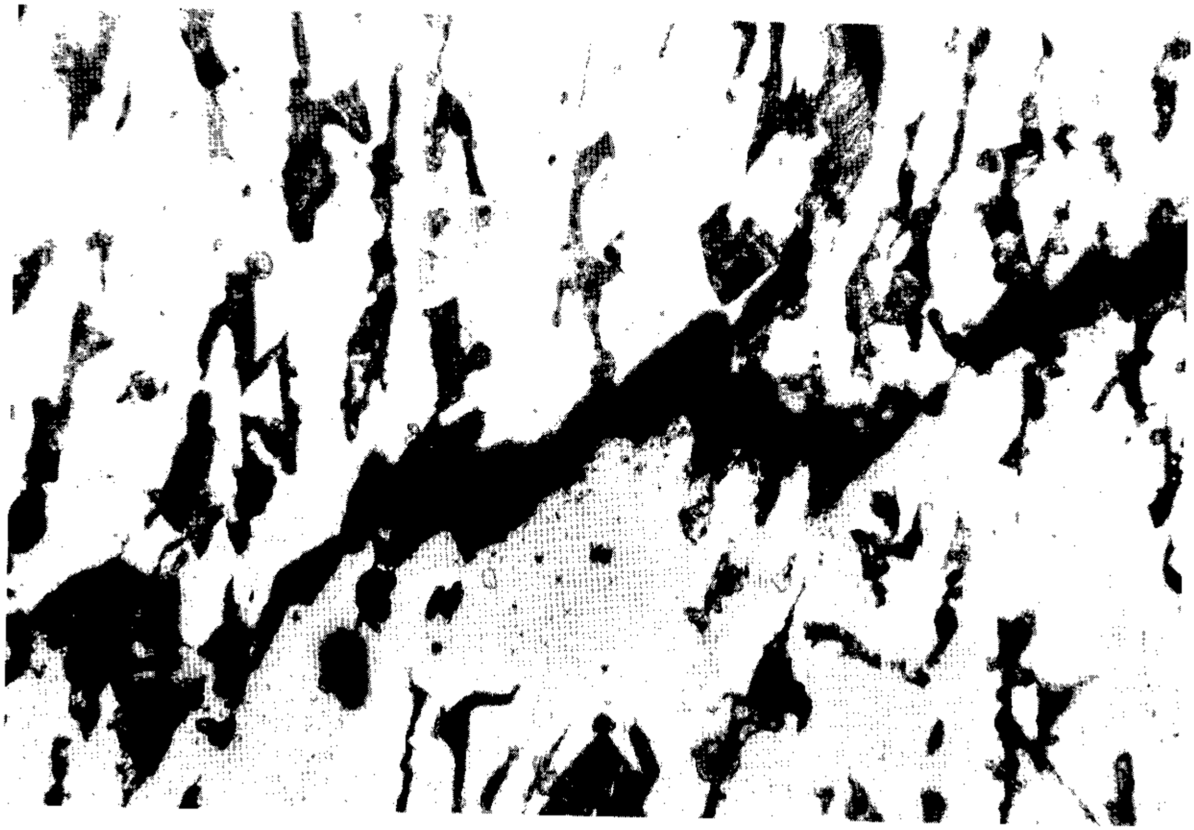


Fig. 19 - Photomicrograph of Internal Crack in Tension Bar - Steel C. Location C. X 250.

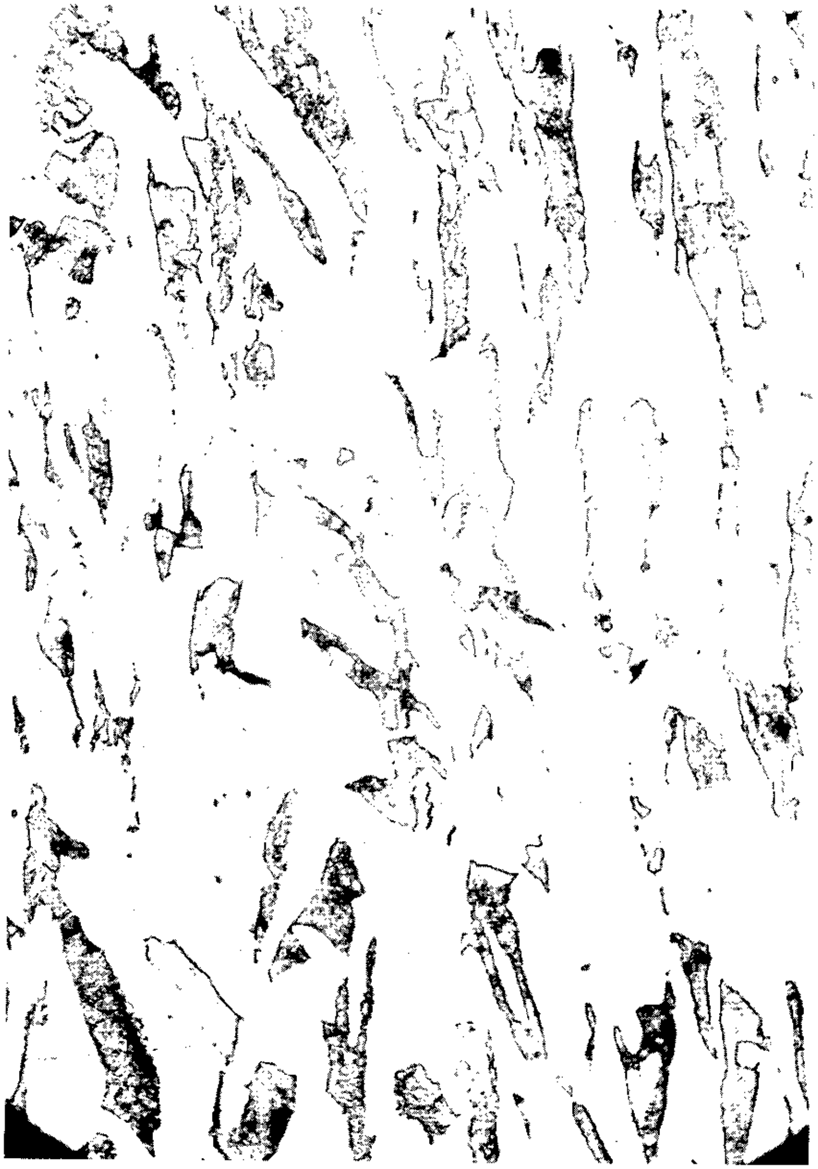


Fig. 20 - Photomicrograph of Plastic Distortion
Ahead of Crack in Tension Bar -
Steel C. Location A. X 250.

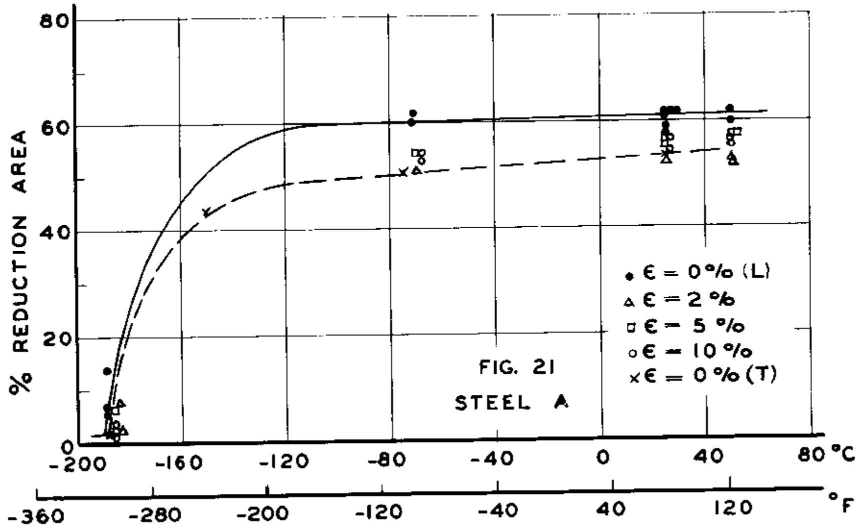


FIG. 21
STEEL A

THE PERCENT REDUCTION OF AREA AT FRACTURE VERSUS TEMPERATURE - STEEL A

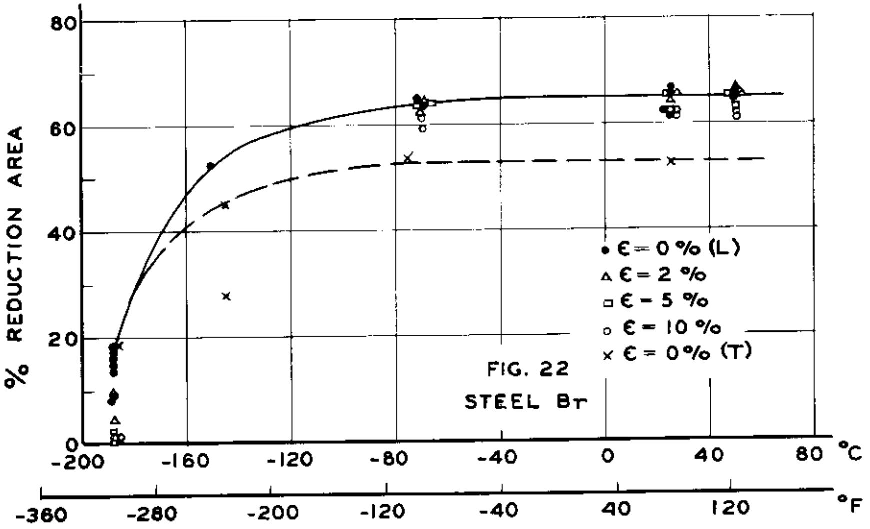


FIG. 22
STEEL Br

THE PERCENT REDUCTION OF AREA AT FRACTURE VERSUS TEMPERATURE - STEEL Br

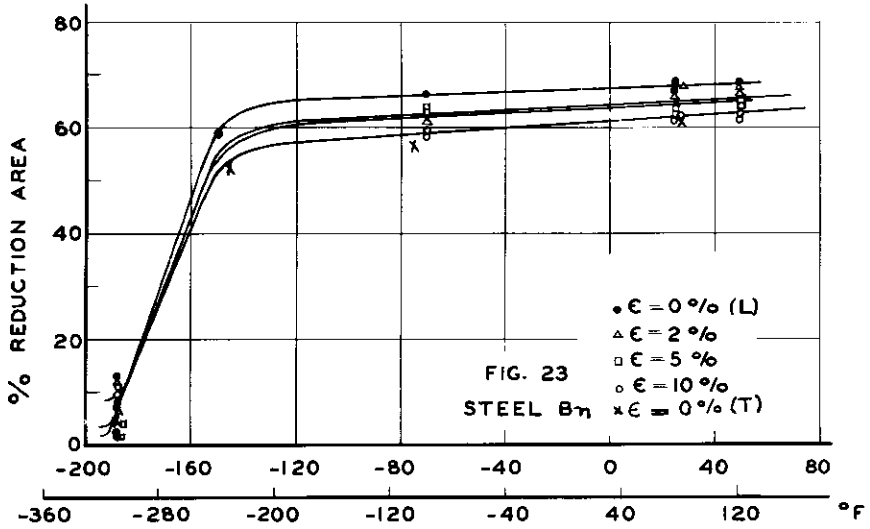


FIG. 23
STEEL Bn

THE PERCENT REDUCTION OF AREA AT FRACTURE VERSUS TEMPERATURE - STEEL Bn

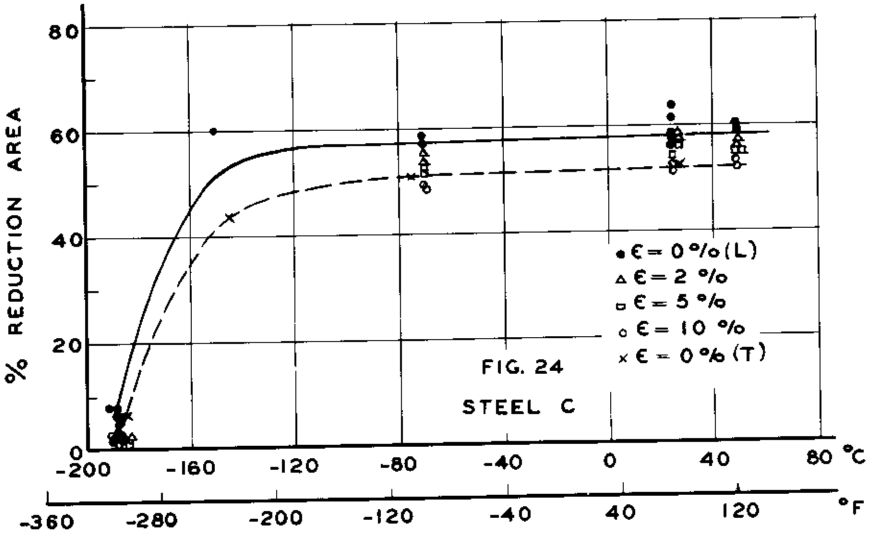


FIG. 24
STEEL C

THE PERCENT REDUCTION OF AREA AT FRACTURE VERSUS TEMPERATURE - STEEL C

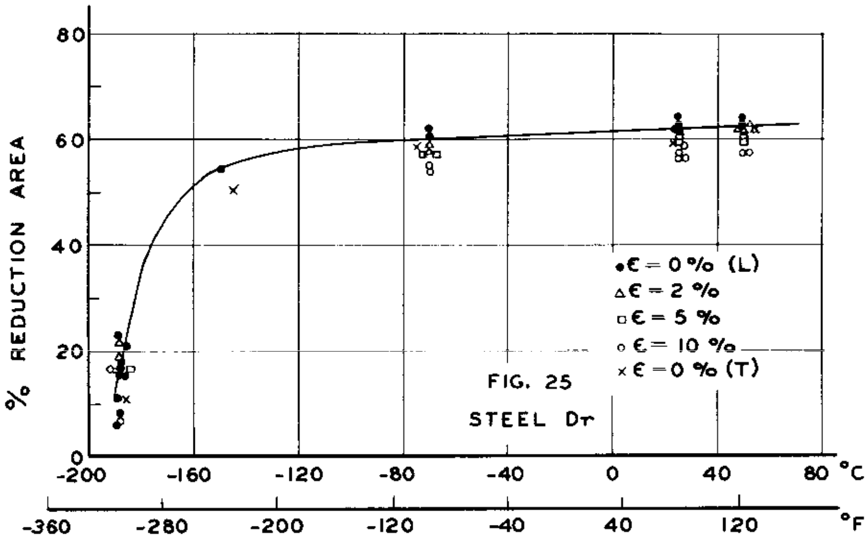


FIG. 25

STEEL Dr

THE PERCENT REDUCTION OF AREA AT FRACTURE
VERSUS TEMPERATURE - STEEL Dr

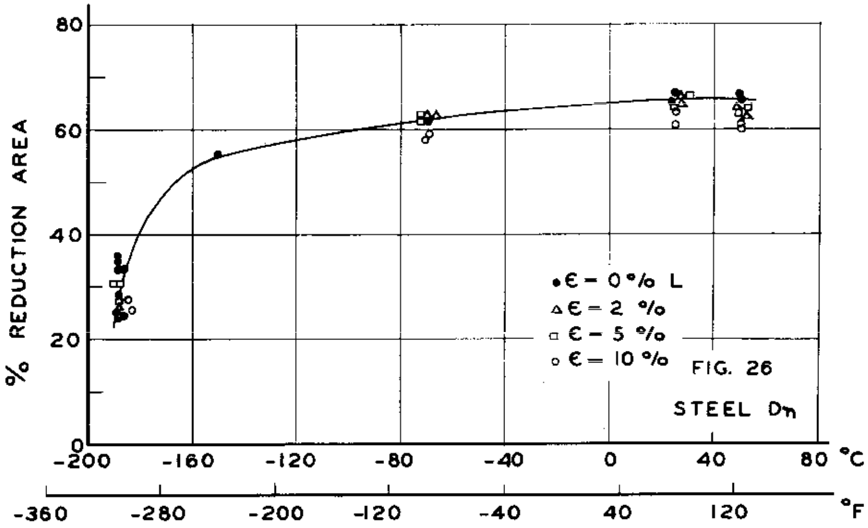


FIG. 26

STEEL Dn

THE PERCENT REDUCTION OF AREA AT FRACTURE
VERSUS TEMPERATURE - STEEL Dn

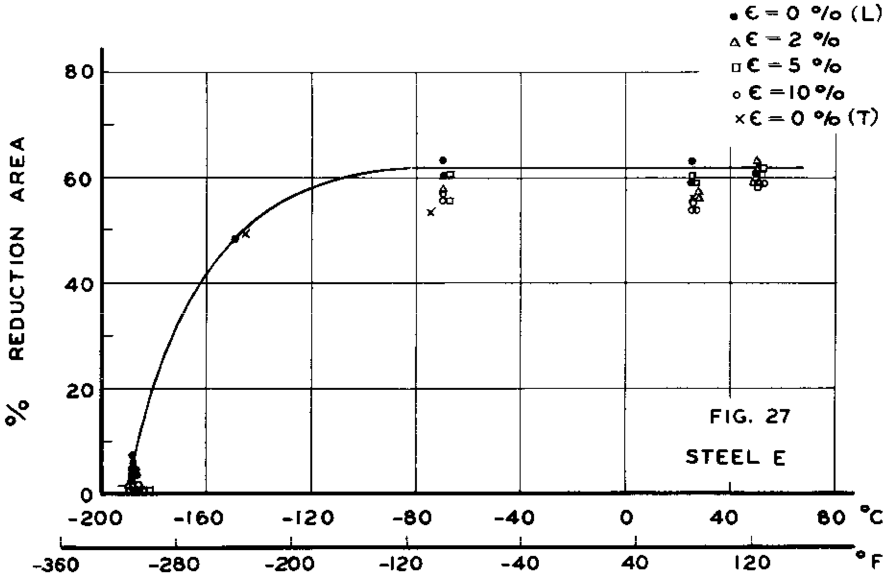


FIG. 27

STEEL E

THE PERCENT REDUCTION OF AREA AT FRACTURE
VERSUS TEMPERATURE - STEEL E

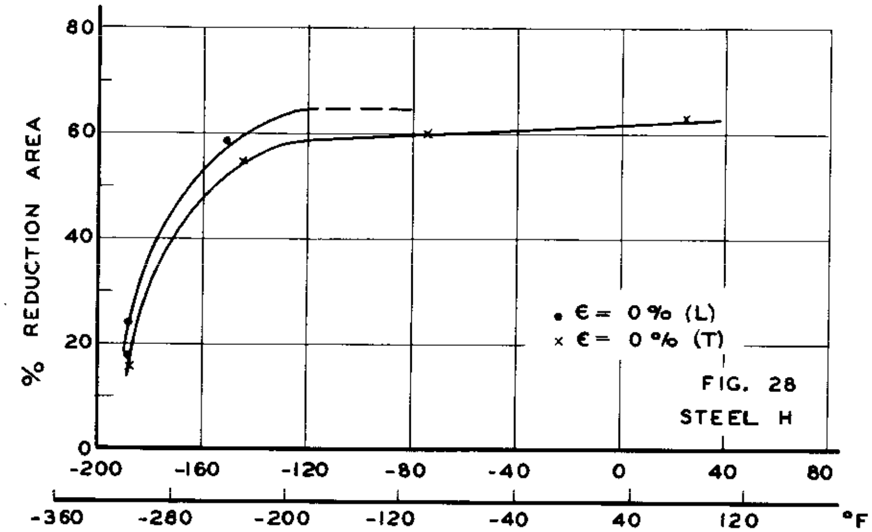
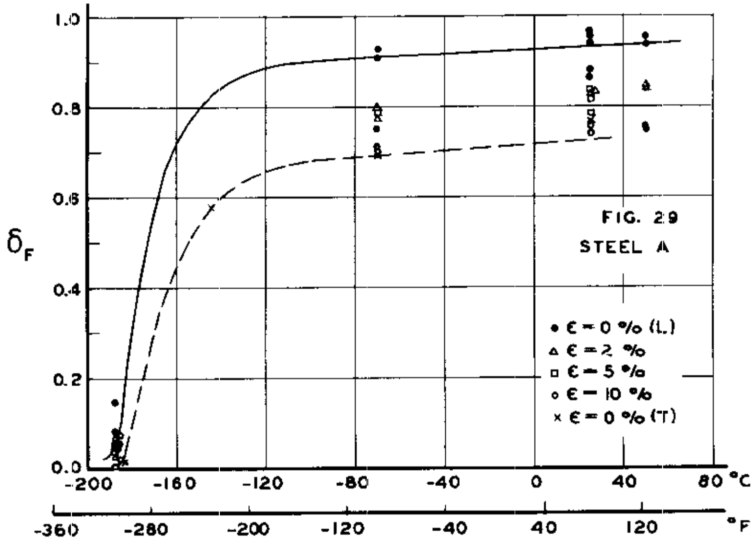


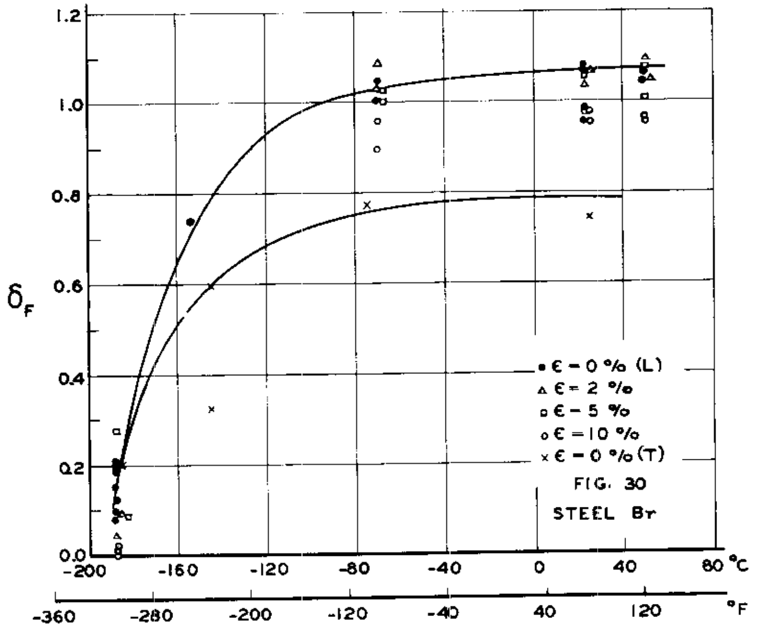
FIG. 28

STEEL H

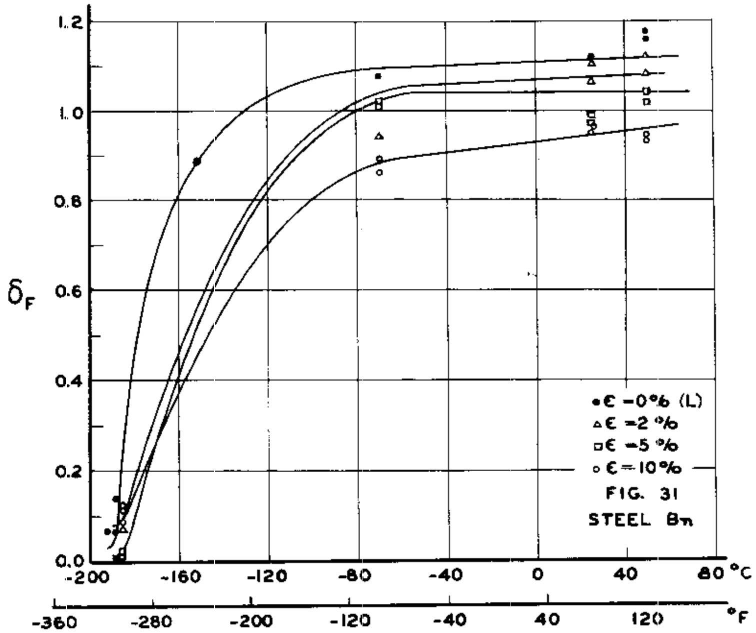
THE PERCENT REDUCTION OF AREA AT FRACTURE
VERSUS TEMPERATURE - STEEL H



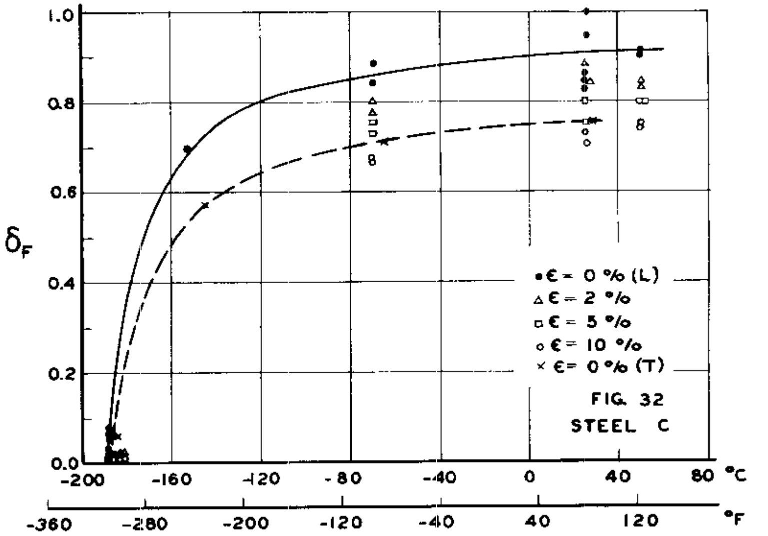
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL A



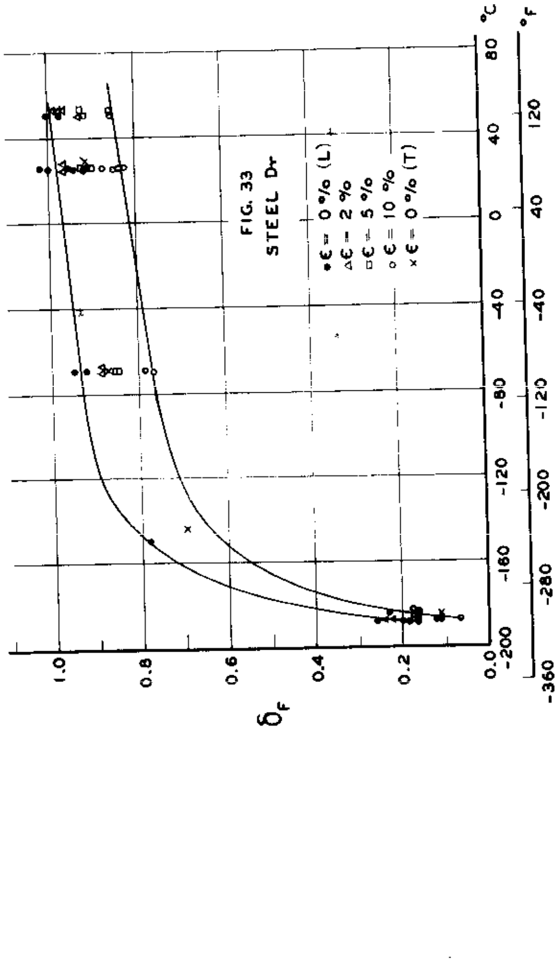
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL Br



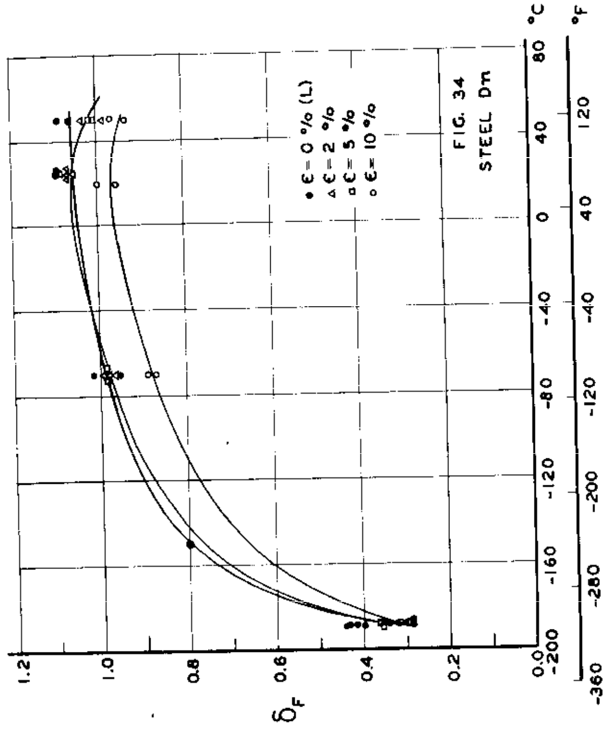
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL Bn



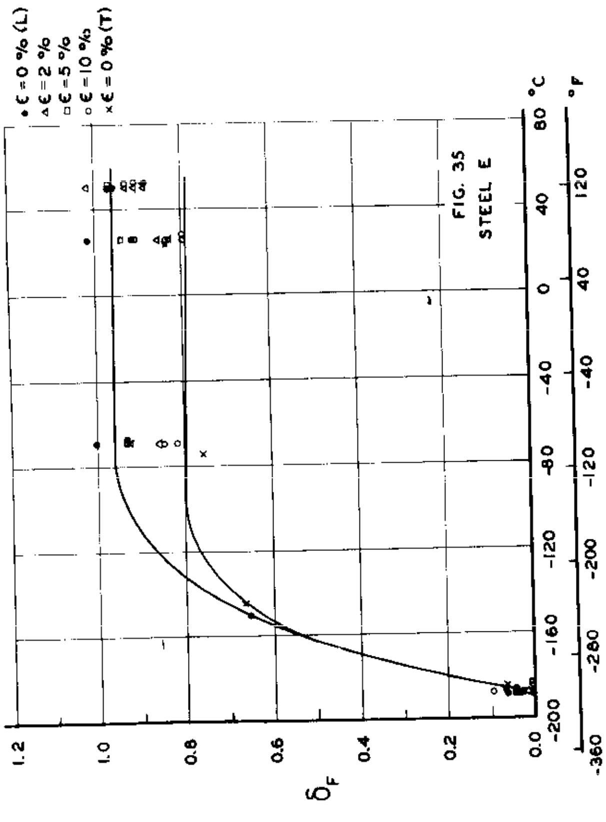
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL C



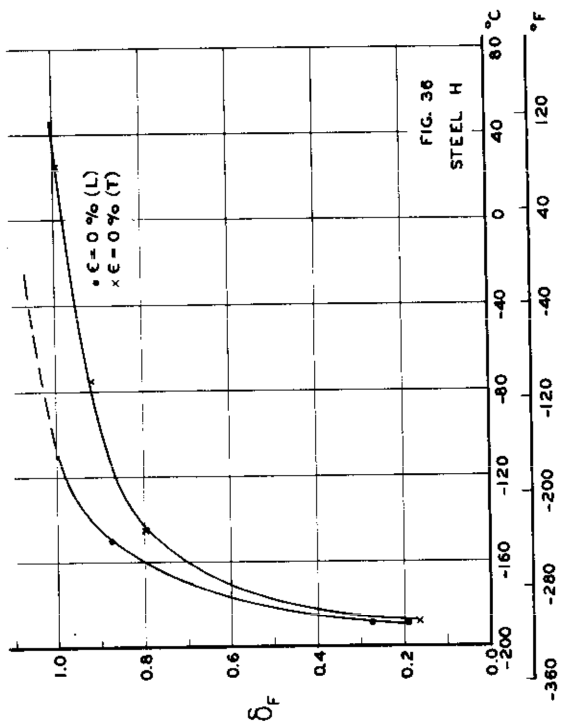
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL Dr



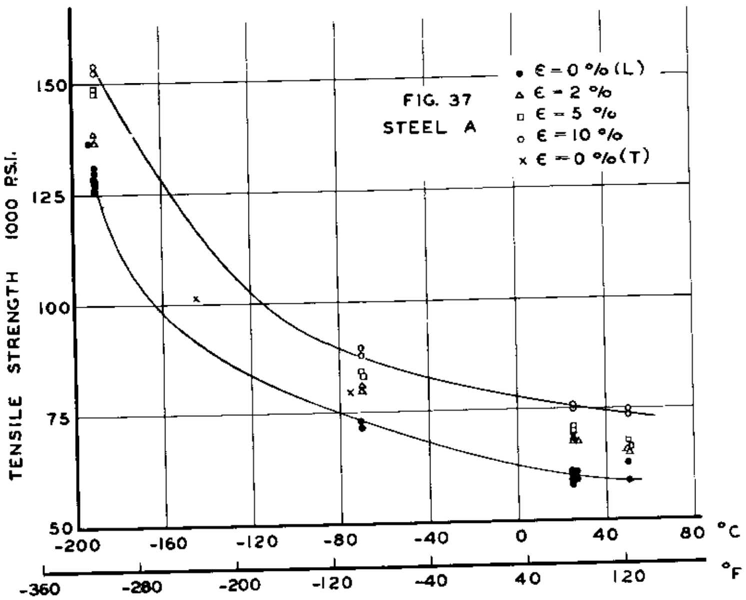
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL Dn



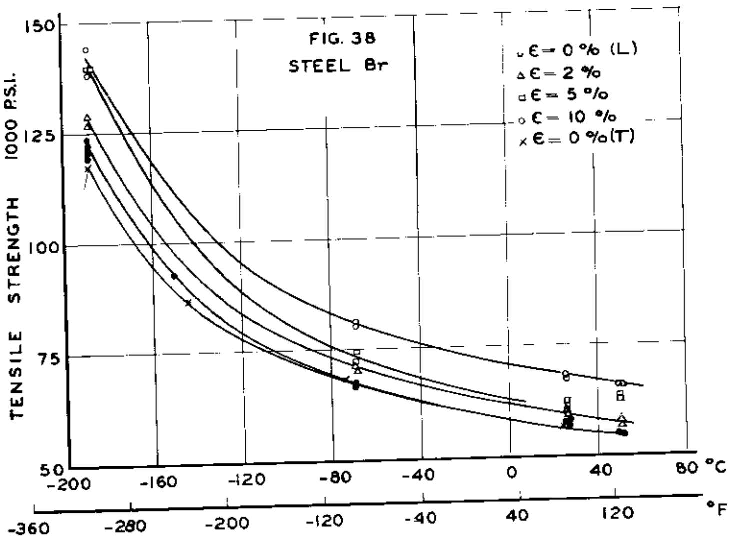
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL E



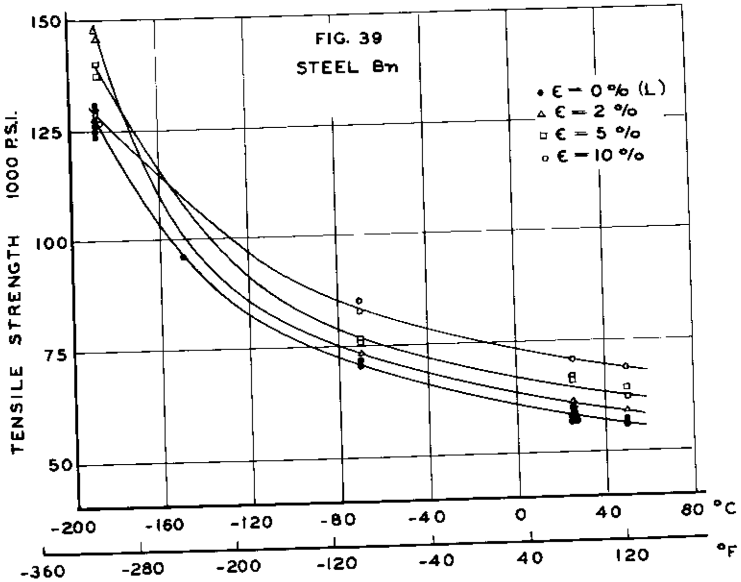
THE NATURAL STRAIN AT FRACTURE (δ_F) VERSUS TEMPERATURE - STEEL H



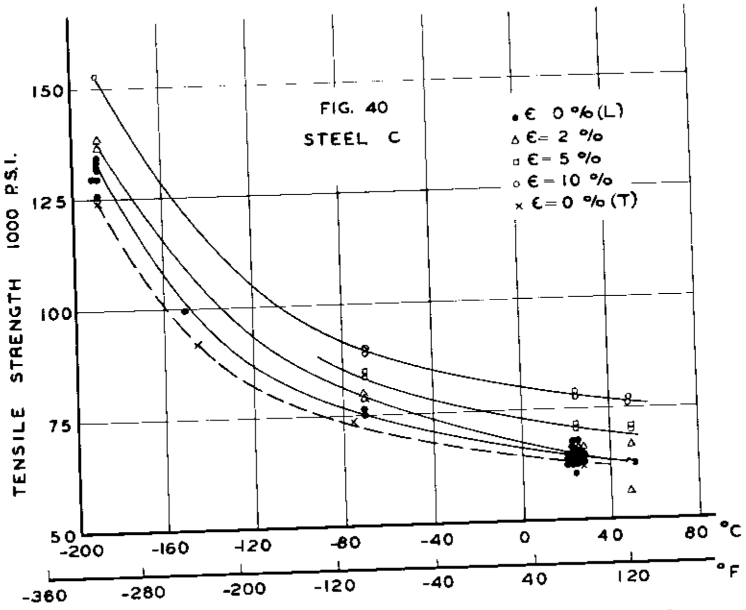
THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL A



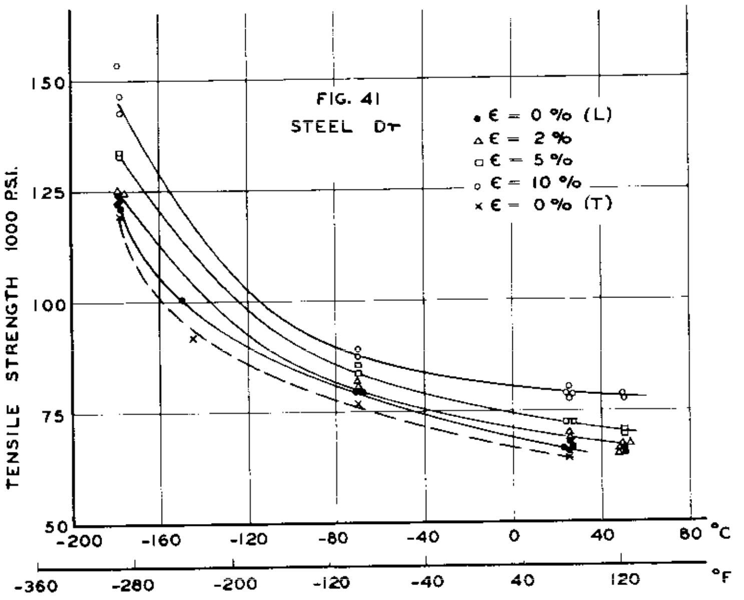
THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL Br



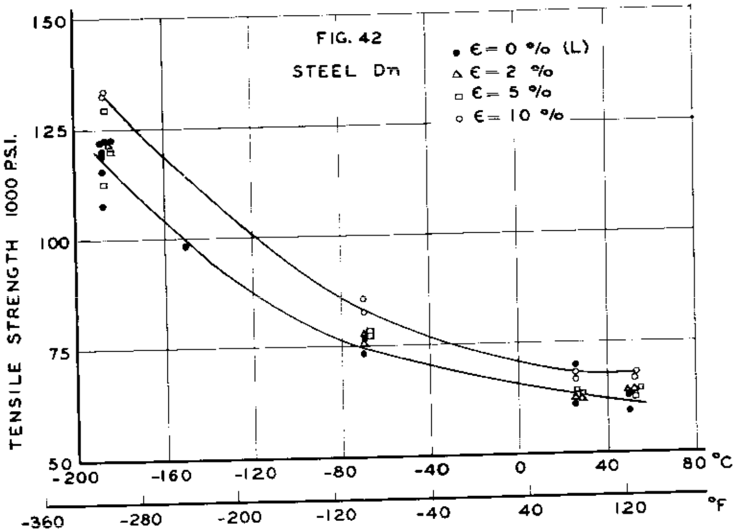
THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL Bn



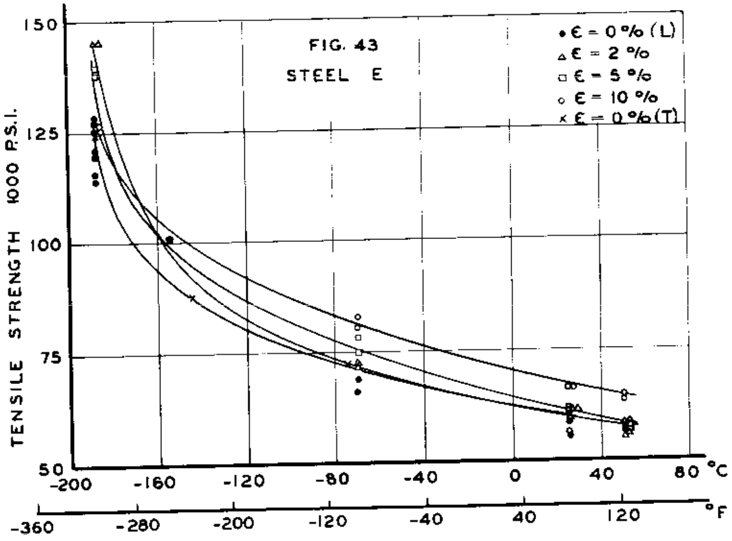
THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL C



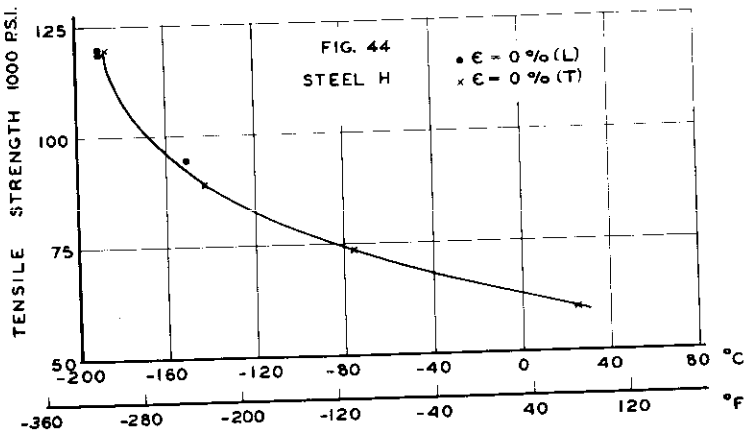
THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL Dr



THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL Dn



THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL E



THE TENSILE STRENGTH VERSUS TEMPERATURE – STEEL H

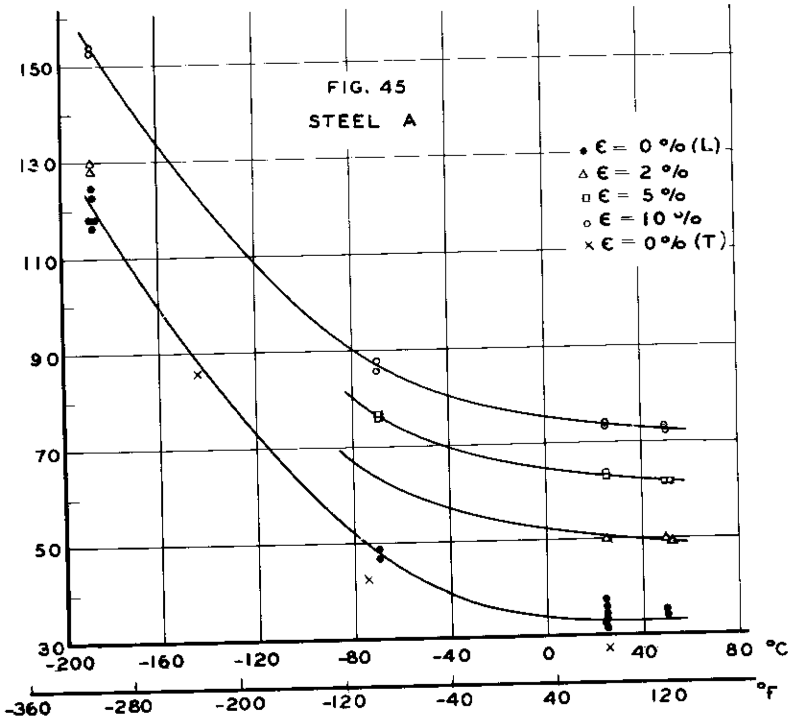


FIG. 45

STEEL A

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL A

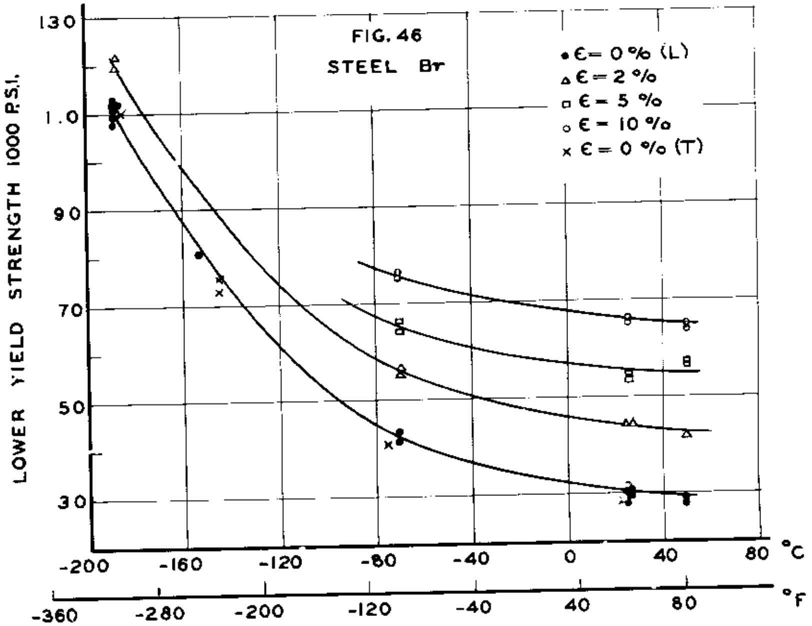


FIG. 46

STEEL Br

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL Br

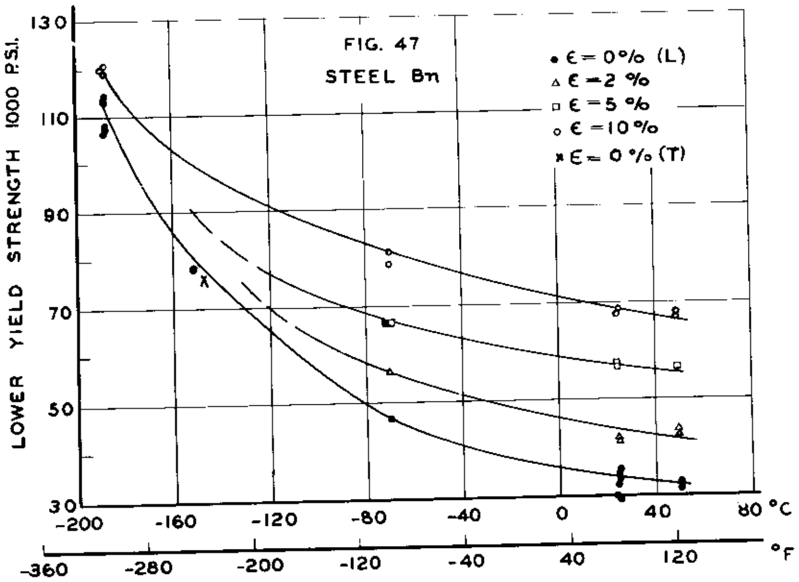


FIG. 47

STEEL Bn

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL Bn

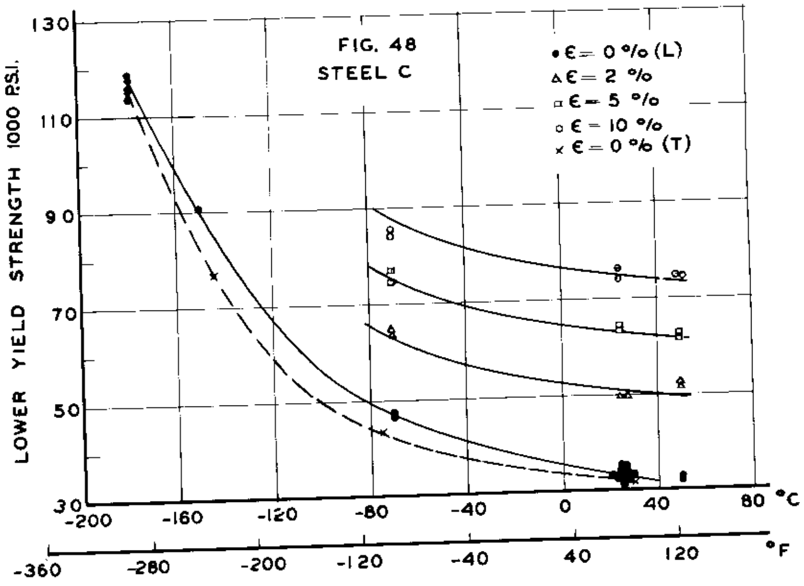


FIG. 48

STEEL C

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL C

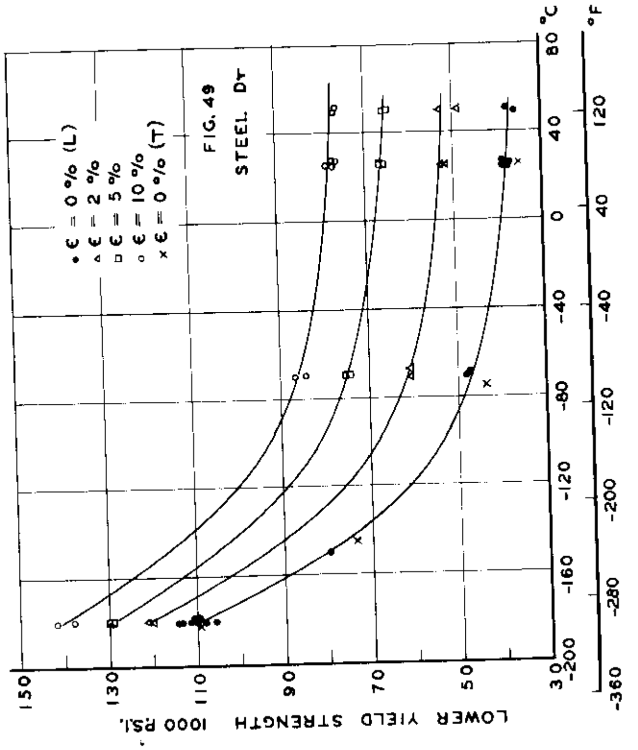


FIG. 49 STEEL Dr

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL Dr

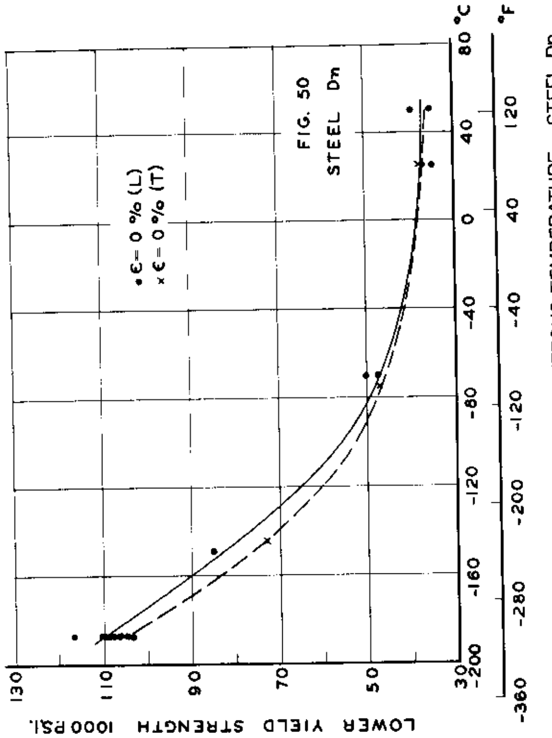


FIG. 50 STEEL Dn

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL Dn

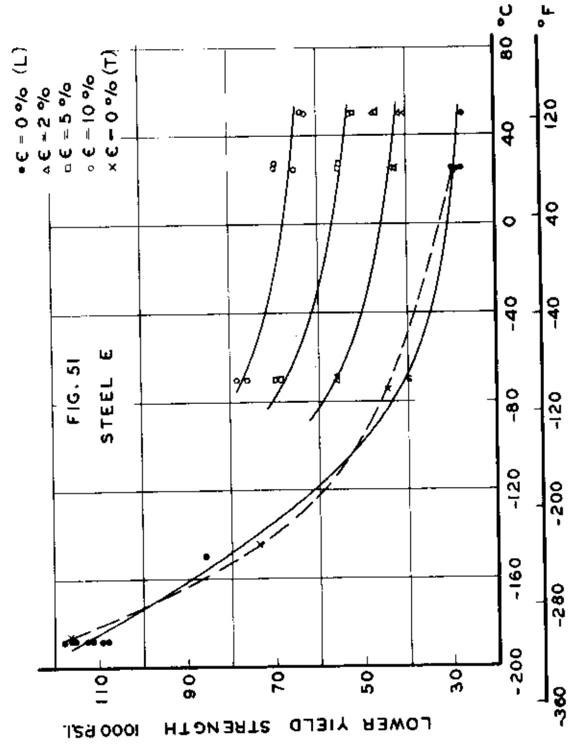


FIG. 51 STEEL E

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL E

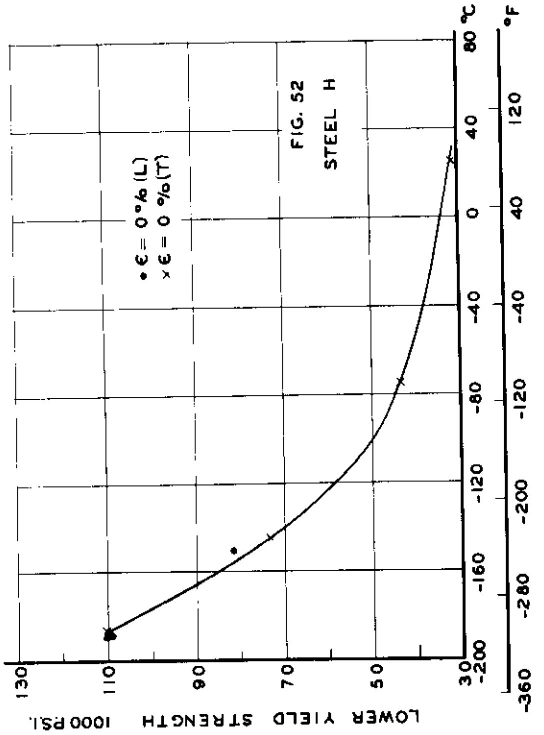


FIG. 52 STEEL H

THE LOWER YIELD STRENGTH VERSUS TEMPERATURE – STEEL H

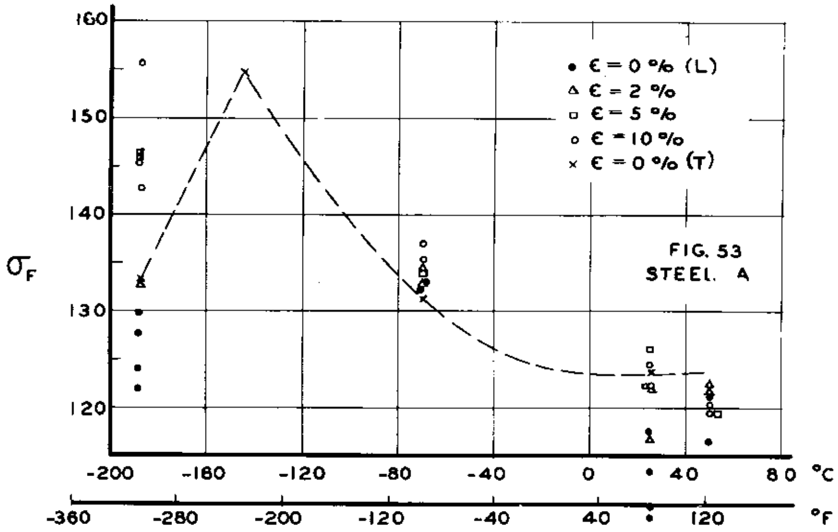


FIG. 53
STEEL A

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL A

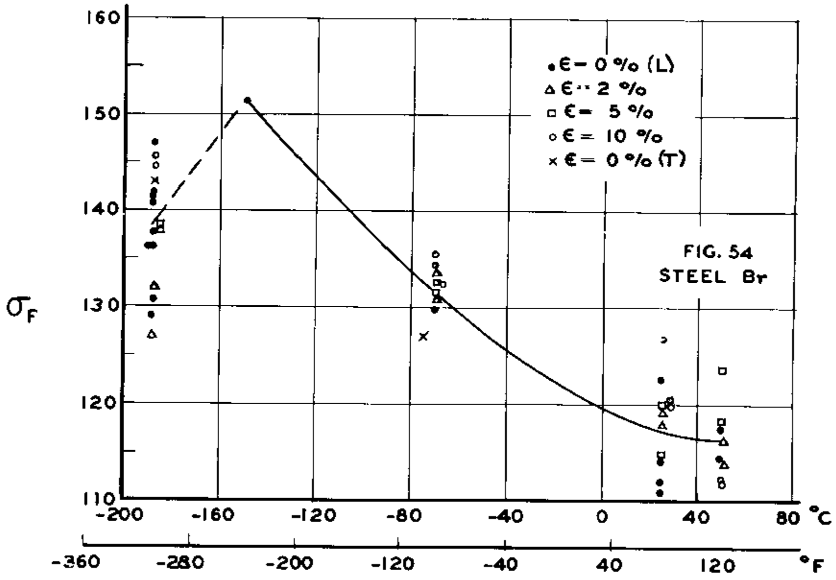


FIG. 54
STEEL Br

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL Br

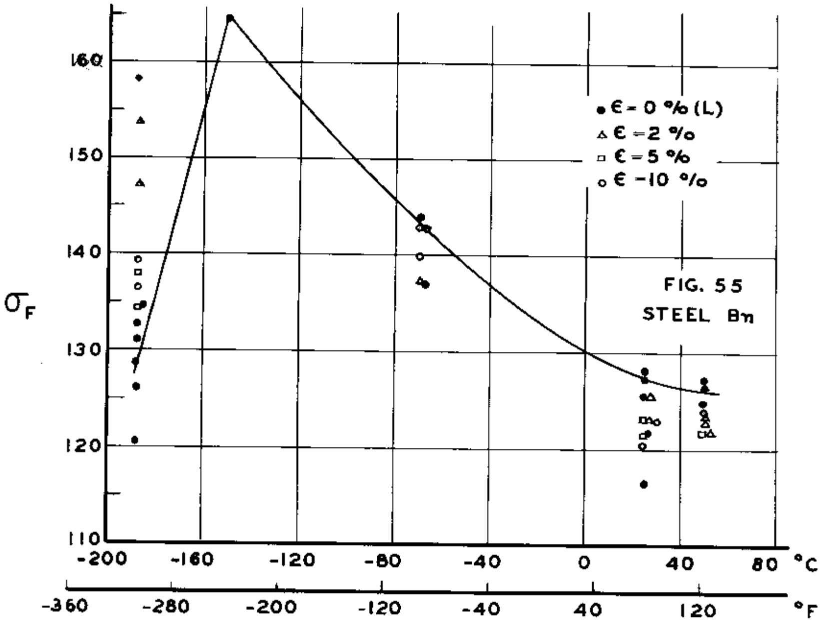


FIG. 55
STEEL Bn

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL Bn

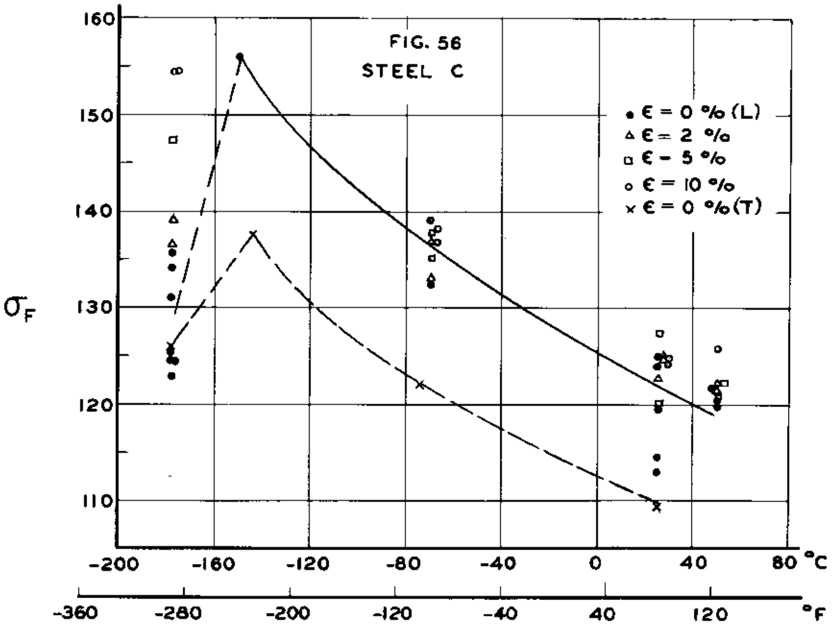


FIG. 56
STEEL C

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL C

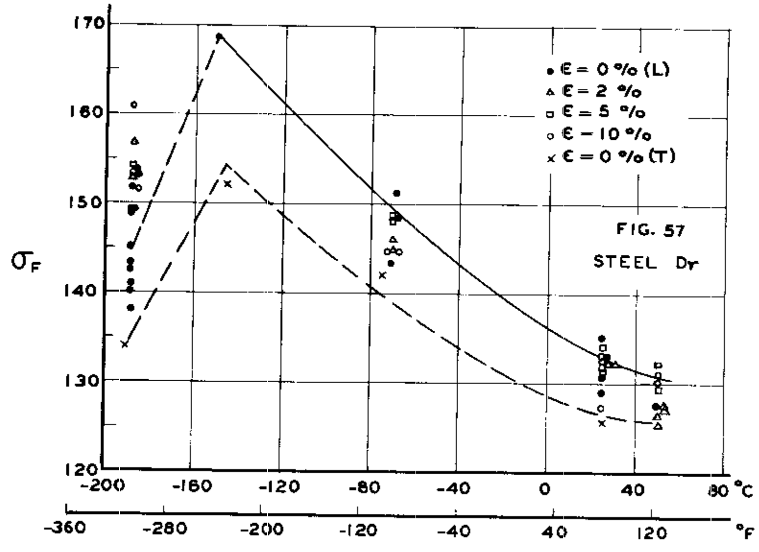


FIG. 57
STEEL Dr

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL Dr

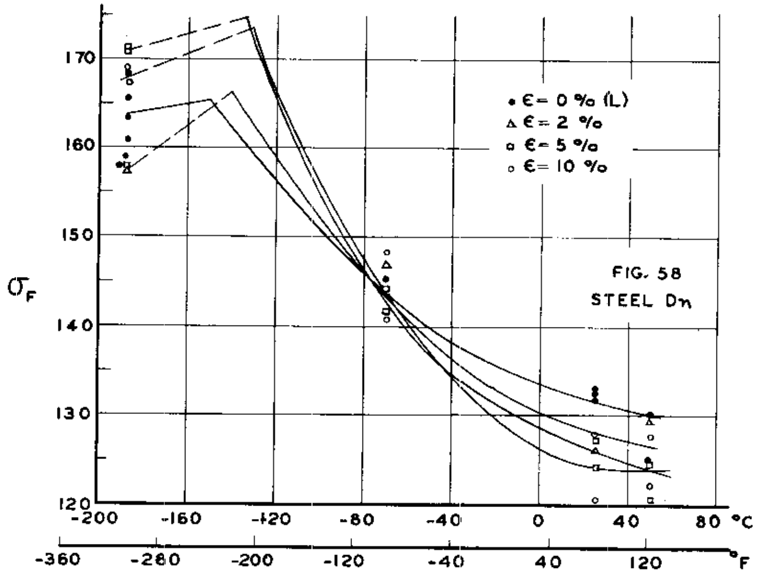


FIG. 58
STEEL Dn

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL Dn

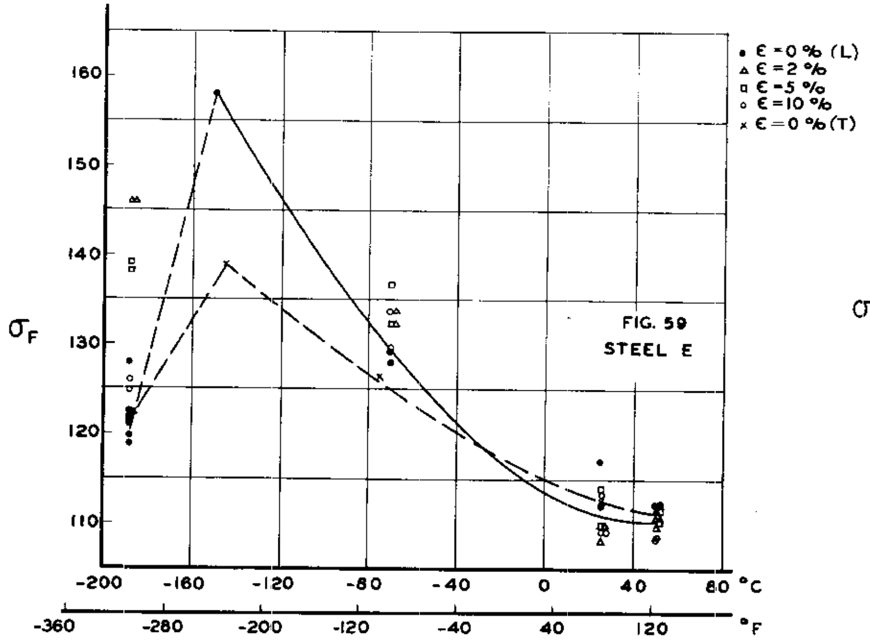


FIG. 59
STEEL E

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL E

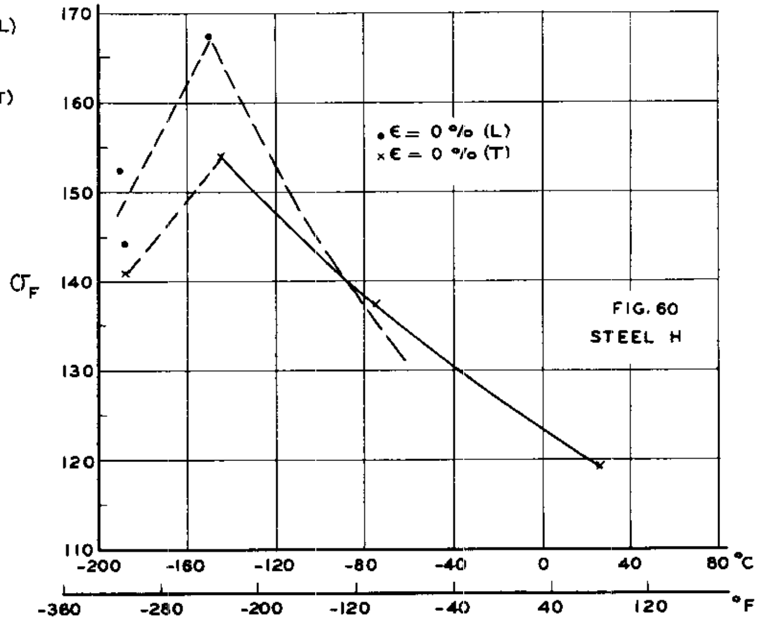


FIG. 60
STEEL H

THE FRACTURE STRENGTH (σ_F) VERSUS TEMPERATURE – STEEL H

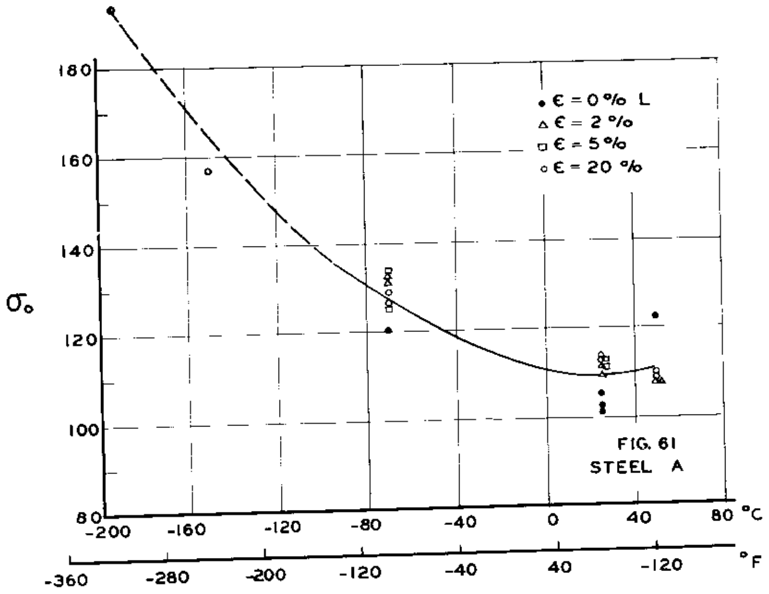


FIG. 61
STEEL A

THE STRENGTH COEFFICIENT (σ_o) VERSUS TEMPERATURE – STEEL A

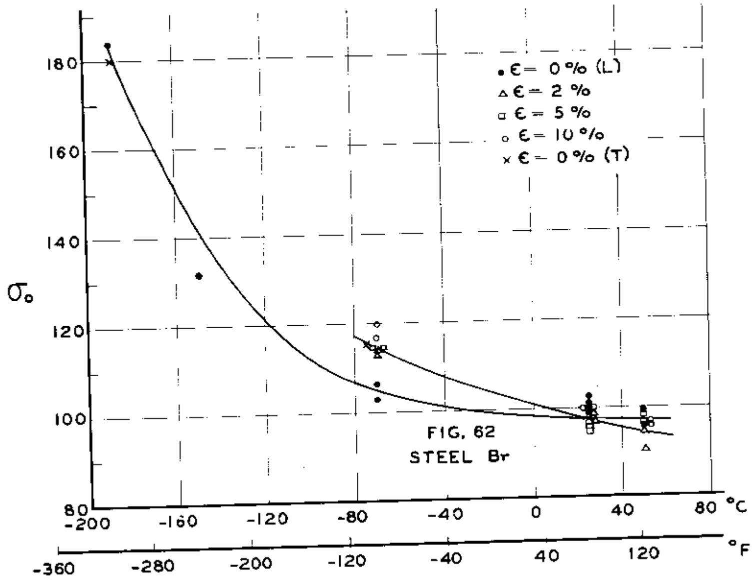


FIG. 62
STEEL Br

THE STRENGTH COEFFICIENT (σ_o) VERSUS TEMPERATURE – STEEL Br

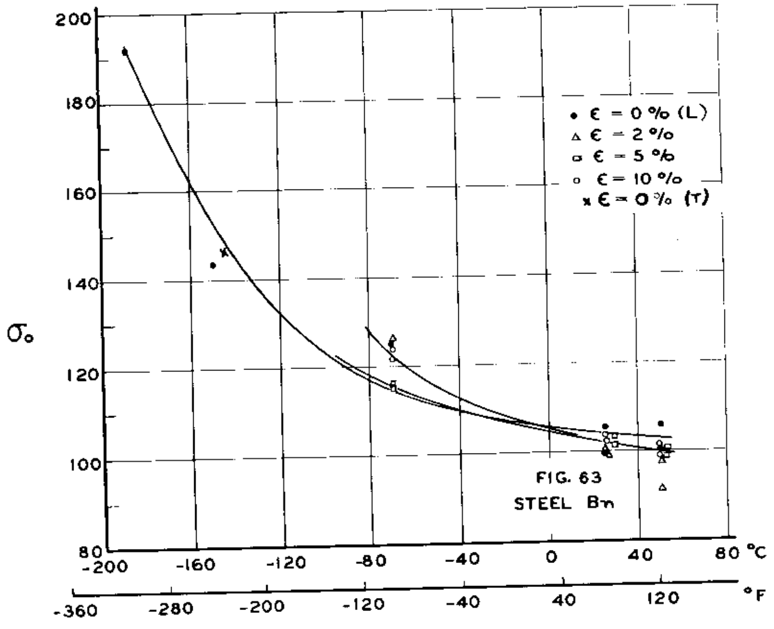


FIG. 63
STEEL Bn

THE STRENGTH COEFFICIENT (σ_o) VERSUS TEMPERATURE – STEEL Bn

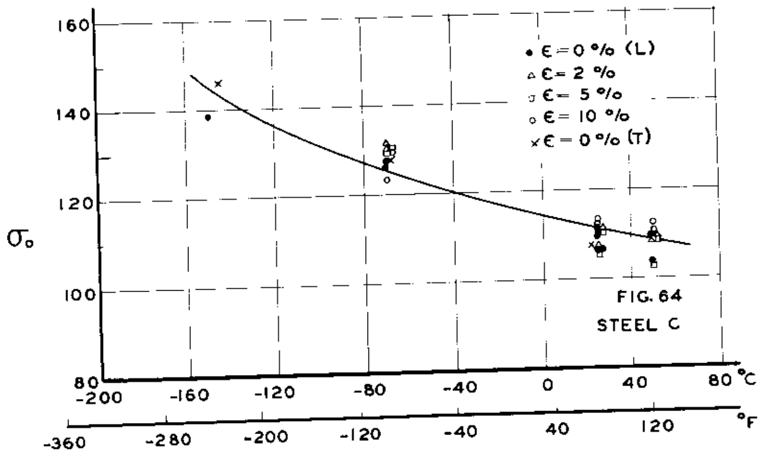


FIG. 64
STEEL C

THE STRENGTH COEFFICIENT (σ_o) VERSUS TEMPERATURE – STEEL C

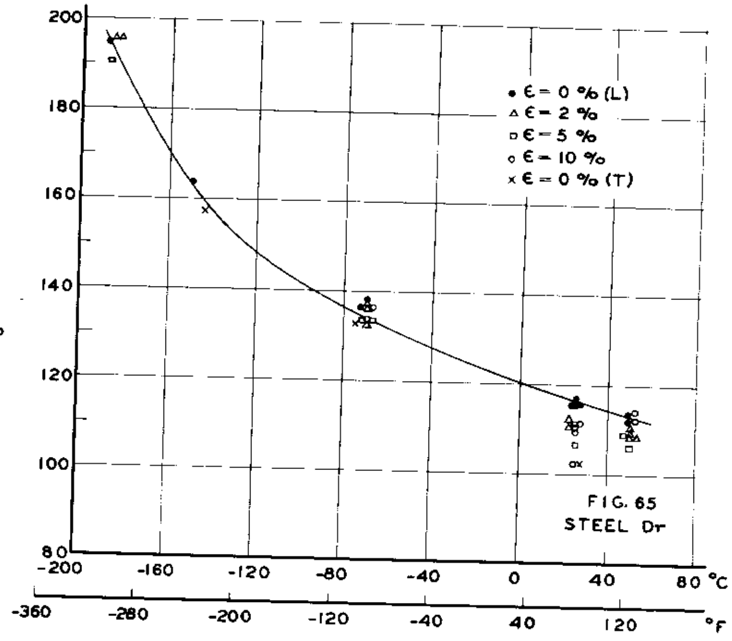


FIG. 65
STEEL Dr

THE STRENGTH COEFFICIENT (σ₀) VERSUS TEMPERATURE – STEEL Dr

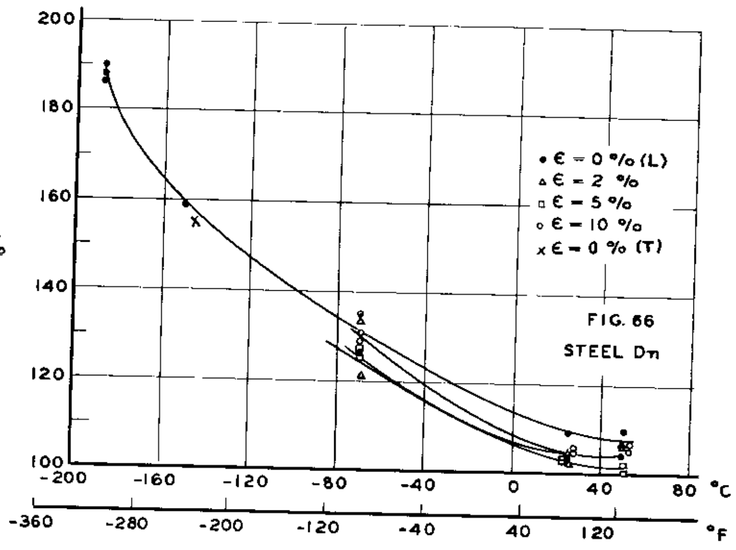


FIG. 66
STEEL Dn

THE STRENGTH COEFFICIENT (σ₀) VERSUS TEMPERATURE – STEEL Dn

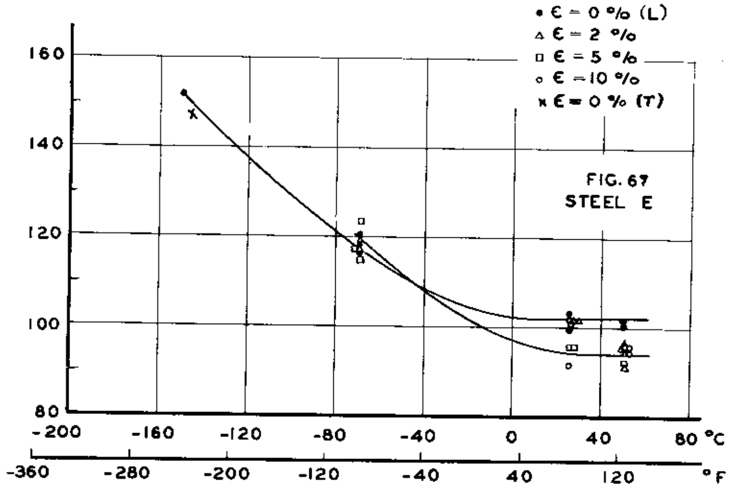


FIG. 67
STEEL E

THE STRENGTH COEFFICIENT (σ₀) VERSUS TEMPERATURE – STEEL E

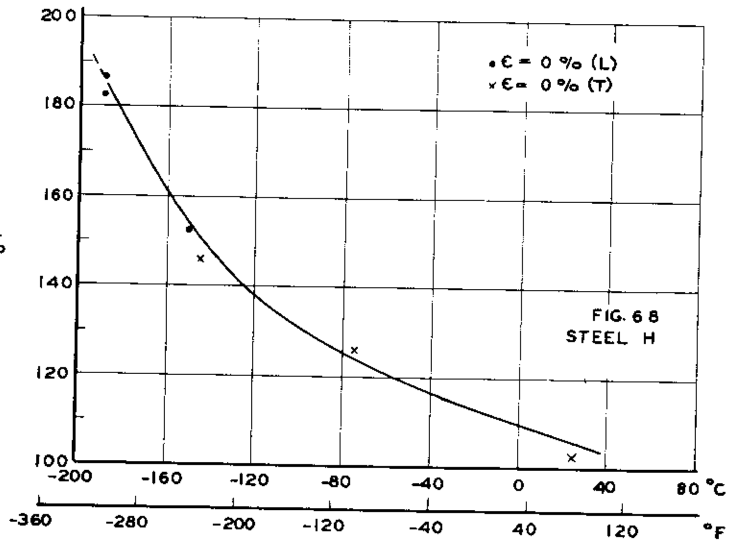


FIG. 68
STEEL H

THE STRENGTH COEFFICIENT (σ₀) VERSUS TEMPERATURE – STEEL H

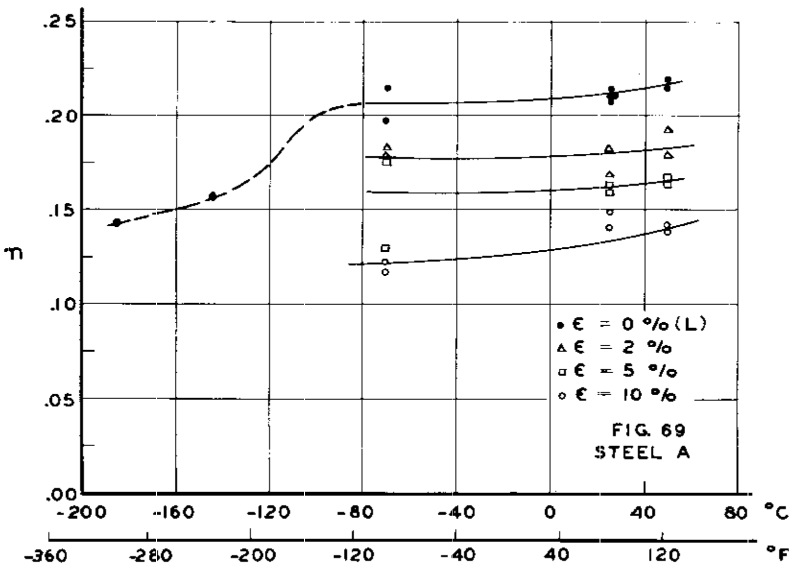


FIG. 69
STEEL A

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL A

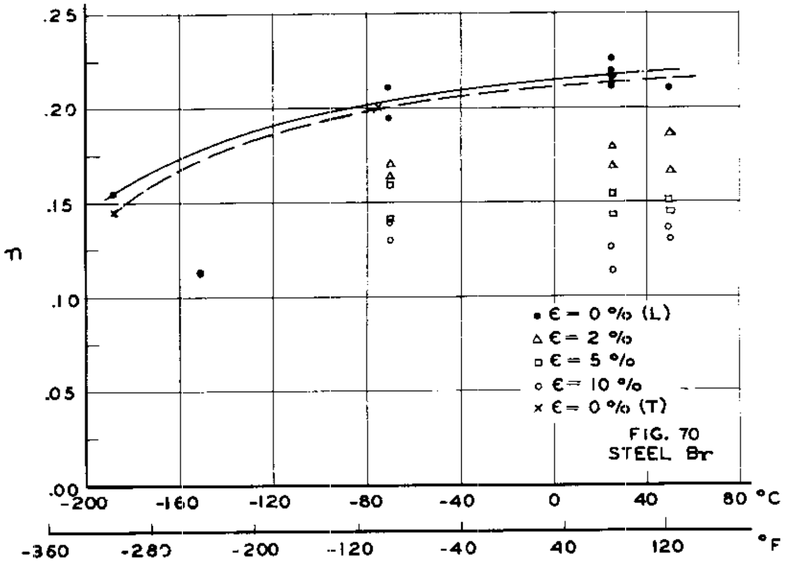


FIG. 70
STEEL Br

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL Br

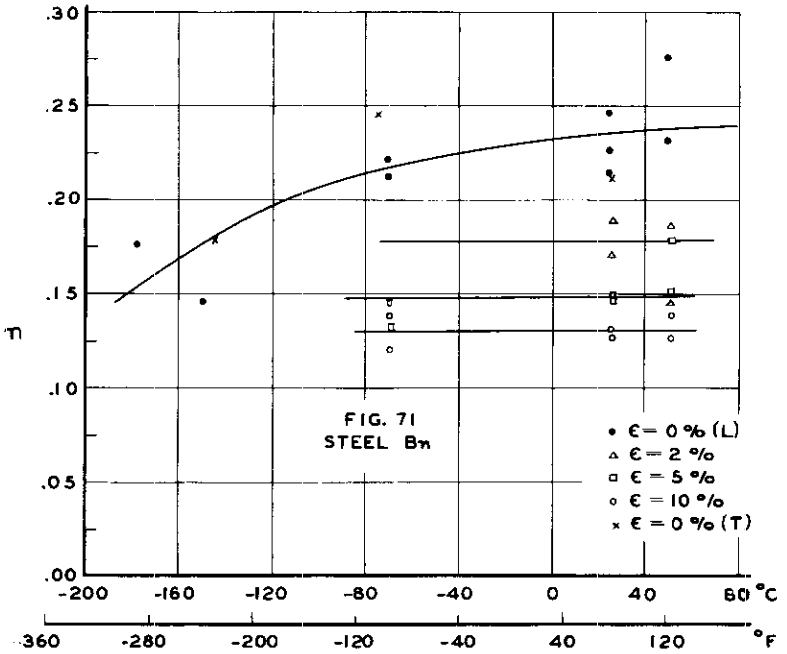


FIG. 71
STEEL Bn

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL Bn

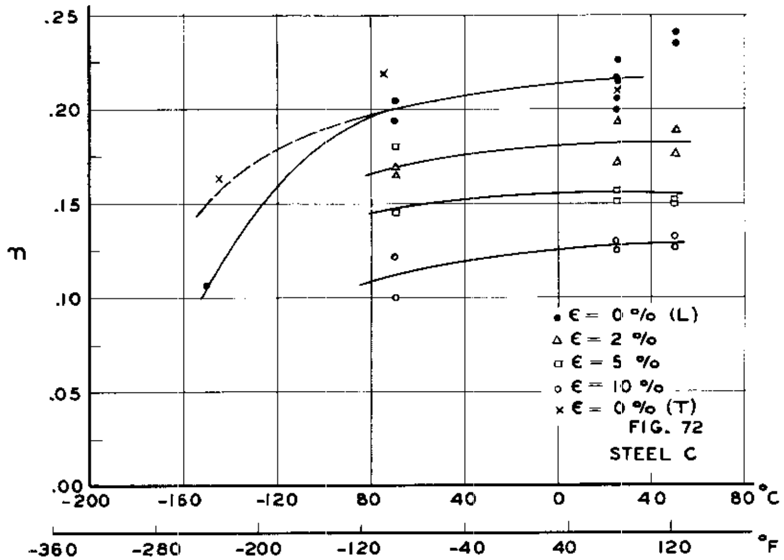


FIG. 72
STEEL C

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL C

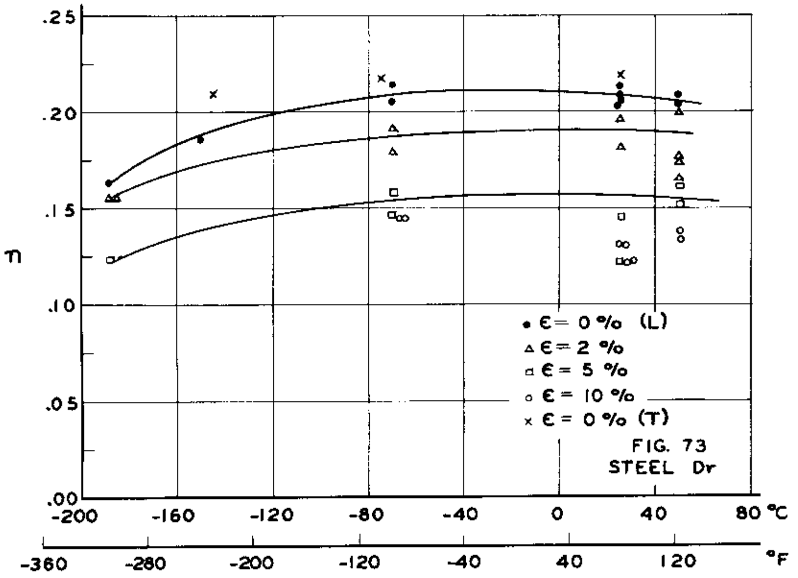


FIG. 73
STEEL Dr

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL Dr

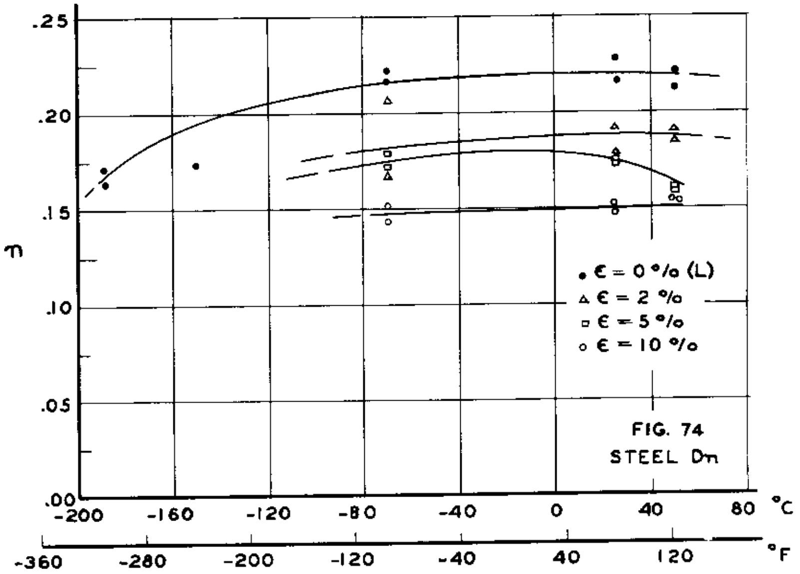


FIG. 74
STEEL Dn

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL Dn

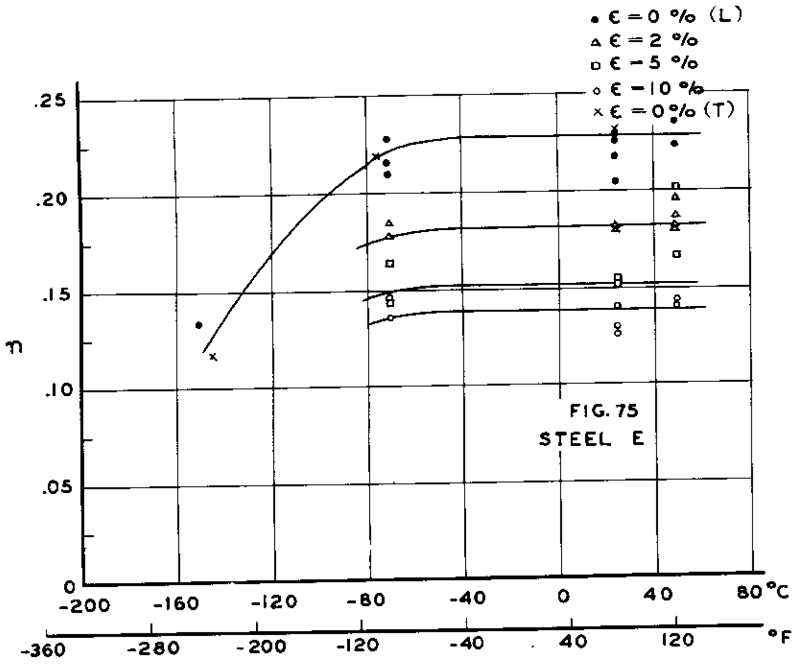


FIG. 75
STEEL E

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL E

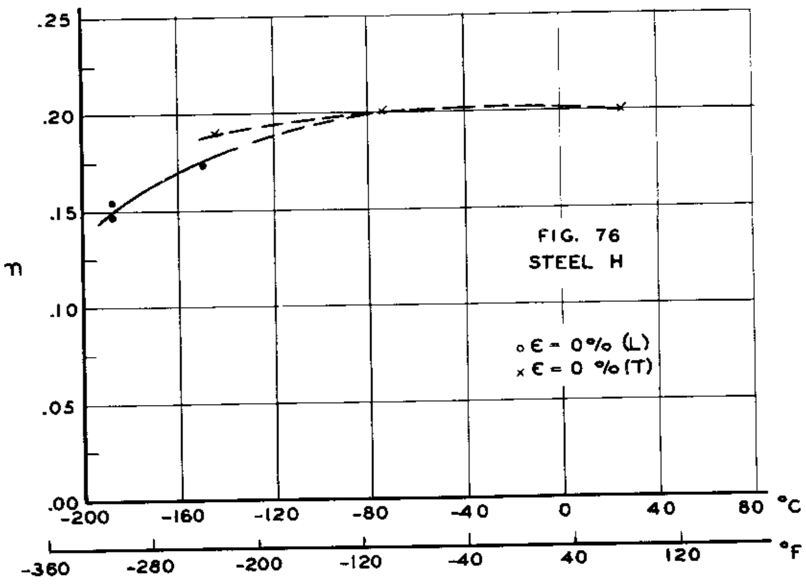


FIG. 76
STEEL H

THE STRAIN HARDENING EXPONENT (n) VERSUS TEMPERATURE – STEEL H

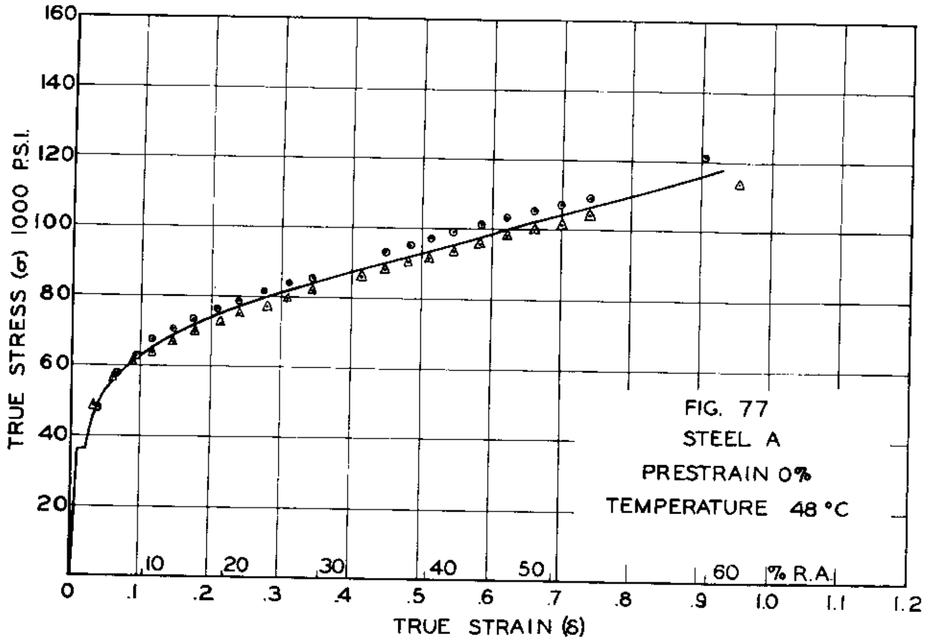


FIG. 77
STEEL A
PRESTRAIN 0%
TEMPERATURE 48 °C

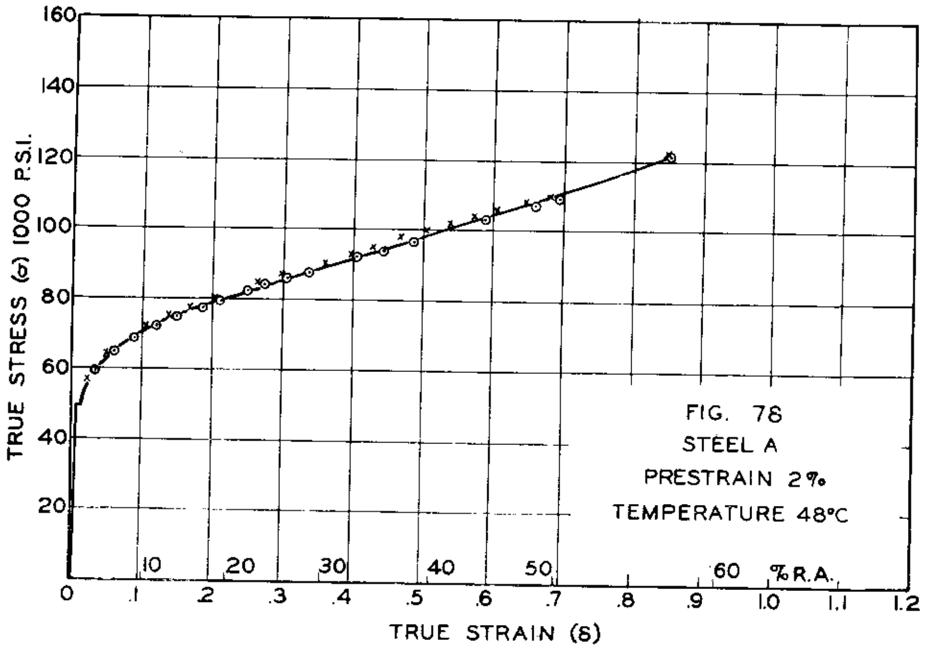


FIG. 78
STEEL A
PRESTRAIN 2%
TEMPERATURE 48°C

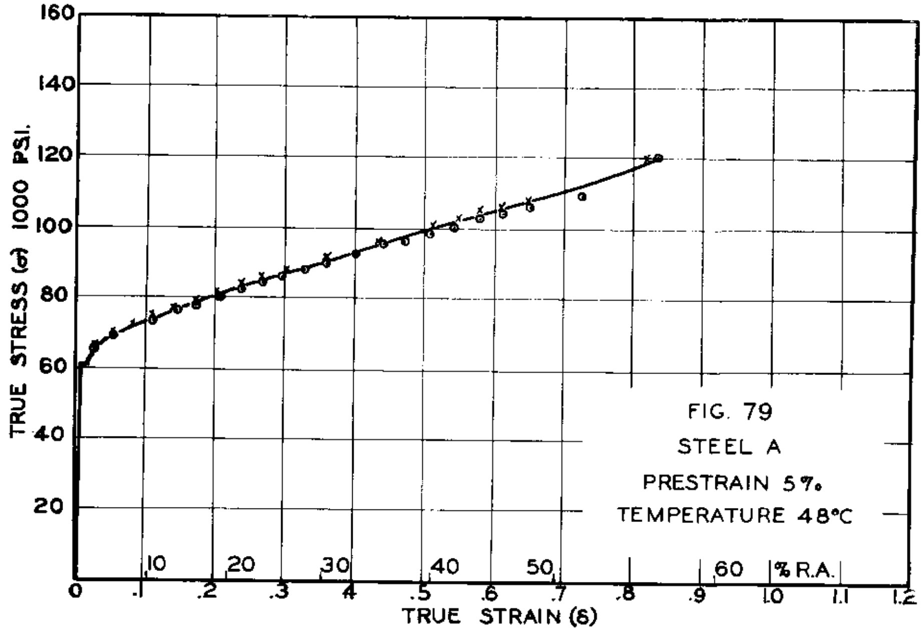


FIG. 79
STEEL A
PRESTRAIN 5%
TEMPERATURE 48°C

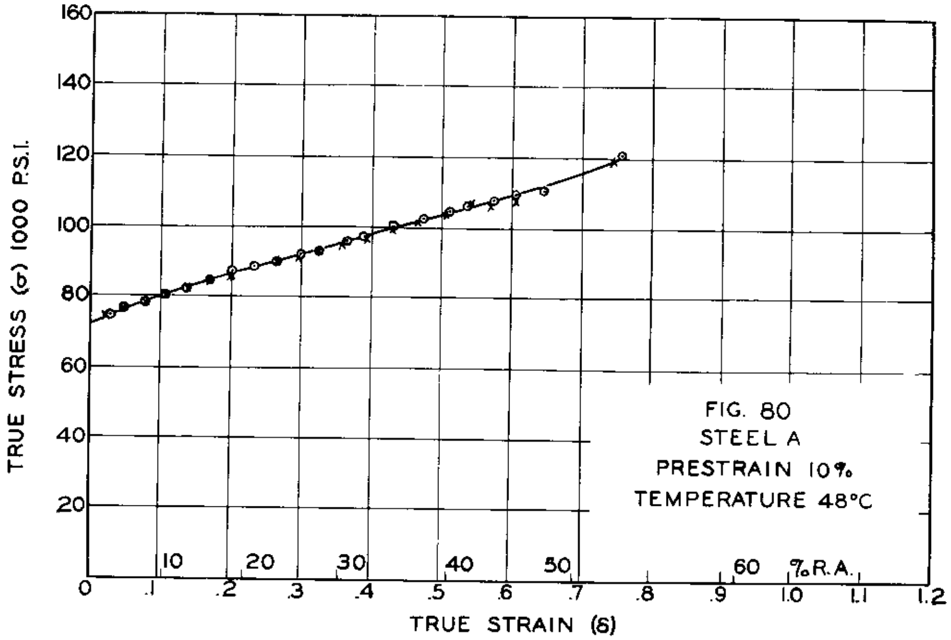


FIG. 80
STEEL A
PRESTRAIN 10%
TEMPERATURE 48°C

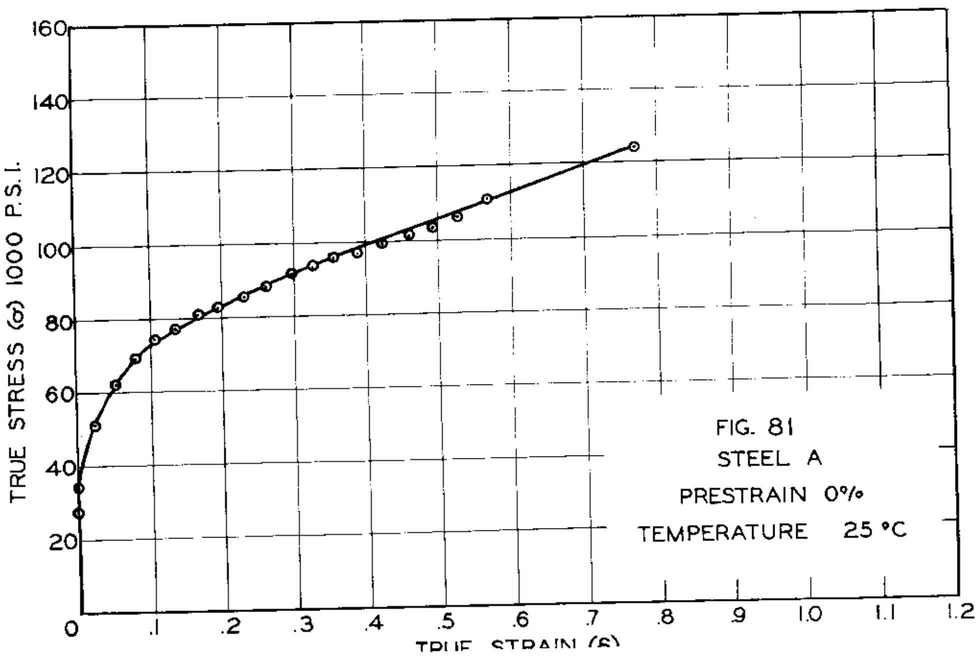


FIG. 81
STEEL A
PRESTRAIN 0%
TEMPERATURE 25 °C

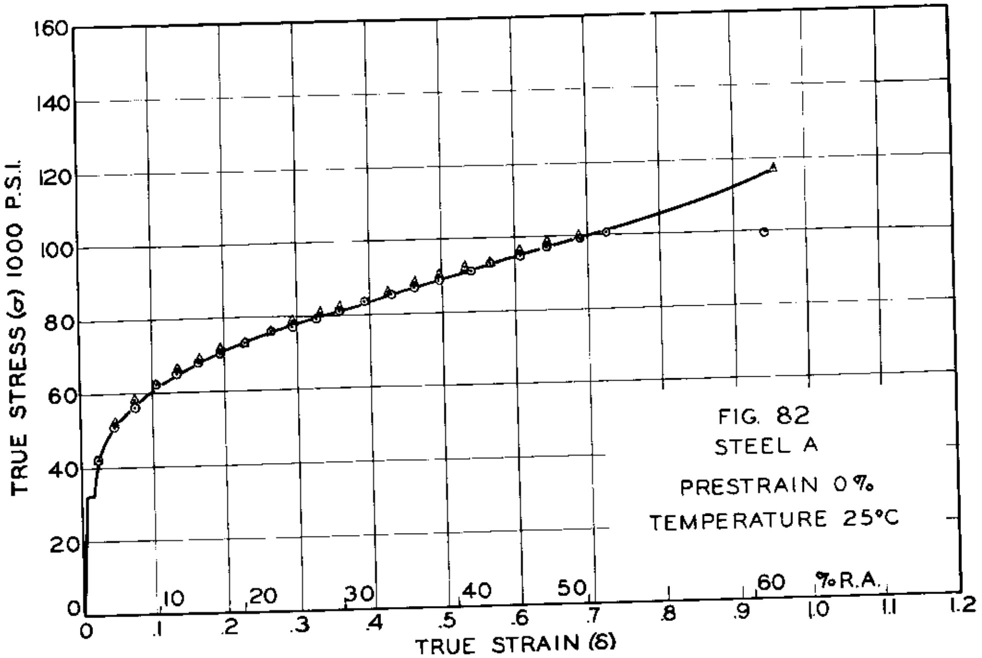


FIG. 82
STEEL A
PRESTRAIN 0%
TEMPERATURE 25°C

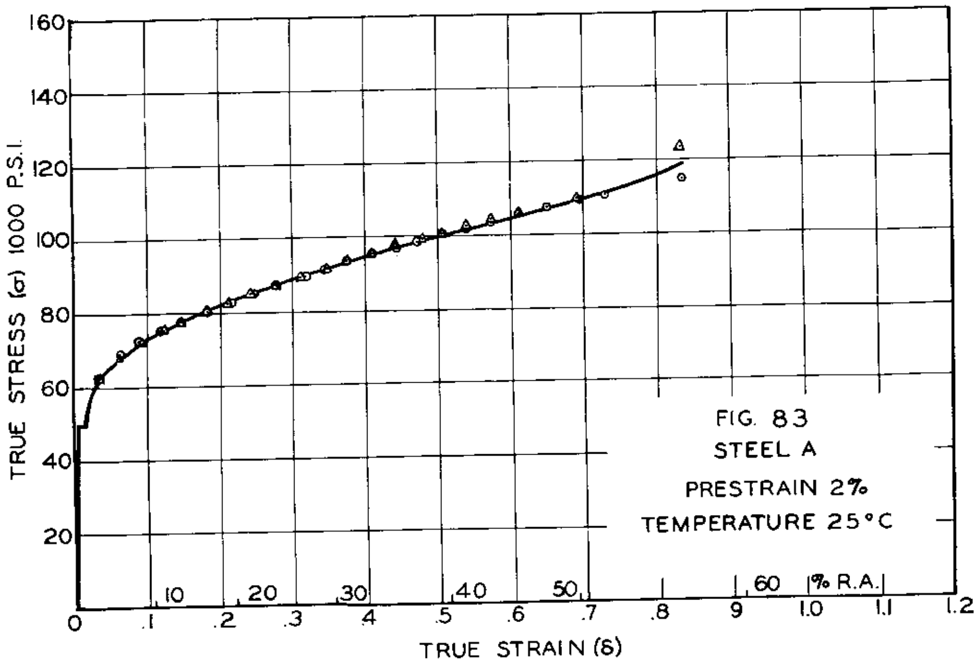


FIG. 83
STEEL A
PRESTRAIN 2%
TEMPERATURE 25°C

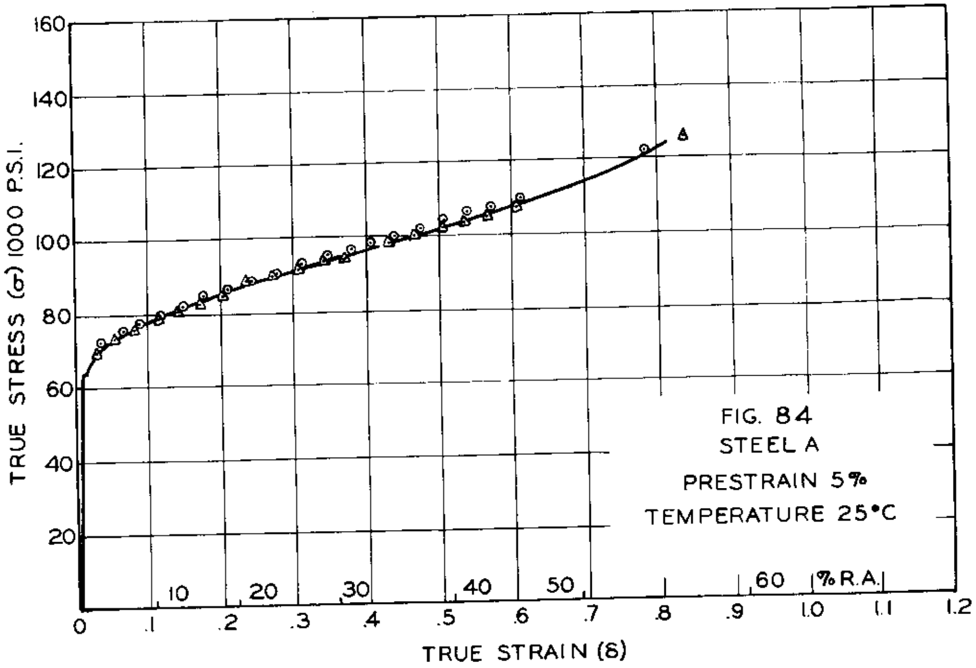


FIG. 84
STEEL A
PRESTRAIN 5%
TEMPERATURE 25°C

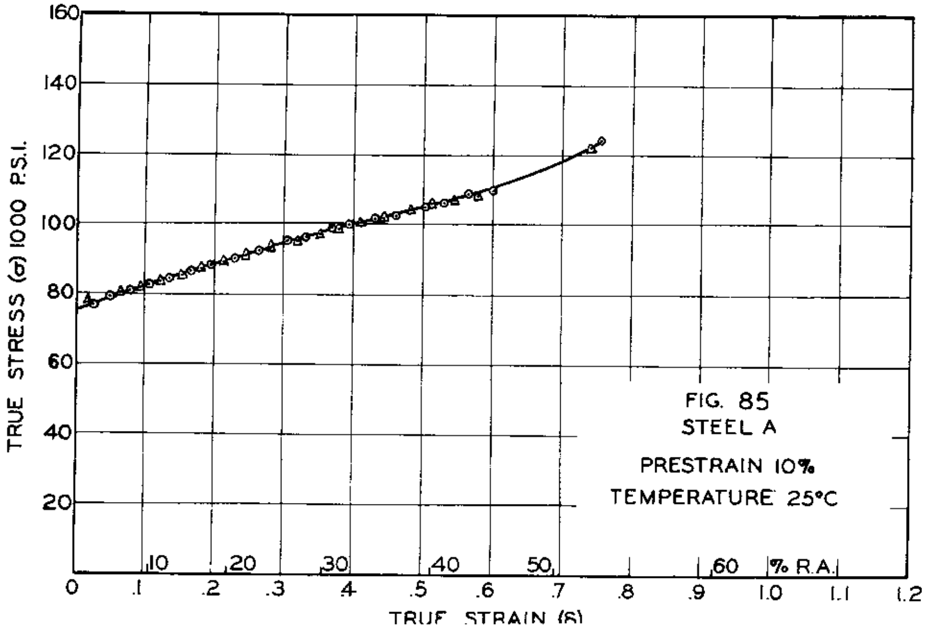


FIG. 85
STEEL A
PRESTRAIN 10%
TEMPERATURE 25°C

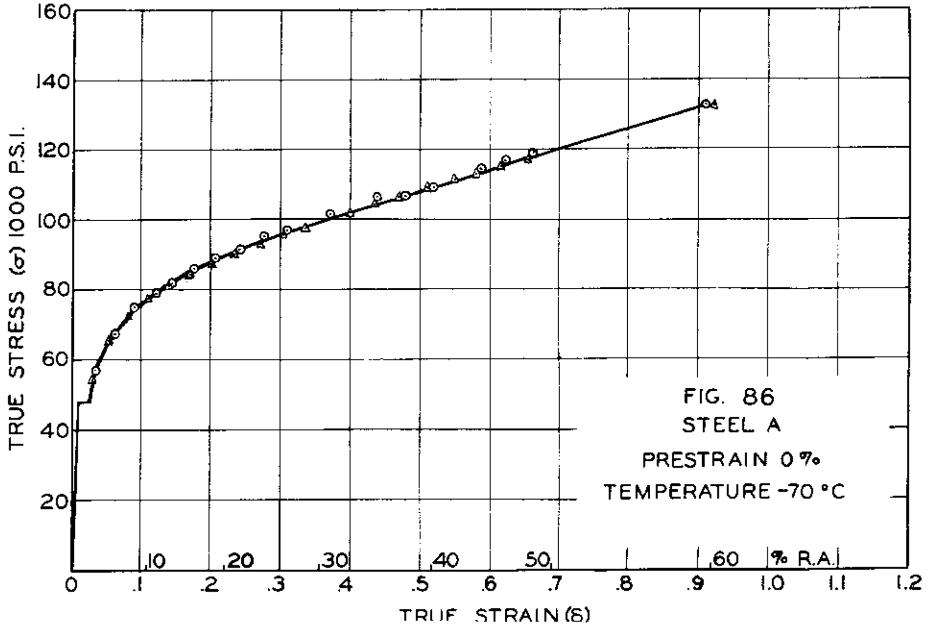


FIG. 86
STEEL A
PRESTRAIN 0%
TEMPERATURE -70°C

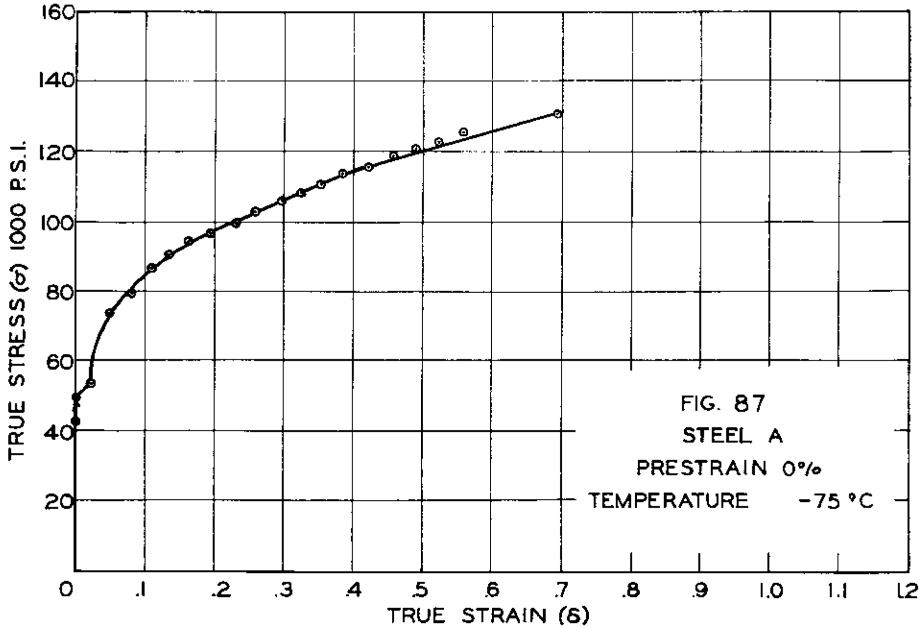


FIG. 87
STEEL A
PRESTRAIN 0%
TEMPERATURE -75°C

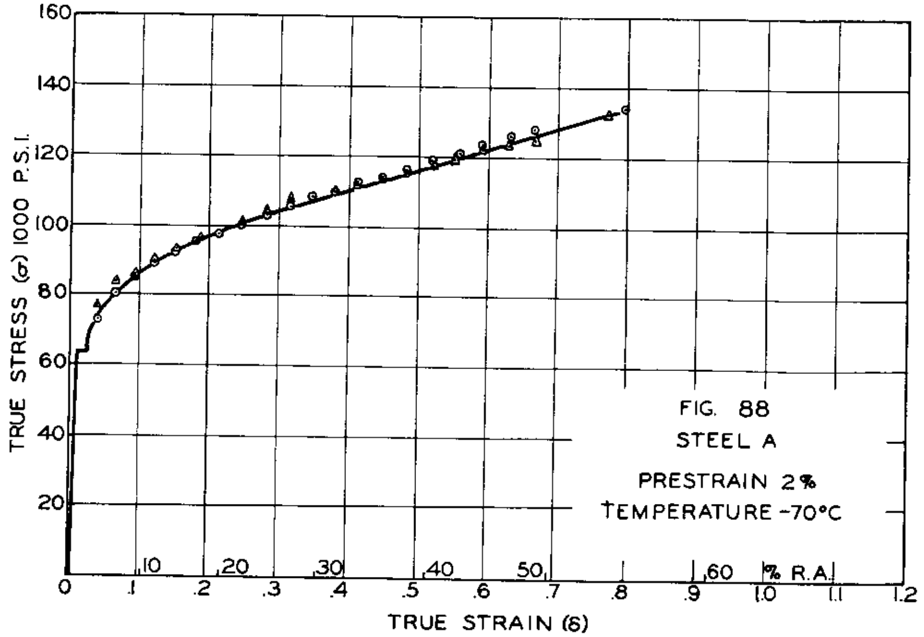


FIG. 88
STEEL A
PRESTRAIN 2%
TEMPERATURE -70°C

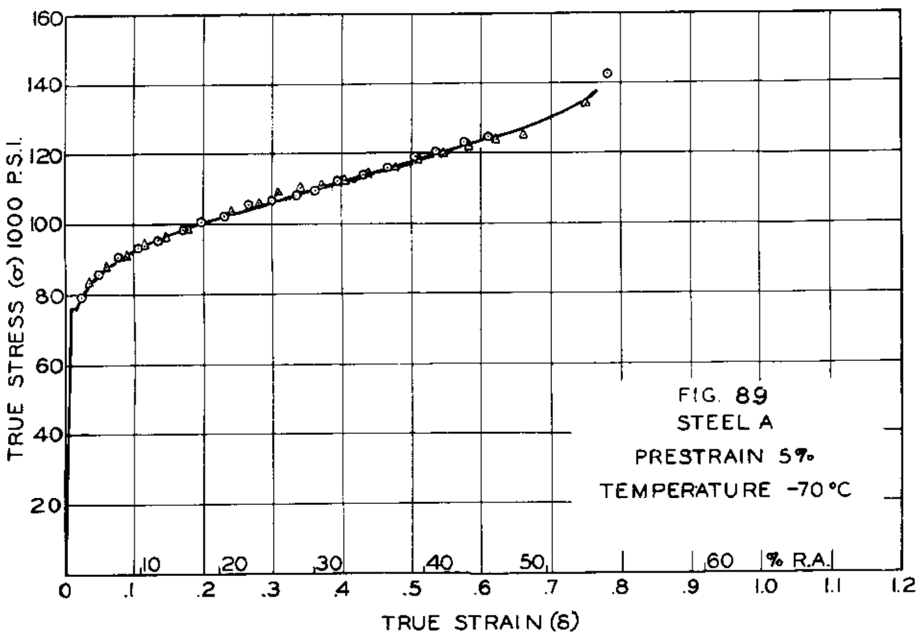


FIG. 89
STEEL A
PRESTRAIN 5%
TEMPERATURE -70°C

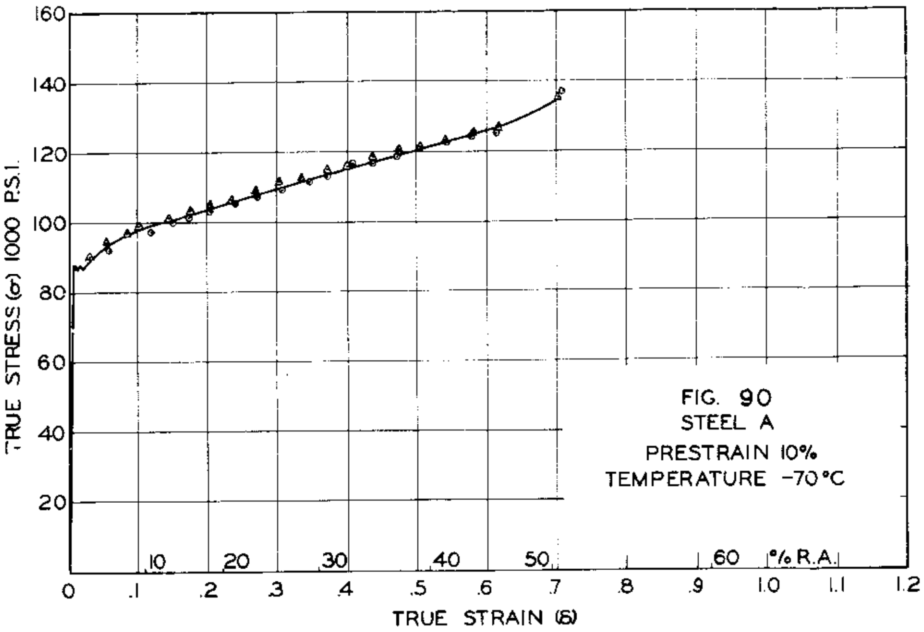


FIG. 90
STEEL A
PRESTRAIN 10%
TEMPERATURE -70°C

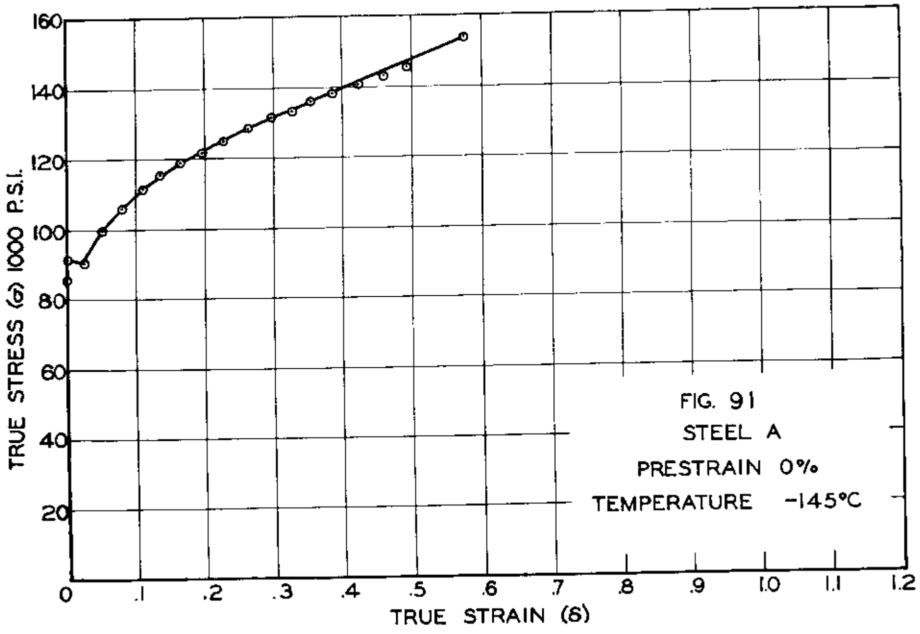


FIG. 91
STEEL A
PRESTRAIN 0%
TEMPERATURE -145°C

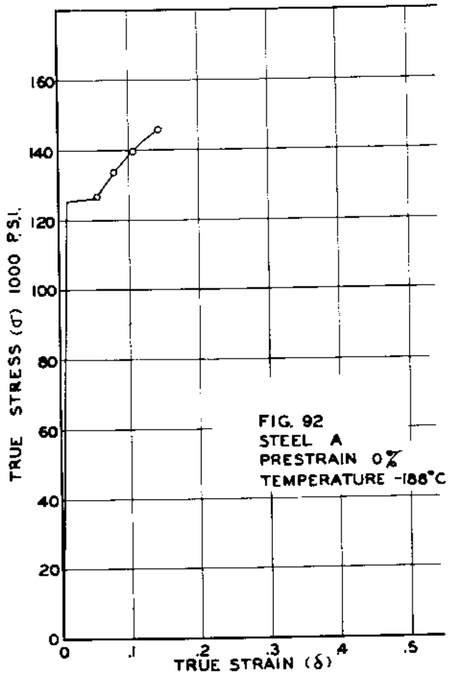


FIG. 92
STEEL A
PRESTRAIN 0%
TEMPERATURE -188°C

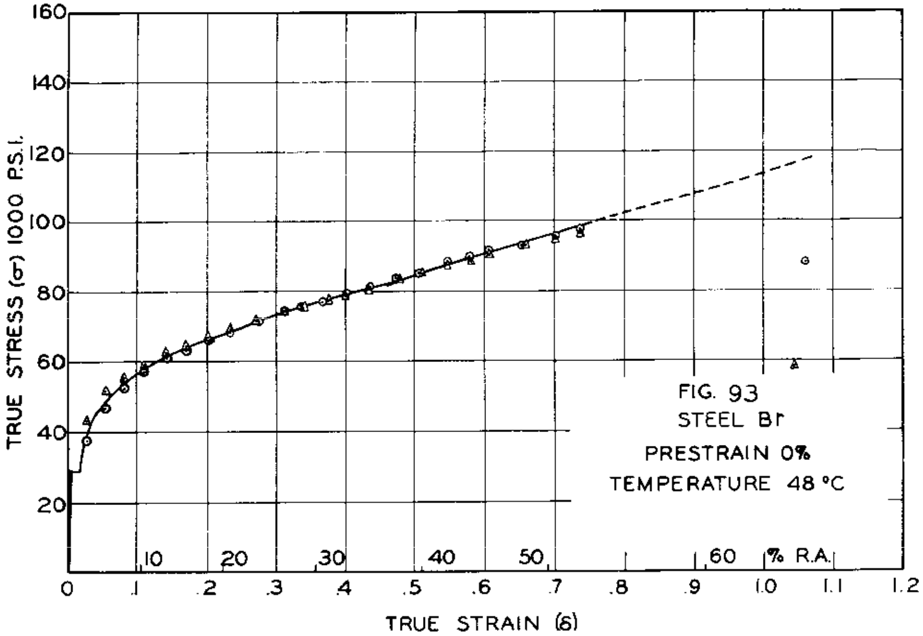


FIG. 93
STEEL Br
PRESTRAIN 0%
TEMPERATURE 48 °C

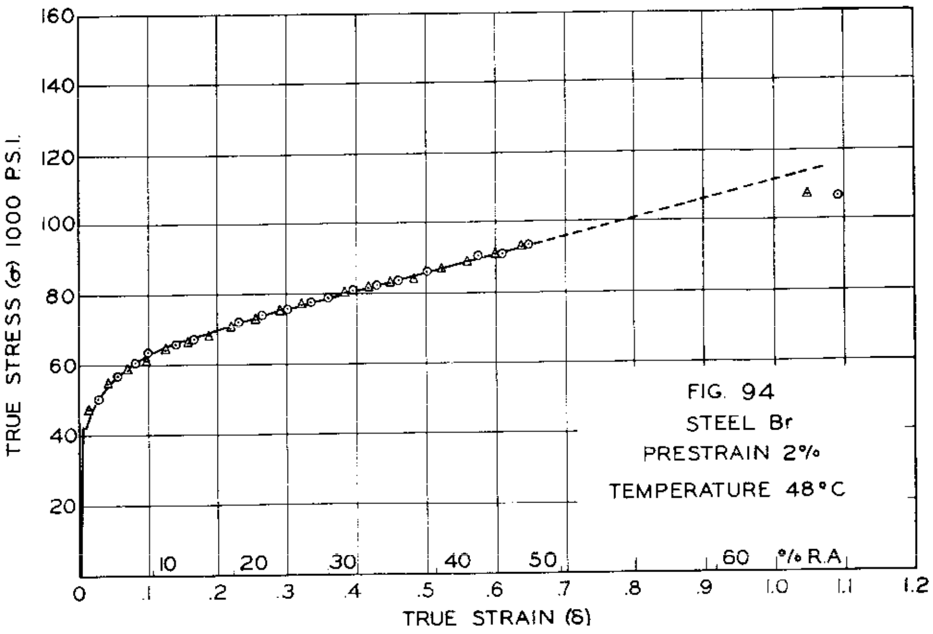


FIG. 94
STEEL Br
PRESTRAIN 2%
TEMPERATURE 48 °C

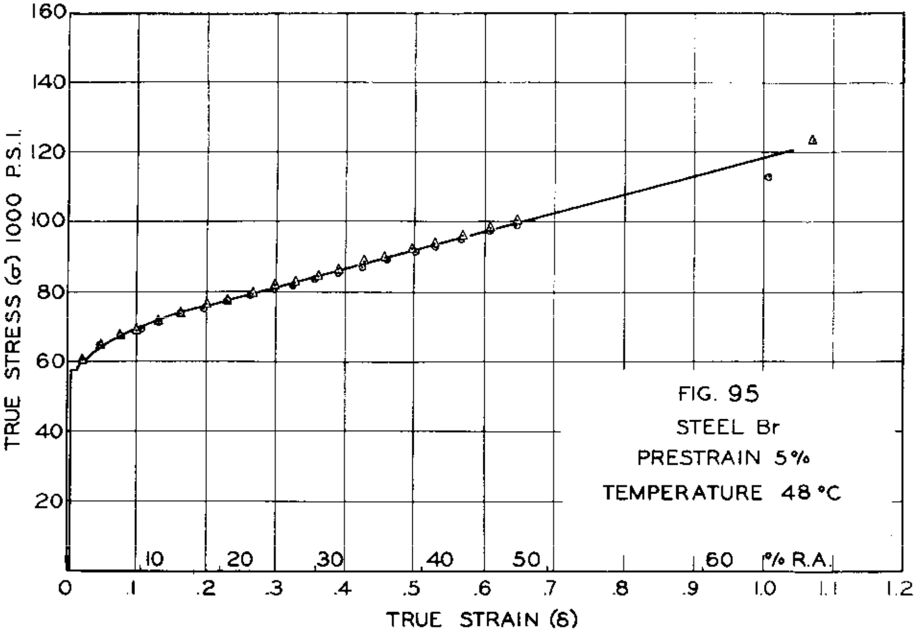


FIG. 95
STEEL Br
PRESTRAIN 5%
TEMPERATURE 48 °C

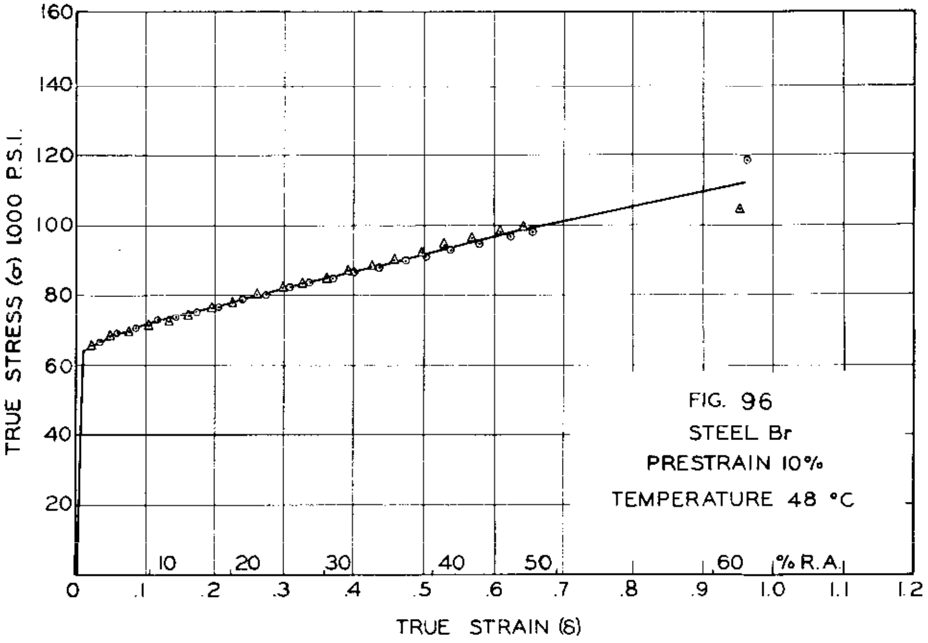


FIG. 96
STEEL Br
PRESTRAIN 10%
TEMPERATURE 48 °C

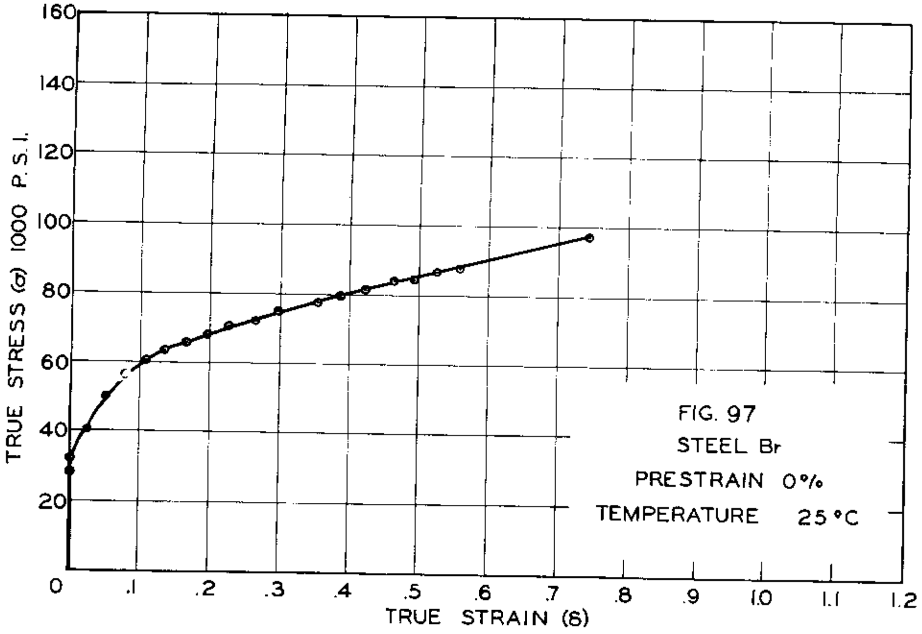


FIG. 97
STEEL Br
PRESTRAIN 0%
TEMPERATURE 25 °C

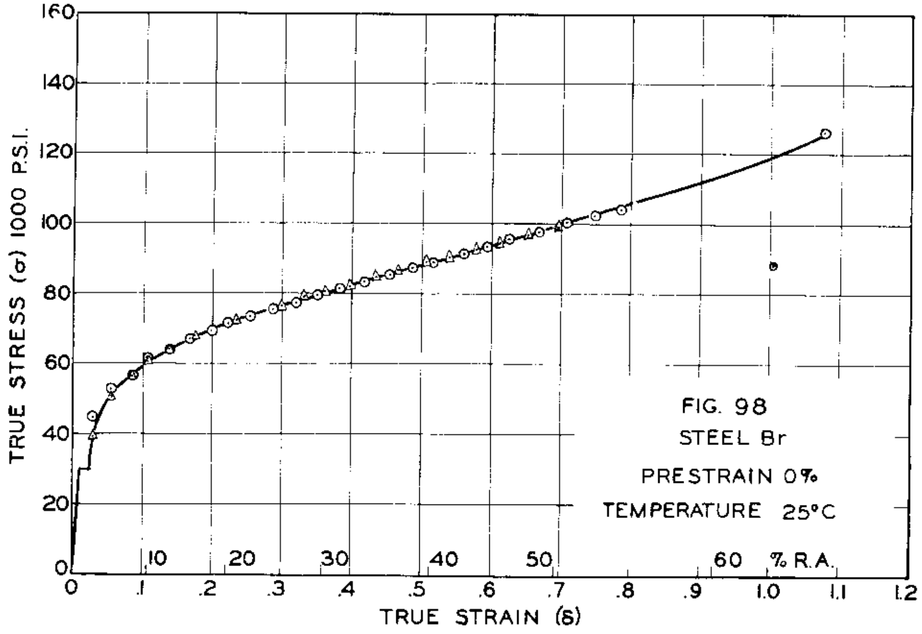


FIG. 98
STEEL Br
PRESTRAIN 0%
TEMPERATURE 25°C

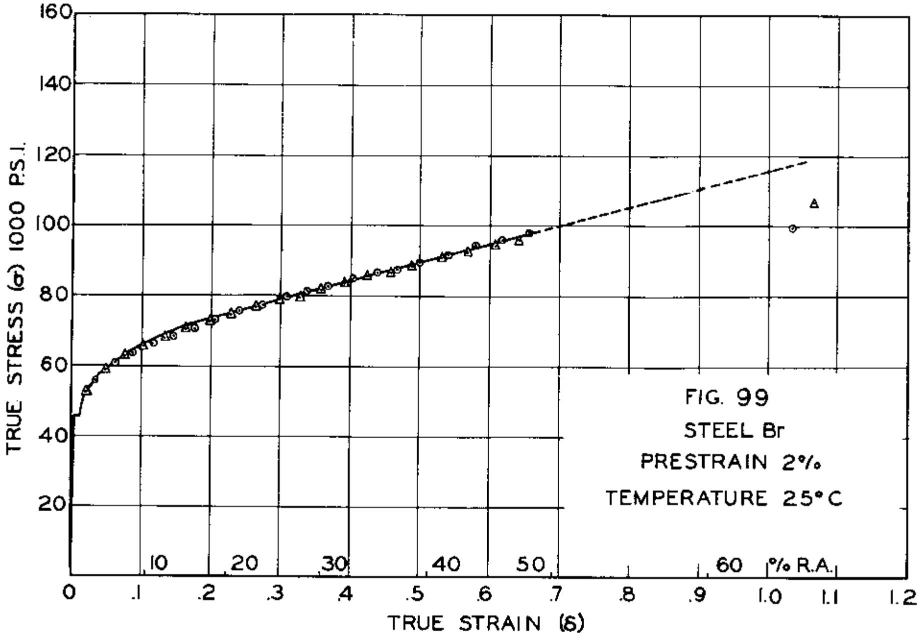


FIG. 99
STEEL Br
PRESTRAIN 2%
TEMPERATURE 25°C

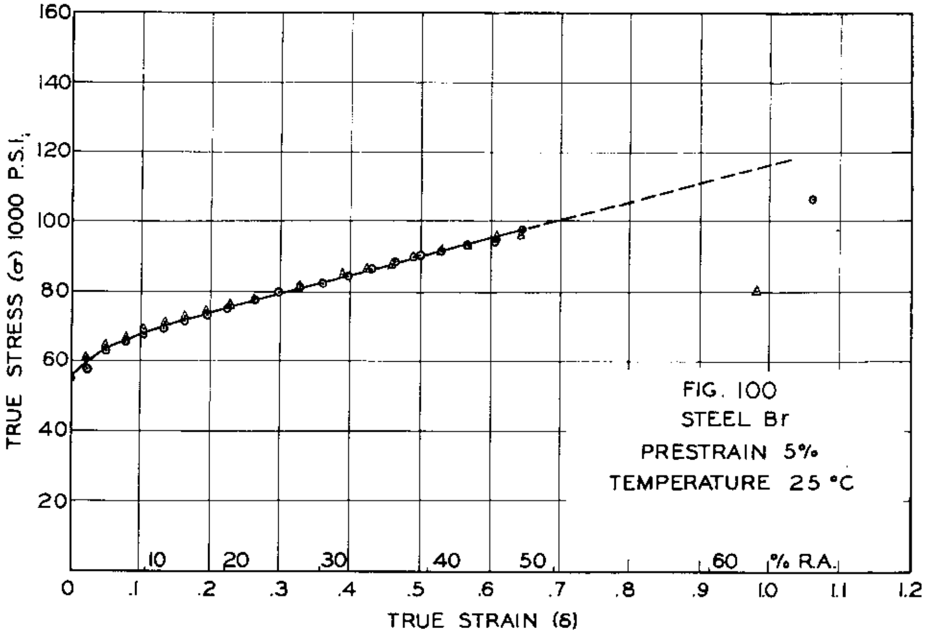


FIG. 100
STEEL Br
PRESTRAIN 5%
TEMPERATURE 25 °C

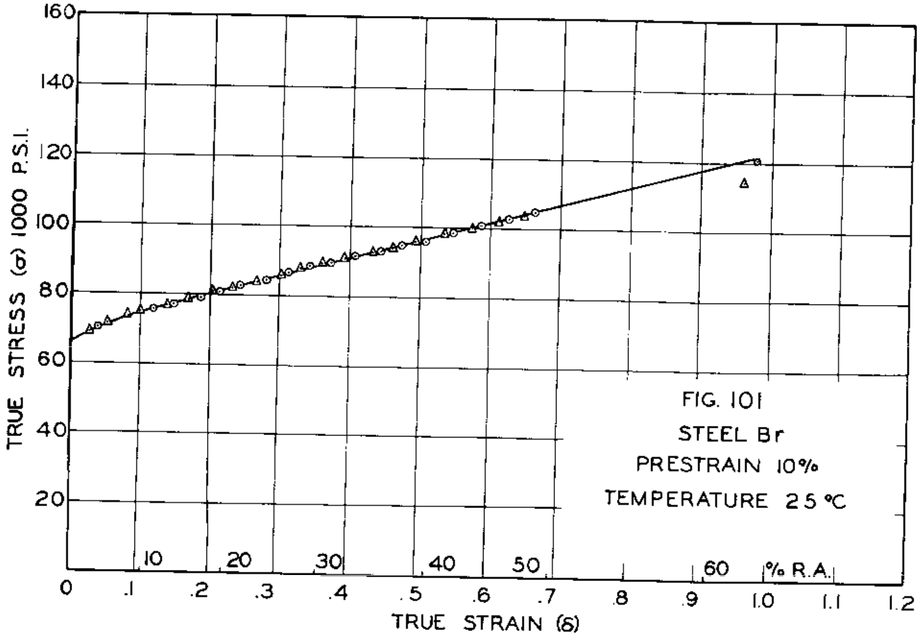


FIG. 101
STEEL Br
PRESTRAIN 10%
TEMPERATURE 25 °C

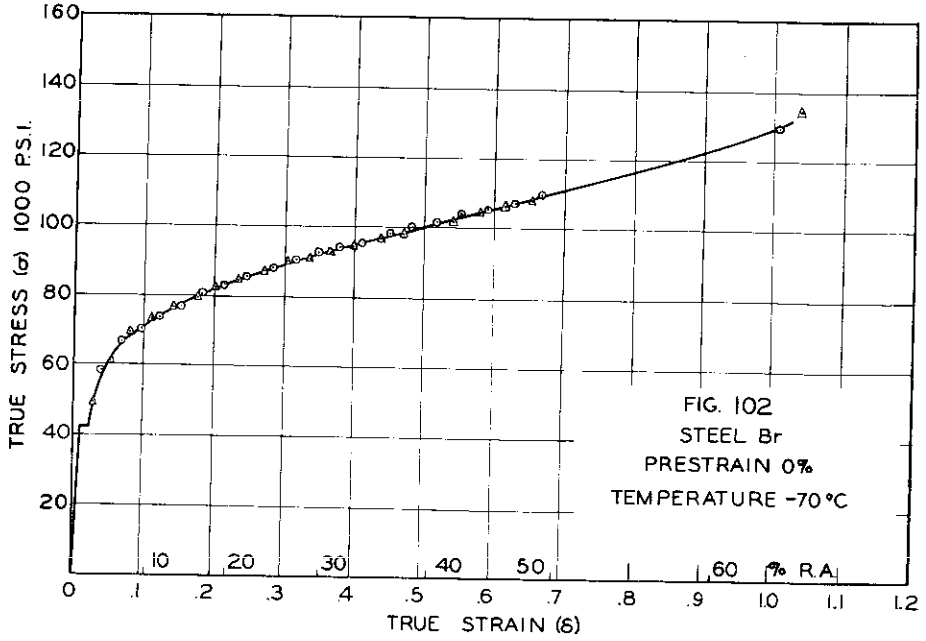


FIG. 102
STEEL Br
PRESTRAIN 0%
TEMPERATURE -70 °C

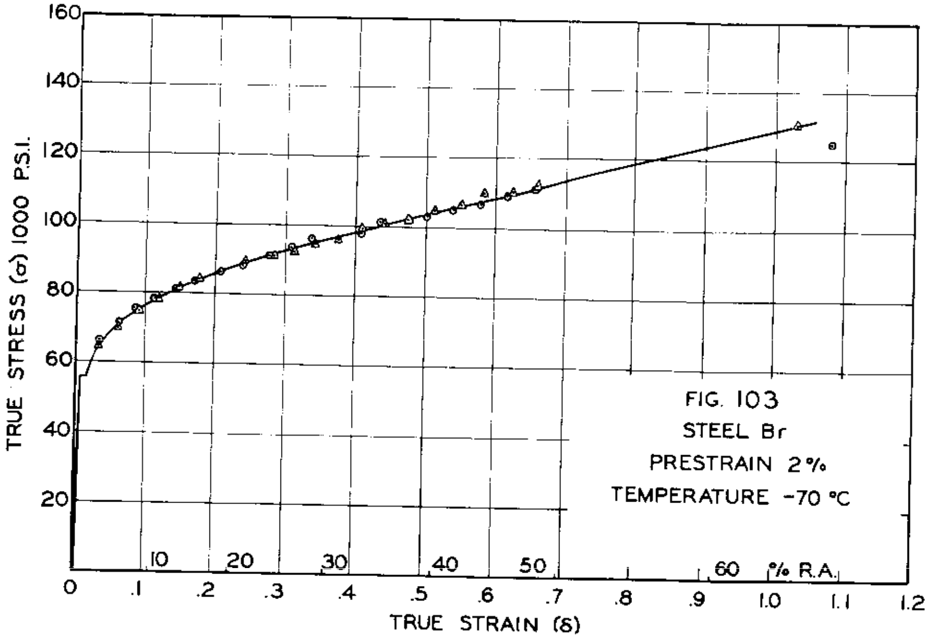


FIG. 103
STEEL Br
PRESTRAIN 2%
TEMPERATURE -70 °C

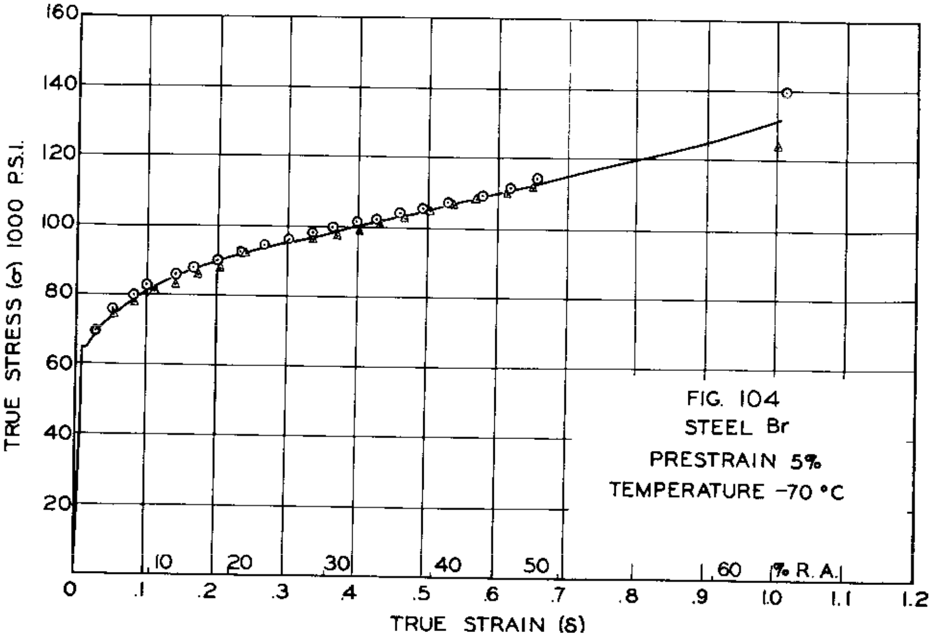


FIG. 104
STEEL Br
PRESTRAIN 5%
TEMPERATURE -70 °C

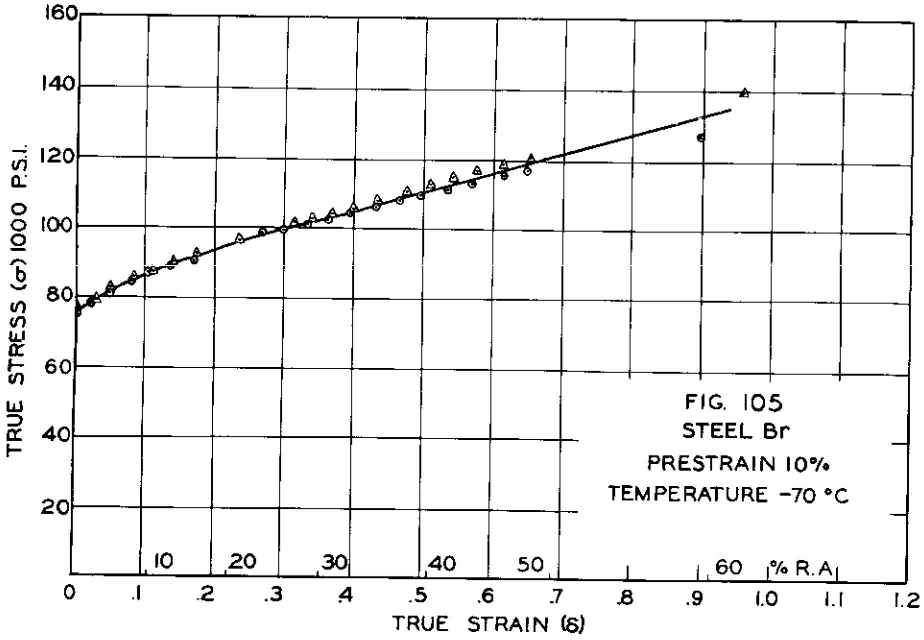


FIG. 105
STEEL Br
PRESTRAIN 10%
TEMPERATURE -70 °C

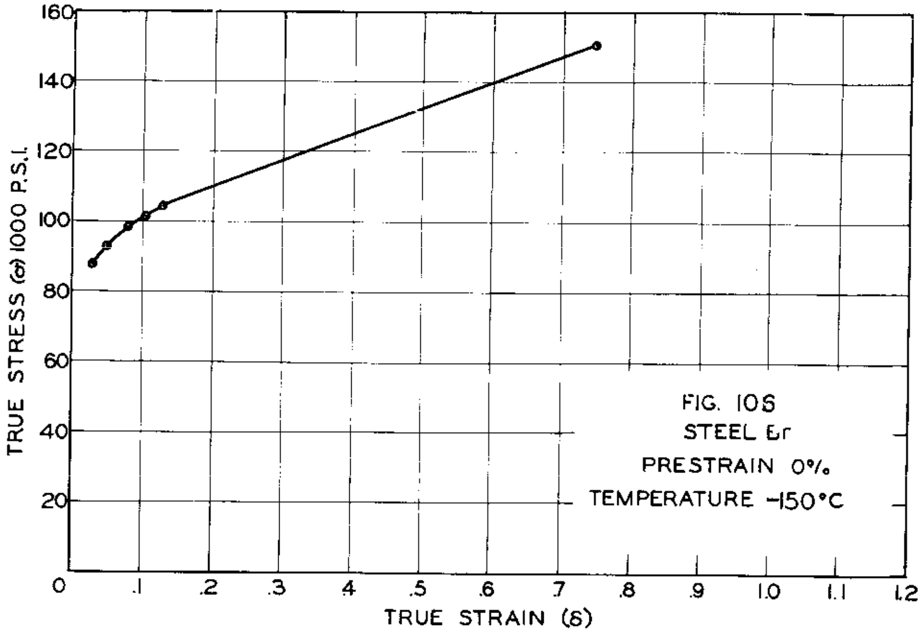


FIG. 106
STEEL Br
PRESTRAIN 0%
TEMPERATURE -150°C

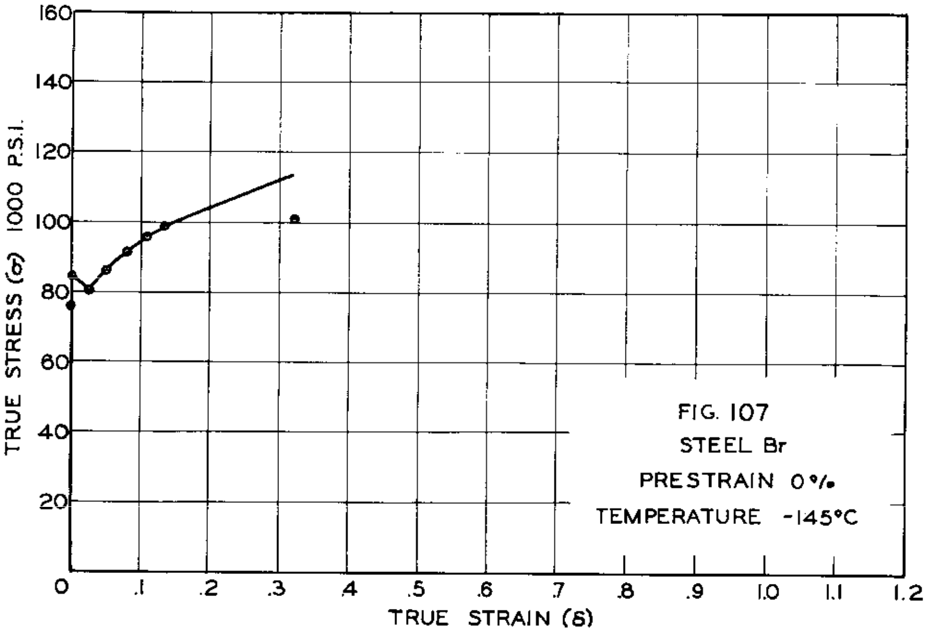


FIG. 107
STEEL Br
PRESTRAIN 0%
TEMPERATURE -145°C

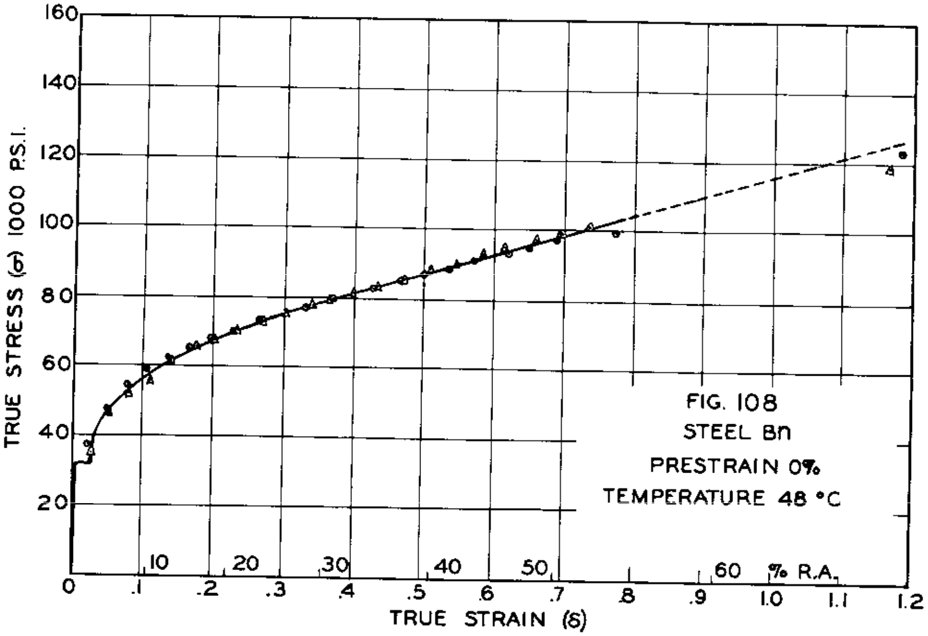


FIG. 108
STEEL Bn
PRESTRAIN 0%
TEMPERATURE 48 °C

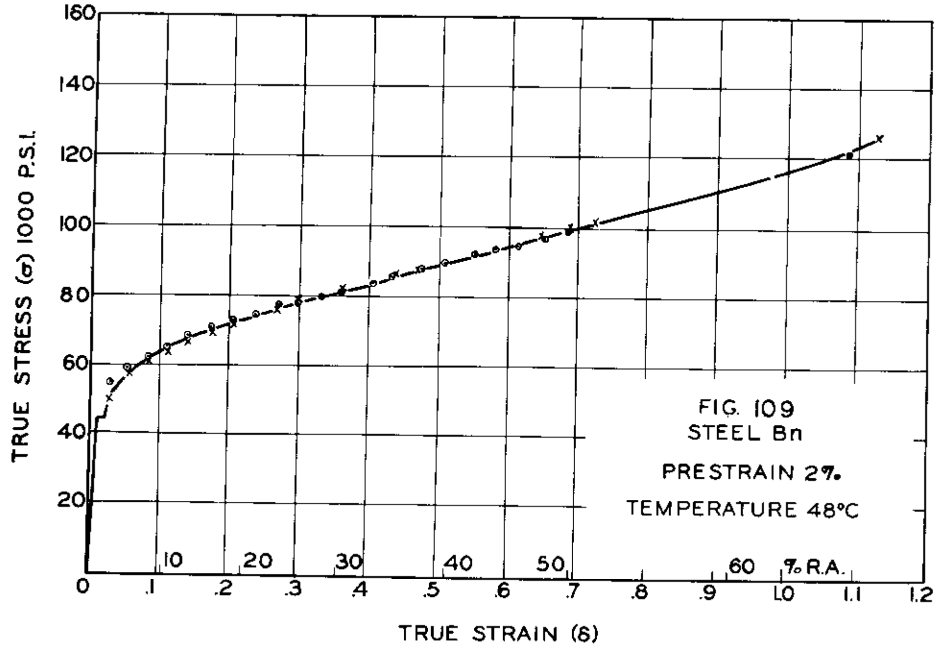


FIG. 109
STEEL Bn
PRESTRAIN 2%
TEMPERATURE 48°C

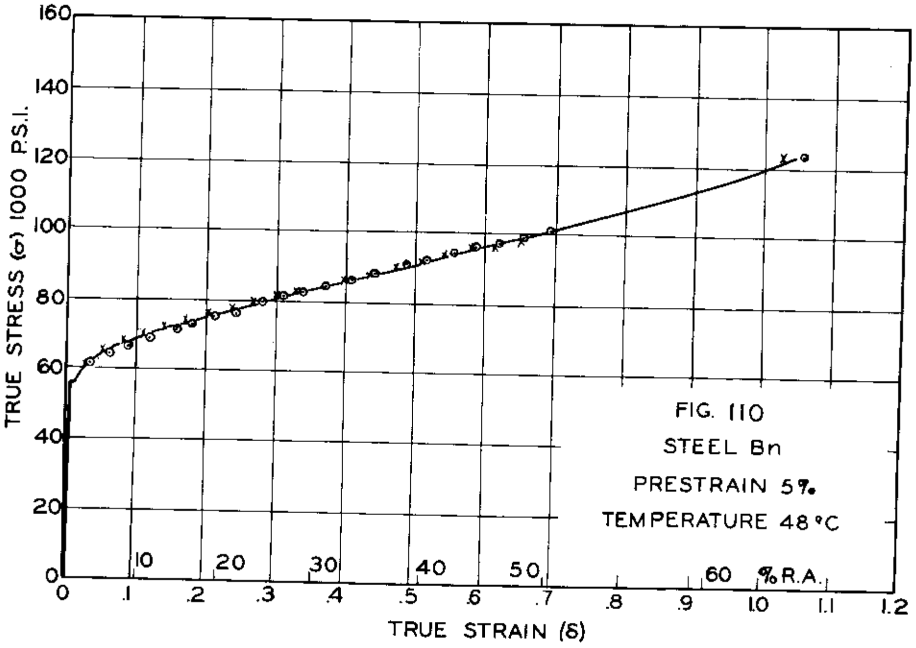


FIG. 110
STEEL Bn
PRESTRAIN 5%
TEMPERATURE 48°C

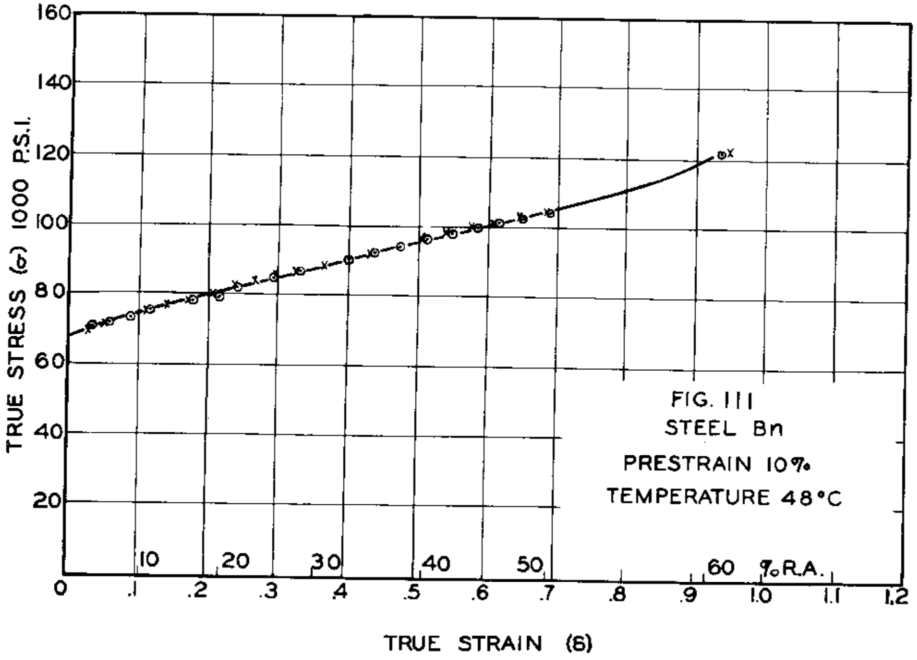


FIG. 111
STEEL Bn
PRESTRAIN 10%
TEMPERATURE 48°C

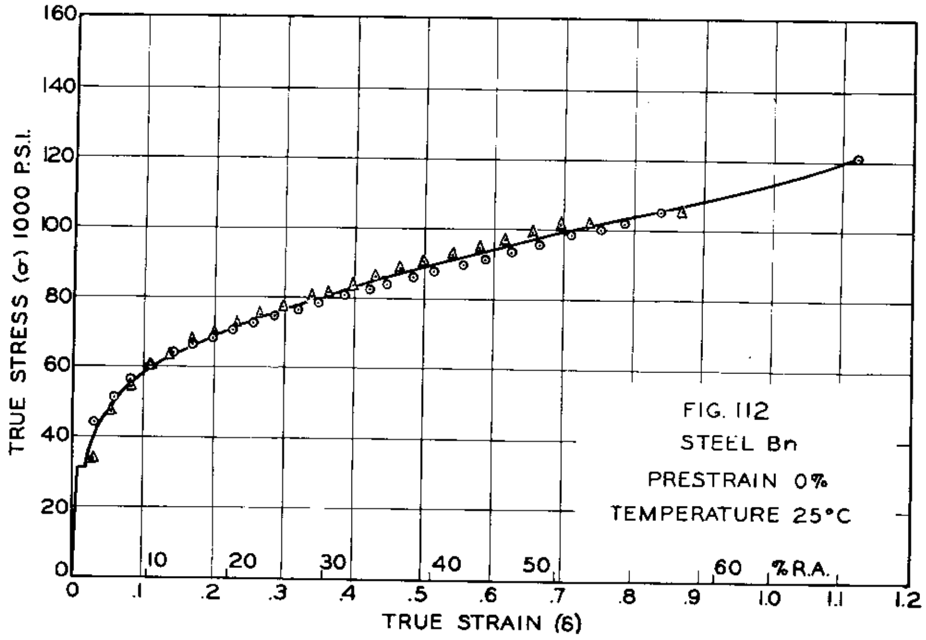


FIG. 112
STEEL Bn
PRESTRAIN 0%
TEMPERATURE 25°C

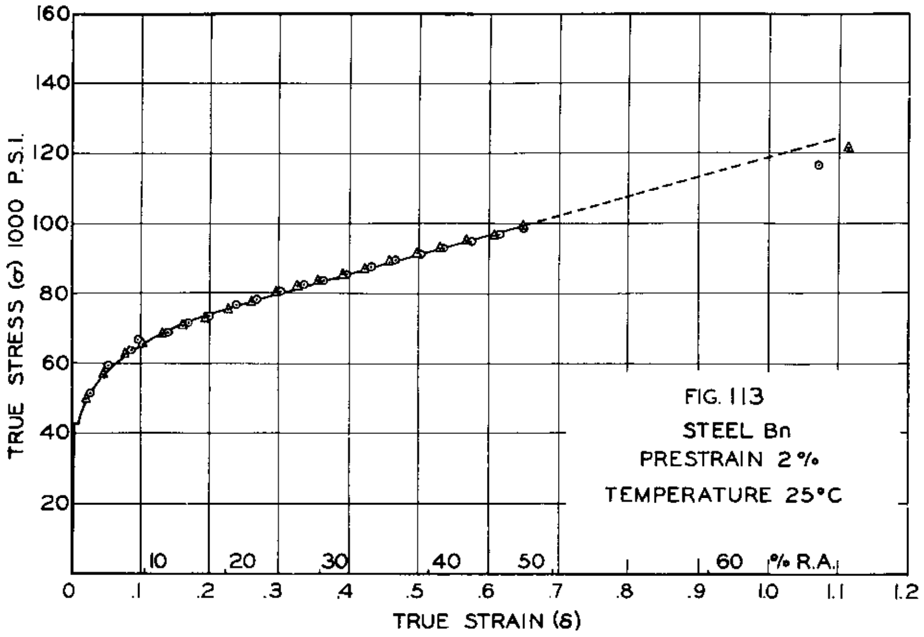


FIG. 113
STEEL Bn
PRESTRAIN 2%
TEMPERATURE 25°C

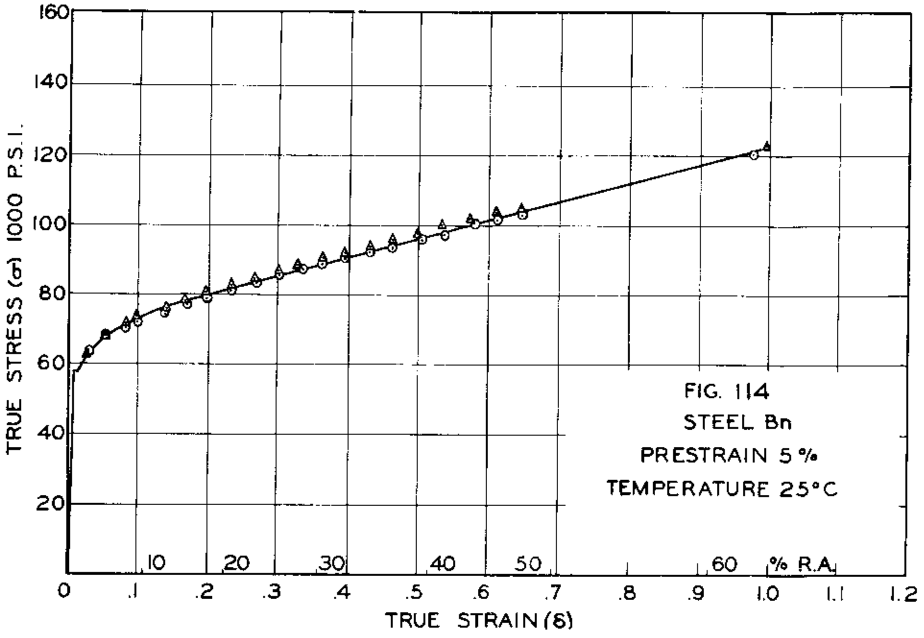


FIG. 114
STEEL Bn
PRESTRAIN 5%
TEMPERATURE 25°C

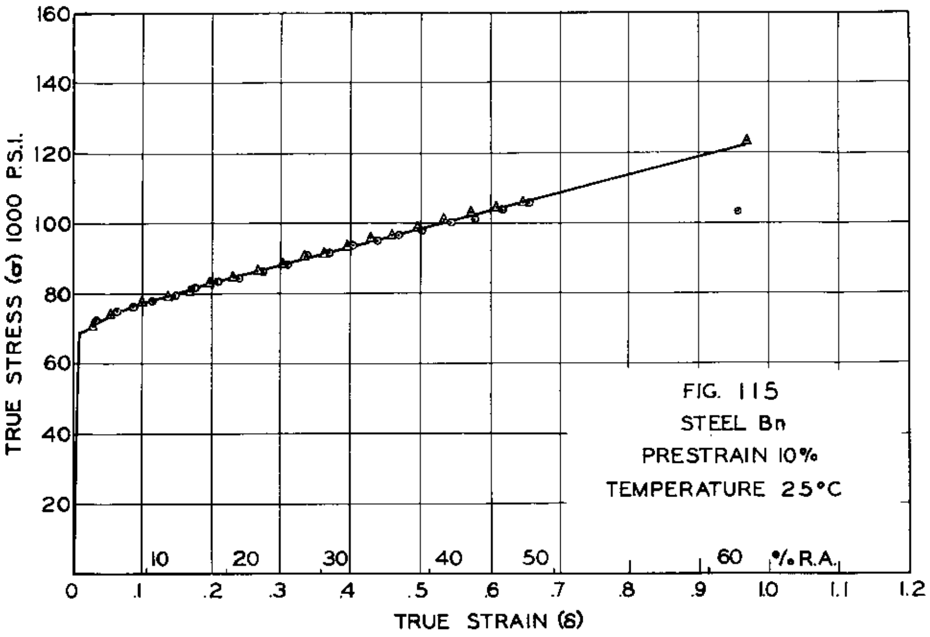


FIG. 115
STEEL Bn
PRESTRAIN 10%
TEMPERATURE 25°C

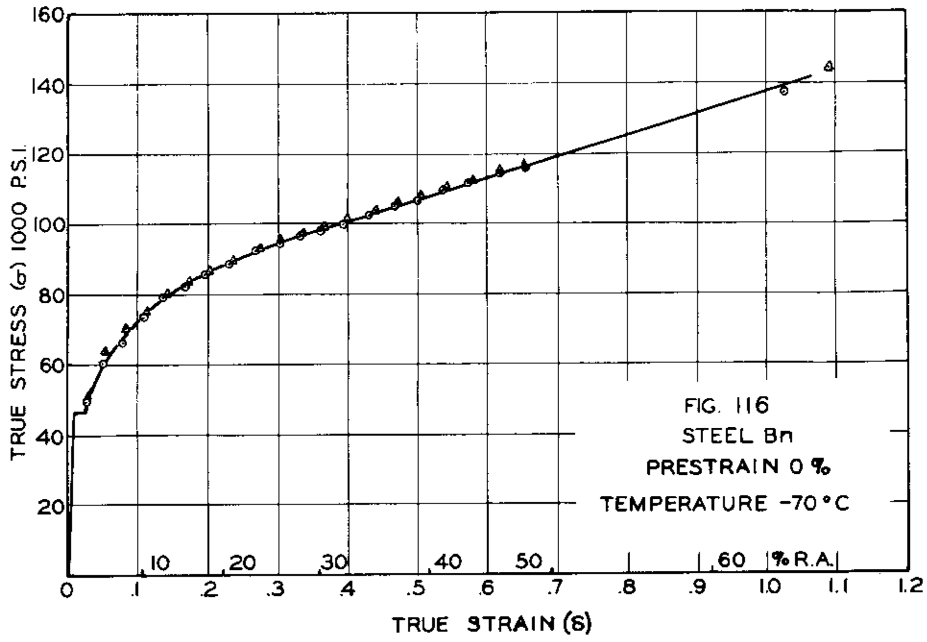


FIG. 116
STEEL Bn
PRESTRAIN 0%
TEMPERATURE -70°C

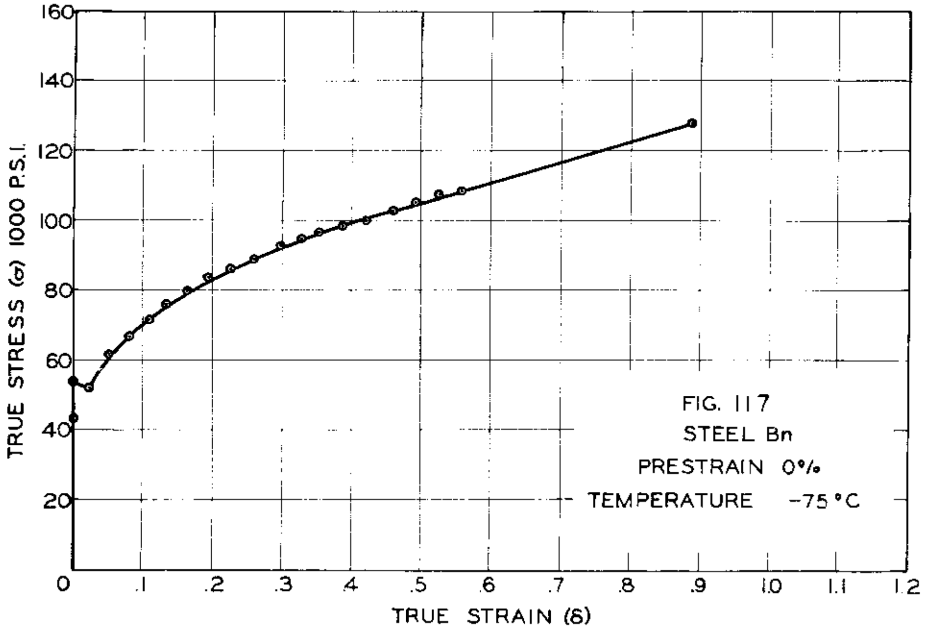


FIG. 117
STEEL Bn
PRESTRAIN 0%
TEMPERATURE -75°C

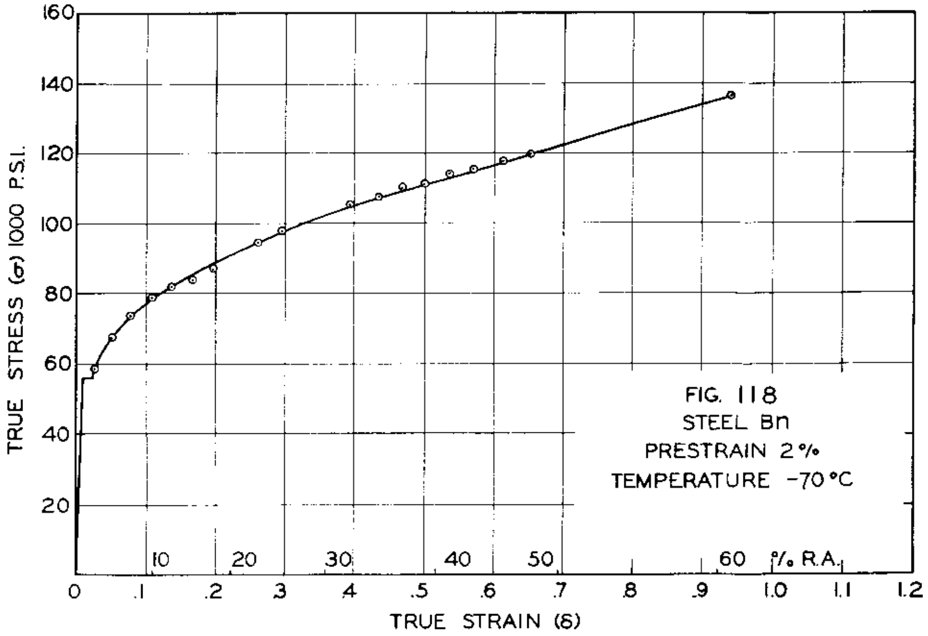


FIG. 118
STEEL Bn
PRESTRAIN 2%
TEMPERATURE -70°C

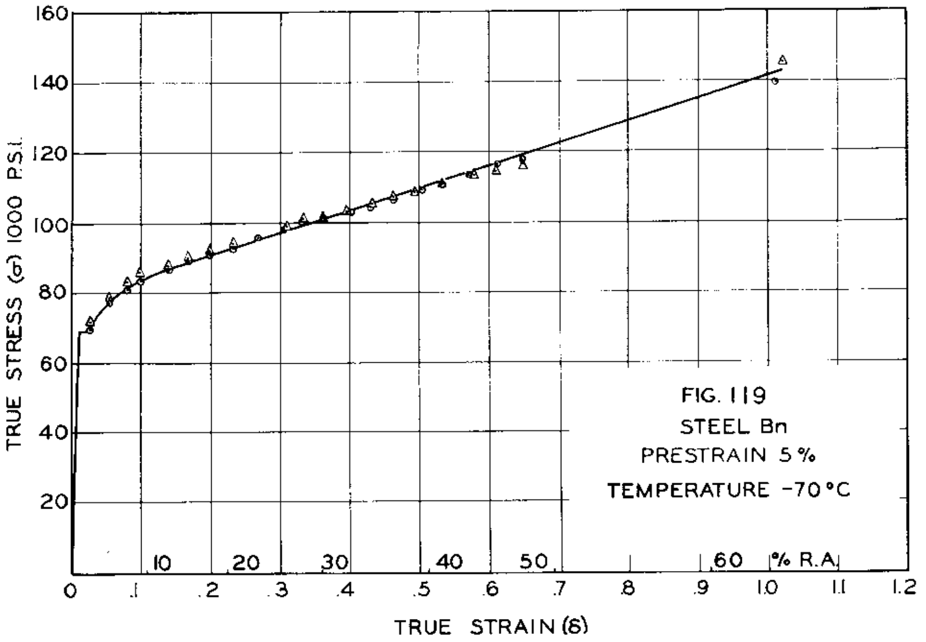


FIG. 119
STEEL Bn
PRESTRAIN 5%
TEMPERATURE -70°C

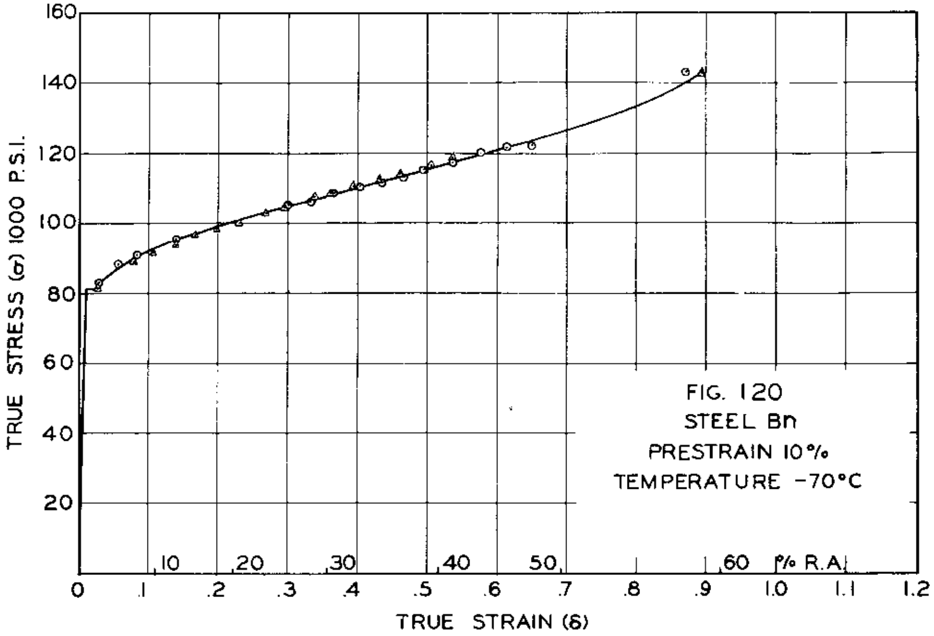


FIG. 120
STEEL Bn
PRESTRAIN 10%
TEMPERATURE -70°C

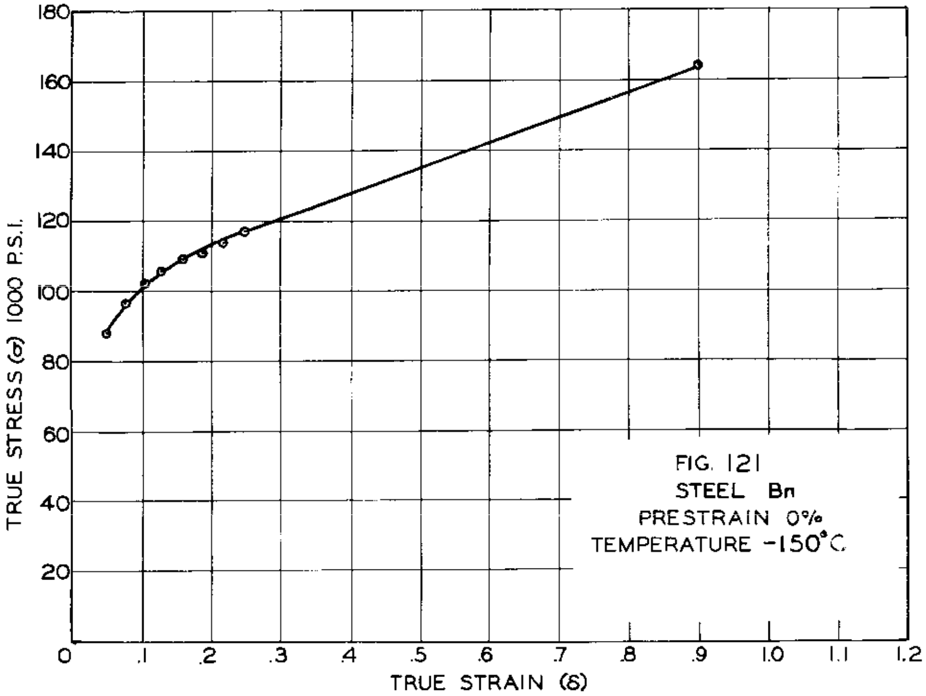


FIG. 121
STEEL Bn
PRESTRAIN 0%
TEMPERATURE -150°C

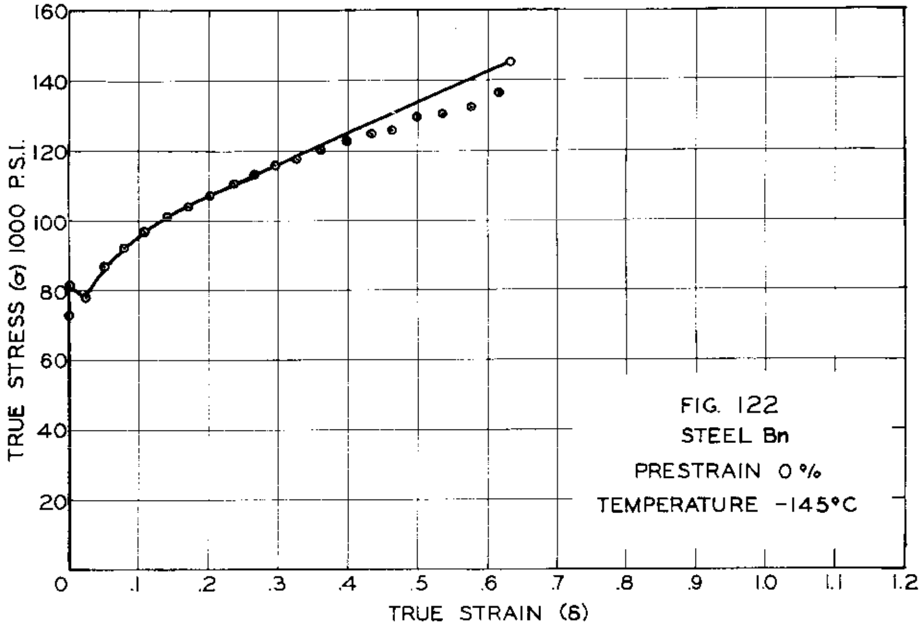


FIG. 122
STEEL Bn
PRESTRAIN 0%
TEMPERATURE -145°C

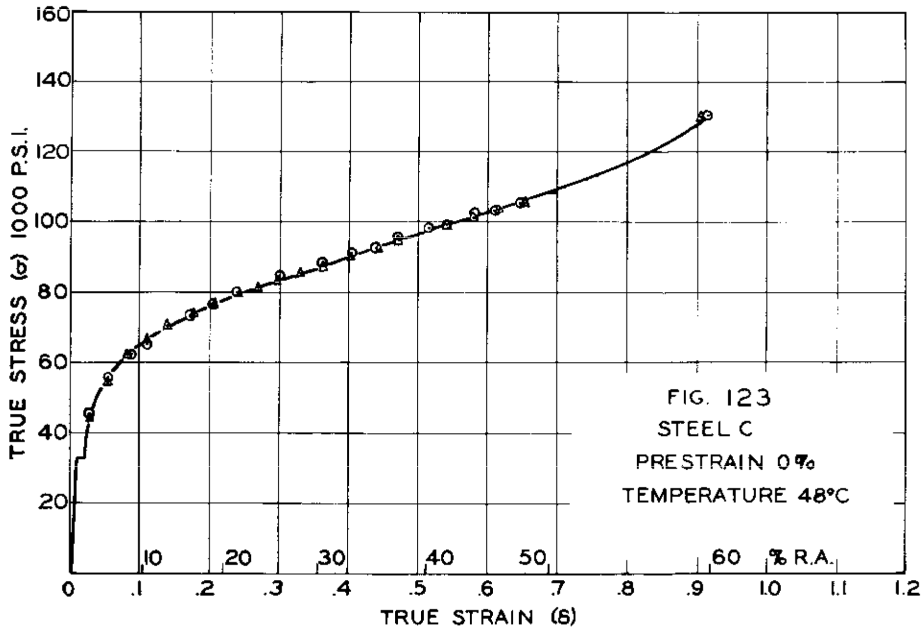


FIG. 123
STEEL C
PRESTRAIN 0%
TEMPERATURE 48°C

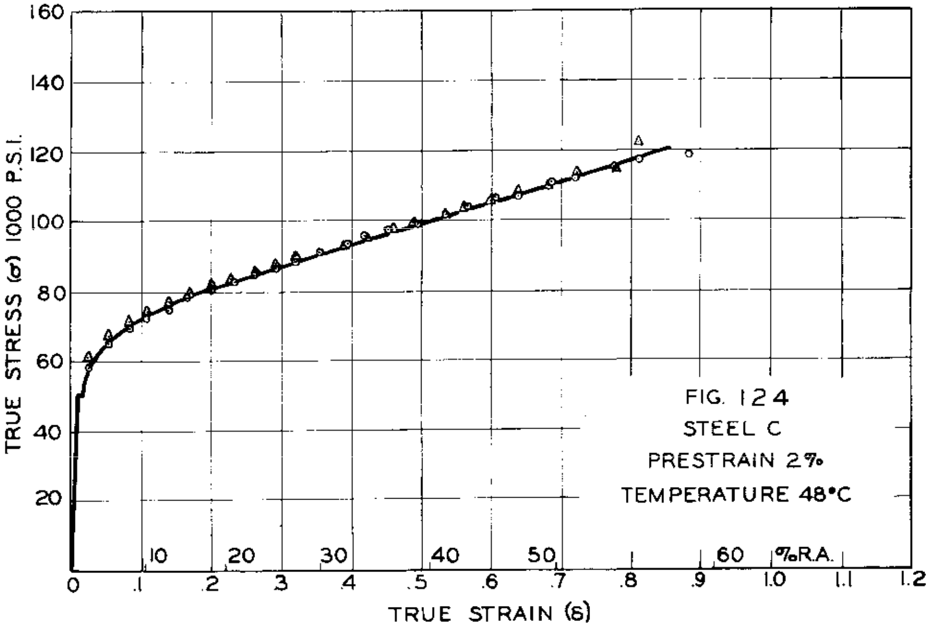


FIG. 124
STEEL C
PRESTRAIN 2%
TEMPERATURE 48°C

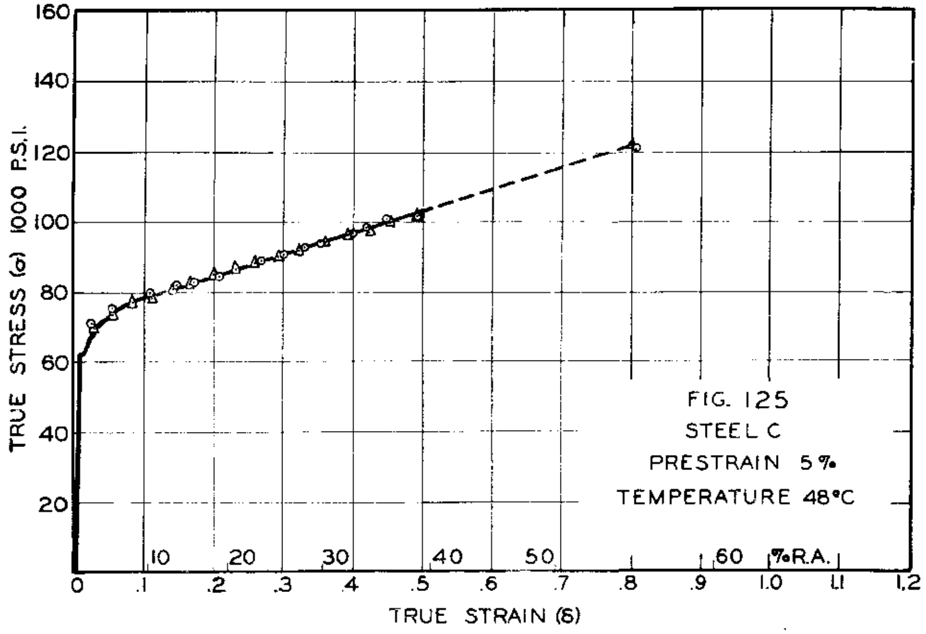


FIG. 125
STEEL C
PRESTRAIN 5%
TEMPERATURE 48°C

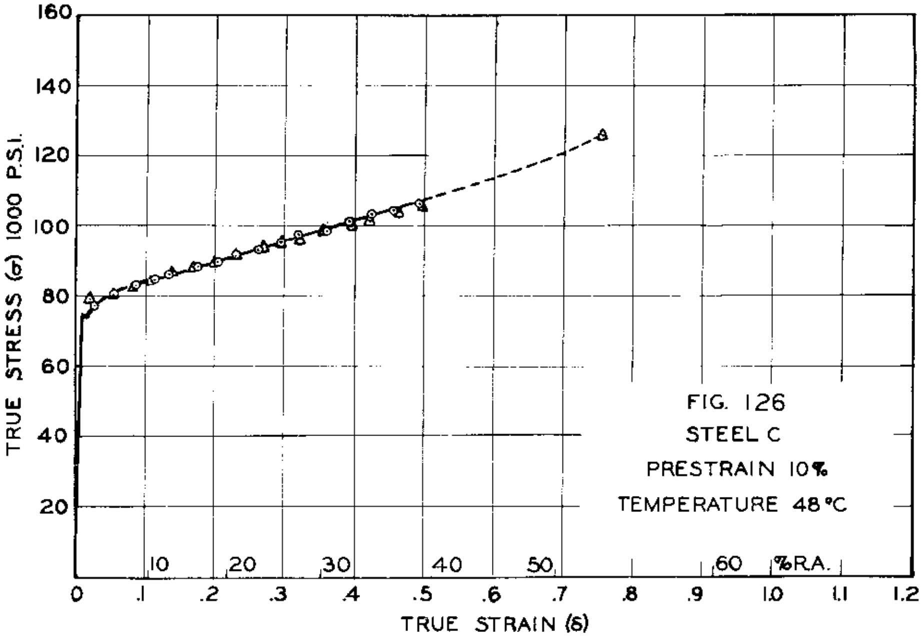


FIG. 126
STEEL C
PRESTRAIN 10%
TEMPERATURE 48°C

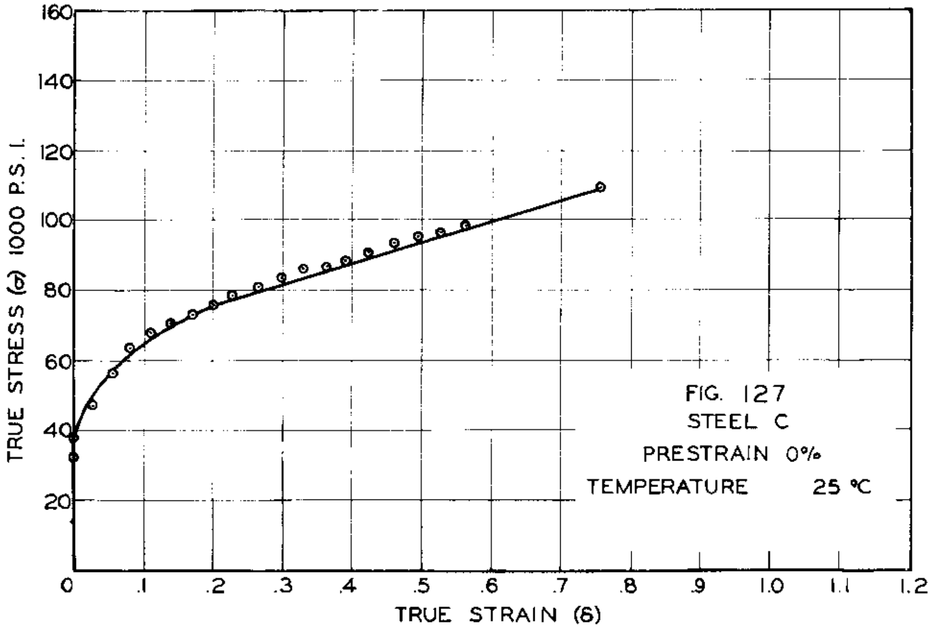


FIG. 127
STEEL C
PRESTRAIN 0%
TEMPERATURE 25 °C

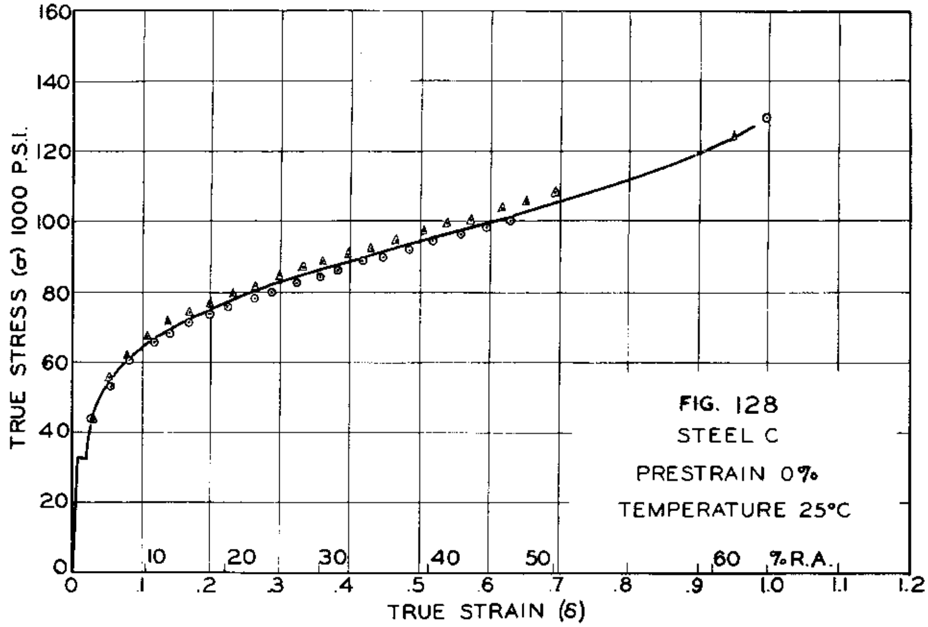


FIG. 128
STEEL C
PRESTRAIN 0%
TEMPERATURE 25°C

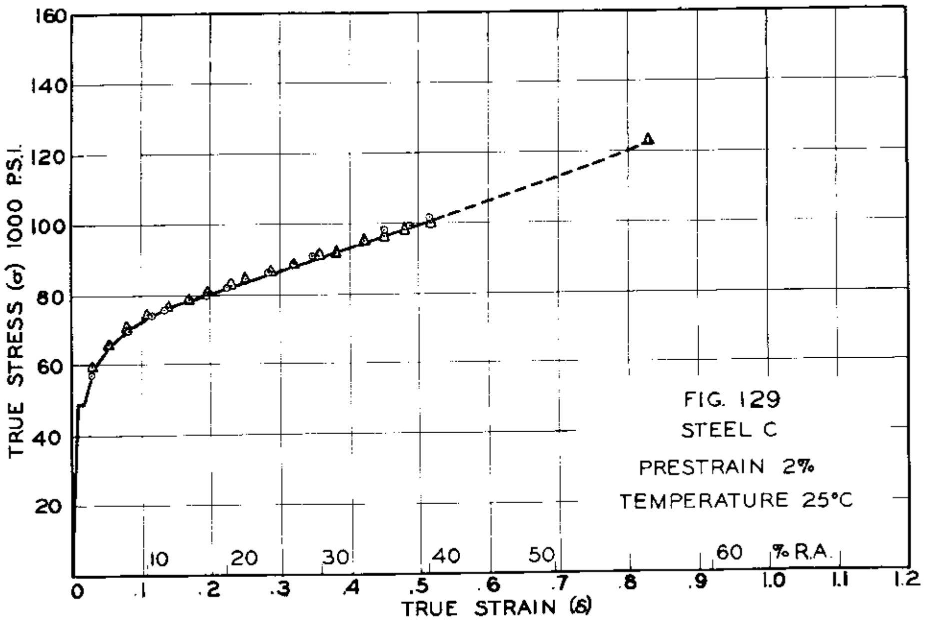


FIG. 129
STEEL C
PRESTRAIN 2%
TEMPERATURE 25°C

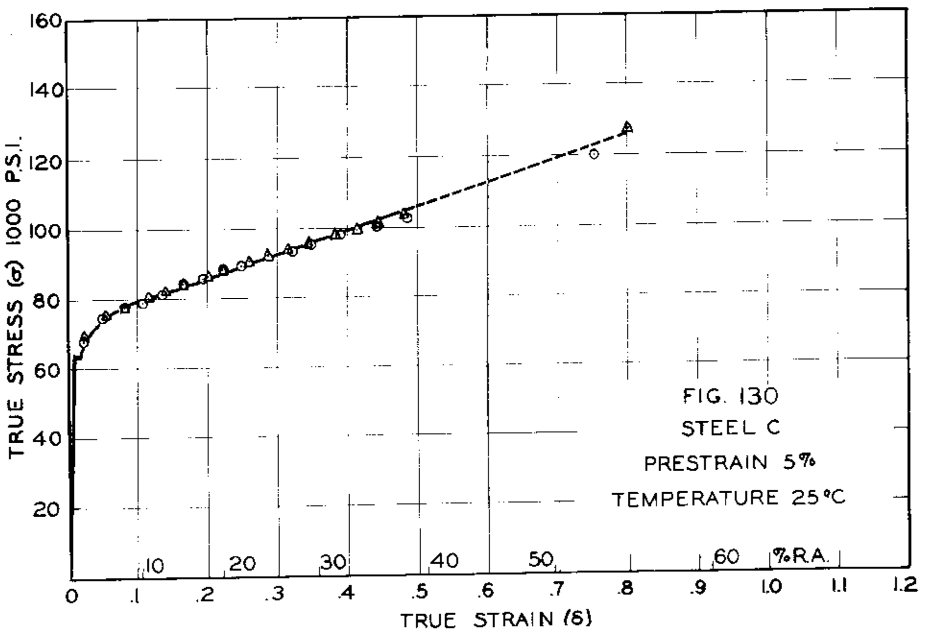


FIG. 130
STEEL C
PRESTRAIN 5%
TEMPERATURE 25°C

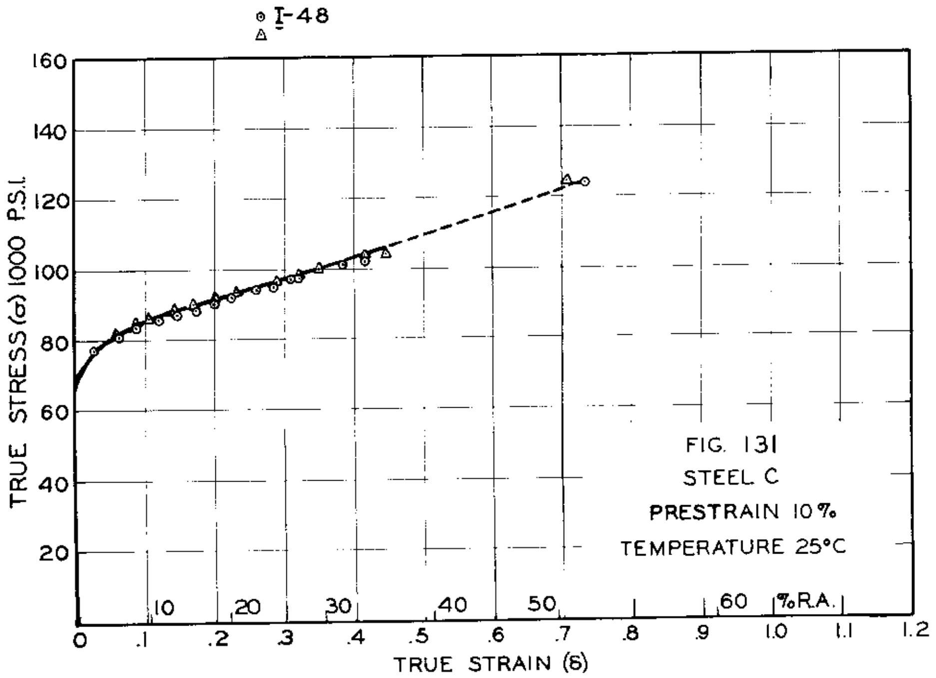


FIG. 131
STEEL C
PRESTRAIN 10%
TEMPERATURE 25°C

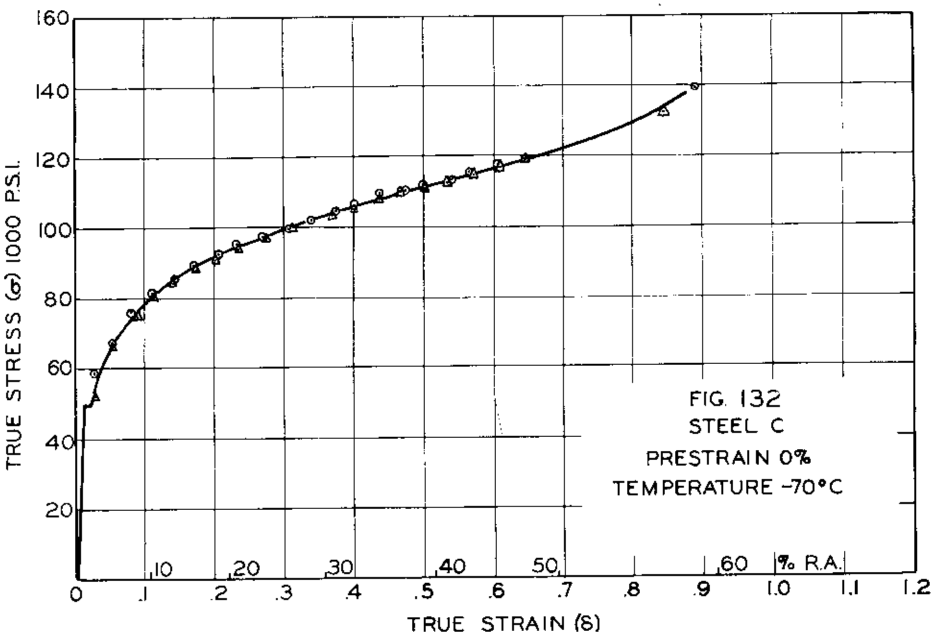


FIG. 132
STEEL C
PRESTRAIN 0%
TEMPERATURE -70°C

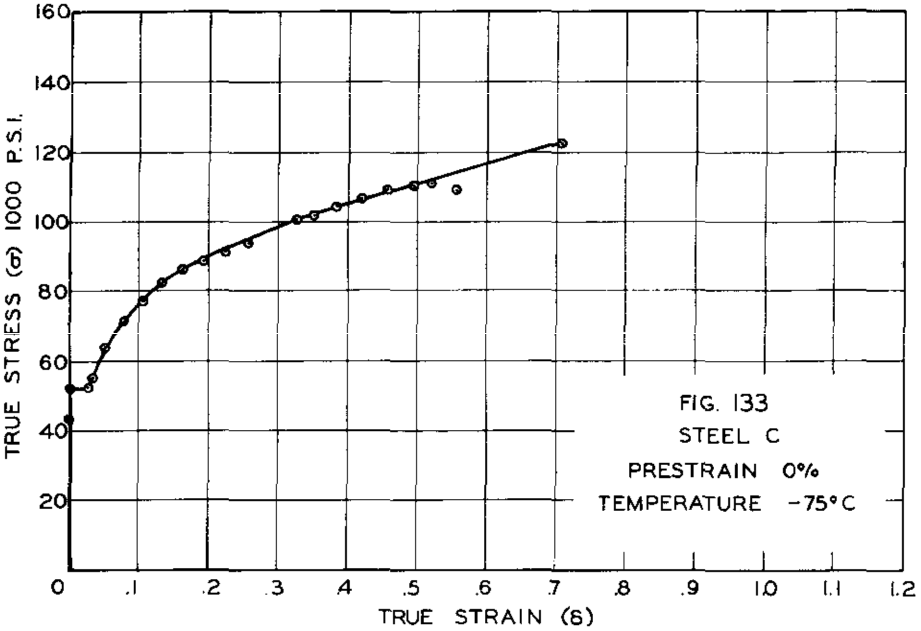


FIG. 133
STEEL C
PRESTRAIN 0%
TEMPERATURE -75°C

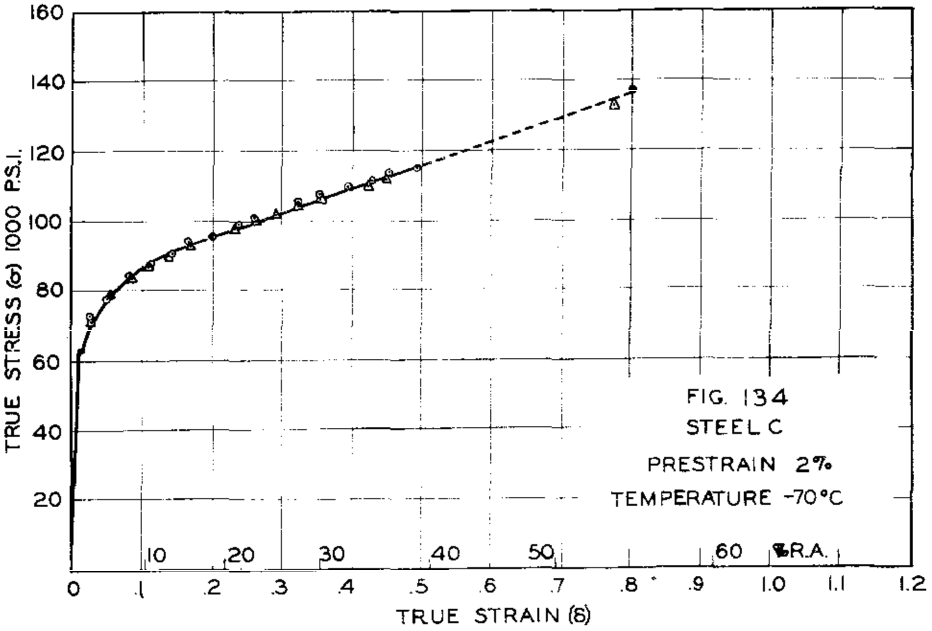


FIG. 134
STEEL C
PRESTRAIN 2%
TEMPERATURE -70°C

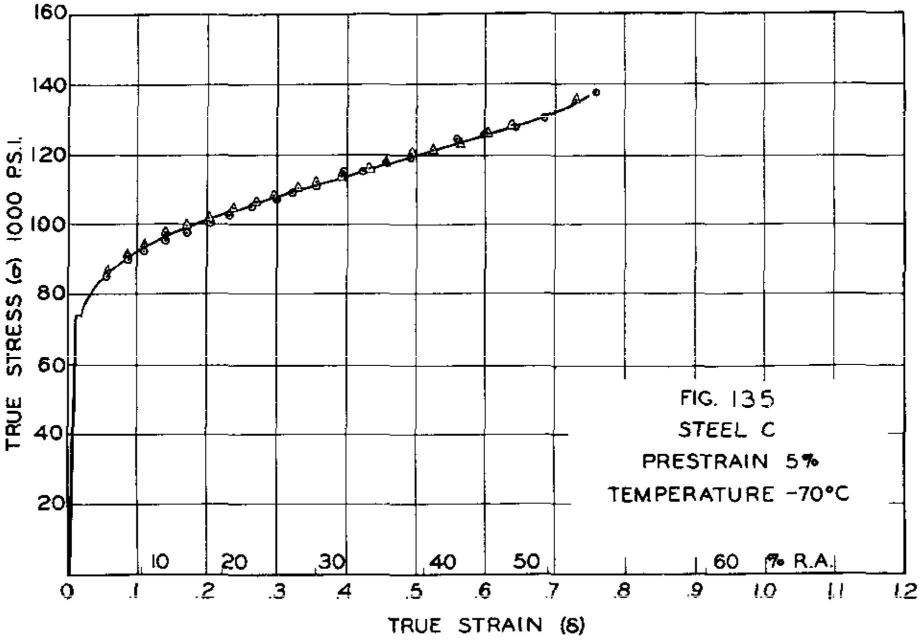


FIG. 135
STEEL C
PRESTRAIN 5%
TEMPERATURE -70°C

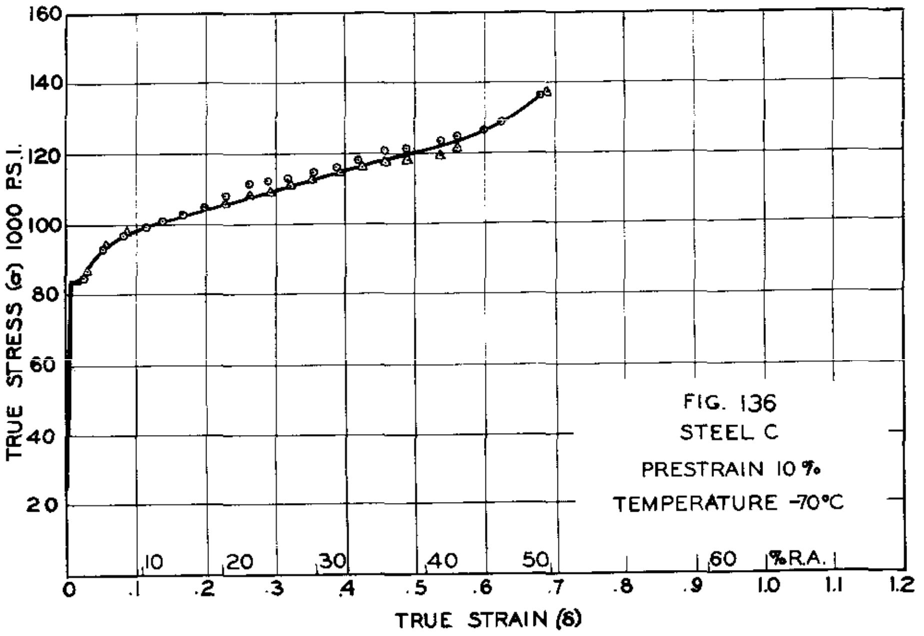


FIG. 136
STEEL C
PRESTRAIN 10%
TEMPERATURE -70°C

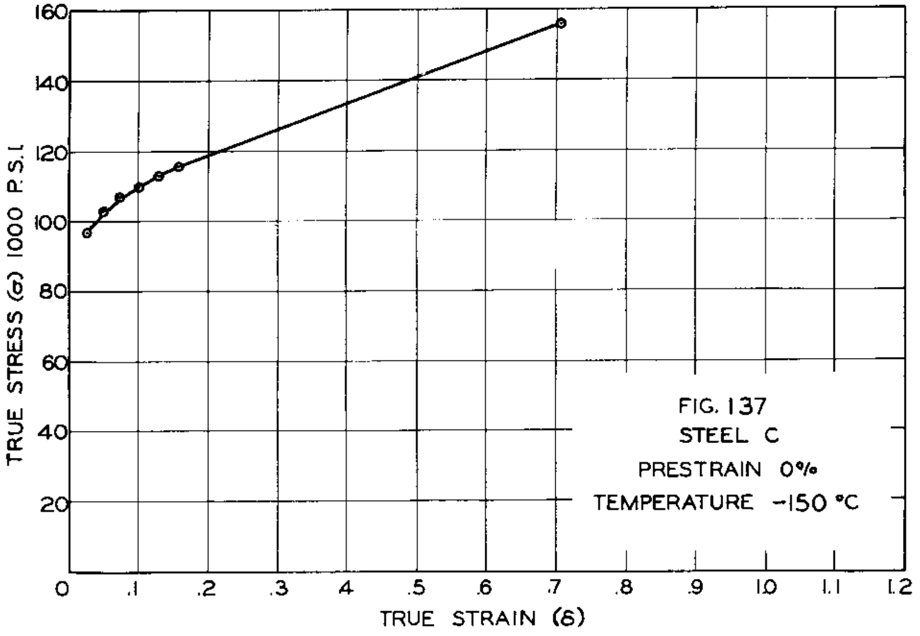


FIG. 137
STEEL C
PRESTRAIN 0%
TEMPERATURE -150 °C

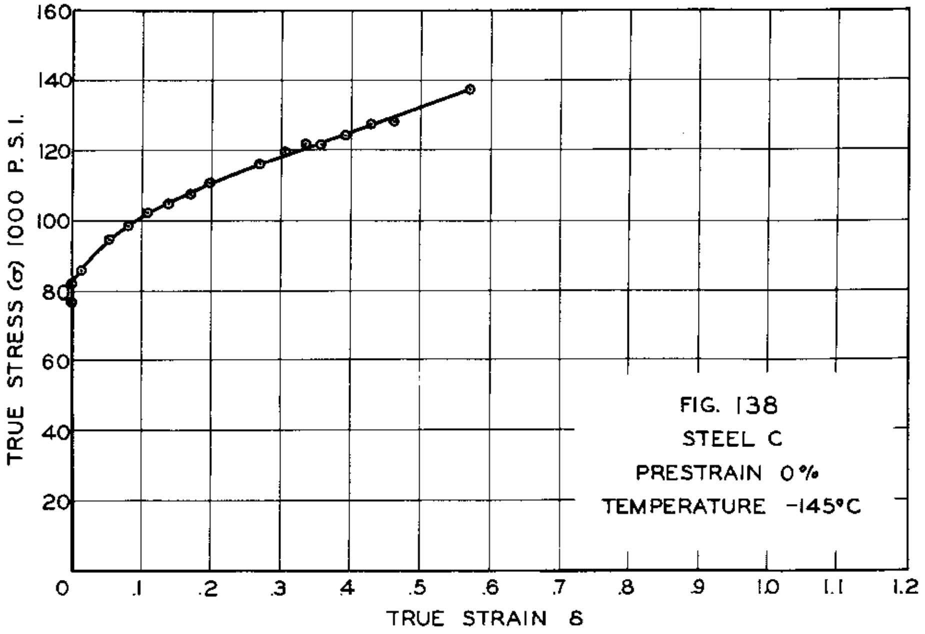


FIG. 138
STEEL C
PRESTRAIN 0%
TEMPERATURE -145°C

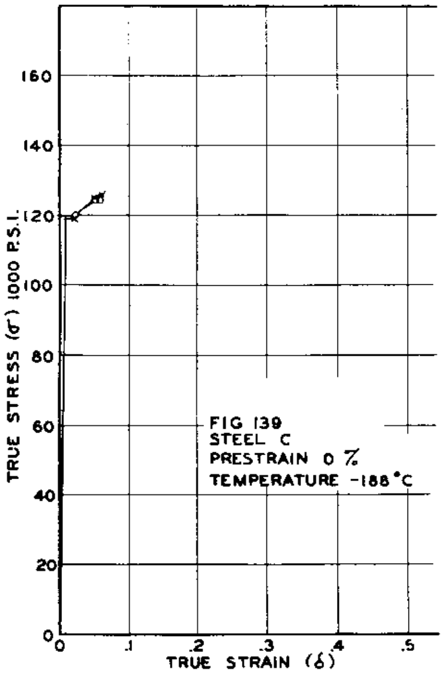


FIG 139
STEEL C
PRESTRAIN 0 %
TEMPERATURE -188 °C

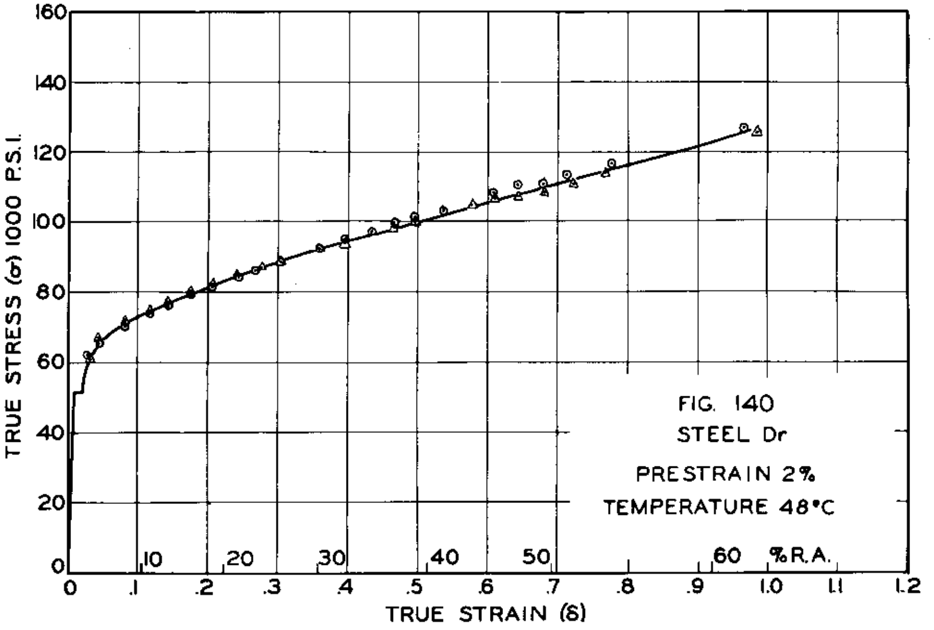


FIG. 140
STEEL Dr
PRESTRAIN 2%
TEMPERATURE 48°C

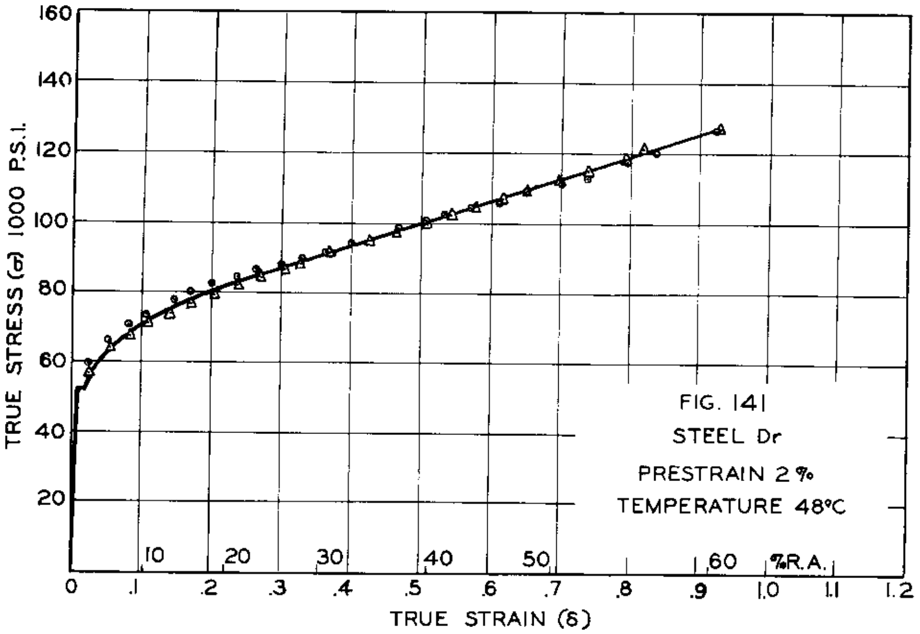


FIG. 141
STEEL Dr
PRESTRAIN 2 %
TEMPERATURE 48°C

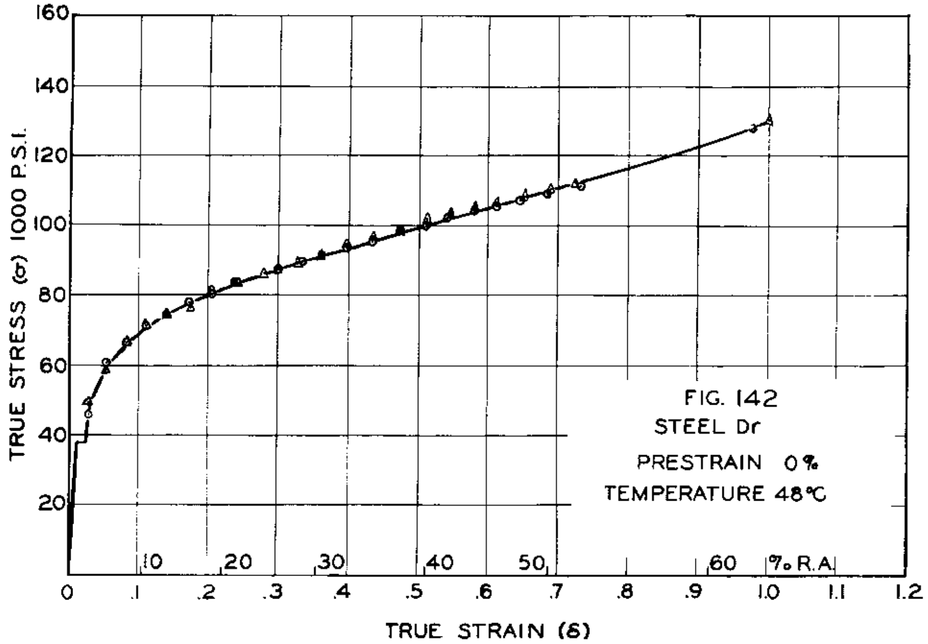


FIG. 142
STEEL Dr
PRESTRAIN 0 %
TEMPERATURE 48°C

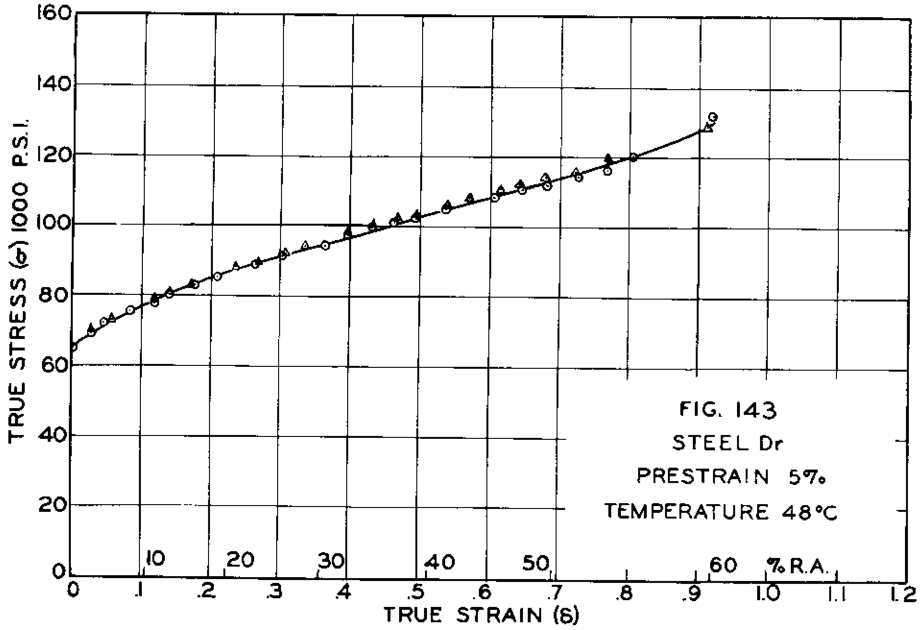


FIG. 143
STEEL Dr
PRESTRAIN 5%
TEMPERATURE 48°C

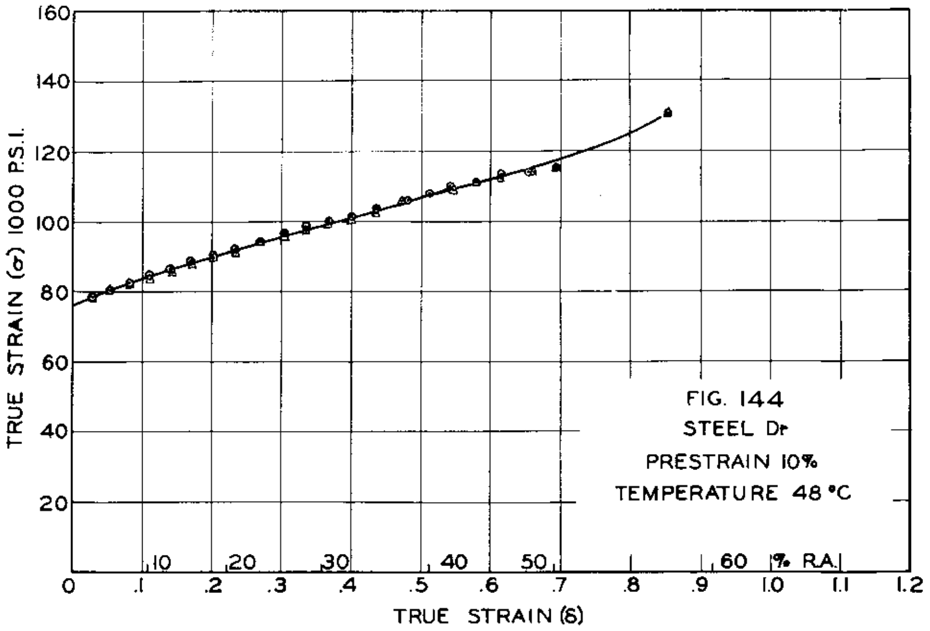


FIG. 144
STEEL Dr
PRESTRAIN 10%
TEMPERATURE 48°C

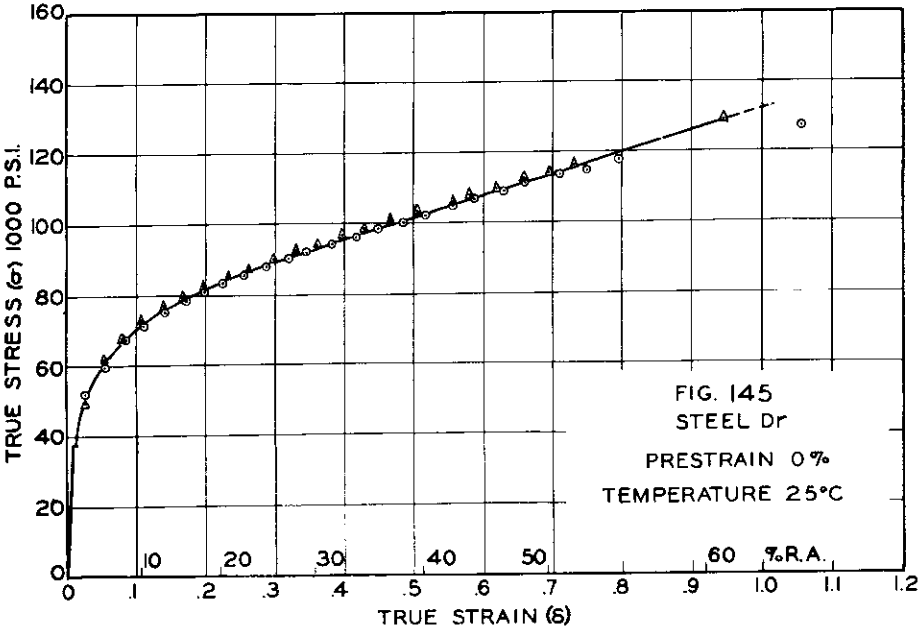


FIG. 145
STEEL Dr
PRESTRAIN 0%
TEMPERATURE 25°C

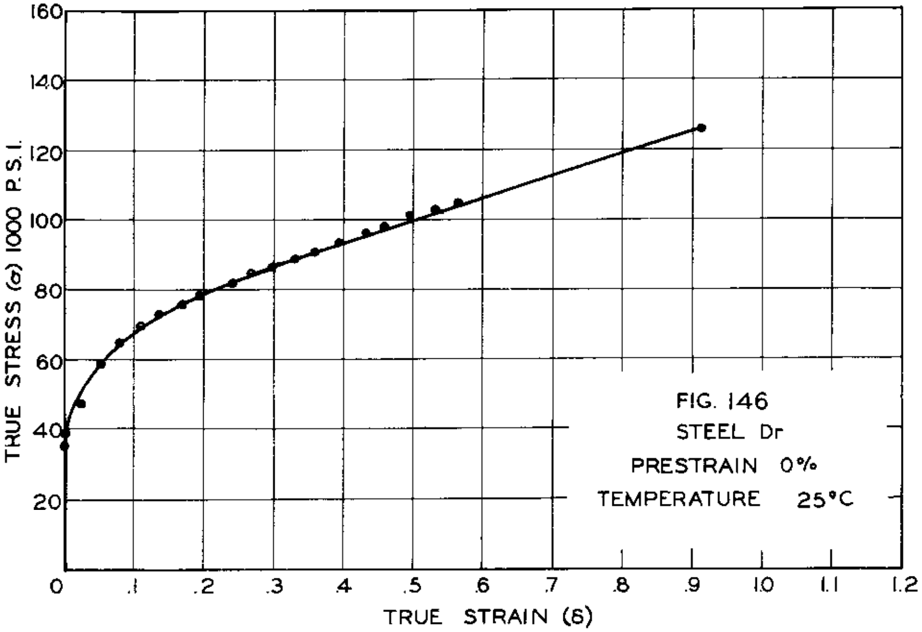


FIG. 146
STEEL Dr
PRESTRAIN 0%
TEMPERATURE 25°C

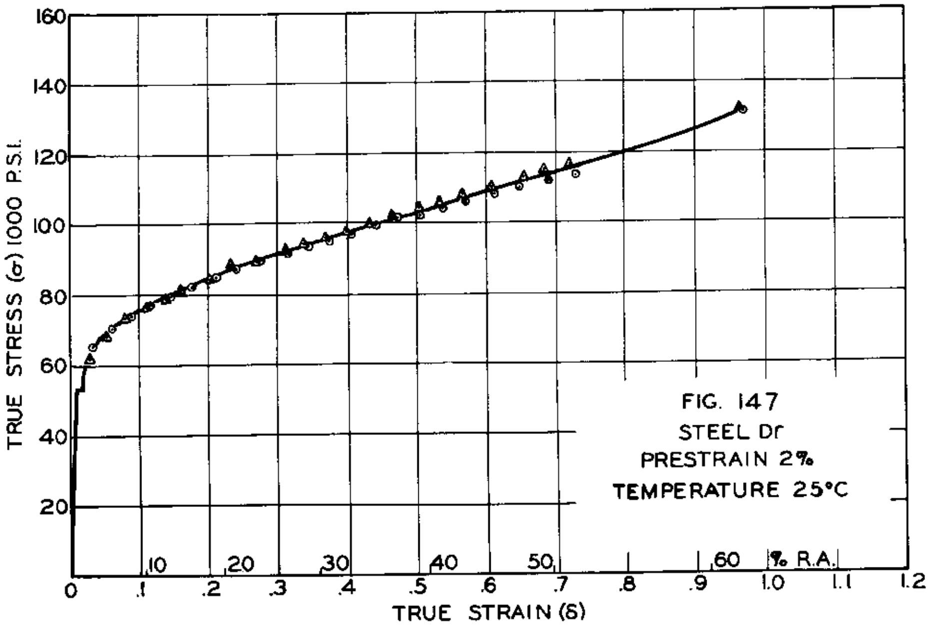


FIG. 147
STEEL Dr
PRESTRAIN 2%
TEMPERATURE 25°C

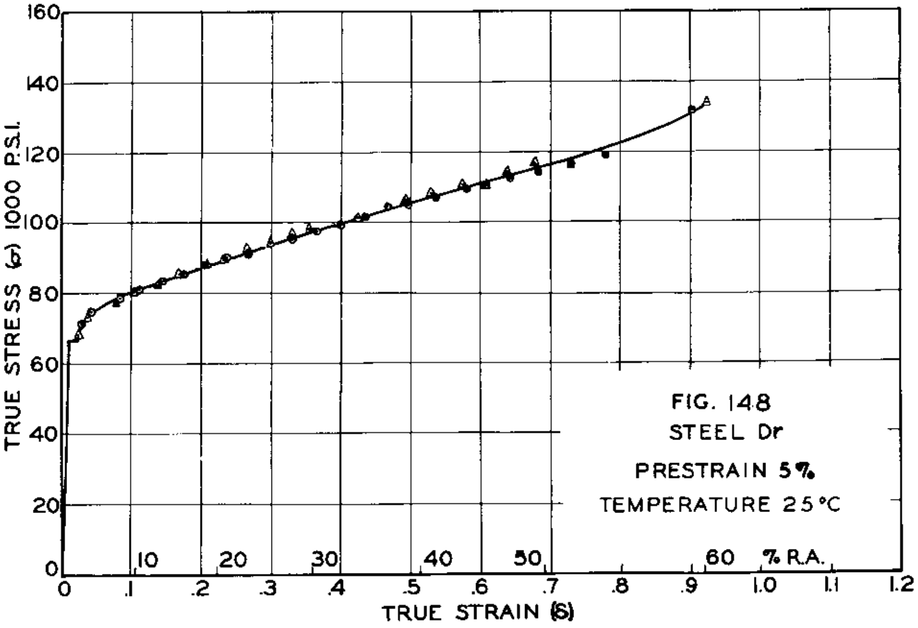


FIG. 148
STEEL Dr
PRESTRAIN 5%
TEMPERATURE 25°C

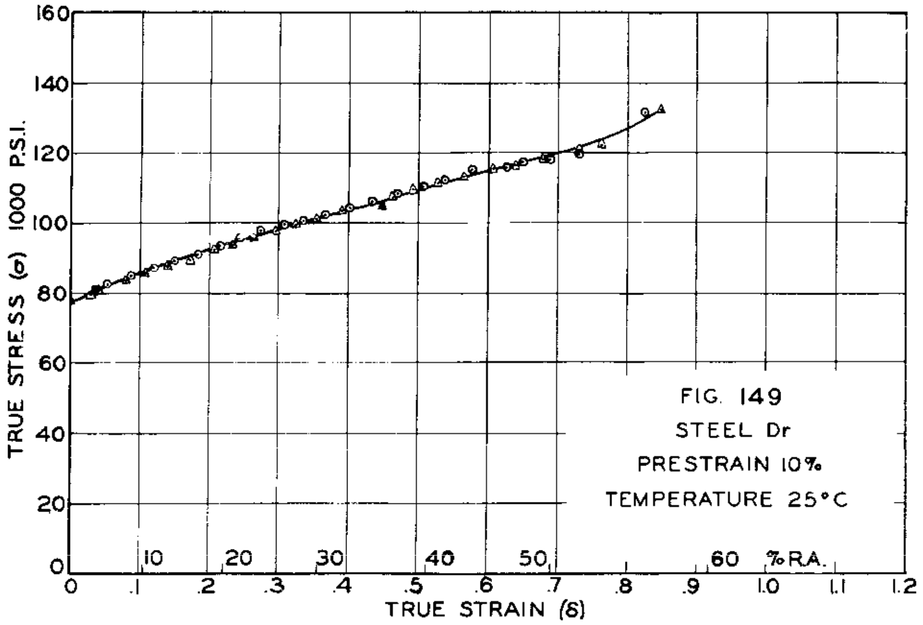


FIG. 149
STEEL Dr
PRESTRAIN 10%
TEMPERATURE 25°C

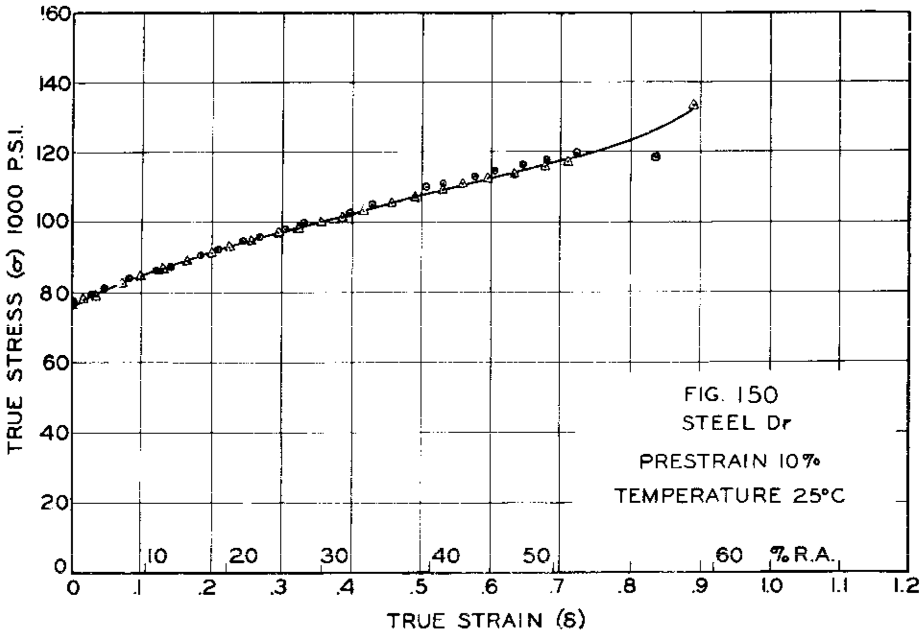


FIG. 150
STEEL Dr
PRESTRAIN 10%
TEMPERATURE 25°C

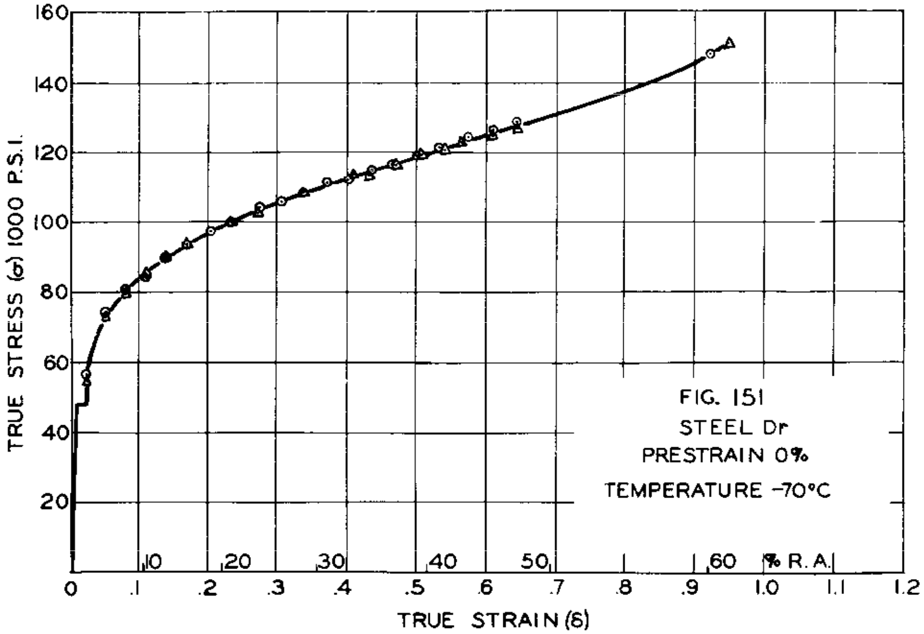


FIG. 151
STEEL Dr
PRESTRAIN 0%
TEMPERATURE -70°C

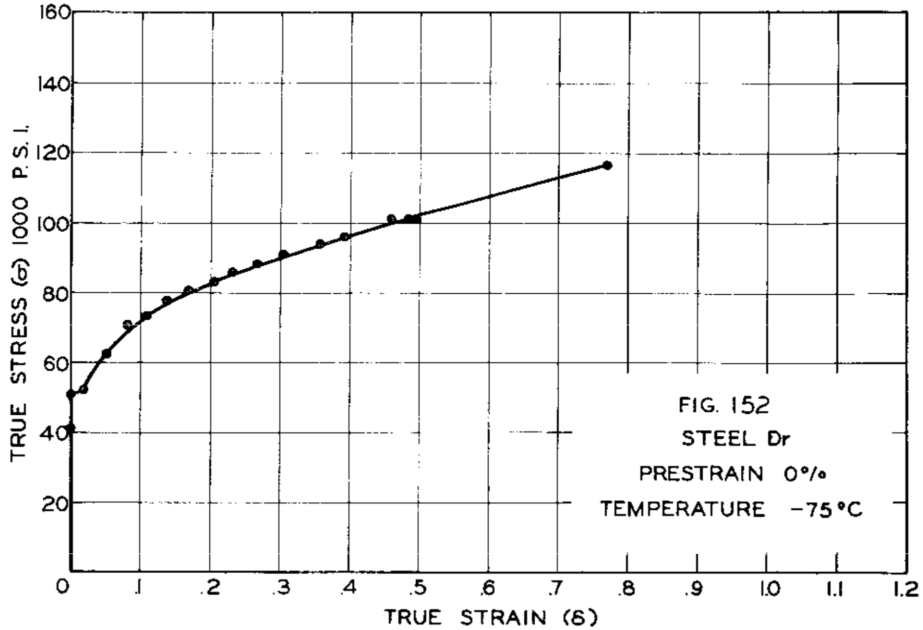


FIG. 152
STEEL Dr
PRESTRAIN 0%
TEMPERATURE -75°C

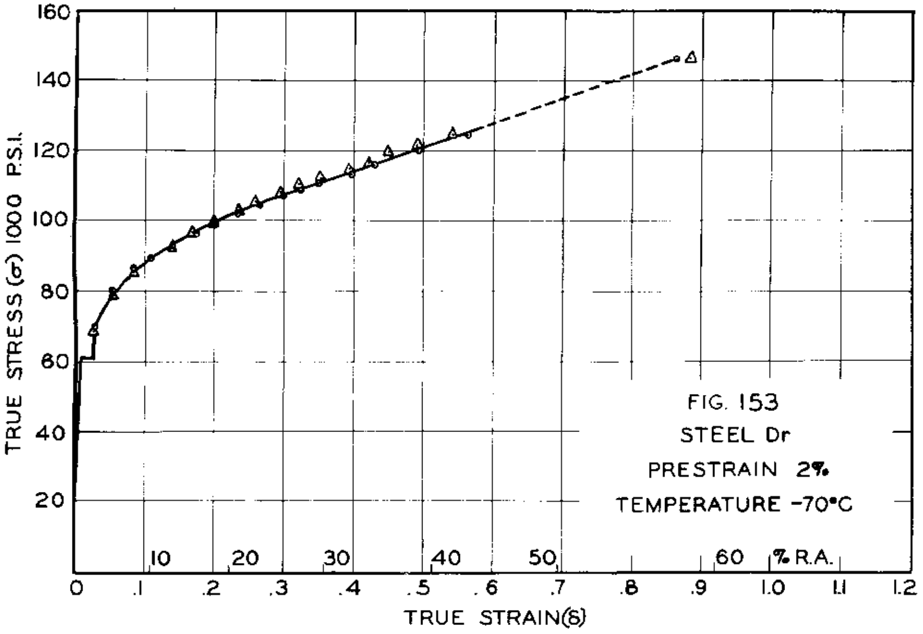


FIG. 153
STEEL Dr
PRESTRAIN 2%
TEMPERATURE -70°C

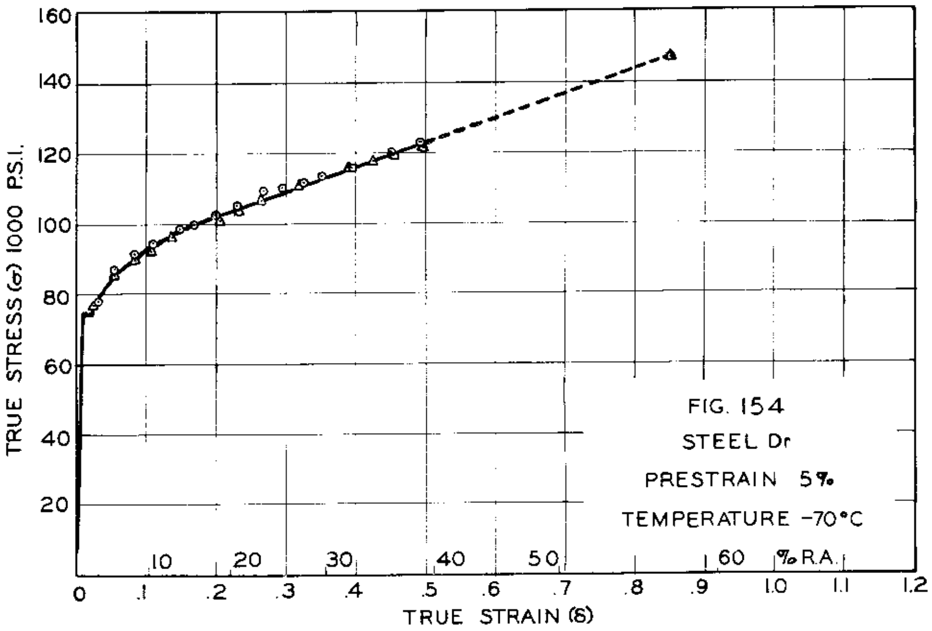


FIG. 154
STEEL Dr
PRESTRAIN 5%
TEMPERATURE -70°C

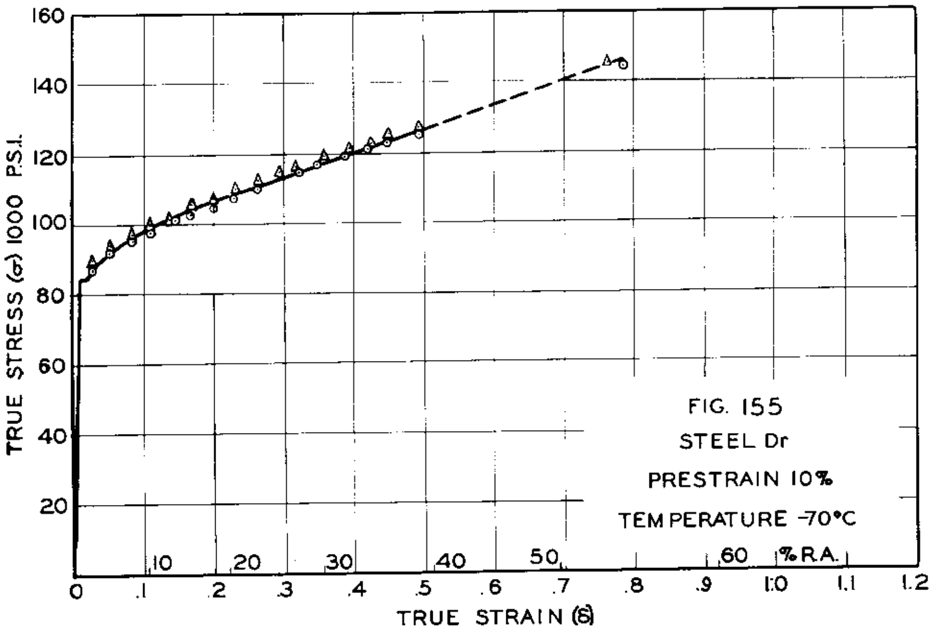


FIG. 155
STEEL Dr
PRESTRAIN 10%
TEMPERATURE -70°C

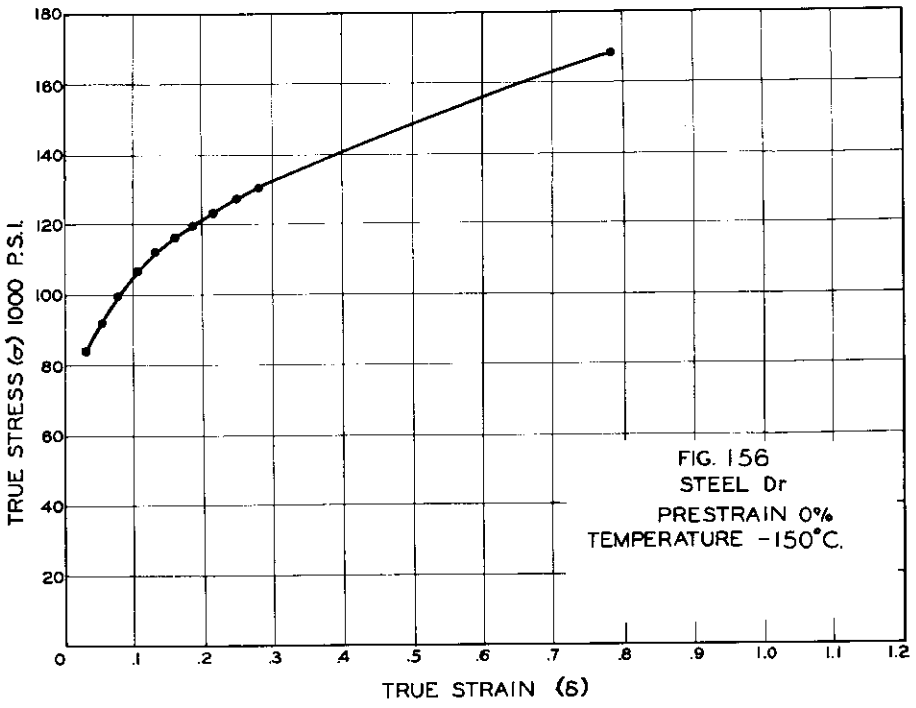


FIG. 156
STEEL Dr
PRESTRAIN 0%
TEMPERATURE -150°C.

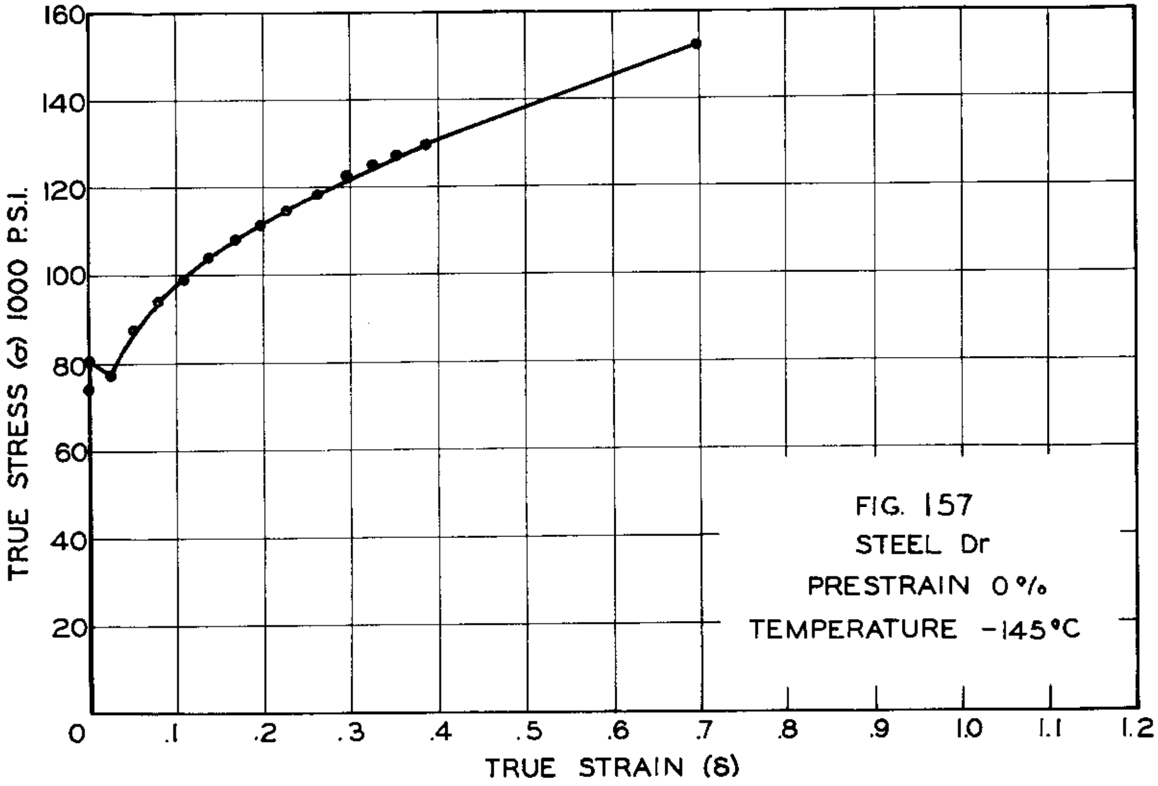


FIG. 157
STEEL Dr
PRESTRAIN 0%
TEMPERATURE -145°C

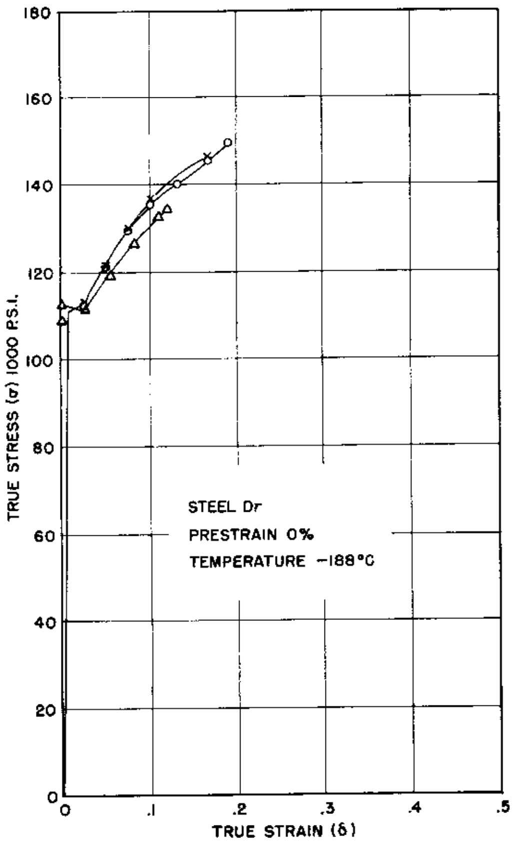


FIG. 158

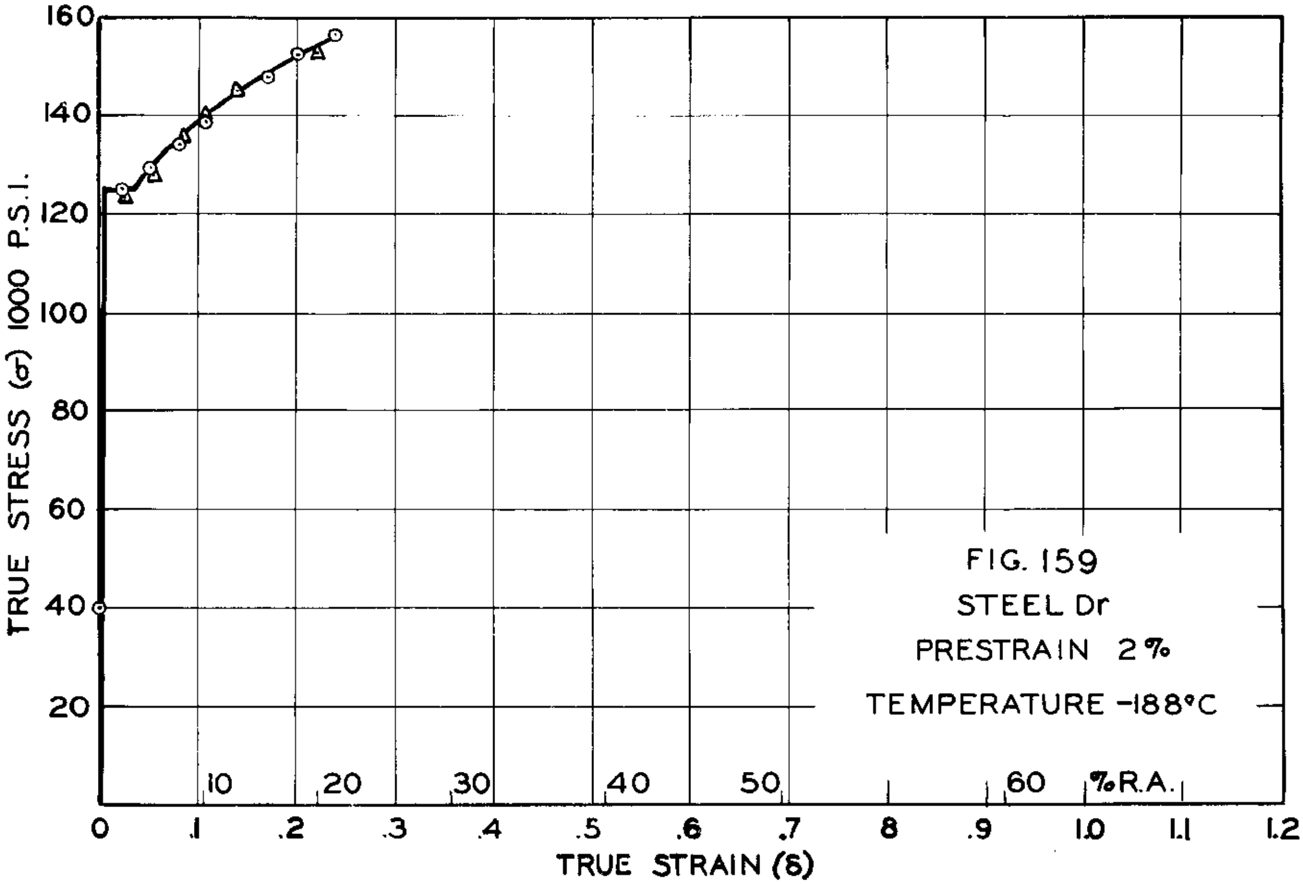


FIG. 159
STEEL Dr
PRESTRAIN 2%
TEMPERATURE -188°C

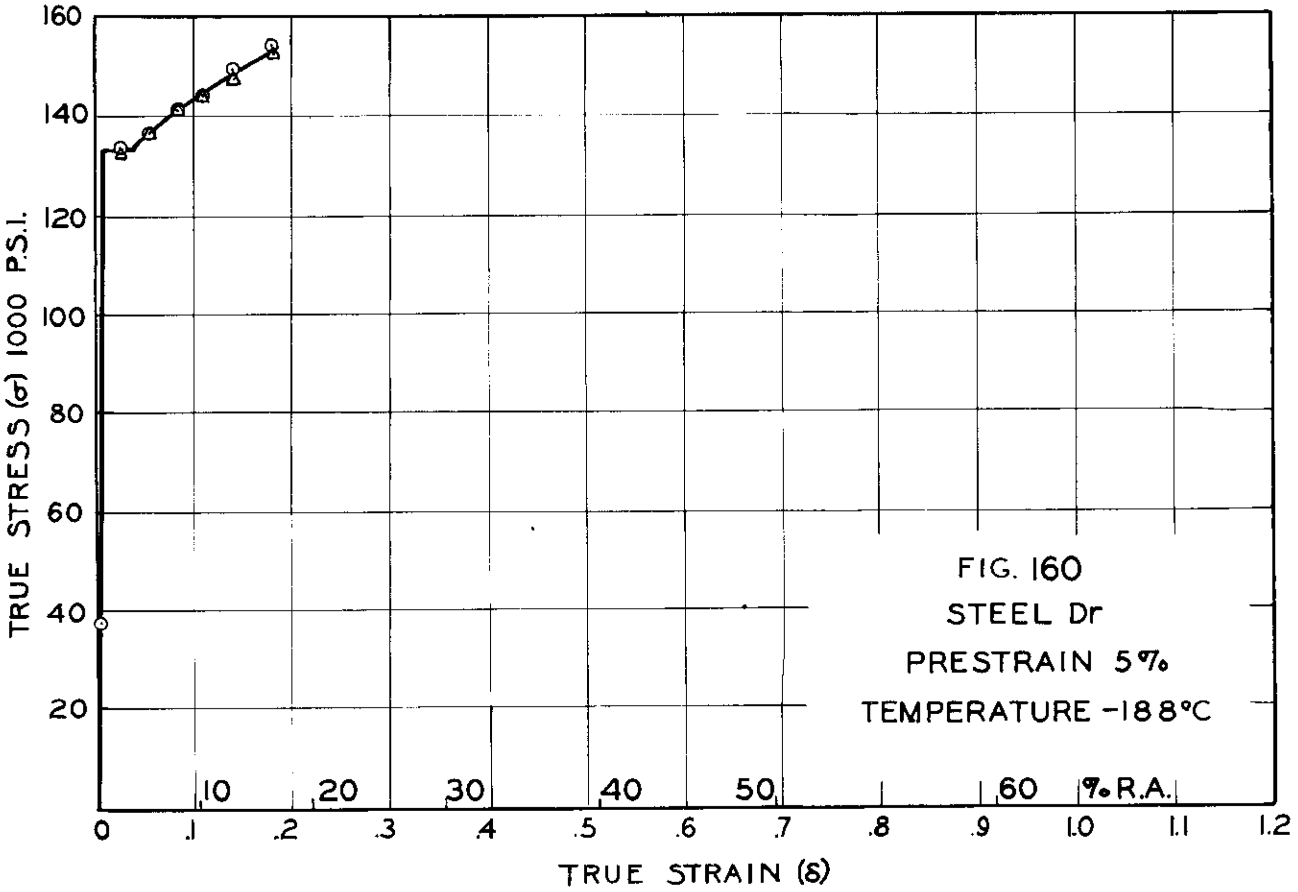


FIG. 160
STEEL Dr
PRESTRAIN 5%
TEMPERATURE -188°C

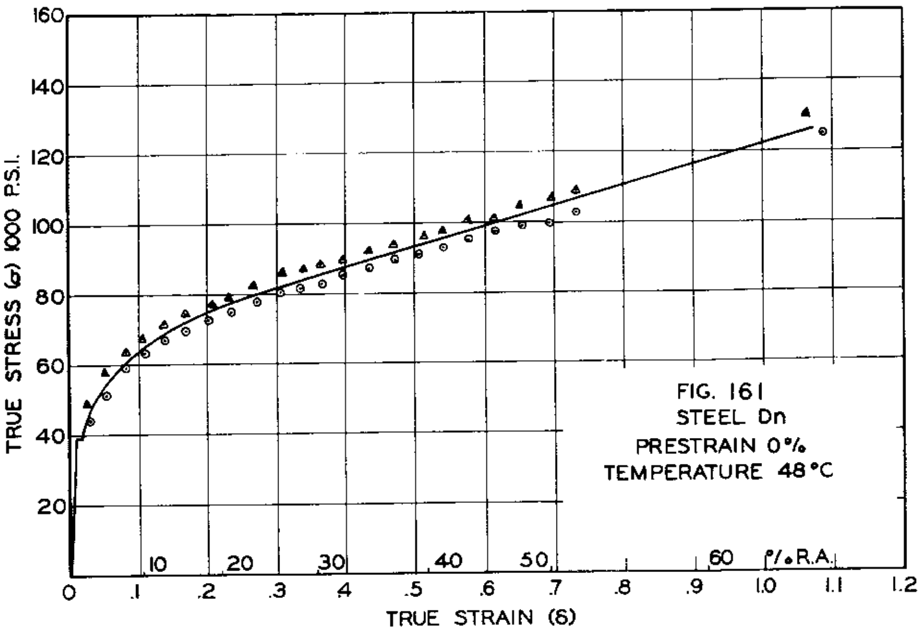


FIG. 161
STEEL Dn
PRESTRAIN 0%
TEMPERATURE 48°C

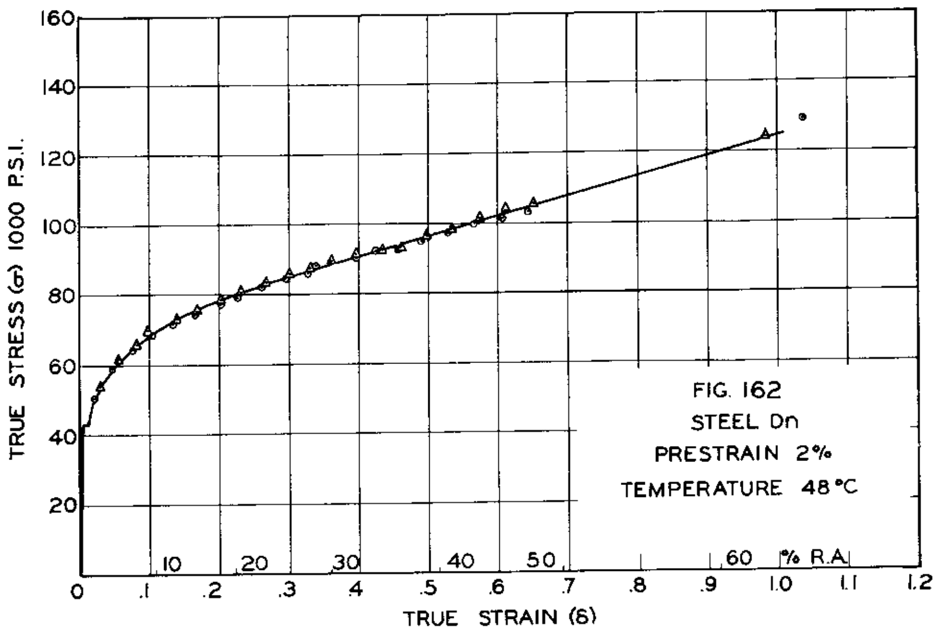


FIG. 162
STEEL Dn
PRESTRAIN 2%
TEMPERATURE 48°C

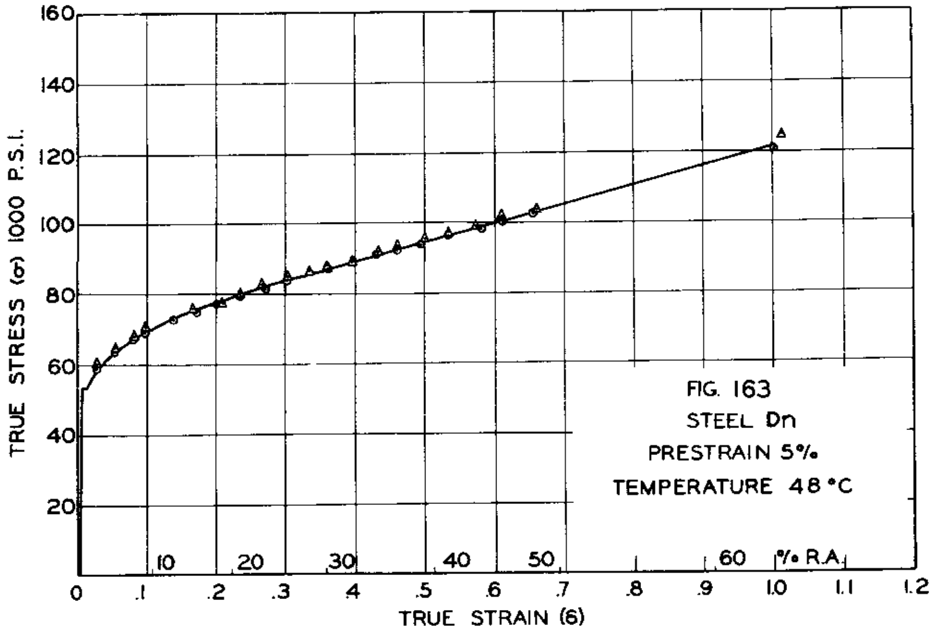


FIG. 163
STEEL Dn
PRESTRAIN 5%
TEMPERATURE 48°C

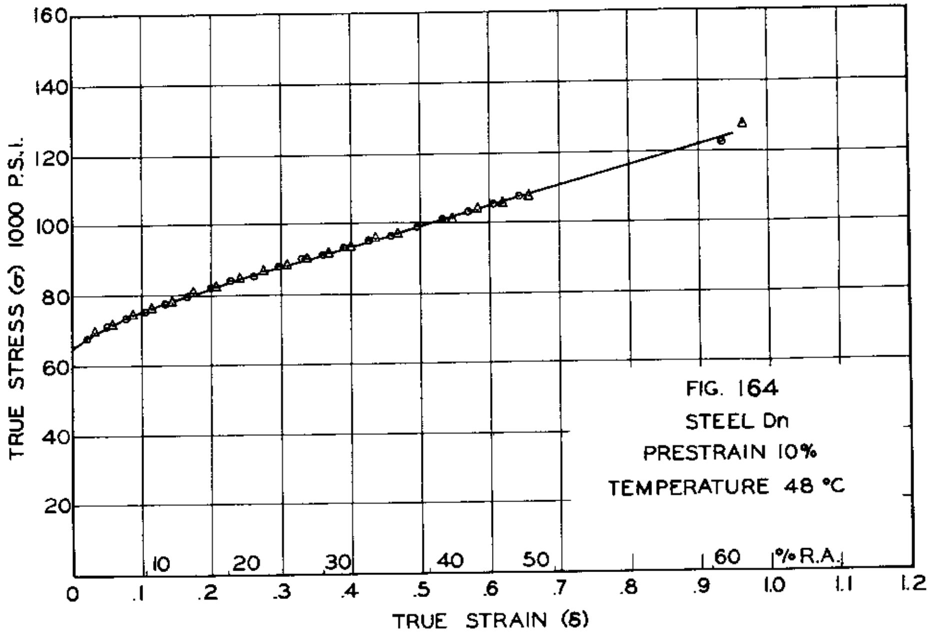


FIG. 164
STEEL Dn
PRESTRAIN 10%
TEMPERATURE 48°C

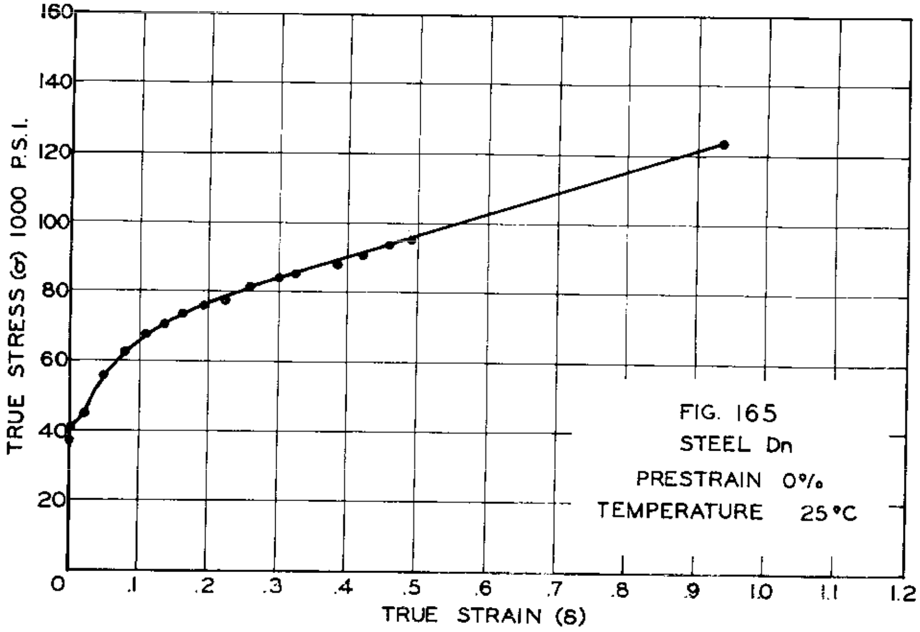


FIG. 165
STEEL Dn
PRESTRAIN 0%
TEMPERATURE 25°C

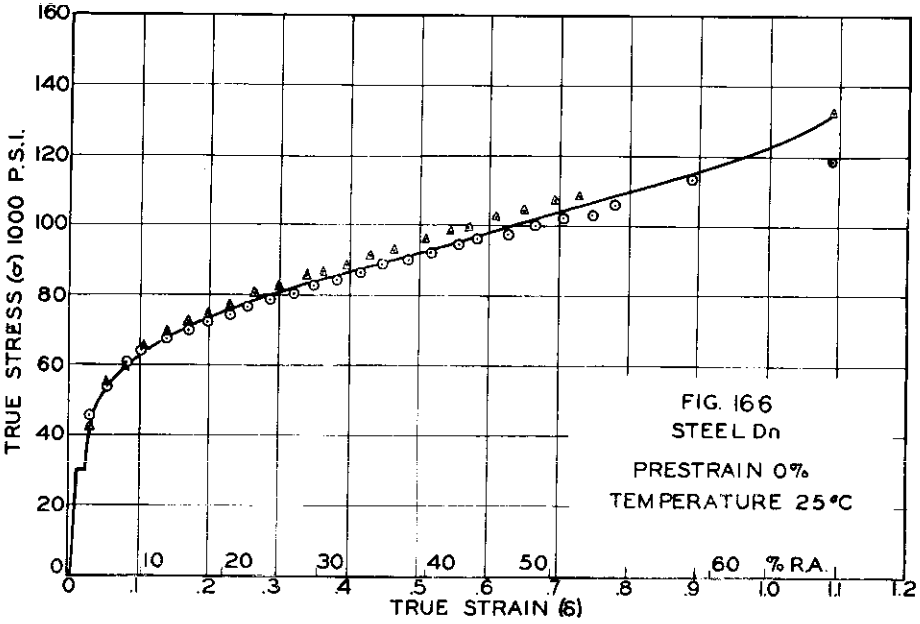


FIG. 166
STEEL Dn
PRESTRAIN 0%
TEMPERATURE 25°C

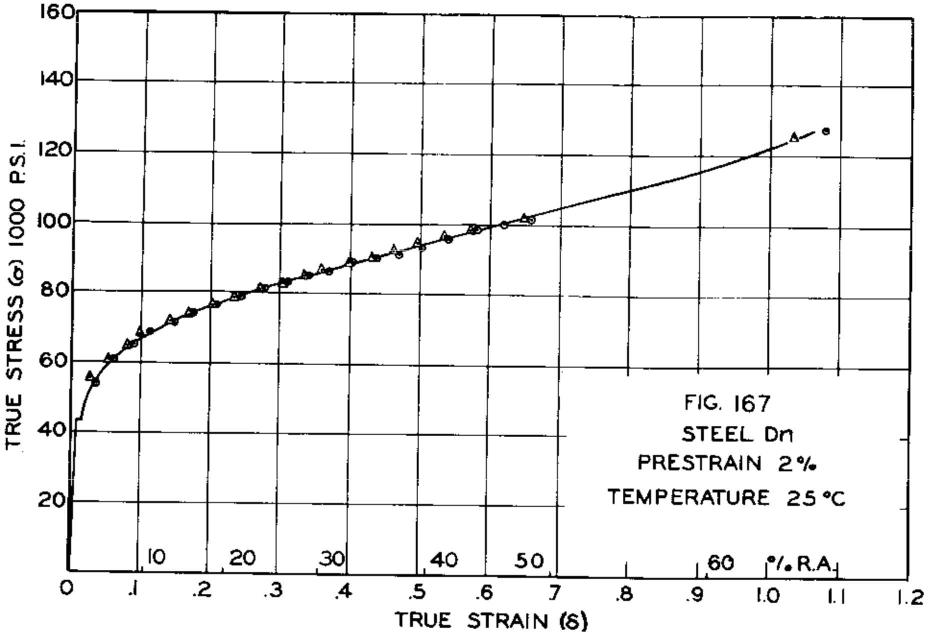


FIG. 167
STEEL Dn
PRESTRAIN 2%
TEMPERATURE 25°C

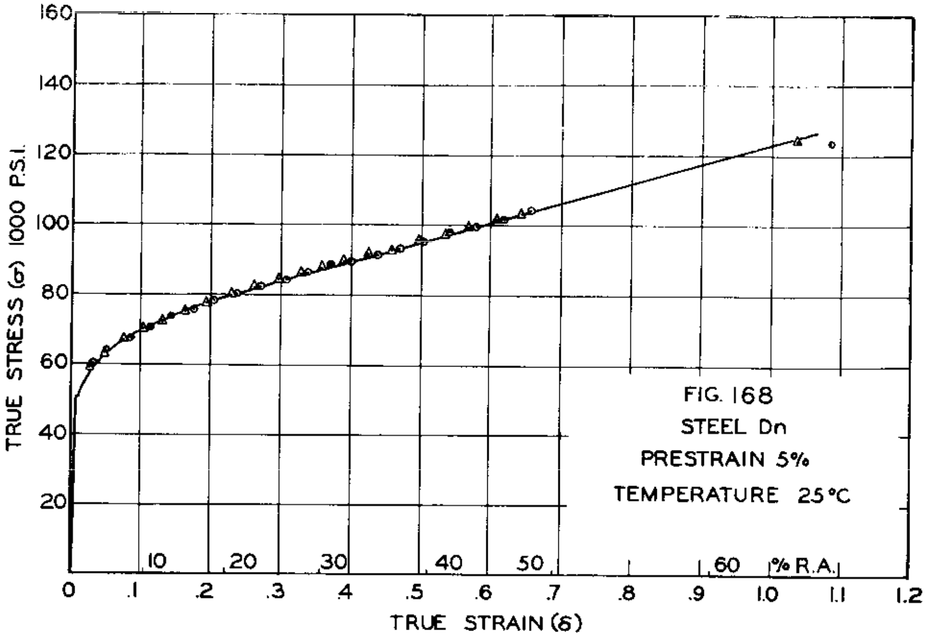


FIG. 168
STEEL Dn
PRESTRAIN 5%
TEMPERATURE 25°C

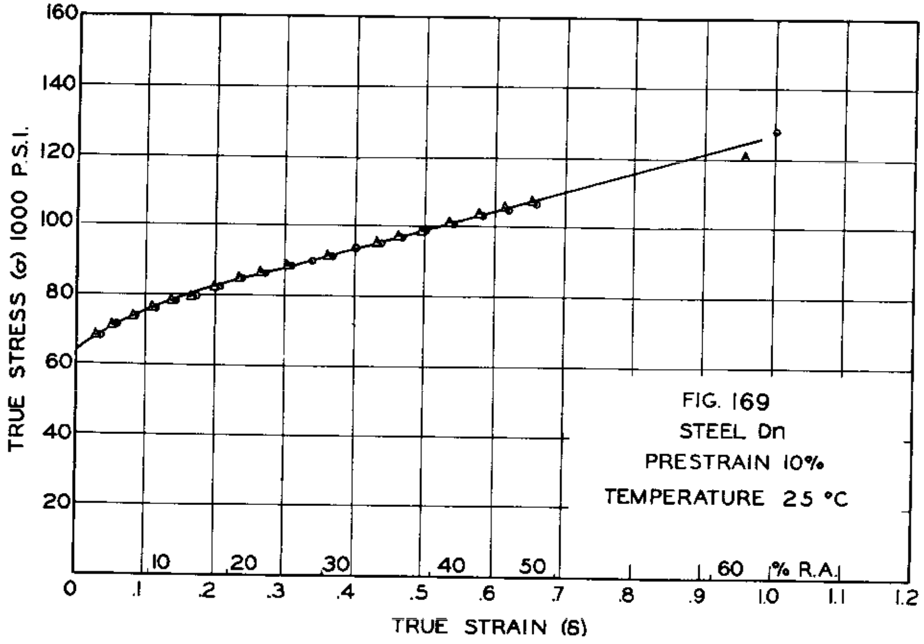


FIG. 169
STEEL Dn
PRESTRAIN 10%
TEMPERATURE 25 °C

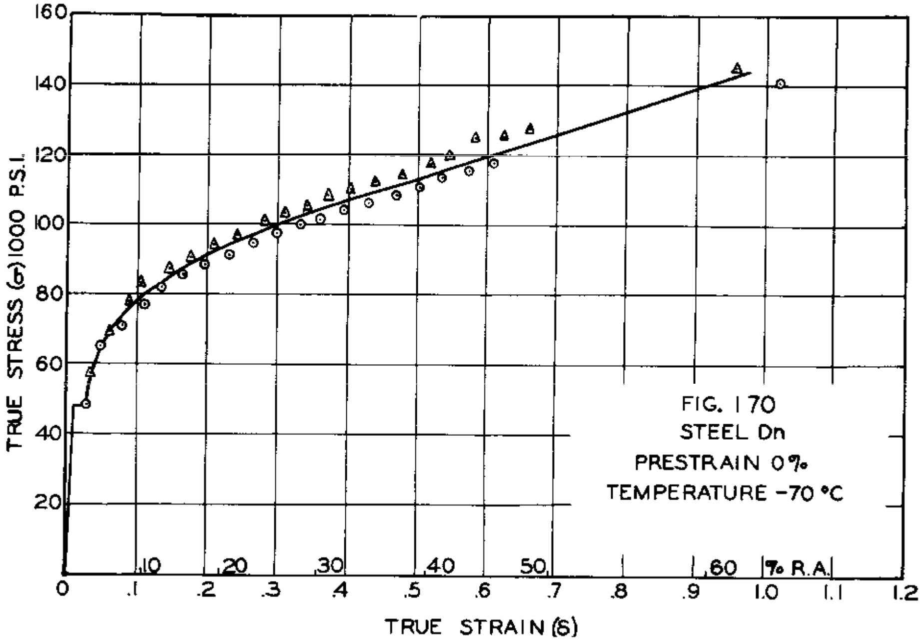


FIG. 170
STEEL Dn
PRESTRAIN 0%
TEMPERATURE -70 °C

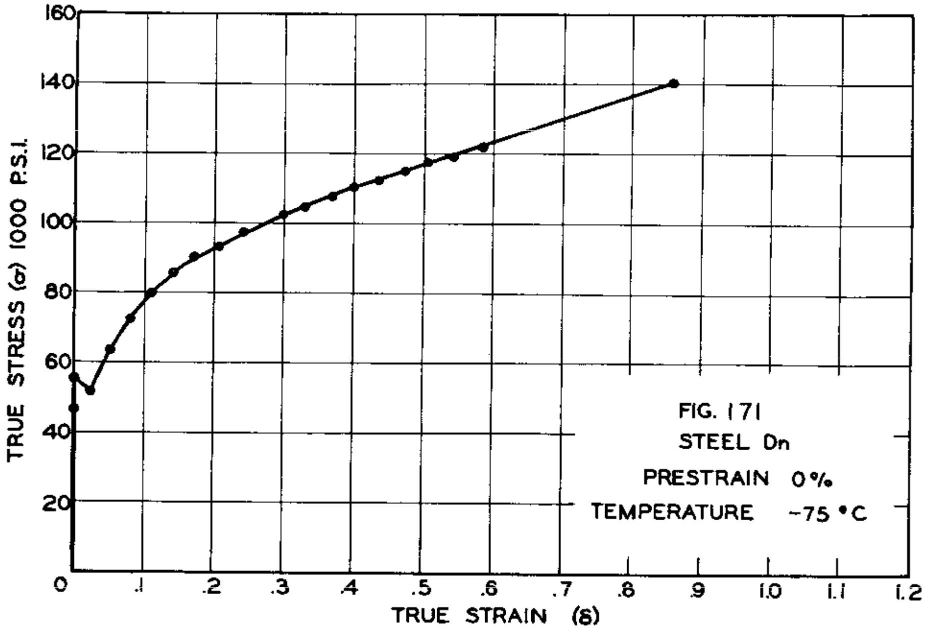


FIG. 171
STEEL Dn
PRESTRAIN 0%
TEMPERATURE -75 °C

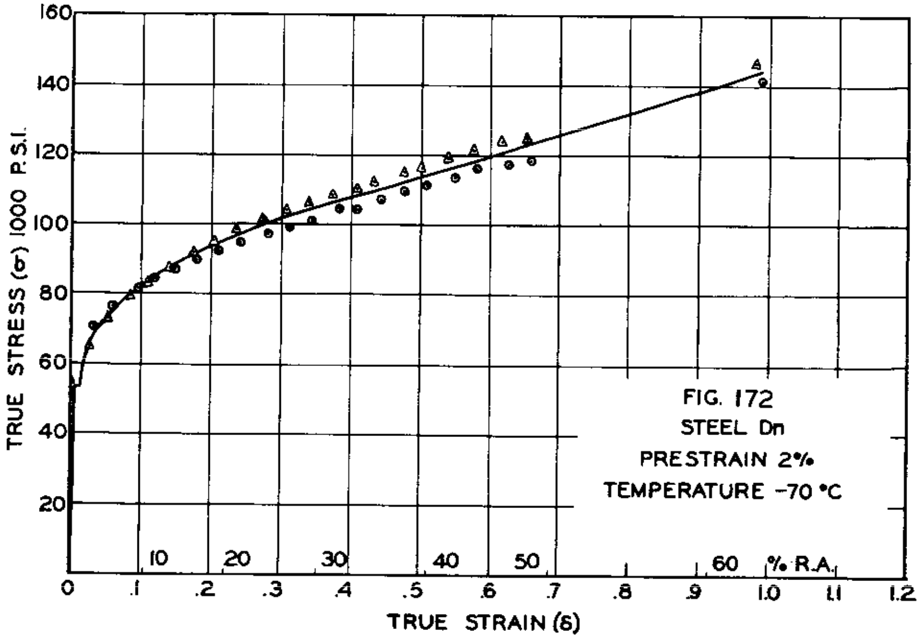


FIG. 172
STEEL Dn
PRESTRAIN 2%
TEMPERATURE -70 °C

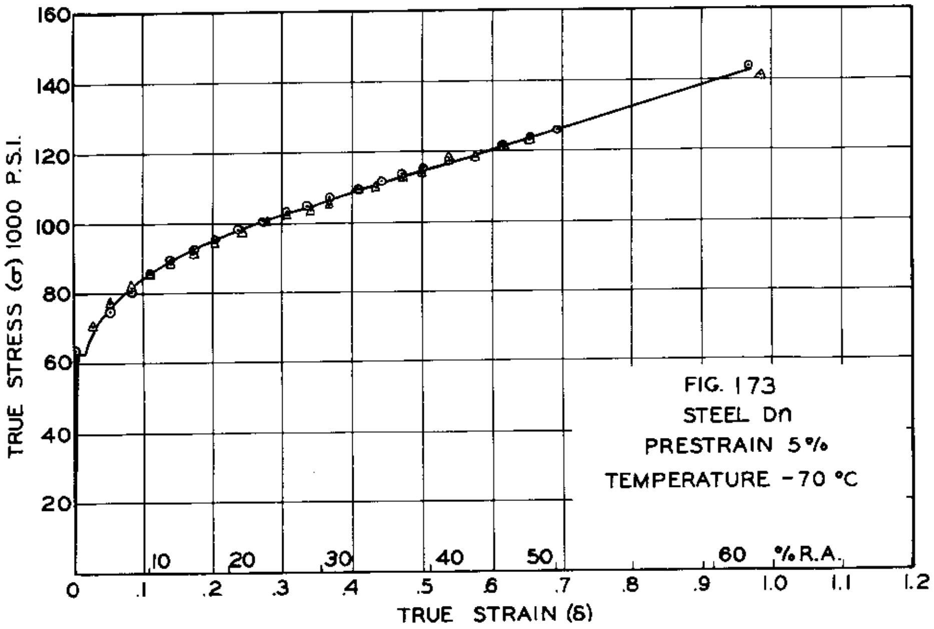


FIG. 173
STEEL Dn
PRESTRAIN 5%
TEMPERATURE -70 °C

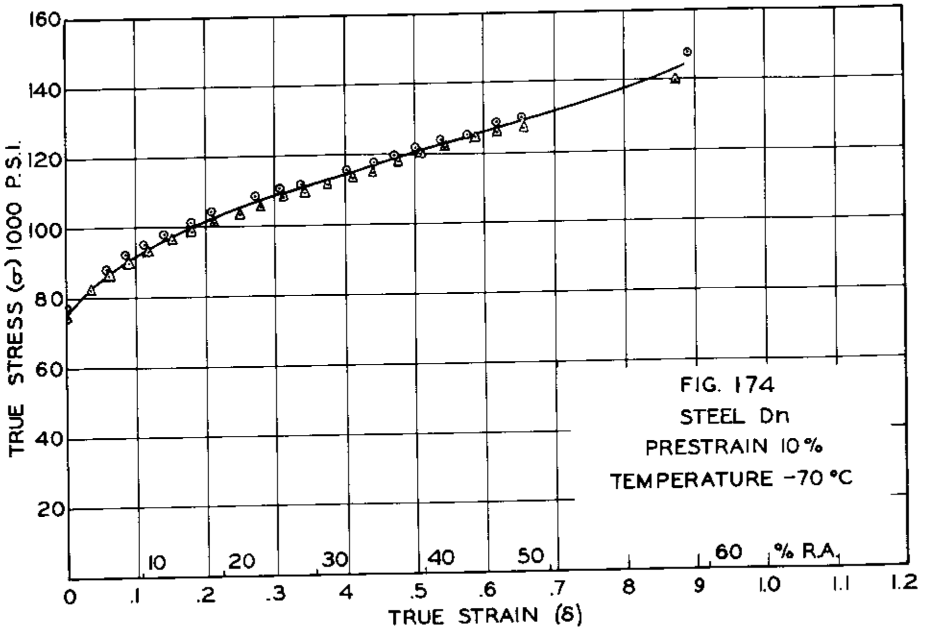


FIG. 174
STEEL Dn
PRESTRAIN 10%
TEMPERATURE -70 °C

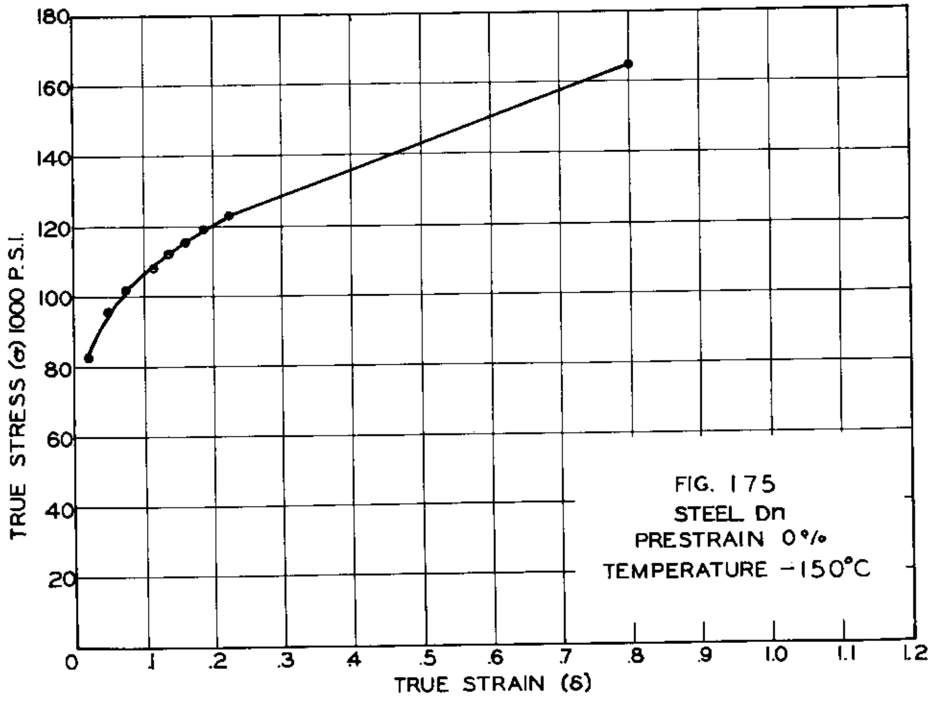


FIG. 175
STEEL Dn
PRESTRAIN 0%
TEMPERATURE -150°C

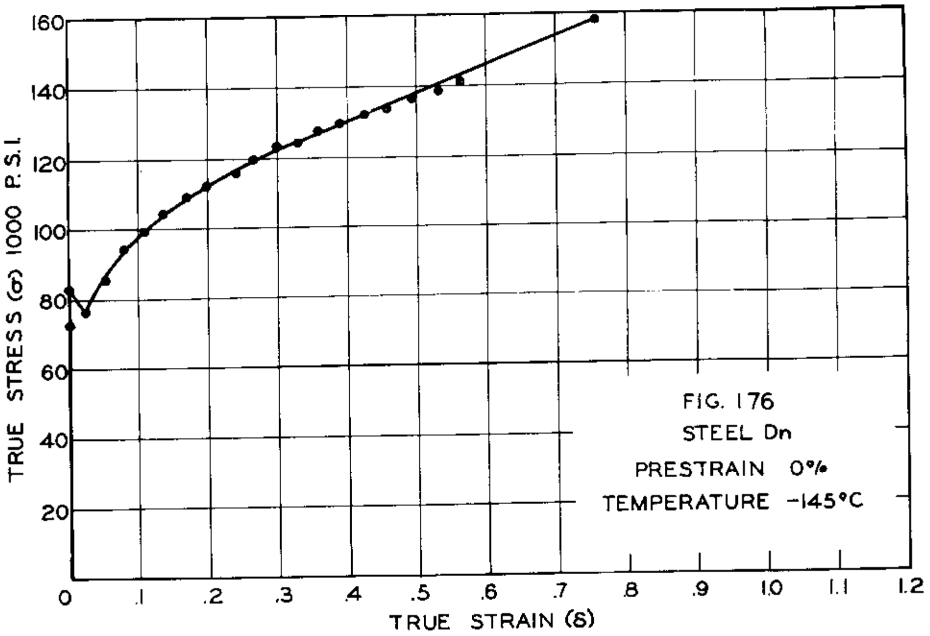


FIG. 176
STEEL Dn
PRESTRAIN 0%
TEMPERATURE -145°C

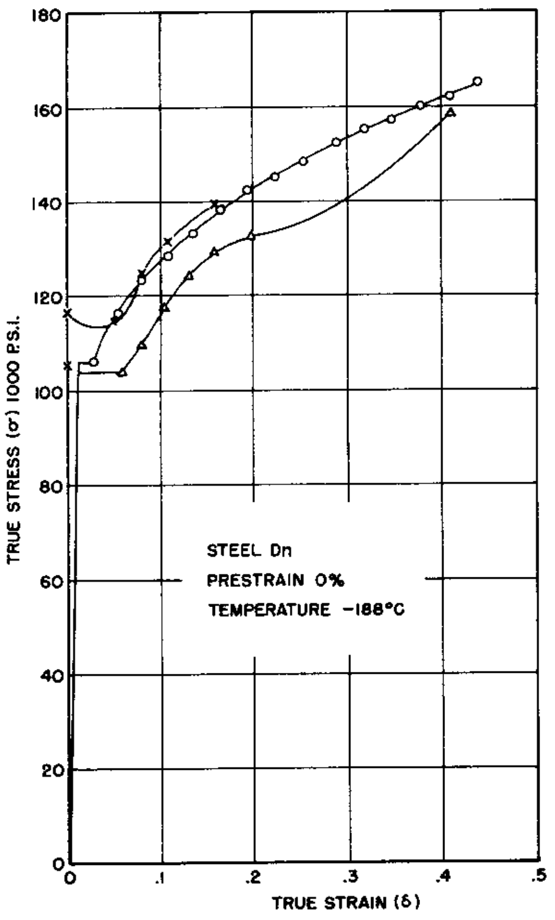


FIG. 177

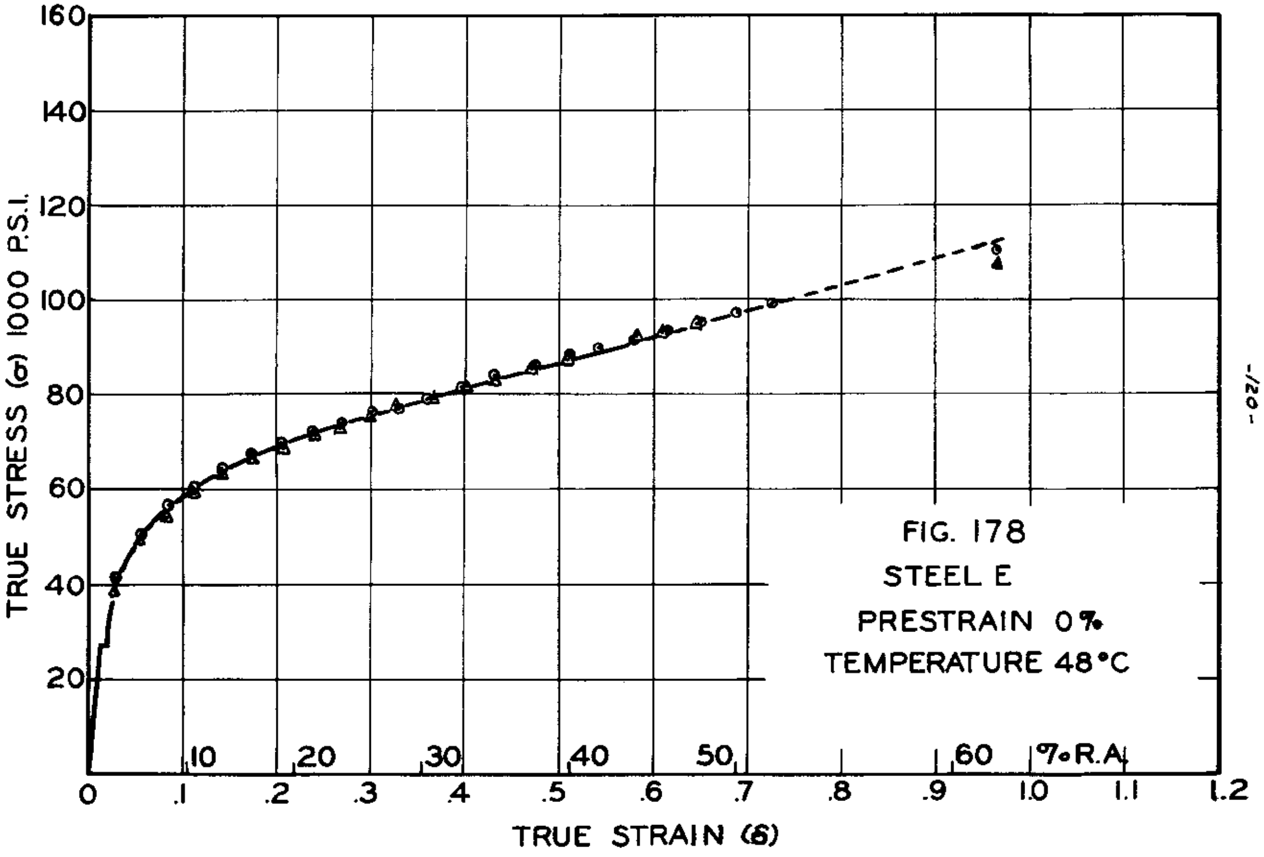


FIG. 178
STEEL E
PRESTRAIN 0%
TEMPERATURE 48°C

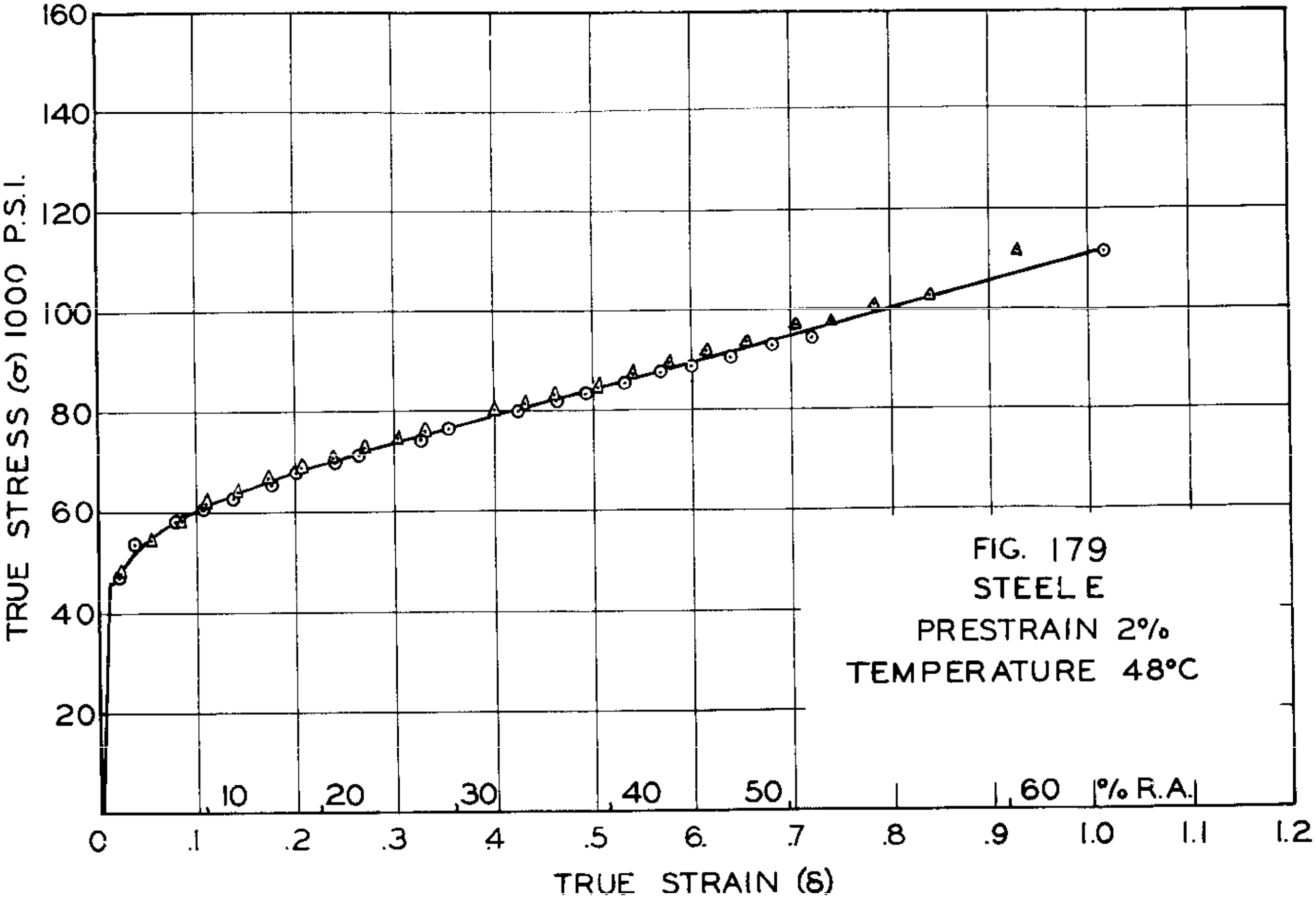


FIG. 179
STEEL E
PRESTRAIN 2%
TEMPERATURE 48°C

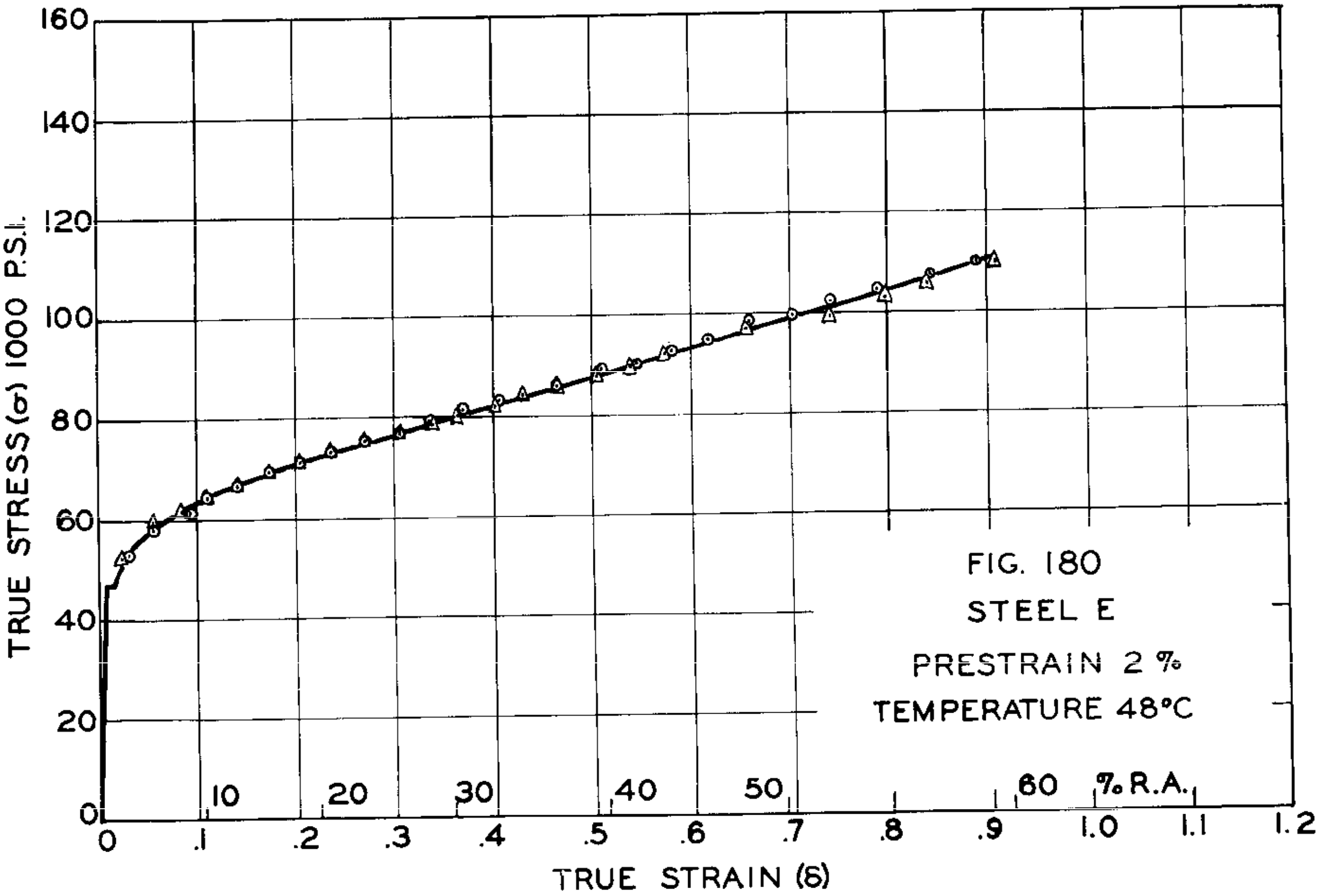


FIG. 180
STEEL E
PRESTRAIN 2 %
TEMPERATURE 48°C

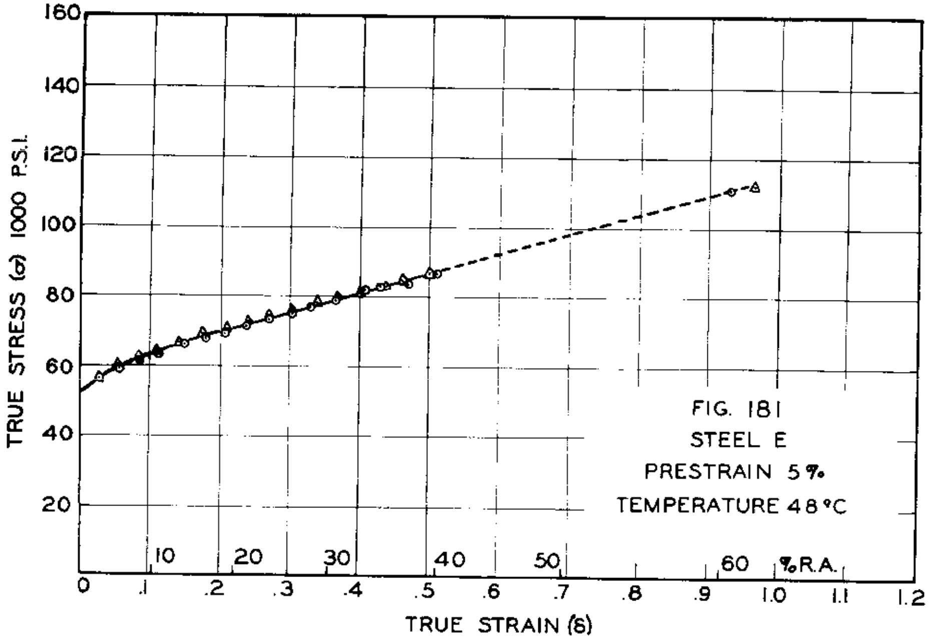


FIG. 181
STEEL E
PRESTRAIN 5%
TEMPERATURE 48 °C

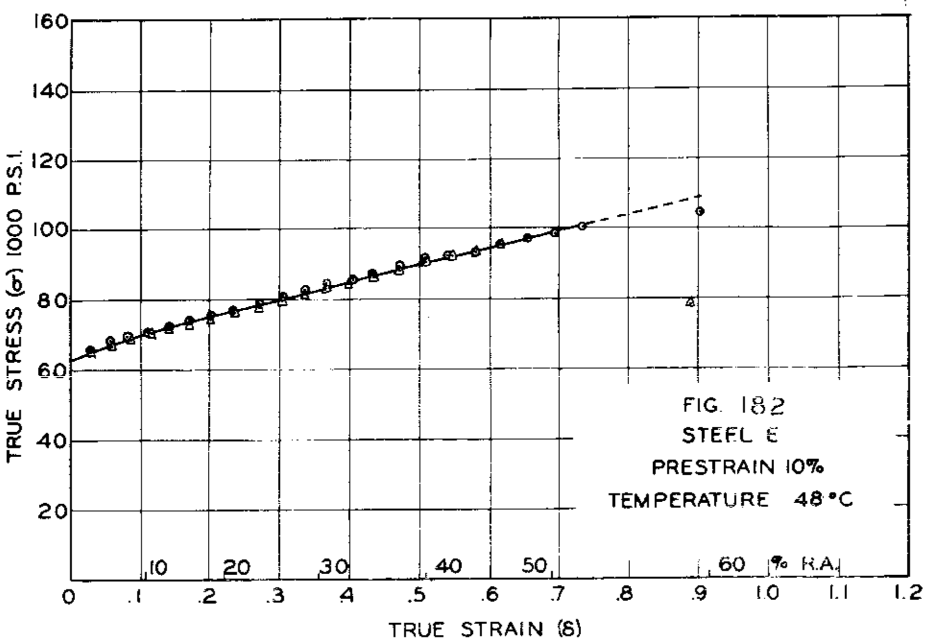


FIG. 182
STEEL E
PRESTRAIN 10%
TEMPERATURE 48 °C

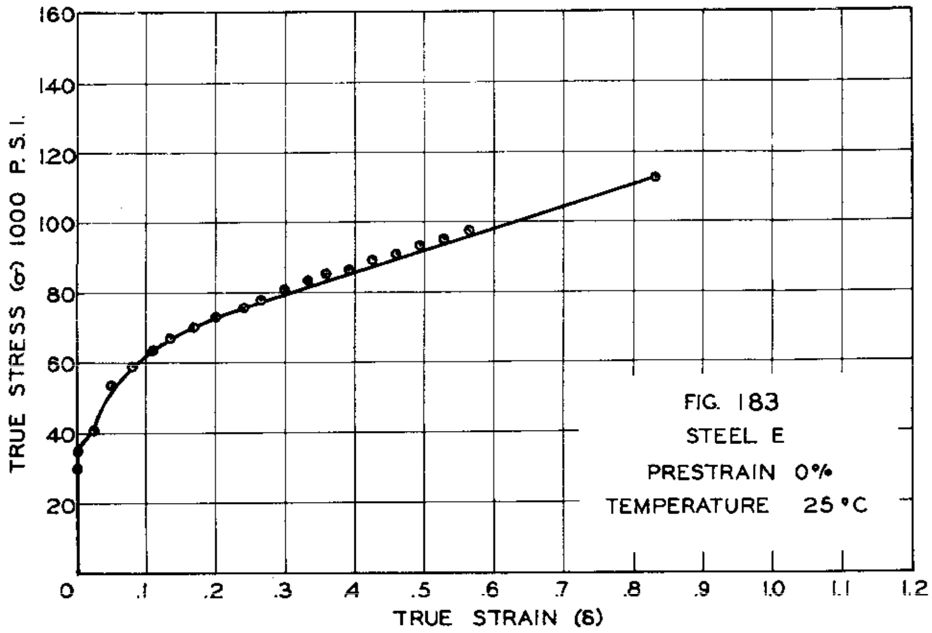


FIG. 183
STEEL E
PRESTRAIN 0%
TEMPERATURE 25 °C

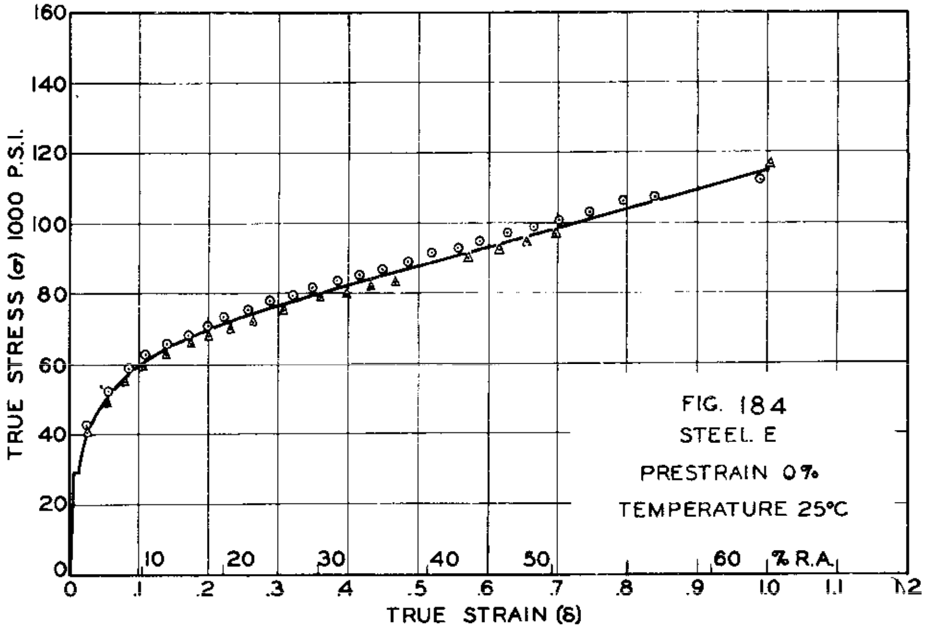


FIG. 184
STEEL E
PRESTRAIN 0%
TEMPERATURE 25°C

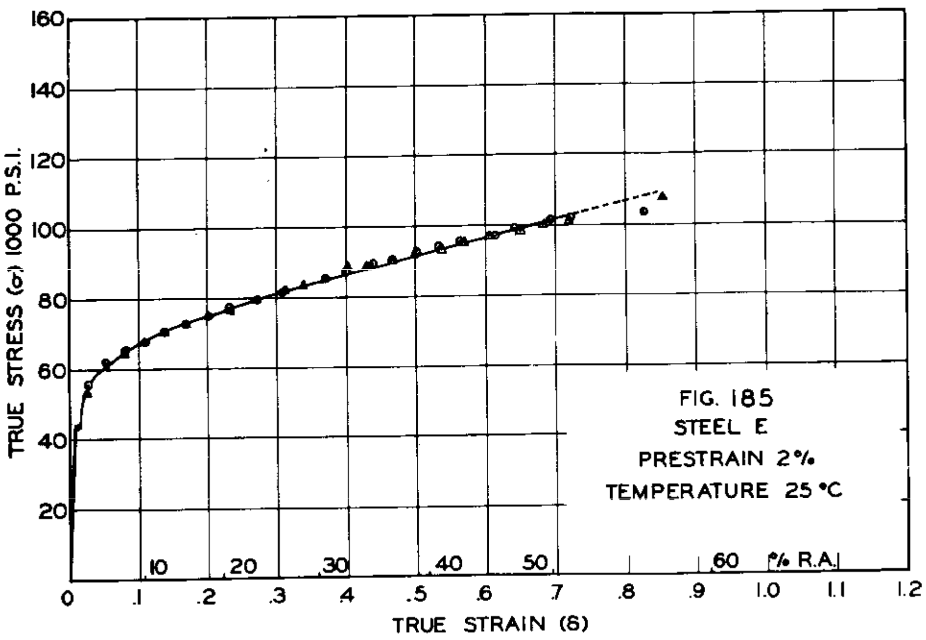


FIG. 185
STEEL E
PRESTRAIN 2%
TEMPERATURE 25 °C

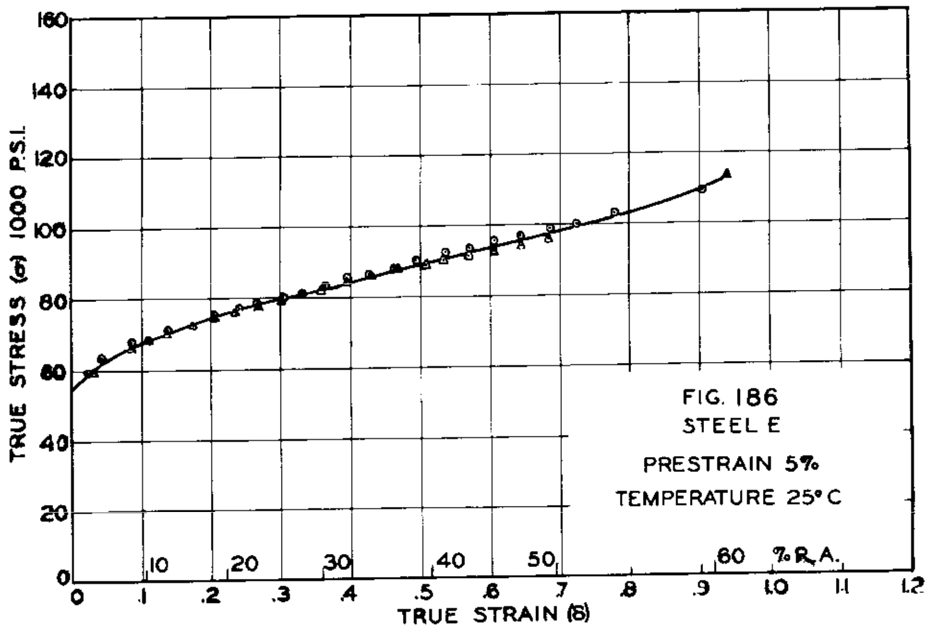


FIG. 186
STEEL E
PRESTRAIN 5%
TEMPERATURE 25° C

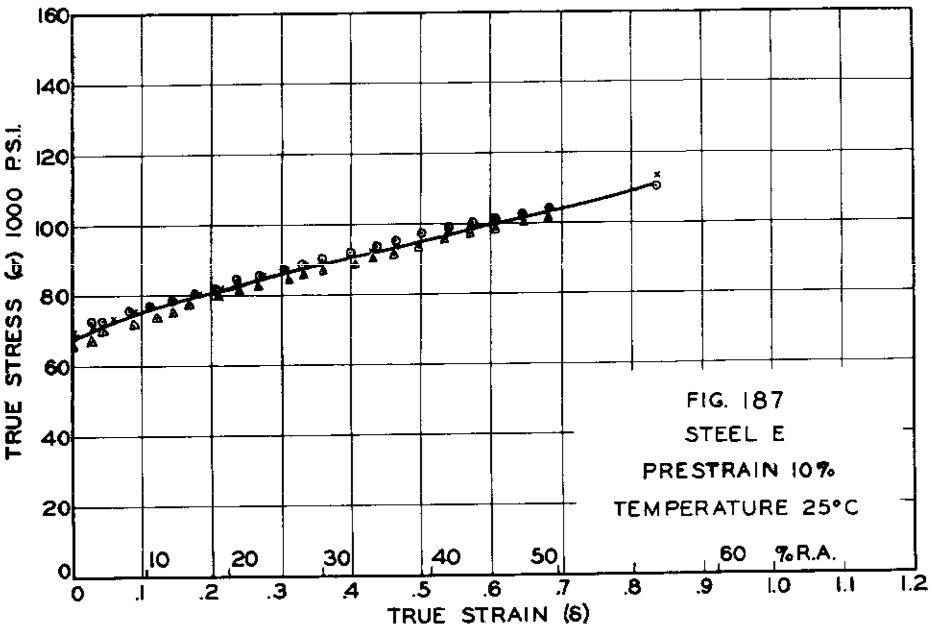


FIG. 187
STEEL E
PRESTRAIN 10%
TEMPERATURE 25°C

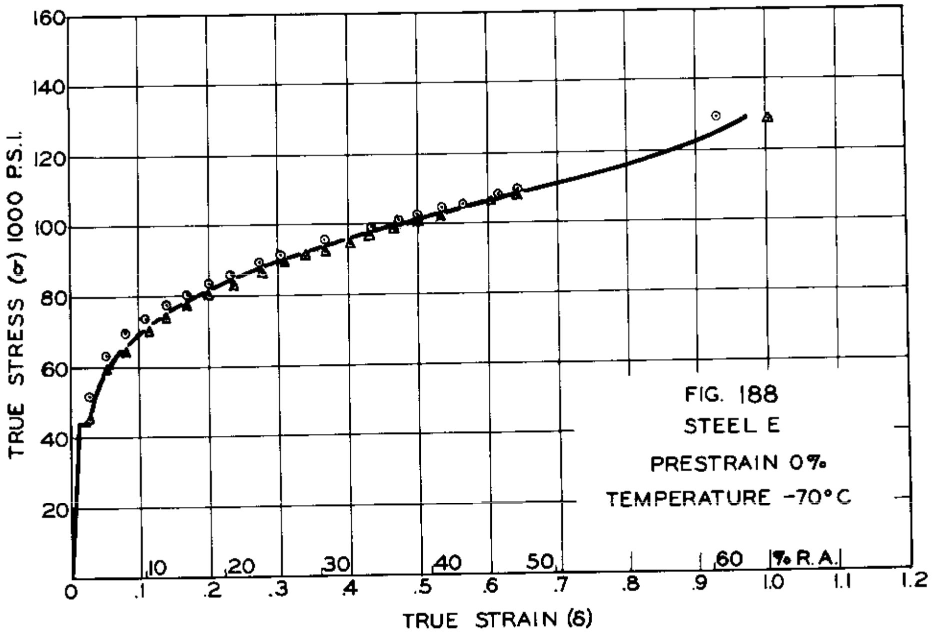


FIG. 188
STEEL E
PRESTRAIN 0%
TEMPERATURE -70°C

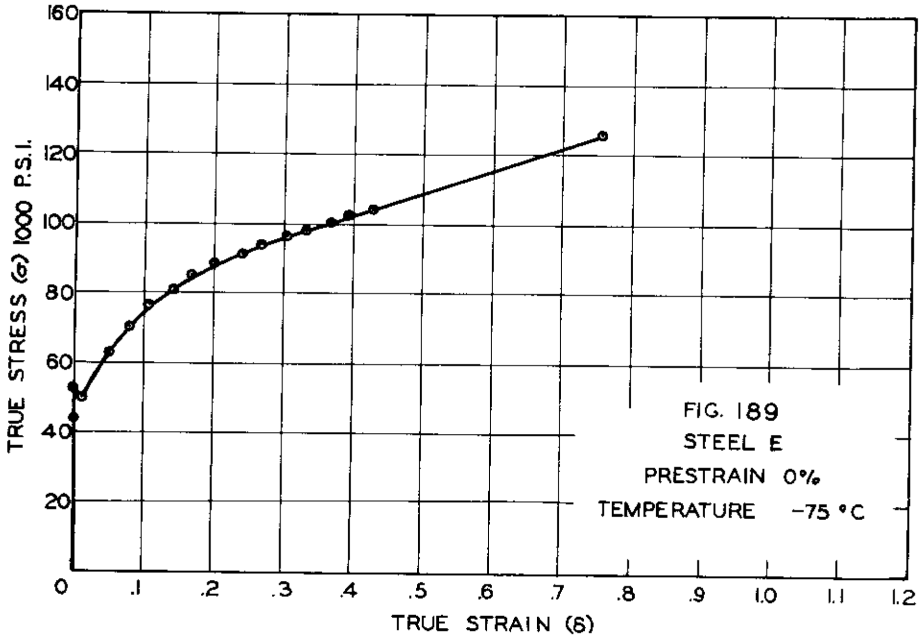


FIG. 189
STEEL E
PRESTRAIN 0%
TEMPERATURE -75 °C

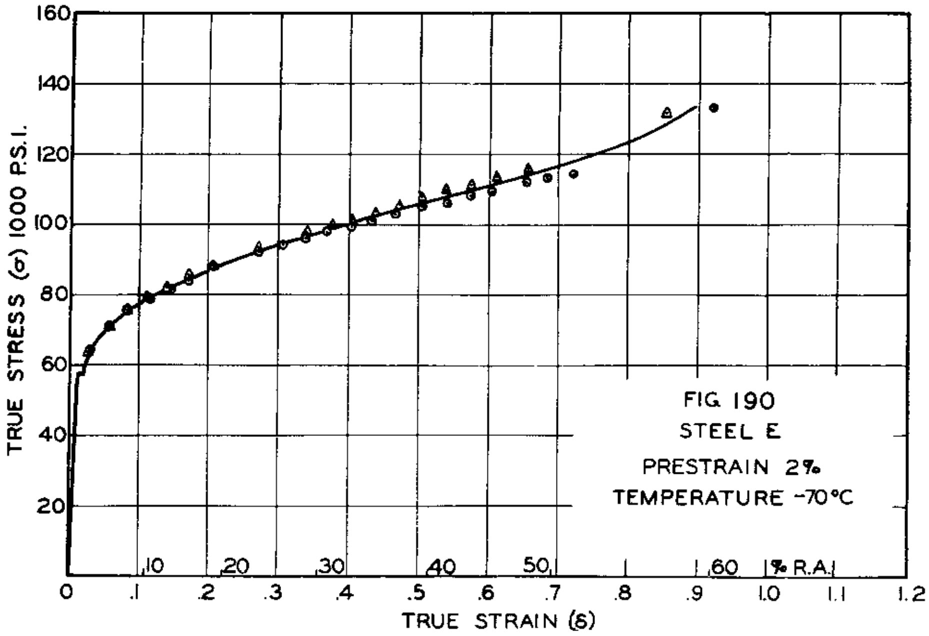


FIG. 190
STEEL E
PRESTRAIN 2%
TEMPERATURE -70 °C

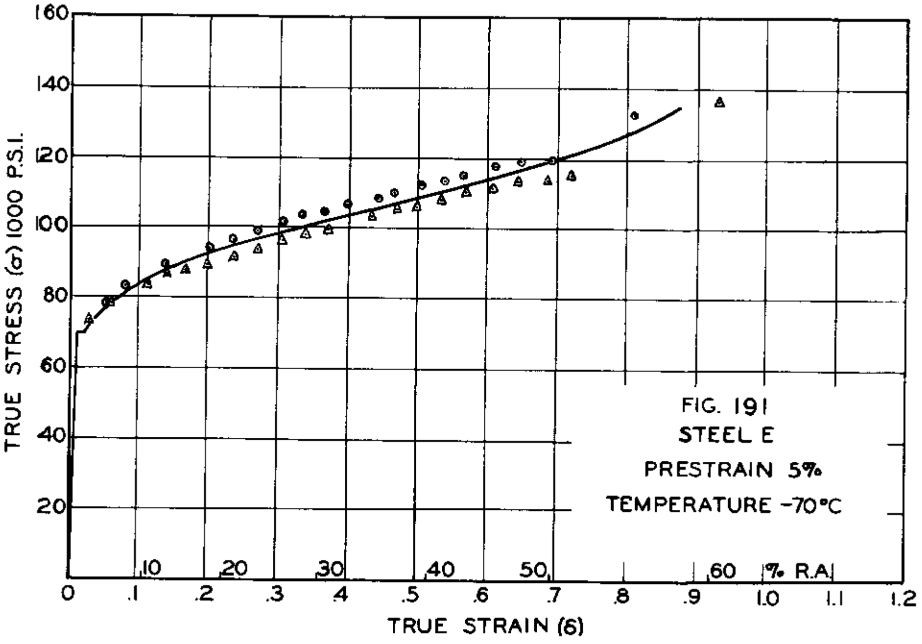


FIG. 191
STEEL E
PRESTRAIN 5%
TEMPERATURE -70 °C

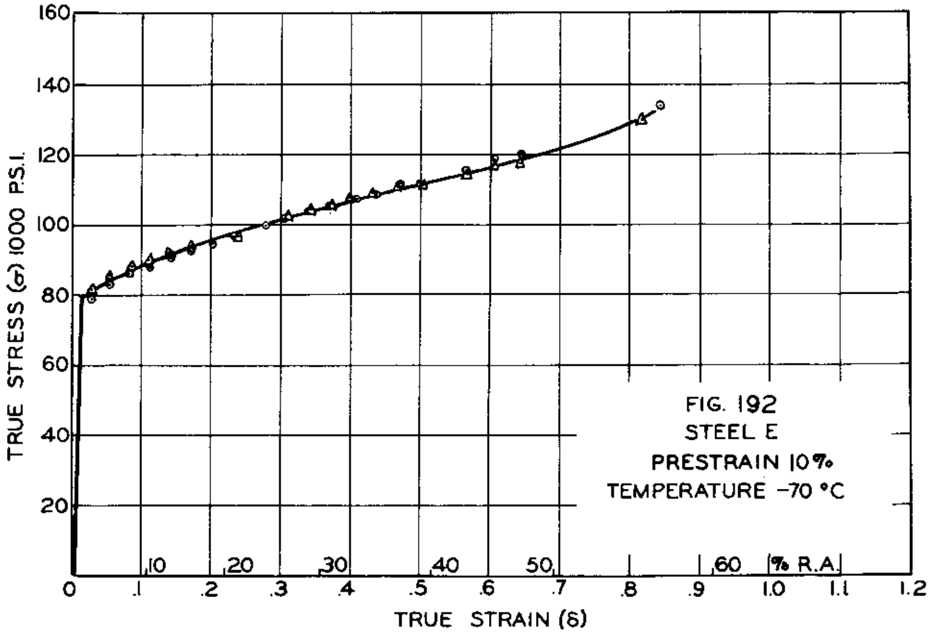


FIG. 192
STEEL E
PRESTRAIN 10%
TEMPERATURE -70 °C

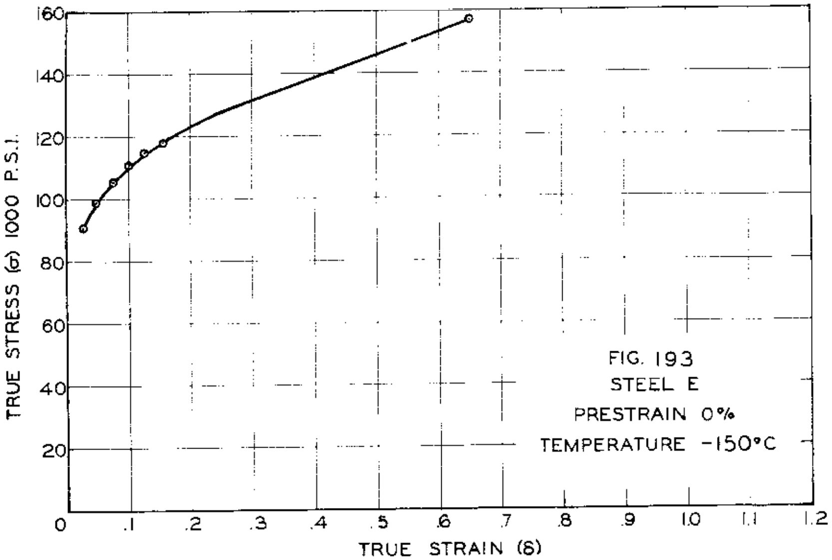


FIG. 193
STEEL E
PRESTRAIN 0%
TEMPERATURE -150°C

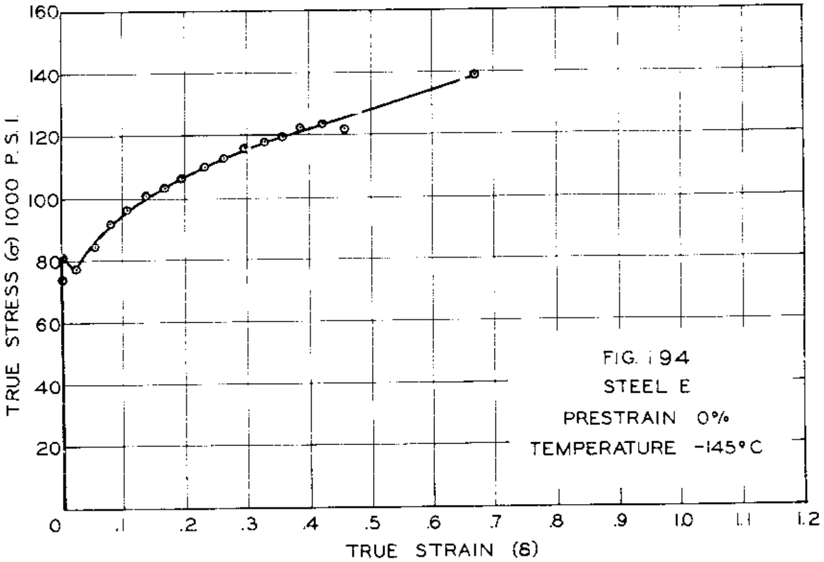


FIG. 194
STEEL E
PRESTRAIN 0%
TEMPERATURE -145°C

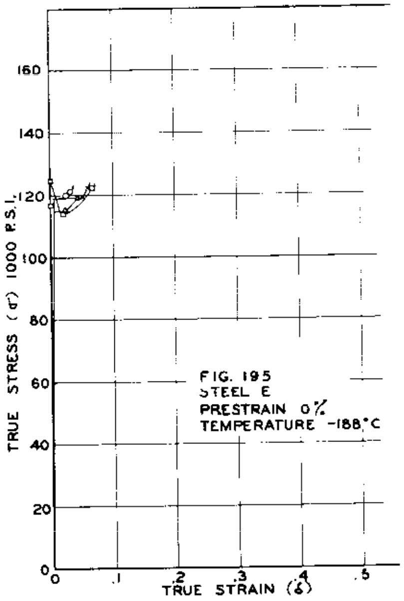


FIG. 195
STEEL E
PRESTRAIN 0%
TEMPERATURE -188°C

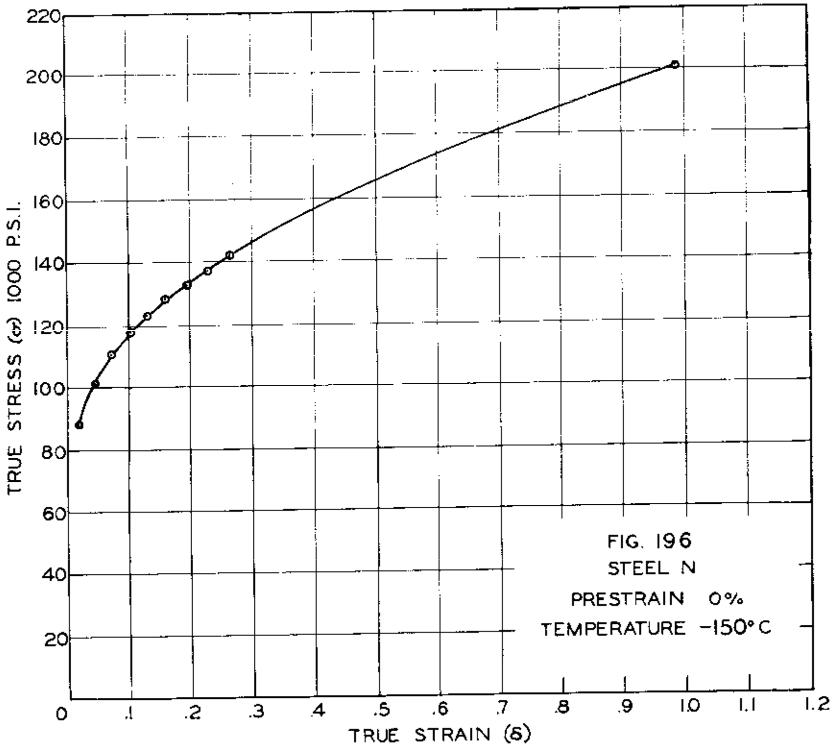


FIG. 196
STEEL N
PRESTRAIN 0%
TEMPERATURE -150°C

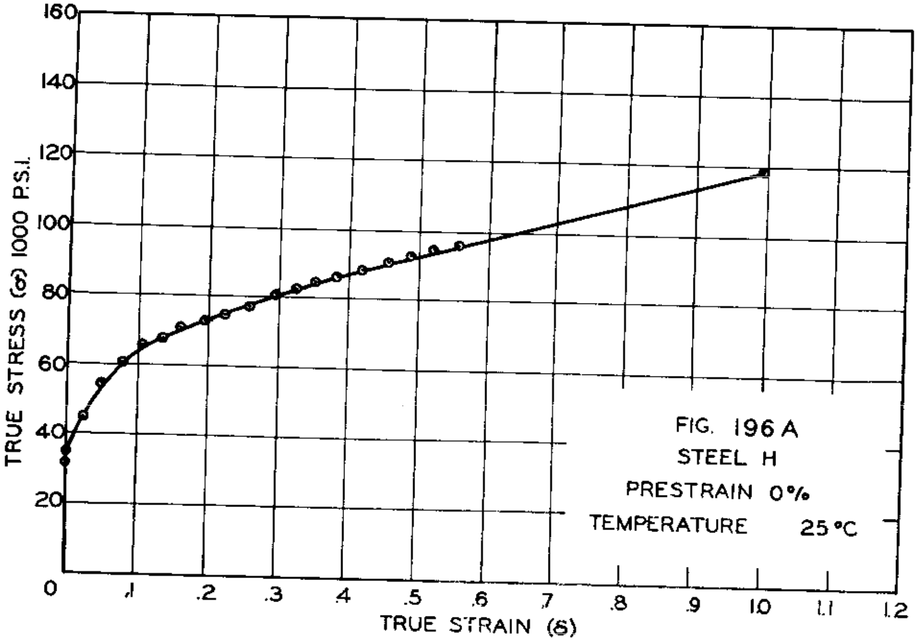


FIG. 196 A
STEEL H
PRESTRAIN 0%
TEMPERATURE 25°C

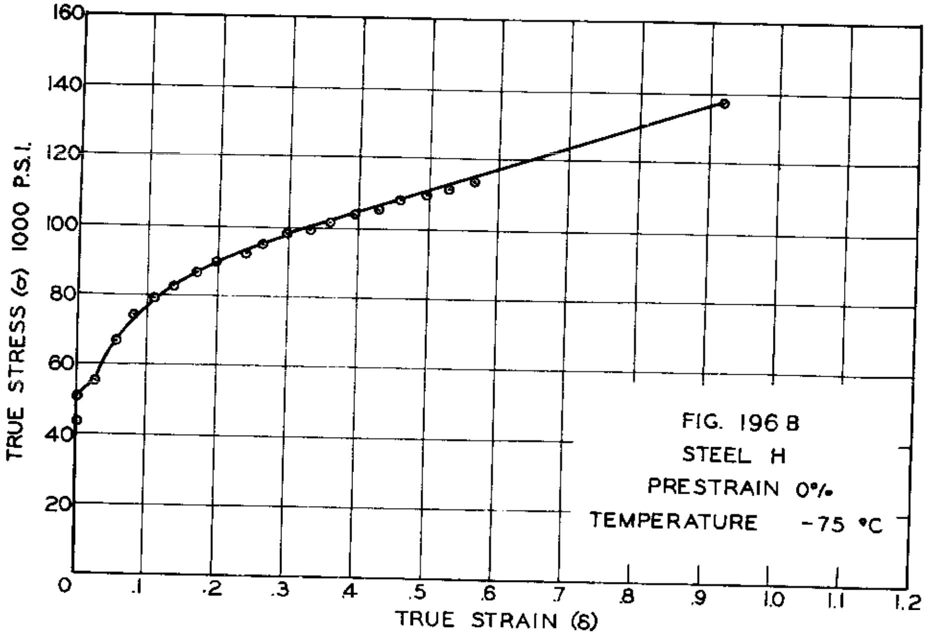


FIG. 196 B
STEEL H
PRESTRAIN 0%
TEMPERATURE -75 °C

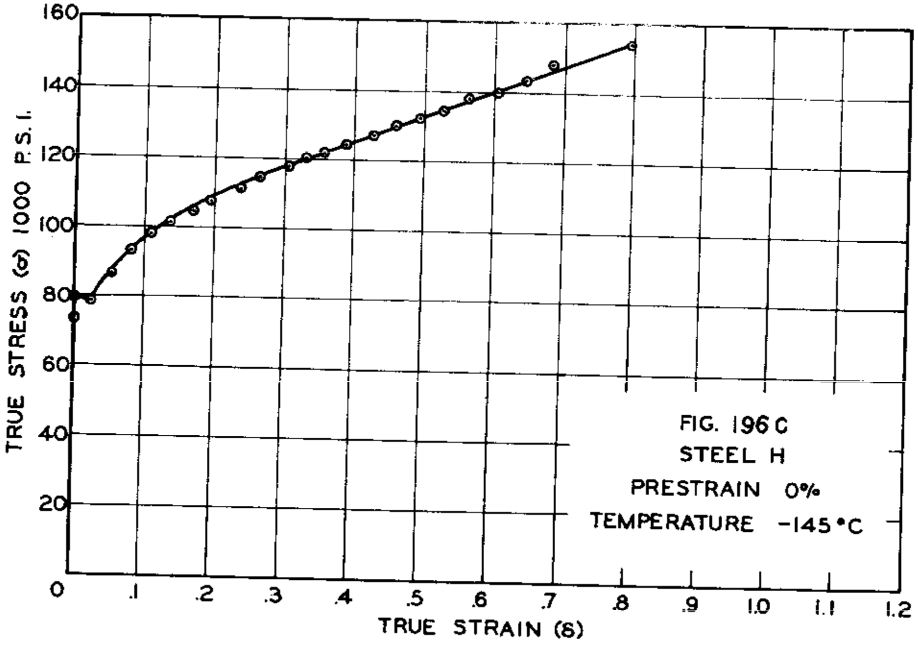


FIG. 196 C
STEEL H
PRESTRAIN 0%
TEMPERATURE -145 °C

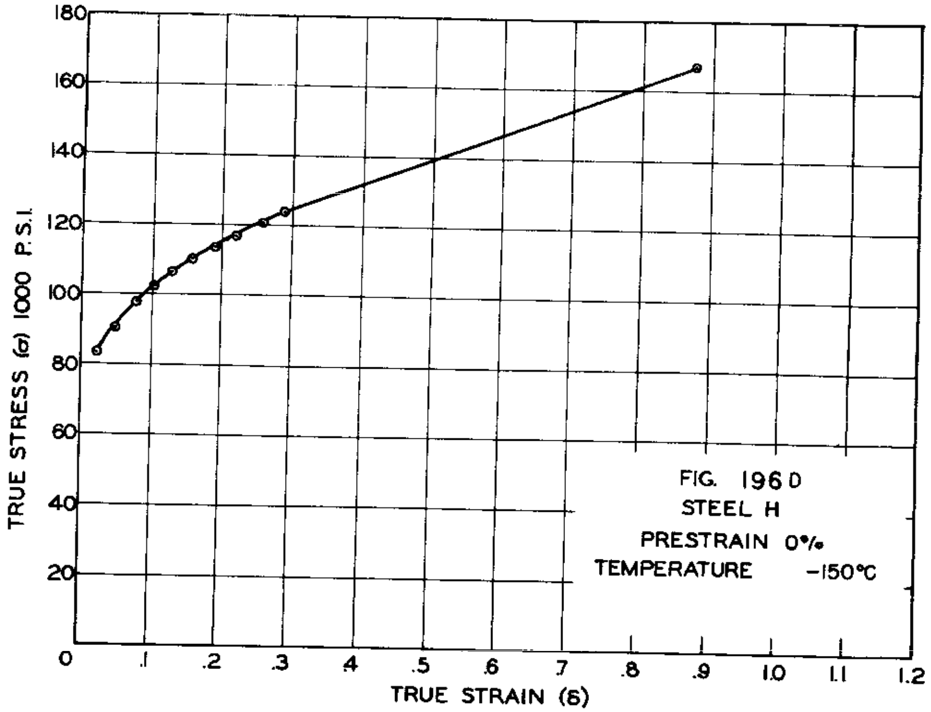


FIG. 196 D
STEEL H
PRESTRAIN 0%
TEMPERATURE -150°C

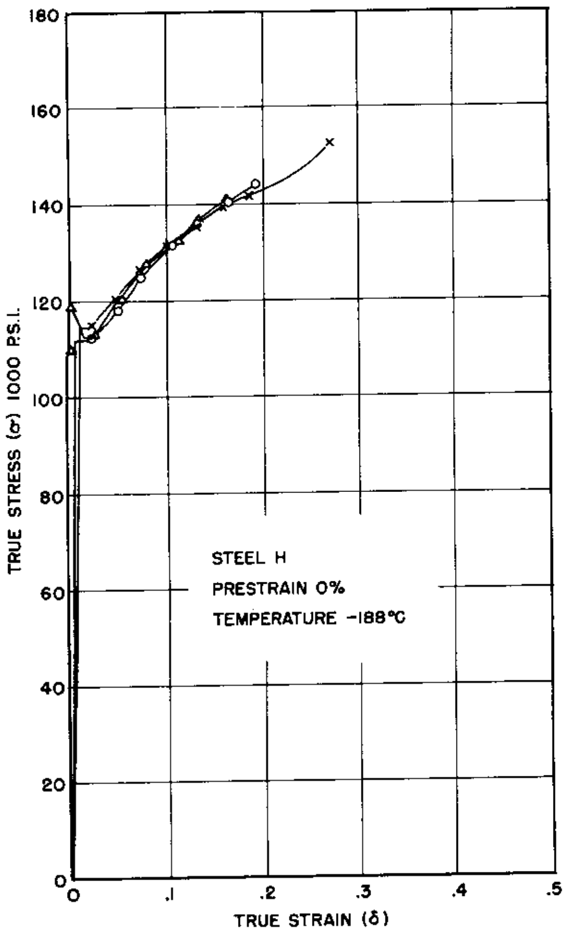


FIG. 196 E

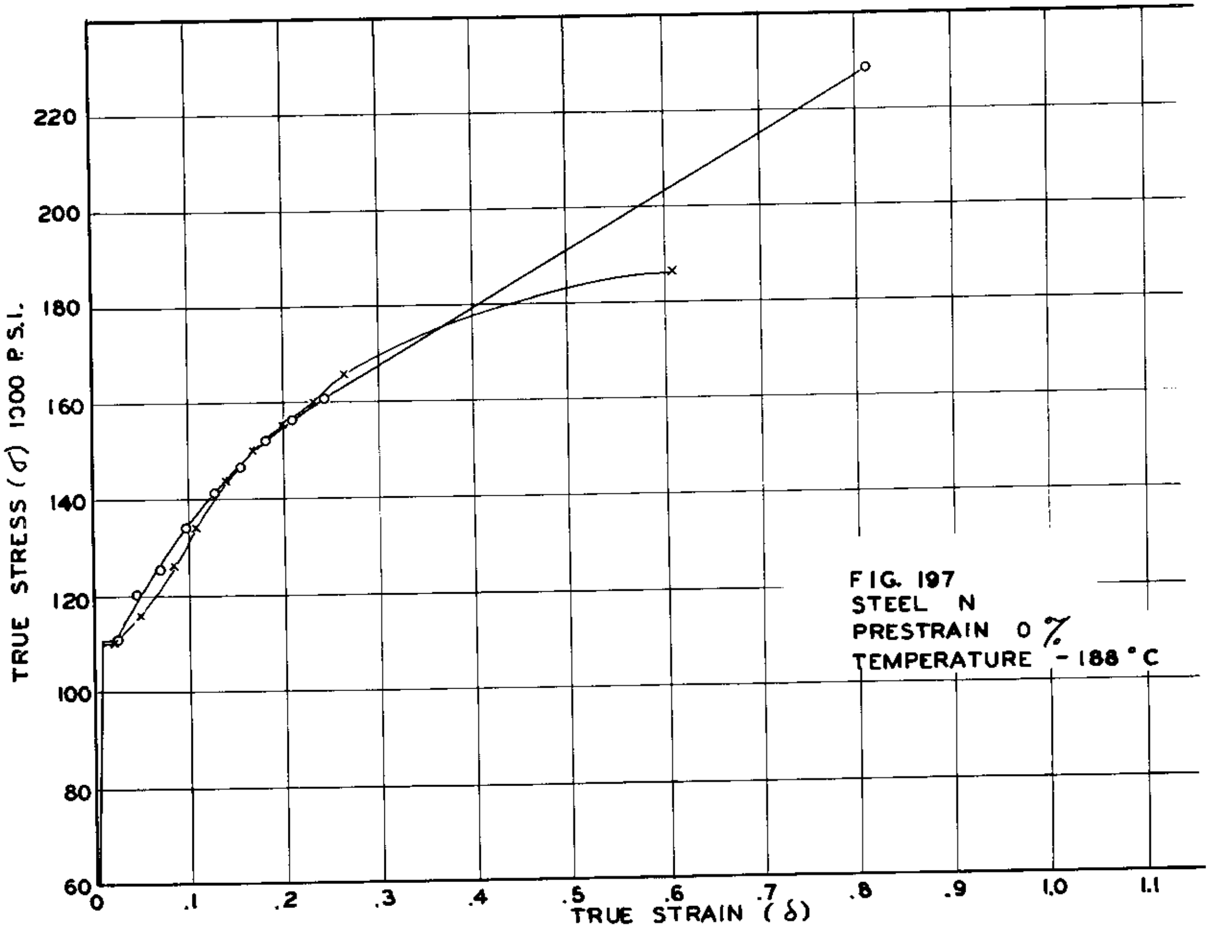


FIG. 197

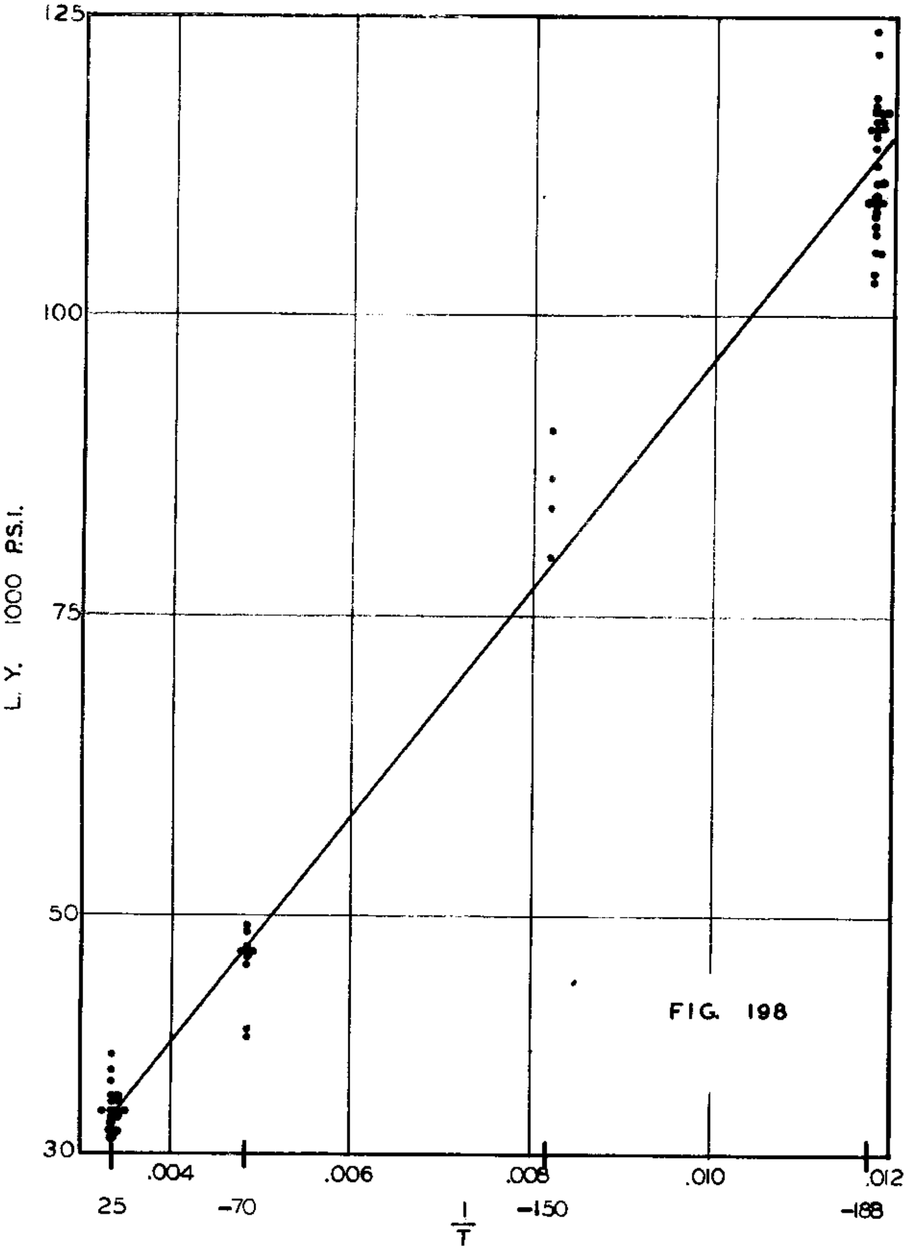


FIG. 198

THE LOWER YIELD STRENGTH VERSUS $\frac{1}{T°K}$ - STEEL Dr

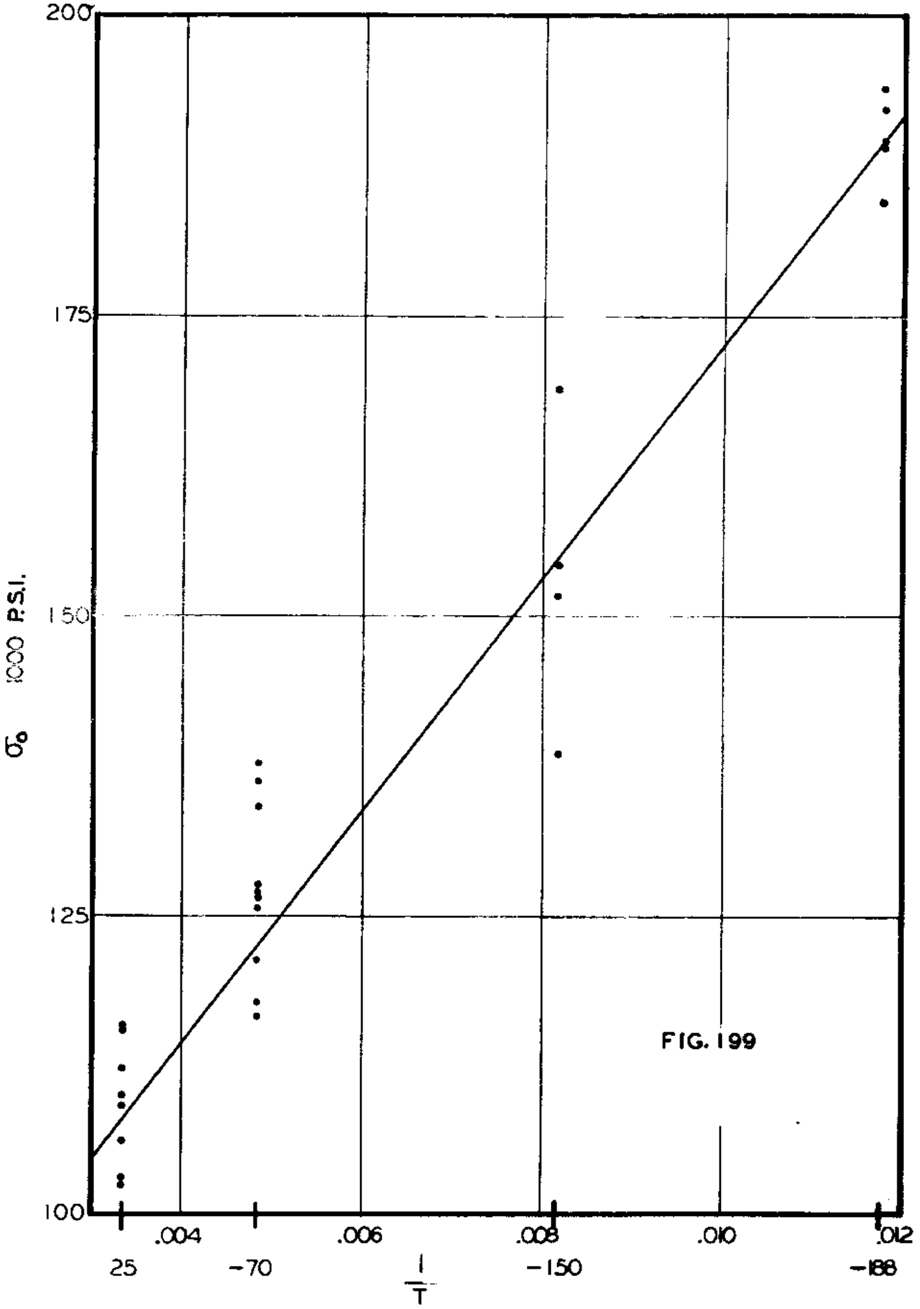
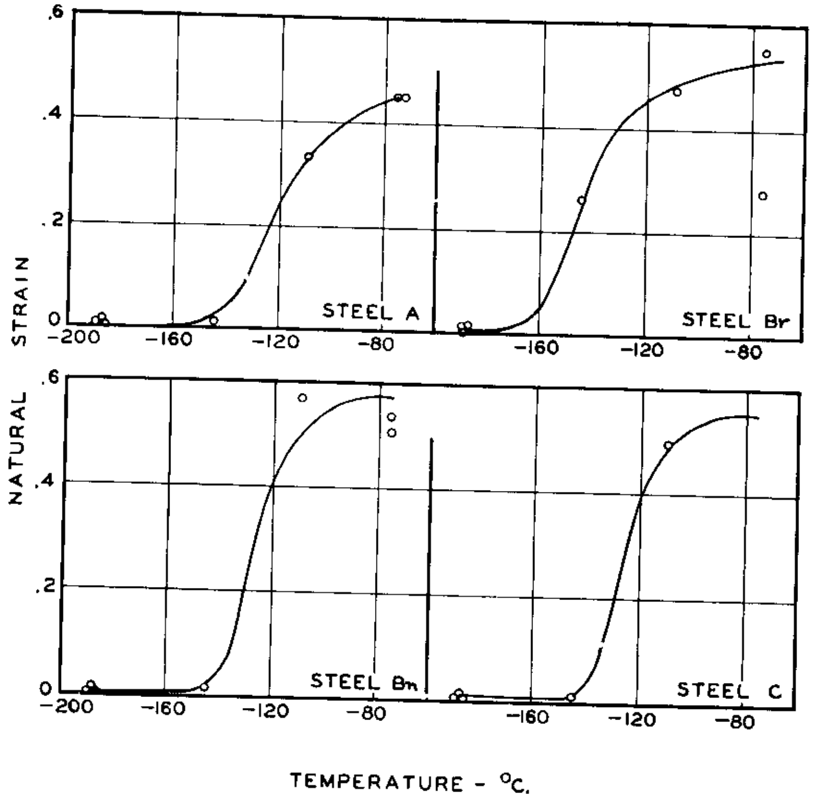
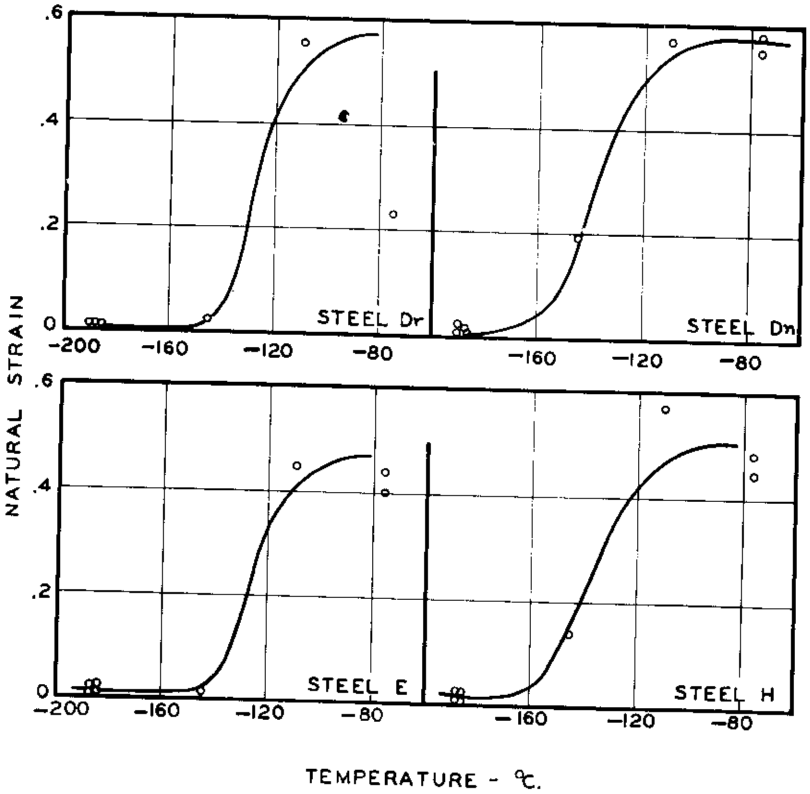


FIG. 199

THE STRENGTH COEFICIENT VERSUS $\frac{1}{T°K}$ - STEEL Dr



FRACTURE STRAIN VERSUS TEMPERATURE - SPECIMEN NO. 3
FIG. 200 A



FRACTURE STRAIN VERSUS TEMPERATURE - SPECIMEN NO. 3
FIG. 200 B

APPENDIX A

Study of Alloyed Ferrites

In the study of the fracture characteristics of ship plate, it became apparent that certain of the alloying elements, which were present as residual elements or as a consequence of the deoxidation practice, had an appreciable effect on the fracture behavior of the steels. A study of the fracture characteristics of alloyed ferrites, therefore, appeared to be desirable. Alloyed ferrites, which were available, were studied in a slow bend test and in a non-standard impact test.

Alloys: The compositions of the ferrites available for study are listed in Table A-I (33). These alloys were prepared by The Westinghouse Electric Company from hydrogen-annealed electrolytic iron and high-purity elements. Melting was conducted in a high-frequency induction furnace under an atmosphere of purified dry hydrogen. The melting was done in magnesia crucibles. The molten iron was allowed to freeze in the furnace, was then reheated to just above the melting temperature, evacuated, and again allowed to freeze. The ingots were forged and hot-rolled and finally ground to 3/4 inch and 5/16 inch diameter bar stock.

Preparation of Specimens: Schnadt-type slow bend test bars were prepared from the 3/4 inch stock for alloys 4, 7, 10, 11, 12, 13, 16 and 19. The test bar dimensions were: length, 2.165 inches; height, 0.625 inches; and width, 0.415 inches. The notch was the 0.0015 inch root radius pressed notch. This specimen is diagrammed in Figure A-1.

Because of lack of material, standard type impact bars could not be prepared. For convenience, therefore, cylindrical impact bars were prepared from the 5/16 inch diameter stock. This test bar is diagrammed in Figure A-1.

For purposes of comparison, comparable impact bars were prepared from the project steels, and were oriented with the long axis in the direction of rolling. These specimens were taken from the center of the plates.

Testing Procedure: The slow bend bars were tested on a 60,000 pound tensile testing machine in the manner described elsewhere (4). The specimens were immersed in a temperature-controlled bath for a period of at least four minutes before testing in order to insure equilibrium conditions. The specimen was then broken and width change measurements made at the pin and the percent fibrous fracture estimated.

The cylindrical impact bars were broken in a pendulum machine with a striking velocity of 12 feet per second. The energy absorption was recorded and the percentage of fibrous fracture surface was estimated.

Presentation of Data: Plots of energy absorption, lateral contraction, and percent fibrous fracture are presented. From these curves, when possible, appropriate temperatures have been selected for comparison purposes and tabulated. Photographs of the broken slow bend specimens and photomicrographs of the microstructures of pertinent alloys are presented.

Experimental Results

In order to isolate the effects of the various alloying elements, in examining the fracture characteristics of ferrite two important conditions must be met; namely, grain size must be controlled and the alloys must be single phase. These restrictions pose some difficulties, all of which have not been satisfactorily solved.

Some of the alloying elements are grain refiners, while others are not. For this reason, adequate control of grain size was obtained only for the materials of highest alloy content. There are exceptions to this, as may be determined from an examination of Table A-II. Because of the grain size control problem, slow bend tests were run only on the alloy-rich materials, with the exception of the cobalt series which will be discussed below.

From the photomicrographs presented in Figures A-2 to A-7 it appears that the alloys, with the exception of #10 (7.25% Mn), are single-phase alloys. An examination of the appropriate equilibrium diagrams indicates that alloy #4 (4.83% Ni) constitutes the only other possible exception.

The probable grain sizes of the ferrites are listed in Table A-II.

<u>Slow bend tests</u>: Initial results of slow bend testing indicated that cobalt probably had little or no effect on the fracture characteristics of the ferrite over the range of compositions available. Since the cobalt alloys were of constant grain size, this made possible the prediction of the fracture characteristics of high-purity ferrite by extrapolation. The slow bend test data for the cobalt alloys were obtained and are presented in Figures A-8 to A-16. Transition temperature data are summarized in Figure A-17. On the basis of these data, the temperature characterizing the transition from fibrous to granular fracture for pure ferrite of grain size ASTM #5 has been taken as 0°F. It is emphasized that this temperature is significant only for the test bar under examination and for the testing velocity used, and for iron deoxidized to the same degree as the cobalt alloys.

The test results for the remaining alloys studied are presented in Figures A-18 to A-29. Transition temperatures taken from these curves are listed in Table A-II. Data for manganese alloys are not presented since these alloys were brittle at all temperatures of testing employed. No conclusions can be drawn because of the uncertain transition temperatures for iron deoxidized to the same degree as in each alloy, and because of the uncertain effect of grain size in this test. Making some allowance for grain size, one suspects that all the alloying elements except cobalt raise the fracture appearance transition temperature.

With reference to the manganese alloy, it might appear that the existence of a two-phase structure would lead to a brittle condition for the alloy. This conclusion, however, may not be warranted as may follow from an examination of the structure of the nickel alloy. Further, the hardness of the manganese ferrite was R_c 35 and this factor might be responsible for the brittleness of this alloy.

The criteria of lateral contraction and fracture appearance are not in complete agreement in indicating the transition from brittle to ductile fracture for some of the alloys studied. This is contrary to the results obtained for the ship plate steels which have been studied in this work. Thus for the 4.83% Ni alloy, the transition for fibrous fracture is at -25°F. while that for lateral contraction is at -55°F. For the 4.83% Cr alloy, however, the transition in fracture type is at -75°F. while that for lateral contraction is at -30°F., but these data for the chromium alloy are questionable.

The two criteria are in full agreement for the cobalt alloys and for the molybdenum alloy. For the silicon alloy the transition in fracture is reported at 90°F while that in lateral contraction is at +15°F.

It is evident that binary ferrites could profitably be studied further.

<u>Impact Tests:</u> On the examination of the data for the impact specimen used, it is immediately evident that an attempted numerical evaluation of the transition curves may lead to very real difficulties. This is especially so for the data obtained for the project steels and presented in Figures A-30 to A-51.

The transition data for the energy absorption values progress regularly from fibrous to granular types through the transition range, but not so fracture-type. These progress irregularly from the maximum value to the minimum value through the transition range. The transition ranges in fracture type and in energy absorption overlap but are not coincident.

A point of particular interest is the relative evaluation of steels A and C. These two steels were not separable in the earlier impact testing program. By energy absorption for the round test bar these two steels are clearly separated and in the proper direction. However, from a consideration of the energy absorption data for the other steels this separation must be considered as fortuitous. The transition in fracture type for steels A and C on the other hand are in qualitative agreement with the earlier results.

An examination of the summary of the impact data for the project steels for the round impact bar indicates that these data are very difficult to evaluate. Thus the order of merit of the steels is entirely different from any heretofore obtained. Further, the transition phenomena as determined from fracture appearance are evaluated in an order different from that by energy absorption. For test materials for which the two transition criteria are in disagreement, this round test bar may be used only with major reservations. When the fracture criteria for a given material are in full agreement for this test bar, the data probably have qualitative significance. Further use of this size round test bar would appear to be inadvisable.

The impact test transition data for the alloy ferrites are presented in Figures A-52 to A-57. Numerical values taken from these curves are given in Table A-II. In these figures the curves through the "X" points are for low alloys; those through the filled circles are for high alloys and those through the open circles are for intermediate alloys.

From the immediate juxtaposition of the fracture type and energy absorption curves it is indicated that here, in contrast to the behavior for the project steels, the transition criteria are in relatively good agreement, with the exception of the data for the 4.83% Cr ferrite.

The data for the ferrites are of uncertain significance quantitatively, but qualitatively they reveal that the respective alloying elements have markedly different effects on the fracture characteristics of ferrite. Thus, both nickel and cobalt tend to lower the temperature of transition from ductile to brittle failure. In the consideration of these data an excellent indication of the sensitiveness of the test to grain size is given for the nickel series, where the respective grain sizes for alloys Nos. 2 and 3 are ASTM Nos. 6 and 3. The action of the increased nickel content is completely concealed by the change in grain size.

On the other hand, the grain size for alloys Nos. 11, 12 and 13, the cobalt alloys, is consistent but is larger than that for the nickel alloys Nos. 2 and 4, and somewhat smaller than that for alloy No. 3. It is not anomalous then that the transition in fracture characteristics for alloy No. 11 should lie at the apparently high temperature.

Some degree of regularity is introduced by correcting the observed transition temperature for the effect of grain size. The correction used is 30°F per grain size number. This correction is suggested by the work of Hodge, Manning and Reichhold (ref. 34), who found this effect of grain size in unalloyed and nickel-bearing ferrites in the keyhole-notched Charpy impact test. It is of course uncertain that the same correction would apply for the test bar used here. A plot of the corrected transition temperature vs. percent alloying element is presented in Fig. A-58.

The data suggest, but certainly do not clearly indicate, that alloying elements first lower the transition temperature, then raise it. Small amounts of Mo, Si, Mn and Cr would be effective in tying up the C, O and/or N and perhaps in this way lowering the transition temperature so that the larger amounts studied are on the ascending curve. It may be that Ni and Co are very ineffective in reacting with

C, O and/or N, and so even up to 8% are still lowering the transition temperature. Extrapolating the Mn and Cr curves, unalloyed iron (except for residuals) might be said to have a transition temperature of about -100°F. at No. 5 grain size. The transition temperature so measured is at variance with the transition temperature indicated by extrapolation of the data for Co, Ni and Mo by a difference of about 200°F. It is conceivable that the residual elements (in particular gaseous elements) could account for this discrepancy.

Table A-I

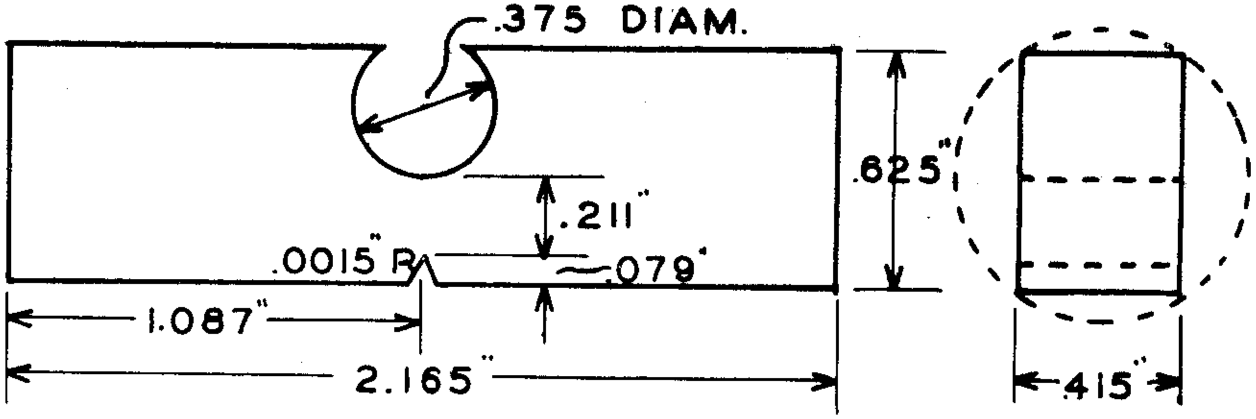
Compositions of the Binary Ferrites (33)

#	Mn	C	P	S	Co	Mo	Ni	Cr	Si
1	0.03	0.02	.010	.013	.005	.004	0.032	0.003	0.003
2	0.03	.03	.010	.011	.005	.004	0.57	.003	.004
3	0.03	.02	.010	.015	.005	.004	1.15	.003	.004
4	0.03	.02	.010	.016	.005	.004	4.83	.003	.004
5	0.05	.03	.011	.011	.005	.004	.032	0.45	.012
6	0.03	.02	.010	.013	.005	.004	.034	0.99	.004
7	0.03	.03	.012	.015	.005	.004	.023	4.83	.008
8	0.69	.02	.010	.014	.005	.004	.032	.003	.004
9	1.33	.06	.011	.020	.005	.004	.030	.003	.004
10	7.25	.03	.012	.022	.005	.004	.035	.003	0.13
11	0.03	.02	.012	.014	0.52	.004	.037	.003	.004
12	0.05	.02	.010	.019	1.00	.004	.043	.003	.004
13	0.03	.02	.012	.015	5.08	.004	.08	.003	.004
14	0.03	.03	.012	.015	.006	.004	.033	.003	0.22
15	0.03	.02	.011	.018	.005	.004	.032	0.045	0.59
16	0.03	.02	.010	.012	.005	.004	.055	.003	1.21
17	0.03	.03	.010	.014	.005	0.11	.054	.003	.004
18	0.03	.03	.010	.014	.005	0.54	.023	.003	.004
19	0.03	.04	.011	.014	.005	1.50	.016	.003	.004

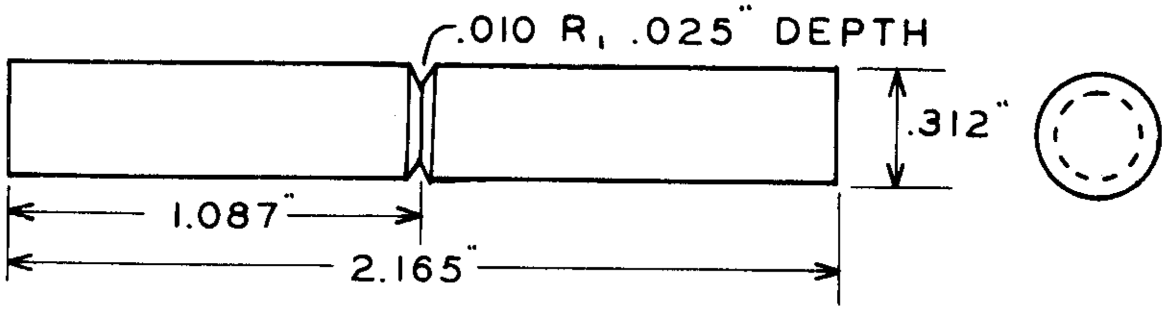
Table A-II

Transition Temperatures of the Iron Binary Alloys for the Slow Bend and Impact Tests by the Indicated Criteria

			Transition Temperature -°F					
		ASTM	SLOW BEND		CYLINDRICAL IMPACT	50% Maximum		
Alloy No.	Alloy Content	Grain Size	50% Fibrous Fracture	50% Maximum Lateral Contraction	50% Fibrous Fracture	Energy Absorption	Correction to No. 5 Grain Size	Corr Tran Temp
2	0.57% Ni	6-7			63	23	+45	
3	1.15% Ni	3			104	91	-60	
4	4.83% Ni	7-8	-25	-55	-22	-100	+75	-
5	0.45% Cr	6-7					+45	
6	0.99% Cr	2-3			10	10	-75	-
7	4.83% Cr	7-8	-75	-30	75	75	+75	1
8	0.69% Mn	3-4			-22	-16	-45	-
9	1.33% Mn	6			-49	-49	+30	-
10	7.25% Mn	10	RT	RT	210	210	+150	3
11	0.52% Co	5			158	167	0	1
12	1.00% Co	5			122	120	0	1
13	5.08% Co	5	10	10	30	30	0	
14	0.22% Si	4			-40	-40	-30	-
15	0.59% Si	8			+14	-31	+90	
16	1.21% Si	6	90	15	162	110	+30	1
17	0.11% Mo	6-7			59	55	+45	1
18	0.54% Mo	7			70	72	+60	1
19	1.50% Mo	6-7	25	25	205	165	+45	2



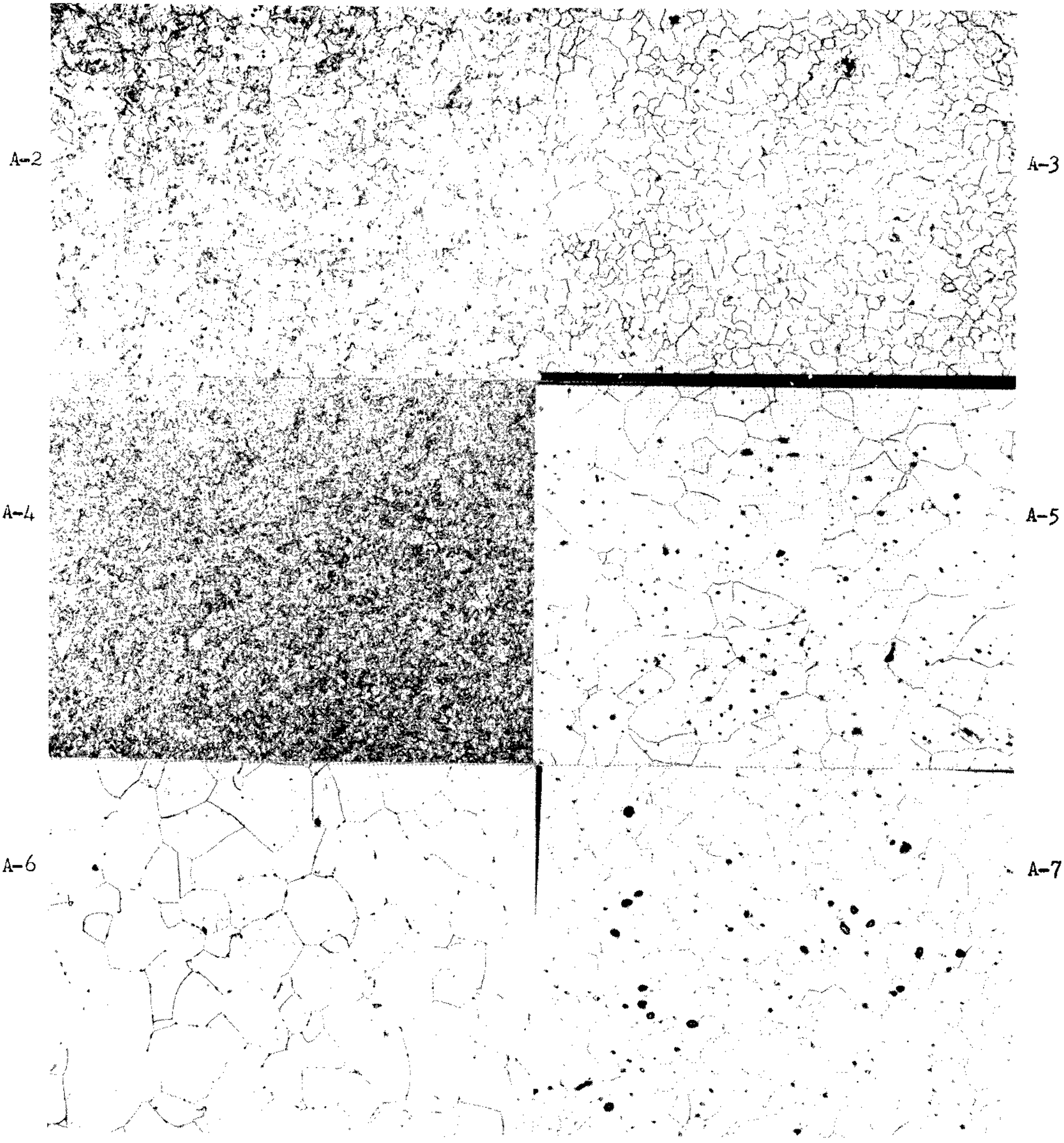
MODIFIED SLOW-BEND NOTCHED BAR
MACHINED FROM 3/4" DIAM. ROUND



CYLINDRICAL NOTCHED
IMPACT SPECIMEN

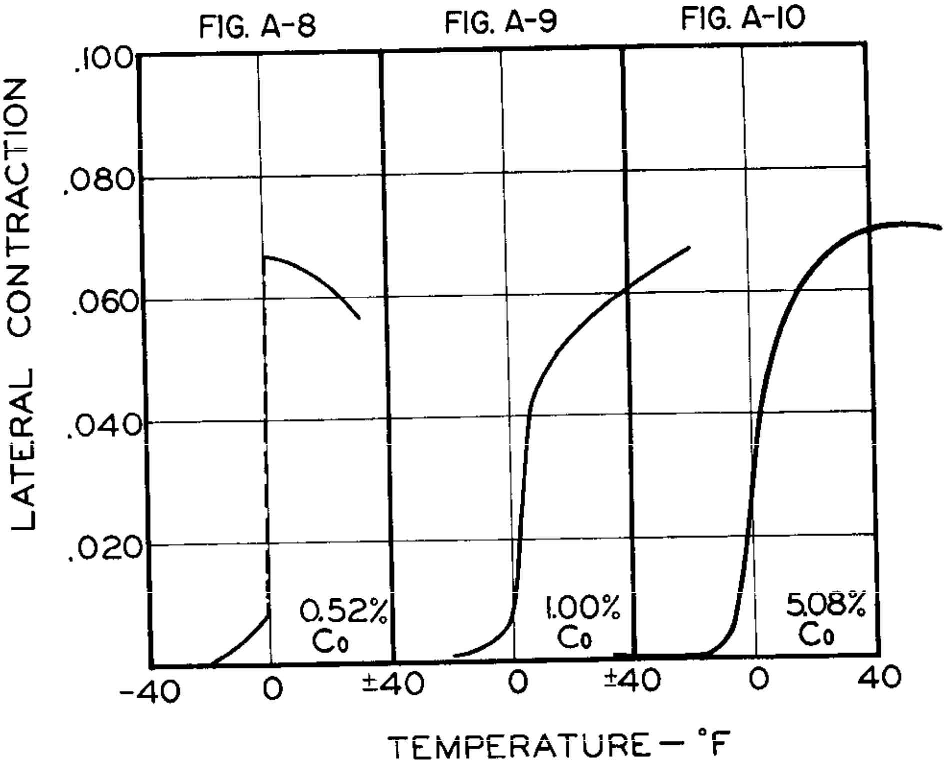
SPECIMENS

FIG. A-1

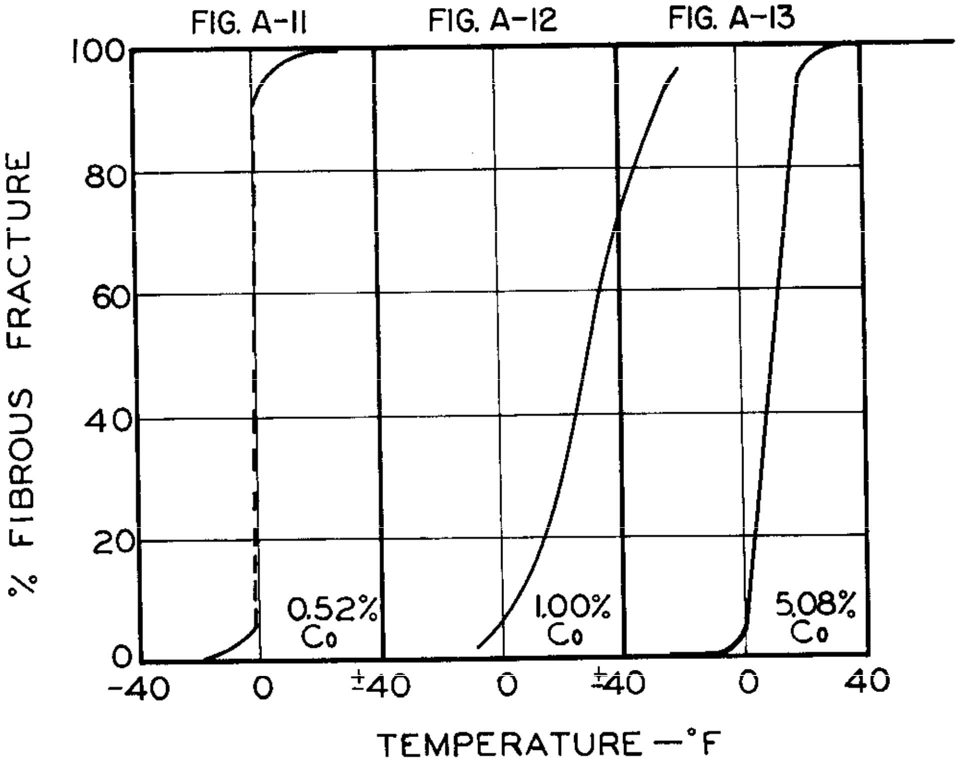


Figures A-2 to A-7: Microstructures of Selected Alloy Ferrites.
10% Nital etch. X100.

Figure A-2: - 4.83% Ni Alloy
Figure A-3: - 4.83% Cr Alloy
Figure A-4: - 7.25% Mn Alloy
Figure A-5: - 5.08% Co Alloy
Figure A-6: - 1.21% Si Alloy
Figure A-7: - 1.50% Mo Alloy

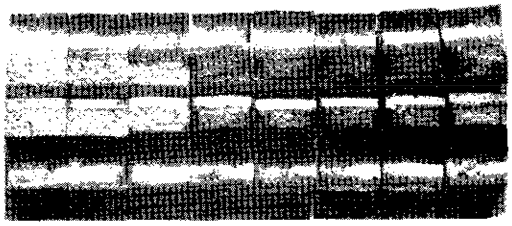


LATERAL CONTRACTION VS. TEMPERATURE DATA
FOR COBALT ALLOYS, SLOW BEND TEST

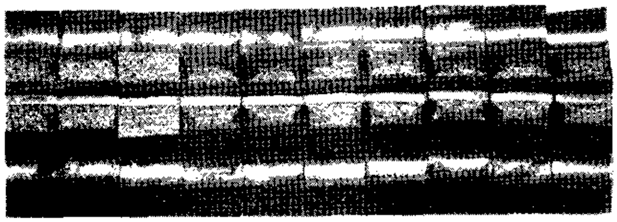


FRACTURE APPEARANCE VS. TEMPERATURE DATA
FOR COBALT ALLOYS, SLOW BEND TEST

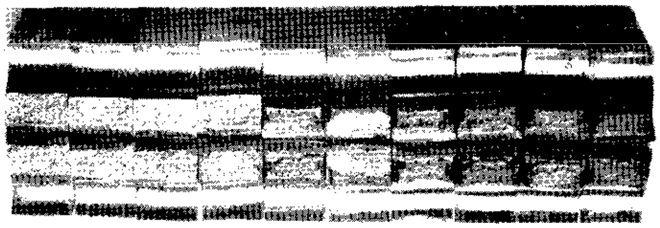
A-14



A-15



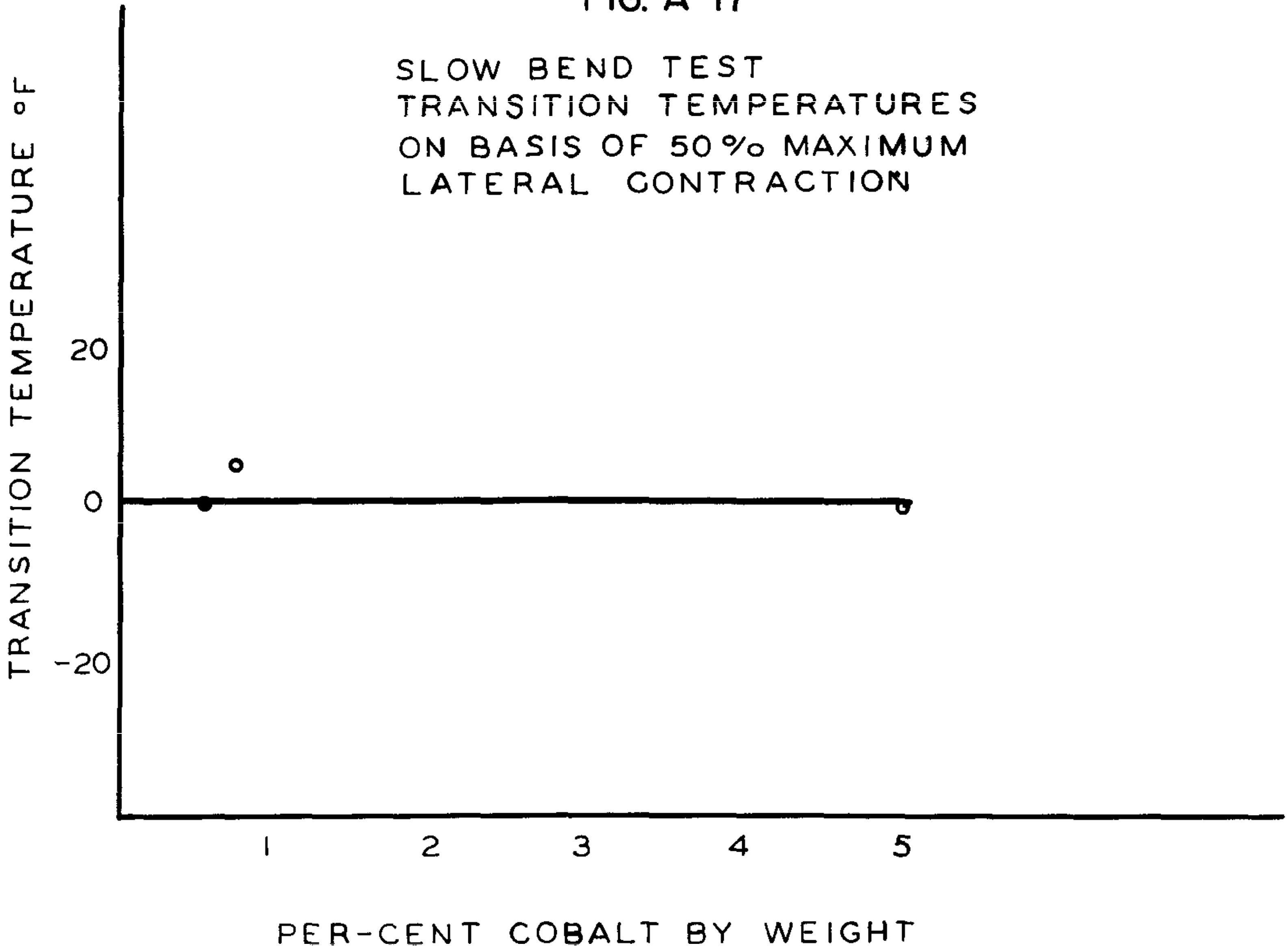
A-16



Figures A-14 to A-16: - The Fracture Surfaces for Slow Bend Specimens - Cobalt Ferrites. About X1.

Figure A-14: - 0.52% Co Alloy.
Figure A-15: - 1.00% Co Alloy.
Figure A-16: - 5.08% Co Alloy.

FIG. A-17



SLOW BEND TEST
TRANSITION TEMPERATURES
ON BASIS OF 50% MAXIMUM
LATERAL CONTRACTION

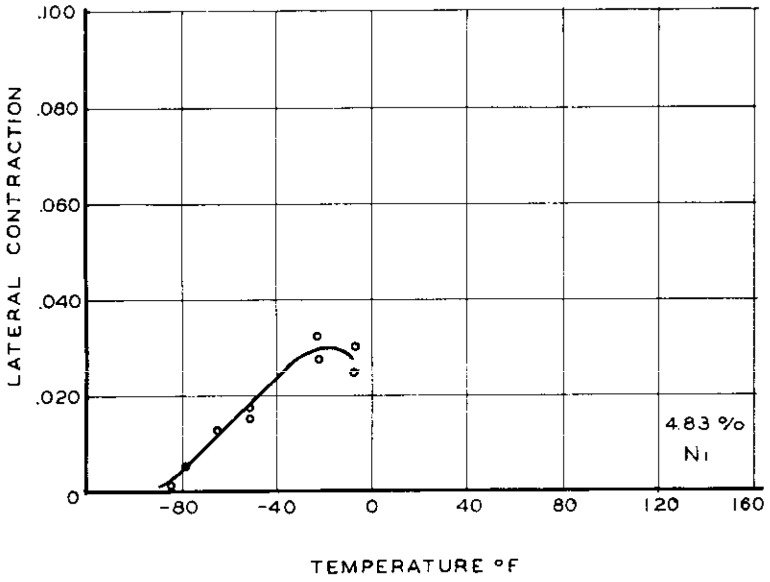


FIG. A-18 LATERAL CONTRACTION VS. TEMPERATURE IN SLOW BEND TEST – 4.83% Ni ALLOY

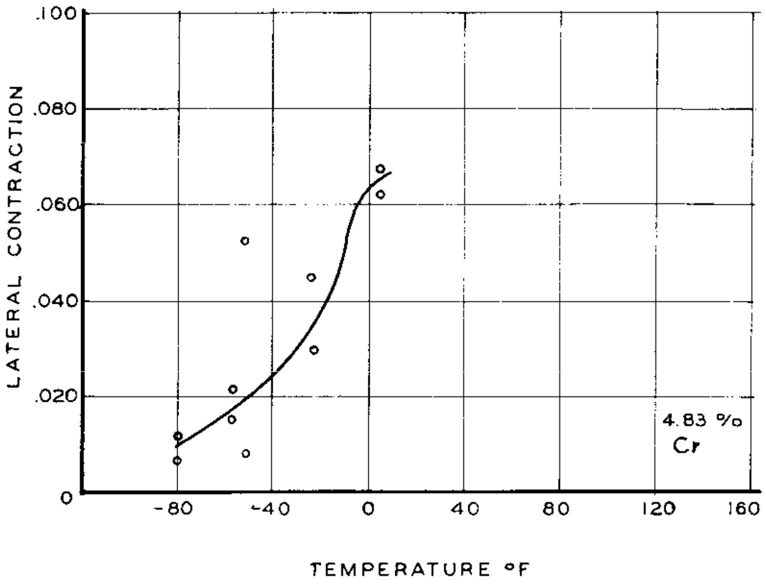


FIG. A-19 LATERAL CONTRACTION VS. TEMPERATURE IN SLOW BEND TEST – 4.83% Cr ALLOY

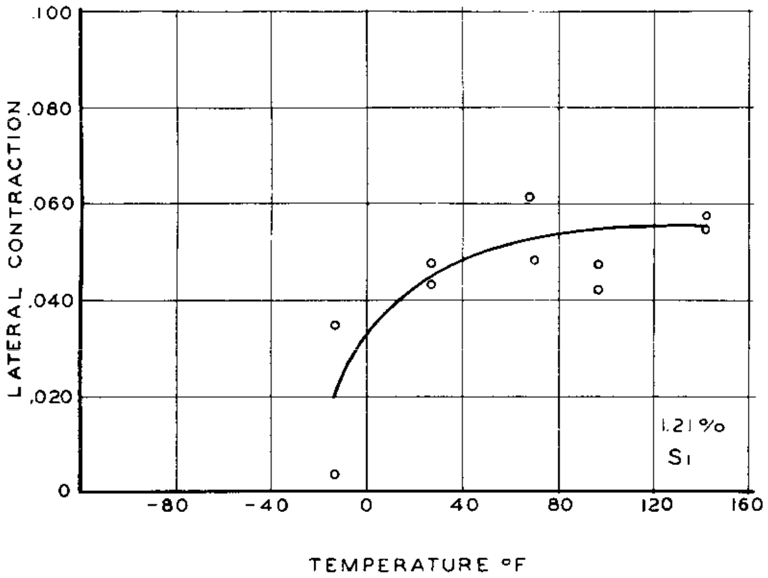


FIG. A-20 LATERAL CONTRACTION VS. TEMPERATURE IN SLOW BEND TEST – 1.21% Si ALLOY

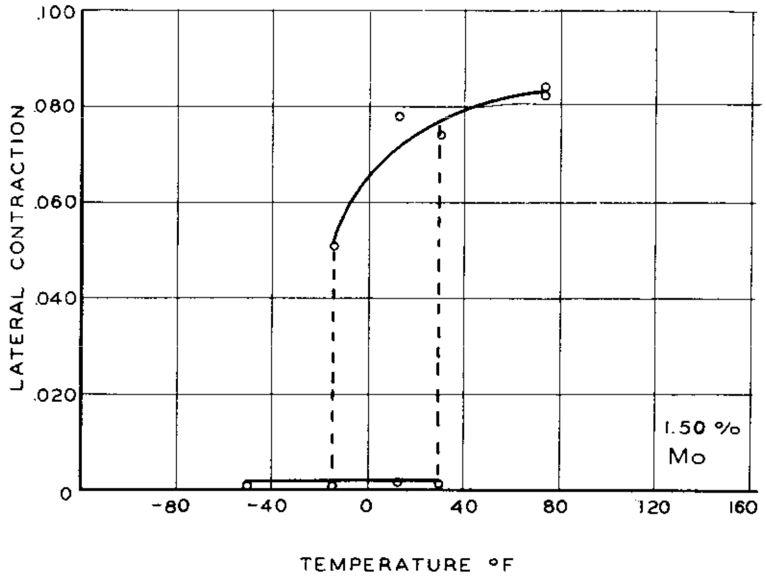


FIG. A-21 LATERAL CONTRACTION VS. TEMPERATURE IN SLOW BEND TEST – 1.50% Mo ALLOY

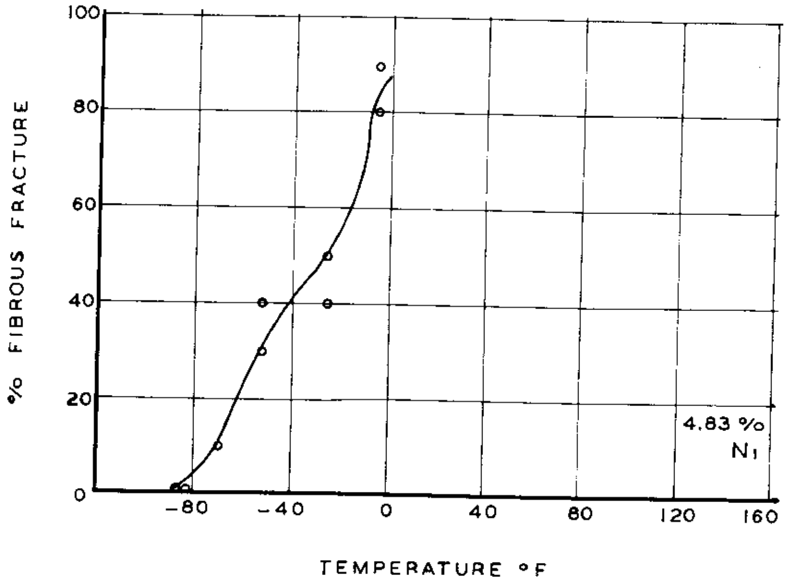


FIG. A-22 FRACTURE APPEARANCE VS. TEMPERATURE IN SLOW BEND TEST - 4.83% Ni ALLOY

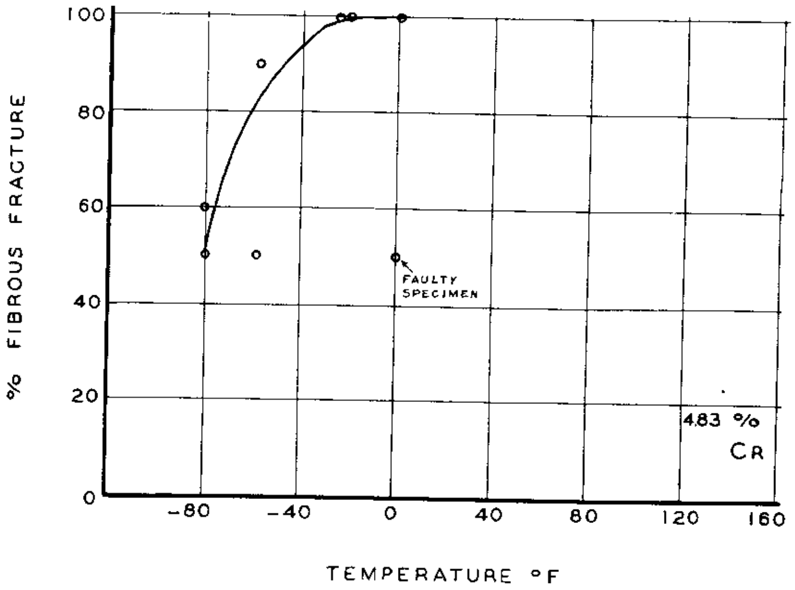


FIG. A-23 FRACTURE APPEARANCE VS. TEMPERATURE IN SLOW BEND TEST - 4.83% Cr ALLOY

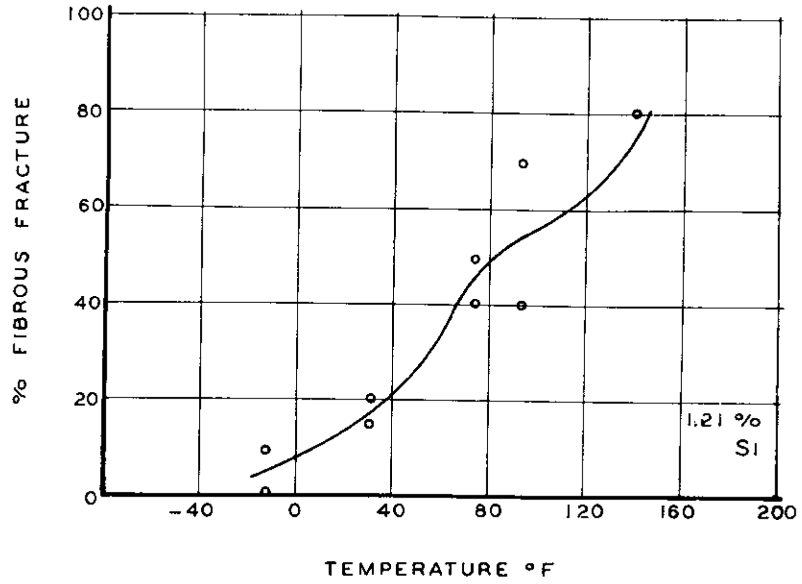


FIG. A-24 FRACTURE APPEARANCE VS. TEMPERATURE IN SLOW BEND TEST - 1.21% Si ALLOY

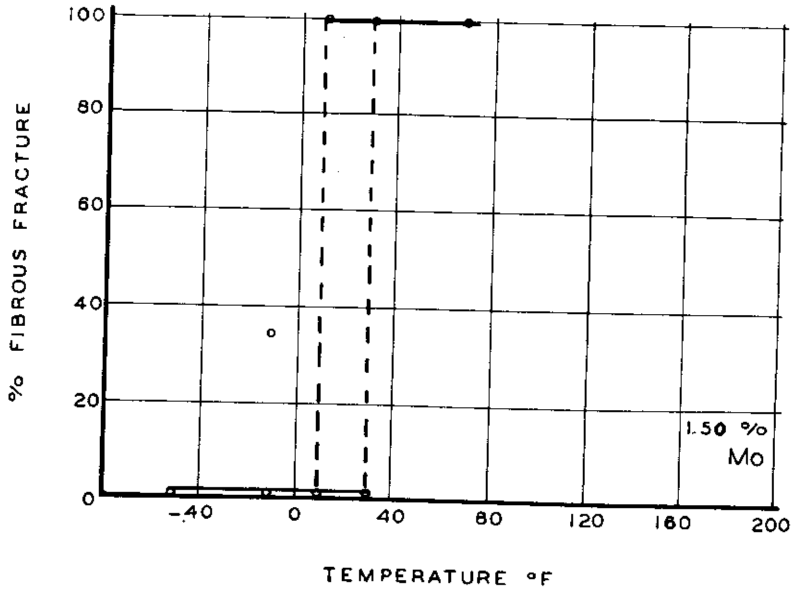
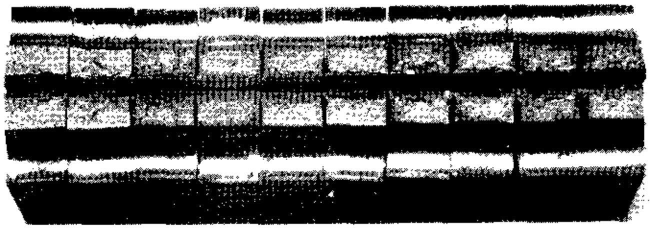
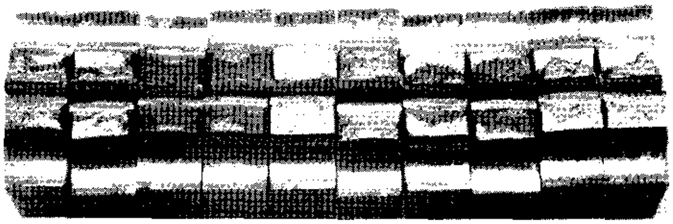


FIG. A-25 FRACTURE APPEARANCE VS. TEMPERATURE IN SLOW BEND TEST - 1.50% Mo ALLOY

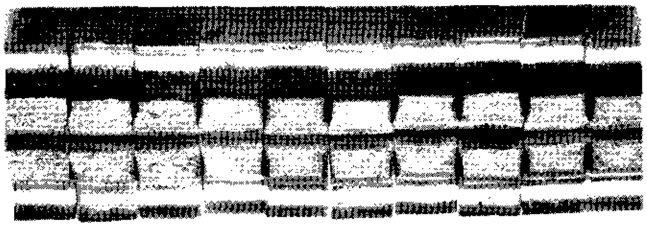
A-26



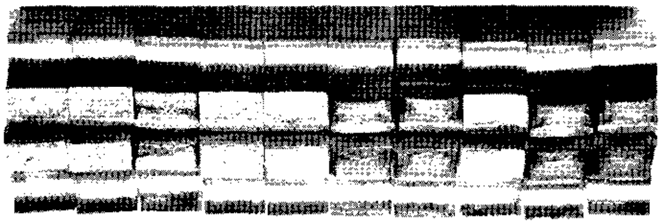
A-27



A-28



A-29



Figures A-26 to A-29: - The Fracture Surfaces for Slow Bend Specimens - Selected Alloy Ferrites. About X1.

Figure A-26: - 4.83% Ni Alloy
Figure A-27: - 4.83% Cr Alloy
Figure A-28: - 1.21% Si Alloy
Figure A-29: - 1.50% Mo Alloy

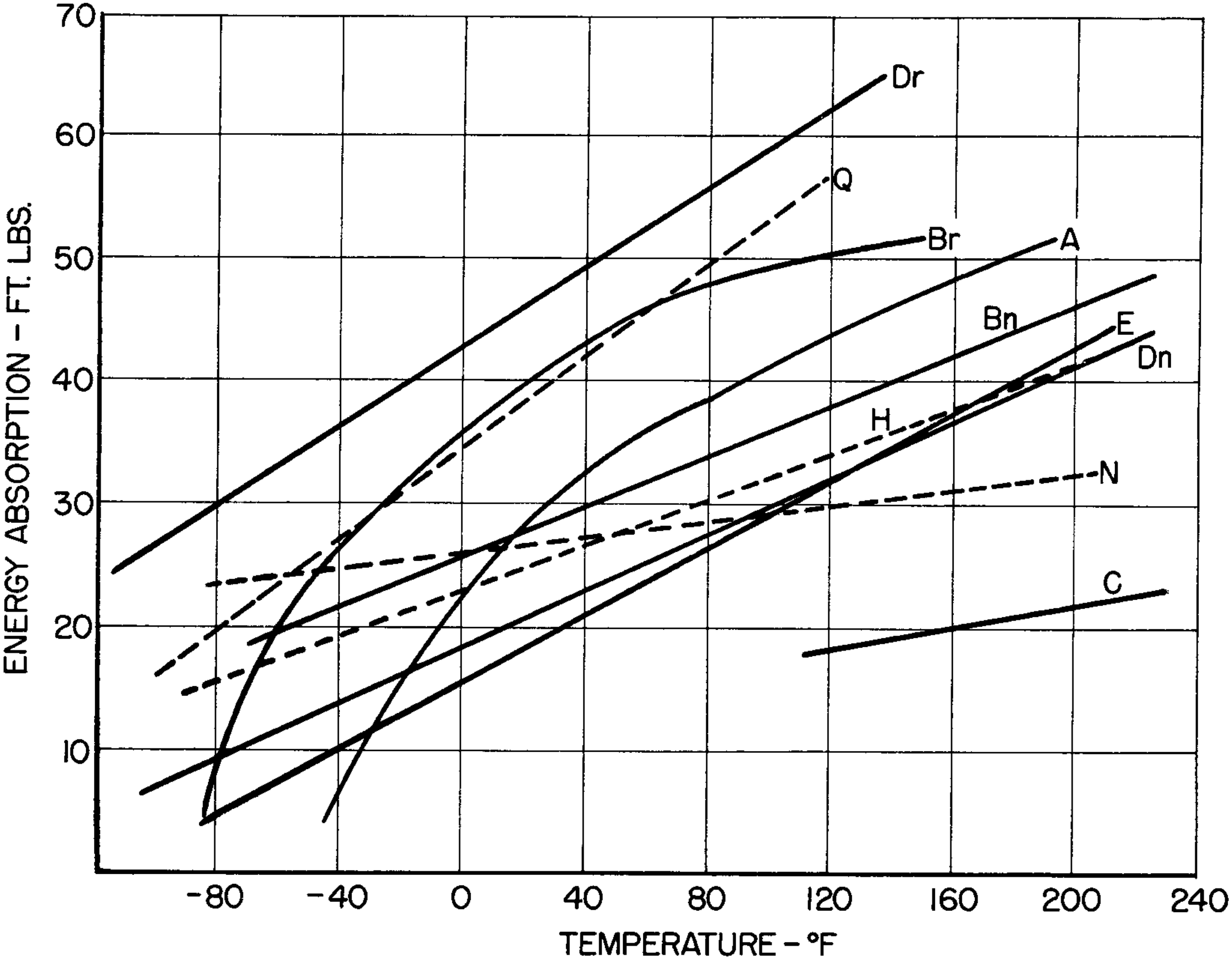


FIG. A-30 SUMMARY ENERGY ABSORPTION VS. TEMPERATURE FOR ROUND IMPACT BAR - AVAILABLE PROJECT STEELS

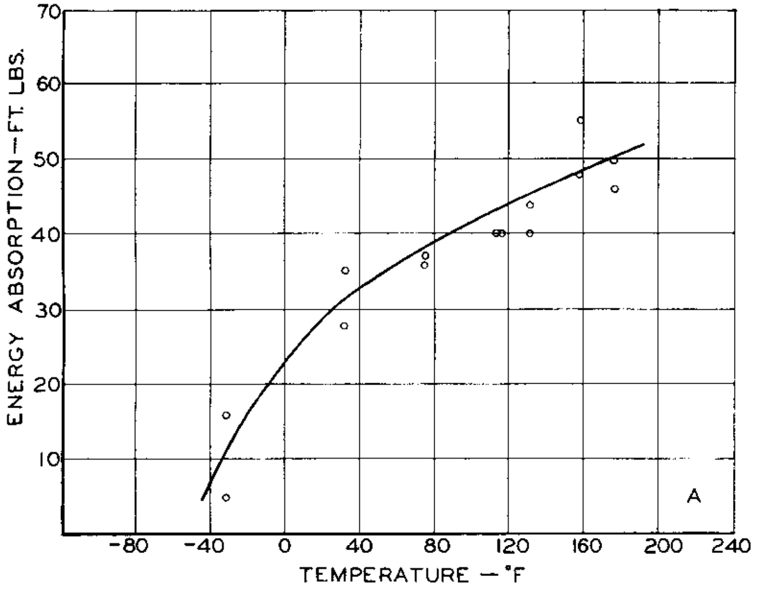


FIG. A-31 ENERGY ABSORPTION VS. TEMPERATURE - STEEL A

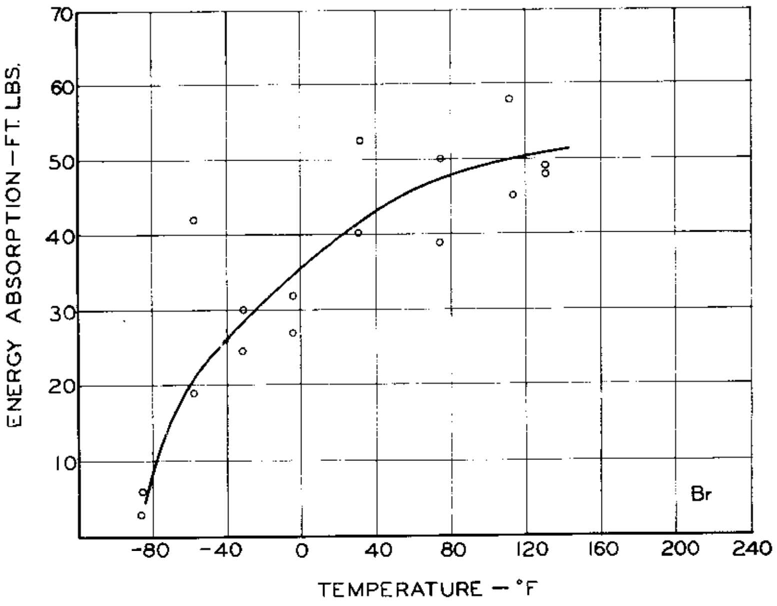


FIG. A-32 ENERGY ABSORPTION VS. TEMPERATURE - STEEL Br

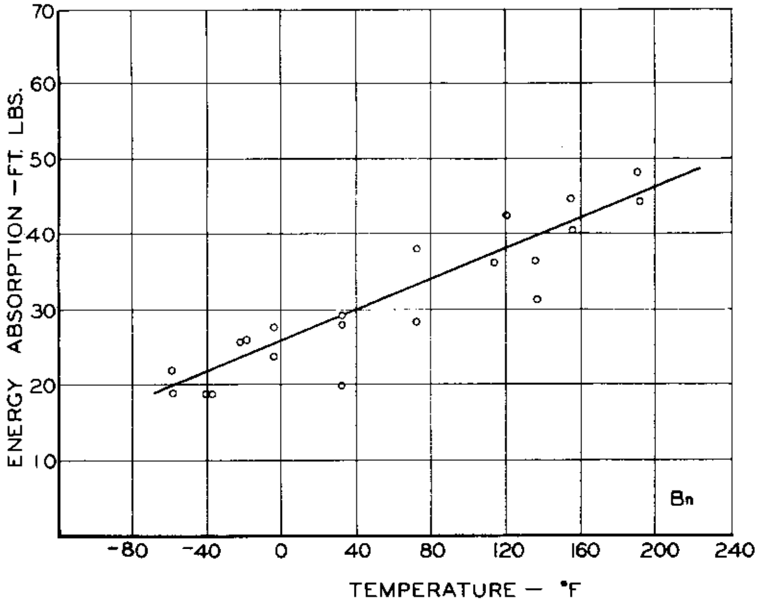


FIG. A-33 ENERGY ABSORPTION VS. TEMPERATURE - STEEL Bn

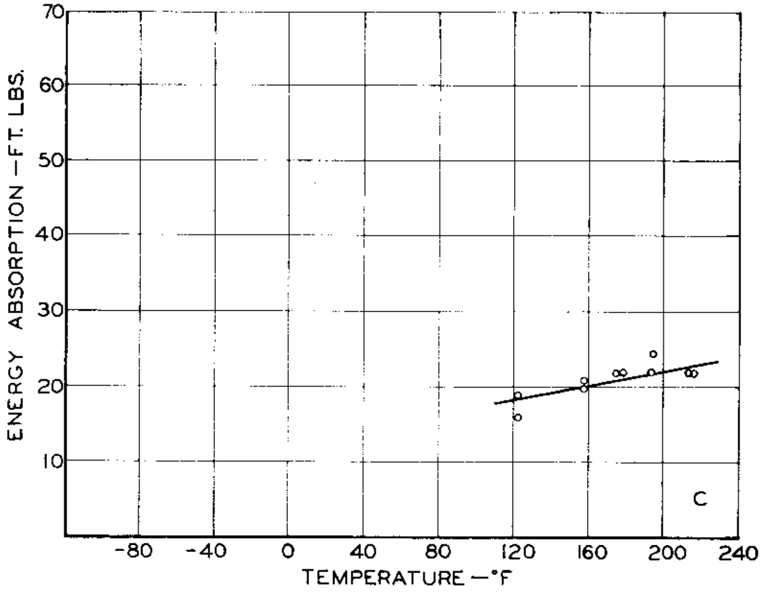


FIG. A-34 ENERGY ABSORPTION VS. TEMPERATURE - STEEL C

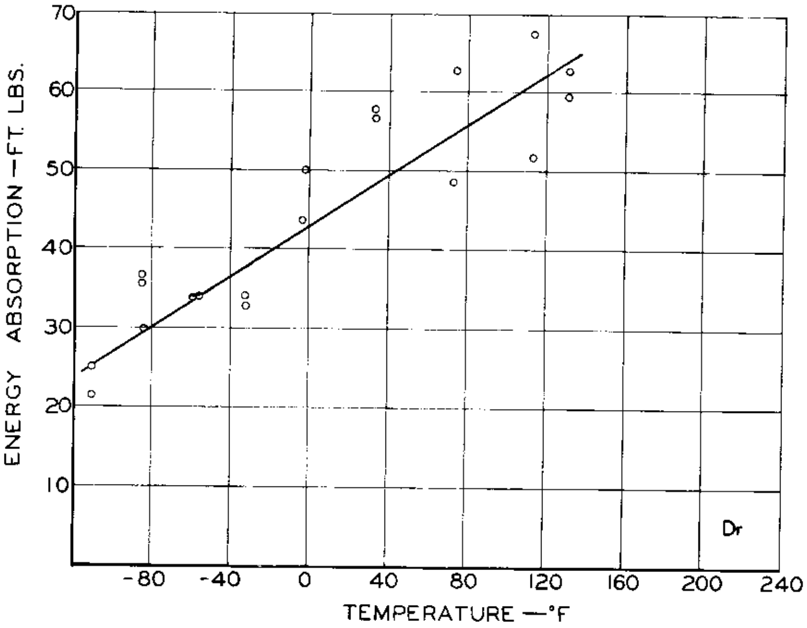


FIG. A-35 ENERGY ABSORPTION VS. TEMPERATURE - STEEL Dr

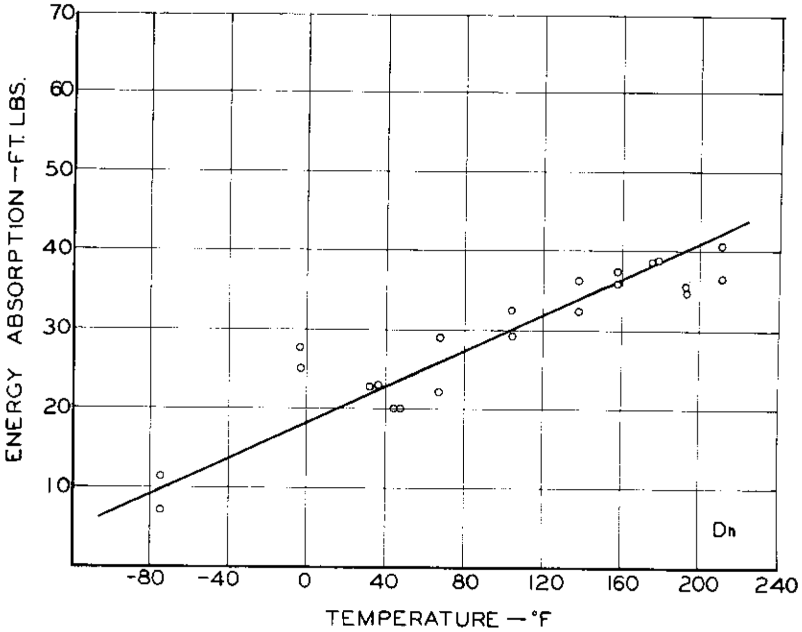


FIG. A-36 ENERGY ABSORPTION VS. TEMPERATURE - STEEL Dn

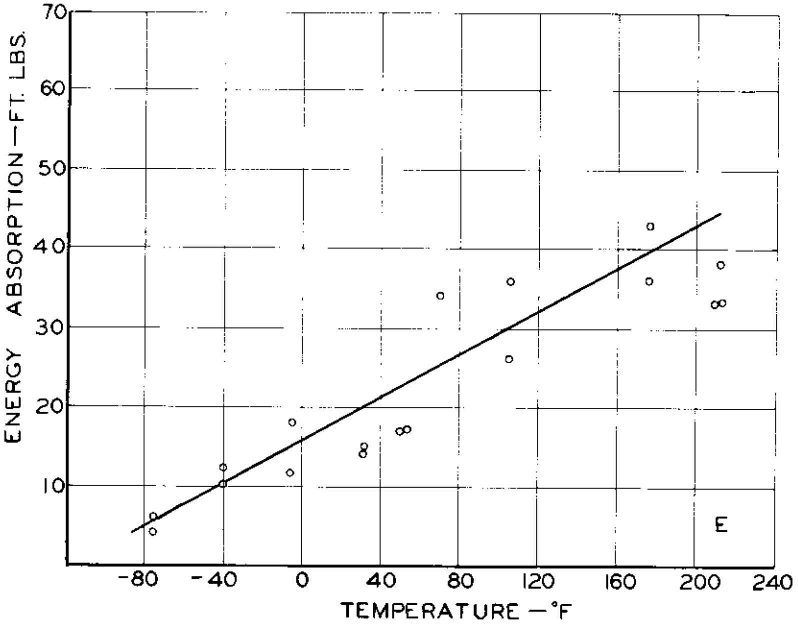


FIG. A-37 ENERGY ABSORPTION VS. TEMPERATURE - STEEL E

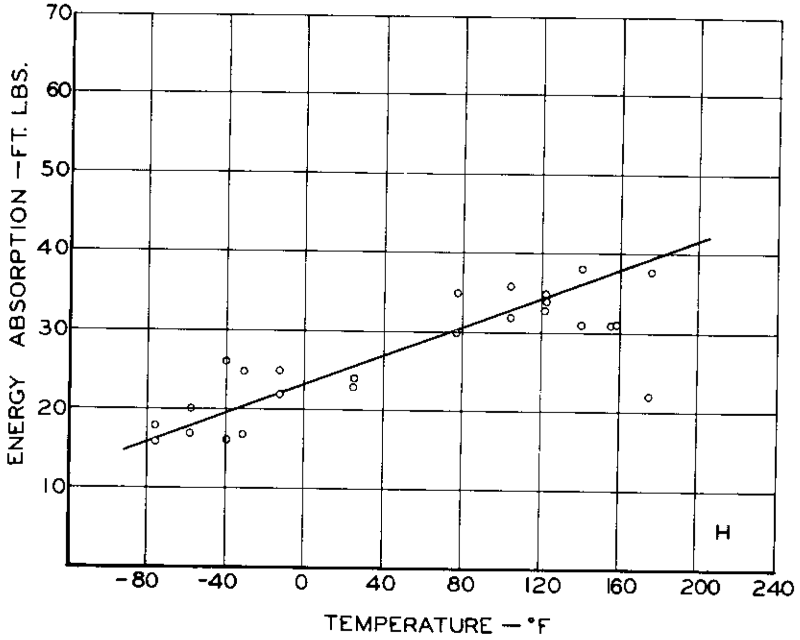


FIG. A-38 ENERGY ABSORPTION VS. TEMPERATURE - STEEL H

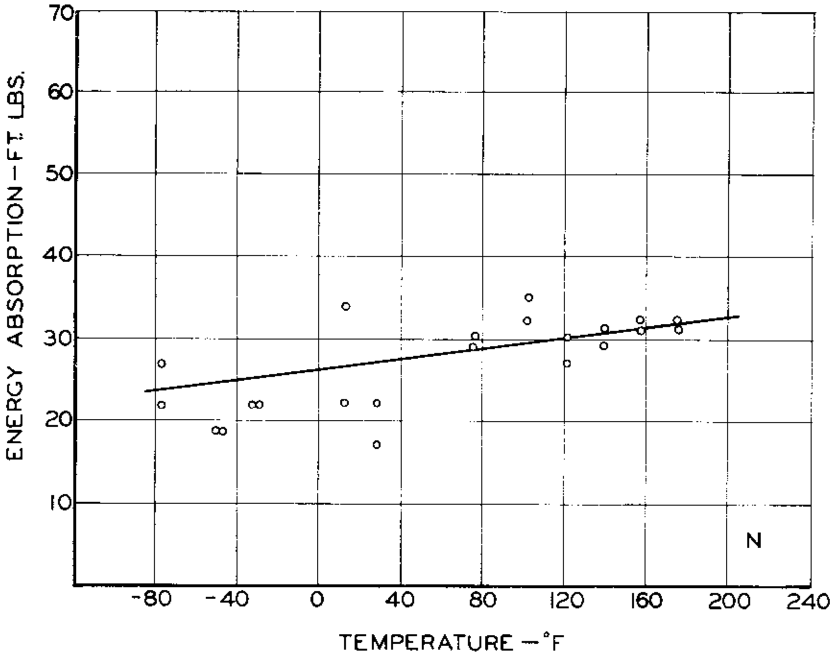


FIG. A-39 ENERGY ABSORPTION VS TEMPERATURE - STEEL N

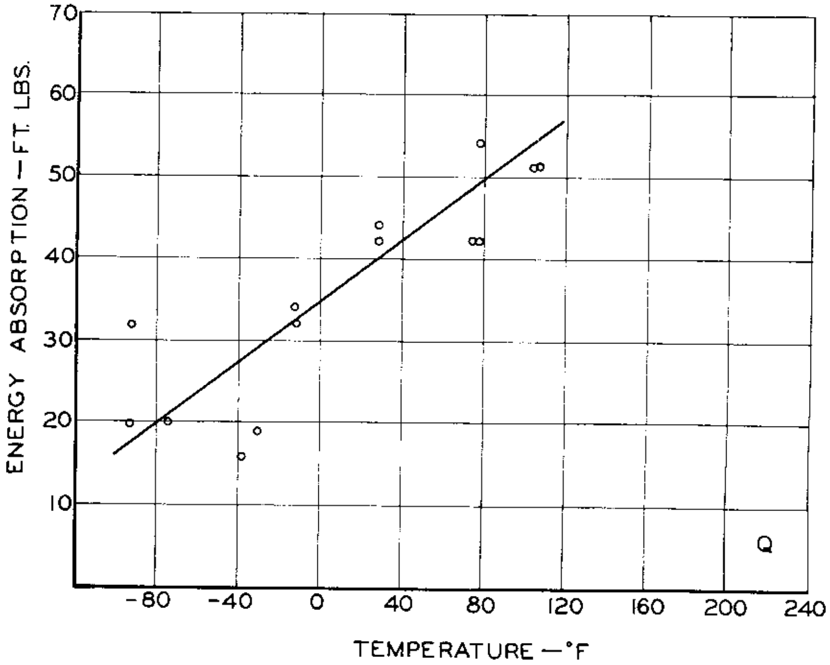


FIG. A-40 ENERGY ABSORPTION VS. TEMPERATURE - STEEL Q

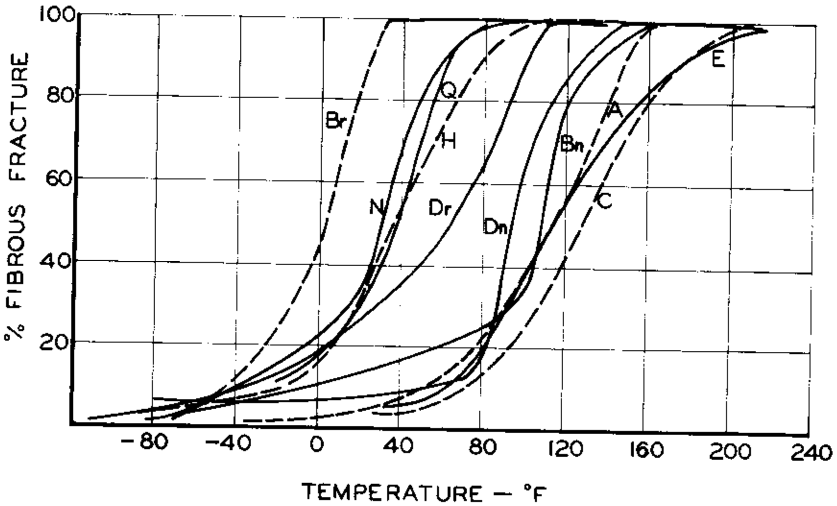


FIG. A-41 SUMMARY, FRACTURE APPEARANCE VS. TEMPERATURE FOR ROUND IMPACT BAR — AVAILABLE PROJECT STEELS

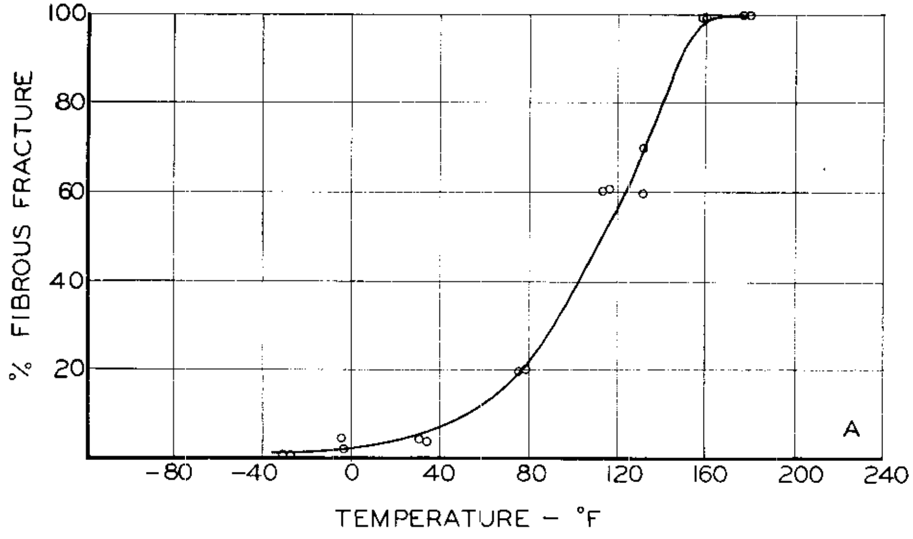


FIG. A-42 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL A

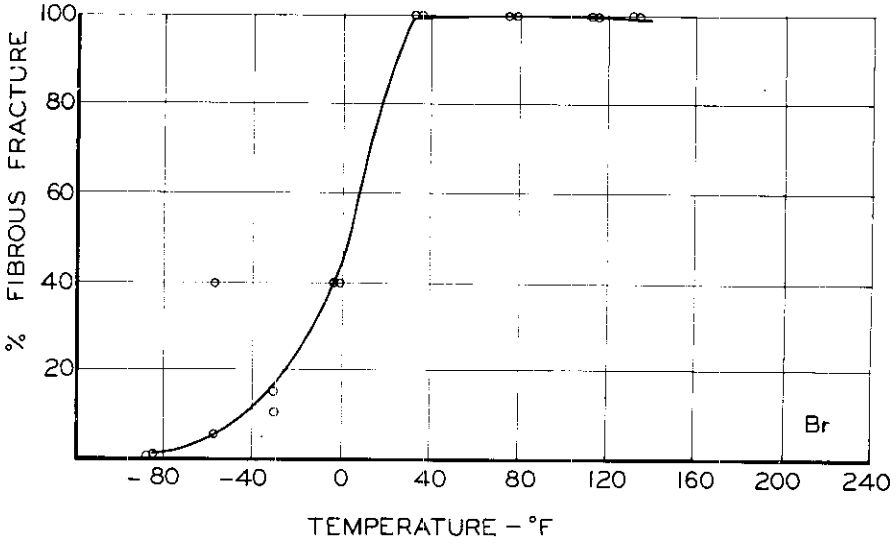


FIG. A-43 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL Br

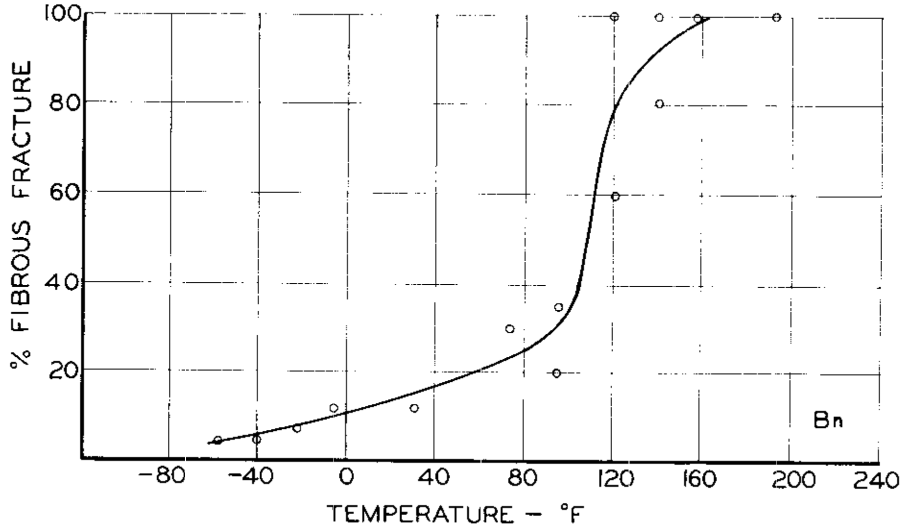


FIG. A-44 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL Bn

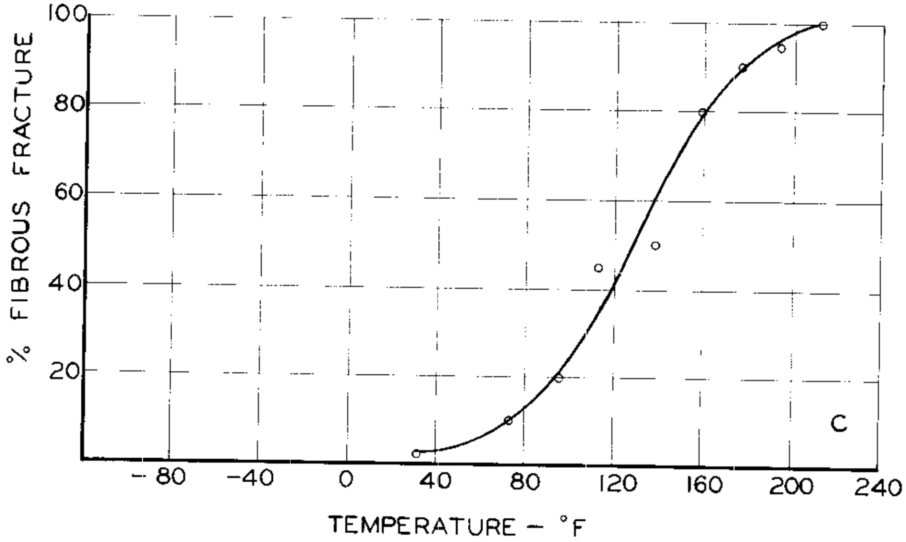


FIG. A-45 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL C

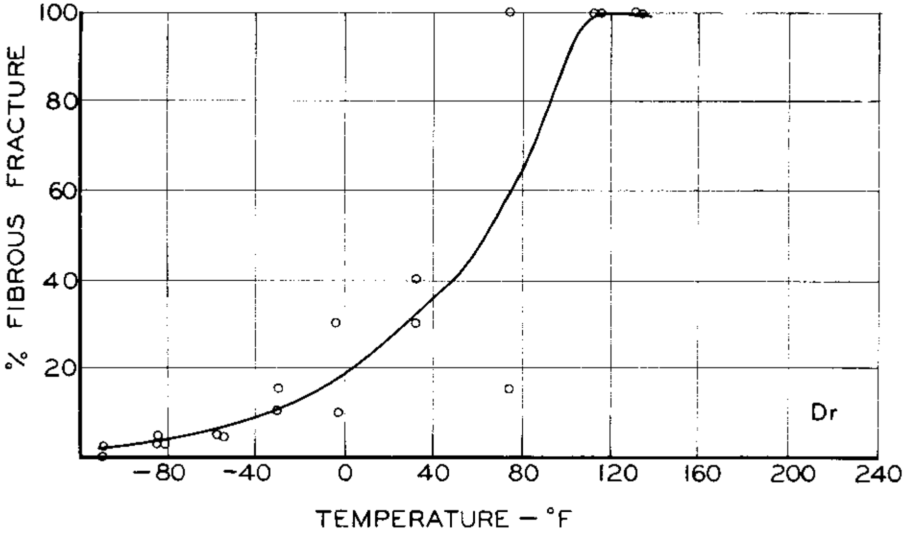


FIG. A-46 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL Dr

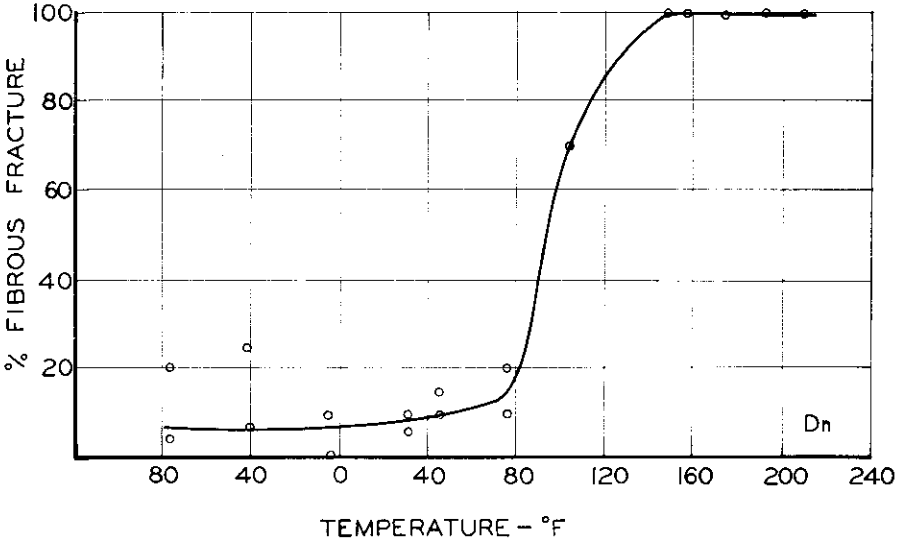


FIG. A-47 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL Dn

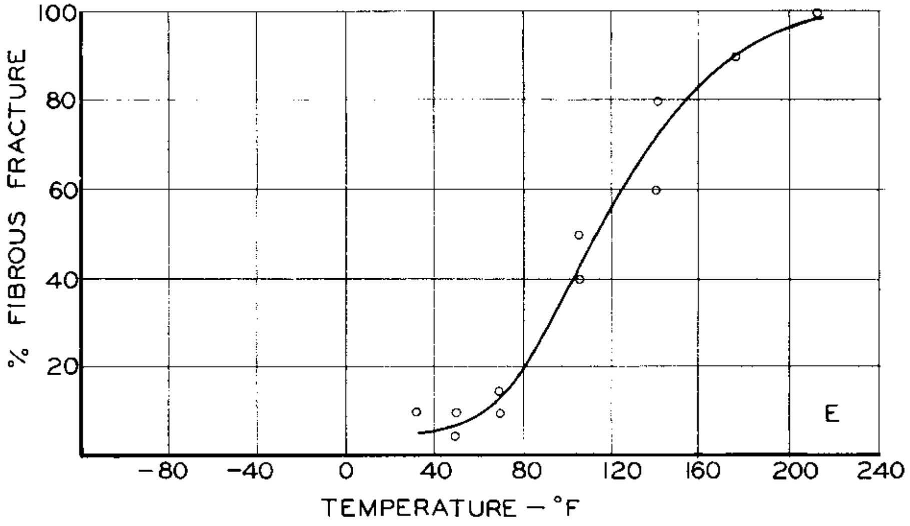


FIG. A-48 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL E

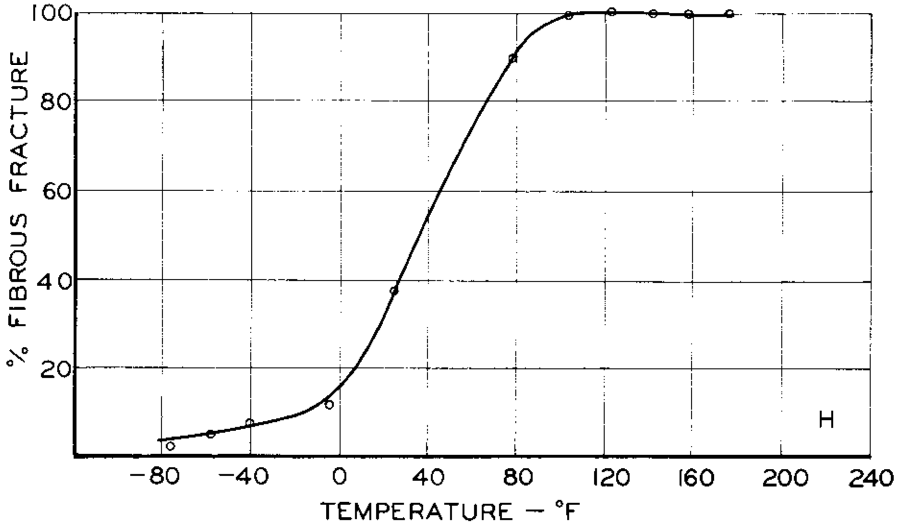


FIG. A-49 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL H

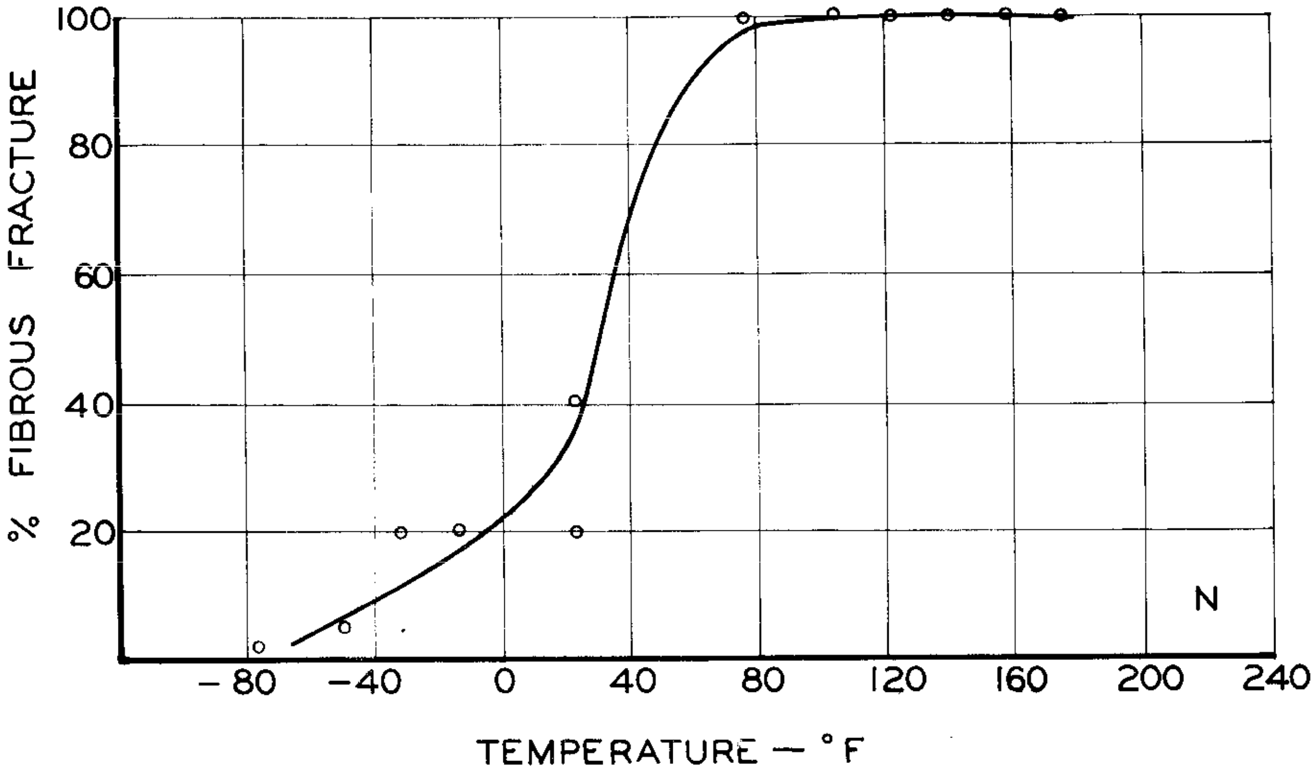


FIG. A-50 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL N

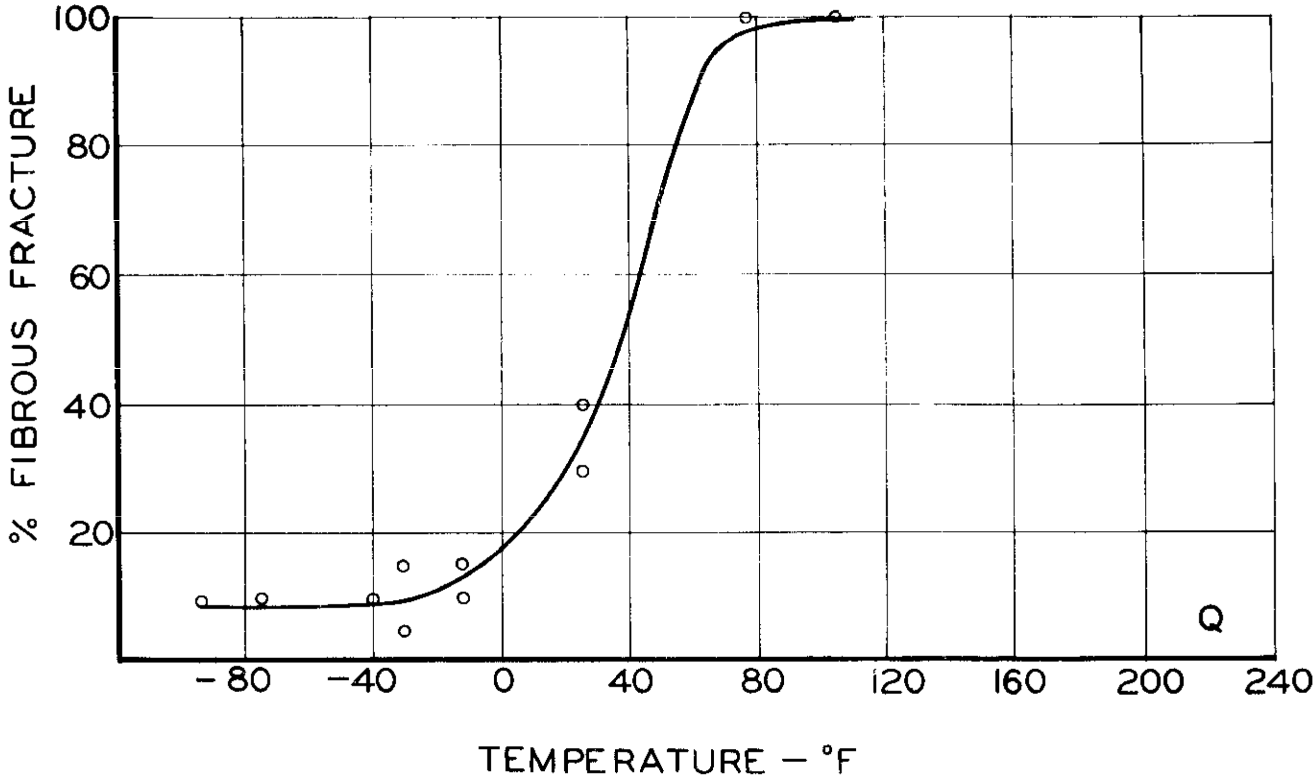


FIG. A-51 FRACTURE APPEARANCE VS. TEMPERATURE - STEEL Q

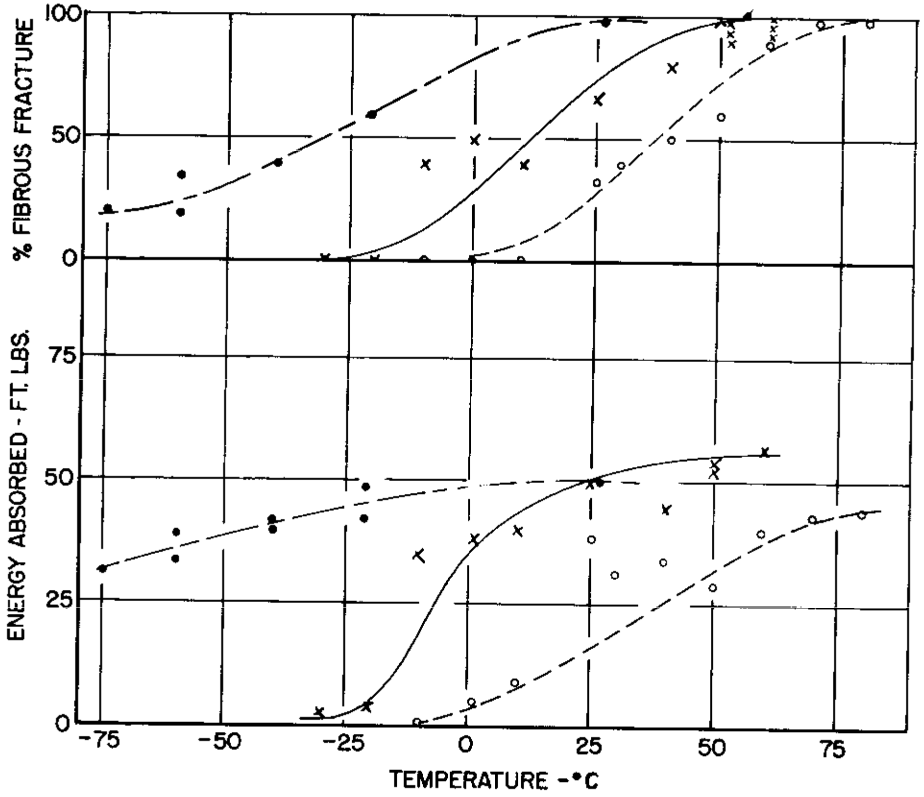


FIG. A-52 FRACTURE APPEARANCE AND ENERGY ABSORPTION VS. TEMPERATURE FOR ROUND IMPACT BAR NICKEL ALLOY FERRITES

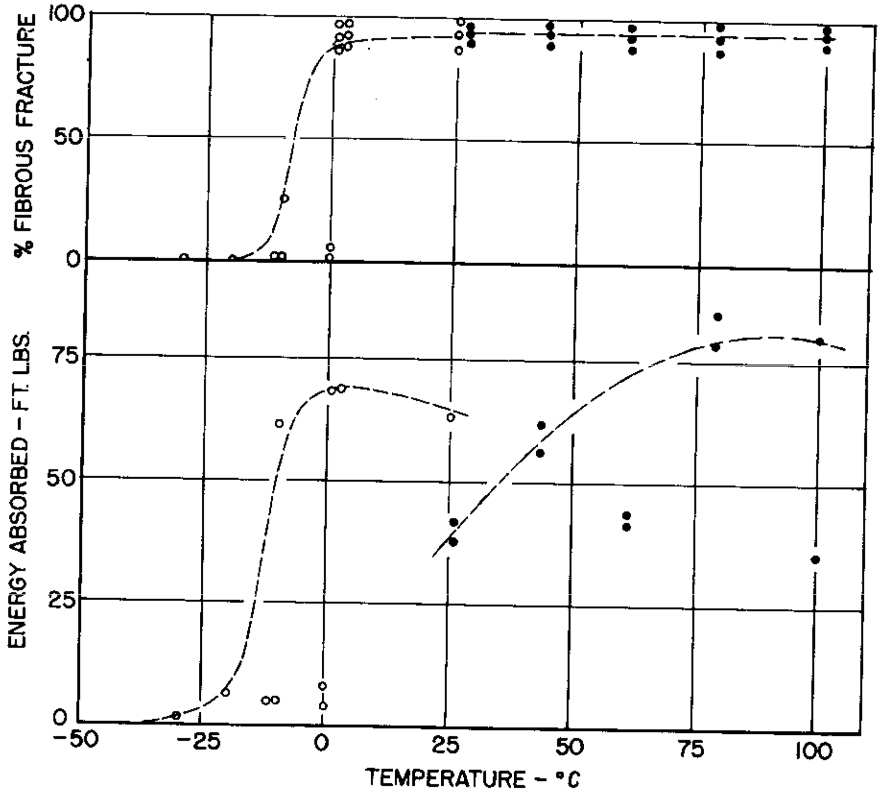


FIG. A-53 FRACTURE APPEARANCE AND ENERGY ABSORPTION VS. TEMPERATURE FOR ROUND IMPACT BAR CHROMIUM ALLOY FERRITES

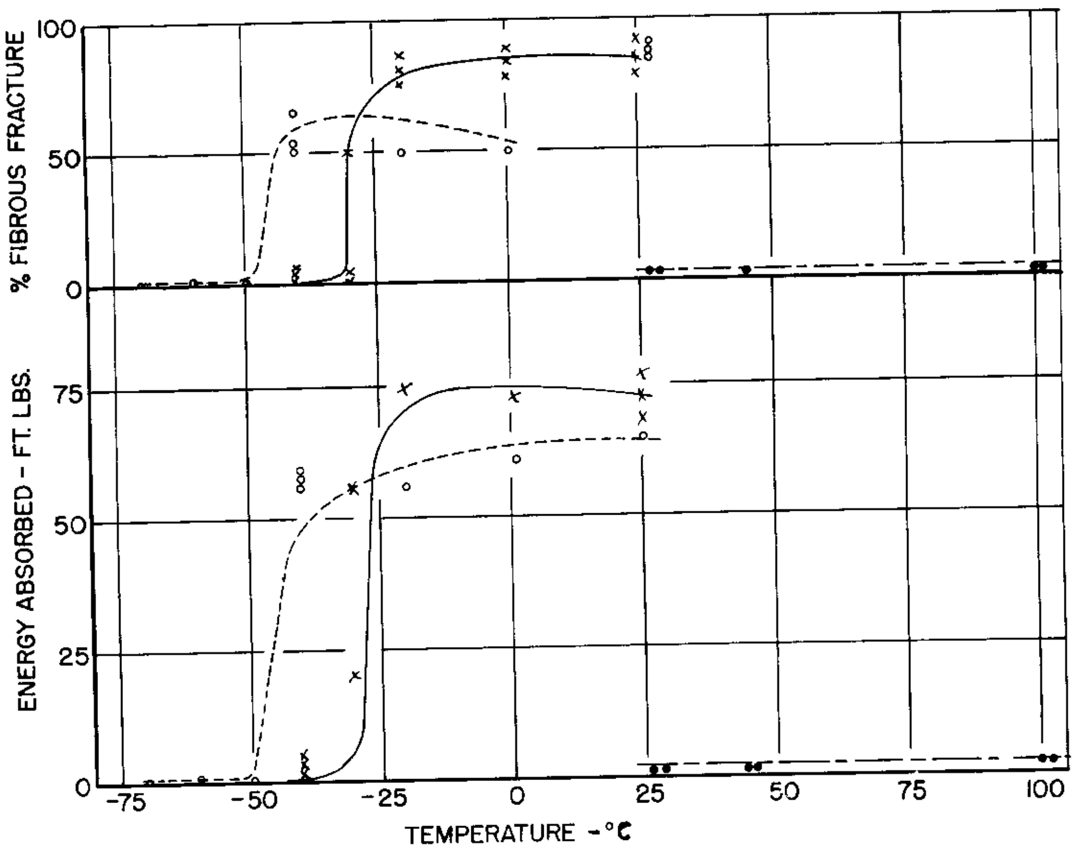


FIG. A-54 FRACTURE APPEARANCE AND ENERGY ABSORPTION
VS. TEMPERATURE FOR ROUND IMPACT BAR
MANGANESE ALLOY FERRITES

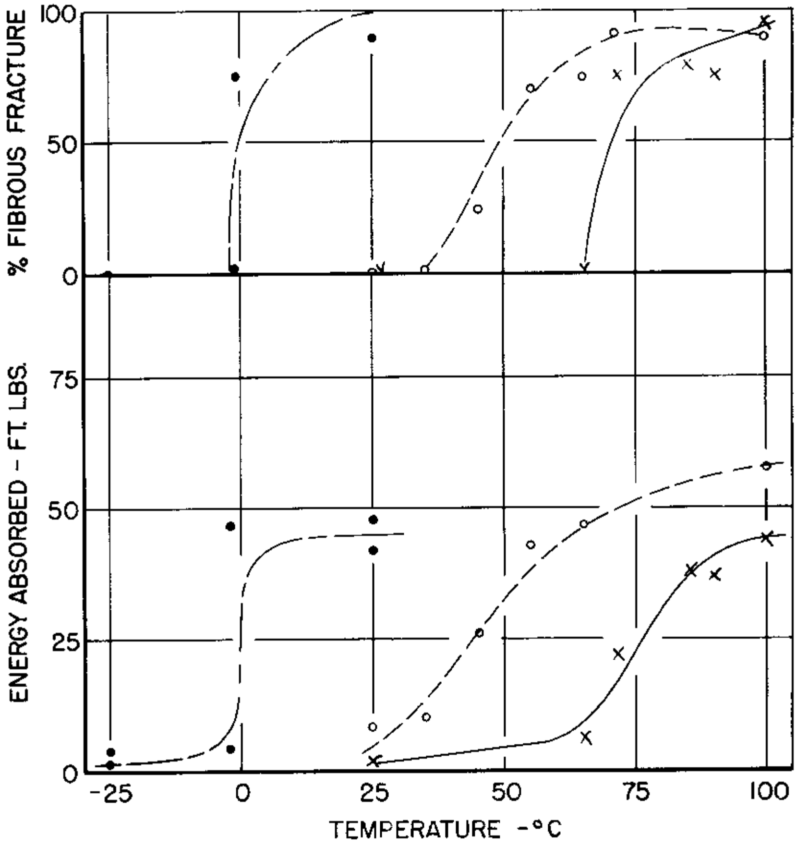


FIG. A-55 FRACTURE APPEARANCE AND ENERGY
ABSORPTION VS. TEMPERATURE FOR ROUND
IMPACT BAR - COBALT ALLOY FERRITES

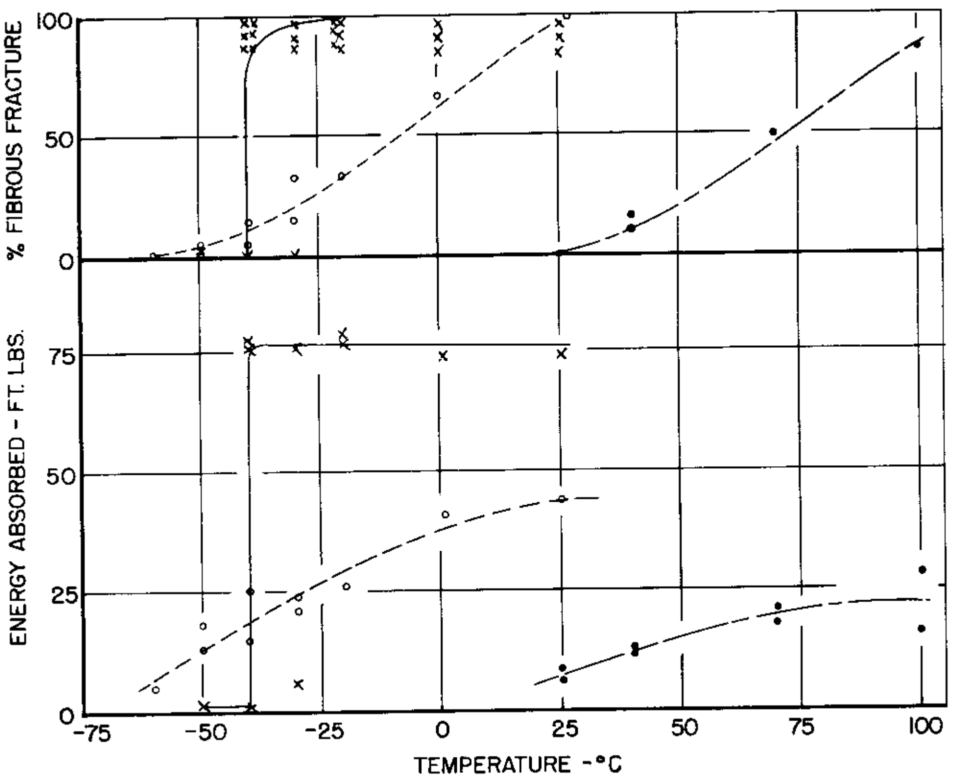


FIG. A-56 FRACTURE APPEARANCE AND ENERGY ABSORPTION VS. TEMPERATURE FOR ROUND IMPACT BAR SILICON ALLOY FERRITES

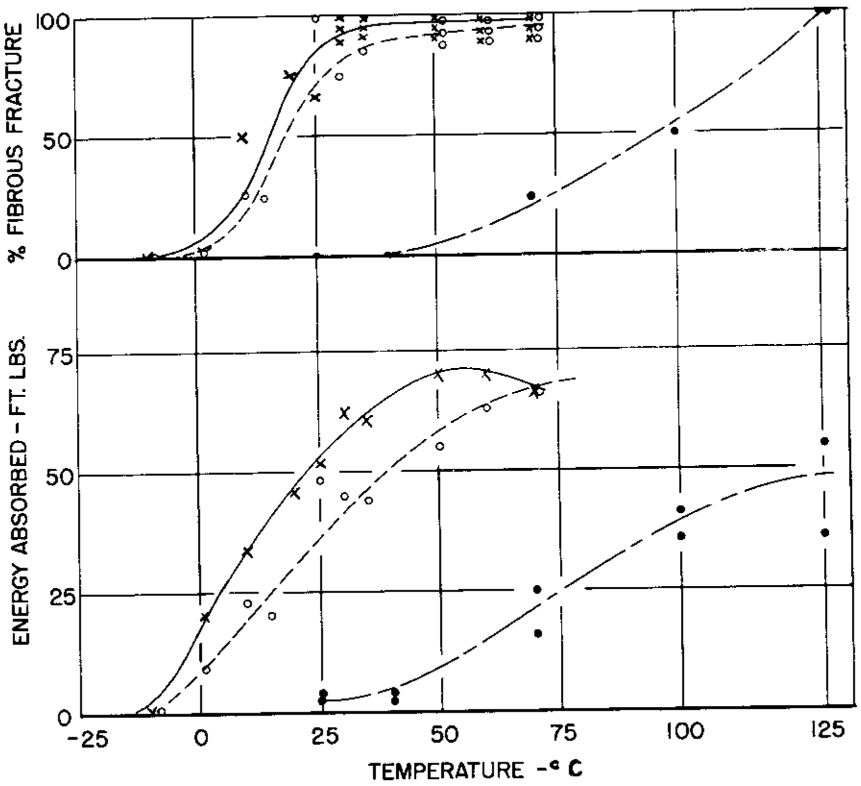


FIG. A-57 FRACTURE APPEARANCE AND ENERGY ABSORPTION VS. TEMPERATURE FOR ROUND IMPACT BAR MOLYBDENUM ALLOY FERRITES

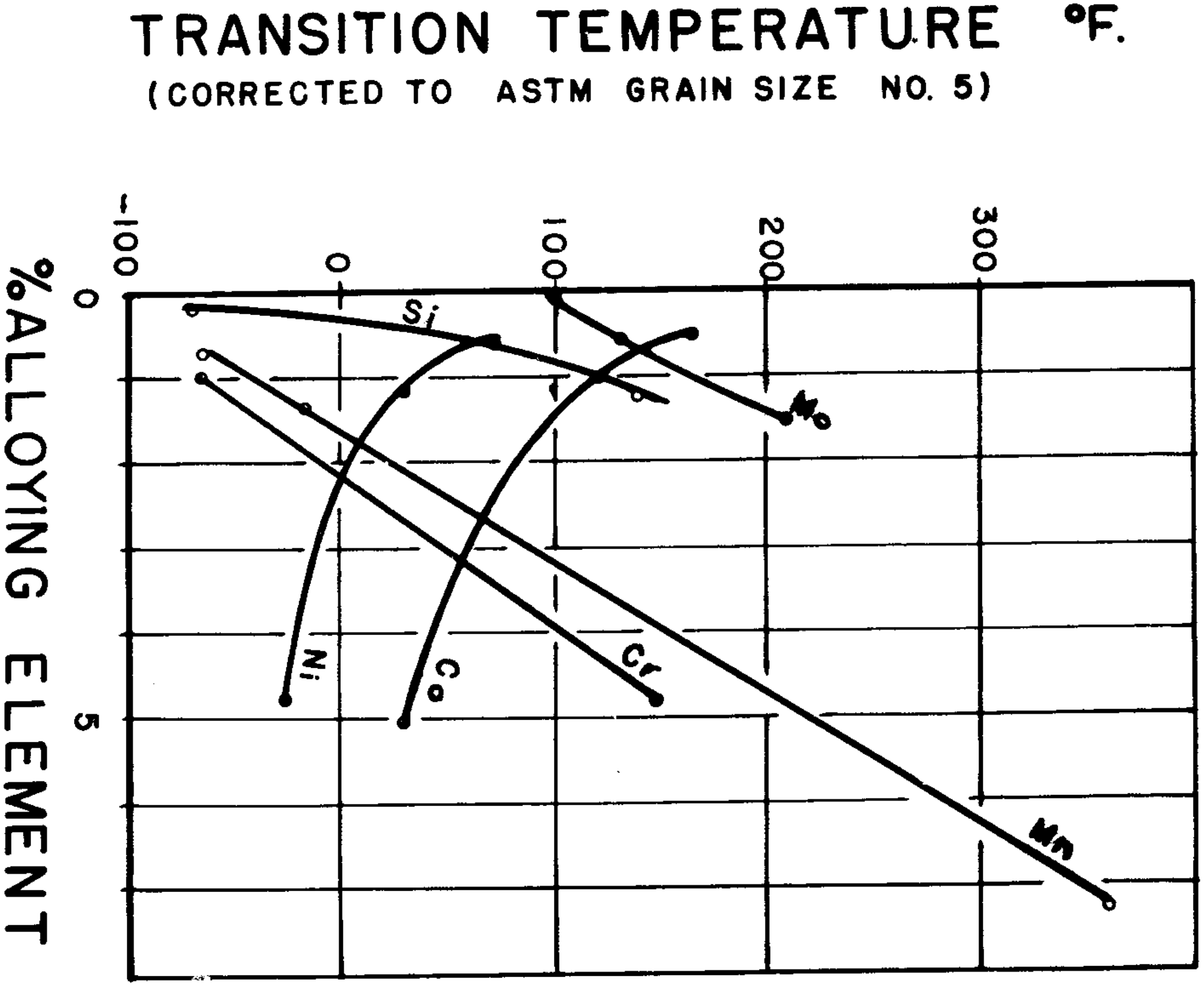

TRANSITION TEMPERATURE °F.
(CORRECTED TO ASTM GRAIN SIZE NO. 5)
-100
0
100
200
300
% ALLOYING ELEMENT
0
5
Si
Mo
Ni
Co
Cr
Mn

FIG. A-58

APPENDIX B

Ludwik (15) first pointed out that strain in the tensile test is most effectively defined as:

$$\delta = \ln \frac{A_o}{A} \qquad (1)$$

where δ is the strain and Ao and A are, respectively, the initial and instantaneous areas. This strain was found to be related to the stress through the equation

$$S = S_o - K\delta^m \qquad (2)$$

where So, k and m are constants.

Hollomon(30) has contended that equation (2) may satisfactorily be replaced by

$$S = K\delta^m \qquad (3)$$

or in the notation of this report

$$\sigma = \sigma_o \delta^n \qquad (4)$$

This expression suffers from not satisfying the boundary conditions in the tension test, which means that the comparison (say) of n for tests for a given steel after different thermal treatments or at different temperatures is not strictly permissible. This error is relatively unimportant in normal tests but might be appreciable under some test conditions. Since equation 4 is simpler to evaluate than equation 2 the determination of the constants is greatly facilitated by the use of equation 4.

The curve in Fig. B-1 is plotted according to equation 4 for $n = 0.165$ and for $\sigma_o = 110{,}000$. The curve from the origin possesses a positive varying curvature and bends sharply at low strain values to pass through the point ($\sigma = 110{,}000$; $\delta = 1$). It is evident that this curve must depart from the experimental true stress-true strain curve in three intervals; namely, (1) that in which elastic strain obtains; (2) that in which inhomogeneous plastic strain - the yield point elongation in steels - is encountered and; (3) that beyond the maximum load in which the specimen is necked down.

The necking of the specimen introduces a state of triaxial stress such that the shear stresses are lowered. This brings about an elevation of the flow curve which as long as the stress system can be evaluated can be in some measure compensated for.

Differentiation of equation 4 leads to

$$\left(\frac{d\sigma}{d\delta}\right)\frac{\delta}{\sigma} = n \qquad (5)$$

while Gensamer (33) has shown that at maximum load

$$\frac{d\sigma}{d\delta} = \sigma \qquad (6)$$

Equation 6 into equation 5 (30) (34) leads to

$$\delta_{\text{max. load}} = n \qquad (7)$$

Equation 6 indicates that necking begins when the slope of the stress-strain curve becomes equal to the stress. Equation 7 indicates the strain at maximum load. Neither of these quantities can be determined experimentally with precision.

In Fig. B-2 is presented the nominal stress vs. reduction in area curve for Steel A tested at 25°C., (Specimen C-19). From this curve and on the basis of equation 7 it is evident that the values of σ and n in equation 4 must be obtained from measurements in the strain interval from approximately 5 to 25-30% reduction in area. The reduction in area values correspond to about .05 to .35 to .40 units natural (true) strain. At lower strain values elastic and yield point phenomena - elastic phenomena are encountered beyond the yield strain - may modify the stress-strain relationships while at higher strains the triaxiality of the stress system becomes important.

In the determination of the numerical values of σ_0 and n analytical or graphical methods may be used. The least squares determination of these functions is obviously the more easily reproducible. The precision with which these values can be stated, however, is not easily determined. This is particularly true for the value of the strain hardening exponent, which in this work has been found to vary between about 0.25 and 0.11. These values of n correspond to fourth and ninth roots and because of the lack of real numbers in the strain values must be uncertain in hundredths place for the ninth root. These values must be accepted, however, as certainly correct in trend. There can be no doubt that for some of the steels a marked decrease in n occurs at low temperatures.

Typical data are treated below by the least squares and graphical procedures. It is apparent that consistent results are obtained.

A. Least Squares Determination of σ_0 and n:

$$\sigma = \sigma_0 \delta^n \tag{1}$$

$$\ln \sigma = \ln \sigma_0 + n \ln \delta \tag{2}$$

Equation 2 can be solved for any combination of two stress-strain values from the stress-strain curve.

An additional equation can be obtained by multiplying equation 2 by ln δ

$$\ln \sigma \ln \delta = \ln \sigma_0 \ln \delta + n \ln^2 \delta \tag{3}$$

and equations 2 and 3 can be used to solve for σ_o and n. Using these two equations average values for σ and δ may be used in the equations

$$\sum \ln \sigma = N \ln \sigma_o + n \sum \ln \delta \tag{4}$$

and

$$\sum \ln \sigma \ln \delta = \sum \ln \delta \ln \sigma_o + n \sum \ln^2 \delta \tag{5}$$

These equations are then solved simultaneously for n and σ_o. This is done here for the test on specimen K-22 conducted at -70°C. The data are presented in Table B-I. These data in equations 4 and 5 lead to $39.998 = 8 \ln \sigma_o + n(-5.5150)$, and $-27.540 = -5.510 \ln \sigma_o + n(3.9842)$ (6)

from which $n = 0.192$

and $\sigma_o = 135\,500$ psi (6)

B. The data in part A are plotted on log-log scale in Fig. B-3. From equation 2, part A

$$\ln \sigma = \ln \sigma_o ; \quad \delta = 1 \tag{7}$$

and n is the slope of the stress-strain curve plotted in this manner. From this curve n = 0.185 and σ_o = 133,400 psi. It is evident that the graphical procedure is satisfactory for the determination of the σ_o and n values. It is pointed out, however, that considerable care must be used in plotting these data to avoid appreciable error in the results.

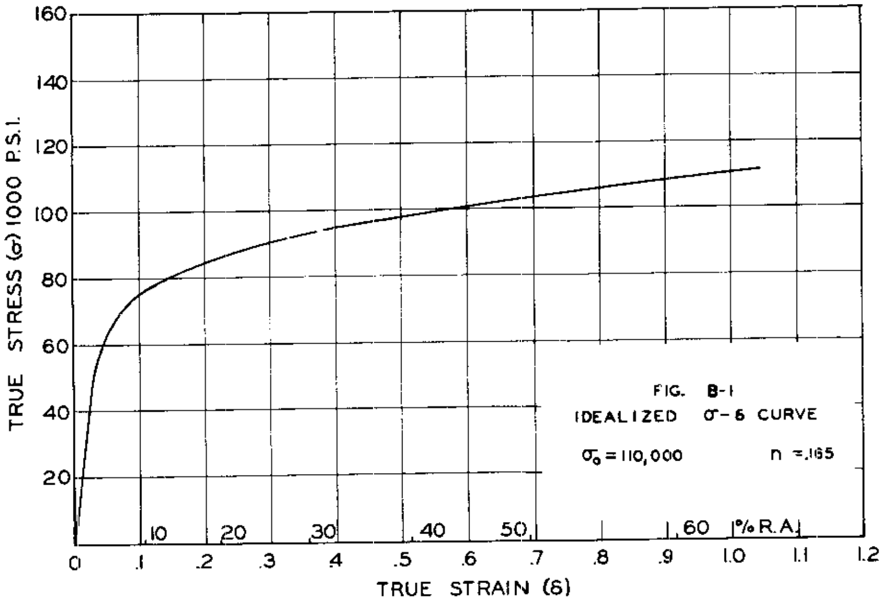
It has been pointed out in the above discussion that it is not possible to eliminate uncertainty in the numerical value of n in hundredths place or in the second real number. It is not possible, however, to check adequately the reproducibility of the σ_o and n values because of insufficient tests. It is also probable that the reproducibility of these values changes considerably with the temperature of test. The values below were obtained for Steel Bn tested at 25°C.

σ_o	n
103,230	.236
104,090	.245
99,100	.227
105,260	.247
102,500	.215

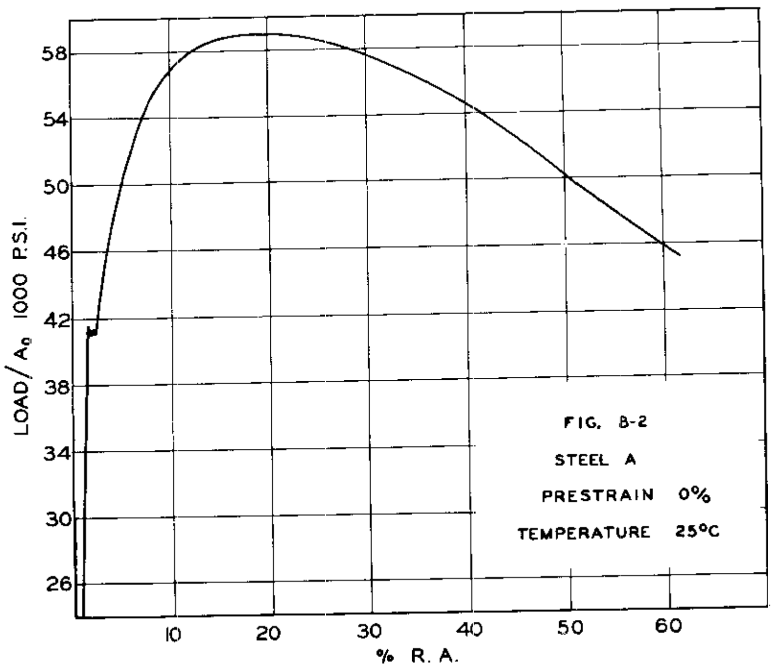
For the strength coefficient σ_o this leads to an average value equal to 102,830 psi with a mean deviation from the mean of 2,030 psi or a mean deviation of about 2%. For the strain hardening exponent the average value of n is 0.234 while the mean deviation from this value is slightly greater than 0.01 or slightly less than 5%. The accuracy of the measurements cannot be expected to be this good in general.

TABLE B-I- DATA FOR LEAST SQUARES DETERMINATION OF σ_o AND n - STEEL Dr. TESTED AT -70°C., SPECIMEN K-22.

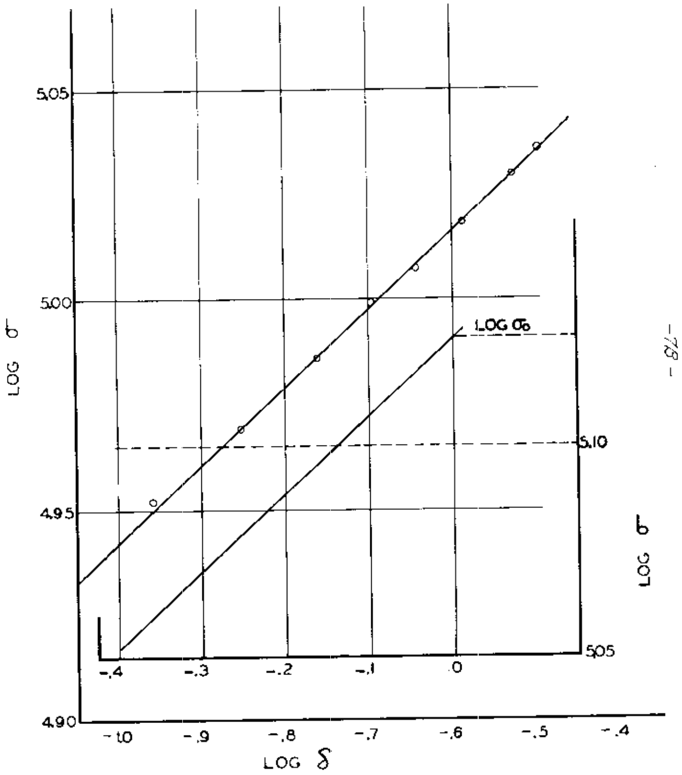
Area	σ	δ	$\ln \sigma$	$\ln \delta$	$\ln \sigma \ln \delta$	$\ln^2 \delta$
.0930	86,300	.0829				
.0906	89,700	.1093	4.95279	-.96138	-4.7615	.92425
.0879	93,100	.1398	4.96895	-.85449	-4.2459	.73015
.0849	96,800	.1724	4.98588	-.76346	-3.8065	.58287
.0827	99,200	.2000	4.99651	-.69897	-3.4924	.48856
.0802	101,800	.2302	5.00775	-.63789	-3.1944	.40690
.0778	104,500	.2615	5.01912	-.58253	-2.9238	.33934
.0749	107,300	.2982	5.03060	-.52549	-2.6435	.27614
.0732	108,700	.3230	5.03623	-.49080	-2.4718	.23598
.0708	111,000	.3553	—	—	—	—
—	—	—	—	—	—	—
—	—	—	—	—	—	—
.0426	145,000	.864	—	—	—	—
		Σ_n =	39.998	= -5.5150	= -27.540	= 3.9842
		N =	8			



IDEALIZED σ-δ CURVE, DERIVED FROM THE EXPRESSION $\sigma = \sigma_o \delta^n$



NOMINAL STRESS VERSUS PERCENT REDUCTION IN AREA – STEEL A



LOG TRUE STRESS – LOG NATURAL STRAIN CURVE
SPECIMEN K-22 – STEEL Dr
FIG. B-3

APPENDIX C

In order to evaluate the effects of pre-strain at room temperature on the fracture strength at -188°C, it was necessary that a fairly large number of tests be run. The most desirable test procedure would consist of setting up the specimen, prestraining it and cooling in liquid air in the testing grips and pulling immediately. Due to the number of specimens to be tested here this procedure was considered too time consuming. Specimens other than specimens of Steel A were prestrained at either 25°C or -76°C and were then held at -76°C for no longer than 24 hours after which they were cooled in liquid air and broken. The storage at -76°C was used to prevent aging which could have occurred on holding at 25°C. These specimens then were removed from the tensile machine and were replaced for final testing.

Because of the removal of the specimens after the initial straining the alignment of the specimens on final testing was questionable. This problem in the final execution of the test proved to be an unimportant one as most of the specimens suffered some additional strain at -188°C. The specimens were necessarily aligned as a consequence of this plastic straining.

In order to determine the degree of alignment comparison was made of the relative elastic strains at the ends of two mutually perpendicular diameters. The specimen for these tests was set-up in the self-aligning grips without any special precaution.

Test Results

1) Test bar loaded to 800 pounds readings taken and then load increased to 1500 pounds with readings again taken. Process reversed. Gages were then turned 90° and test repeated.

	Gage A		Gage B
1)	783		802
2)	897		692
	114	$\Delta = \frac{4}{112}$	110
2)	897		690
	776		814
	122	$\Delta = \frac{2}{120}$	124

Ave. Δ = 3/120

Turn 90°:

1)	1428		1202
2)	1302		1081
	126	$\Delta = \frac{5}{120}$	121

2) Specimen unloaded, all screw connections completely loosened, test repeated.

	Gage A		Gage B
1)	1118		381
2)	1000		263
	118	$\Delta = 0$	118
2)	1000		263
	1120		384
	120	$\Delta = \frac{1}{120}$	121

Ave. $\Delta = \frac{1}{120}$

Turn 90°

1)	821		1478
2)	702		1601
	119	$\Delta = \frac{4}{120}$	123
2)	703		1600
3)	818		1478
	115	$\Delta = \frac{7}{120}$	122
3)	818		1478
4)	700		1599
	118	$\Delta = \frac{3}{120}$	121

Ave. $\Delta = \frac{5}{120}$

3) Specimen removed from test grips turned end over end and replaced.

	Gage A		Gage B
1)	1345		829
2)	1464		938
	119	$\Delta = \frac{10}{110}$	109
2)	1466		941
3)	1355		833
	111	$\Delta = \frac{3}{110}$	108
4)	1355		833
	1459		937
	104	$\Delta = 0$	104

Ave. $\Delta = \frac{4}{110}$

Turn 90°:

1)	907		885
2)	1004		784
	97	$\Delta = \frac{4}{100}$	101
2)	1004		781
3)	900		890
	104	$\Delta = \frac{5}{105}$	109

Ave. $\Delta = \frac{4}{100}$

4) The specimen was loaded while disaligned $\approx$ 5% to determine plastic strain required to bring about good alignment.

Yield = 32,500 psi.

Y. P. elongation = .002%

½% strain at 38,500 psi.

	Gage A		Gage B
1)	721		998
2)	1180		1450
	459	$\Delta = \frac{7}{450}$	452
2)	1190		1457
3)	775		1045
	415	$\Delta = \frac{1}{415}$	414

Ave. $\Delta = \frac{1}{110}$

Turn 90°:

1)	1011		864
2)	600		456
	411	$\Delta = \frac{3}{410}$	408

2) 600 455

3) $\underline{1000}$ $\underline{859}$

400 $\Delta = \frac{4}{400}$ 404

Ave. $\Delta = \frac{1}{100}$

CONCLUSIONS

From the single specimen tested, the disalignment to be expected for normal insertion of the specimens is less than 5%. This disalignment is reduced to the order of 1% by a plastic strain of ½%. From the strain results at 25° and -188°C which are reported in Table IV it would appear that the fracture strength measurements should not be seriously affected by non-axiality of the stress system resulting from the removal and reinsertion of the test specimens in the testing grips. The total strain at -188°C may, however, be appreciably affected by the slight non-axiality of loading.

References

(1) E. P. Klier, F. C. Wagner, J. L. Fisher, and M. Gensamer: "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests". (SSC-22) NObs-31217. (1948).

(2) M. Gensamer, E. P. Klier, T. A. Prater, F. C. Wagner, J. O. Mack, and J. L. Fisher: "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests". (SSC-9) NObs-31217. (1946).

(3) M. Gensamer, F. C. Wagner, and E. P. Klier: "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests". (SSC-15) NObs-31217. (1947).

(4) F. C. Wagner and E. P. Klier: "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests". (SSC-18) NObs-31217. (1948).

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