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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 818

THE TENSILE ELASTIC PROPERTIES AT LOW TEMPERATURES OF 18:8 Cr-Ni STEEL AS AFFECTED BY HEAT TREATMENT AND SLIGHT PLASTIC DEFORMATION

By R. W. Mebs and D. J. McAdam, Jr.
National Bureau of Standards

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THE TENSILE ELASTIC PROPERTIES AT LOW TEMPERATURES OF 18:8 Cr-Ni STEEL AS AFFECTED BY HEAT TREATMENT AND SLIGHT PLASTIC DEFORMATION

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SUMMARY

The relationship between stress, strain, and permanent set for 18:8 Cr-Ni steel, as measured at -110° F, is given. The influence of annealing and slight plastic extension upon the derived elastic properties is also discussed.

The test bath consisted of equal parts of carbon tetrachloride and chloroform, to which was added an excess of solid carbon dioxide. A modification of the Tuckerman optical strain gage was employed for measuring strain.

Curves of variation of proof stress with annealing temperature were derived from stress-set data and were compared with previously reported results of tests at room temperature.

Curves of variation of the secant modulus with stress were derived from corrected stress-strain curves. From these curves were derived the modulus of elasticity at zero stress (E_0) and the linear stress coefficient of the modulus (C_0). These values are plotted against the annealing temperature. Room-temperature values are plotted on the same graphs.

The results of these tests are qualitatively similar to those previously obtained at room temperature. An elevation of proof stress and tensile modulus of elasticity with decrease of test temperature is noted.

It is concluded that room-temperature tests will suffice to determine whether an 18:8-type Cr-Ni steel will meet minimum elastic property requirements for applications in the temperature range below normal.

I. INTRODUCTION

This report considers one phase of an investigation of the tensile-elastic properties of high-strength aircraft metals, sponsored by the National Advisory Committee for Aeronautics. In earlier reports (references 1 and 2) the authors described results obtained at room temperature upon a number of stainless steels and nonferrous metals.

The elastic properties discussed were the modulus of elasticity and the "elastic strength." The elastic strength was expressed in terms of five indices, each representing the stress that resulted in permanent extensions of 0.001, 0.003, 0.01, 0.03, and 0.1 percent, respectively, after removal of the tensile load. Such stresses may be termed proof stresses and are obtained by interpolation from curves of variation of the measured permanent set with the previously applied stress.

Curves of the variation of the elastic strain with stress were obtained from stress-strain data by subtracting the permanent set from the measured strain at any given stress. From these curves were derived curves of variation of the secant modulus with stress. For fully annealed metals these stress-modulus curves were more curved than for cold-worked metals, cold-work making the curves almost straight lines.

An equation was derived, representing the stress-modulus line, in which Young's modulus at any stress could be expressed in terms of the modulus at zero stress and linear and quadratic stress coefficients of the modulus. A fairly good picture may be obtained of the elastic properties of a metal by evaluating various indices of elastic strain and elastic strength. A study was made of these properties, as influenced by plastic extension and by heat treatment. A study was made also of the effects of plastic and thermal creep upon the measured properties, and of the influence of repeated short extensions and of the duration of rest interval after these extensions.

An evaluation was made of the influence of several basic factors associated with plastic extension and heat treatment. These factors are: the internal stress, the work-hardening factor, and the reorientation factor.

In the present investigation the same methods have

been applied to a comparison of the elastic properties of 18:8 Cr-Ni steel at -110° F with those measured at room temperature. The influence of prior annealing treatment is also considered.

No attempt will be made to give references to all earlier experiments upon the mechanical properties of metals at low temperatures. Outstanding among the early investigators was Hadfield (reference 3), who measured mechanical and other properties of iron at liquid-air temperatures. Excellent résumés of this and later work were given by Greaves and Jones (references 4 and 5) and by Russell (reference 6). References to more recent work were given by Rosenberg (reference 7).

The metals used in this investigation, the apparatus, and the methods employed, are discussed in section II. A discussion of the influence of decrease of the testing temperature upon the stress-set curve is given in section III. Section IV describes the stress-strain relationship as affected by change in the test temperature, and section V gives a general discussion of the elastic properties at low temperatures.

II. MATERIALS, APPARATUS, AND METHOD OF TEST

1. Materials and Treatment

The materials used in this investigation were chromium-nickel steel bars of the 18:8 type, cold-drawn to two different degrees of hardness. The chemical composition of this steel is given in table I. One bar, DM, had been cold-drawn by a series of reductions from annealed stock of 7/8-inch diameter to 5/8-inch diameter. The second bar, DH, had been cold-drawn from 7/8-inch diameter to 3/8-inch diameter. Both reductions were obtained without intermediate anneals. Steels DM and DH, designated "half-hard" and "hard," respectively, were also used in an investigation of their elastic properties at room temperature, as described in a previous technical report on this same project (reference 2). They were supplied by the Allegheny-Ludlum Steel Corporation.

Some of the material was used in the "as received" condition and, in order to investigate the effect of prior heat treatment upon elastic properties at low temperatures,

bars of each steel were annealed (before machining) at different temperatures, 500°, 700°, 900°, and 1830° F. Each bar was held at the selected temperature for a period of 30 minutes, followed by cooling in air. Some of the specimens, however, were given a softening treatment consisting in heating at 1830° F followed by water quenching. The heating at 1830° F dissolved any carbides and the rapid cooling prevented reprecipitation.

2. Apparatus

For a test at low temperature the specimen was immersed in a bath consisting of equal parts of carbon tetrachloride and chloroform, to which had been added an excess of solid carbon dioxide. A special extensometer was used to transfer a change of the gage length to a point exterior to the bath, where measurement could be made.

The extensometer was the same as that used at the National Bureau of Standards a number of years ago for the measurement of stress-strain characteristics of steels at high temperatures (reference 8). By slight modification it was adapted for low-temperature use, as illustrated in figure 1. Clamps A and A' were attached to the specimen S at the extremes of the gage length and were fastened to extension arms F and F', G and G', which extended somewhat above the level of the cooling bath. (The extensometer was mounted in a position inverted to that employed in high-temperature tests.) An insulated chamber D, attached to the specimen at the junction of the lower adapter B, permitted the cooling solution to be added so as to surround the specimen and extensometer over a range extending above and below the gage length. The stellite lozenges J and J' were situated between the upper ends of the inner and outer extension arms. To the upper ends of the outer extension arms on each side of the specimen were attached adjustable roof prisms K and K', these parts being similar to those employed in a standard Tuckerman optical strain gage (reference 9). Helical springs E, fastened to the opposite outer extension arms, held the lozenges in position. A special adapter C connected the upper adapter B' of the testing machine with the specimen. Celluloid strips were placed between extension arms F and G and F' and G', and between G, G', and adapter C, in order to minimize thermal flow between these parts.

Careful placing of clamps A and A' at the gage marks, and rigid connection of all elements of the extensometer, permitted the relative motion of the gage marks to cause accurate rotation of the lozenges J and J'. A Tuckerman autocollimator (not shown) (reference 9) was employed to measure this rotation; the roof prisms K and K' completed the optical systems. The readings taken upon opposite sides of the specimen were averaged.

When the specimen and the extensometer were placed in the cooling bath, moisture condensed upon the optical surfaces which were cooled by the conduction of heat along the extension arms to the bath. This condensation prevented strain measurements.

Several methods were tried in an effort to maintain the optical surfaces above the condensation temperature. Individual coils were wound about arms F, F', G, and G', and adapter C, immediately below the level of the lozenges. Various combinations of currents were then passed through these coils during immersion in the freezing mixture of a sample specimen with extensometer attached. With the optical surfaces thus heated to slightly above the condensation point, the variation of the strain with change in the bath level, owing to sublimation of the solid carbon dioxide, was obtained for each combination of coil currents. Because of differential changes in length of the extension arms with small changes in bath level, however, no arrangement was found which would produce only a negligible change in strain. Also, as no practicable method was found for maintaining a constant level of the bath, intermittent additions of dry ice to the liquid were necessary.

Another method involved an analysis of the heat flow in the various elements of the apparatus. It was found that the temperature gradients in the outer arms F and F' were more nearly linear than those in the inner arms G and G', because of the proximity of the large adapter C to these inner arms. For any combination of coil currents, therefore, a balance in the rate of thermal expansion of the inner and outer arms was possible over only a very limited range of the bath level change. In fact, the differential expansion of the extension arms was actually increased by the use of heating coils.

A compromise step adopted was to place very small

coils H and H' as near as possible to the optical surfaces, so that these coils alone supplied the heat necessary to keep the optical surfaces clear. Those coils, which were very small and tightly wound, were suspended directly beneath each lozenge and made no direct contact with either extension arm. In addition, solid carbon dioxide was added to the solution at frequent and regular intervals, in order to minimize the change of bath level. The mixture was stirred frequently, and the various operations were maintained on a strict time schedule throughout the test.

Since the quantity of heat necessary to prevent moisture deposition varied directly with the absolute humidity of the air, tests were limited to days which were both dry and cool.

Before each test the following procedure was standardized. After assembly of the specimen, extensometer, and container in the testing machine, the low-temperature mixture was poured into the container to a level about 1/2 inch below its upper edge. During the subsequent period of 1½ to 2 hours, while the temperature distribution among the various parts was approaching equilibrium, the current through the two heating coils was adjusted to its optimum value. Following this interval the stress-strain and stress-set measurements were made. The level of the bath was maintained by additions of dry ice at regular intervals during the preliminary period and during the test. Additions were made immediately after readings of the extensometer.

3. Method of Investigation

The experiments consisted in determining the total strains at various stresses and the corresponding permanent extensions after release of load for a series of increasing values of stress until the total permanent extension reached about 0.1 percent. These results were used in plotting correlated stress-strain and stress-set curves. Proof stresses, corresponding to permanent extension of 0.003, 0.01, 0.03, and 0.1 percent, were determined from intercepts on the stress-set curves. From stress-deviation curves, which were plotted as deviations of the stress-strain curves from a stress-strain line representing an assumed modulus, were obtained the secant moduli of elasticity for a series of stresses over the extent of the curves.

Following the measurement of the first stress-strain and stress-set curves, a rest interval of about 30 minutes was permitted before a second series of stress, strain, and permanent-extension measurements upon the same specimens was started. Only one pair of stress-strain and stress-set curves was obtained with each specimen.

As in earlier experiments, the stress at each load was maintained constant for two minutes before a strain or set measurement was made. The minimum load at which permanent set was measured was 200 pounds, this load being just sufficient to maintain proper alinement of the specimen and the adapters.

4. The Accuracy of Determination of Stress and Strain

In the previous experiments (references 1 and 2), the principal errors of measurement were due to (a) the limit of sensitivity of the strain gage, (b) the accuracy of setting the load, and (c) the change in length of the specimen due to thermal creep. In the investigation at low temperature, the errors due to these causes were found negligible in comparison with errors due to other causes, these being changes in length of the specimen with the bath temperature and variations in level of the cooling bath. In an earlier investigation at the National Bureau of Standards, under similar low-temperature test conditions, the variation of temperature over the gage length of the specimen was found to be insignificant. The principal cause for error in strain measurement, therefore, was the variation in the bath level during test.

A simple experiment was therefore made to determine the maximum variation of strain during a test due to causes other than change in the applied load. A sample specimen, with extensometer attached, was mounted with the container in position, and the freezing solution added. Without loading in the testing machine, the regular procedure was otherwise followed, including adjusting the heating current to its optimum value during the equalization period. Subsequently, extensometer readings were taken upon the specimen, at intervals approximating those at which strain and set would be measured in a regular test. Under these conditions, it was found that the total strain did not vary more than 0.004 percent over a period approximating that in which a pair of stress-strain and

stress-set curves could be measured. This variation, however, is about 10 times as great as that obtained under room temperature conditions.

The proof stress producing 0.001-percent set therefore was not derived in this investigation, as it is meaningless, and even the 0.003-percent proof stress is subject to considerable error. This error has been minimized, however, by the fairing of the curves through the mean position of a number of points.

III. THE STRESS-SET CURVE AND THE DERIVED PROOF STRESSES AS MEASURED AT LOW TEMPERATURES

1. The Influence of Annealing Temperature upon the Stress-Set Curve

Figure 2 shows pairs of stress-set curves, as measured at low temperatures (-110° F) upon 18:8 chromium-nickel steel specimens, in the "as received" condition and after annealing at various temperatures.* The second curve of each pair was obtained from the same specimen 30 minutes after completing the determination of the first curve. The curves for the half-hard material DM are given in the lower left portion of the figure, and those for hard material DH are placed in the lower right.

These curves are similar in form to those obtained at room temperature, as shown in the second technical report on this project (reference 2). The steepness of these curves, as determined by the average slope, up to the stress producing 0.1-percent set, will now be considered. The initial curve of each pair (which is generally much less steep than the second curve) increases in steepness with increase in the annealing temperature, up to 900° F. After annealing at 1830° F, both curves are much less steep than after annealing at any lower temperature. The variation of steepness with annealing

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*The proof stresses were actually derived from corresponding curves, plotted from the original data on a more open scale, over the entire range of measured permanent deformation (about 0.1 percent).

temperature is less for the second curve than for the first curve.

2. The Effect of the Annealing Temperature on the Proof Stresses

The variation of the proof stresses with the annealing temperature is given by the curves in the four diagrams of figure 3. Ordinates represent proof stresses, and abscissas represent annealing temperatures. Proof stresses are plotted for proof sets of 0.003, 0.01, 0.03, and 0.1 percent. The 0.1- and 0.03-percent proof stresses may be considered as indices of yield strength; the 0.01- and 0.003-percent proof stresses as indices of elastic strength. The diagrams designated "first loading" and "second loading" are derived from the first and second curves, respectively, of the pairs of curves in the lower row of figure 2. An abscissa of 100° F is used to represent results obtained with specimens in the "as received" condition, this being approximately the highest temperature reached by the bar stock material during storage in the laboratory.

All the curves in the diagrams, representing first loading, show a maximum corresponding to an annealing temperature between 600° and 1000° F and then descend rapidly.* With the exception of the curve for 0.003-percent proof stress for half-hard material DM, all the second-loading curves show corresponding characteristics. Because of the great scatter of values for the 0.003-percent curve, the indicated curve can be considered only approximate. The maximums are at somewhat lower temperatures in the curves representing the lower values of permanent set than in those representing the higher values.

Annealing for relief of internal stress increases the proof stress, when measured at -110° F, for both first and second loading. In addition, the second-loading curves are higher than the first-loading curves. This indicates that slight plastic extension will cause an improvement of proof stress in addition to that obtained by stress-relief.

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*The forms of these curves between 900° and 1830° F are based upon the general forms of numerous curves of variation of proof stress with annealing temperature, for 18:8 Cr-Ni steel, obtained in other investigations.

annealing. Some evidence of such improvement for the 0.01- and 0.03-percent proof stresses, for room temperature measurements, is given in the second technical report on this subject (reference 2).

3. Comparison of Results Obtained at Room Temperature and Low Temperature

Figure 3 shows the variation of the several proof stresses with annealing temperature, as measured at -110° F. Figure 4 gives the corresponding curves obtained from room-temperature tests described in an earlier report (reference 2). The values obtained upon materials annealed at 1830° F, which are averages of several determinations, include additional values procured since completion of that report. Comparison of figures 3 and 4 shows that the 0.03- and 0.1-percent proof stresses measured at -110° F are generally higher than the values at room temperature. The second-loading curves representing 0.01-percent proof stresses are generally higher at -110° F than at room temperature. For first loading, curves representing the 0.001-percent and 0.003-percent proof stresses for hard metal DH differ little in height in the two diagrams. The 0.003-percent proof stress, second-loading curve, as measured at low temperature, is predominantly higher over a large portion of the annealing range. The 0.003-percent and 0.01-percent first-loading curves for half-hard metal DM at room and low temperatures occupy approximately the same positions over the temperature range up to 900° F. The 0.01-percent second-loading low-temperature curve for this metal is perdominantly higher over a major portion of the range; whereas the room- and low-temperature 0.003-percent second-loading curves are each higher over separate portions of the range. Because of the inherent errors arising in the low-temperature measurements, the positions of the lower curves cannot be determined accurately. It will be noted that the proof stresses as measured on specimens annealed at 1830° F are all higher when measured at -110° F.

The decrease in testing temperature gives higher values for proof stresses which may be considered as indices of yield strength, but does not produce variation, greater than the limit of accuracy of measurement, of proof stresses which may be considered as indices of elastic strength.

IV. STRESS-STRAIN RELATIONSHIP OF 18:8 Cr-Ni STEEL, AS MEASURED AT LOW TEMPERATURES

1. Comparison of Stress-Deviation and Stress-Set Curves

Stress-deviation curves for 18:8 Cr-Ni steel specimens annealed at various temperatures and tested at -110° F are illustrated in the upper part of figure 2. Ordinates represent stresses, and abscissas represent deviations of strain corresponding to an assumed modulus E_A. The broken stress-deviation curves represent deviations of the total measured strain from an assumed straight stress-strain line, whose slope corresponds to the assumed value of the modulus. By a suitable choice of the assumed modulus value, the stress-deviation curve gives a very sensitive representation of the variation of strain with stress. The solid-line curves have been obtained from the broken-line curves by deducting values of permanent set obtained from the stress-set curve directly below. These solid-line curves may be referred to as the elastic stress-deviation curves. The first stress-deviation curve of a pair is generally steeper than the second curve as determined by the average slope. In this respect, such a pair of curves generally differs from the corresponding pair of stress-set curves.

2. The Variation of the Modulus of Elasticity with Stress

The elastic stress-deviation curves of figure 2, with few exceptions, show prominent curvature from the origin. The slope of each curve generally decreases continuously with increase of stress and thus indicates a corresponding decrease of the secant modulus of elasticity. The secant modulus, given by the ratio of stress to elastic strain, has been used as in the previous reports, to study the variation of the modulus with stress and with annealing temperature.

Figure 5 shows the variation of the secant modulus of elasticity with stress at -110° F. With the exception of the second-loading curve for the specimen annealed at 500° F, all the stress-modulus lines for the half-hard metal DM are curved. The stress-modulus curves for the hard metal DH are straight or nearly straight.

As indicated in reference 2, the secant modulus of elasticity E of a metal at any stress S may be represented by the equation

$$E = E_0(1 - C_0S - C'S^2) \tag{1}$$

where E_0 is the modulus at zero stress, and C_0 and C' are the linear and the quadratic stress coefficients of the modulus, respectively.

When the stress-modulus line is straight, C' is zero, and the corresponding stress-deviation line is a quadratic parabola. When C_0 is zero and C' is not, the stress-modulus line is a quadratic parabola and the corresponding stress-deviation line a cubic parabola. Positive values of C_0 are obtained from stress-deviation curves of all specimens except those of the fully annealed, hard steel. C' evidently is zero (fig. 5) for curves of the hard metal DH, but not for the half-hard metal DM. The stress-deviation curves for the half-hard materials evidently may be viewed as superpositions of quadratic and cubic parabolas.

3. The Effect of the Annealing Temperature on the Modulus of Elasticity and Its Stress Coefficient

The values of E_0 and C_0 for the pairs of stress-modulus lines have been used in deriving the solid-line curves in figures 6 and 7. These curves show the variation of E_0 and C_0 with annealing temperature. (An abscissa of 100° F has been used in plotting the results for metals as received.) The derived points are connected by straight lines.

The solid E_0 curve in each diagram for both first and second loading rises at a gradually increasing rate with annealing temperature; the value of E_0 for the fully annealed material is much higher than that obtained for the metal as received. No significant trend can be assigned to the C_0 curves, as in previous reports (references 1 and 2). In view of the probable errors inherent in the method of experiment, errors of measurement do not permit a reliable determination of the course of such

curves. The unusually high value of E_0 obtained for the fully annealed hard material (the average of several determinations) is not explainable. This value exceeds that obtained at room temperature in previous experiments (reference 1) with some 18:8 Cr-Ni steel specimens which had been received in the fully annealed condition.

4. Comparison of Results Obtained at Room and Low Temperatures

The broken line graphs in figures 6 and 7 represent results of tests made at room temperature. The values plotted at an annealing temperature of 1830° F are the average of several determinations, including some additional results procured since the completion of the second technical report (reference 2).

The room-temperature curves of variation of E_0 with annealing temperature (figs. 6 and 7) lie beneath, and are roughly parallel to, the corresponding low-temperature curves. These relative positions are found for both first and second loadings. The differences between the low-temperature and high-temperature results for the hard material, however, is greater after annealing at 1830° F than after annealing at the other temperatures. Such a relationship was not obtained with the half-hard specimens.

For half-hard metal DM, the values of C_0 are generally higher at low temperature than at room temperature. A single exception is noted at the 900° F point, in the second-loading diagram. For hard metal DH, no consistent difference in the values of C_0 is obtained at the two temperatures.

When the value of the linear stress coefficient of the modulus, C_0 at -110° F exceeds the value at room temperature, it may be important to determine, by use of equation (1), the value of the stress S above which the secant modulus at -110° F is less than the value at room temperature. Calculations show that this stress will in each case exceed the yield strength of the metal. It can therefore be stated that the secant modulus of this material at any stress within the working range will never be less at -110° F than at room temperature.

Because of the fact that the modulus of elasticity

increases with decrease of test temperature, a structure suitably designed on the basis of the modulus of elasticity at room temperature, evidently would be stiffer at lower temperatures.

V. CONCLUSIONS

The conclusions drawn in earlier reports (references 1 and 2) with respect to the influence of heat treatment and slight plastic deformation upon the tensile-elastic properties of 18:8 Cr-Ni steel, tested at room temperature, will also generally hold true for this steel tested at -110° F.

In addition, the following conclusions may be drawn from a survey of results of room- and low-temperature tests.

1. The proof stresses that may be considered as indices of <u>yield strength</u>, as measured at -110° F, are generally higher than the values obtained at room temperature, irrespective of previous annealing temperature.

2. The proof stresses that may be considered as indices of <u>elastic strength</u> are less easily determinable at low temperatures because of decreased accuracy of measurement. For steels annealed at 1830° F, however, the results do show that these lower proof stresses are predominantly greater when measured at -110° F. For steels annealed at other temperatures, no general conclusions can be drawn.

3. The modulus of elasticity at zero stress (E_0) for these steels is greater at -110° F than at room temperature, irrespective of previous annealing treatment.

4. The evidence is not conclusive, but even on the most unfavorable interpretation of the evidence, the secant modulus of elasticity measured at -110° F would not be less than the value at room temperature, at any stress below the yield strength of the metal.

5. In general, the tensile-elastic properties of 18:8 Cr-Ni steel are higher when measured at -110° F than at room temperature. Aircraft parts may be subjected to both low and normal temperatures during operation, but the measurement of the elastic properties of this metal at room

temperature should determine whether limiting values at low temperatures are met. The value measured at room temperature could be used also as a basis for design.

Various investigators have shown that such conclusions cannot be drawn with respect to such properties as impact strength and fatigue. (See references 4, 5, 6, 7, and 10.)

National Bureau of Standards,
Washington, D. C., June 30, 1941.

TABLE I.- COMPOSITION OF STEEL

Material	Chemical composition (percent)						
	C	Cr	Ni	Mn	Si	P	Fe
18:8 Cr-Ni steel	0.10	18.82	9.38	0.47	0.35	0.015	diff.

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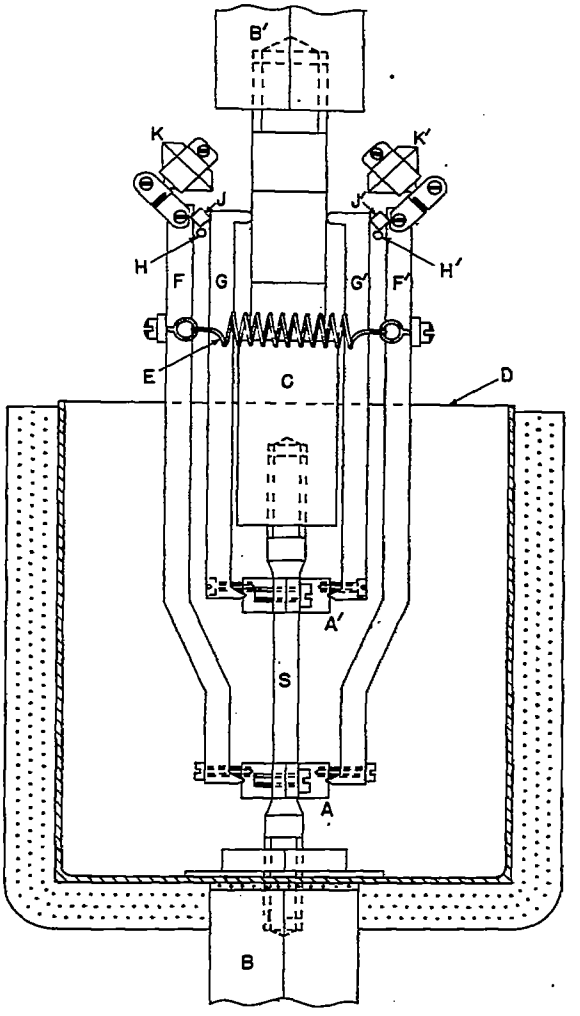

S Test specimen

A,A' Specimen clamps

B,B' Amsler testing machine adapters

C Special adapter

D Insulated cooling chamber

E Helical spring

F,F' Outer extension arms

G,G' Inner extension arms

H,H' Heating coils

J,J' Stellite prismatic lozenges

K,K' Roof prisms

Figure 1.- Assembly of low temperature, tension testing apparatus.

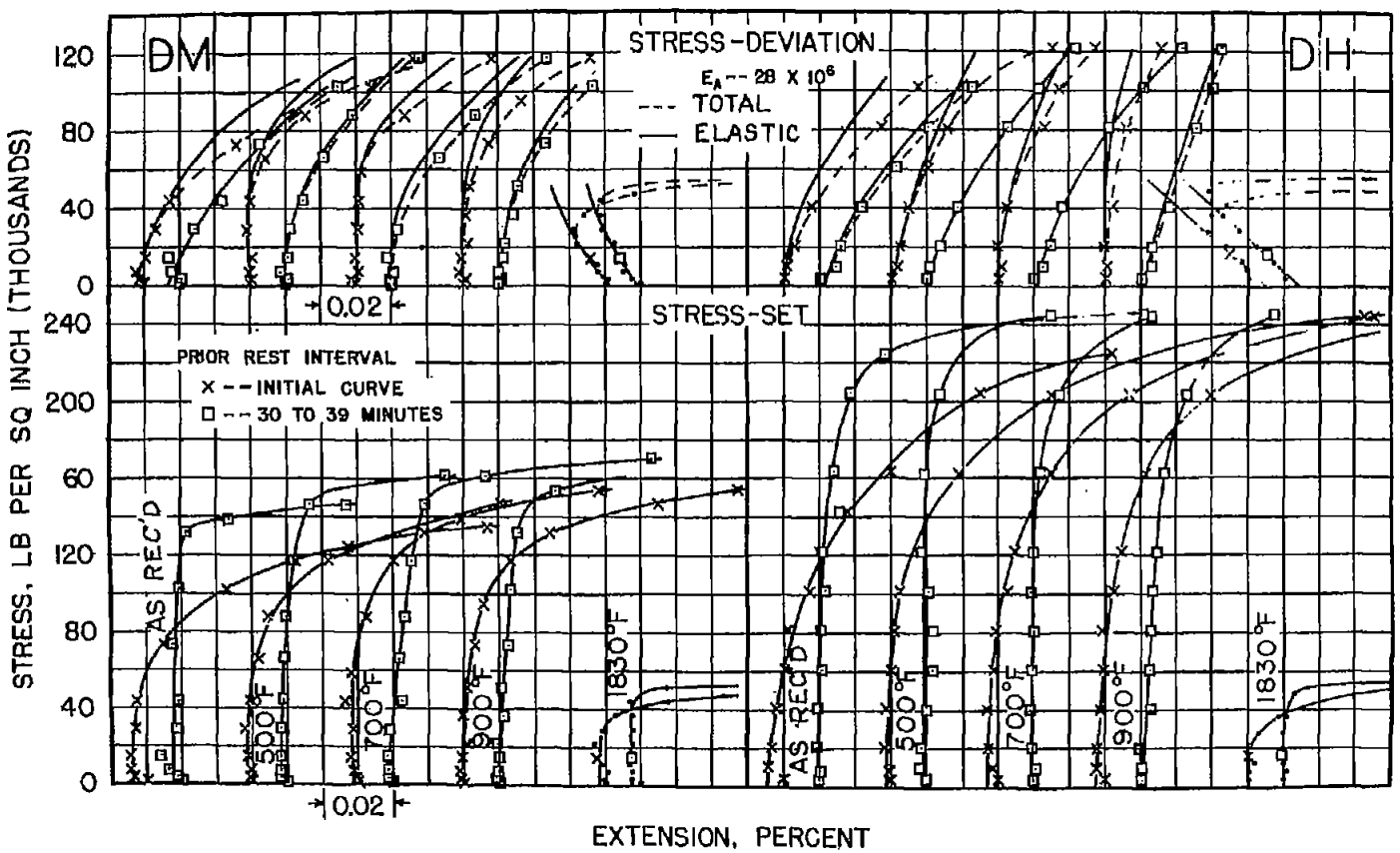

Figure 2.- Influence of annealing temperature on stress-deviation and stress-set curves, measured at -110° F.

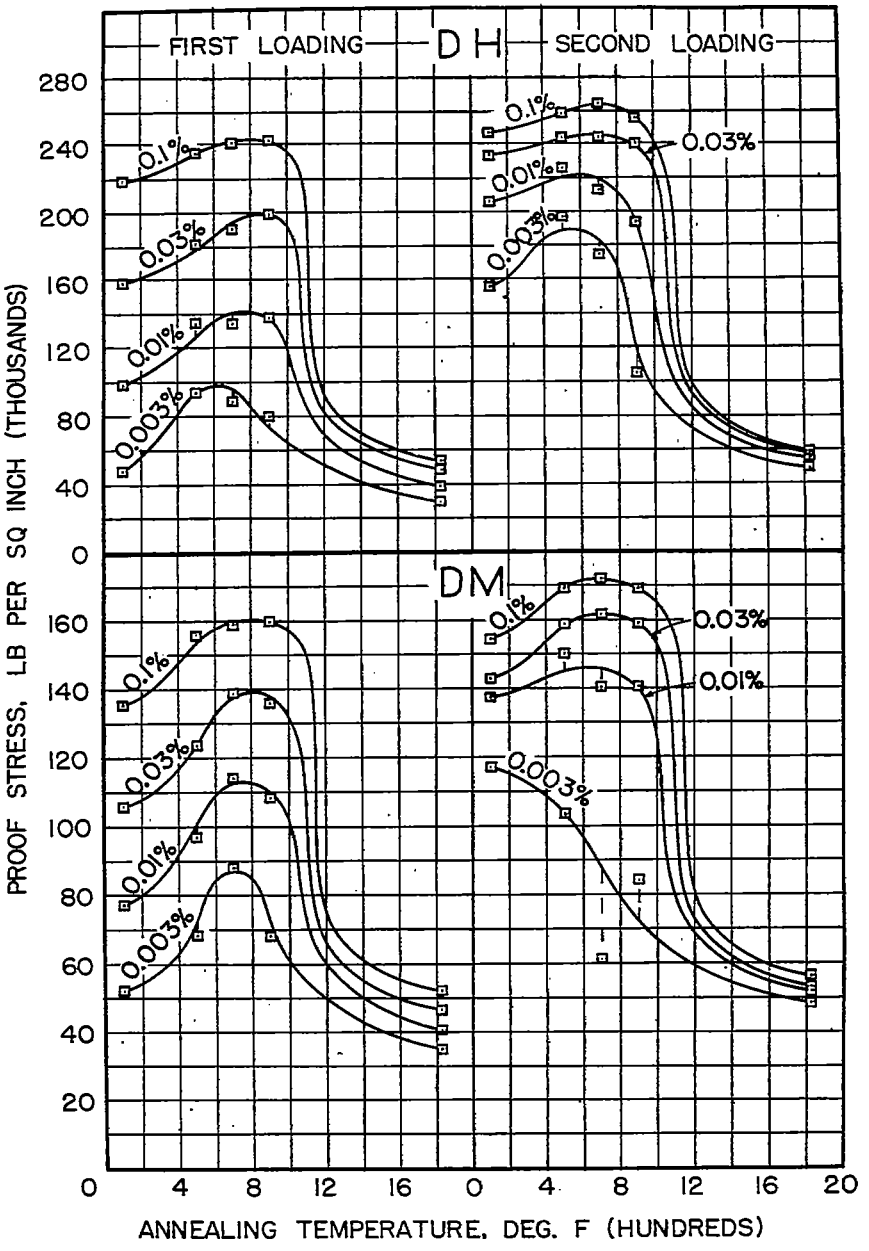

Figure 3.- Influence of annealing temperature on proof stresses, measured at -110° F. The rest interval between first and second loading ranges from 30 to 39 minutes.

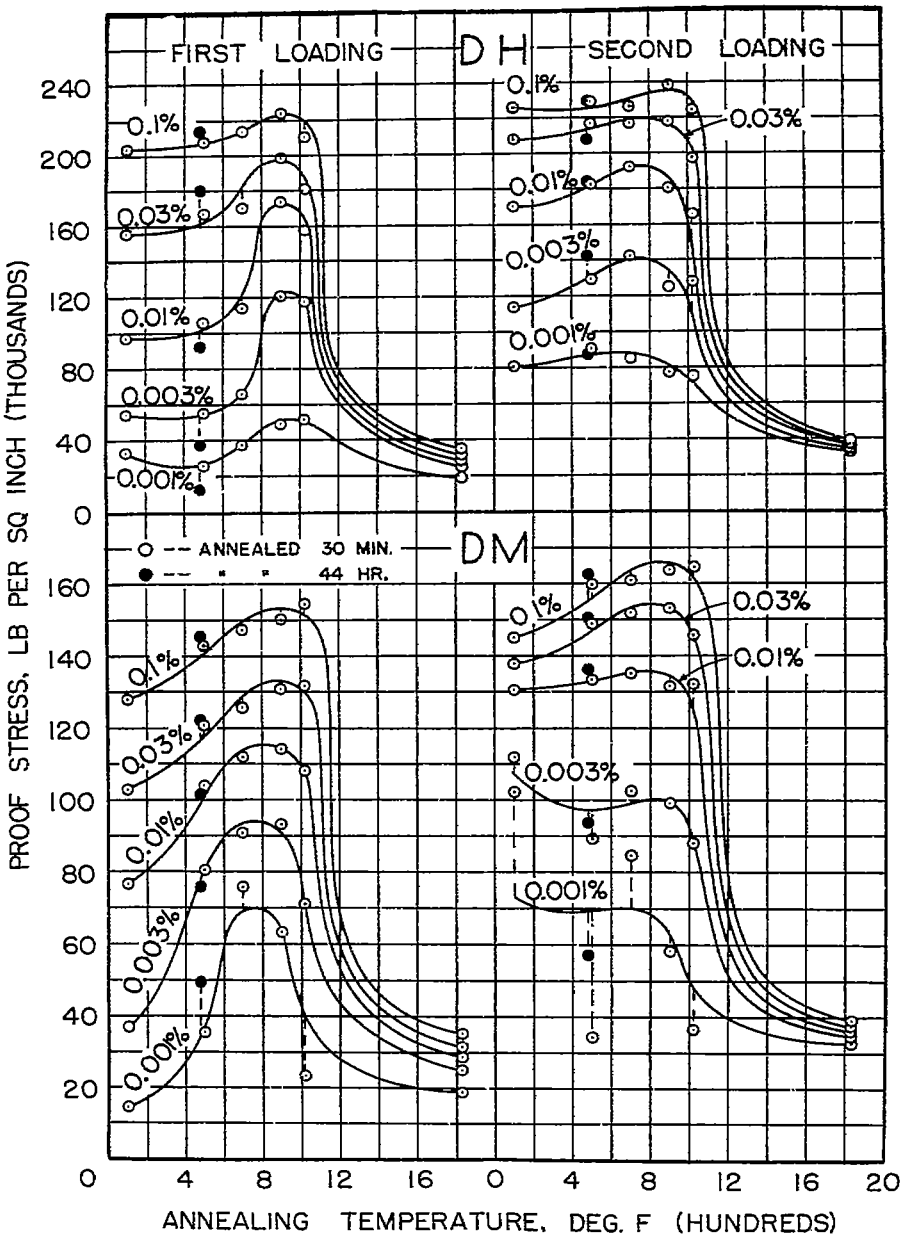

Figure 4.- Influence of annealing temperature on proof stresses, measured at room temperature. The rest interval between first and second loading ranges from 31 to 37 minutes.

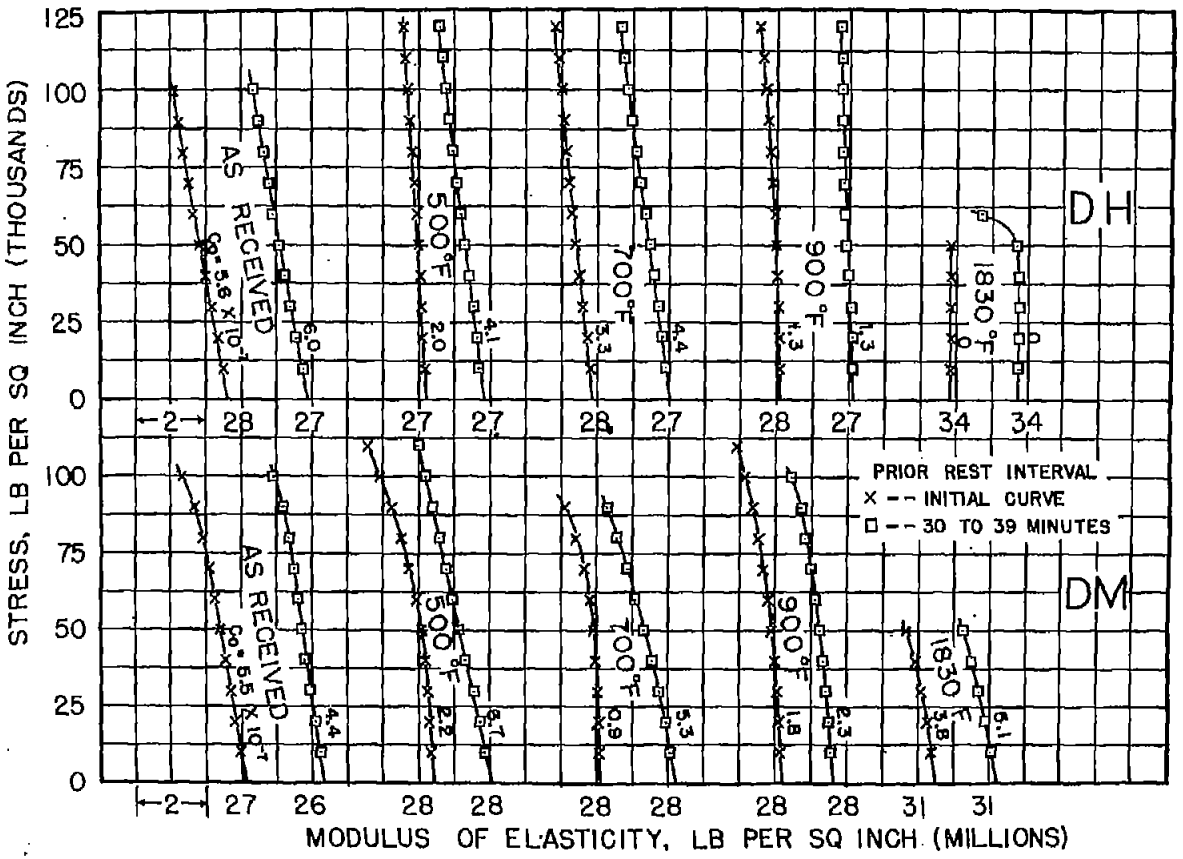

Figure 5.- Influence of annealing temperature on stress-modulus curves, measured at -110° F.

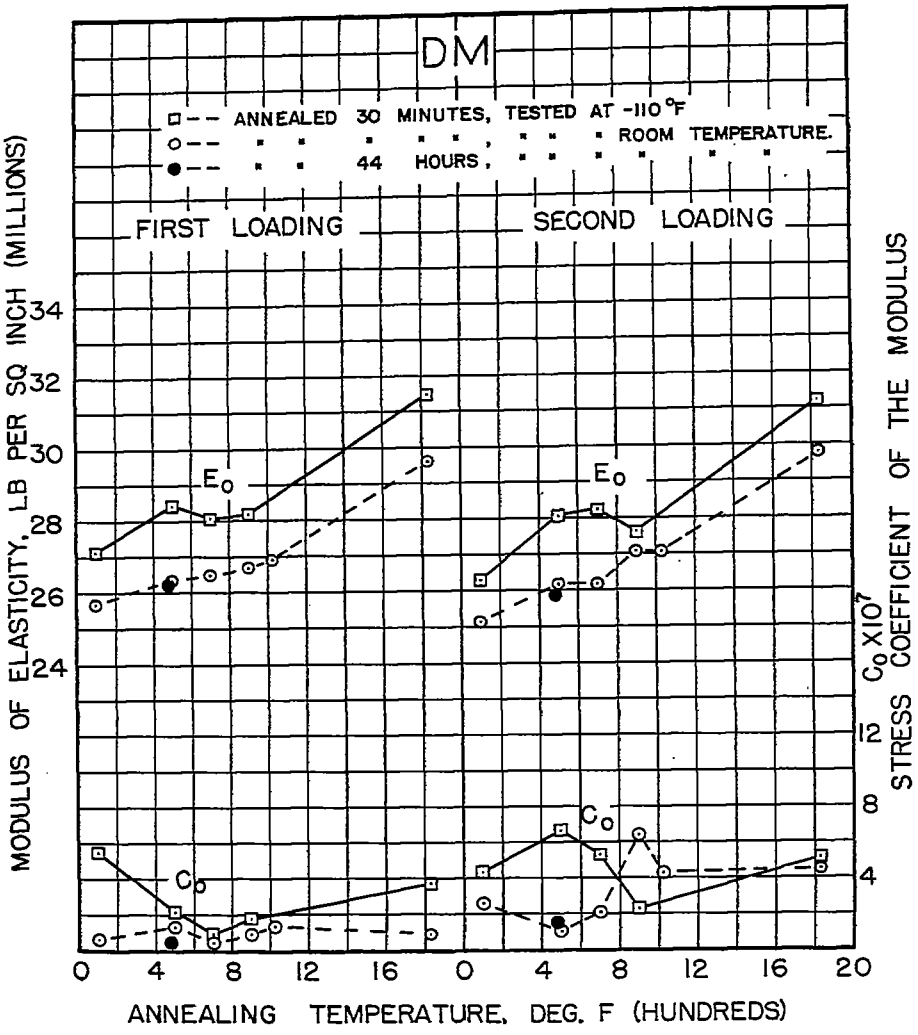

Figure 6.- Comparison of measurements at -110° F and at room temperature, of the modulus of elasticity and its linear stress-coefficient, for steel DM, half-hard. The rest interval between first and second loading ranges from 30 to 39 minutes.

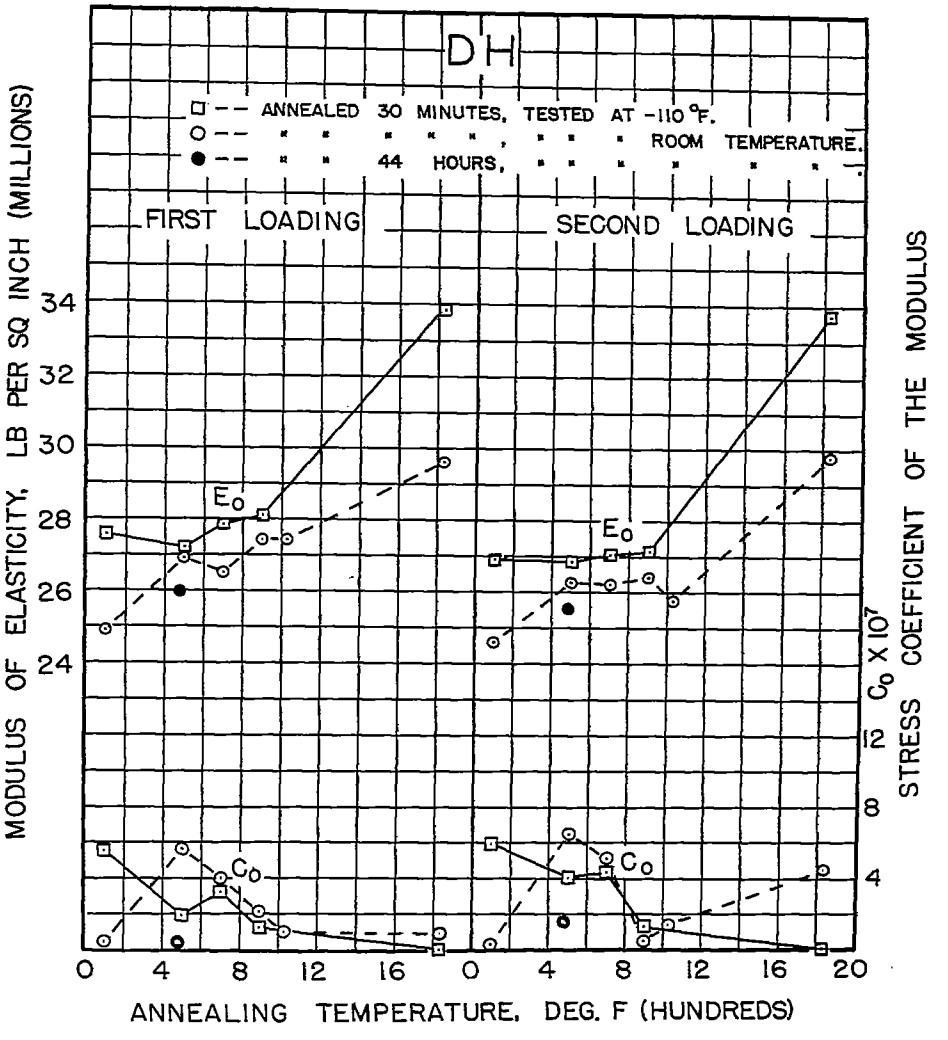

Figure 7.- Comparison of measurements at -110° F and at room temperature, of the modulus of elasticity and its linear stress-coefficient for steel DH, hard. The rest interval between first and second loading ranges from 30 to 37 minutes.

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Steel, * Tensile Properties

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