EFFECT OF TEMPERATURE, DEFORMATION, AND RATE OF LOADING ON THE TENSILE PROPERTIES OF LOW-CARBON STEEL BELOW THE THERMAL CRITICAL RANGE

By H. J. French

ABSTRACT

An apparatus for determining tensile properties of metals at high temperatures (including limit of proportionality) and the results of tests of several grades of boiler plate from 20 to 465° C. are described. The effects of cold and blue work on the properties of these steels throughout the range given are discussed, and in addition, some results are given showing the effect of tensional elastic overstrain on the proportional limit at different temperatures and its subsequent behavior with time. Effects of variations in rates of loading (both rapid and slow) and the modified apparatus used for this work are also described.

CONTENTS

I. INTRODUCTION

During 1919 the Bureau of Standards was requested by a committee of the engineering division,[1] National Research Council, to determine the effects of cold work on the proportional limit of boiler plate at elevated temperatures, as a result of a similar request received by this committee. Following the early work of development of a suitable apparatus for such tests about July, 1919, and the determination of the tensile properties of the hot-rolled steel for a basis of comparison, there arose the questions of deformation in the "blue-heat range" and the effects of variations in rate of stress application on the properties of steel at high temperatures, so that the original program was greatly extended.

The complete research necessitated investigation along five different lines, which may be summarized as follows:

1. Development of apparatus for determination of the limit of proportionality at various temperatures, and investigation of the tensile properties of several grades of boiler plate up to about 465° C (870° F).
2. Effect of permanent deformation (by rolling cold and at blue heat) on the properties of steel at different temperatures.
3. Study of the behavior of steel subjected to tensional elastic overstrain at several temperatures.
4. Effect of rate of stress application on the tensile properties of hot-rolled boiler plate at various temperatures.
5. Microscopic examination.

As progress was made in this work new questions arose, but because of the almost unlimited field for investigation it was not possible to follow more than a few of such leads or to satisfy these inquiries. The tests are not considered complete in any of the several phases dealt with, but are presented as detailed data relative to several questions concerning which there have

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[1] Committee on Physical Changes in Iron and Steel below the Thermal Critical Range. Dr. Zay Jeffries, chairman.

been conflicting opinions and likewise show effects, which, as far as the author is aware, have not before been so completely determined quantitatively. In some cases the practical applications of results of tests are indicated, while at the conclusion of the report is given a selected bibliography on the mechanical properties of steels at high temperatures, which will be referred to throughout the text as required.

II. TENSILE PROPERTIES OF STEELS AT HIGH TEMPERATURES

1. PREVIOUS INVESTIGATIONS

It has long been known that increase in temperature above the ordinary atmospheric range is accompanied by changes in steels, particularly in strength and ductility. A large number of interesting and important papers dealing with various phases of this subject have appeared from time to time, but as recently pointed out by Jeffries (34) [2] our knowledge is still unsatisfactory, and a better understanding of these changes will undoubtedly be of benefit to industry. White (35) is of the opinion that our knowledge of the tensile properties of steels at high temperatures is wholly inadequate and has not kept pace with advancement of knowledge in other branches of engineering, while Howe (38) long ago called attention to the apparent anomalies found in studying the effects of work at temperatures under the thermal transformations on the properties of wrought iron and steel used in boiler construction. Certainly, from the standpoint of engineering design, it is important to know the variations in limit of proportionality with changes in temperature, but unfortunately this is the more difficult to determine of those factors considered in tensile tests, and the data available are conflicting.

In Figures 1A and 1B is given a summary of results obtained in some of the more important published investigations of the tensile properties of steels and wrought iron at high temperatures.[3] Increase in strength with first rise in temperature above that of the room is reported by Rudeloff (9), (13), Huntington (24), Epps and Jones (32), and Bregowsky and Spring (25), while Martens (7), Perrine and Spencer (30), and J. E. Howard (8) find a slight decrease between about 50 and 150° C (125 and

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[2] These figures relate to the numbered references in the "Selected bibliography" at the conclusion of this paper.

[3] Refer to the bibliography at the conclusion of this report for more complete data.

300° F), which is followed by increase to a maximum between 205 and 345° C (400 and 600° F). In a very complete series of tests of steels of varying carbon contents Howard further found that the minimum tensile strength occurring with first rise in temperature was generally more quickly reached the lower the carbon content, and that the higher carbon steels attained their maximum strength at lower temperatures than medium or low-carbon alloys (Fig. 2).

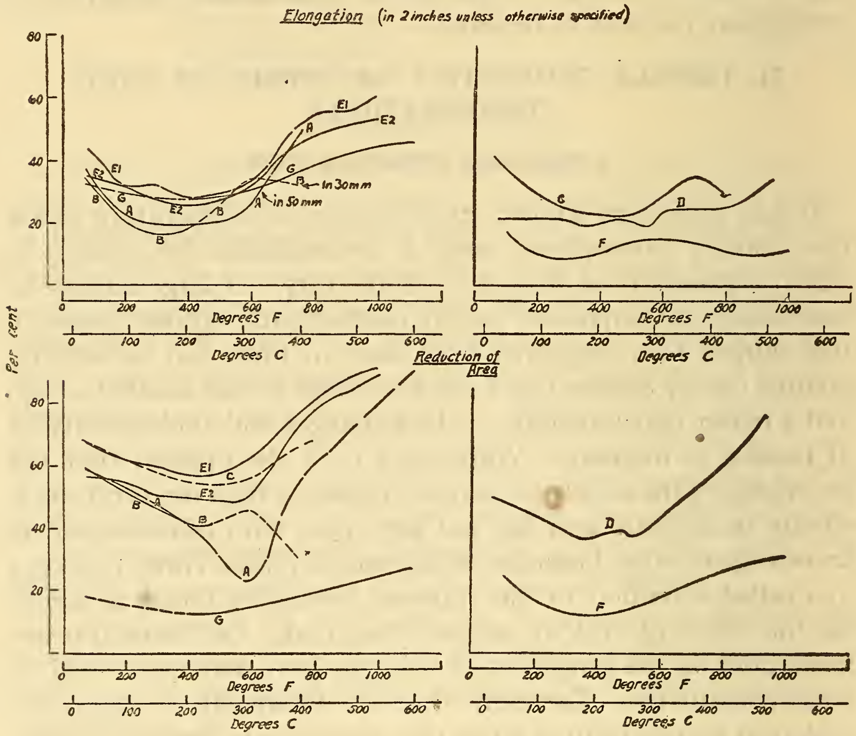

FIG. 1A.—*Tensile properties of wrought iron and steels at various temperatures as determined by different investigators*

A Martens (1890), "Hartestufe"
B Rudeloff (1893), Martin Stahl
C Huntington, mild steel
*C*₁ Huntington, wrought iron
D Bregowsky & Spring, cold-rolled Bessemer shafting
*E*₁ Perrine & Spencer, 0.23 per cent C, Bessemer steel
*E*₂ Perrine & Spencer, 0.39 per cent C, Bessemer steel
F Epps and Jones, wrought iron
G Shelby Laboratory, 0.36 per cent C steel

Various investigators have from time to time reported decrease in elastic properties with increase in temperature, but one of the earlier investigators, Martens (7), has distinguished between the gradual decrease in yield point and the behavior of the proportional limit which, after a slight decrease at about 100° C (210° F) in "soft steel," increased to a maximum at 200° C (390° F) before final decrease occurred. Epps and Jones obtained similar inflections in a proportional limit temperature curve for wrought iron with first decrease at a slightly higher temperature and the maximum at about 180° C (360° F), while both the Shelby laboratory[4] and Bregowsky and Spring (25) report direct increase in yield point to a maximum at about 200° C (390° F).

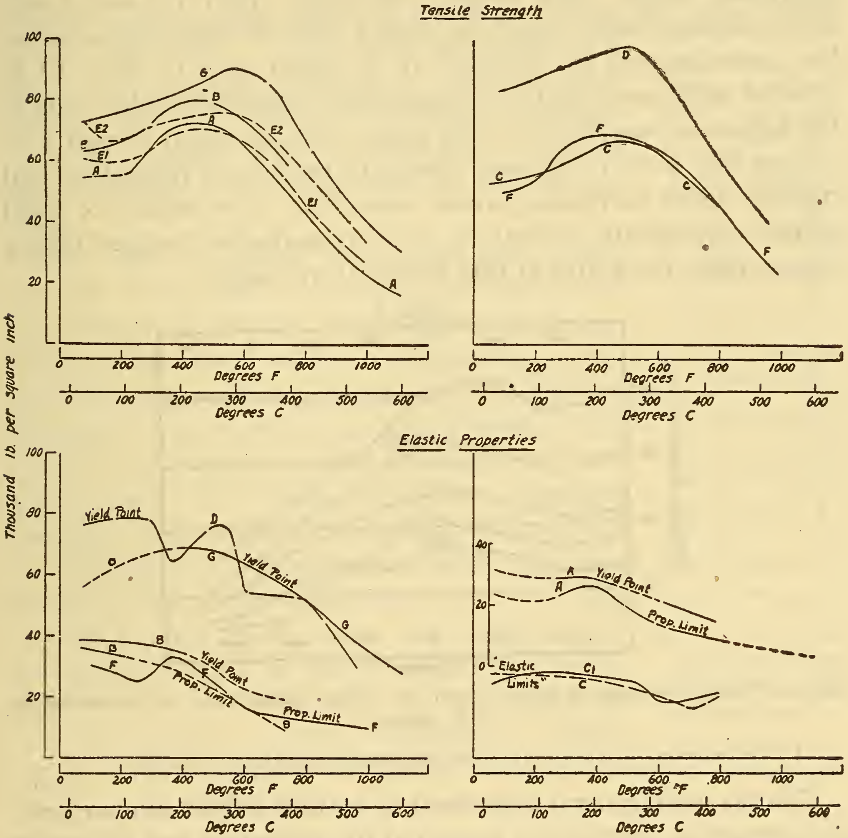

FIG. 1B.—*Tensile properties of wrought iron and steels at various temperatures as determined by different investigators*

A Martens (1890), "Hartestufe"
B Rudeloff (1893), Martin Stahl
C Huntington, mild steel
*C*₁ Huntington, wrought iron
D Bregowsky & Spring, cold-rolled Bessemer shafting
*E*₁ Perrine & Spencer, 0.23 per cent C, Bessemer steel
*E*₂ Perrine & Spencer, 0.39 per cent C, Bessemer steel
F Epps and Jones, wrought iron
G Shelby Laboratory, 0.36 per cent C Steel

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[4] Private communication from Luken's Steel Co., 1920.

In his tests Howard (8) found that the interval between the elastic limit and the maximum stress showed particularly interesting features. Several of the different steels tested showed a yield point at the elastic limit, this period being marked by rapid stretching which, once begun, continued under reduced loads. Such yielding rarely occurs in testing steel at room temperature, but was observed by Howard up to about 260° C (500° F) in tests of mild steels and at temperatures somewhat below this in the higher carbon alloys. Bars tested between about 95 and 205° C (200 and 400° F) showed alternate periods of relaxation and rigidity under increasing stress resembling a succession of yield points, apparently indicating some remarkable changes taking place within the metal in this temperature range.

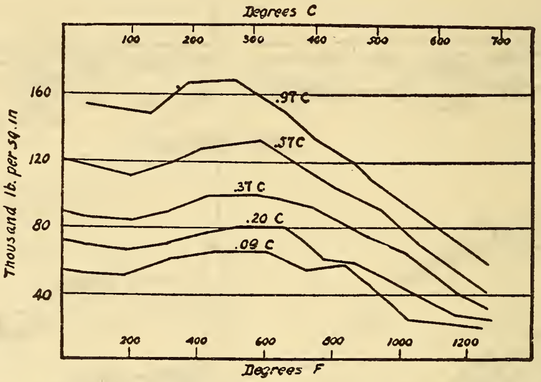

FIG. 2.—*Tensile strength of carbon steels at various temperatures as determined by J. E. Howard*

See Physical properties of iron and steel at higher temperature. Iron Age, 45, p. 585; 1890

There is more general agreement in various publications regarding changes in ductility as measured by elongation and reduction of area. Elongation decreases slowly just above room temperature and thereafter more rapidly to a minimum variously reported as occurring between 125 and about 200° C (255 and 390° F). It then increases rapidly. Reduction of area likewise decreases but little just above the temperature of the room, but then drops rapidly to a minimum reported to occur between 200 and 300° C (390 and 570° F), which is higher than the temperature of occurrence of minimum elongation and is followed by rapid increase in values. Howard (8) also found a tendency for bars broken at temperatures between 205 and 315° C (400 and 600° F) to fracture in an oblique shearing direction.

2. MATERIALS AND METHODS USED

(*a*) STEELS TESTED.—The steels tested in this investigation were received as half-inch boiler plates of fire box and marine grades. The specified tensile strength and composition for each are shown in Table 1, but the third class listed showed slightly higher tensile values than the limits prescribed and was supplemented by class 4. The former was used, however, and the tensile properties at high temperatures of the hot-rolled steel were determined because the number of plates of the first two series was insufficient for completion of the desired tests.

The steels were made in the basic open hearth and the baths kept in a boiling condition up to the moment of casting. Such metal is often referred to as "open steel" to distinguish it from that which has been "killed" in the ordinary manner. It is porous in its cast condition and shows some segregation, but is nearly free from pipe. Variations in composition have, however, been kept to a minimum by cutting the patterns from which the test specimens were machined from steel originally in the central and least segregated portion of the ingot, but unfortunately no detailed record of this procedure is available except in the case of series 4, where the patterns were distributed as given in Figure 3. Check analyses show excellent uniformity and agree closely with the compositions shown in Table 1.

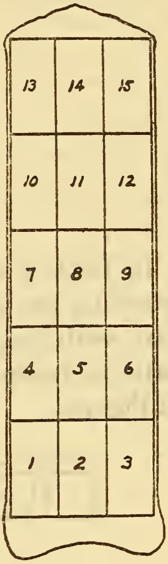

FIG. 3.—*Distribution of patterns cut from railway firebox plate (Series 4 Steel)*

TABLE 1.—Steels Tested

Series	Grade	Specified tensile strength	Composition			
			C	Mn	P	S
		Lbs./in.^{2}	Per cent	Per cent	Per cent	Per cent
1	A. S. T. M. fire box[1]	52 000–62 000	0.19	0.43	0.020	0.031
2	Marine	60 000–70 000	.25	.38	.019	.031
3	Railway fire box	45 000–55 000	.17	.36	.024	.031
4	Railway fire box	45 000–55 000	.18	.43	.017	.035

[1] American Society for Testing Materials, fire-box steel. Specification A 30–18.

A detailed description of ingots and plates produced in the manner referred to above is contained in a report by Charles Huston,[5] which includes many excellent photographs and charts showing the porosity of the cast metal and the chemical and physical characteristics of the rolled plates.

TABLE 2.—Ingot Size and Rolling Record of Steels Tested

Series	Original weight	Ingot size	Reduction in rolling	Pattern size
	Pounds	Inches		Inches
1	5900	36 by 15	30 to 1	36 by 18
2	5650	32 by 12	24 to 1	36 by 12
3	3150	26 by 12	24 to 1	36 by 18
4	3150	26 by 12	24 to 1	40 by 15

In Table 2 is given a record of original ingot size and reduction in rolling the various plates tested in this investigation. Flat test bars, with long dimension in the direction of rolling, were cut from patterns taken from these plates and machined to the form shown in Figure 4.

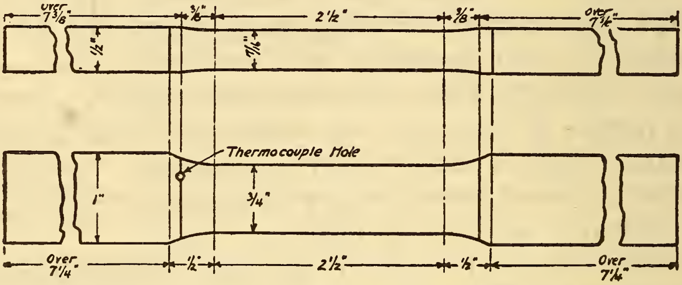

FIG. 4.—*Form and dimensions of test specimen used*

(*b*) APPARATUS FOR DETERMINATION OF PROPORTIONAL LIMIT.—At the outset emphasis is laid on the fact that, for the work required throughout the various sections of this investigation, suitable and readily manipulated apparatus and not the most accurate mechanism available was sought. The material under test is lacking in entire uniformity (which condition is usual in engineering material), so it appeared undesirable to construct elaborate equipment requiring a great deal more time in development and actual test.

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[5] C. L. Huston, Experiments on the segregation of steel ingots in its relation to plate specifications, Proc. Am. Soc. Test. Mat. 6 (1906), p. 182.

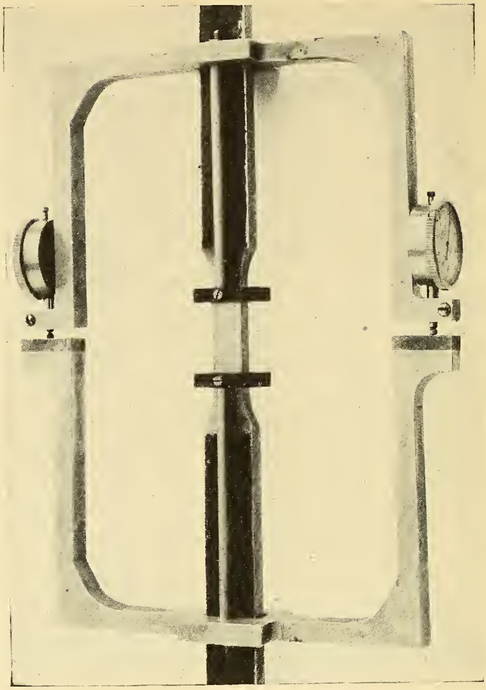

FIG. 5.—*Apparatus used for determining proportional limit*

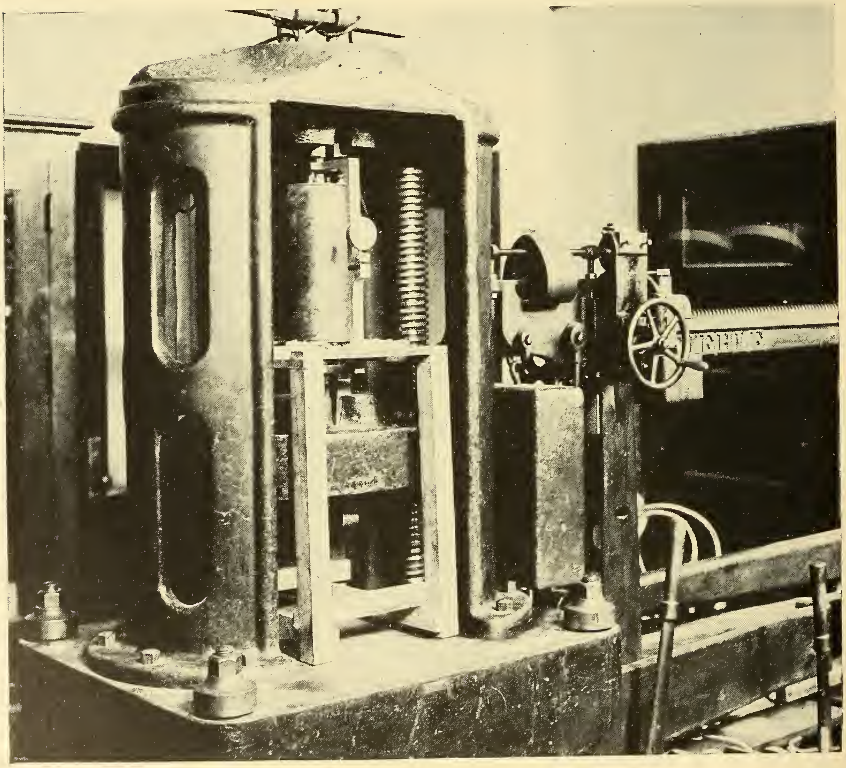

FIG. 8.—*Apparatus for determining tensile properties of metals at high temperatures*

The apparatus used in determination of the limit of proportionality at various temperatures is shown in Figure 5 and consisted primarily of two aluminum-alloy frames each rigidly fastened to a quenched and tempered steel yoke (shown in Fig. 6) by two annealed low-carbon steel rods. The specimen passed freely through the holes in the base of each of the frames. Yokes were each clamped to the specimen by three quenched and tempered high-speed steel screws, while the spreading of the former was overcome by the long screw. The flanges on the upper frame were so arranged that dial micrometers for indicating deformation might readily be securely fastened to them, while those of the lower frame were capped with polished steel plates to give a smooth bearing surface to the plungers of the dials.

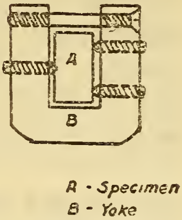

Fig. 6.—*Yoke*

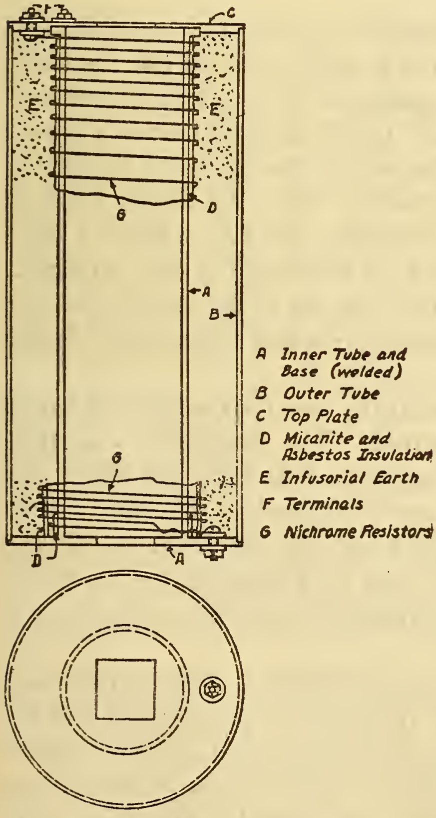

Fig. 7.—*Heating furnace*

The smallest division on the instruments used was equal to 0.001 inch, but estimated readings to the nearest 0.0001 inch were readily obtained. When stress is applied to the specimen, half the algebraic sum of the deformation recorded by the two dials represents the deformation of the specimen, which is centrally located with respect to the entire apparatus. For example, upon application of load the apparatus may twist to some extent, the dial on the left showing a negative deformation (decrease in length) of 0.004 inch, while that on the right registers a positive deformation (increase in length) of 0.009 inch. Half the algebraic sum (½ (+0.009 inch − 0.004 inch) = 0.0025 inch) represents the deformation (increase in length) of the specimen under the load applied.

(*c*) HEATING FURNACE.—The test specimens were heated by means of an electric tube furnace of the form shown in Figure 7. Two spiral resistors in series were used. The one covered the entire length of the inner tube (11 inches) and the other was concentrated at the ends, the two requiring about 80 feet (24 m) of 22-gage nichrome wire. Yokes and the greater part of the 18-inch (46 cm) test bar and rods were contained in the heating chamber, which was 11 inches long. A comparatively small temperature gradient was obtained under suitable operating conditions, as the effective heating length during test was about one-third of this at the center of the tube length, or approximately 3 inches. The furnace was operated on either 110 or 220 volts, direct current, close regulation being obtained by variable resistance in series in the circuit.

(*d*) TEST PROCEDURE.—The method of setting up the apparatus, together with procedure followed in actually carrying out the tests, was substantially as follows: A specimen was marked on one surface with a double-pointed center punch leaving marks 2 inches apart. Next, the yokes were attached to the specimen by setting the single screw into these impressions. Then, by lightly tapping the opposite side of the yoke containing the two screws, a light impression of their exact location on the test bar was obtained. These points were then enlarged by the use of the double-pointed center punch, and the yokes carrying rods and frames were firmly attached to the test piece.

Bolts holding the upper frame to the two rods were next taken off and the upper frame removed. The specimen was then passed up through the furnace until the rods appeared above the top, when the upper frame was again fastened to the rods. After the furnace was placed on a stand and the specimen was in the jaws of the testing machine the dials were attached to the frame and adjusted to zero. The completely assembled apparatus is shown in Figure 8.

When thermal equilibrium at the desired temperature was reached, an initial load of about 1500 lbs./in.^{2} was applied and the dials read or, as a matter of convenience, again set at zero. Readings were then taken at increments of 500 or 1000 pounds actual load until the proportional limit was passed. The dials were then removed and the specimen was broken in the usual manner with a low rate of extension which approximated the intermittent increases of stress applied during determination of the limit of proportionality. Tests at each temperature were made in duplicate or triplicate, and the proportional limit was obtained from a stress-strain diagram. Typical curves obtained from tests at various temperatures throughout the range covered are shown in Figure 9. Temperature was measured by a 22-gage standardized chromel-alumel couple connected to a Leeds & Northrup portable potentiometer. The end of the couple was inserted directly into a small hole drilled in the specimen at the fillet, its exact location being shown in Figure 4.

(*e*) THERMAL EQUILIBRIUM.—In order to obtain reliable and satisfactory results with the method described in the preceding paragraphs, thermal equilibrium must be reached prior to the start of the loading and maintained during the actual 8 to 15 minutes during which the test is being carried out. The adjustable resistance in series in the electrical circuit makes current adjustment possible, so that the loss of heat from the heating unit, ends of test specimen, and auxiliary apparatus by radiation, convection, and conduction balances the energy added to this entire system. The effect of temperature variations may be large unless care is taken to allow sufficient time for the specimen to become uniformly heated throughout after the potentiometer has once indicated the desired temperature. The dial readings will assist in determining when equilibrium has been reached and is being maintained.

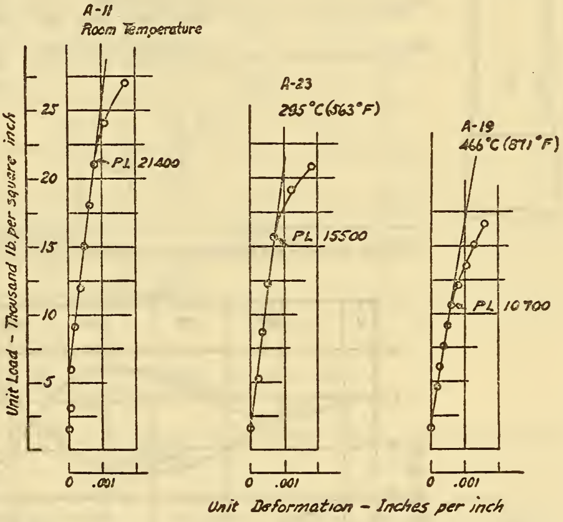

FIG. 9.—*Typical stress-strain diagrams obtained at various temperatures*

Temperature determinations under actual test conditions, made by placing thermocouples in holes located at various points in a specimen carrying entire auxiliary apparatus, show that the position chosen for the single thermocouple (in the fillet) is representative of about the mean of the gradient throughout the gage length, where the temperature gradually decreased from top to bottom (see Fig. 10 for partial reproduction of these variations). This variation is within 30° C (54° F). It is the greatest in the upper temperature ranges under consideration, and does not exceed 20° C (36° F) at the lower temperatures used. However, as the thermocouple, specimen with auxiliary apparatus, and furnace are in the same relative position in each test, the results obtained at various temperatures throughout the range 20 to 465° C (70 to 870° F) are comparable.

Desired temperature, degrees Centigrade	Temperature of specimen at positions indicated, degrees Centigrade					Time after couple No. 1 first reached desired temperature, minutes	Average temperature of couples 2, 3, 4, and 5, degrees Centigrade	Maximum temperature variation, degrees Centigrade
	1	2	3	4	5			
165	165	173	167	158	165	15	166	15
320	320	327	327	310	322	0	322	17
	325	334	334	320	329	5	329	14
	325	336	334	318	332	20	330	16
400	402	415	412	393	402	10	405	22
	402	415	412	393	402	20	405	22

Fig. 10.—*Temperatures at various parts of test specimen*

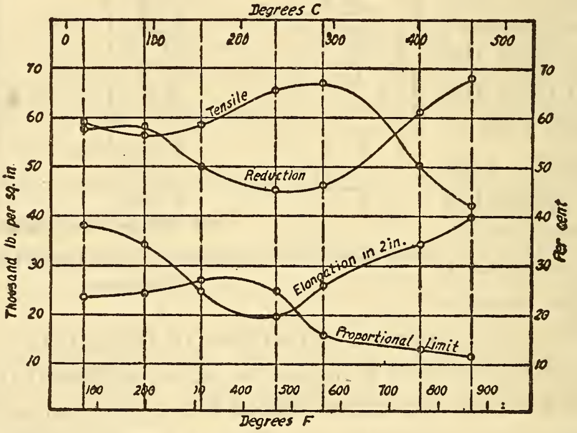

Fig. 11.—*Tensile properties of half-inch A. S. T. M. firebox boiler plate at elevated temperatures (Series 1)*

Plates rated as 52–62 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.19; manganese, 0.43; phosphorus, 0.020; and sulphur, 0.031 per cent.

3. TENSILE PROPERTIES OF HOT-ROLLED BOILER PLATE AT ELEVATED TEMPERATURES

As a basis for comparison with steels subjected to deformation in various ways tensile tests were made on the four grades listed in Table 1. Results obtained are graphically represented in Figures 11, 12, 13, and 14. In all grades of plates increase in temperature above the ordinary atmospheric range is accompanied by distinct changes in strength and ductility, namely:

(*a*) Tensile strength decreases a few thousand pounds per square inch in the neighborhood of 95° C (200° F). This is followed by an increase to a maximum, which occurs at 290° C (550° F) in plates of the first three series and at about 250° C (480° F) in series 4, representing plates of lowest tensile strength. With further increase in temperature the strength decreases, and again approximates ordinary atmospheric temperature values in the range 370 to 400° C (700 to 750° F).

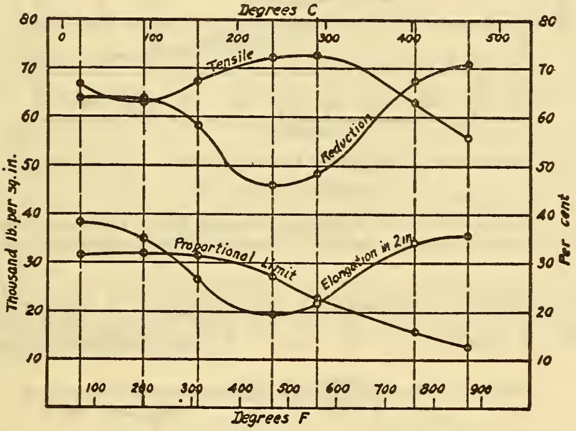

FIG. 12.—*Tensile properties of half-inch marine boiler plate at elevated temperatures (Series 2)*

Plates rated at 60–70 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.25; manganese, 0.38; phosphorus, 0.019; and sulphur, 0.031 per cent.

(*b*) The limit of proportionality increases and is a maximum in the neighborhood of 150° C (300° F). In the case of the fire-box grade plates this increase is more marked, and is maintained above room temperature value to a higher temperature than is the case with the marine plate, which has, in effect, constant proportional limit up to about 175° C (350° F). While such differences are noticeable at these relatively low temperatures, the proportional limit of the higher tensile strength marine plate is practically the same at 465° C (870° F) as that of series 1 and 3 fire-box grade plates and but slightly higher than that of the fourth series (railway fire-box plate of lowest tensile strength).

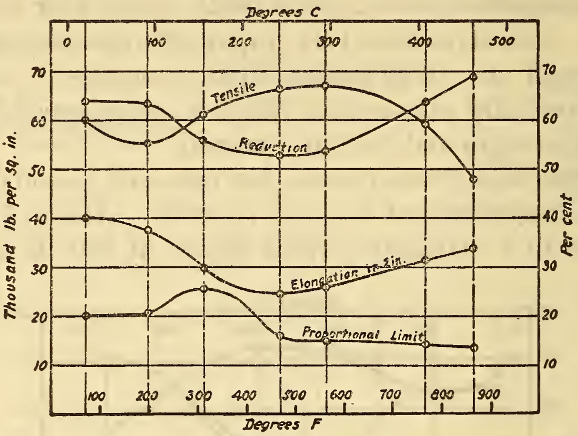

FIG. 13.—*Tensile properties of half-inch railway firebox boiler plate at elevated temperatures (Series 3)*

Plates rated as 45-55 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.17; manganese, 0.36; phosphorus, 0.024; and sulphur, 0.031 per cent.

(*c*) Only a slight decrease in elongation is observed until a temperature of about 95° C (200° F) is reached, above which

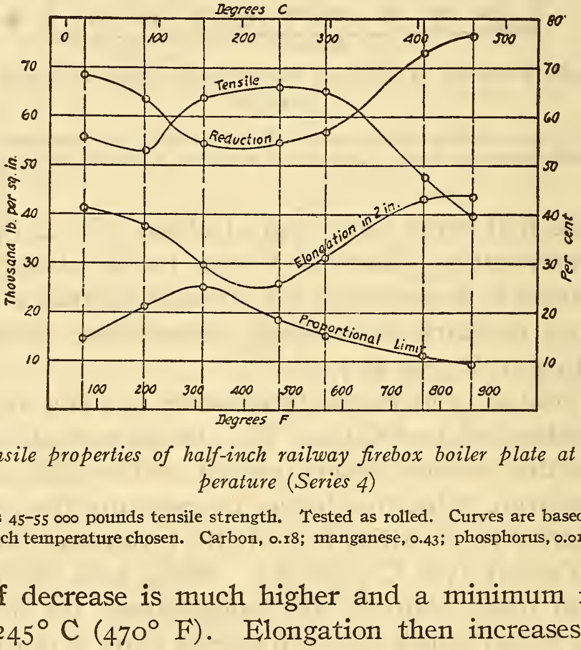

FIG. 14.—*Tensile properties of half-inch railway firebox boiler plate at elevated temperature (Series 4)*

Plates rated as 45-55 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.18; manganese, 0.43; phosphorus, 0.017; and sulphur, 0.035 per cent.

the rate of decrease is much higher and a minimum is reached at about 245° C (470° F). Elongation then increases but does not throughout the range under consideration reach the ordinary atmospheric temperature value in the marine plate (rated 60 000–70 000 pounds tensile strength) and but slightly exceeds its room temperature value in the case of the fourth series at 465° C (870° F).

(*d*) Reduction of area closely follows the inflections registered in the curves for elongation but reaches a minimum at a slightly higher temperature, except in the case of the lowest tensile strength fire-box plate where the minimum occurs at practically the same temperature as that for elongation. At 465° C (870° F) reduction of area is greater than the value obtained at atmospheric temperature in each of the four series of plates tested.

It is to be noted that maximum tensile strength does not coincide with minimum reduction of area or maximum proportional limit, but examination of Figures 11 to 14, inclusive, indicates that the inflections in the curves for reduction of area are, in general, more nearly coincident with the reverse inflections in the curves for tensile strength, and that elongation and proportional limit may be similarly paired.

III. EFFECT OF PERMANENT COLD AND BLUE DEFORMATION ON THE TENSILE PROPERTIES OF STEEL AT VARIOUS TEMPERATURES

1. COLD-ROLLING

The effect of cold work on the tensile properties of steel at ordinary temperatures is to increase the elastic properties and to a smaller degree the tensile strength with an accompanying decrease in ductility as measured by elongation and reduction of area. The greater the total reduction within the capacity of the material the greater is the increase in strength. The tensile properties of steel at elevated temperatures are likewise modified by such cold deformation. Jeffries (33) reports increased strength at blue heat (200 to 300° C) when Armco iron is drawn at room temperature with moderate reductions, but with 96 per cent reduction of area by cold-drawing the tensile strength is greater at room temperature than at any higher one.

The tensile properties at various temperatures of cold-rolled fire-box and marine grades of boiler plate are shown in Figures 15 and 16. Comparison between the cold and hot rolled properties is also shown in Figure 17.

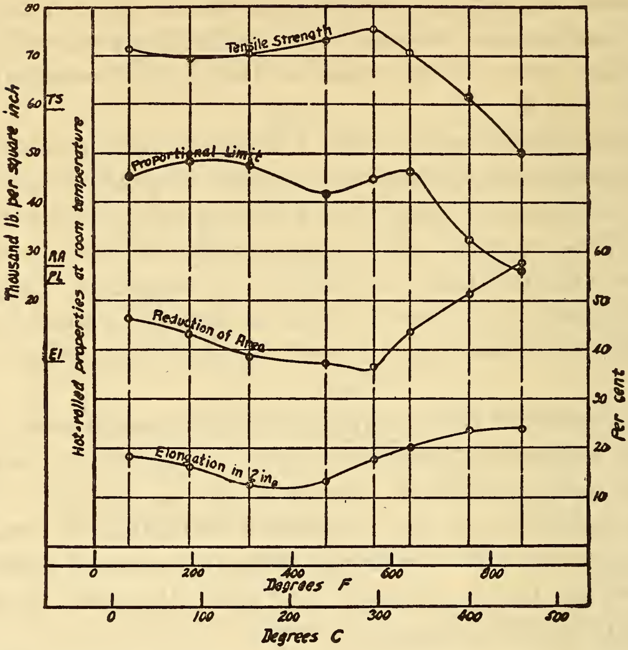

FIG. 15.—*Tensile properties of cold-rolled A. S. T. M. firebox boiler plate at various temperatures (Series 1 steel)*

Carbon, 0.19; manganese, 0.43; phosphorus, 0.020, and sulphur, 0.031 per cent. Plates reduced cold $\frac{1}{16}$ inch from $\frac{1}{2}$ inch thickness

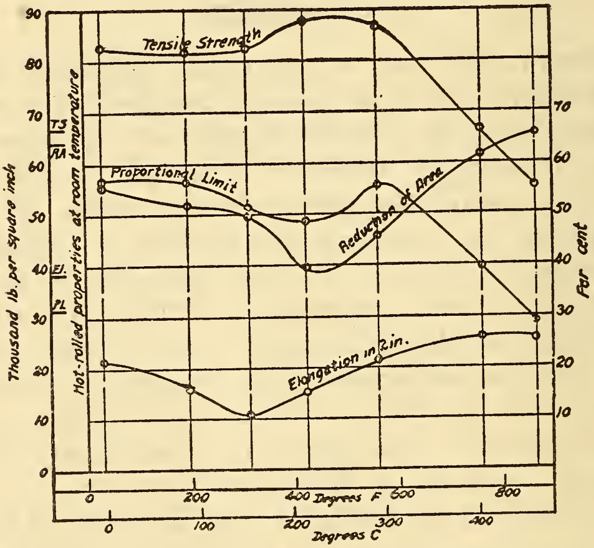

FIG. 16.—*Tensile properties of cold rolled marine boiler plate at various temperatures (Series 2 steel)*

Carbon, 0.25; manganese, 0.38; phosphorus, 0.019; and sulphur, 0.031 per cent. Plates reduced cold, $\frac{1}{16}$ inch from $\frac{1}{2}$ inch thickness.

One-sixteenth inch "cold reduction," approximating 12.5 per cent of the original plate thickness, increases the tensile strength at room temperature about 20 per cent. It also increases the strength of the hot-rolled plates up to about 465° C (870° F) by a similar amount, showing that this effect is maintained until relatively high temperatures are reached.

The changes in proportional limit are more marked and of considerable interest. At ordinary temperatures an increase of about 80 to 95 per cent is shown. Similarly, an increase of 60 to 100 per cent above the values obtained in tests of hot-rolled plates is found at temperatures up to and including 245° C (470° F). In the blue-heat range, 295° C (565° F), the increase in proportional limit due to cold work reaches the very high value of 150 per cent in the marine plate and nearly 200 per cent in the fire-box grade. This, however, is not accomplished at the expense of ductility, as the relation between elongation of cold and hot rolled plates has also increased. The relation between reduction of area of cold

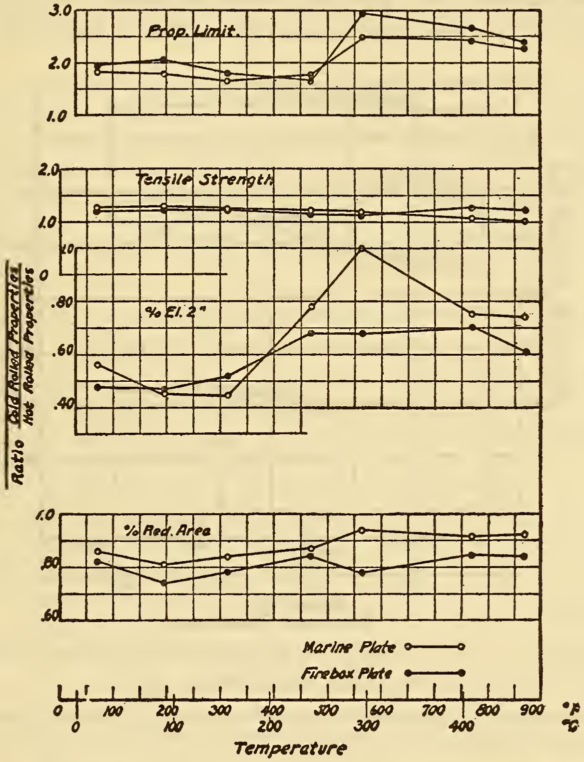

FIG. 17.—*Comparison of tensile properties at various temperatures of cold and hot-rolled firebox and marine boiler plate*

and hot finished marine steel has likewise increased to some extent, while that for the fire-box grade has decreased but slightly.

Bregowsky and Spring (25) in a report of tests of cold-rolled Bessemer shafting show secondary inflections in their tensile properties—temperature curves similar to those described above though occurring at somewhat lower temperatures. However, no direct comparison with the hot-rolled steel is available.

In order to determine whether these changes at blue heat are maintained at ordinary temperatures specimens were annealed at successively increasing temperatures and then tested in the usual manner at the temperature of the room. The results, which are graphically represented in Figure 18, illustrate, as far as the tensile properties are concerned, the benefits derived from the "bluing" of cold-finished products, such as thin-wall seamless steel tubes, and show the effects of final partial annealing on low-carbon steel cold rolled in the ordinary manner. Short-time annealing in the blue-heat range, 295° C (565° F), has little effect on the tensile strength and elongation but materially increases the elastic ratio with only a minor decrease in reduction of area.

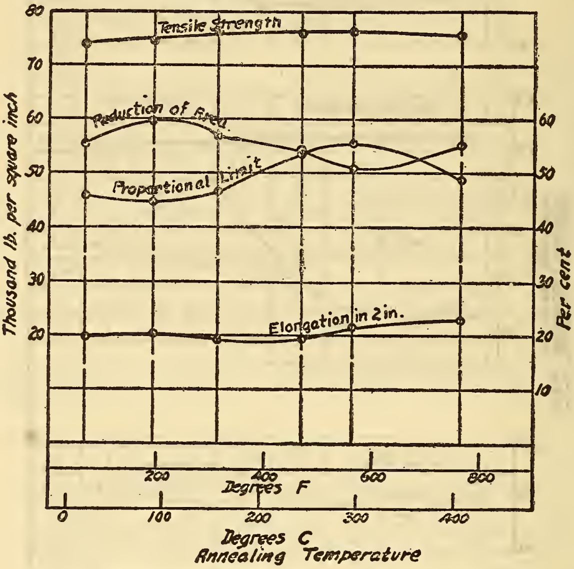

FIG. 18.—*Effect of partial annealing on the tensile properties of cold-rolled railway firebox boiler plate (Series 4 steel)*

Carbon, 0.17; manganese, 0.36; phosphorus, 0.024; and sulphur, 0.031 per cent. Plates reduced cold, $\frac{1}{16}$ inch from ½ inch thickness. Held 30 minutes at annealing temperature and air cooled.

In the case of the fire-box steel under test this increase in the limit of proportionality is about 20 per cent. It is likewise apparent from Figure 18 that a short time annealing at somewhat higher temperature, 405° C (765° F), accomplishes little, if anything, in the improvement of the tensile properties of this cold-rolled steel.

2. BLUE ROLLING

Working steel in the ranges where ordinarily temper colors are obtained has long been considered deleterious and even dangerous. Stromeyer (37) warns against such practice and, in referring to his series of tensile and bending tests on iron, mild and hard steels, writes:

> All these results point unmistakably to the great danger which is incurred if iron or steel is worked at a blue heat. * * * It is very common practice amongst boiler makers to "take the chill out of the plate" if it requires a little setting, or to set a flanged plate before it is cold. This is really nothing else than working it at a blue heat and should not be allowed. * * * All hammering or bending of iron and steel should be avoided, unless the metals are either cold or red-hot. Where this is impossible and where the plate or bar has not broken while blue-hot, it should be subsequently annealed.

Howe (38) in 1891 summarized available information relating to what he calls "blue shortness" and states in part:

> Not only are wrought iron and steel much more brittle at a blue heat[6] than in the cold or at redness, but, while they are probably not seriously affected by simple exposure to blueness, even if prolonged, yet if they be worked in this range of temperature they remain extremely brittle after cooling and may indeed be more brittle then than while at blueness. This last point, however, is not certain.
>
> The loss of ductility as measured by endurance of bending and drifting is enormous. That this is not due to incipient cracks is shown by the simultaneous increase of tensile strength and by the restoration of ductility by annealing. The effect of blue working on ductility as measured by elongation (on rupture by static tensile stress) is very irregular and apparently anomalous. * * * Heating to redness may completely remove the effects of blue working.

Howe further called attention to the resemblance between the effects of cold working and those of blue working, and that the immediate effect of these two operations might be suspected to be identical in nature. He states:

> It is true that the gain in elastic limit does not seem to excel that in tensile strength as markedly in the case of blue as in the case of cold working, nor is it clear that the tensile strength and elastic limit increase during rest after blue as they do after cold working. But this is natural, for we see reason to believe that heating cold-worked iron to blueness greatly accelerated the changes which cold working starts, so that, when this change is started by distortion at blueness instead of in the cold it may occur so rapidly and so nearly reach its full growth before the metal grows cold that no considerable further change occurs thereafter. The effects of blue working are more intense and more injurious than those of cold working.

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[6] The terms "blue work," "blue shortness," etc., as used by Howe, refer to temperatures where ordinarily temper colors are obtained and may be considered to be within the range 220–320° C (430–600° F).

Ridsdale (40) referred to blue heat, 315–370° C (600–700° F), as the state of minimum plasticity and showed that soft steel developed brittleness when worked or soaked in a furnace for a long time in this range. He further pointed out that by reheating to a suitable temperature the good qualities of such steel were restored.

Kurzwernhart (39) reported that a brittle boiler plate returned to the Teplitz Steel Works gave rise to investigation showing that the plate had been removed from the furnace at an uneven temperture extending from red-hot on one side to brown-hot on the other. Experiments showed that not only was the blue heat dangerous, but working the metal at certain other temperatures was likewise deleterious. Bending tests showed the most dangerous temperature to be that at which the surface assumed a light yellowish coloration. Blue brittleness could be removed, however, by heating to a dull red such as could only be observed in a darkened room.

Jeffries (34) has studied the effects of blue work on the tensile properties of Armco iron and reached the following conclusions:

1. Armco iron deformed at room temperature a given amount does not increase as much in tensile strength as when deformed the same amount at blue heat.
2. The effect of drawing Armco iron at 200 to 400° C is to produce greater tensile strength at all temperatures up to 550° C than would obtain with the same amount of deformation in the cold. The elongation is less after drawing at 200 to 400° C than after drawing at room temperature. The same conclusion is true, in general, of the reduction of area.

Jeffries also reports results obtained in private communication from W. E. Ruder to show the effects of rolling cold and at various elevated temperatures on the strengths of mild steel and annealed nickel-chromium steel. These data are reproduced, respectively, in Tables 3 and 4.

TABLE 3.—Tensile Strength of Mild Steel Drawn at Various Temperatures [1]

Size and condition of material	Tensile strength	Size and condition of material	Tensile strength
	Lbs./in.^{2}		Lbs./in.^{2}
0.192 inch diameter	58 200	0.192 inch diameter	112 700
Annealed	55 200	Reduced to 0.179 inch at 300° C	113 500
0.192 inch diameter	67 000	0.192 inch diameter	114 100
Reduced to 0.179 inch cold	69 500	Reduced to 0.179 inch at 400° C	105 300
0.192 inch diameter	110 200		
Reduced to 0.179 inch at 240° C	112 300		

[1] Zay Jeffries, Physical changes in iron and steel below the thermal critical range, Mining and Metallurgy, 158 (1920), section No. 20.

TABLE 4.—Tensile Properties of a Nickel-Chromium Steel Heat-Treated and Worked in Different Ways [1]

Condition of material	Tensile strength	Yield point	Percentage elongation in 2 inches
	Lbs./in.²	Lbs./in.²	
Annealed	101 500	67 100	25.5
Annealed, then reduced 10 per cent at 300° C	137 600	132 500	10.5
Heat treated and reduced 10 per cent at 300° C	199 100	163 700	7.5
Annealed and reduced 10 per cent cold	114 200	102 000	19.5

[1] Zay Jeffries, Physical changes in iron and steel below the thermal critical range, Mining and Metallurgy, 158 (1920), section No. 20.

While there seems to be unanimity of opinion that blue work is deleterious to steel, Howe (38) early called attention to the fact that—

> Millions of car axles, blue from "hot boxes," are chilled with snow and jarred under heavy load at loose rail joints, yet are apparently unharmed. Among the many thousand steel boilers tens of thousands of plates must have been worked more or less at blueness, yet failures are rare * * *. Again, though many recognize that machine riveting has a great advantage over hand riveting, in that its work ceases before the rivet cools to blueness, while the hand riveter usually continues hammering while the rivet is passing blueness, yet relatively few hand worked rivets fail in use * * *. Finally, much crucible steel in the form of bars, plates, etc., is habitually rolled or hammered till its temperature has fallen below visible redness.

More recently the question of effects of deformation at temperatures below the thermal transformations has become of interest in connection with the straightening of crank shafts for airplane engines while cooling from the tempering heat. Whether such work is detrimental or can safely be applied to these and other types of forgings has for some little time been under discussion.

In order to determine the effect of permanent deformation at blue heat on the high-temperature properties of boiler plate several patterns were reduced at about 300° C from ½ inch to $\frac{15}{32}$ and $\frac{7}{16}$ inch, respresenting, respectively, 6.25 and 12.5 per cent reduction in thickness. The patterns were rolled in a single-stand 16-inch mill, a number of light reductions to effect the totals mentioned above being used. Considerable difficulty was encountered at first in producing flat plates suitable for test; probably, in the main, because of the short length of the patterns. An attempt was made to straighten the first plates cold and also at blue heat immediately after rolling, but they broke transversely with a very coarsely crystalline fracture as soon as pressure was applied.

It was found after discarding these plates that all the patterns of series 1 and 2 steels had been used, so that it was necessary to carry out the desired tests on series 4, railway fire-box steel, quite similar in composition and properties to series 3. This, however, does not affect consideration of the relative effects of blue and cold work as shown in Table 5 based on data represented graphically in Figures 17 and 19.

TABLE 5.—Effect of Blue and Cold Rolling on the Tensile Properties of Fire Box Boiler Plate at Various Temperatures

Temperature of tests					Hot-rolled (series 1)	1/16-inch "cold reduction"	Ratio[1]	Hot-rolled (series 4)	1/32-inch "blue reduction"	Ratio[1]	1/16-inch "blue reduction"	Ratio[1]
Hot rolled steel	Cold rolled steel	Blue rolled steel	Average									
					Tensile strength, pounds per square inch							
°C	°C	°C	°C	°F								
21	21	21	21	70	59 000	71 130	1.21	55 600	72 000	1.29	79 800	1.43
91	89	91	90	194	55 530	69 300	1.25	52 800	68 900	1.30	77 700	1.47
156	156	156	156	313	58 100	70 100	1.21	63 800	69 400	1.09	78 300	1.23
243	243	243	243	469	65 130	72 930	1.12	65 800	74 300	1.13	79 100	1.20
295	295	295	295	563	66 700	75 540	1.13	65 200	73 650	1.13	78 000	1.20
407	402	407	405	761	49 150	61 850	1.26	47 800	53 850	1.12	57 700	1.21
465	463	463	463	865	41 850	50 400	1.20	39 900	43 600	1.09	44 400	1.11
					Proportional limit, pounds per square inch							
21	21	21	21	70	23 300	45 130	1.94	14 500	42 800	2.95	53 500	3.69
91	89	91	90	194	23 630	48 550	2.05	21 200	52 500	2.48	60 200	2.84
156	156	156	156	313	26 600	47 450	1.78	25 100	48 350	1.93	58 800	2.34
243	243	243	243	469	24 900	41 700	1.67	18 500	48 500	2.62	57 200	3.09
295	295	295	295	563	15 250	44 630	2.92	15 000	34 200	2.28	54 800	3.65
407	402	407	405	761	12 960	32 000	2.66	11 500	29 650	2.58	40 200	3.50
465	463	463	463	865	11 430	26 050	2.36	9 400	22 750	2.42	27 400	2.92
					Percentage elongation in 2 inches							
21	21	21	21	70	37.8	18.2	0.48	41.0	22.2	0.54	18.0	0.44
91	89	91	90	194	34.7	16.4	.47	37.5	17.5	.47	15.1	.40
156	156	156	156	313	24.9	12.8	.52	29.6	17.3	.58	13.3	.45
243	243	243	243	469	19.9	13.4	.68	25.8	18.2	.70	15.1	.58
295	295	295	295	563	25.7	17.5	.68	31.0	25.0	.81	16.4	.53
407	402	407	405	761	33.8	23.6	.70	43.0	32.8	.76	25.8	.60
465	463	463	463	865	39.2	23.8	.61	43.5	34.2	.79	27.9	.64
					Percentage reduction of area							
21	21	21	21	70	57.1	46.7	0.82	68.2	50.7	0.74	46.2	0.68
91	89	91	90	194	58.3	43.2	.74	63.4	47.7	.75	43.4	.68
156	156	156	156	313	49.3	38.6	.78	54.3	41.0	.75	37.3	.69
243	243	243	243	469	45.1	37.3	.84	54.7	41.2	.75	36.3	.66
295	295	295	295	563	45.6	36.5	.78	56.8	46.6	.82	42.6	.75
407	402	407	405	761	60.7	51.2	.84	73.0	62.4	.85	57.5	.79
465	463	463	463	865	67.7	57.2	.84	76.8	66.0	.86	63.6	.83

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[1] In each case the ratio given is the blue or cold rolled properties to the hot-rolled properties as determined by tests on patterns of the same plate.

1. The increase in strength at room temperature resulting from "cold reduction" of 12.5 per cent is about the same as that produced by half this reduction (6.25 per cent) at blue heat.

This, in general, is also true at temperatures up to 295° C (565° F) (blue heat). Above this temperature the increase in strength resulting from "blue deformation" is somewhat less than that from cold rolling.

2. A "blue reduction" of twice the amount given above (6.25 per cent) does not increase the strength at room or elevated temperatures proportionally.

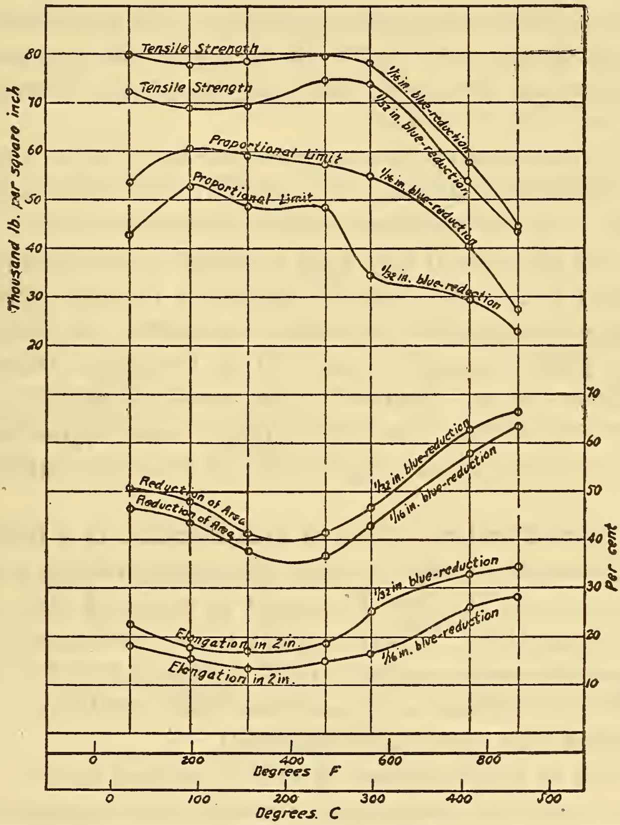

FIG. 19.—*Tensile properties of blue-rolled railway firebox boiler plate at various temperatures (Series 4 steel)*

Carbon, 0.18; manganese, 0.43; phosphorus, 0.017; and sulphur, 0.035 per cent. Plates reduced at about 300° C from ½ inch thickness.

3. At 245° C (470° F) the strength of the blue worked steel is little in excess of that hot rolled and about the same whether the "blue reduction" is 6.25 or 12.5 per cent.

4. The maximum tensile strength of the steel subjected to 6.25 per cent "blue reduction" is obtained at blue heat, 295° C (565° F), and the shape of the tensile strength temperature curve shown in Figure 19 is similar to that for the cold-rolled

steel, while with twice this "blue reduction" (12.5 per cent) about the same strength is obtained at 295° C (565° F) as at room temperature. In both cases, however, the tensile strength temperature curves change direction quite abruptly at or about 295° C (565° F).

5. The increase in the limit of proportionality at room temperature resulting from 6.25 per cent "blue reduction" is greater than that obtained from twice as much "cold reduction." This is also true up to 245° C (470° F), above which temperature the increase resulting from cold work is about equal to that produced by the blue work in question.

6. The proportional limit increases with first rise in temperature and is a maximum at about 90° C (195° F), after which it decreases. The form of the proportional limit temperature curve for steel reduced 6.25 per cent at blue heat is similar to that reduced twice this amount in the cold, but the secondary increase which in the cold worked steel appears to attain its maximum at about 340° C (645° F) occurs at 245° C (470° F) in the blue worked metal. This inflection is not observed in the steel subjected to 12.5 per cent "blue reduction," the proportional limit decreasing slowly from 90 to about 245° C (195 to 470° F) and more rapidly thereafter.

7. Elongation and reduction of area decrease to a minimum in the neighborhood of 200° C (410° F) and thereafter increase to high values at 465° C (870° F) greatly in excess of those obtained at room temperature. There appears to be a more rapid increase in elongation between 295 and 410° C (565 and 770° F) coincident with the rapid decrease of proportional limit mentioned above for steel reduced 6.25 per cent at blue heat.

The effect of partial annealing of blue worked steel is shown in Figure 20. As the temperature increases the strength at room temperature decreases, and this is accompanied by increase in elongation and reduction of area. The proportional limit decreases until an annealing temperature of about 500° C (930° F) is reached, but with slow cooling from above this to about 600° C (1110° F) the elastic ratio is greatly increased. Annealing for 30 minutes at about 730° C (1345° F) completely removes the effects of "blue deformation."

3. DEPTH OF PENETRATION OF EFFECT OF BLUE AND COLD ROLLING.

Since the effects of blue and cold work are so marked and maintained over a considerable temperature range, the question naturally arises as to whether the increased strength of the plate is due to hardening of the "skin," so that there is a decrease in strength from surface to center or whether the magnitude of the observed effect is substantially the same throughout the cross section, especially in light plates such as are under investigation. The surfaces of cold and blue rolled bars were accordingly milled to progressively increasing depths and tested in the usual manner at room temperature.

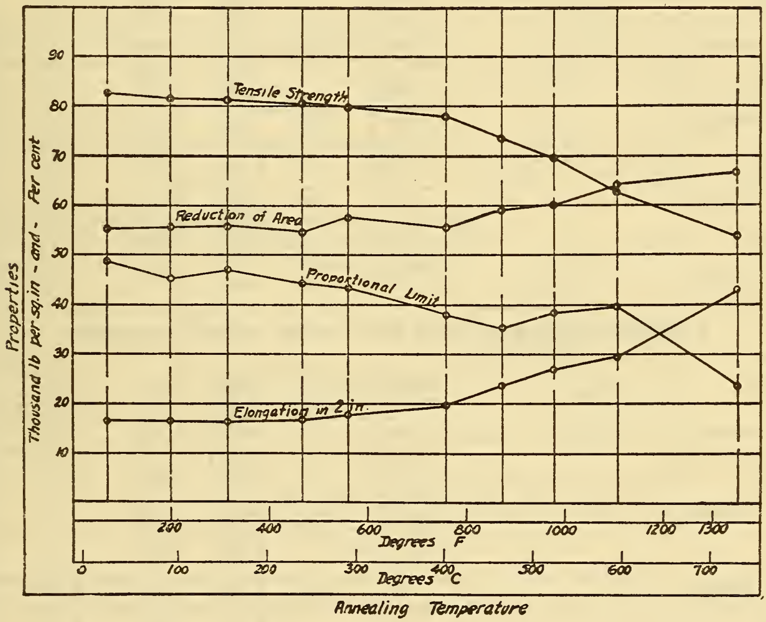

FIG. 20.—*Effect of partial annealing on the tensile properties of blue-rolled railway firebox boiler plate (Series 3 steel)*

Carbon, 0.17; manganese, 0.36; phosphorus, 0.024; and sulphur, 0.031 per cent. Reduced 1/32 inch at about 300° C from ½ inch thickness. Held 30 minutes at annealing temperatures and air cooled.

The results of these tests are given in Table 6 and show that there is substantially no difference in the strength factors when even a considerable depth of surface metal has been removed, whereas the ductility as measured by elongation and reduction of area gradually decreases with removal of increasing layers of metal. The origin of this effect is, without doubt, due to the decrease in thickness of the specimen, while the width has been kept constant.[7]

TABLE 6.—Tensile Properties of Cold and Blue Rolled Fire-Box Boiler Plate upon Removing Successively Increasing Depths of Surface Metal (Series 3 steel)

REDUCED 1/16-INCH COLD FROM 1/2-INCH THICKNESS

Sample number	Sample thickness	Surface metal removed	Proportional limit	Tensile strength	Percentage elongation in 2 inches	Percentage reduction of area
	Inch	Inch	Lbs./in.²	Lbs./in.²		
E 13	0.437	....	52 000	82 200	18.5	47.4
E 20	.437	....	47 200	74 800	18.5	47.1
Average	.437	....	49 600	78 500	18.5	47.2
E 14	.377	....	54 500	74 900	18.0	46.9
E 19	.371	....	56 500	78 600	17.0	41.2
Average	.374	0.031	55 500	76 750	17.5	44.0
E 18	.317	....	54 000	76 400	15.5	44.3
E 15	.310	....	53 000	76 000	17.0	41.5
Average	.313	.062	53 500	76 200	16.2	42.9
E 25	.250	....	56 000	77 300	14.0	39.8
E 11	.252	....	59 000	76 500	13.0	40.0
Average	.251	.093	57 500	76 900	13.5	39.9
E 21	.188	....	53 500	77 900	14.5	36.8
E 16	.192	....	53 500	77 500	13.0	34.5
Average	.190	.124	53 500	77 700	13.8	35.6
REDUCED 1/16-INCH AT BLUE HEAT FROM 1/2-INCH THICKNESS						
P 3	0.438	....	70 000	94 600	13.0	33.7
P 9	.442	....	69 500	94 300	12.5	38.6
Average	.440	....	69 750	94 450	12.8	36.2
P 11	.377	....	70 000	94 700	11.5	38.2
P 10	.375	....	66 000	95 600	10.5	35.3
Average	.376	.032	68 000	95 150	11.0	36.8
P 8	.311	....	68 500	95 700	9.5	36.0
P 4	.311	....	70 000	95 700	10.5	36.6
Average	.311	.064	69 250	95 700	10.0	36.3
P 12	.249	....	66 000	95 200	9.0	32.0
P 13	.250	....	73 000	94 800	8.0	31.2
Average	.250	.095	69 500	95 000	8.5	31.6
P 2	.185	....	71 000	96 400	6.5	22.4
P 1	.185	....	70 000	96 400	6.5	23.0
Average	.185	.128	70 500	96 400	6.5	22.7

4. TENSILE TESTS OF TRANSVERSE SPECIMENS OF HOT, COLD, AND BLUE ROLLED BOILER PLATE AT VARIOUS TEMPERATURES

Tests of longitudinal specimens taken from plates rolled at various temperatures do not fully define the effects of such work even when only considering the tensile properties. Accordingly

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[7] H. L. Moore, Tension tests of steel with test specimens of various size and form. Report of subcommittee to Committee E 1. Proc. Am. Soc. Test. Mat. 1918, part 1, p. 403.

tests were made on samples taken transversely from hot, cold, and blue rolled fire-box steel, series 4, Table 1. The results are given in Figure 21 and summarized to show the high temperature comparisons in Table 7.

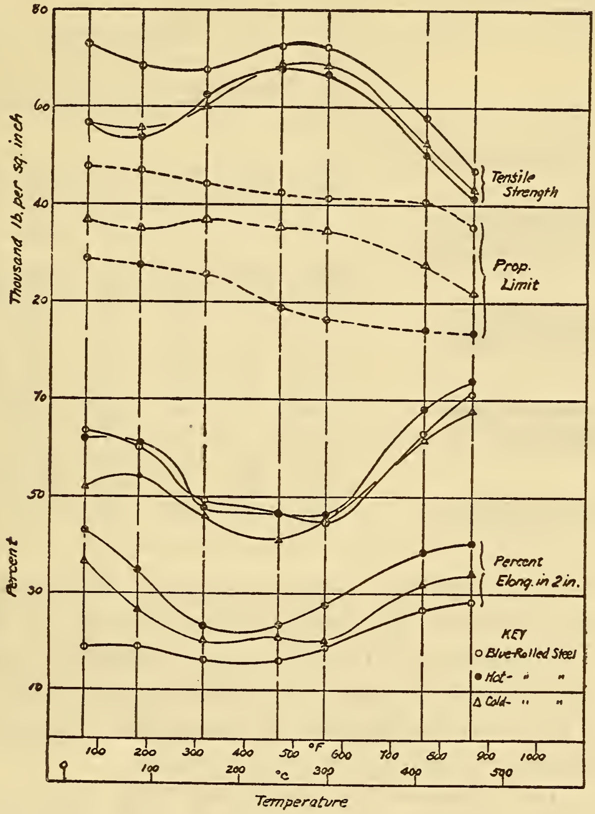


FIG. 21.—*Tensile properties of hot-, cold-, and blue-rolled railway firebox boiler plate at various temperatures as determined on transverse test specimens* (*Series 4 steel*)

Carbon, 0.18; manganese, 0.43; phosphorus, 0.017; and sulphur, 0.035 per cent. Cold- and blue-rolled plates reduced $\frac{1}{16}$ inch from ½ inch thickness, respectively, at room temperature and at about 300 C°.

It is at once evident that the general form of the tensile properties temperature curves is similar to those for longitudinal tests, with the exception of the limit of proportionality, which does not increase with the first rise in temperature. In general, the first changes are slight, but there is a decrease in hot and cold rolled steel, while in that rolled at blue heat there is a decided tendency for the limit of proportionality to remain at nearly its room temperature value over a considerable range. The agreement between duplicate determinations of this factor at slightly elevated temperatures is not so good as that obtained under similar conditions in longitudinal samples, so that the values will be considered as tentative, and in Fig. 21 are shown as dotted lines.

TABLE 7.—Comparison of Tensile Properties at Elevated Temperatures of Hot, Cold, and Blue Rolled Fire-Box Boiler Plates as Determined on Transverse Test Specimens (Series 4 Steel)

	Temperature of test.						
	21° C (70° F)	92° C (198° F)	156° C (313° F)	243° C (469° F)	295° C (563° F)	407° C (764° F)	463° C (865° F)
Proportional limit, pounds per square inch:							
Hot rolled	28 850	27 250	25 500	18 600	16 400	14 200	13 500
Cold rolled	37 000	34 700	36 900	34 700	34 500	27 500	21 400
Blue rolled	47 500	74 000	44 000	42 350	41 000	40 450	35 000
Ratio of cold rolled to hot rolled	1.28	1.27	1.44	1.87	2.10	1.94	1.59
Ratio of blue rolled to hot rolled	1.65	1.72	1.72	2.28	2.50	2.74	2.59
Tensile strength, pounds per square inch:							
Hot rolled	56 700	53 300	62 350	67 400	66 900	50 000	41 100
Cold rolled	56 900	55 500	60 000	68 400	68 500	52 700	42 400
Blue rolled	72 750	68 150	67 250	72 300	72 250	57 700	46 500
Ratio of cold rolled to hot rolled	1.00	1.04	.96	1.02	1.02	1.06	1.03
Ratio of blue rolled to hot rolled	1.28	1.29	1.08	1.08	1.08	1.15	1.13
Percentage of elongation in 2 inches:							
Hot rolled	42.8	34.8	23.2	23.3	27.3	38.5	40.2
Cold rolled	36.5	26.5	20.6	21.0	19.8	31.8	33.7
Blue rolled	18.5	19.0	16.2	16.2	18.8	26.5	28.2
Ratio of cold rolled to hot rolled	.85	.76	.89	.90	.72	.82	.84
Ratio of blue rolled to hot rolled	.43	.55	.70	.69	.69	.69	.70
Percentage reduction of area:							
Hot rolled	62.1	61.3	47.8	46.4	46.3	67.7	73.6
Cold rolled	63.7	60.3	49.2	46.7	44.7	62.8	70.9
Blue rolled	52.2	54.9	46.2	41.0	45.6	61.3	67.8
Ratio of cold rolled to hot rolled	1.02	.98	1.03	1.00	.96	.93	.96
Ratio of blue rolled to hot rolled	.84	.90	.97	.88	.98	.91	.92

The increase in transverse tensile strength at room temperature resulting from blue or cold rolling is very much less than that observed in longitudinal tests for the same mechanical reductions. However, the relation between the strength of blue, cold, and hot rolled steel at room temperature is maintained throughout the entire temperature range under consideration.

Similarly, the increase in proportional limit and decrease in ductility resulting from deformation at room temperature or blue heat are less than the effects observed in longitudinal tests, but the ratio of limit of proportionality of cold or blue rolled steel to that of the hot rolled metal is greater at blue heat than at room temperature.

The proportional limit of steel deformed cold or at blue heat is raised more than is the transverse strength, but this difference is not so marked as in the case of tests made of longitudinal samples.

5. PERMANENT DEFORMATION PRODUCED BY STRETCHING

Huston (42) found that in loading bridge iron to just above the "so-called elastic limit" the ductility or toughness remained unaffected, so that the metal would yield with every small increase in load, while when stressed just below the iron became rigid and would not elongate without decided load increase.

From a large number of tests of wrought iron and low-carbon steel Bauschinger (43) made certain empirical deductions regarding the behavior of proportional limit and yield point when such metals were subjected to overstrain at ordinary temperatures. Among these deductions were the following:

He found that when stretching was produced by a load between the proportional limit and yield point the former was raised, whereas an applied stress above the yield point resulted in a decrease in the limit of proportionality. Upon aging for a long time at room temperature or for shorter periods at higher temperatures elevation of this factor was produced.

Raised proportional limit and yield point brought about by aging subsequent to overstrain were again lowered by high heating, but the method of cooling was observed to play an important part. Rapid cooling was more effective in lowering these factors than slow cooling, but the time of rest after heating and cooling exerted no further effect.

Howe (38) reported that stretching at room temperature lowered the limit of proportionality of steel, often to zero, so that if retested immediately no proportional limit or a very low one was found. The effect of rest was to slowly restore the elasticity and finally raise it above the load that caused the previous deformation, but this occurred more slowly at room temperature than when the steel was warmed. While Howe's statements are not in entire agreement with the work of Bauschinger, his results appear consistent with the tests reported by the latter.

Muir (44) found that the elastic recovery of overstrained steel was as marked after three or four minutes at 100° C (212° F) as in two weeks at room temperature and was impeded or entirely prevented at lower temperatures around 0° C (32° F).

Howard (8) stated that "the effect of straining hot on the subsequent strength when tested cold appears to depend upon the magnitude of the straining force and the temperature when overstrained. There is a zone of temperature in which the effect of hot straining elevates the elastic limit above the applied stress and above the primitive value, and if the straining force approaches the present tensile strength there results a material elevation of that value when cooled. After exposure to higher temperatures a gradual loss occurs in both elastic limits and tensile strength, and generally there follows a noticeable increase in the contrac-

TABLE 8.—Experiments Showing Some Effects of Tensional Elastic Overstrain at Various Temperatures on the Tensile Properties of Fire-Box Boiler Plate (Series 1 Steel)

Sample number	Treatment	Proportional limit	At temperature	Sustained load				Aging		Final tensile properties				
				Pounds per square inch	Pounds per square inch overload	Time maintained	At temperature	Time	At temperature	Proportional limit	Tensile strength	Per cent elongation in 2 inches	Per cent reduction of area	At temperature
		Lbs./in.^{2}	°C			Minutes	°C	Minutes	°C	Lbs./in.^{2}	Lbs./in.^{2}			°C
J 9	Single overload at room temperature.	30 300	Room.	39 650	9 350	5	Room.	5	Room.	35 700	58 700	39.0	48.1	Room.
J 10		30 600	Room.	40 000	9 400	5	Room.	5	Room.	Very low.	58 450	42.0	48.8	Room.
J 16		24 000	Room.	40 000	16 000	5	Room.	[1] 5	Room.	37 000	58 100	42.0	47.7	Room.
H 26	Single overload at 295° C for various periods and different times at rest	13 500	295	30 000	17 500	5	295	5	295	28 000	65 900	23.5	41.5	295
H 20			295	16 250		44	295	45	295	17 800	65 800	24.8	35.2	295
H 22			295	16 250		42	295	8	295	17 100	66 000	24.8	42.6	295
H 24	Repeated overload at 295° C	15 500	295	16 250	750	5	295	5	295					
	After 15 repetitions at 16 250 pounds									16 400	64 300	27.0	41.5	295
H 25	Repeated and increasing overload at 295° C	15 000	295	16 250	1 250	5	295	5	295					
		17 700	295	22 680	7 680	5	295	5	295					
		22 000	295	25 920	10 920	5	295	5	295					
		24 800	295	29 160	14 160	5	295	5	295					
		27 700	295	30 780	15 780	5	295	5	295					
		30 600	295	34 000	19 000	5	295	5	295					
		33 000	295	35 600	20 600	5	295	5	295					
		[2] 35 500	295	37 200	22 200	5	295	5	295					
		35 000	295	40 500	25 500	5	295	5	295					
		39 900	295	43 740	28 740	5	295	5	295					
		40 000	295	42 120	27 120	5	295	5	295					
		40 500	295	45 360	30 360	5	295	5	295					
		45 000	295	46 980	31 980	5	295	5	295					
		45 500	295	48 600	33 600	5	295	5	295					
		47 500	295	50 220	35 220	5	295	5	295					
		49 000	295	57 840	36 840	5	295	5	295					
		50 500	295	53 460	38 460	5	295	5	295					
		51 000	295	55 080	40 080	5	295	5	295					

		52 750	295	56 700	41 700	5	295	5	295	....	....	....	....	....
		55 000	295	58 940	43 940	5	295	5	295	....	....	....	....	....
		53 500	295	63 180	48 180	5	295	5	295	....	....	....	....	....
		56 000	295	64 800	49 800	5	295	5	295	56 250	66 340	26.8	40.3	295
H 21.....	Single overload at 407° C.......	....	407	13 960	....	4[2]	407	43	407	13 400	50 450	37.3	59.9	407
H 23.....		....	407	13 960	....	45	407	5	407	15 750	53 300	34.8	54.3	407
J 11......	Single overload at 463° C.......	16 600	463	31 400	14 800	5	463	5	463	15 500	44 300	35.0	64.3	463
J 17......		16 600	463	25 000	[3]8 400	5	463	5	463	23 000	43 600	39.0	63.0	463
J 23......	Effect overload at 295° C on room temperature properties.	....	....	32 900	....	5	295	(4)	(4)	Very low.	58 600	35.0	47.0	Room.
J 15......	Effect of long rest on J 23.......	....	....	30 000	....	5	463	(5)	(5)	36 500	59 100	32.5	48.0	Room.
J21.......	Effect of overload at 465 ° C on room temperature properties	....	....	25 000	....	5	463	(6)	(6)	No curves.	58 450	37.5	48.1	Room.
J20.......		....	....	25 160	....	5	463				59 200	38.5	48.7	Room.
J18.......	Effect of long rest on J20........	....	....	25 000	....	5	463	(7)	(7)	35 500	59 600	39.0	48.7	Room.
J 19......	Effect of normalizing on recently overloaded steel.............	....	....	30 000	....	5	295	(8)	(8)	32 000	58 250	40.5	50.7	Room.

---

[1] At 1,550 pounds per square inch.

[2] Cooled while resting overnight. Then reheated.

[3] Approximate value.

[4] Cooled 1 hour to room temperature.

[5] Cooled; then 46 2/3 hours at room temperature.

[6] Cooled in 30–40 minutes to room temperature.

[7] Cooled, then 45 1/6 hours' rest at room temperature.

[8] Cooled 3 minutes, normalized 843° C cooled 2½ hours to room temperature.

tion of area." Howard found the zone of elevation of the elastic limit had apparently been passed when the steel was subjected to overstrain at about 395 to 425° C (740 to 800° F) and noted the importance of time between overload at high temperatures and subsequent test.

Because of the extended field for research along these lines, as pointed out by Howard (8), Jeffries (34), and others, and because of the character and purpose of this investigation, the tests of overstrained steel made by the author were limited and undertaken with the view that the results might show some differences in deformational characteristics of steel above and at or below blue heat, for the most marked changes in tensile properties have been found in this temperature range. No generalizations are made from the data obtained in view of the omission of yield point determinations, but attention is drawn to certain of the observed effects shown in Table 8.

At blue heat, 295° C (565° F), tensional stress in excess of the limit of proportionality raises this factor in a short time after release of load to a value approximating the stress producing the previous deformation, but when this stretching at blue heat is followed by cooling to room temperature and subsequent test the immediate effect of the "blue overstrain" is a lowering of the proportional limit. This also appears to be the case at 465° C (870° F).

Repeated overstrain at blue heat, whether at constant or increasing loads, raises the apparent limit of proportionality at this temperature in a like manner and to a similar degree. The magnitude of this increase may be considerable, as in the case of sample H 25, Table 8, where the proportional limit has been raised from 15 000 lbs./in.^{2} to a little more than 56 000 lbs./in.^{2}, equivalent to 375 per cent. Such deformation does not, however, appear to modify the values of tensile strength, total elongation, or reduction of area when the specimen is finally broken. These results appear consistent with Bauschinger's deductions and the work of others mentioned, for a very rapid recovery from elastic overstrain and almost immediate elevation of the proportional limit would be expected at the temperature at which the stresses were applied.

Heating to a temperature above Ac_1 and thereafter cooling steel which has been overstrained at blue heat, 295° C (565° F), immediately restores the apparent elasticity of the metal at room temperature. Such thermal treatment does not lower the limit of proportionality which in test at room temperature remains at a value approximating the previous overload at blueness.

Metal which is imperfectly elastic at room temperature because of previous overstrain at blue heat, 295° C (565° F), regains its elasticity after rest at room temperature. Steel subjected to overstrain at 465° C (870° F) behaves similarly, in so far as an increase above its original limit of proportionality is concerned. It is not quite clear from the several tests made if the immediate effect is to destroy the elastic properties, but such is probably the case.

Rosenhain (45) reported in some cases at least the hardening of steel by plastic strain was unidirectional, and that a piece of steel which had attained an apparently raised proportional limit as a result of tensile overstrain was really not hardened in every way, for, if tested in compression, it was found that for stresses of that kind the apparent proportional limit had been lowered, so that the total range of elasticity from the limit of compression to that in tension had not been materially altered.

In the search for differences in deformational characteristics with rise in temperature samples of marine boiler plate were subjected to stretching at several temperatures beyond the limit of proportionality and then tested in compression. The effect of such tensional overstrain at room temperature, blue heat and about 465° C (870° F) is a lowering of the limit of proportionality in compression at room temperature. When the steel is allowed to rest, the samples stretched at blue heat or below show a gradual decrease with time of the compressive limit of proportionality which, when taken in conjunction with the rise in this factor in tension, indicates that the range of elasticity is not altered but merely shifted. Steel similarly stretched at 465° C (870° F) behaves differently, however, for with increase in time of rest the compressive limit of proportionality rises until it approximates its original value, which in the cases shown in Figure 22 is reached after 71 hours. No interpretation of this latter effect can be attempted pending investigation of the effect of the magnitude of the tensional overstrain. There are, of course, many other questions which arise in connection with this subject which, as indicated heretofore, lead into a wide field for research but are not considered within the scope of this investigation.

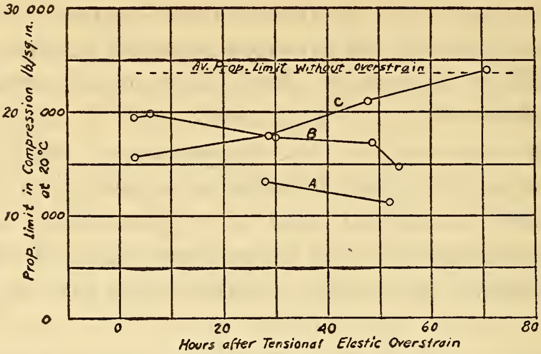


FIG. 22.—*Effect of time at room temperature on compressive proportional limit of marine boiler plate previously subjected to tensional elastic overstrain at various temperatures*

	Stressed in tension	
	Lb./in.^{2}	At °C
A	45 000	20
B	45 000	295
C	30 000	563

Size of compression samples: ¾ inch diameter, 1½ inches long. Gage length of 1 inch used.

IV. EFFECT OF RATE OF LOADING ON THE TENSILE PROPERTIES OF STEEL AT VARIOUS TEMPERATURES

Whether or not steel is susceptible to variations in rate of loading in those ranges of temperatures including superheater and boiler operation, crude oil distillation, nitrogen fixation, etc., is of decided interest both from practical and theoretical standpoints, especially as there are comparatively little definite data available in the literature.

H. H. Campbell (47) reported the tensile properties of structural steel obtained under pulling speeds of 0.07 to 4.5 inches per minute. Both the yield point and tensile strength were shown to increase with rate of loading while the elongation and reduction of area remained practically constant. The fact that the last two factors which are independent of the accuracy of beam balance were not variable gives ground for thought concerning the causes for the susceptibility of strength and yield point to speed changes. When high pulling speeds are used, it becomes increasingly difficult for the operator properly to balance the beam of the testing machine, and the tendency toward "overbalancing" often results in high values.

A committee of the American Society for Testing Materials (46) has shown that the tensile properties of steels at room temperature are independent of the rate of extension, at least within limits of commercial practice or covered by speeds of from 1 to 6 inches per minute.

Little exact information is available relative to effects of rate variations in application of stress at elevated temperatures. Hopkinson and Rogers (18) reported that as the temperature rose the stress-strain relations in steel underwent remarkable changes, which might best be expressed by saying that the variously called "time effect," or "elastische nachwirkung," or "creeping," increased greatly with temperature. While such effects might be detected at ordinary temperatures, they attained a different order of magnitude at red heat (600° C).

The effect of "creeping" was found to make the determination of Young's Modulus a matter of some uncertainty, for the extension of a bar stressed at 600° C varied 15 per cent or more, depending upon the time of application of the load. For very short applications of the order of one or two seconds the strain produced approached a definite limiting value which, if used in determination of the modulus, made it independent of the manner of loading and a physical constant.

J. E. Howard (8) reported that the "rate of speed of testing which might modify the results somewhat with ductile material at atmospheric temperature had a very decided influence upon the apparent tenacity at high temperature." Steel containing 0.81 per cent carbon was tested at the adopted speed of the series (5 to 10 minutes for rupture) and also under rapidly applied stresses (in which case the time employed to reach the maximum stress was from 2 to 8 seconds). Nearly the same strength was displayed whether slowly or rapidly fractured at temperatures below about 315° C (600° F), this being a comparatively brittle metal at moderate temperatures. Above this temperature the apparent strength of the rapidly fractured specimens largely exceeded the strength of the others. The higher the temperature the wider apart in general were the results. An extreme illustration of this kind was furnished by a specimen tested at 766° C (1412° F) which when ruptured in two seconds showed a tensile strength of 62 000 lbs./in.^{2} as nearly as could be weighed, whereas at ordinary speed of testing a corresponding bar fractured at 33 240 lbs./in.^{2}.

Howard considered that the forces of cohesion tending to prevent rupture in a plane normal or oblique to the direction of the straining force and intermolecular friction developed during the flow of the metal were prominent or controlling elements in the explanation of the behavior of steel under the conditions outlined.

More recently Rosenhain and Humfrey (29) have investigated the strength and fracture of soft steel at temperatures between 600 and 1100° C (1100 and 2000° F). They found mechanical discontinuity in the thermal critical range and an increased tenacity with rising rates of extension in testing small samples in vacuum.

In this investigation both increase in rates of extension over that adopted as standard (about 0.05 inch per minute average extension) and slow loading throughout the elastic range were studied and will be considered in order.

1. RAPID LOADING

(*a*) Apparatus Used—The ordinary method of determining the limit of proportionality at room temperature by measurement of deformation under successive increases in load, which has also been used in this investigation at higher temperatures, probably requires the simplest form of apparatus but is not sufficiently flexible to allow much variation in rate of extension without materially affecting the accuracy of the results obtained, as obviously it is more than difficult to read several continuously moving indicators simultaneously even with a number of observers. The original apparatus for determination of the proportional limit as described in the first part of this report was therefore modified in some essential details, so that instruments indicating stress and strain could together be rapidly and repeatedly photographed by a motion-picture camera. The dials fastened to the frames shown in Figure 5 were turned so that their faces and a large load-indicating disk (Fig. 23) were practically in one plane. This latter was fastened to the uprights of the testing machine and by a system of pulleys connected to the screw operating the rider on the beam. One revolution of the disk, which was calibrated at 50-pound intervals, is equivalent to 42 500-pound load. Heavy white twine treated with resin was used to operate the various pulleys and served very well without noticeable slippage. The purpose of the auxiliary load indicator is to bring the instruments measuring applied stress and resulting strain together in a small field in order that they may be simultaneously photographed and as large an image as possible obtained on the motion-picture film.

For measuring deformation two geared dials with smallest direct reading of 0.001 inch were tried, as they were the only

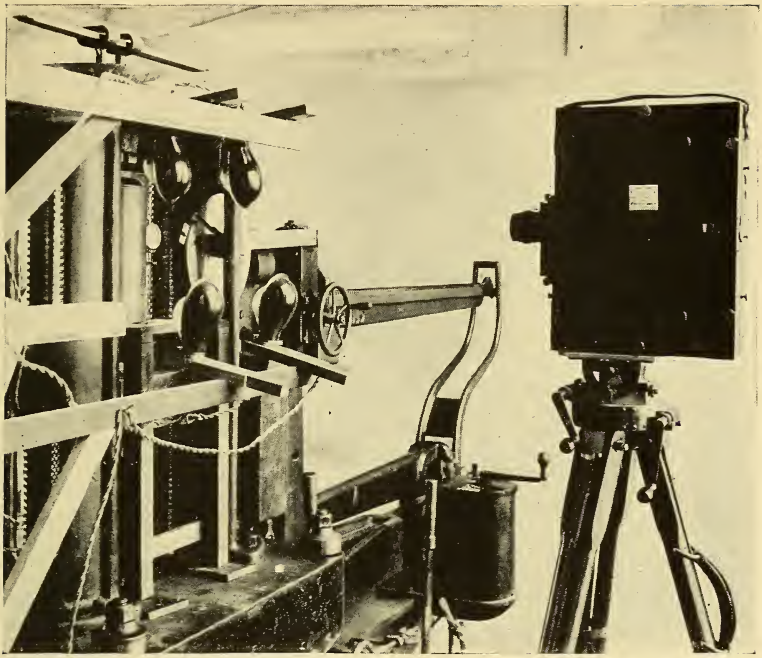


FIG. 23.—*Special apparatus used in determining tensile properties of steels at various temperatures under different rates of extension. (Auxiliary load indicator and motion-picture camera used in determining proportional limit)*

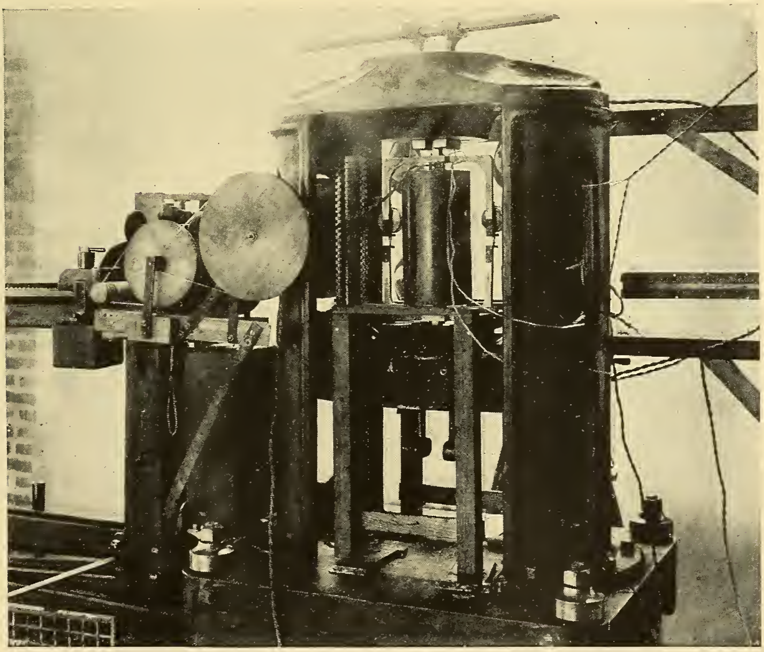


FIG. 24.—*Special apparatus used in determining tensile properties of steels at various temperatures under different rates of extension. (Shows method used in operating auxiliary load indicator)*

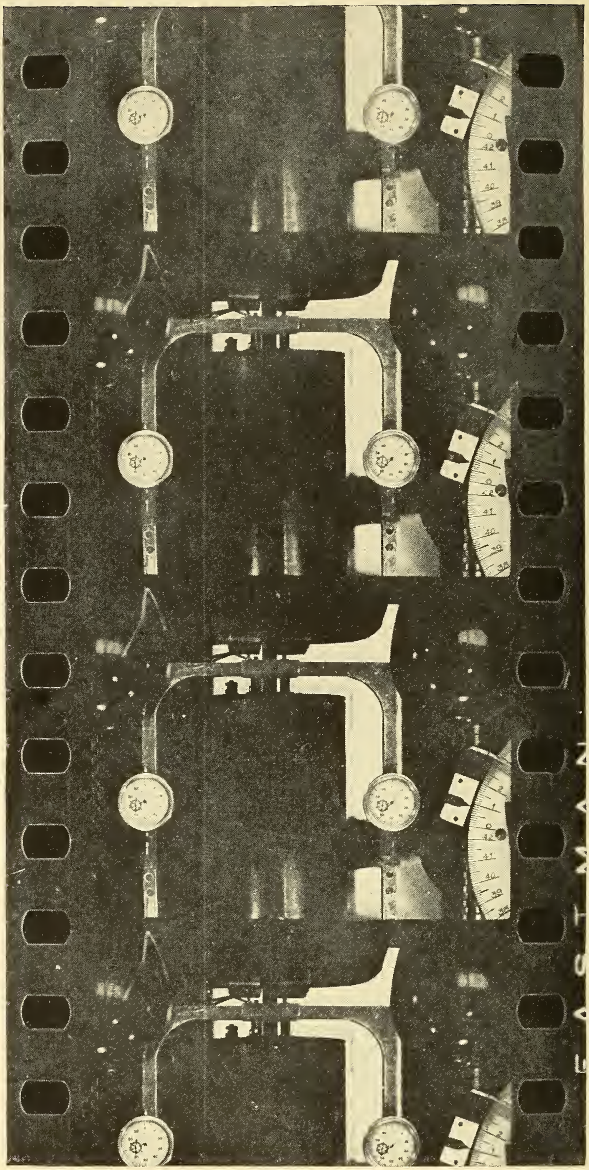
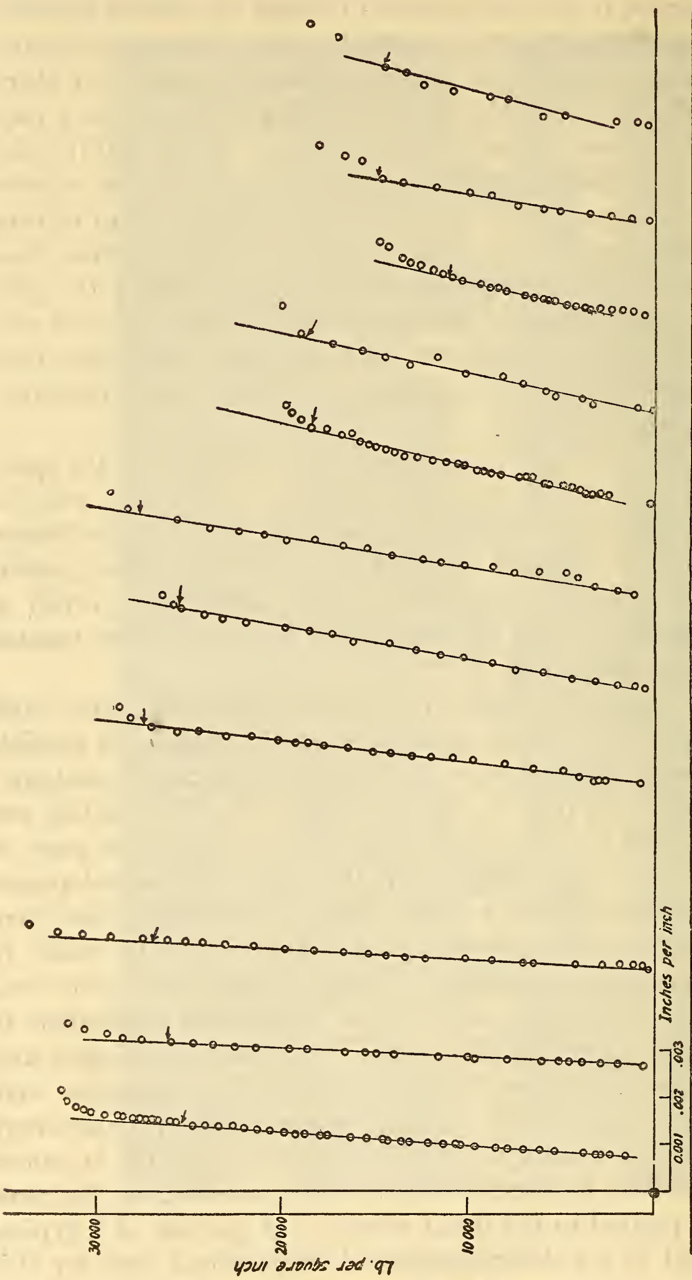


FIG. 25.—*Enlargement of portion of film obtained with apparatus shown in figures 23 and 24*

type available but, owing to the relatively small distortion obtained at room and slightly elevated temperatures with moderate load increments, it was not possible to obtain the desired accuracy in strain measurements without reading the dials, in projecting the film, to one-tenth of the smallest division. These were therefore discarded in favor of dials reading directly to 0.0001 inch, but these latter instruments proved erratic at times, and it is felt that they were responsible for the greater part of the rejected runs where it was impossible to obtain any stress-strain diagrams from the dial movements. This difficulty can be overcome, however, by the use of a special camera or lenses widening the field, so that dials with smallest direct reading of 0.001 inch, and estimated ten-thousandths can be used and read with ease from larger images on the films or preferably by the use of indicators free from gears.

The frames carrying the dials were firmly attached to the specimen at the 2-inch gage marks by means of two yokes, and the bar was then placed in the testing machine, heated to the desired temperature, and thermal equilibrium established before loading began. The complete assembly of this apparatus, which is shown in Figures 23 and 24, was carried out in the same manner as described in Section II, 2.

Load was next applied at any predetermined rate, and while the beam was at all times kept as nearly in balance as possible by the operator photographs were taken of the three constantly moving dials at the rate of about one a second. The loading was continuous until the bar was broken and no changes in gears or motor speed were made throughout the test. After development the film was projected on a screen where images of the dials were enlarged and as much time as was desired might be taken in obtaining individual readings. A simple projection device was used, and with this equipment it was found most convenient to obtain readings at a magnification of four times the original size. Under the conditions outlined above more photographs were obtained than required, but these served as a check on the accuracy of beam balance, which if not closely maintained resulted in serious deflections readily detected in the resulting stress-strain diagrams which were plotted in the usual manner. A portion of a typical film obtained in the determination of proportional limit by this method is shown enlarged in Figure 25, while a summary of results of tests made at various temperatures under different rates of extension is given in Figures 26 and 27.



Temperature, °C	Room	Room	Room	156	156	156	295	295	463	463	463
Extension Inch/min	0.5	0.8	1.6	0.5	0.8	1.6	0.5	1.6	0.5	0.8	1.6
No.	W-11	L-3	K-19	K-8	L-16	L-5	K-11	L-24	K-10	L-15	L-21

Fig. 26.—*Stress-strain diagrams obtained under different rates of extension at various temperatures*

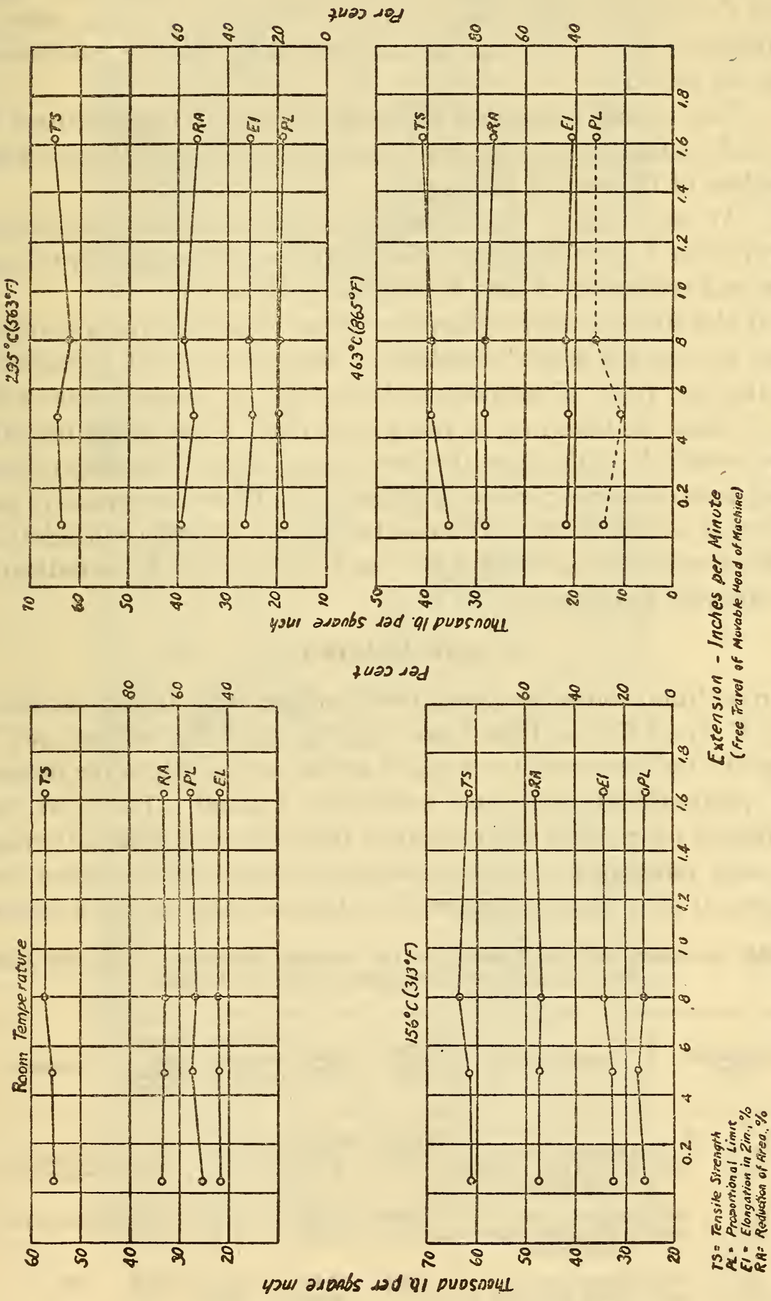


FIG. 27.—*Effect of rate of loading on the tensile properties of firebox boiler plate at various temperatures*

(*b*) Experimental Results.—Based on tests made at room temperature, about 155° C (315° F), in the blue-heat range, 295° C (565° F), and at 465° C (870° F) under varying rates of extension up to 1.6 inches per minute, the following conclusions may be drawn:

1. The tensile properties of fire-box steel at temperatures up to and including the blue-heat range, 295° C (565° F), are independent of the rate of loading.

2. At 465° C (870° F) the tensile strength appears to increase slowly with rate of loading, while ductility as measured by elongation and reduction of area is practically constant.

At this highest temperature the stress-strain diagrams obtained were not, on the whole, satisfactory, largely due in all probability to the low limit of proportionality which is reached soon after the "slack" is taken up in the geared dials, these being the only type available at the time the tests were made. The proportional limit rate of loading curve in Figure 27 is therefore tentative and shown as a dotted line. There is, however, a difference in behavior of the metal at or below blue heat and 465° C (870° F) as indicated by strength variations.

2. SLOW LOADING

In addition to the foregoing tests samples were broken at about 155° C (315° F), at blue heat, 295° C (565° F), and at 465° C (870° F) by increasing the applied stress very slowly while passing the proportional limit and somewhat beyond. The load was increased 100 pounds at five-minute intervals over a definite range at each temperature, and subsequently the test specimen was broken at slow speed comparable to that adopted as the standard

TABLE 9.—Effect of Slow Loading on the Tensile Properties of Fire-Box Boiler Plate at Different Temperatures (Series 1 Steel)

Temperature of test		Rate of loading	Proportional limit	Tensile strength	Percentage elongation in 2 inches	Percentage reduction of area	Remarks
° C	° F		Lbs./in.^{2}	Lbs./in.^{2}			
156	313	Adopted standard[1]	26 600	58 100	24.9	49.3	Average 3 tests
156	313	6⅔ hours from 22 000 to 47 000 lbs./in.^{2}	. . . .	64 350	22.8	45.9	Average 2 tests
295	563	Adopted standard[1]	14 330	66 430	25.9	53.1	Average 3 tests
295	563	3½ hours from 9000 to 20 000 lbs./in.^{2}	. . . .	60 000	36.0	59.2	
463	865	Adopted standard[1]	13 200	47 460	33.6	68.5	Do.
463	865	6 hours from 9000 to 30 000 lbs./in.^{2}	. . . .	33 600	42.0	78.4	

[1] Adopted standard averages about 0.05 inch per minute extension.

FIG. 28.—*Microphotographs of the fractures of hot-rolled fire box boiler plate at various temperatures.* × *500*

a, Specimen A8; broken in tension at room temperature. *b*, Specimen A22; broken in tension at blue-heat (295° C). *c*, Specimen A5; broken in tension at 465° C. Etched with 2 per cent nitric acid in alcohol

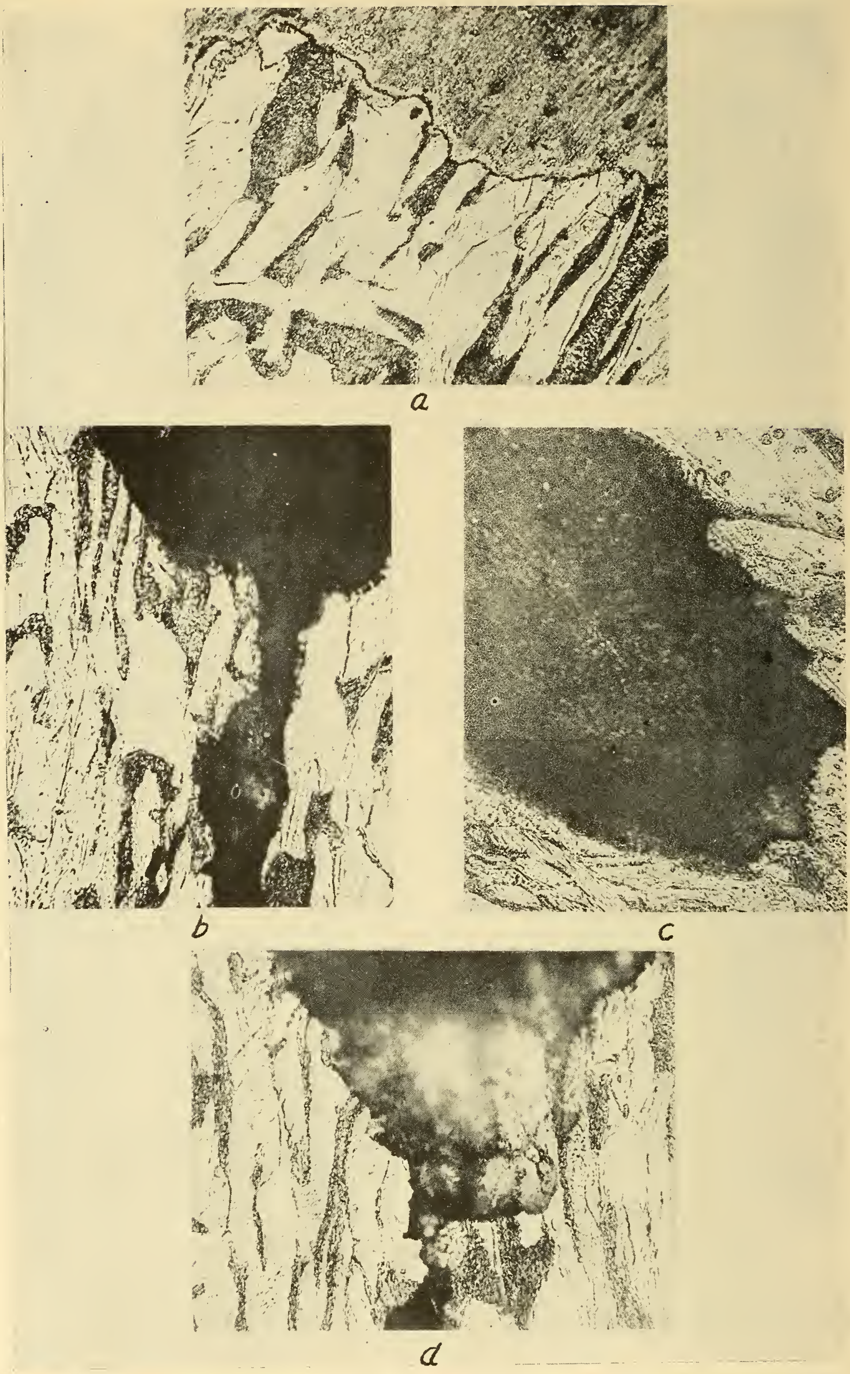


FIG. 29.—*Microphotographs of the fractures of cold-rolled marine boiler plate at various temperatures.* × *500*

a, Specimen F1; broken in tension at room temperature. *b*, Specimen F9–A; broken in tension at blue-heat (295° C). *c*, Specimen F9–B; broken in tension at blue-heat (295° C). *d*, Specimen F14; broken in tension at 465° C. Etched with 2 per cent nitric acid in alcohol

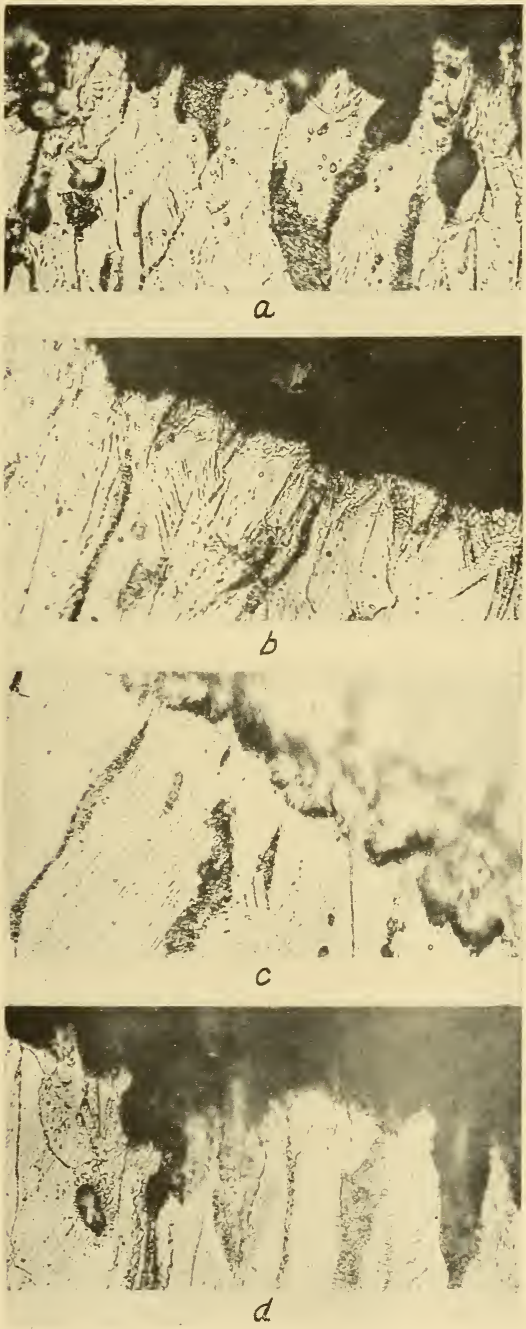


FIG. 30.—*Microphotographs of the fractures of blue-rolled fire box boiler plate at various temperatures.* × 500

a, Specimen X7–1A; broken in tension at room temperature. *b*, Specimen X7–1B; broken in tension at room temperature. *c*, Specimen X7–4; broken in tension at blue-heat (295° C). *d*, Specimen X7–7; broken in tension at 465° C. Etched with 2 per cent nitric acid in alcohol

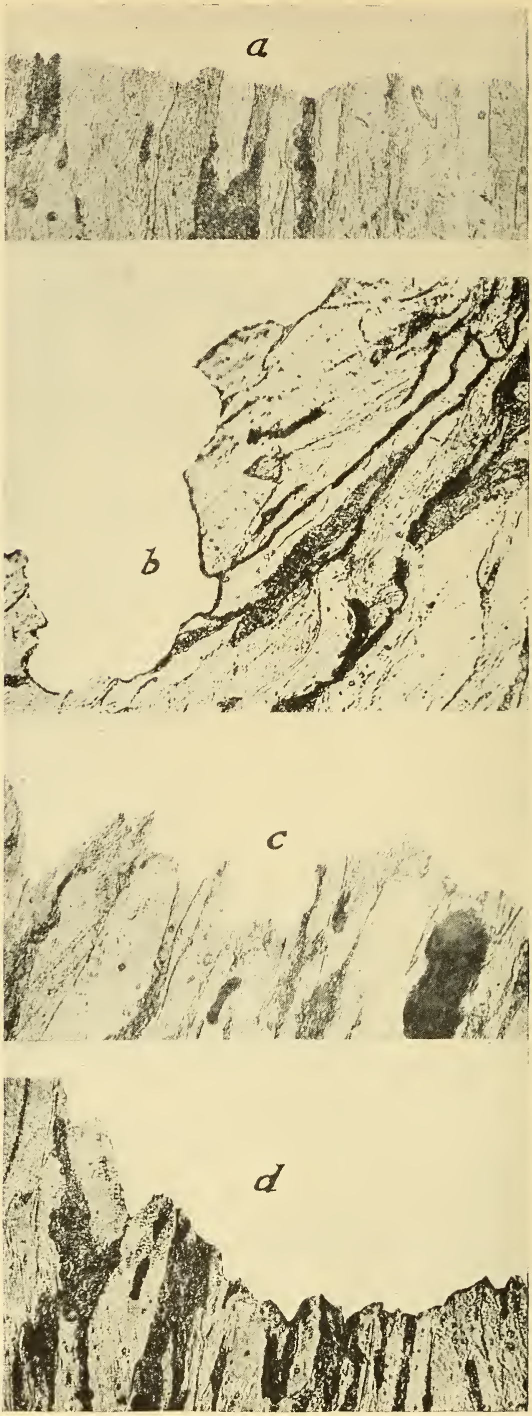


FIG. 31.—*Microphotographs of the fractures of fire box boiler plate obtained at 465° C. under different rates of loading.* × *500*

a, Specimen K24; broken under standard rate of loading adopted. (About 0.05 inch per minute free pulling speed of head of testing machine.) *b*, Specimen K7-A; broken at 0.5 inch per minute. (Free travel of head of testing machine.) *c*, Specimen K7-B; broken at 0.5 inch per minute. (Free travel of head of testing machine.) *d*, Specimen L20 broken at 1.6 inch per minute. (Free travel of head of testing machine.) Etched with 2 per cent nitric acid in alcohol throughout the investigation. Such slow loading raises the strength and decreases ductility at 155° C (315° F), but the steel exhibits decreased strength and higher ductility when so tested at blue heat, 295° C (565° F), or above than when broken in the ordinary manner (Table 9).

V. MICROSCOPIC EXAMINATION

Fractures of steel broken at various temperatures at different rates of loading and under varying conditions of mechanical work were examined under the microscope and were found to be generally transcrystalline. Minor differences appear under certain conditions, such as, for example, the apparent tendency for the fracture to follow more deeply along the grain boundaries and particularly at the junctions of ferrite and pearlite when the steel is broken under very slowly increasing stress. In general, no marked differences in behavior were observed, as will be evident from microphotographs shown in Figures 28 to 31, inclusive.

VI. DISCUSSION AND SUMMARY

1. AMORPHOUS METAL THEORY

Before concluding this report some of the observed phenomena will be briefly examined in the light of the amorphous theory of metals by which deformation is considered to take place along planes of easy slip in crystals. Along these gliding surfaces amorphous metal is formed which is likewise assumed to have temporary mobility and is followed by "setting" to produce extremely hard and rigid layers. This temporary mobility has been conveniently used in explaining the immediate loss of elasticity of overstrained metal and the subsequent elevation of the elastic limit with time.

At the melting point the cohesion of the amorphous phase is zero and that of the crystalline a finite value. As the temperature is lowered the cohesion of the former increases more rapidly than that of the latter until at some temperature (called the equicohesive temperature) the cohesion-temperature curve of the amorphous phase intersects that of the crystalline.

The difficulties of explaining certain observed phenomena and the basis for assuming a low-temperature allotrope in iron have recently been very completely stated by Jeffries (33) (34), but while such questions as why metals other than iron show no "blue-heat" range can not be satisfactorily answered by the amorphous metal theory or by differences in cohesion alone, the former is probably the most widely used and the hypothesis most generally adhered to.

The differences in behavior of the limit of proportionality in compression with time in steel previously subjected to tensile overstrain above and at blue heat (respectively, 465 and 295° C) are not easily explained. The assumption of temporary mobility of the amorphous phase which has been used in explaining apparent loss of elasticity of iron overstrained at room temperature serves likewise for similar effects obtained at room temperature for steel subjected to overstrain at high temperatures. It is not clear why the unidirectionality of elastic recovery at room temperature, and in these tests found at blue heat, should be upset at the highest temperature, 465° C (870° F), though it is suggested that the lowered cohesion of the crystalline phase permits more nearly indiscriminate slip along crystallographic planes instead of those most nearly normal to the straining force, so that after setting of the amorphous phase and coincident recovery of elasticity hardening is produced in all directions instead of along certain ones as found at blue heat and temperatures below. Such indiscriminate slip might, of course, be favored under certain conditions of overstrain at blue heat and temperatures below, but, as previously indicated, insufficient data have been obtained to allow definite statements. That the hardening produced by blue and cold rolling is largely in the direction parallel to the axis of deformation is shown by the relatively small increases in strength obtained from such work on transverse samples.

It is also conceivable that block movement of masses of atoms may break up into movements of smaller blocks if sufficient time is allowed. In other words, when a definite load in excess of the limit of proportionality is applied to steel at about 465° C (870° F), deformation which at first takes place in block movement along planes of easy slip proceeds by further movement in these original blocks of smaller units resulting in creeping observed by Hopkinson and Rogers (18), Howard (8), and others. This crystalline fragmentation would result in a general weakening of the cross section as the amorphous metal formed is weakened by the high temperature. As such an effect requires time and relatively large deformation, the slower the loading the lower the strength expected.

At 155° C (315° F) the cohesion of the amorphous phase is considerably greater than that of the crystalline and, in slow loading, time may be given for the "setting" of the amorphous metal formed. Hardening is therefore produced and results in higher strength. At both ordinary and rapid rates of loading insufficient time is allowed for this setting and no marked changes in strength are observed.

At blue heat, 295° C (565° F), the cohesion of the amorphous phase is less than at 155° C (315° F) but greater than at 465° C (870° F), which makes the behavior of steel in this range apparently anomalous, for in the range of maximum strength slow loading results in a decrease in this factor.

While the amorphous metal theory is at this time the most widely used, it is not wholly adequate but is probably the best working hypothesis. Our knowledge of the fundamentals connected with changes in iron and steel below the thermal critical ranges will probably not be greatly enhanced by further determinations of the mechanical properties alone. Such other methods as used by the Braggs [8] and others, while perhaps offering serious experimental difficulties, will without doubt more quickly lead to more truthful conceptions and explanations of observed phenomena.

2. SUMMARY

1. An apparatus has been devised for studying the changes in tensile properties of metals at various temperatures, including determination of the limit of proportionality. A modified form of this equipment has been devised for studying the effects of variation in rapid rates of stress application on these properties, and this has been described.

2. The proportional limit of low-carbon steel determined on longitudinal specimens does not decrease directly with first rise in temperature above that of the room, as has been so often reported, but is either maintained at about its room temperature value throughout a definite temperature range or increases before a marked drop in its value is observed.

3. Changes in tensile strength and ductility of several grades of boiler plate from about 20 to about 465° C (70 to 870° F) have been determined. The general inflections in curves representing variations in these factors with rise in temperature are the same for longitudinal and tranvserse specimens, and show maximum

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[8] W. H. Bragg and W. L. Bragg, X rays and crystal structure.

strength between 250 and 300° C (480 to 570° F). Maximum ductility occurs in longitudinal tests at 200 to 300° C (390 to 570° F) and in transverse throughout a wider range from 150 to 300° C (300 to 570° F). Above blue heat, 295° C (565° F), there is a marked drop in strength which is accompanied by decided inflections in curves showing elongations and reductions of area, indicative of a change in the character of the metal.

4. The effect of moderate cold-rolling, which raises the elastic properties and to some extent the tensile strength and likewise lowers ductility at room temperature, is, in general, maintained throughout the range 20 to 465° C (70 to 870° F). However, at blue heat the increase in limit of proportionality due to previous cold work is greatly in excess of that observed at room temperature and is accompanied by an increased ratio, cold to hot rolled elongation.

5. If cold-rolled steel is heated for a short time at this temperature (blue heat) and cooled, there results a decided elevation in the limit of proportionality with no material change in tensile strength or lowering of the ductility. This is of practical interest in production of such material as cold-drawn light-wall tubing often manufactured under definite tensile requirements, where "bluing" subsequent to the last cold pass will result in improved tensile properties.

6. The fact that blue-rolling is more effective than the same amount of cold-rolling in raising the strength of low-carbon steel and in decreasing ductility at room temperature has been confirmed. Six and one-quarter per cent reduction in thickness at blue heat produces about the same increase in strength at temperatures up to and including 295° C (565° F) (blue heat) as twice this cold reduction. Above blue heat the strength of the cold rolled steel is slightly in excess of that blue-rolled, though the general shape of the tensile properties temperature curves for both conditions mentioned is the same.

7. Blue work (6.25 per cent reduction in plate thickness) is more effective in raising the limit of proportionality of low-carbon steel at temperatures below the blue-heat range than twice this work in the cold, but at blue heat the increase in this factor is very much greater in the cold-worked metal. At higher temperatures the increase produced by both methods of working is approximately the same.

8. In samples taken transversely the changes in tensile properties throughout the range 20 to 465° C (70 to 870° F) resulting

from cold and likewise blue rolling are small compared to those observed in longitudinal tests. The similarity in the observed changes in tensile properties of low-carbon steel brought about by blue and cold deformation indicates that the character of the effects produced are similar but effected more rapidly at blue heat. While longitudinal and transverse tensile tests do not wholly define the character of the metal, sufficient evidence is presented to show the extreme susceptibility of steel to deformation in the blue-heat range, and for that reason alone such working should be avoided. A marked decrease in ductility results both at room and elevated temperatures. There is, however, little or no evidence to prove that a limited amount of blue work permanently injures the metal, for, as pointed out by Howe (38) and here substantiated by the author, restoration of ductility may be obtained by annealing.

9. A few experiments relating to the effects of tensional elastic overstrain at various temperatures on the tensile properties of low-carbon steel at room temperature, blue heat, and 465° C (870° F) have been carried out.

10. A study of the effects of variations in rate of stress application from the adopted standard estimated at 0.05 inch average extension per minute to 1.6 inch per minute shows the tensile properties of steel to be independent of the rate of loading at temperatures up to and including blue heat. At 465° C (870° F) the tensile strength appears to increase slightly with increased rate of loading without noticeable change in ductility.

11. Slow loading in the range about the proportional limit results in increased strength and decreased ductility at 155° C (315° F) and decreased strength and increased elongation and reduction of area at blue heat 295° C (565° F), and above 465° C (870° F).

12. A brief discussion of the observed effects in the light of the amorphous metal theory has been given.

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