DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 267
[Part of Vol. 18]

EFFECT OF HOT-ROLLING CONDITIONS ON THE PHYSICAL PROPERTIES OF A CARBON STEEL

BY

JOHN R. FREEMAN, Jr., Physicist
A. T. DERRY, Associate Physicist
Bureau of Standards

October 27, 1924

PRICE, 10 CENTS
$1.25 PER VOLUME ON SUBSCRIPTION
Sold only by the Superintendent of Documents, Government Printing Office
Washington, D. C.

WASHINGTON
GOVERNMENT PRINTING OFFICE
1924

EFFECT OF HOT-ROLLING CONDITIONS ON THE PHYSICAL PROPERTIES OF A CARBON STEEL

By J. R. Freeman, Jr., and A. T. Derry

ABSTRACT

A study has been made of the following five factors of rolling conditions, namely, initial temperature of rolling, finishing temperature of rolling, total reduction, pass reduction, and roll speed on the following physical properties of a medium carbon steel: Tensile properties (ultimate strength, yield point, proportional limit, elongation, reduction of area), resistance to impact, hardness, microstructure, and density. The steel was rolled in one direction only in order to study the effect of unidirectional rolling on the properties of the steel in the direction longitudinal and transverse to that of rolling.

The results obtained indicate that the total reduction and finishing temperature are the most important factors in rolling. A change in these conditions has a greater influence on the mechanical properties of the steel than either of the other three factors studied, which were found to have very little influence. An increase in total reduction decreases the ultimate strength and increases the yield point, ductility, and impact resistance. A slightly lower ultimate strength, but greater yield point, ductility, and impact resistance were obtained with a finishing temperature of 700° C. as compared with a finishing temperature of 1,000° C. Unidirectional rolling causes a slight difference in the mechanical properties of the steel between the longitudinal and transverse directions; the properties in the transverse direction are, in general, inferior. Normalizing the rolled plate tends to eliminate all differences produced by the different rolling conditions.

The density of the steel is the same in the cast and rolled conditions and is not affected by rolling conditions.

CONTENTS

I. INTRODUCTION

The greater part of all steel manufactured is subjected to a large amount of mechanical work by rolling, forging, or drawing. This working of the metal serves a two-fold purpose, the securing of the desired finish form, such as bars or plates, and the breaking up of the coarse, weak crystalline structure of the cast ingot into a finer-grained structure which greatly improves the mechanical properties of steel.

Trinks,[1] Meringer,[2] and others have studied the theories of rolling, but very few exact data are available in the literature on the rolling of steel relating to the effect of rolling conditions on the physical properties of the metal. Burgess[3] has studied the finishing temperatures of rolling and its relation to the properties of steel rails. Charpy[4] has investigated the subject with particular reference to the difference in the longitudinal and transverse mechanical properties of the steel as affected by the amount of work by forging put on the metal, and in the discussion of his paper much evidence is presented. However, no detailed systematic studies of the rolling conditions, such as initial and finishing temperatures of rolling, pass reductions and speed of rolling in conjunction with the total reductions, seem available. It was, therefore, the purpose of the investigation presented in this paper to study the effect of the different variables involved in rolling practice upon the physical properties of the steel itself. The following five variables, therefore, were selected for study: Initial temperature of rolling, finishing temperature of rolling, total reduction, pass reduction, and rolling speed.

II. PROGRAM OF INVESTIGATION

1. MATERIAL USED

(*a*) Manufacture and Chemical Composition.—In order to eliminate in so far as possible all differences in physical properties that might be due to chemical inhomogeneity a special heat of electric-furnace steel was cast in a commercial plant for this investigation. The steel was all poured from the same heat into ingots 6 inches square at the top by 5 inches square at the bottom which

[1] The present status of the rolling mill, W. S. Trinks., Proc. Eng. Soc. of West Pa., 36, p. 275; 1920–21.

[2] Les Theories du Laminage a Chaud, P. Meringer, Rev. Universelle des Mines, 1, 1919, p. 1; 2, pp. 133–209.

[3] Observations on Finishing Temperatures and Properties of Rails, Burgess, Crowe, and Rawdon, B. S. Tech. Paper No. 38

[4] The influence of hot deformation on the qualities of steel, George Charpy, Journ. Iron and Steel Institute, 98, 1918, p. 7.

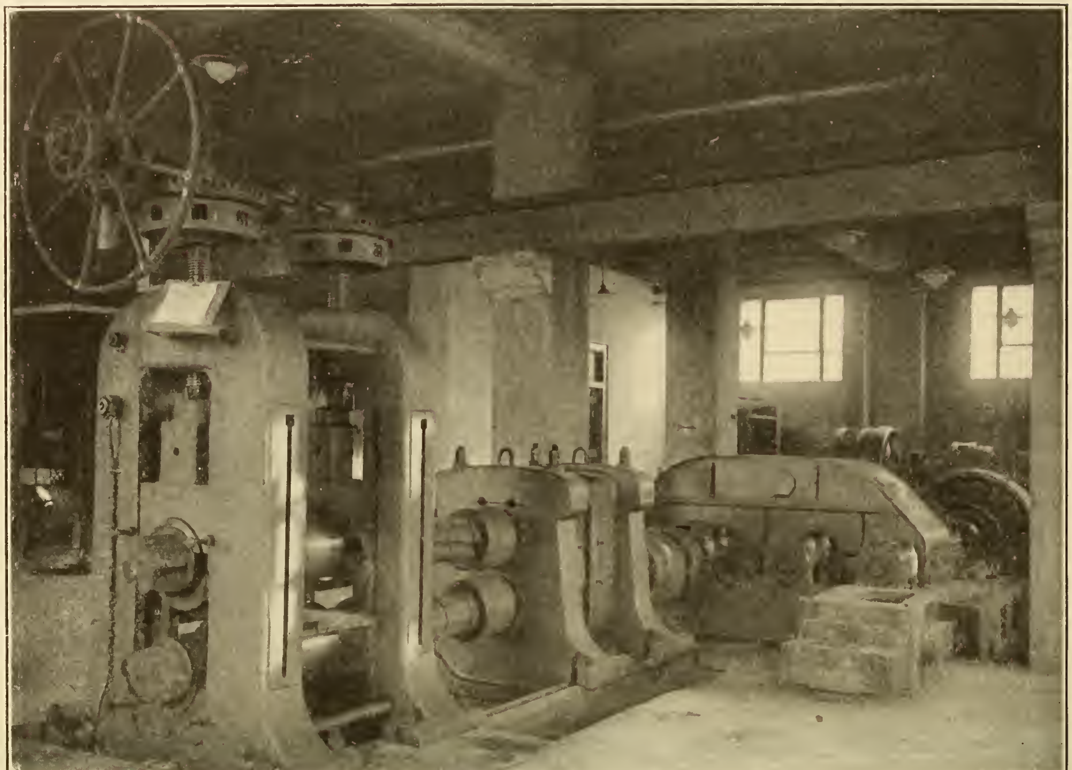

Fig. 1.—*Rolling mill*

were approximately 30 inches long exclusive of the hot tops. The manufacturer's heat analysis was: Carbon, 0.46 per cent; manganese, 0.66 per cent; phosphorus, 0.018 per cent; sulphur, 0.020 per cent; and silicon, 0.23 per cent. The rounded bottoms and the hot tops were removed from 34 of the ingots and drillings taken from the center of the cross section of each cropping, both top and bottom, for analysis.[5] Two of the ingots were also analyzed at distances of 6 inches along their axes. Out of a total of 78 analyses thus secured, the maximum carbon content was 0.54 per cent and the minimum 0.42 per cent, a maximum difference of 0.12 per cent carbon. The maximum difference in any one ingot was between 0.52 per cent at top and 0.43 per cent at bottom, or 0.09 per cent. For this investigation ingots were selected which showed but slight segregation, only one of the 11 ingots used having a variation of over 0.06 per cent carbon. Analysis for the detection of alloying elements showed a total of 0.13 per cent for all elements, distributed as follows: Copper, 0.096 per cent; chromium, 0.025 per cent; nickel, less than 0.01 per cent; and vanadium and molybdenum, not detected. The average manganese content for all ingots was 0.71 per cent, with a minimum of 0.65 per cent and a maximum of 0.75 per cent. The average of the sulphur content was 0.016 per cent, with a maximum of 0.021 per cent and a minimum of 0.014 per cent.

(*b*) THERMAL ANALYSIS.—The thermal critical points of a sample of the steel were determined by the methods in use at the Bureau of Standards.[6] The inverse-rate curve indicated the Ac_1 transformation to take place at 730° C. and the Ar_1 at 670° C.

2. EQUIPMENT

The rolling mill used was a two-high 16-inch plate mill, a photograph of which is given in Figure 1. This mill is driven by a 150 horsepower, 230 volt direct-current motor and is nonreversing. The motor speed may be varied from 250 to 1,000 revolutions a minute, which with the reduction gearing gives a roll speed of from 20 to 80 revolutions a minute. The maximum opening of the rolls is approximately 4 inches. A gas fired semimuffle furnace was used for heating the steel. The furnace temperature was determined by suitable thermocouple and potentiometer equipment.

---

[5] All chemical analyses were made by H. A. Bright, chemist, Bureau of Standards.

[6] A modified Rosenhain Furnace for Thermal Analysis, Scott and Freeman, B. S. Sci. Paper No. 348.

3. VARIABLES IN ROLLING PRACTICE AND METHODS OF MEASUREMENT

The variables in rolling practice studied were as previously stated in the introduction. The method employed to determine the individual effects of any of the five variables was the usual one of holding all of the variables constant except one, and changing that one a predetermined and definite amount during a series of rollings. In this manner a separate series of plates was rolled for each of the five variables of rolling practice studied.

The values used for these variables are given in Table 1, and the method of determining the effect of any one of the variables may be illustrated as follows:

A working "standard condition" was adopted, namely, initial temperature, 1,130° C.; finishing temperature, 850° C.; pass reduction, 5 per cent; total reduction, 5 to 1; and peripheral roll speed, 125 feet per minute.

A series of plates was then rolled with all conditions "standard" except the initial temperature, the series of temperatures given in Table 1 being used. Then a similar series was rolled with all conditions "standard" except the finishing temperature, which varied over the temperature range stated in Table 1. Similarly, three further series of rollings were made in which the pass reduction, the total reduction, and roll speed, respectively, were varied, using the values given in Table 1.

TABLE 1.—Rolling Conditions Originally Outlined

Initial temperature		Finishing temperature		Pass reduction	Total reduction	Peripheral roll speed
° C.	° F.	° C.	° F.	Per cent		Ft./min.
1,200	2,190	1,000	1,830	12	7 to 1	250
[1] 1,130	2,065	900	1,650	8	[1] 5 to 1	175
1,060	1,940	[1] 850	1,560	[1] 5	3.5 to 1	[1] 125
1,000	1,830	750	1,380	3	2 to 1	85
950	1,740	700	1,290	2	1.3 to 1	----------
900	1,650	650	1,200	----------	----------	----------

[1] "Standard" values.

In carrying out the above tests originally outlined in the program, results were obtained which indicated the desirability of rolling other slabs under different conditions from those given in Table 1. These further conditions of rolling are given in Table 2.

TABLE 2.—Further Rolling Conditions

Combination number	Initial temperature		Finishing temperature		Pass reduction	Total reduction	Peripheral roll speed
	° C.	° F.	°C.	° F.	Per cent		Ft./min.
1 [1]	1,130	2,065					
2	1,130	2,065	850	1,560	5	1.05:1	125
3	1,130	2,065	850	1,560	2	1.3 :1	125
4	1,130	2,065	1,000	1,830	2	1.3 :1	125
5	1,130	2,065	700	1,290	5	3.5 :1	125
6	1,130	2,065	700	1,290	12	3.5 :1	125

[1] As cast, heated but not rolled.

On account of the limitation that the maximum opening obtainable between the rolls was approximately 4 inches, the slabs for rolling were cut transversely from the ingots so that the rolling was perpendicular to the longitudinal axis of the ingot. The initial thickness of slab rolled under the so-called standard condition was 3 inches. Although the usual direction of rolling in commercial practice is parallel to the longitudinal axis of the ingot, all the results in this investigation are comparable to each other, and, therefore, indicate the influence of the different variables.

All the slabs were rolled in one direction only; that is, none of the plates were cross rolled. This was done in order to study the influence of unidirectional rolling on the relative longitudinal and transverse properties of the steel. Two slabs were rolled for each set of conditions, and in order that they should be as nearly identical as possible each pair of slabs was cut adjacently from the same ingot.

The initial temperature was determined by means of a chromel-alumel thermocouple placed in the heating furnace adjacent to the metal to be rolled and the finishing temperature was observed by means of a Leeds and Northrup optical pyrometer, the observations being made on the slabs as they came from the rolls at the back of the mill. In making this temperature measurement time was always allowed to permit the temperature of the surface of the plate, which had been chilled by contact with the rolls, to become uniform and representative of the true temperature of the slab.

In many instances it was necessary to reheat the slab before the desired total reduction had been obtained. In such cases it was returned to the furnace, which had been maintained at the initial temperature of rolling, allowed to come to the initial temperature, and then further rolled. Care was always taken that the slab should not be rolled at any time below the desired finishing temperature, and that the final passes should be near and at the desired finishing temperature.

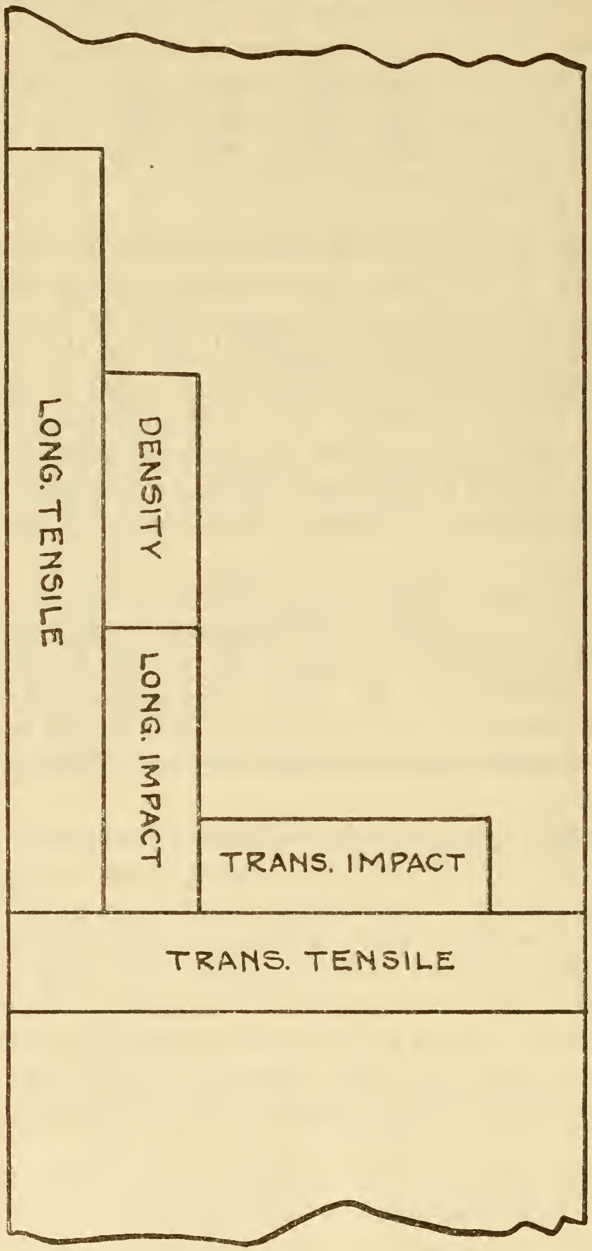

FIG. 2.—*Position of test coupons in rolled plate*

The pass reduction was easily controlled by the setting of the rolls between the passes and the total reduction was controlled by starting with slabs of different thickness and rolling all of them into plates of the uniform thickness of 0.6 of an inch. This uniform thickness of finished plate was adopted in order to avoid in so far as possible any difference in the rate of cooling of the plates. Such a variable would exist if a uniform original thickness were adopted. The ratios of total reduction and the corresponding original thickness of slabs rolled were as follows:

Ratio	1.3 to 1	2 to 1	3.5 to 1	5 to 1	7 to 1
Original thickness, inches	0.78	1.2	2.1	3.0	4.2

As of possible interest, the energy consumed during each pass of a slab through the rolls was measured by a recording wattmeter connected in the motor circuit.

4. LIST OF PROPERTIES DETERMINED AND METHODS OF TEST

The following properties of the rolled plates were determined: Longitudinal and transverse tensile properties, which included

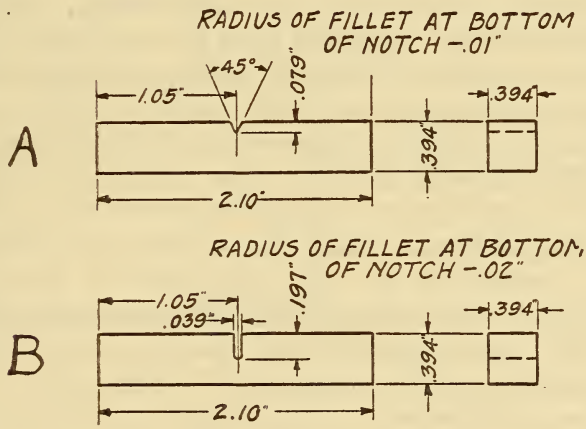

FIG. 3.—*Types of impact specimens used*

A. V-notch
B. Mesnager notch

determinations of the proportional limit, yield point, ultimate strength, elongation, and reduction of area; impact resistance; microstructure; density; Brinell and scleroscope hardness.

In some cases the rolled material was normalized and the same properties determined in order to compare the characteristics of the material "as rolled" and after normalizing.

The positions in the plates from which the test specimens were cut are indicated in Figure 2. One longitudinal and one transverse test specimen were taken from each plate.

The tensile tests were made on specimens having a reduced section of 0.4-inch diameter and 2-inch gauge length in an Amsler tensile testing machine of the hydraulic type of 50,000 pounds capacity. Data for the stress-strain curves, taken on all specimens, were obtained with a Ewing extensometer. The limits of proportionality and yield points were obtained from these curves in the usual manner.

The impact tests were made on a Charpy type impact testing machine. Two types of impact specimens were machined and tested for each condition of rolling, as illustrated in Figure 3.

The Brinell hardness was determined under the standard conditions of a 3,000 kg load applied for 30 seconds, using a 10 mm diameter ball. A "recording" scleroscope was used for the determination of scleroscope hardness.

III. PROPERTIES OF STEEL "AS CAST"

As a basis for comparison of the effect of the rolling on the properties of the steel a series of tests were made on the steel in the "as cast" condition. Also, in order to determine the effect of the heating preparatory to rolling, plates were cut to the uniform thickness of 0.6 inch, which was the final thickness adopted for the rolled material, heated to the "standard" rolling temperature of 1,130° C. held at temperature for the same length of time used preparatory to rolling, but cooled in air without rolling (Table 2, combination No. 1). The results of these tests are given in Table 4, the material having of course a reduction ratio of 1:1. The values obtained from the tests of the "as cast" material heated to rolling temperature, but not rolled, to permit of easy comparison between cast and rolled material, are incorporated in Figure 4, showing the effect of total reduction.

IV. INFLUENCE OF THE ROLLING PRACTICE ON THE MECHANICAL PROPERTIES

1. TESTS OF LONGITUDINAL SPECIMENS

The averages of the results obtained from the longitudinal tensile tests and from the longitudinal impact tests, with both types of notches, are summarized in the five sets of curves given in Figures 4, 5, 6, 7, and 8; each value plotted representing the average of two or more tests, one from each of at least two plates rolled under the conditions stated. In each set or family of curves the independent variable is plotted as the abscissa and the mechanical properties, being the dependent variables, as ordinates.

The values obtained for the limit of proportionality indicated that rolling conditions have very little if any influence on this

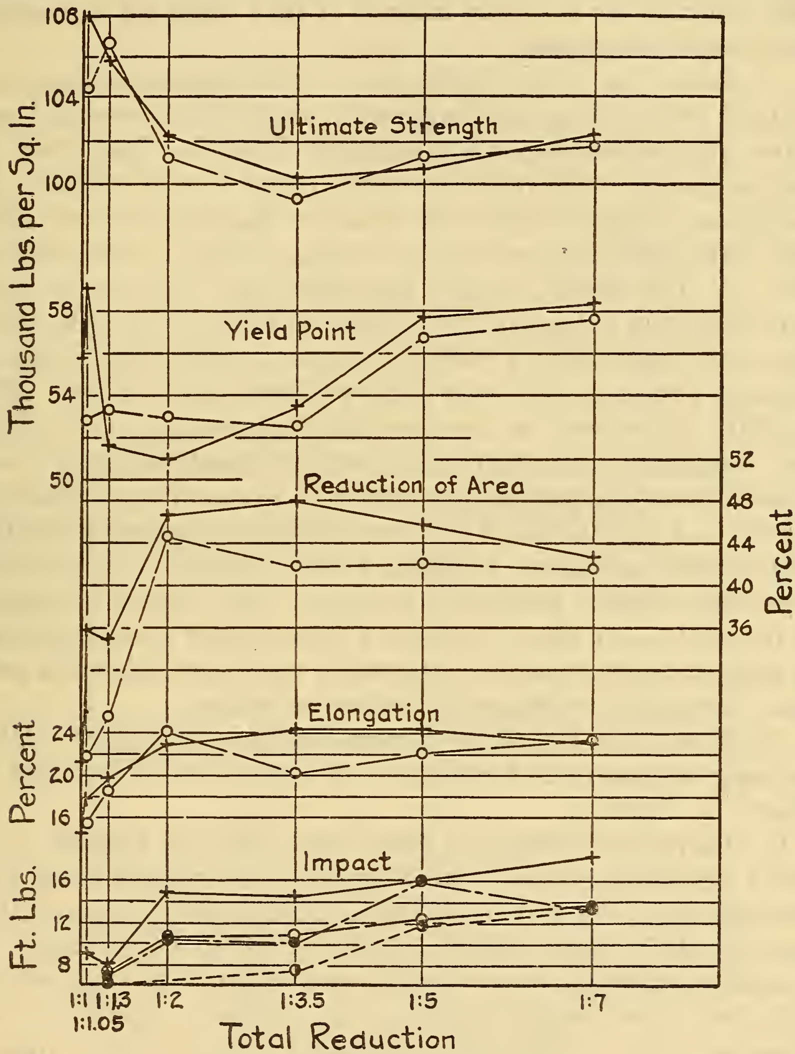

FIG. 4.—*Effect of total reduction*

○———— longitudinal specimens	} Tensile tests and Type A notch	
+— — — transverse specimens		
●—— - —— longitudinal specimens	} Type B notch	
◐— — — — transverse specimens		

property of the steel, any such influence being within the limits of experimental error of the determination.

The yield points as plotted on the curves were taken as that stress where yielding without increase in load was first noticeable with the Ewing extensometer. The loading of the specimen in the tensile-testing machine was always increased in increments of 250 pounds or approximately 2,000 lbs./in.^{2} with the 0.40-inch diameter specimen used. The load on the specimen was always held constant for a certain interval of time while the extensometer reading was noted.

(*a*) Effect of Total Reduction.—The effects of the amount of total reduction on the longitudinal mechanical properties are shown by the continuous line curves in Figure 4. The effect of the mechanical work received by the metal is very evident. A maximum tensile strength and minimum ductility are shown by the metal which had received no working (Table 2, combination No. 1). The tensile strength and yield point decrease at first with increasing reduction, but increase on further total reduction; the yield point shows a marked increase, whereas the ultimate strength attains a value only slightly above the minimum. The ductility of the steel as measured by the reduction of area and the elongation is markedly increased by a small amount of mechanical work and reaches a maximum at a ratio of approximately 3.5 to 1. The reduction of area then apparently decreases slightly with further mechanical working or total reduction, whereas the elongation remains practically constant. The impact resistance of the steel is seen also to be greatly improved by a small amount of mechanical work rapidly attaining a relatively high value and then increasing but little with further reduction.

(*b*) Effect of Finishing Temperature.—The effect of the finishing temperature of rolling on the properties of the steel is shown in Figure 5.

In studying this group of curves and those of Figures 6, 7, and 8 it should be borne in mind that the total reduction has the constant ratio of 5 to 1 in all cases. The absolute values of the mechanically-worked material plotted in these curves may be compared with the values for the cast material by comparison with the values plotted with the 1 to 1 ratio in Figure 4, or as given in Table 4. The values obtained for the so-called "standard" conditions (Table 1) are, of course, common to all five sets of curves.

The effect of lowering the finishing temperature of rolling is very evident. There is a slight drop in the ultimate strength and a very marked increase in the yield point. The ductility of the steel increases slightly, attaining a maximum value at a finishing temperature of about 700° C. and then apparently dropping off slightly. The impact resistance of the steel is also apparently improved by finishing the rolling at the lower temperature, the impact values obtained at 700° C. being considerably higher than those for 1,000° C.

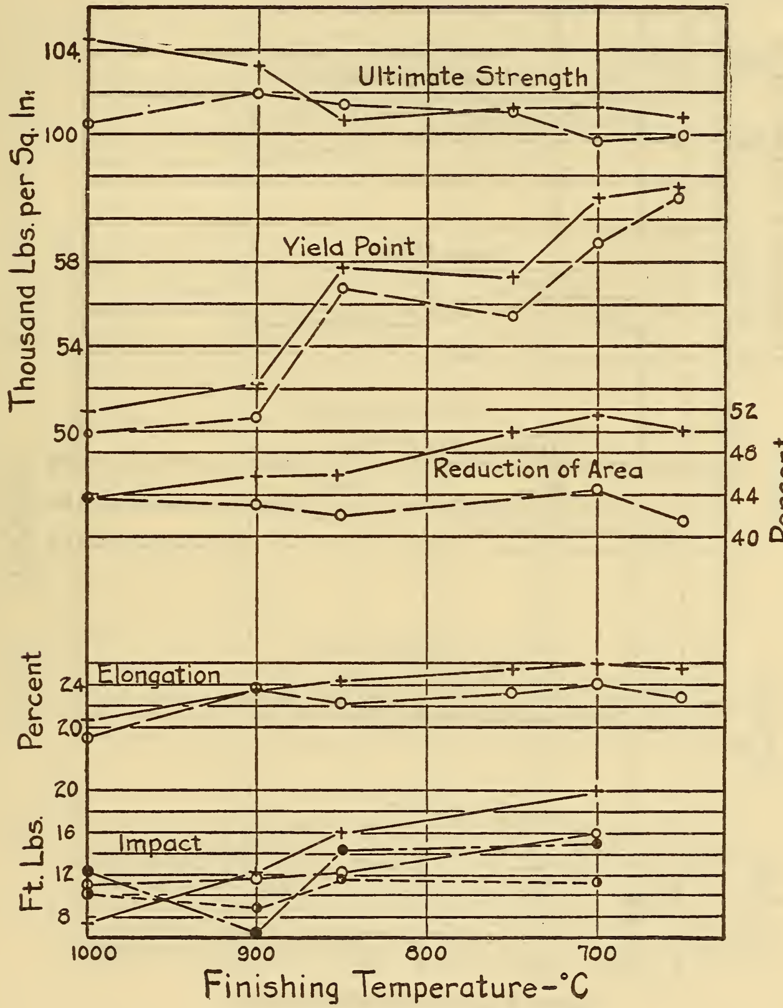

FIG. 5.—*Effect of finishing temperature*

○———— longitudinal specimens, +— — — transverse specimens } Tensile tests and Type A notch
●— - — - longitudinal specimens, D— — — transverse specimens } Type B notch

The apparent slight decrease in ductility for a finishing temperature of 650° C. (1,200° F.) as compared with 700° C. (1,290° F.) is probably due to the fact that the Ar_1 transformation of this steel as determined by thermal analysis is at 670° C. (1,240° F.), and the steel was, therefore, worked at a temperature slightly below its transformation range. The maximum values obtained with a finishing temperature of 700° C. (1,290° F.) indicate that the best finishing temperature is just above or within the Ar_1 transformation.

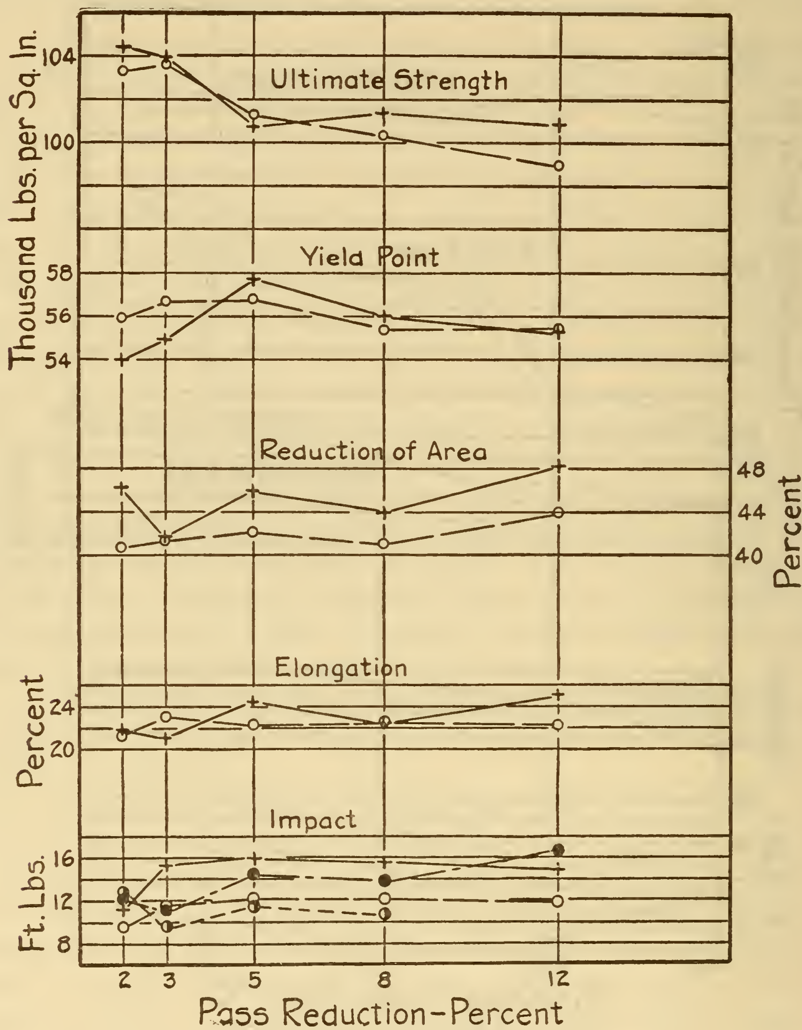

FIG. 6.—*Effect of pass reduction*

○——— longitudinal specimens, +— — — transverse specimens } Tensile tests and Type A notch

●—— - —— - longitudinal specimens, ◑— — — — - transverse specimens } Type B notch

(*c*) EFFECT OF PASS REDUCTION.—In Figure 6 the effect of varying the pass reduction is shown. It is to be noted that the pass reduction does not seem to influence the mechanical properties to the same extent as do the total reduction and the finishing temperature. The ultimate strength is slightly lower for the larger pass reductions while the yield point, ductility, and impact values do not indicate any very definite trend.

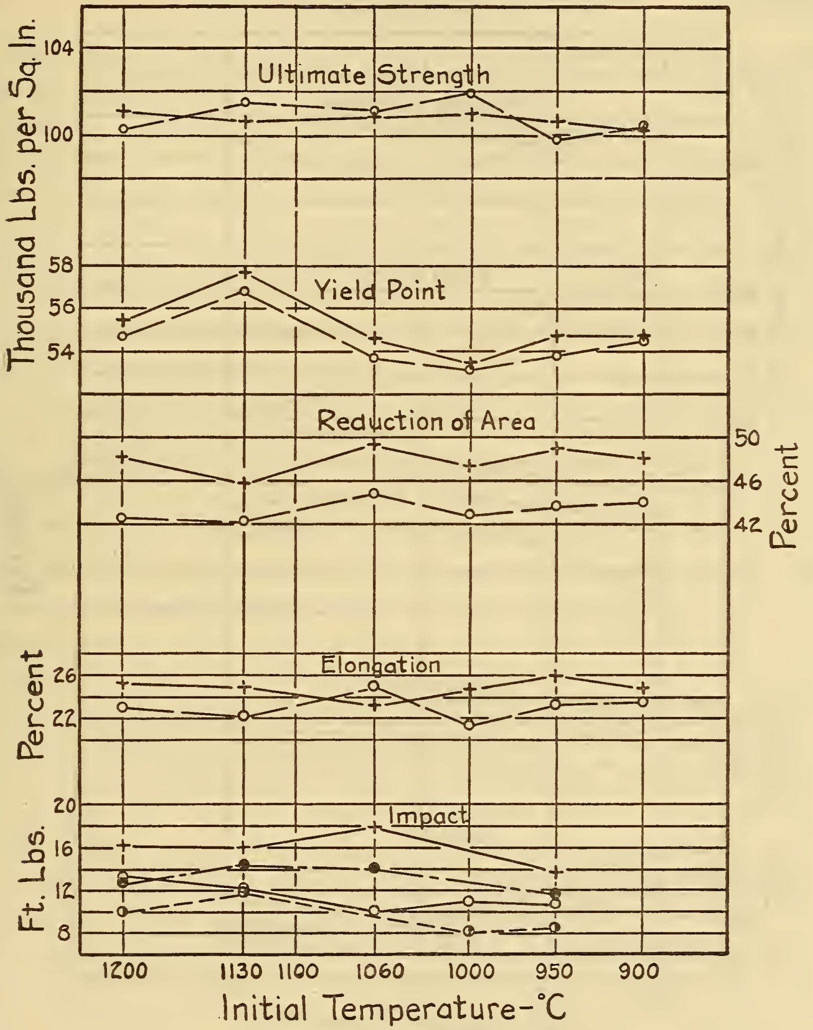

FIG. 7.—*Effect of initial temperature*

○———— longitudinal specimens, +— — — transverse specimens } Tensile tests and Type A notch

●—— - —— longitudinal specimens, ◐— — — — transverse specimens } Type B notch

(*d*) EFFECT OF INITIAL TEMPERATURE.—The curves in Figure 7, illustrating the effect of initial temperature of rolling on the mechanical properties of the steel, are rather irregular and indefinite, showing no definite trend in the properties other than a possibly slight decrease in the yield point. It may be concluded that the initial temperature of rolling has practically very little influence on the properties of the steel within the temperature range studied.

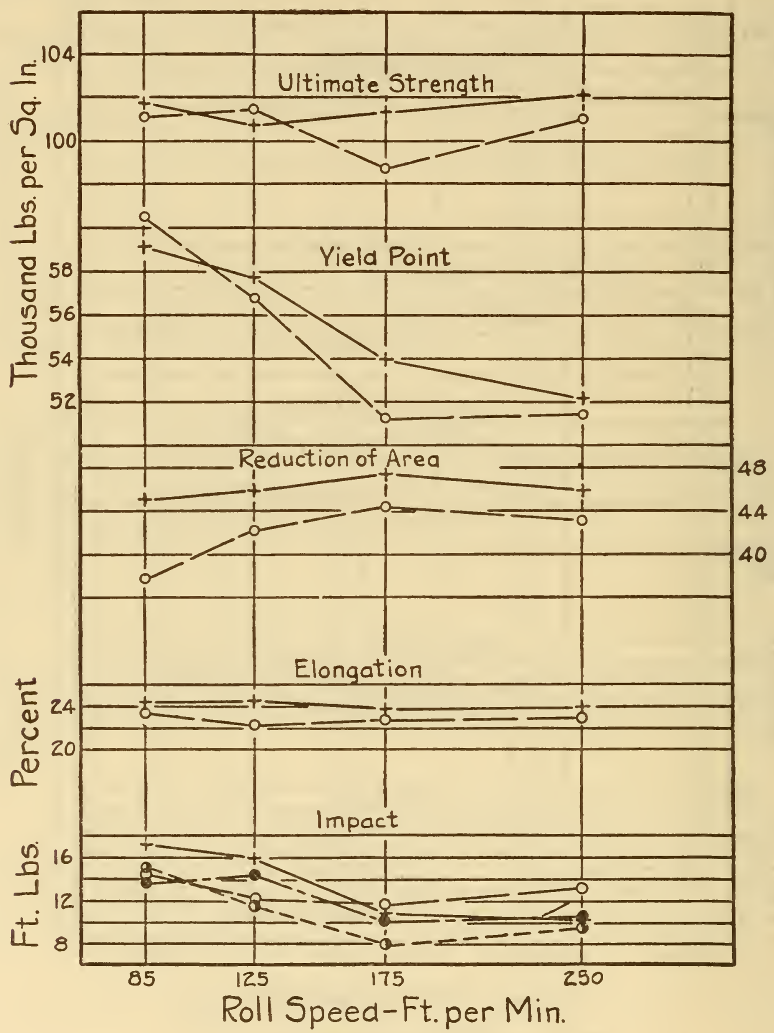

FIG. 8.—*Effect of roll speed*

○——— longitudinal specimens	Tensile tests and Type A notch	
+— — — transverse specimens		
●——- —— - longitudinal specimens	Type B notch	
◗— — — — - transverse specimens		

(*e*) EFFECT OF ROLL SPEED.—The effect of roll speed on the properties of the steel is shown in Figure 8. The ultimate strength and ductility are not appreciably affected. The yield point shows a marked decrease with increasing roll speed, which is not readily explained in view of the slight variation in other properties. The impact resistance also indicates a slight decrease with increased roll speed.

2. TESTS OF TRANSVERSE SPECIMENS

The curves showing the results of specimens taken transversely to the direction of rolling are incorporated in Figures 4 to 8, for ease of comparison with the longitudinal tests. It is evident from these curves (broken line) that the mechanical properties of the steel in the direction perpendicular to that of rolling are, in general, inferior to its properties in the direction parallel with that of rolling. This difference is not so evident in comparing the ultimate strengths, but there is a very consistent difference between the longitudinal and transverse yield point, ductility, and impact resistance values.

That there is a difference between the longitudinal and transverse ultimate strengths and that there is greater variation in the properties of the steel in the transverse direction may be shown by some comparisons of values taken from the tensile tests. In the entire series of tests made on rolled steel plate where both longitudinal and transverse tests were made, the maximum tensile strength obtained was 108,750 lbs./in.^{2} and the minimum, 99,750 lbs./in.^{2}, giving a maximum difference of 9,000 lbs./in.^{2} for the longitudinal tests. The corresponding values for the transverse direction are 108,250 lbs./in.^{2} maximum and 95,250 lbs./in.^{2} minimum; or a maximum difference of 13,000 lbs./in.^{2} Further, the differences between the comparable longitudinal and transverse tests showed greater differences within the transverse series, the maximum difference between the comparable longitudinal tests being 3,250 lbs./in.^{2}; whereas between comparable transverse tests it was 4,250 lbs./in.^{2}, and there were only two instances other than above stated where in the longitudinal tests the difference was greater than 2,000 lbs./in.^{2}, namely, 2,750 and 2,500 lbs./in.^{2} On the other hand, there were four instances in the transverse tests where the difference between comparable tests was greater than 2,000 lbs./in.^{2}, these differences being 3,000, 2,750 in two cases, and 2,000 lbs./in.^{2}

It is to be noted, however, that the trend of variation in the transverse properties due to the variation in rolling conditions is, in general, parallel to the trend in the longitudinal properties.

3. SPECIAL ROLLING CONDITIONS

Some plates were rolled under conditions other than those at first outlined, as previously stated. These special rollings were made in order to determine whether two or three conditions of rolling which independently gave maximum values would, if combined, give even greater values. The results of these tests can not be included in Figures 4 to 8, due to the fact that more than one of the variables at a time was changed from the so-called "standard" value. For example, it is to be observed that in the total-reduction series a total reduction of 1.3 to 1 gave a high tensile strength, being 105,750 lbs./in.^{2} In the pass-reduction series the 2 and 3 per cent pass reductions show ultimate strengths higher than any of the other values of this series. The 2 per cent value is slightly the higher, being 104,000 lbs./in.^{2} To determine if combining the rolling conditions, which gave these two high tensile values, would, when combined, give a result higher than either one, plates were rolled, using a pass reduction of 2 per cent, total reduction of 1.3 to 1, and other conditions standard. (Table 2, combination No. 3.) The results given in Table 3 indicate a decided increase in tensile strength and yield point. The elongation and reduction of area, however, become somewhat inferior; that is, the tensile strength becomes greater at the expense of the ductility. The impact value remains about the same.

In the finishing-temperature series, the highest tensile strength is obtained with a finishing temperature of 1,000° C. Combining this value of finishing temperature, a total reduction ratio of 1.3 to 1 and a pass reduction of 2 per cent (Table 2, combination No. 4), the results given in Table 3, combination No. 4, were obtained. This combination of rolling conditions gives the same tensile strength, but a further small decrease in the ductility of the steel.

In a similar manner the rolling conditions giving high-ductility values in the finishing-temperature series and in the total-reduction series were combined (Table 2, combination No. 5). Then a combination of these two conditions with the rolling conditions giving a high ductility in the pass-reduction series was tried. The results of tests of these plates given in Table 3 (combinations Nos. 5 and 6) failed to show an improvement in the ductility in either case and showed slightly lower values than some of those shown on the curves in the standard series. The tensile strengths were not very appreciably affected.

TABLE 3.—Tests of Plates Rolled Under Conditions Given in Table 2

Combination number (see Table 2)	Tensile strength	Yield point	Elongation	Reduction of area	Impact resistance
	Lbs./in.²	Lbs./in.²	Per cent	Per cent	Ft./lbs.
3	108, 000	60, 900	19. 5	36. 5	9. 0
4	108, 000	55, 000	18. 5	35. 0	8. 0
5	102, 500	59, 000	23. 5	51. 0	20. 5
6	101, 750	55, 600	22. 5	43. 5	18. 5

4. EFFECT OF NORMALIZING THE ROLLED PLATES

In order to determine the effect of normalizing on the properties of the rolled material a series of plates, which had been tested in the "as rolled" condition, were normalized by heating to 800° C. and air cooling. Longitudinal and transverse test specimens were then machined from these plates and tested. The results are tabulated in Table 4 for both the longitudinal and transverse tests in both the "as rolled" and normalized condition to permit of easy comparison.

It will be noted that the apparent effect of normalizing, as would be expected, is to equalize the values obtained on tests from all conditions of rolling. Further, the normalizing causes a slight decrease in the average ultimate strength accompanied by an increase in the ductility and resistance to impact.

TABLE 4.—Effect of Normalizing on Mechanical Properties of Material "As Rolled"

LONGITUDINAL DIRECTION

Rolling conditions standard, except as stated	Tensile tests						Impact resistance—V notch	
	Ultimate strength		Elongation		Reduction of area			
	As rolled	Normalized	As rolled	Normalized	As rolled	Normalized	As rolled	Normalized
	Lbs./in.²	Lbs./in.²	Per cent	Per cent	Per cent	Per cent	Ft./lbs.	Ft./lbs.
Standard [1]	102, 250	99, 750	23. 5	27. 5	45. 0	50. 0	16. 0	18. 5
Finishing temperature 1,000 ° C	104, 500	100, 250	20. 5	25. 5	41. 5	48. 0	10. 0	18. 5
Finishing temperature 650° C	101, 000	101, 500	26. 0	25. 0	50. 5	50. 5		18. 0
Pass reduction, 2 per cent	106, 250	99, 500	21. 0	27. 5	51. 0	48. 5	13. 5	16. 5
Pass reduction, 3 per cent	105, 000	101, 000	23. 5	26. 0	45. 0	48. 0	8. 5	16. 0
Pass reduction, 12 per cent	100, 250	98, 250	25. 0	26. 5	49. 0	49. 5	17. 5	20. 0
Total reduction, 7:1	104, 250	98, 750	23. 0	25. 5	45. 5	46. 5	12. 0	16. 5
Total reduction, 3.5:1	100, 250	99, 500	26. 0	25. 5	47. 0	48. 0	15. 0	17. 5
Total reduction, 3.5:1	104, 250	99, 500	24. 0	26. 0	46. 5	46. 5	14. 0	17. 5
Total reduction, 1.3:1	104, 750	101, 750	21. 0	21. 5	38. 5	43. 5	10. 0	16. 0
Total reduction, 1:1	[2] 92, 700	[3] 108, 250	[2] 6. 0	[3] 15. 0	[2] 5. 0	[3] 23. 0	[2] 3. 5	[3] 7. 0

TRANSVERSE DIRECTION

Rolling conditions standard, except as stated	Ultimate strength As rolled	Ultimate strength Normalized	Elongation As rolled	Elongation Normalized	Reduction of area As rolled	Reduction of area Normalized	Impact As rolled	Impact Normalized
Standard [1]	103, 750	99, 500	21. 0	22. 5	38. 0	45. 5	16. 0	18. 5
Finishing temperature 1,000° C	100, 250	101, 750	19. 0	24. 0	44. 0	46. 0	10. 0	18. 5
Finishing temperature 650° C	99, 250	102, 250	21. 5	22. 5	40. 5	43. 5		18. 0
Pass reduction, 2 per cent	104, 500	100, 500	20. 5	23. 5	42. 5	53. 0	13. 5	16. 5
Pass reduction, 3 per cent	101, 100	101, 500	17. 5	23. 0	44. 5	44. 0	8. 5	16. 0
Pass reduction, 12 per cent	100, 500	98, 250	24. 0	21. 0	45. 0	46. 0	17. 5	20. 0
Total reduction, 7:1	100, 800	102, 750	22. 5	21. 0	42. 0	41. 5	12. 0	16. 5
Total reduction, 3.5:1	97, 000	99, 250	19. 0	22. 0	38. 0	45. 5	15. 0	17. 5
Total reduction, 3.5:1	103, 750	100, 250	22. 5	23. 5	44. 5	42. 0	14. 0	17. 5

[1] See Table 1, p. 550. [2] As cast. [3] As cast, heated to 1,130° C. and air cooled without rolling.

V. MISCELLANEOUS DETERMINATIONS

1. DENSITY

Density determinations were made on 25 samples selected from representative plates which covered the extreme cases that were likely to show differences. Two samples in the cast condition showed densities in grams per cubic centimeter at 24° C. of 7.828 and 7.827, respectively. Of the other tests, 3 had a density of 7.828, 10 of 7.831, 4 of 7.830, 3 of 7.832, 1 of 7.833, and 1 each of 7.834 and 7.835. The three lower values were from plates having a high tensile strength. The two higher density values were from plates rolled under standard conditions and the 7.833 value is for a plate rolled with a finishing temperature of 700° C. and a reduction ratio of 3.5 to 1. It appears from these results that plates which received more than the smallest amount of reduction were made slightly more dense, but even the extreme difference between values was only 0.008 gram per cubic centimeter, or one-tenth of 1 per cent.

2. HARDNESS

In regard to the hardness determinations it may be briefly stated that neither the Brinell hardness determinations nor the scleroscope hardness values showed any direct relation to the rolling conditions. In general, the plates having the greater hardness had the higher tensile strength. The maximum Brinell hardness obtained was 226 and the minimum 166.5. The maximum scleroscope hardness was 34.5 and the minimum 30.0.

3. MICROSTRUCTURE

Microscopic examination was made of specimens taken from rolled plates showing considerable difference in longitudinal and transverse properties. Sections were taken on all three faces in order to determine if there were any apparent difference in the grain structure which might account for the difference in the observed longitudinal and transverse mechanical properties. No observable difference was to be found. In general, it may be stated that the finer grain sizes were associated with the higher ductility values.

4. POWER

The power determinations could, from the nature of the determination, only give results of a very general nature, due particularly to the difficulty in determining the inertia and friction losses of the mill. The results obtained were quite in line with what would be expected. The power reached a peak value for a given pass as soon as the metal entered between the rolls and dropped off immediately the metal left the rolls. The greater the pass reduction the greater the energy consumed, other conditions being equal. The temperatures of rolling had a very important bearing on the energy consumed, and in these experiments had a greater effect than the actual volume of metal displaced. The conditions for observing this fact were quite favorable, as there was always a series of passes between each two heatings of the metal in those cases where total reduction could not be obtained without reheating. In a given series the actual reduction per pass is decreasing, although the per cent reduction is constant throughout the series. Also, as the plate becomes thinner, the loss of temperature is more rapid. By the end of a series of rollings it was apparent from the power record that the lower temperature of the plate had had a much greater effect on the peak load per pass than the actual reduction per pass. For example, in one series of 31 passes the peak load for the first pass was 36 kilowatts, while for the last pass it was 76 kilowatts. In the series of passes with 12 per cent reductions already referred to, with a peak load on the first pass of 82 kilowatts a peak load of 200 kilowatts was attained on the last pass.

VI. SUMMARY AND CONCLUSIONS

A study has been made of the influence of the following five factors of rolling conditions, namely, initial temperature of rolling, finishing temperature of rolling, total reduction, pass reduction, and roll speed on the following physical properties of a medium carbon steel: Tensile properties (ultimate strength, yield point, proportional limit, elongation, reduction of area), resistance to impact, hardness, microstructure, and density.

The steel was rolled in one direction only, permitting a study of the effect of the unidirectional rolling on the relative properties of the steel in the directions longitudinal and transverse to that of rolling.

The results obtained indicate that the total reduction and finishing temperature are the most important factors in rolling. A change in these conditions has a greater influence on the mechanical properties of the steel than either of the other three factors studied. The pass reduction, initial temperature, and roll speed apparently have very little influence on the properties of the steel.

An increase in the total reduction decreases the ultimate strength, but increases the yield point, ductility, and impact resistance of the steel. A finishing temperature of 700° C. as compared to 1,000° C. gives a steel of higher yield point, greater ductility, and resistance to impact, although the ultimate strength is slightly lower.

The effect of rolling the steel in one direction only is to produce a slight difference in its mechanical properties between the directions longitudinal and transverse to that of rolling; the steel being, in general, inferior in the transverse direction. Normalizing the rolled steel tends to equalize all values by eliminating differences caused by rolling conditions.

The steel has practically the same density in the cast as in the rolled condition and the density is not affected by the conditions of rolling.

It is appreciated that a series of tests, such as reported in this paper, must be confirmed by the results of tests and experience under production conditions before definite conclusions may be drawn. It is believed, however, that the results reported here are indicative of the influence and magnitude of the several factors studied on the properties of the steel.

The authors desire to express their appreciation of the valued suggestions of R. G. Waltenberg and R. W. Woodward. They are indebted to H. S. Rawdon for the microscopic study, to R. D. France and to the late R. P. Neville for temperature measurements and assistance in rolling.

WASHINGTON, May 22, 1924.