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OBSERVATIONS ON FINISHING TEMPERATURES AND PROPERTIES OF RAILS

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1. INTRODUCTION

The dean of American metallurgists, Prof. H. M. Howe, in his presidential address before the American Society of Testing Materials in 1912, sounded a timely note of warning as to the responsibility of those societies and organizations which draw up model specifications. Said Prof. Howe:

> We set up standards for rails. It is strongly suspected and at times asserted that the breakage of these rails causes many needless deaths. If these rails are bought under our specifications, and if those specifications do not fully secure the very least attainable danger of breakage, we, as the experts on whose judgment these rails have been permitted, through their breakage, to kill our fellowmen, are in a measure responsible.
>
> The question thus seems to resolve itself into these: First, is there a considerable number of rail breakages capable of prevention by means of better specifications? Second, can we contribute directly or indirectly toward bettering these specifications by directing attention to their present defects?

It is common knowledge that there are an alarming number of failures of rails in service on the railroads of the country, and, unfortunately, these failures are not on the decrease. Thus the reports of the rail committee of the American Railway Association[1] show 36 641 rail failures, in 12 688 714 tons laid, for the year ending October 31, 1911, and 61 047 failures for 13 736 956 tons in 1912.

It is natural, on the one hand, for the rail manufacturer to claim that the railroads, with their increased speed and weight of trains, are mainly responsible for this condition, and that the rails now made are better than ever before; and, on the other hand, for the railroads to claim that the fault lies mainly with the rail manufacturer, who might furnish a sounder product. With the many deplorable and still unsettled aspects of this very vital question this paper makes no pretension of dealing.

That the railroads and rail manufacturers appreciate the gravity of the situation and the necessity of producing sound rails is shown by the fact, among others, of the introduction in some instances of a more comprehensive inspection system in the mills on the part of the railroads. As reported by R. W. Hunt,[2] "a great number of heats have not been rolled into rails, which, under old conditions, would have gone."

There is one phase of the process of rail manufacture that has received attention from time to time and to which it seems worth while to call attention again. We refer to the problem of the most suitable temperatures of rolling and particularly of finishing rails.

We shall recall briefly some of the salient points in the history of American practice in this matter of finishing temperatures, as shown in the proceedings and specifications of the several engineering societies, discussing in this connection the shrinkage clause first suggested about 1900, by which it was attempted to define the allowable upper limit of the finishing temperature by specifying the maximum contraction of the rail after it leaves the rolls and is cut into lengths at the hot saws. The desirability of setting

[1] Bull. A. R. E. A., 15, p. 161, 1913; 14, p. 335, 1912.

[2] See R. W. Hunt: "The American steel rail situation," Bull. Am. Inst. Mining Engrs. No. 86, 1914, p. 251; "Recent developments in the inspection of steel rails," ibid., No. 72, December, 1912, p. 1487; "Discussion," p. 1571.

limits of temperature of rolling rails will be considered with some mention of the data and experiments bearing on this subject. A short discussion of suitable methods of measuring rail temperatures will also be included; and, finally, the present American practice will be illustrated by measurements on ingot and finishing temperatures as observed in four representative rolling mills. Accompanying these temperature observations will also be found some of the characteristic properties of steel-rail material, as illustrated by samples taken from rails, the rolling temperatures of which were observed, including determinations of their critical points by means of cooling curves, temperature distribution through rail section on cooling, microstructure, expansion, tensile strength, and hardness. It will also be shown that, admitting the desirability of temperature control, this may be accomplished in a convenient, reliable, practical, and inexpensive manner.

2. IMPORTANCE OF LIMITING TEMPERATURES OF ROLLING RAILS.

It seems to be generally recognized that the factor of greatest importance in the manufacture of rails is the making of sound steel ingots; but it is also recognized that, starting with sound ingots in the rolling mill, the quality of the rails produced will depend in a very considerable measure on the process of rolling, and in particular on the temperatures. The undesirable effects of rolling too cold and too hot were very early recognized, and have been stated many times by competent authorities, although it should be pointed out that there is not complete agreement or conclusive evidence regarding the effects of finishing rails too hot.

As usually given the argument, briefly stated, is as follows:

Rolling steel below the critical range distorts and weakens the crystalline structure, while rolling and finishing at too high temperatures above the critical range produces a coarsely grained steel which is weaker than the finer-grained structure obtained by doing work continuously on the rail down to the critical range, which usually lies between 650° and 750° C (or 1200° to 1400° F) for rail steels, and is rarely above 700° C (1300° F.).

The manufacturer prefers to roll his rails hot, as less power is then required to operate the mill and there is less wear and tear

of the rolls so that, in practice, fixing a lower temperature limit is of relatively less importance, although the results of too cold or uneven rolling should not be overlooked in framing specifications. It is also claimed that a rolling temperature only slightly above the critical range tends to produce mechanical defects in the rail which are absent with higher rolling temperatures.

It appears to be the general consensus of opinion that with the high carbon rails of heavy section, with their greater tendency to brittleness, now so generally manufactured, the necessity of more closely limiting the upper temperature of rolling is of greater importance than with the lower carbon rails of a few years ago. Nevertheless, an examination of the specifications generally in use for the purchase of rails in this country will show that there has been a tendency to raise rather than lower the allowable upper limit of finishing temperatures as defined by rail shrinkage, and the question arises, if Prof. Howe's admonition is well taken, whether this specification should not now be subject to revision, both as to its numerical value and as to the manner of its measurement. More experimental work will also have to be done before satisfactory specifications can be drawn as to finishing temperatures, and it would be highly desirable if one or more of the mills could make a series of a considerable number of rails (several thousand at least), similar in all other respects as possible but each series rolled at a definite well determined temperature. This would not be difficult of accomplishment, and a record of their behavior in the track could easily be kept.

3. METHODS OF MEASURING RAIL TEMPERATURES

Almost all known methods of pyrometry have been applied to the measurement of rail temperatures, but for the most part with indifferent success and usually, it would appear, attended by some skepticism on the part of the engineers responsible for rail manufacture, which skepticism has perhaps prevented the introduction of temperature control even in rail mills of which the management was convinced of the importance of controlling rolling temperatures.

The problem, however, appears to present no unusual difficulties from the pyrometric point of view, and can be solved satis-

factorily in several ways; and, if desired, the temperature control may even be made automatic and continuous with only occasional supervision.

What is desired is a measure of the actual temperature of each of the rail bars, either as they emerge from the finishing pass, or, perhaps better, if we assume a constant speed of rolling through the rail passes, a measure of the temperature of the blooms as they enter the rail mill. There may be some advantage in the latter procedure, due to the fact that it permits holding a bloom if too hot before entering the rail passes and discarding a bloom that is too cold; or, for mills which give the blooms a wash heat, or a reheat, it might merely be necessary to control the temperature of this reheating furnace and the shortest time the blooms may remain in it. In a continuous mill it would perhaps be preferable to control the ingot temperatures.

The present "shrinkage clause" in American specifications would appear to be an unsatisfactory way of gauging temperatures, for one reason, among others, that rails finished too hot can not be checked out until they are cold, and in the meantime several tons of rails may also have been rolled too hot. Practically, of course, the shrinkage has to be allowed for, at least approximately, for convenience in manufacturing.

It has also been strongly advocated to control rolling temperatures by microscopic examination of the cold rail section. Unquestionably the microscope is an indispensable instrument for deciding from examination of its structure whether a rail has been rolled at a suitable temperature, but it would appear to be impracticable to use the microscope to replace a pyrometric method for the actual measurement of rail temperatures, for much the same reasons that the shrinkage method should be rejected.

Attempts have been made to measure rail temperatures by a calorimetric method, such as immersing in water a piece cut from a rail bar at the hot saws. This method can hardly be recommended as a convenient one for ordinary mill practice requiring, in spite of its apparent simplicity, the very active participation of several persons. Its only apparent merit would be the hope that it might give the average temperature throughout a rail section,

but there are so many uncertain features here involved, such as the specific heat and loss of heat during transfer, for instance, to mention only two, that the method can not be considered other than crude, cumbersome, complicated, and costly.

The center of the head of a rail at the hot saws is undoubtedly hotter than the surface. (See sec. 11.) Bearing in mind, however, the tendency of present rolling-mill practice to roll rails hot, there is no present danger that a measurement of the surface temperature properly made will cause the rejection of rails as being too cold.

One of the earliest methods of measuring surface temperatures of rails, and one still advocated by some, was by means of the thermoelectric couple provided with various mechanical devices for thrusting it up to, and holding momentarily against the rail during its pause at the hot saws. This method can probably be made to give consistent and reliable results, but is subject to considerable uncertainties, not the least of which is the deterioration of the thermocouple. In general, contact methods of measuring surface temperatures are to be avoided when other suitable methods are available.

Fortunately, there are available at least two reliable and convenient methods based on the use of optical and total radiation pyrometers, which permit an exact measure of the temperature of a hot rail in motion, and possessing the further great advantage of not requiring any contact with the rail.

In general, an optical or a total radiation pyrometer, if calibrated to read correctly when sighted through a small opening into a clear furnace, will read low when sighted upon any substance exposed in the open. For the oxides of iron, however, the radiation from which is measured or observed in case of rail temperature measurement, this correction is small, being quite insignificant for any of the optical pyrometers using a single colored light and from 20° to 60° C for the total radiation pyrometers, the amount of this correction depending on the pyrometer and the rail temperature, Any given radiation instrument may readily be calibrated to give correct readings of rail temperatures, and allowance may also be made, if desired, for the hotter interior of the head which is usually

from 10° to 100° C hotter at the hot saws than the surface of the head of the rail, depending on weight and section. (See sec. 11.) Heavy scale will influence the pyrometer readings somewhat, especially for the total radiation instruments, causing them to read low, but it is probably safe to say that when the scale begins to cause serious trouble the rails are coming through the rolls decidedly too hot.

There are a considerable number of types of optical and radiation pyrometers available.[3] Of the former, the LeChatelier and Shore optical and Féry absorption pyrometers require no accessories, such as electric battery and ammeter, but contain a kerosene lamp, which is influenced by drafts. The Wanner pyrometer, or its improved form, known as Scimatco, is made in two ranges, 600° to 1100° C and 900° to very high temperatures; the former meets the requirements for rails except that one can not see the object sighted upon and the instrument has to be brought uncomfortably near the hot body. The Morse pyrometer, especially the German type known as the Holborn-Kurlbaum pyrometer in the small telescope form, is very convenient to use and exact to 1° or 2° C, has a range from 600° C up, and can be sighted on a railhead 50 feet or more distant. With any of these optical instruments, nearly instantaneous measurements may be taken—that is, in two or three seconds—with practice.

A simple, self-contained optical device suitable for a rough estimate of a definite temperature interval is the stereopyrometer, which may be so adjusted as to permit determining whether rails lie above, within, or below two arbitrarily fixed upper and lower limits of temperature. Another optical pyroscope is the instrument of Mesuré and Nouel, with which readings consistent to within 25° or 50° C may be obtained with practice.

Among the total radiation instruments may be mentioned the Thwing, Féry, Foster fixed focus, and the Féry spiral pyrometers, the last requiring no galvanometer but apparently slightly less constant than the others. All of these instruments may be made to give a continuous record. They all, in their present forms, require to be brought rather close to the hot body, but the galvanometer

[3] See "Optical pyrometry": Waidner and Burgess, Scientific Paper No. 11, 1904, Bureau of Standards; also Burgess and LeChatelier: "The measurement of high temperatures," 3d ed., 1912, Wiley.

or reading dial may be read at any desired distance and the recorder may be placed in the superintendent's office. The total radiation pyrometers may be clamped in position and do not require the intervention of an operator to obtain the temperature indications, as is the case with the optical pyrometers. On the other hand, with the total radiation pyrometers it is necessary to make sure that one has an instrument which will take up its final reading closely enough within five or six seconds.

From the above considerations concerning pyrometers and from a study of rolling-mill practice, it appears clear that if it be considered desirable to control the temperatures of rails during their manufacture, the problem may be easily and exactly solved by means of several types of optical and radiation pyrometer which have given excellent service in other technical fields, and also with very small cost of installation and maintenance.

We have dwelt at some length on this question of the availability of pyrometers suitable for measuring the temperatures of rapidly moving rails, mainly for the reason that considerable misapprehension and ignorance of this subject appears to be common among engineers acquainted with rolling-mill practice. This attitude is well illustrated by the following quotation published within a year, which might have been excusable 10 years ago:

> The control of the finishing temperature by the amount of contraction which the rail undergoes in cooling from the finishing to atmospheric temperature, appears to be the only method practical to use. Other efforts have been made to determine the finishing temperature by the use of pyrometers and by the examination of the microstructure of the rails. The use of pyrometers naturally suggested itself at first as the most promising means of accomplishing that purpose, but it was soon found that no pyrometric device existed which could be applied in a practical way to the detection of the temperature of quickly moving rails.[4]

A similar statement appears in the 1911 edition of Harbord and Hall's "Steel."

We hasten to add that this pessimistic impression concerning the availability of pyrometers is by no means general as is illustrated, for example, by the investigations of Puppe,[5] who used the Wanner and Holborn-Kurlbaum instruments and of Wick-

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[4] W. H. Sellew: "Steel rails," etc., published by Van Nostrand Co., 1913.

[5] J. Puppe: Ueber Versuche zur Ermitteilung des Kraftbedarfs an Walzwerken Berlin, 1909. (See also Iron and Steel Institute, I, 1912.)

horst,[6] (see sec. 4) who used the Thwing radiation pyrometer. The Féry instruments are also in use occasionally in several rolling mills.

4. WICKHORST'S EXPERIMENTS

M. H. Wickhorst[7] made an investigation of the influence of finishing temperatures on the properties of 85-pound Bessemer rails, using five ingots rolled, or rather finished, at temperatures ranging from 938° C to 1028° C, as measured with a total radiation pyrometer. The ingot temperatures were not measured and the blooms were reheated before rolling into rails, according to the practice of the Edgar Thomson Works.

No very definite conclusions as to the effect of rolling temperatures on the properties of rails can be drawn from this series of experiments covering only a 90° range in temperature, the lower temperature limit being close to the maximum allowed by present American specifications, as defined in terms of shrinkage, and higher than the upper limit allowed for example in 1905 by the American Railway Engineering Association. It is to be regretted that this investigation did not include rails finished at least as low as 800° C (1472° F) and as high as 1150° C (2102° F).

In spite of no marked influence detectable within this narrow range of finishing temperatures on the ductility, deflection and number of blows in the drop test, yield point, and tensile strength, Mr. Wickhorst apparently found a slight decrease in elongation and reduction of area with increase in finishing temperature, and a notable increase in size of grain.

The measurements of Mr. Wickhorst on shrinkage and temperature permit an approximate calculation of the mean coefficient of expansion of Bessemer steel of 0.49 per cent carbon and 1.10 manganese content. Although the temperature (t_c) at which the length (l_c) of the cold rails was measured, is not given, we may assume in the formula for expansion coefficient $\alpha = \frac{l - l_o}{l_o(t - t_o)}$ in which t is the finishing temperature of hot rail of length l, that

[6] M. H. Wickhorst: "Influence of rolling temperature on properties of Bessemer rails," American Railway Engineering Association Report 21, November, 1911.

[7] M. H. Wickhorst: Ibidem.

this length l_c is equal to l_o the length at 0° C; this is equivalent to adding a legitimate, small correction to the readings of the total radiation pyrometer used, which we know gives readings that are somewhat low when sighted on exposed objects.

In the accompanying table are given the results of these computations of the expansion coefficient.

Calculation of Expansion Coefficients from Wickhorst's Data

Finishing temperature	Shrinkage	Length of rail, cold		α_{0-t}
°C	Inches	Feet	Inches	
938	$6\frac{4}{16}$	33	$\frac{5}{16}$	0.0_4168_1
963	$6\frac{3}{16}$	33	$\frac{1}{16}$	170_4
990	$6\frac{13}{16}$	32	$11\frac{13}{16}$	173_9
1028	7	32	$11\frac{9}{16}$	172_1
1023	7	32	$11\frac{9}{16}$	

Mean value of $\alpha_{0-983°}=0.0_4171_1$.

This value of the expansion coefficient α is considerably higher than that found by the authors for Bessemer steels, for which $\alpha_{0-1000°C}=0.0_4146$ (see sec. 12) and also for open-hearth steels ($\alpha_{0-1000°C}=0.0_4157$). To reduce Wickhorst's expansion results to those for Bessemer steel requires adding nearly 200° C to his temperature measurements. This correction is not beyond the bounds of possibility; since it is shown, for instance (sec. 11), that the outside of the head of a rail may be over 100° C below the temperature of the middle of the head while cooling; and in addition the correction to the radiation pyrometer used by Mr. Wickhorst will be over 50° C for lack of "blackness" of the iron oxide (see sec. 3); and finally if the Thwing radiation pyrometer is held too far away its readings will be lowered further due to the radiation not filling completely its aperture.

It is, of course, also conceivable that the Bessemer rails, as they leave the rolls, have the very high expansion coefficient deduced from Mr. Wickhorst's observations on shrinkage. Further experiments are necessary to demonstrate this. (See also sec. 12.)

5. MEASUREMENTS OF INGOT AND FINISHING TEMPERATURES

These were made in the spring of 1913 at four representative rail mills,[8] designated by A, B, C, D. The portable pyrometer used, the Holborn-Kurlbaum type of the Morse instrument,[9] is shown in Fig. 1 with samples cut from the rails. Temperature observations were taken by sighting on the rail bars at the instant of cutting by the hot saws, the pyrometer being located so as to view the head of the rails at the first saw, except for mill C, at which, for convenience, the base of the rails was sighted as they passed to No. 1 bed. Since mill C was rolling a rail of heavy base, the measurements are comparable with those made by sighting on the heads. That such was the case was also shown by direct observations. The only considerable element of non-uniformity of the measurements at the several mills lies in the fact that the distance and time from the finishing pass to the hot saws is not the same for the several mills. This time for mill D is about half that for mills A, B, and C, while the ratio of distances is, roughly, A = 4, B = 5, C = 3, and D = 1 for the positions at which temperature measurements were taken. Two of the mills, A and B, used one saw and the others four saws. For the former it was possible to measure the temperature of practically every rail, while for mills C and D the average temperature of the rail bar as it passed to be cut (for mill D, and after cutting for mill C) was measured. In mills A and B the blooms were not reheated and in C and D they were reheated before rolling into rails.

Measurements were also made at each mill of a series of ingot temperatures, observations being taken as the ingot entered the blooming mill and for each alternate pass. It was possible in some cases to take observations on rail bars from ingots the rolling temperatures of which had also been measured. Auxiliary temperature measurements were also made at mill A, including observations at the bloom shears, open hearth, Bessemer, and blast furnaces, before and during tapping, pouring into ingot molds,

[8] The names of the mills are not published, due to objection from one of them.

[9] See Waidner and Burgess: "Optical pyrometry," Scientific Paper No. 11 of Bureau of Standards, 1904.

and temperature of ingots at stripping and removing from soaking pits. These last will be published elsewhere.

In the following tables, 1 to 16, are given the measurements taken in the several mills. All observations were taken without any interference with the regular operation of the mills, and no special arrangements or installations were found necessary for manipulating the pyrometer.

MEASUREMENTS AT MILL A

TABLE 1

Temperatures of Successive Ingots Passing Through Blooming Mill With Times Taken to Pass Through

[Each temperature is the average of all taken (5 to 10) on each ingot]

Number of ingot	(a) Ingots [10] for 75-pound Bessemer rails		(b) Ingots for 100-pound open-hearth rails	
	Temperature	Time	Temperature	Time
	°C	secs.	°C	secs.
1	1138		1117	119
2	1138		1085	116
3	1136	111	1101	135
4	1134		1063	127
5	1132	90	1082	170
6	1138	95	1069	132
7	1122	101	1068	
8	1127	92	1076	123
9	1165	96	1093	108
10	1158	103	1062	120?
11	1144	110	1070	95
12	1160	109	1051	135
13	1139	139	1069	150
14	1121	134	1071	123
15	1124	108	1071	97
16	1159	161	1076	88
17	1152	161	1088	130
18	1139	96	1123	96
19	1152	179	1121	
20	1135	159		
Mean	[11] 1140±10	120±25	1082±16	121±16

[10] These ingots had been an unusually long time in the soaking pits.

[11] The sign ± refers to the agreement of ingot temperatures and not to the accuracy of temperature measurements, which last is about 5° C.

TABLE 2

Sample Detailed Observations on Ingot Temperatures at Blooming Mill, Showing Precision of Method

Ingots	Temperature	Ingots	Temperature
(a) Bessemer ingots:	°C	(b) Open-hearth ingots:	°C
No. 2	1133	No. 4	1100
	1135		1082
	1152		1094
	1147		1076
	1135		1052
	1123		1070
			1064
Mean	1138	Mean	1063
No. 6	1147	No. 7	1088
	1147		1076
	1123		1064
	1123		1062
	1129		1051
	1147		1050
			1076
Mean	1138	Mean	1068
No. 10	1182	No. 14	1064
	1152		1076
	1135		1084
	1147		1088
	1158		1064
	1158		1040
	1164		1064
Mean	1158	Mean	1069
No. 16	1170	No. 20	1124
	1158		1130
	1170		1124
	1176		1124
	1147		1111
	1147		1111
	1176		
	1135		
Mean	1159	Mean	1121

TABLE 3

Temperatures of End of Bessemer Blooms Under Shears, on Freshly Cut End

Temperature	Temperature
°C	°C
1170	1194
1200	1186
1194	1209
1190	1176
1205	1175
1212	1200
1200	1190
1212	1203
1194	1141
1192	1144

Mean=1189±15.

The values given are the average of the two or three cuts observed for each ingot.

The interior of the bloom, the temperature of which is here measured approximately, is at a somewhat higher temperature than the surface.

TABLE 4

Temperatures of 75-pound Bessemer Rails at Hot Saw

[Each reading represents a rail. Brackets are used to tie rails in same ingot]

Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails	Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails
°C	°C	°C	°C	°C	°C
{916	909	909	{956	947	931
{922	...	903	{926 [14]	916	903
{928 [12]	916	903	928	916	...
{890	903	890			
			{913	909	913
{916	926	903	{916	926	890
{909	909	895			
			{929	926	916
{894 [12]	903	888	{928	917	909
{890 [12]	878	...			
			{909	928	...
{926	922	893	{928	909	896
{916	890	...			
			{922 [13]	921	896
909	909	...	{928	928	900
{926	909	...	{928	930	913
{918	916	900	{922	914	900
{953	941	...	{896	890	...
{947	931	903	{928	903	877
{928 [13]	922	913	{941	931	931
{890	877	871	{922	916	877
{947	965	953	{921	938	928
{950	928	934	{956	917	896
{943	941	941	Mean=924±13	918±13	906±15
{941	928	922			

[12] Test-piece top. [13] Test-piece middle. [14] Test-piece bottom.

TABLE 5

Temperatures of Open-Hearth and Bessemer 90-pound Rails at Hot Saw

[Brackets tie rails from same ingot]

Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails	Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails
°C	°C	°C	°C	°C	°C
[15] 978	991	...	966	975	...
996	963	...	976	966	951
991	981	...	976	965	...
966	924	...	966	940	928
[16] 947	978	...	958	958	942
978	947	...	[16] 991	971	...
1001	999	...	976	955	941
970	953	...	963	955	...
1003	982	...	968	964	940
969	951	...	991	991	...
974	975	...	978	969	951
1000	966	928	976	966	...
981	957	...	980	963	941
978	955	938	Mean =976±10	964±12	942±7
976	950	956			
[16] 966	954	...			
958	951	...			

[15] Open-hearth heat. [16] Bessemer new heat.

TABLE 6

Temperatures of Open-Hearth 100-pound Rails at Hot Saw

[Brackets tie rails from same ingot]

Temperatures of A and C rails	Temperatures of B and D rails	Temperatures of A and C rails	Temperatures of B and D rails	Temperatures of A and C rails	Temperatures of B and D rails	Temperatures of A and C rails	Temperatures of B and D rails
°C	°C	°C	°C	°C	°C	°C	°C
916	898	1017	984	970	968	997	991
916	890	980	959	972	942	991 [17]	[18] 959–896
953	932	1029	1003	1003 [17]	991	1005	997
953	938	1004	967	984	963	991	964
928	905	1025 [17]	996	982	971	Mean=	
900 [17]	876	1004	966	981	952	988±23	962±24
1013	997	1025	1000	1005	989		
966	928	1009 [17]	968	1001	970		
1015	993	1021	1002	1001	977		
991	943	1001	957	991	[18] 968		
1013 [17]	989	982	973	1018	1001		
991	953	981	948	972	947		

[17] Test piece. [18] Discarded.

MEASUREMENTS AT MILL B

TABLE 7

Measurement of Temperatures of Ingots for Open-Hearth Rails at Blooming Mill

Temperature	Time	Temperature	Time	Temperature	Time	Temperature	Time
°C	Seconds	°C	Seconds	°C	Seconds	°C	Seconds
1102	...	1085	111	1104	92	1091	87
1096	88	1057	105	1091	93	1095	95
1086	88	1092	97	1121	87	1095	90
1091	86	1088	118	[19] 1135	100	1121	84
1102	88	1102	94	1130	91	1109	82
1096	100	1094	107	1132	91	1100	85
1093	106	1100	99	1120	97		
1101	93	1110	91	1107	102		

Mean temperature=1102° C±12; mean time=91 seconds±7.

[19] New heat.

TABLE 8

Measurement of Temperatures of Head of Rail at Hot Saws for 72-pound Rails

A	B	C	D	Mean ABCD	E	F	G	H	Mean EFGH
°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
954	942	942	926	941	954	943	926	896	930
966	953	948	928	948	965	945	919	898	932
956	955	943	917	943	954	931	919	902	927
956	945	926	929	939	952	944	920	906	928
966	960	943	832	950	960	...	922	905	929
968	945	940	929	945	954	940	920	901	929
943	931	918	914	927	...	...	...	...	...
...	...	...	...	...	948	933	918	908	919
958	951	937	929	944	948	929	918	894	922
962	923	920	917	928	940	920	908	894	915
942	934	922	908	912	940	920	902	878	904
922	912	908	887	907	926	906	894	872	902
922	909	899	897	907	912	897	882	866	889
926	917	905	897	912	926	908	902	882	904

TABLE 8—Continued

NEW HEAT

A	B	C	D	Mean ABCD	E	F	G	H	Mean EFGH
953	947	935	920	938	932	931	913	903	920
966	954	932	912	939	954	937	929	...	940
954	945	934	922	938	954	945	922	914	934
956	957	936	919	941	960	952	935	918	941
964	949	934	926	943	954	943	...	913	936
968	957	945	934	951	949	929	915	...	930
952	943	937	930	940	950	943	924	920	934
962	958	940	936	951	957	940	934	910	935
966	957	940	932	949	951	934	918	897	924
954	943	935	926	939	938	937	918	896	922
956	943	929	922	936	955	943	922	901	930
968	954	943	931	947	958	943	924	916	935
964	946	943	935	946	964	952	932	918	942
958	943	943	931	944	965	946	931	920	940
960	946	944	931	945	946	943	926	918	934
961	954	946	930	947	954	948	935	918	938
958	949	945	943	949	957	935	931	920	936
955	947	939	929	943	945	942	932	908	931
965	953	939	939	949	968	953	941	917	945
963	942	932	919	939	958	936	919	907	930
962	951	937	919	943	957	940	912	896	927
943	937	922	914	929	945	922	908	901	920
960	944	943	929	944	966	957	932	908	940
969	954	946	931	950	964	944	928	912	936
975	962	953	934	957	954	952	920	908	934
957	939	928	908	933	946	931	916	888	921
Mean 957±8°	945±9°	935±9°	923±9°	939±9°	951±8°	937±10°	920±9°	903±11°	928±9°

MEASUREMENTS AT MILL C

TABLE 9

Measurement of Temperatures of Ingots at Blooming Mill for 90-pound Rails

HEAT NO. X

Temperature	Time	Temperature	Time	Temperature	Time	Temperature	Time
°C	Seconds	°C	Seconds	°C	Seconds	°C	Seconds
1090	..	1091	66	1099	65	1104	73
1094	..	1091	69	1088	77	1072	76
1101	..	1114	71	1088	68	1094	..
1099	72	1108	68	1082	66		

TABLE 9—Continued

HEAT NO. Y

Temperature	Time	Temperature	Time	Temperature	Time	Temperature	Time
°C	Seconds	°C	Seconds	°C	Seconds	°C	Seconds
1104	..	1094	71	1060	72	1056	76
1121	71	1079	69	1072	70	1059	75
1132	71	1059	72	1060	..		
1100	71	1053	70	1055	73		

Mean temperature=1087±17° C; mean time=71 seconds±3.

TABLE 10

Measurement of Temperatures of Base of 90-pound Rails Opposite No. 1 Bed Immediately Next Hot Saws

HEAT NO. X

Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails	Mean	Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails	Mean
°C	°C	°C	°C	°C	°C	°C	°C
899	902	890	898	923	920	902	915
902	906	898	902	922	916	901	913
899	899	907	901	929	917	903	916
920	910	884	905	910	905	888	901
920	910	884	905	906	902	...	903
906	896	881	894	909	906	878	897
912	912	895	906	896	886	882	888
926	912	892	909				

HEAT NO. Y

918	920	893	910	917	888	873	893
923	922	900	915	902	888	870	886
897	885	873	885	928	900	881	903
912	900	885	898	928	906	884	906
911	906	885	900	920	905	873	898
896	894	878	889	895	890	878	868
905	900	881	895	912	896	881	896
887	...	875	881	910	901	878	896
906	896	875	893	922	908	884	905
920	895	878	897	908	886	868	888
906	890	869	888	910	895	875	894
910	889	874	892	907	901	889	898
906	887	...	896				
916	896	866	893	Mean=911±8	901±8	853±8	899±7
922	898	884	902				

TABLE 11

Rails from Reheated Blooms which had Previously Become Cold

Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails	Mean	Temperatures of A and D rails	Temperatures of B and E rails	Temperatures of C and F rails	Mean
°C	°C	°C	°C	°C	°C	°C	°C
931	922	905	920	931	921	908	920
920	905	882	902	931	922	908	921
918	908	893	907	935	931	921	929
917	908	897	908	930	912	...	921
938	924	909	928	922	920	897	914
924	921	905	916	929	920	912	920
931	931	909	924				
937	930	912	927	Mean=928±6	920±7	904±8	920±6
935	929	...	931				

MEASUREMENTS AT MILL D

TABLE 12

Measurement of Temperatures of Ingots for Rails at Blooming Mill

	Temperature	Time		Temperature	Time
	°C	Seconds		°C	Seconds
Heat No. a...	1074	..	Heat No. e...	1127	38
	1076	..		1144	35
	1088	34		1136	36
	1088	36		1110	38
	1097	..		1112	32
	1091	35		1111	36
Heat No. b...	1112	..	Heat No. f....	1122	38
	1122	..		1123	38
	1121	34		1114	41
	1111	36		1107	36
	1113	32		1104	36
	1112	39		1104	32
Heat No. c...	1106	..	Heat No. g...	1143	38
	1102	41		1144	35
	1088	..		1153	41
	1102	34		1146	33
	1105	..		1138	39
	1115	..		1125	49
Heat No. d...	1131	32		1125	37
	1117	41			
	1126	36			
	1124	37			
	1136	39			
	1128	34			

Mean temperature of all ingots=1118±15; mean time=37±2.3 seconds.

TABLE 13

Measurement of Temperatures of Head of 100-pound Bessemer Rails at Hot Saws

[Each reading is the average for a rail bar (two rails) before being cut. Time from last pass to station=8 seconds; time for rail bar (two rails) to pass observing station=8 seconds.]

Temperature	Temperature	Temperature	Temperature
°C	°C	°C	°C
1043	1056	1045	1030
1066	1053	1037	1044
1047	1045	1043	1006
1056	1048	1045	1053
1056	1047	1043	1037
1039	1048	1069	1034
1048	1057	1047	1064
1054	1053	1056	1049
1053	1057	1044	1023
1053	1034	1043	

Mean=1047±8° C.

TABLE 14

Measurement of Temperatures of Head of 100-pound Open-Hearth Rails at Hot Saws

[Each reading is the average for a rail bar (two rails) before being cut. Time from last pass to station=8 seconds; time for rail bar (two rails) to pass observing station=8 seconds.]

Temperature	Temperature	Temperature	Temperature
°C	°C	°C	°C
980	993	1000	1004
1019	992	1000	998
988	999	1005	1004
968	993	997	1011
956	1009	991	991
953	1016	974	[20] 1005
959	982	975	991
[20] 998	978	987	988
1013	951	1005	972
1013	940	1019	980
1008	956	1021	982
1009	979	1021	991
1002	989	1009	
991	1015	1008	

Mean=992±15° C.

[20] New heat.

TABLE 15

Summary of Ingot Temperatures at Blooming Mill

Mill	Ingots observed	Average temperature	Average time in blooming mill	Remarks
		°C	Seconds	
A	20	1140±10	120±25	Excessive time in pits
	19	1082±16	121±16	In pits 1 hour 35 minutes to 2 hours
B	30	1102±12	91±7	Two heats
C	29	1087±17	71±3	Do.
D	43	1118±15	37±2.3	Seven heats

TABLE 16

Summary of Rail Finishing Temperatures

Mill	A			B	C	D
Location of station	Hot saw				Cooling bed No. 1	Just before hot saws
Distance last pass to station	4			5	3	1
Number of rails	120	70	80	312	171	186
Weight of rails	75	90	100	72	90	100
Type of rail	Bessemer	O. H.	O. H.	O. H.	O. H.	Bessemer and O. H.
(Letters indicate location of rails in ingot)	A & D 924±13 B & E 918±13 C & F 906±15	A & D 976±10 B & E 964±12 C & F 942±7	A & C 988±23 B & D 962±24	A=957±8 B=945±9 C=935±9 D=923±9 E=951±8 F=937±10 G=920±9 H=903±11 Mean ABCD 939±9 Mean EFGH 928±9	A & D 911±8 B & E 901±8 C & F 883±8 2d series A & D 928±6 B & E 920±7 C & F 904±8	Mean of A, B, C, D Bessemer 1047±8 Mean of A, B, C, D O. H. 992±15

An inspection of the data shows that there is practical uniformity among the several mills for the rolling temperatures of ingots for steel rails. the range being from 1080° C (1975° F) to

1140° C (2085° F). With the exception of the Bessemers of mill D, rolled at an average temperature of 1047° C (1917° F), there is no very considerable difference among the finishing temperatures of the rails as observed at the hot saws for the several mills, the range being about 880° C (1615° F) to 990° C (1815° F); or, in other words, the four mills all finished their rails to within 50° C of 935° C (1715° F) on the average, excepting the Bessemers of mill D. This temperature of 935° C is 270° C (520° F) above the mean value, 665° C (1230° F), of the critical ranges of these rail steels. (See sec. 9.) As shown in section 11 on the distribution of temperatures within the head of a cooling rail, the center of the head is some 50° C (120° F) to 60° C hotter than the optical pyrometer reading at 935° C; therefore the center of the head is finished, on the average, at about 325° C (615° F) above the critical range for 100-pound sections.

The tables on finishing temperatures show several other facts of interest. For example, it is evident that it is a possible and easy operation to determine accurately the temperature of each rail length in succession as it arrives at the hot saw. (See in particular Tables 4, 5, 6, and 8.) From the measurements at mill A the relative temperatures of rails differing in weight of section, rolled from ingots having closely the same weights and temperatures, are shown. (See Tables 4, 5, 6, and 16.) Thus the average of the finishing temperatures of the top rails (A and D or A and C) for 100, 90, and 75-pound sections were, respectively, 988°, 976°, and 924°, and similarly for the others.[20a]

6. SAMPLES AND CHEMICAL ANALYSES OF RAIL STEELS

Samples from rails were taken as follows: Mill A, samples 1 to 6, open-hearth, 100 pounds, 7 to 12, Bessemer, 75 pounds; mill B, samples 13 to 23, Bessemer, 72 pounds; mill C, samples 34 to 40, open-hearth, 90 pounds; mill D, samples 24 to 28 and 33, Bessemer, 100 pounds, 29 to 32, open-hearth, 100 pounds.

In Table 17 are given the analyses, as determined at the Bureau of Standards, of several rails from each of the mills, together with

[20a] In June, 1914, additional measurements were taken in mill B, as follows: At hot saw on 100-pound open-hearth rails, average temperature = 948±7° C; at last pass, 1089±10° C; of blooms leaving the reheater, 1257±23° C. (This mill had installed reheater since the measurements of 1913.)

the corresponding heat analyses as furnished by the mills (in case of mill C the rail analyses were furnished). These samples are representative of the composition of the rails, the finishing temperatures of which were observed. Although there are discrepancies, some of them of considerable magnitude, the heat and rail analyses, in general, check fairly well; and Table 17 gives what may be considered as a representative picture of the accuracy to be expected from such analyses as made to-day on a technical basis. Four of the rails were also examined for segregation by taking analyses of head, web and base, the results indicating, in so far as any conclusion can be drawn from so few determinations, that the order of difference in composition throughout a rail may be as great as the difference between heat and rail analyses.

More extended experiments along these lines would be desirable; and, in this connection, the Bureau, in cooperation with a committee of the American Society for Testing Materials, is beginning a study of segregation in test ingots, and this will be extended to a more comprehensive comparison of analyses of heats and finished products.

TABLE 17

Chemical Analyses of Rail Steels

[O. H.=open hearth; Bes.=Bessemer; Ht=heat analysis at mill; Rl=rail analysis at Bureau of Standards; H=head; W=web; B=base, of rail; a=Ni and Co.]

Mill	Heat	Rail No.	Carbon		Sulphur		Phosphorus		Manganese		Silicon		Copper		Nickel		Chromium		Weight of rail
			Ht	Rl	Ht	Rl	Ht	Rl	Ht	Rl	Ht	Rl	Ht	Rl	Ht[a]	Rl	Ht	Rl	
A	O. H.	R 1H	0.64	0.63	0.040	0.032	0.018	0.017	0.77	0.67	0.075	0.037	.....	0.098	0.59	0.30	0.56	0.57	100
		R 1W		.60		.047		.021		.67		.047		.079		.24		.60	
		R 1B		.60		.033		.018		.67		.056		.107		.16		.53	
A	Bes.	R 7H	.43	.43	.065	.091	.056	.072	1.04	.84	.....	.023	.....	.139	.60	.20	.15	.13	75
		R 7W		.46		.051		.068		.75		.022		.112		.19		.17	
		R 7B		.44		.099		.072		.73		.022		.086		.09		.19	
A	Bes.	R 9H	.49	.47	.054	.055	.066	.070	.98	.89	.051	.032	.....	.085	.52	.22	.17	.17	75
		R 9W		.47		.058		.071		.92		.025		.148		.28		.17	
		R 9B		.46		.055		.069		.93		.040		.137		.34		.15	
A	Bes.	R 11	.49	.33	.054	.053	.066	.062	.99	.94	.051	.048	.....	.124	.52	.15	.27	.15	75
B	O. H.	R 22	.59	.63	.042	.042	.023	.027	.63	.67	.....	.101	.....	.109	.....	.10	.....	.10	72
B	O. H.	R 18	.55	.55	.032	.029	.024	.022	.80	.78	.....	.126	.....	.074	.....	.00	.....	.00	72
C	O. H.	R 34	.66	.70	.052	.057	.025	.025	.68	.72	.056	.079	.....	.026	.....	.00	.....	.01	90
C	O. H.	R 35	.65	.57	.032	.027	.018	.017	.67	.57	.056	.033	.....	.014	.....	.00	.....	.01	90
D	Bes.	R 28	.53	.49	.042	.037	.098	.087	.86	.86	.093	.099	.....	.011	.....	.03	.....	.00	100
D	O. H.	R 30	.62	.62	.036	.031	.025	.023	.66	.60	.154	.175	.....	.024	.....	.00	.....	.01	100
D	O. H.	R 32	.73	.69	.040	.036	.036	.033	.80	.73	.149	.144	.....	.008	.....	.00	.....	.01	100
D	Bes.	R 25	.44	.50	.051	.042	.092	.081	.76	.92	.098	.101	.....	.007	.....	.06	.....	.00	100

7. MECHANICAL PROPERTIES OF RAILS

In Tables 18 to 20 are shown the mechanical properties of rails from the several mills (see Table 17 for chemical analyses and mills), as measured by R. P. Devries, of this Bureau, on samples taken as indicated.

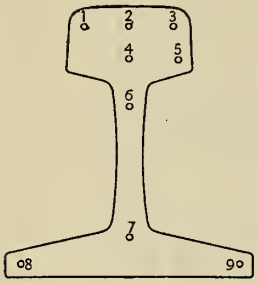

Fig. 2.—*Rail section, hardness survey*

An inspection of the tables shows a considerable variation in properties, especially hardness and ductility. The Brinell hardness numeral, as determined on the rail sections (Fig. 2), indicates in general a harder metal at the center of the head than for any other region of a cross section (Table 18). The values of the ultimate strength (Table 20) are quite uniform, and there is a somewhat less good agreement for modulus of elasticity (Table 19).

TABLE 18

Brinell Hardness Tests on Sections of Rail Parallel to Direction of Rolling

[Pressures applied by method of successive loading in the same indentation]

Rail No.	Hardness numeral [21] in kilograms; for positions—									
	1	2	3	4	5	6	7	8	9	Mean
R1	1025	1075	1034	1055	1000	1213	1043	.....	1043	1061
R7	794	811	758	821	804	774	876	.....	854	811
R9	788	794	760	810	833	772	840	.....	732	791
R11	618	658	642	689	615	678	670	.....	684	657
R18	785	704	800	804	724	712	792	.....	787	764
R22	824	793	880	894	846	834	866	830	870	849
R25	768	712	752	746	704	682	758	682	705	723
R28	764	740	726	779	754	758	786	.....	764	759
R30	724	678	734	840	694	766	772	731	708	739
R32	888	888	852	848	778	880	862	.....	781	872
R35	756	810	780	805	757	779	774	.....	818	785

[21] Hardness numeral is the load in kilograms for 0.1 mm indentation with a steel ball of 10 mm diameter.

TABLE 19

Transverse Tests on Rail Specimens Taken from Flange

[Span 9″; section of specimen 1.″25×0.″37]

Rail No.	Modulus of elasticity (lbs. per sq. in.)	Fiber stress at proportional limit (lbs. per sq. in.)	Brinell hardness numeral in kg.	Rail No.	Modulus of elasticity (lbs. per sq. in.)	Fiber stress at proportional limit (lbs. per sq. in.)	Brinell hardness numeral in kg.
R1	35 000 000	92 500	987	R24	29 680 000	71 700	653
R6	26 720 000	62 800	595	R31	30 020 000	73 800	904
R7	27 300 000	71 200	849	R32	27 900 000	44 800	946
R11	26 080 000	69 900	661	R33	24 600 000	64 000	592
R17	27 700 000	80 600	795	R34	26 400 000	73 300	860
R18	26 300 000	75 100	801	R39	33 100 000	69 400	830
R19	32 170 000	80 800	832				

TABLE 20

Tension Tests of Rail Specimens Cut from Head of Rails

Rail No.	Proportional limit (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Ultimate strength (lbs. per sq. in.)	Elongation in 2 inches in per cent	Reduction of area in per cent	Appearance of fracture
R1	56 000	66 500	126 500	17.5	36.6	Dull granular, 98 per cent Bright granular, 2 per cent
R7	40 000	56 600	112 000	21.5	40.2	Dull granular
R9	37 000	56 200	111 500	21.0	42.8	Dull granular interspersed with 5 per cent bright circular
R11	37 000	49 000	93 400	27.5	51.0	Dull granular
R18	41 000	50 500	106 200	23.5	38.8	Dull granular, 98 per cent; bright granular, 2 per cent
R22	.....	.....	113 000	9.5	8.3	Bright granular
R25	53 000	54 400	109 800	22.0	32.5	Dull granular, 65 per cent Bright granular, 35 per cent
R28	43 000	52 700	107 200	22.5	35.8	Inner circular section 50 per cent dull granular; outer circular section 50 per cent bright granular
R30	30 000	43 000	104 800	20.0	27.6	Dull granular, 30 per cent; bright granular, 70 per cent
R32	47 000	59 600	124 700	9.0	6.6	Bright granular; broke four times in threaded portion of specimen
R24	39 000	56 400	117 000	7.0	8.3	Bright granular
R35	35 000	46 000	104 500	19.0	27.1	Inner circular section 50 per cent dull granular; outer circular section 50 per cent bright granular

8. MELTING TEMPERATURES OF RAIL STEELS

The temperatures at which samples from several steel rails became completely liquid were determined in hydrogen by the method of the micropyrometer [22] and the melting and freezing ranges of two samples in hydrogen vacuum in the Arsem electric furnace. The temperatures as given in Table 21 are reported on the basis of the melting point of pure iron equals 1530° C (2786° F). Some of the irregularities in the table are probably due to lack of homogeneity, especially in the microscopic samples observed with the micropyrometer.

It is interesting to note that steel of the compositions used in rails, at least up to 0.75 per cent carbon, is not completely melted until the melting point of pure iron is nearly reached, 1530° C. Melting of these steels begins and freezing ends, however, in the neighborhood of 1470° C (2680° F).

TABLE 21

Melting Temperatures of Rail Steels

Rail No.	Kind of steel	End of melting with micropyrometer		Melting and freezing ranges	
		Observed	Mean	Melting	Freezing
R 24	Bess.	1510	1516		
		1520			
		1518			
R 32	O. H.	1530	1531	1478 to 1531	1527 to 1454
		1532		1485 to 1527	1533 to 1480
					1515 to 1445
					1531 to 1471
					1531 to 1475
R 40	O. H.	1525	1523		
		1522			
R 14	O. H.	1522	1522		
		1522			
R 22	O. H.	1519	1528	1482 to 1529	1527 to 1465
		1581			
		1533			
		1528			
R 6	O. H.	1527	1528		
		1530			
R 11	Bess.	1528	1525		
		1522			

[22] G. K. Burgess, "A Micropyrometer," Scientific Paper No. 198, Bureau of Standards, 1913; G. K. Burgess and R. G. Waltenberg, "Melting points of the refractory elements, I," Scientific Paper No. 205, Bureau of Standards, 1913.

9. CRITICAL RANGES OF RAIL STEELS

In Figs. 3 and 3*a* are given the first heating and cooling curves by the inverse rate method in vacuo, of samples from several Bessemer and open-hearth rails.[23] The ordinates are degrees centigrade and the abscissæ the number of seconds for the sample to change 2° C in temperature. Each dot represents an observation. The samples were of about 11 g contained within a nickel cylinder of 42 g. The beginning and end of a critical range is, in general, less well defined than its maximum.

In Table 22 are given the location of the critical ranges and rates of heating and cooling, together with the carbon and manganese content of the rails for all the observations taken. It will be noted that on heating all these steels develop a single, well pronounced critical range, the maximum of which, Ac123, is situated for all of them to within 7° C of 732° C (1350° F).

The cooling curves, which are of main interest, all show a very pronounced maximum, Ar1, between the limits 680° C (1256° F) and 650° C (1202° F) and some of the steels relatively lower in carbon show also the Ar23 range between 670° and 690° C. The difference between Ac1 and Ar1 is therefore of the order of 65° C (150° F).

From the thermal data, it follows that all these rails could have had work done on them then to advantage during the rolling process down to 700° C (1292° F), whereas for none of them was the actual finishing temperature lower than 880° C (1615° F).

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[23] The methods and apparatus for determining critical ranges are described at length in the following: "On methods of obtaining cooling curves," G. K. Burgess, Scientific Paper No. 99, Bureau of Standards, 1908; "Critical ranges A_2 and A_3 of pure iron," G. K. Burgess and J. J. Crowe, Scientific Paper No. 213, Bureau of Standards; and "The measurement of high temperatures," G. K. Burgess and H. LeChatelier, 3d ed., 1912, Wiley, Pub.

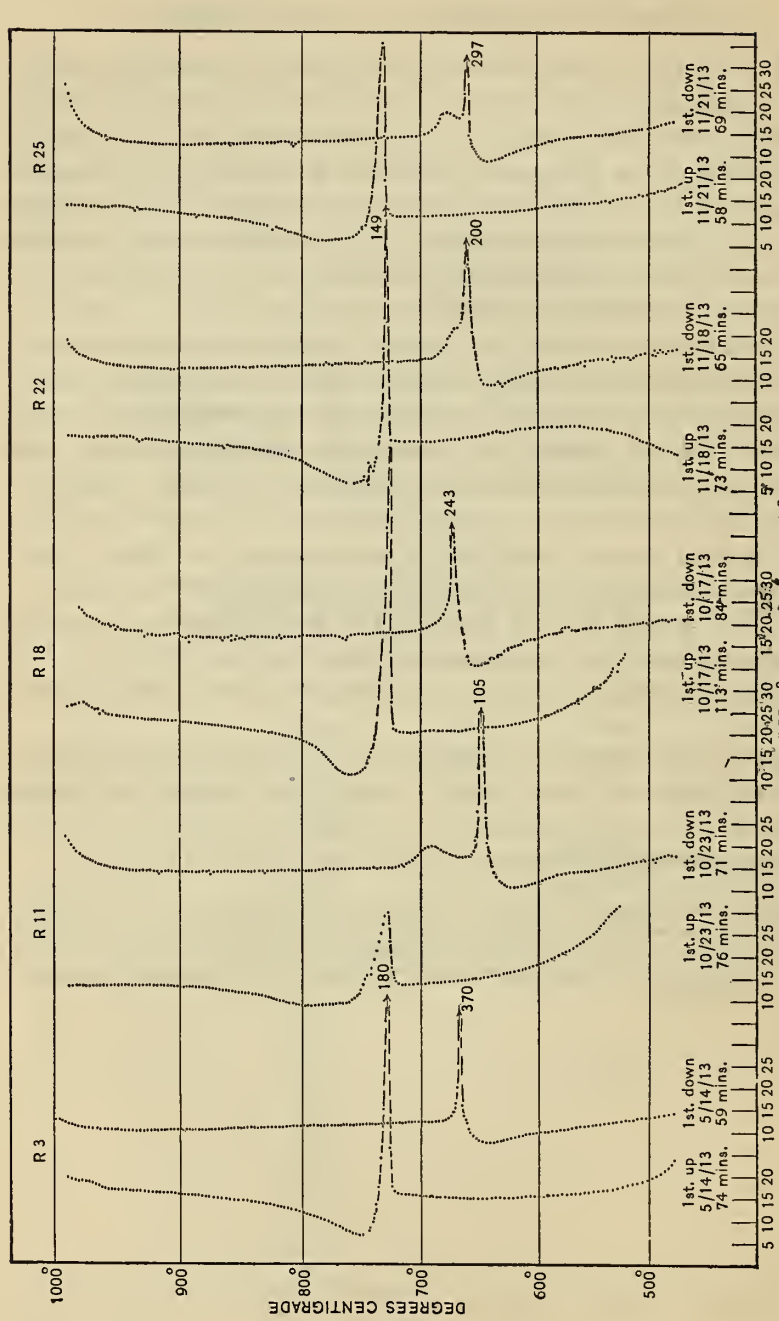

Fig. 3.—*Cooling and heating curves of rail steels*

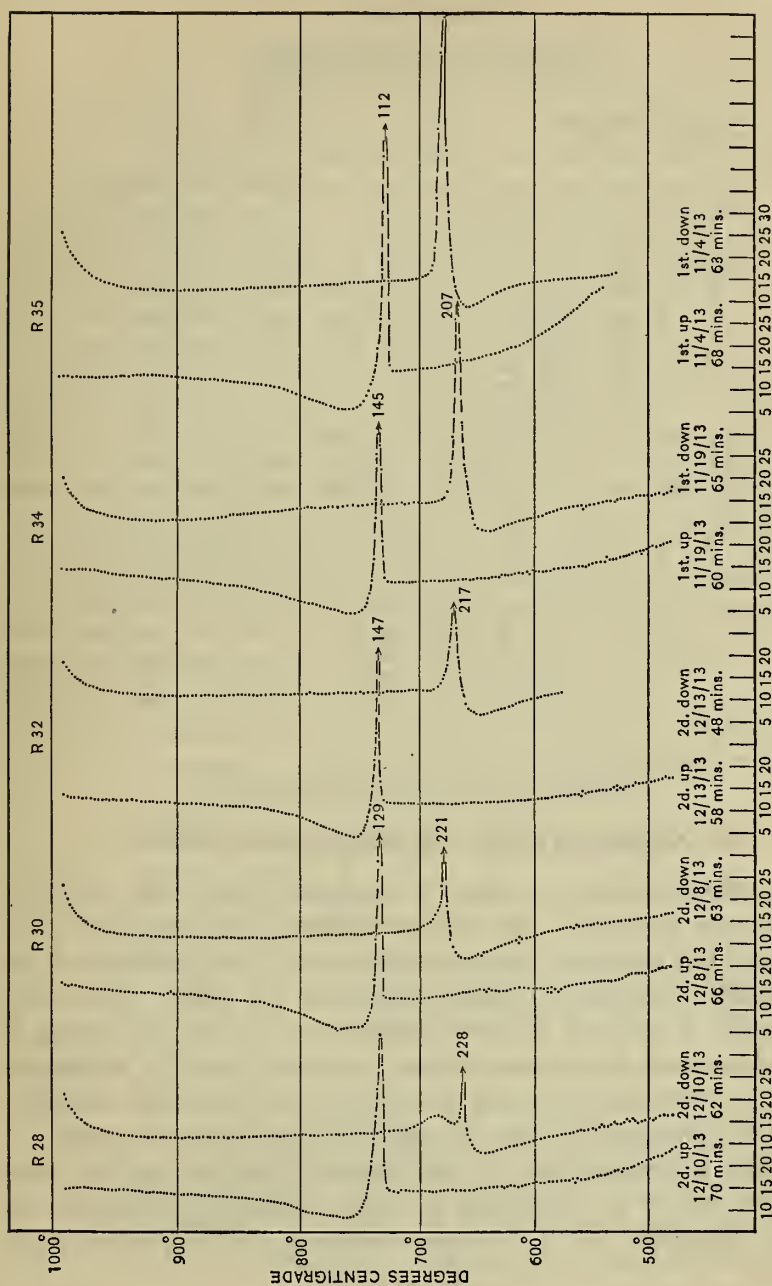

Fig. 3a.—*Cooling and heating curves of rail steels*

TABLE 22

Critical Ranges of Rail Steels

Rail No.	Analysis per cent		Rate=deg secs		Ac123			Ar23			Ar1		
	C	Mn	Up	Down	Begin	Max	End	Begin	Max	End	Begin	Max	End
R3	.....	.....	0.116	0.145	729	*739*	758	.....	.....	.....	691	*675*	653
R11	0.33	0.94	.113	.121	720	*729*	762	720	*692*	664	664	*649*	625
			.252	.156	730	*736*	.....	712	*690*	.....	649	*646*	.....
			.194	.139	726	*733*	742	708	*687*	659	659	*655*	645
			.108	.128	720	*728*	761	719	*697*	664	664	*649*	625
R18	.55	.78	.076	.102	720	*726*	757	.....	.....	.....	729	*674*	654
			.126	.133	727	*729*	.....	.....	.....	.....	693	*673*	.....
			[24].382	.125	720	*734*	758	.....	.....	.....	689	*675*	666
R22	.63	.67	.115	.132	726	*728*	742	690	*672*	668	668	*662*	647
R25	.50	.92	.148	.124	726	*732*	762	695	*678*	667	667	*661*	641
R28	.49	.86	.121	.136	726	*732*	766	690	*672*	660	660	*649*	620
			.....	.....	727	*734*	760	711	*689*	671	671	*662*	647
R30	.62	.60	.125	.134	732	*734*	748	.....	.....	.....	674	*665*	642
			.130	.136	729	*732*	748	.....	.....	.....	711	*676*	664
R32	.69	.73	.150	.132	729	*732*	748	.....	.....	.....	683	*663*	634
			.....	.....	730	*734*	751	.....	.....	.....	687	*670*	649
R34	.70	.72	.143	.132	725	*732*	748	.....	.....	.....	682	*667*	640
R35	.57	.57	.126	.136	725	*737*	757	.....	.....	.....	693	*679*	664
			.105	.084	[24] 725	*731*	757	.....	.....	.....	718	*680*	664
					[24] 729	*731*	744	.....	.....	.....	689	*681*	674

Mean location of maxima: (Ac123) 732°±*3*; (Ar1) 665°±*7*.

[24] Observations with Leeds and Northrup drum recorder.

10. OBSERVATIONS ON MICROSTRUCTURE [25]

The microstructure of steel is dependent upon the chemical composition, especially the carbon content, the heat treatment the metal has received, and, to a less extent, the influence of the mechanical work which is done in shaping the piece. Rail steel, in general, is allowed to cool undisturbedly after the rolling is finished so that the factor of heat treatment may be neglected. Fig. 4 is introduced in order to simplify the necessary explanations and references to the iron-carbon equilibrium diagram. It represents a portion only of the complete diagram and is taken from the report of committee 53 of the International Society for Testing Materials on "The nomenclature of the microscopic sub-

[25] By H. S. Rawdon.

stances and structures in iron and steel." No attempt is made to give the exact temperatures of transformation, and a few features have been added to illustrate the results of some of the work discussed. The line A_1 is apparently too high.

Pure iron, like all solid metals, has a crystalline structure, though the crystals lack the definite geometrical form usually associated with this term. During the solidification of a metal, crystallization begins at a great number of points throughout the mass, and the shape of any individual crystal will depend upon its contact with neighboring ones. The addition of carbon, for the formation of steel, means the introduction of a new constituent into the microstructure. In low-carbon steels, the greater part of the metal is still pure iron, i. e., practically so; this is the ferrite and appears white after the ordinary method of etching. The second constituent, the pearlite, i. e., the one containing the carbon, is a mechanical mixture of two others, the ferrite and a definite compound of iron and carbon, Fe_3C, or cementite. Under low magnifications after the ordinary acid etching pearlite appears dark and homogenous. Examination under higher magnification shows that it is really a very finely laminated mixture of two

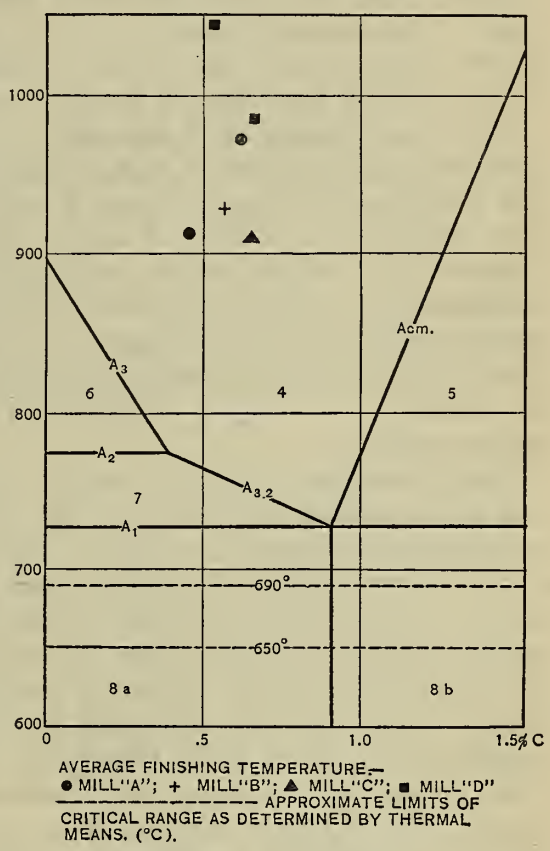

Fig. 4.—*Portion of iron-carbon diagram*

constituents which are alternate lamellæ of ferrite and cementite. As the percentage of carbon is increased the amount of pearlite correspondingly increases at the expense of the ferrite until at the eutectoid composition, about 0.85 per cent C, the whole mass is composed of crystals of pearlite. In steels having carbon contents of 0 to 0.85 per cent, the percentage of pearlite is directly proportional to the carbon content; in steels with a carbon content greater than 0.85 per cent a new constituent, free cementite, appears, and the percentage of pearlite correspondingly decreases.

When the temperature of any steel is raised above the transformation or critical range, i. e., it is represented by some point in area 4 of Fig. 4, the carbon exists in solid solution in the iron. This definite solid solution of carbon in iron, which is called Austenite, is crystalline and the size of crystals depends upon the temperature to which it has been raised above the critical, also upon the sojourn at this temperature. There is also an allotropic change in the iron itself in passing through the critical range so that the variety of iron existing in region 4 is entirely different from that in region 8a.

Upon cooling any steel with a carbon content between 0.00 per cent and something less than 0.85 per cent from a temperature corresponding to some point in area 4, the metal cools uniformly until the upper limit of the critical range is reached (A_3, A_{32} in Fig. 4). As the metal in cooling reaches the temperature represented by the proper point in this line, ferrite begins to precipitate out from the individual crystals of the austenitic mass and is ejected to the exterior of the crystal, thus forming a more or less complete wall or boundary for the crystal. This ejection of ferrite (iron) consequently enriches the remaining central nucleus in carbon. The process of ejection of iron or ferrite is continued until the temperature represented by the line A_1 (Fig. 4) is reached, at which temperature the remaining central austenite crystal has a carbon content of approximately 0.85 per cent, the eutectoid composition, and on further cooling changes bodily into a laminated mass of ferrite and cementite, i. e., pearlite. Further cooling is accompanied by no marked structural change.

Upon heating from below the critical range, the process is reversed as this range is passed through, i. e., the laminated

pearlite grain is changed bodily into a homogeneous solid solution of carbon in iron, austenite, as the lower limit of the transformation range is passed and, as the temperature continues to rise, more and more of the ferrite is dissolved until finally the solid solution of carbon in iron of the concentration corresponding to the carbon content, results as the upper limit of the critical range is reached. Above the eutectoid composition, a similar process goes on with the substitution of free cementite for ferrite as the constituent which is thrown off by the austenite crystal.

The grains of ordinary annealed steel of less than the eutectoid percentage of carbon consist therefore of a central mass of pearlite with a more or less definite boundary of ferrite. In steels of very low carbon content the amount of pearlite is so small that it is often mistaken for the boundary of the crystals of ferrite. Under certain conditions much of the ferrite which is expelled from the austenite during the cooling through the transformation range is retained within the cleavage spaces of the crystal of austenite and the ferrite network is consequently masked.

The study of the microstructure of the rails in question is largely limited to observations on and to measurements of grain size. The steels lie within a comparatively narrow range in carbon content, 0.33 to 0.73 per cent; all but five fall within the limits 0.45 to 0.66 per cent. The only prominent differences in microstructure are the amount of ferrite thrown out during cooling and the size of the crystals. Inasmuch as the investigation deals primarily with the temperature of rolling of the different steels rather than the method of manufacture, the occurrence and amount of impurities, "slag," etc., was not emphasized in the study of the microstructure.

Grain-Size Measurement.—The term "grain size," as ordinarily used to describe the fracture of steel, is a rather loose one and not clearly defined. As here used, in describing the microstructure, it is the number of pearlite grains or cells (with the accompanying ferrite boundary) per unit area of section (square inch). This is easily determined with an accuracy sufficient for the purpose by projecting the magnified image of the polished and etched specimen upon a ground glass screen ruled in inch squares. By means

of an accurately divided microscope slide, the linear magnification at any camera extension may be quickly determined by the direct measurement of the projected image of the divided scale. A linear magnification of 50 diameters was used; each square inch as measured on the screen represents, then $(0.02)^2$ square inch. The centers of the pearlite cells were indicated on the projection screen and the actual number per square inch is quickly calculated. In each rail measurements were taken at four different spots of each of the three samples—one each from head, web, and base—and the average taken for each. In computing the general mean for the rail, weights of 2, 1, and 2 were assigned to the grain count of head, web, and base, respectively, as these numbers represent very closely the relative areas of these three parts. The magnification used, 50 diameters, was found to be the best for general purposes. A lower magnification, e. g., 25 diameters, while giving a larger area for observation, makes the counting laborious and, in the case of the finer-grained steels, the difficulties in counting offset the increased accuracy due to the larger area. The specimens for microstudy were taken as illustrated in Fig. 5.

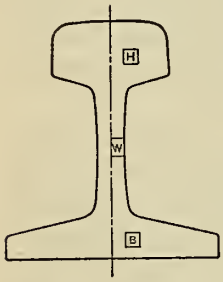

Fig. 5.—*Rail section, microstructure*

Relation of Temperature of Rolling to Microstructure.—The steel, as it comes to the rolling mill, is in the condition represented by a point in area 4 of Fig. 4, i. e., austenite. The effect of the various passes through the rolls is to crush and shatter the crystalline grains. At the temperature at which the rolling is carried on, the molecules of the metal have considerable mobility and consequently any distortion or disarrangement of crystalline structure is quickly repaired and the crystal begins to grow again in size until the next pass through the rolls repeats the distorting process. The latter passes, therefore, represent the temperature range which determines the size of the austenite crystals and subsequently the "grain-size" of the finished product. The nearer the temperature of the latter passes is to the upper limit of the critical range the smaller will be the austenite crystals and consequently the final "grain-size" of the steel.

If the rolling is continued down into the critical range, the microstructure of the finished rail will show this by the distortion of the ferrite which is precipitated in passing through this range. If rolling is carried on much below the lower limit of the range, the "pearlite-point," the distortion of both ferrite and pearlite crystals will record this fact.

The pyrometric observations upon the different rails during the process of rolling show that this process was finished well above the critical range of the steel. The microscopic examination confirms this in every one of the 40 rails. An examination of the photomicrographs given which illustrate the typical structure of the rails they represent shows that the ferrite outline of the pearlite grain has not been distorted or disturbed in the least after being formed. The rolling process with its attendant crushing and distortion of the crystalline structure of the austenite crystal has been completed before any ferrite appeared. In nearly all of the rails, the size of the pearlite cells indicate that the rolling process was discontinued at a temperature well above the upper limit of the critical range so that the crystal (then austenite) has time to reorient itself and grow to a fair size before any ferrite appeared. In Fig. 4 the average temperature at which the rolling was completed is indicated and, in all cases, is a considerable distance above the critical range as determined by direct thermal observations.

No definite conclusions can be drawn as to the relation of grain size and finishing temperature. The maximum difference in temperatures observed is approximately 135° C. Rails 1–6 of mill A and 34–40 of mill C, finished at approximately 908° C, are the coarsest of the series, but this large grain size may be the resultant of two important factors, high finishing temperature and large rail section, i. e., less "work" in rolling the stock.

The statement is sometimes made that the finishing temperature of rolled steel is equivalent to the highest temperature of objects heated but not rolled or forged so far as "grain size" is concerned.[26] The results here obtained do not seem to bear out this contention entirely. Though finished at a relatively high

[26] H. M. Howe: Proc. Am. Soc. Test. Materials, 11, p. 340; 1911.

temperature, the resulting structure is not to be described as excessively coarse. The average grain size of 29 rails in which a count could be made with certainty is 34 600 which is inclined toward the medium fine-grained rather than the extremely coarse.[27] The most striking variations from this mean value are rails Nos. 29, 38, and 40 (Table 23), in which both the head and base are coarsest of any observed.

TABLE 23

Rail No.	Mill	Wt.	Average finishing temperature	Kind	Mn.†	C.†	Number of grains per square inch			
							Head	Web	Base	Average
		Pounds	° C							
1	A	100	975±23	O. H.	0.67	0.61	(*C)	(*)	(*C)	(C)
2	A	100	975±23	O. H.	.67	.61	19 500	(*)	(*)	(C)
3	A	100	975±23	O. H.	.67	.61	(*)	(*)	(*)	(C)
4	A	100	975±23	O. H.	.67	.61	14 600	30 000	17 500	18 800
5	A	100	975±23	O. H.	.69	.59	(*C)	(*C)	(*C)	(C)
6	A	100	975±23	O. H.	.69	.59	(*)	(*)	(*)	(*)
7	A	75	916±13	Bess	.77	.44	43 100	40 300	28 600	36 700
8	A	75	916±13	Bess	.98	.49	33 800	53 500	43 900	42 000
9	A	75	916±13	Bess	.91	.47	19 800	25 700	17 700	35 700
10	A	75	916±13	Bess	.99	.46	11 900	38 200	43 700	29 900
11	A	75	916±13	Bess	.94	.33	30 700	44 500	48 200	40 500
12	A	75	916±13	Bess	.96	.43	18 700	29 700	41 300	29 200
13	B	72	934±9	O. H.	.78	.55	35 500	43 000	53 500	44 200
14	B	72	934±9	O. H.	.78	.55	41 000	58 500	61 400	52 700
15	B	72	934±9	O. H.	.78	.55	20 100	61 500	46 700	39 000
16	B	72	934±9	O. H.	.78	.55	33 900	45 900	43 200	40 000
17	B	72	934±9	O. H.	.78	.55	39 000	66 300	73 400	58 200
18	B	72	934±9	O. H.	.78	.55	15 200	60 600	51 100	38 600
19	B	72	934±9	O. H.	.78	.55	45 600	61 000	57 600	53 500
20	B	72	934±9	O. H.	.78	.55	41 500	52 200	55 500	49 200
21	B	72	934±9	O. H.	.78	.55	33 700	49 200	49 700	43 200
22	B	72	934±9	O. H.	.67	.63	36 400	54 300	53 500	46 800
23	B	72	934±9	O. H.	.67	.63	33 700	57 000	57 000	47 700
24	D	100	1 047±8	Bess	.84	.52	(**C)	(**C)	(**C)	(**C)
25	D	100	1 047±8	Bess	.92	.50	15 800	38 400	23 500	23 400
26	D	100	1 047±8	Bess	.84	.52	28 500	54 000	27 500	33 200
27	D	100	1 047±8	Bess	.84	.52	37 700	43 500	27 000	34 600
28	D	100	1 047±8	Bess	.86	.49	32 200	71 300	21 100	35 600
29	D	100	992±15	O. H.	.64	.65	10 000	24 400	15 000	15 300
30	D	100	992±15	O. H.	.60	.62	12 200	47 900	47 900	33 600

* Not enough ferrite precipitated to permit of a grain count with certainty.

** Too much ferrite in cleavage planes of the crystals which so breaks them up that no count can be made.

C Rather coarse; estimated by comparison as approximately 20 000 g. per square inch.

† The C and Mn. percentages were taken from B. S. analyses where available; otherwise from the heat analyses.

[27] The scale of reference is that proposed by Robt. Job. Wm. H. Sellew, Steel Rails, p. 424.

TABLE 23—Continued

Rail No.	Mill	Wt.	Average finishing temperature	Kind	Mn.	C.	Number of grains per square inch			
							Head	Web	Base	Average
		Pounds	° C							
31	D	100	992±15	O. H.	.82	.73	(*)	(*)	(*)	(*C)
32	D	100	992±15	O. H.	.73	.69	(*)	(*)	(*)	(C)
33	D	100	1 017±8	Bess	.76	.44	(**)	32 300	(**)	.....
34	C	90	908±8	O. H.	.72	.70	(*)	(*)	21 500	(C)
35	C	90	908±8	O. H.	.57	.57	17 200	45 000	17 000	22 700
36	C	90	908±8	O. H.	.67	.65	(10 000 est.)	48 900	12 500	18 800
37	C	90	908±8	O. H.	.67	.65	13 800	29 100	18 400	18 700
38	C	90	908±8	O. H.	.67	.65	11 200	25 500	14 100	15 200
39	C	90	908±8	O. H.	.68	.66	(est. ½ W)	43 300	(est. ½ W)	26 000
40	C	90	908±8	O. H.	.67	.65	13 200	22 200	16 500	16 300

* Not enough ferrite precipitated to permit of a grain count with certainty.

** Too much ferrite in cleavage planes of the crystals which so breaks them up that no count can be made.

C Rather coarse: estimated by comparison as approximately 20 000 g. per square inch.

William Campbell has called attention to this point.[28] He states that rails finished, e. g., at 1000° C are not to be classed as coarse-grained material; that reheating rail steel to this same temperature will render it very coarse in comparison.

It would appear probable, then, that the restoration of the crystalline arrangement which is so badly shattered by the squeezing action of the rolls is not so rapid as is generally supposed, and though the restoring process begins immediately after the rolling ceases it is not complete until at a lower temperature, which in fact is the temperature which determines the grain size of the finished product.

Grain Size v. *Amount of Reduction.*—One of the important factors in the determination of the grain size of the rolled piece is the amount of reduction in the rolls. A comparison of the results given in Table 23 shows that for two rails finished at practically the same temperature, the one having the smaller cross section is very much finer grained. The average grain size of the 90-pound and 100-pound rails is 24 000 per square inch, while that of the 72-pound and 75-pound rails is 42 800 per square inch. This is also illustrated by the different parts of the same rail; the web is

[28] Proc. Am. Soc. Test. Materials, 8, p. 353; 1908.

found to have a much finer grain in nearly every case than either the head or base, as is to be expected. The average of the measurements made on 29 rails in which the ferrite network was distinct enough to permit a reliable count gives the following: Head, 26 200 per square inch; web, 44 800 per square inch; base, 36 900 per square inch. These give a practicable working ratio of 2:4:3. The temperature variation throughout the rail and the difference in the rate of cooling in head, web, and base, while exerting some influence upon grain growth, are not great enough to mask or materially alter the effect of the amount of reduction.

Though no definite conclusions can be drawn as to the relative importance of this factor in determining the final structure, since the difference in practice of the various mills, especially in the case of the heavier rails, makes a close comparison impossible; the results are very suggestive, however, and emphasize the importance of further investigation along this line.

Mechanical Properties v. *Grain Size.*—The relation of grain size to mechanical properties is too well determined to require any further support. The results obtained with some of the steels in question are, however, interesting in that they appear as striking exceptions. The following short table (24) is given by Sauveur as typical results showing the variations in mechanical properties with increasing grain size.[29]

TABLE 24

Grains per square inch	Tensile strength per square inch	Elongation of length	Reduction of area
		Per cent	Per cent
44 000	99 000	15	20
54 000	100 000	19	22
104 000	110 000	22.5	35

A comparison of Tables 20 and 23 shows much higher tensile strengths, as well as other mechanical properties with coarser grained steels than is indicated above. The following are a few of the most striking exceptions. Since the tensile specimen was from the head the grain size given is that of the head rather than the mean for the rail.

[29] W. H. Sellew: "Steel rails," p. 424.

TABLE 25

Rail No.	Grains per square inch	Ultimate strength, pounds per square inch	Reduction in area	Elongation in 2 inches
			Per cent	Per cent
9	27 300	111 500	42.8	21.0
18	15 200	106 200	38.8	23.5
30	12 200	104 800	27.6	20.0
11	30 700	93 400	51.0	27.5

The results are interesting, however, in emphasizing the fact that the material used for any such comparison must always be strictly defined. Nos. 9, 18, and 30 are of progressively increasing carbon content (0.47, 0.55, and 0.62 per cent) and hence of decreasing percentages of ferrite. This explains, in part at least, the apparent contradiction in properties. No. 11 is low in carbon (0.33) and hence high in ferrite, which accounts for its apparent low tensile strength in spite of the finer grain size. For the accurate determination of the relation between grain size and mechanical properties, it is imperative that the steels compared be of the same composition chemically and differ in no other important respects save in grain size. No such comparison is possible here.

Chemical Composition v. *Microstructure.*—The presence of a high manganese content materially modifies the microstructure of an iron carbon alloy. The general effect of manganese and nickel also is to render the metal slower in its response to any transformation or change, either on heating or cooling.[30] All of the rail steels examined are relatively high in manganese, i. e., they have much more than is actually required to combine with the sulphur present. To this influence of the excess of manganese is to be ascribed the sharp definite boundaries of ferrite surrounding the grains of pearlite. Ordinarily the ferrite coalesces and gathers together while in a semiplastic state during slow cooling under the action of its surface tension, thus obscuring the clear outlines of the network. This action is hindered and partially prevented by the retarding influence of the manganese and this explains why the ferrite net work is clear and definite even after

[30] H. M. Howe: Proc. Am. Soc. Test Materials, 11, p. 365, 1911.

rather slow cooling. The amount of ferrite precipitated also is usually less than is expected from the carbon content.

This is especially true of the open-hearth rails. Due to the higher carbon content of these steels, the influence of the manganese, which is here considerably less than in the Bessemer rails, is great enough to almost entirely prevent the appearance of any ferrite in some cases. The rails thus have the structural appearance of eutectoid steels at low magnification. That the amount of reduction in the rolls bears some relation to the amount of ferrite precipitated seems possible from a comparison of the results obtained with open-hearth rails of different sections (Table 23 and photomicrographs). Though cooled at a slower rate than the rails of smaller section and in some cases finished at a lower temperature (rails 34 to 40) the heavier rails in all cases have a much fainter ferrite network than do the rails of smaller section. This appears to be the case even when the carbon contents of the two sizes are practically the same. (Rails 22–23 *v.* 1–4.) This apparent relation may, however, be only fortuitous. In the Bessemer rails which are lower in carbon, the influence of the manganese is not enough to prevent the precipitation of the ferrite but does hinder its coalescence and makes possible the clear outlines for the grains which are observed. The rate of cooling must be considered in this also. The steel then has the structural appearance, and properties also, of one of higher carbon content. In using the microscopical method for the estimation of carbon in steel, this point merits consideration. This indirect effect of manganese upon the structure of carbon steels is perhaps not as well known by some users of steel as it should be.

Summary.—1. An "effective finishing temperature" somewhat below the observed one is suggested as a possible explanation why rails finished, e. g., at 900°–1000° are not as coarse grained as might be expected.

2. So far as can be judged from the data in hand the amount of reduction of section in the rolls appears to be as effective in determining the grain size as any other factor.

3. For the determination of any numerical relation between mechanical properties and grain size a study of the same kind of steel under varying conditions is essential.

4. The effect of manganese in retarding the condition of equilibrium during cooling is an important one upon the structure and properties of rail steel of composition similar to the 40 rails studied.

Representative photomicrographs illustrating the microstructure typical of the different conditions are given in Figs. 12, 13, 14, and 15, at the close of the paper.

11. TEMPERATURE DISTRIBUTION IN A COOLING RAIL

In order to determine how much the readings of the optical pyrometer differ from the true temperatures of the inner metallic surface and center of railhead, measurements were made in the laboratory on the cooling of a 24-pound length of a 100-pound rail section (for analysis, see R. 30 of Table 17) 8½ inches long, which was heated in a muffle to a uniform temperature throughout of about 1070° C, then removed from muffle and allowed to cool in the air, resting on its base.

As shown in Fig. 6 for one of three series, measurements of the temperature of the center of head (A) and inner surface (B) were taken with thermocouples and the head was also sighted upon at B with the same optical pyrometer used in the mills. (See sec. 5.) The three time-temperature cooling curves obtained (1) with thermocouple at center of head A, indicated by + + +; (2) with another couple at surface B, indicated by × × ×; and (B) with optical pyrometer, indicated by ⊙ ⊙ ⊙; all show the critical range very markedly, and even the optical pyrometer detects the recalescence or rise in temperature accompanying the reaction.

It will be seen that, after cooling has set in, the center of the head remains about 40° C (100° F) to 30° C hotter than the inner surface until the critical range is approached, when the rail takes on a nearly uniform temperature throughout. The readings of the optical pyrometer are about 40° C lower than the inner surface temperature at 1000° C (1830° F) and 80° C lower than the center of the head, but all three become practically identical from 800° C (1470° F).

In Table 26 are given the relations between these various temperatures for the three series taken. The observations with the optical pyrometer were made by a different observer for each

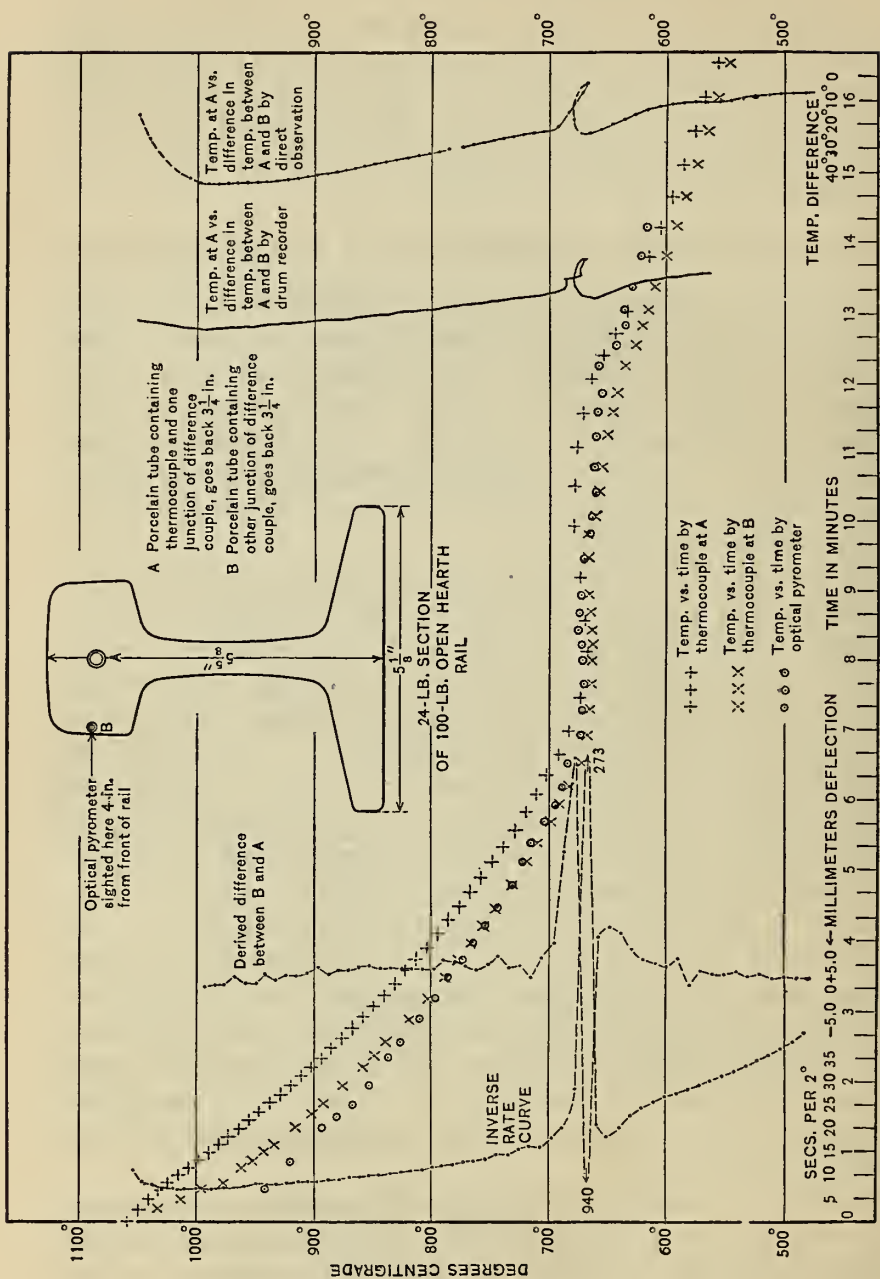

Fig. 6.—*Cooling of 100-pound rail section*

series. It is evident that the three series are in substantial agreement. The average time for the rail to cool from 1070° C to the beginning of the critical range, 670° C, was 8 minutes 30 seconds.

In Fig. 6 are also shown other types of cooling curves taken simultaneously with the above, namely, the inverse rate curve taken with the thermocouple at A; the derived difference curve taken with the thermocouple at A, and a differential thermocouple, the junctions of which are at A and B, respectively; and two difference curves, one giving the temperature of A in terms of the difference in temperature between A and B by direct observations of the thermocouple readings, and the other giving the same phenomenon taken with a Leeds and Northrup drum recorder connected in parallel with the observing circuits. The cooperation of five observers was required to obtain the data for all the plotted curves.

TABLE 26

Temperature Distribution in 100-pound Rail Cooling from 1070° C

Time intervals	With thermocouples		With optical pyrometer outer surface at B	Average differences	
	Center of head at A in fig. 6	Inner surface at B in fig. 6		(2)-(3)	(2)-(4)
(1)	(2)	(3)	(4)	(5)	(6)
Secs.	°C	°C	°C	°C	°C
40	1050	1040	---	15	70
38		1035	---		
([31])	----	---	---		
40	1000	955	920	40	85
41		970	915		
36		950	910		
42	950	905	885	40	70
44		920	885		
38		905	870		
51	900	860	845	35	55
51		870	850		
43		865	845		
56	850	810	805	30	40
56		825	810		
50		820	805		
64	800	765	765	25	30
66		780	775		
57		775	770		

[31] Third series from a temperature less than 1070° C.

TABLE 26—Continued

Time intervals	With thermocouples		With optical pyrometer outer surface at B	Average differences	
	Center of head at A in fig. 6	Inner surface at B in fig. 6		(2)-(3)	(2)-(4)
(1)	(2)	(3)	(4)	(5)	(6)
Secs.	° C	° C	° C	° C	° C
80	750	720	720	20	20
80		730	730		
70		735	735		
75	700	675	685	15	10
67		685	690		
66		685	700		
288	670	665	670	5	0
295		665	675		
258		665	...		
	650	630	640	10	0
		635	660		
		655	...		

12. EXPANSION OF RAIL STEELS

The determinations of the expansion of rail steels were made on strips 50 by 0.95 by 0.65 cm, cut from representative steel rails from the several rail mills. The expansion apparatus was kindly loaned by Dr. A. L. Day, director of the Geophysical Laboratory, Carnegie Institution of Washington.

The bars were cut from the flange of the rails, and as the rail lengths at our disposal were less than 50 cm it was necessary to weld two pieces to obtain a specimen for expansion. Platinum inserts were put in the ends of the specimens and 0.5 mm divisions were marked with a dividing engine. The telescopes, fitted with micrometer screws, were sighted on these divisions. All the bars were heated in an oxidizing atmosphere (air), no attempt being made to close the small openings through which the telescopes were sighted. The bars oxidized slowly, but hardly enough to influence their expansion. Bar 7–11 was packed in steel filings inclosed in a marquardt tube. The filings oxidized and expanded, binding the bar. This probably accounts for the

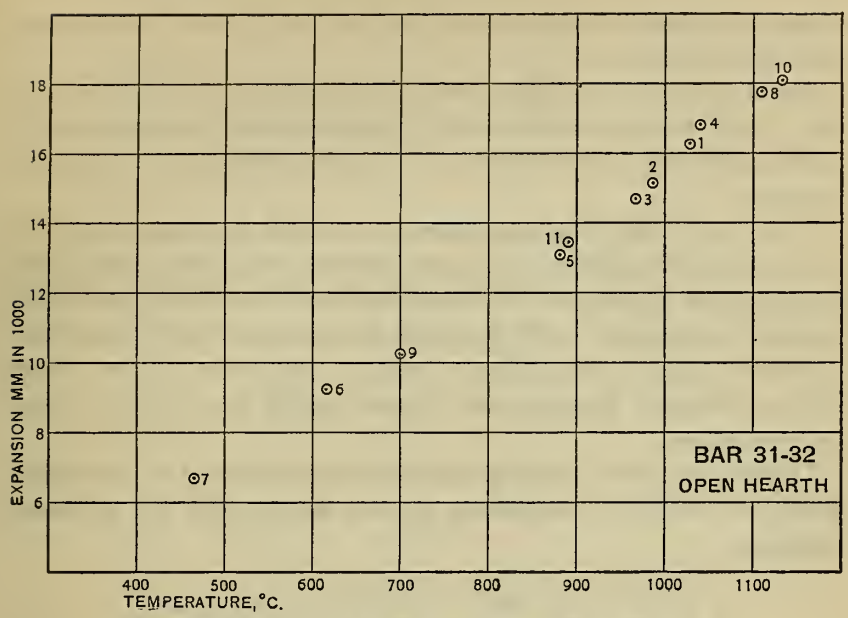

Fig. 7.—*Expansion observations of open-hearth steel*

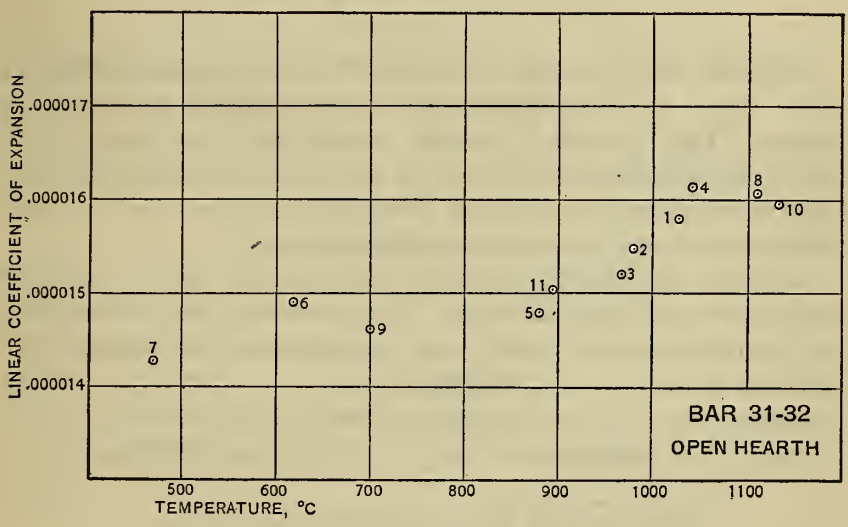

Fig. 8.—*Expansion coefficient of open-hearth steel*

unusual increase in length found for this bar at room temperature after each heating.

The data and results given in Tables 27 to 30 and in Figs. 7, 8, and 9 show determinations of the expansion and expansion coefficient at different temperatures for an open-hearth and a Bessemer specimen.

It appears that the expansion coefficient increases with the temperature, the increase for open-hearth steel being much more than that for Bessemer. It was also found that with some of the bars the expansion would increase on repeated heatings, so that in showing graphically, Figs. 10 and 11, the values of the expansion at different temperatures more weight was given to early determinations.

The dotted curves of these figures show the results of determinations by Driesen [32] on cooling carbon steels with the following analyses:

Fig.	C	Mn	Si	P	S	Cu
10	0.81	0.10	0.06	Tr.	0.025	0.02
11	0.56	0.09	0.04	Tr.	0.023	0.02

He found, as have other observers,[33] that on heating steel above 700° C there is a contraction, and a corresponding expansion on cooling. This feature is plainly marked in the curves. Our results would indicate this break in the expansion, but as we were interested primarily in higher temperatures, the exact location and extent of this change was not investigated.

Quite an appreciable difference was found in the expansion of open-hearth and Bessemer rails. An open-hearth rail, of the chemical composition here given, with a shrinkage after rolling of 6 inches in 33 feet would be finished at 975° C, or 1790° F, while a Bessemer with the same shrinkage would be finished at 1030° C, or 1890° F, a difference of 100° F. This great difference in the

[32] Joh. Driesen, Ferrum, 5, p. 17; 1914.

[33] Svedelius, Phil. Mag., **96**, 1898; Charpy and Grenet, C. R., **134**, 1902.

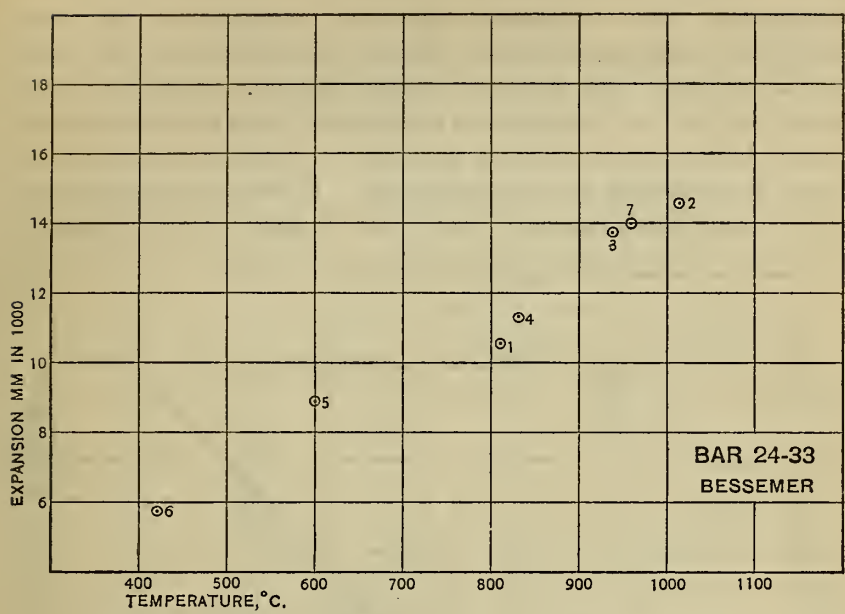

Fig. 9.—*Expansion observations of Bessemer steel*

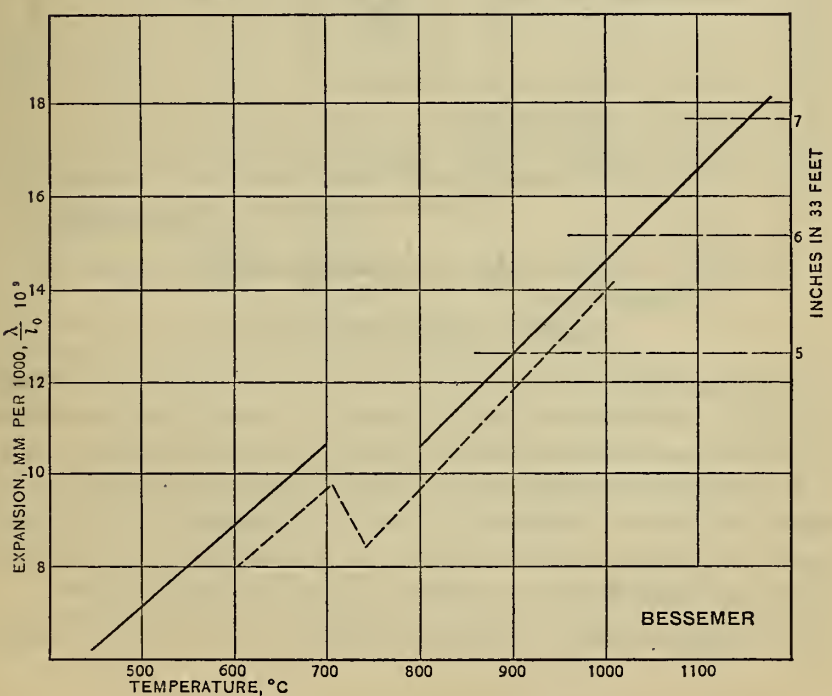

Fig. 10.—*Expansion of Bessemer steel*

shrinkage of the two classes of rails does not appear to have been considered in rail specifications, although this difference must have been detected in mill practice.[34] This difference is probably still greater for the very high carbon open-hearth rails now so common.

Any change in the finishing temperature makes a corresponding change in the length of the finished rail. If the hot saws are set to cut a 33-foot open-hearth rail at 1800° F, 980° C, a shrinkage of

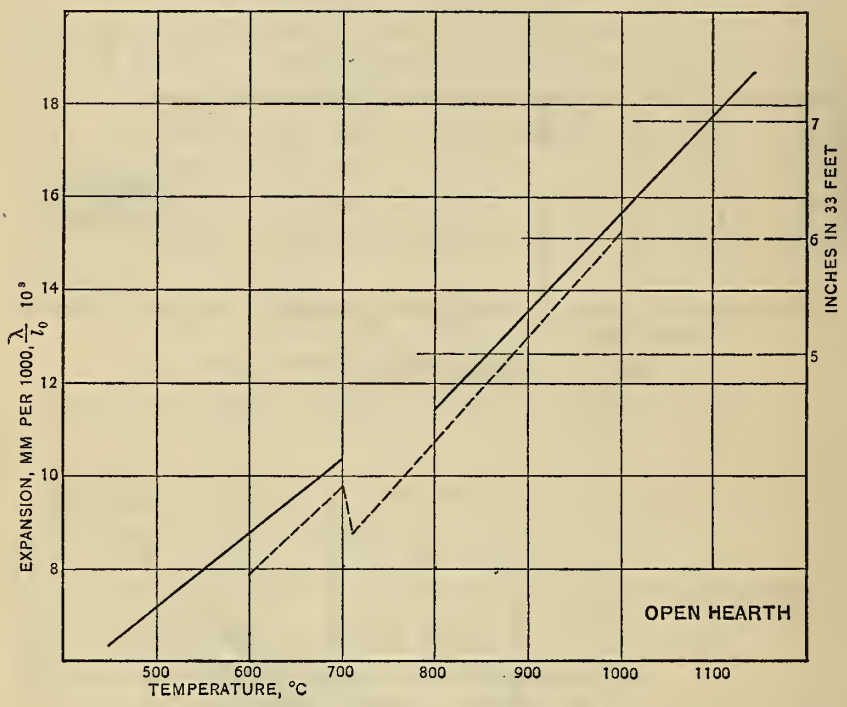

Fig. 11.—*Expansion of open-hearth steel*

$6\frac{1}{16}$ inches must be allowed. If another rail with the same setting of the hot saws is cut at 1900° F, 1040° C, the shrinkage would be $6\frac{9}{16}$ inches, and the final length would be ½ inch less than 33 feet. Rail specifications usually allow ¼ inch variation from the desired length, so that a variation of 100° F in finishing temperature appears to be more than sufficient to differentiate the rails that would pass from those that would not pass the specifications.

[34] See, for example, S. S. Martin, Rail rolling at lower temperatures in 1901. Iron Age, 68, p. 4; sec. 26; 1901.

In Figs. 10 and 11 are given the expansions in millimeters per 1000 mm for the Bessemer and open-hearth rails, respectively. The mean expansion coefficient for any temperature (C) may be obtained[35] by dividing the expansion by that temperature × 1000.

TABLE 27

Bar 24–33

[Bessemer rails; bars electrically welded. Analysis: C, 0.50; S, 0.042; P, 0.081; Mn, 0.93; Si, 0.101; Cu, 0.007; Ni, 0.06; Cr, 0.00]

Date	Length—		Temperature t° C	Expansion	
	At 20° C	At t° C		In 500 mm 0–t	Coefficient
	Mm	Mm		Mm	
November 25, 1913	500. 25				
Do		505. 08	810	5. 29	. 00001305
Do	499. 96				
November 28, 1913	499. 90				
Do		506. 73	1014	7. 25	1429
November 29, 1913	499. 70				
Do		505. 79	936	6. 87	1469
December 1, 1913	499. 12				
Do		504. 31	830	5. 67	1367
Do		303. 08	600	4. 42	1473
Do		501. 58	423	2. 90	1371
December 2, 1913	498. 81				
Do		505. 59	968	6. 99	1444

[35] Sample computation of expansion (see formula, sec. 4): Take from Table 29, rail bar 31–32, the observation at 1028° C. Assume the coefficient of expansion between 0° and 20° the same for all rails, or $\alpha^{20}_{0}=0.000011$.

Expansion from 20° to 1028°: 507.17−499.29=7.88 mm.

Length at 20° C=l_{20}=500−7.88=492.12 mm.

Length at 0° C=$l_0=\frac{492.12}{1+0.000011\times 20}$=492.01 mm.

Expansion 0° to 1028° C=500−492.01=7.99 mm.

Mean coefficient between 0° and 1028° C: $\alpha^{t}_{0}=\frac{7.99}{492.01\times 1028}=0.00001580$

Expansion: mm in 500 between 0° and 1028° C: 0.00001580×500×1028=8.13 mm.

TABLE 28

Bar 7–11

[Bessemer rails; bars threaded together and welded with oxyacetylene. Analysis: C, 0.39; S, 0.071; P, 0.067; Mn, 0.90; Si, 0.035; Cu, 0.105; Ni, 0.12; Cr, 0.17]

Date	Length—		Temperature t° C	Expansion	
	At 20° C	At t° C		In 500 mm 0–t	Coefficient
	Mm	Mm		Mm	
January 23, 1914	499.98				
Do		507.18	1051	7.42	.00001412
Do		506.39	919	6.61	1438
Do		506.20	855	6.41	1500
January 24, 1914	501.37				
Do		508.28	1040	7.12	1369
January 26, 1914	501.65				

TABLE 29

Bar 31–32

[Open-hearth rails; bars threaded together and welded with oxyacetylene. Analysis: C, 0.66; S, 0.033; P, 0.028; Mn, 0.66; Si, 0.160; Cu, 0.016; Ni, 0.00; Cr, 0.01]

Date	Length—		Temperature t° C	Expansion	
	At 20° C	At t° C		In 500 mm 0–t°	Coefficient
	Mm	Mm		Mm	
February 18, 1914	499.97				
Do		507.17	1028	8.13	.00001580
Do		506.65	980	7.59	1548
Do		506.43	968	7.36	1520
February 20, 1914	499.29				
Do		506.92	1042	8.41	1614
Do		505.09	880	6.51	1480
Do		503.21	617	4.60	1492
Do		501.98	470	3.35	1427
Do		507.42	1110	8.92	1608
February 21, 1914	498.76				
February 24, 1914	498.68	503.64	701	5.12	1461
Do		507.02	1132	9.03	1595
Do		504.78	894	6.72	1503
February 25, 1914	498.26				

TABLE 30

Bar 34–39

[Open-hearth rails; bars threaded together and electrically welded. Analysis: C, 0.70; S, 0.057; P, 0.025; Mn, 0.72; Si, 0.079; Cu, 0.026; Ni, 0.00; Cr, 0.01]

Date	Length—		Temperature t° C	Expansion	
	At 20° C	At t° C		In 500 mm 0–t° C	Coefficient
	Mm	Mm		Mm	
January 9, 1914	499.96				
Do		507.37	1040	8.31	.00001599
January 10, 1914	499.30				
January 12, 1914		508.11	1036	9.10	1757
Do		507.45	904	8.42	1863
January 13, 1914	499.28				
Do		508.11	1021	9.43	1848
Do		507.15	909	8.44	1857
January 15, 1914	498.96				
Do		503.43	621	4.54	1462
January 16, 1914	499.04				
Do		503.30	625	4.41	1411
Do		502.06	462	3.15	1364
Do		509.19	1022	10.34	2023
January 17, 1914	499.17				

Shrinkage Measurements.—In addition to the measurements on the expansion of the 50 cm specimens of rails, one series of shrinkage observations was taken in mill B on 75 open-hearth 100-pound G section rails. (See Table 31.) The rails had the following heat analysis: C=0.710; Mn=0.90; P=0.025; S=0.045; Si=0.100.

First, the distance between the hot saw and stop was carefully measured with a steel tape, then as the rails were stopped under the hot saw the temperatures were measured and a note made of the thickness of the paddle used against the stop. The rails were marked and left on the cooling beds over night and the length of each measured cold.

From the observations thus obtained the coefficient of shrinkage was found to be 0.0000161,[35a] which is in good agreement with the

[35a] Computation of shrinkage coefficient:

Temperature of rails as measured with pyrometer, 947° C.
Temperature of rails corrected by Table 26, 997°.
Shrinkage of rails, measured at 25° C, 6.24 inches.
Shrinkage of rails, corrected to 0° C, 6.35 inches.
Length of rails, 396 inches.

$$a=\frac{6.35}{997\times 396}$$

$$a=0.0000161$$

results obtained on the shorter lengths for the expansion coefficient of open-hearth rails, namely, $\alpha = 0.0000156$.

TABLE 31.—Shrinkage Measurements on Open-Hearth 100-Pound G Section Rails

Mean ABCDEF=947° C.=0.520 feet=6.24 inches

A rail		B rail		C rail		D rail		E rail		F rail	
Temperature	Shrinkage	Temperature	Shrinkage	Temperature	Shrinkage	Temperature	Shrinkage	Temperature	Shrinkage	Temperature	Shrinkage
° C	Feet	° C	Feet	° C	Feet	° C	Feet	° C	Feet	° C	Feet
974	0.530	951	0.517	945	0.509	970	0.541	949	0.518	939	0.509
950	.528	930	.520	.....	.....	968	.530	948	.505	.....	.....
945	.529	934	.518	936	.509	945	.528	928	.519	.....	.....
959	.540	954	.519	945	.504	965	.535	958	.520	948	.510
939	.520	943	.500	930	.514	959	.530	956	.510	944	.509
951	.530	943	.505	.....	.....	968	.530	958	.530	.....	.....
975	.530	965	.520	.....	.....	960	.520	943	.502	.....	.....
954	.530	951	.505	951	.501	945	.530	945	.520	935	.511
958	.530	957	.515	946	.507	949	.535	956	.515	939	.514
928	.525	934	.520	928	.519	936	.520	943	.515	934	.528
951	.541	943	.510	930	.500	951	.525	923	.510	.....	.....
958	.540	943	.510	936	.529	945	.510	926	.514	.....	.....
961	.540	956	.522	950	.514	948	.532	945	.528	939	.517
953	.540	956	.525	945	.524	953	.530	946	.510	934	.511
Mn 954	.532	947	.515	940	.512	954	.528	945	.515	939	.515

13. "SHRINKAGE CLAUSE" IN RAIL SPECIFICATIONS

It may be of some interest to recall certain salient features in the history of the "shrinkage clause" in American rail specifications. We shall pay particular attention to those of the A. S. T. M. and A. R. E. A. as typical.

Mr. Cushing, in his instructive account of the improvement of rail design and specifications from 1893 to the present time,[36] states that:

In view of the agitation for colder rolling, the Pennsylvania Railroad had introduced into its specifications in 1900 a clause requiring that the rail at the last pass should be at a red heat, preferably a dull red, but in 1901 they replaced it with a so-called "Shrinkage clause," which was intended to control the temperature of the rail when being finished, by prescribing that the shrinkage, after the rail was sawed, should not exceed a certain number of inches. This clause was also introduced into

[36] W. C. Cushing; A. R. E. A. Bull., 13, p. 853, 1912.

the proposed specifications of the engineering association, making an additional requirement for the details of manufacture.

The rail specifications adopted in 1901 by the A. S. T. M. contained no shrinkage clause. The A. Ry. A. and A. Ry. E. & M. W. A. proposed such a clause in 1902 and in 1904 adopted the following:

The number of passes and speed of train shall be so regulated that on leaving the rolls at the final pass the temperature of the rail will not exceed that which requires a shrinkage allowance at the hot saws of 6 inches (in 33 feet) for 85-pound and 6⅛ inches for 100-pound rails, and no artificial means of cooling the rails shall be used between the finishing pass and the hot saws. The above shrinkage allowance may be varied, if necessary, so as to give a finishing temperature of not exceeding 1600° F at finishing rolls for mills rolling from reheated blooms and not exceeding 1750° F at finishing rolls for mills rolling direct from the bloom to finished rail.

A shrinkage of 6⅛ inches in 33 feet is equivalent to a finishing temperature of about 1815° F (990° C) for open-hearth rails and of 1913° F (1045° C) for Bessemer rails, according to the expansion measurements of section 12.

The adoption of a shrinkage clause was discussed annually from 1901 by the A. S. T. M., but without action until 1907. In 1906 the iron and steel committee of the A. S. T. M. recommended the adoption of a shrinkage allowance of $6\frac{11}{16}$ inches in 30 feet ($7\frac{11}{32}$ inches in 33 feet), equivalent to 2075° F for open-hearth or 2190° F for Bessemer rails, as compared with the 6⅛ inches in 33 feet of the A. R. E. A., or advocating a finishing temperature of over 250° F higher than the A. R. E. A. specifications allowed.

In 1907 the A. S. T. M. adopted the following shrinkage clause:

The number of passes and speed of train shall be so regulated that on leaving the rolls at the final pass the temperature of the rail will not exceed that which requires a shrinkage allowance at the hot saws, for a 33-foot rail of 100-pound section, of $7\frac{5}{16}$ inches and $\frac{1}{16}$ inch less for each 5 pounds decrease in section. These allowances to be decreased at the rate of 0.01 inch for each second of time elapsed between the rail leaving the finishing rolls and being sawn. No artificial means of cooling the rails shall be used between the finishing pass and the hot saws.

This was practically equivalent to the committee recommendation of the preceding year and in effect permitted finishing Bessemer rails at 2187° F (1197° C) or at 940° F (505° C) above the recalescence region of rail steel.

The A. S. T. M. in 1909 reduced this shrinkage allowance on 100-pound sections to 6¾ inches in 33 feet, or to an equivalent of 1947° F (1064° C) for open-hearth and 2055° F (1124° C)

for Bessemer rails. This specification, which also does not contain the time restriction from last pass to hot saws, is still in force (1914) and reads as follows (see 1913 Year Book, A. S. T. M.):

The number of passes and speed of train shall be so regulated that on leaving the rolls at the final pass the temperature of rails of sections 75 pounds per yard and heavier will not exceed that which requires a shrinkage allowance at the hot saws of $6\frac{7}{16}$ inches for a 33-foot 75-pound rail, with an increase of $\frac{1}{16}$ inch for each increase of 5 pounds in the weight of section.

The shrinkage allowed by the specifications of the A. Ry. A. and A. R. E. & M. W. A. has been in general less than for those of the A. S. T. M. (See Bull. A. Ry. A., p. 254, 1910.)

In 1910 the former associations had the following shrinkage clause "intended as a guide in the preparation of future specifications":

Shrinkage: 5. The number of passes and speed of train shall be so regulated that, on leaving the rolls at the final pass, the temperature of the rails will not exceed that which requires a shrinkage allowance at the hot saws, for a 33-foot rail of 100 pounds section, of 6½ inches for thick base sections and 6¾ inches for A. S. C. E. sections, and ⅛ inch less for each 10 pounds decrease of section, these allowances to be decreased at the rate of $\frac{1}{100}$ inch for each second of time elapsed between the rail leaving the finishing rolls and being sawed.

This is equivalent to a maximum finishing temperature of 1895° F (1035° C) for thick base open-hearth rails of 100-pound section.

The American Society of Civil Engineers allow only $6\frac{7}{16}$ inches for 100-pound sections, or the equivalent of a maximum finishing temperature of 1880° F (1027° C) for open-hearth rails.

The Association of American Steel Manufacturers have no temperature clause in their specifications for rails and those of the United States Steel Products Co. state that "a uniform finishing temperature (must be) also maintained."

The practice of the rail mills regarding the actual shrinkage used as given by Sellew [37] in 1913 shows a minimum shrinkage allowance for rails of 100-pound section of 5⅝ inches (1705° F for open hearth) and a maximum of 6¾ inches (1947° F for open hearth), most of the mills using a shrinkage of 6⅝ inches or over, corresponding to finishing temperatures of 1920° F or over for open-hearth rails.

[37] W. H. Sellew: "Steel rails," p. 444, Van Ostrand Co., Pub., 1913.

As shown in section 5, and as would be expected from the nature of the process of rolling, starting with blooms of a given weight and section, the rails of heavy section are generally finished at a higher temperature than those of light section, although this is not the practice for all mills. This is recognized in most specifications by allowing a shrinkage of "one-eighth inch less for each 10 pounds decrease in section" (from, say, the 100-pound section). This clause is equivalent to finishing 80-pound rails at 50° F lower temperatures than 100-pound rails.[38]

If it be considered desirable to finish rails of all sections at the same temperature, this could readily be accomplished in practice by starting with ingots (in a continuous mill) or with blooms (in a mill with reheated blooms), the temperatures of which have been adjusted (see also sec. 3) before rolling into rails. On the whole, it would seem to be better practice, if the best possible product is desired, to finish the rails of heavy section at a lower temperature than those of lighter sections. It should perhaps be again emphasized at this point that it is not difficult to control pyrometrically rolling temperatures.

To recapitulate concerning the shrinkage clause, it is apparent that an intelligent effort was made about 1901 to limit excessive rolling temperatures by endeavoring to define the maximum finishing temperature at about 1600° to 1750° F, but the methods of measuring temperatures then in vogue did not permit a suitable pyrometric control, so that recourse was had to the shrinkage of the rail at the hot saw to define the finishing temperature, although no account was then or has been since taken of the different contraction for various steels.

It would seem, moreover, that the value then generally assigned to the shrinkage (say from 1904) did not give an exact idea of the finishing temperature, and this shrinkage allowance, as finally adopted, is unduly high, due in part to pressure from the manufacturers. It will also be recalled that the present rolling practice in four representative mills (sec. 9, Table 3) is on the average some 500° F or more above the recalescence region, but well within the shrinkage specifications.

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[38] For example, see A. R. E. A. specifications of November, 1912, in Bull. A. R. E. A., 14, p. 185, 1912; also A. S. T. M. 1913 year book, p. 325.

The maximum finishing temperature allowed by the A. S. T. M., 2055° F (1124° C), is above the temperature of rolling of many ingots for rails, as shown by the measurements in section 5.

From an examination of the voluminous literature on the subject of finishing temperatures as influencing properties of rails, one readily gathers the consensus of opinion to the effect that rails should not be finished too high above their critical region. Nevertheless they are actually finished at very much higher temperatures, and this under a clause in specifications originally drawn with the purpose to limit the maximum allowable finishing temperature to slightly above the critical range.

It would appear therefore that the present "shrinkage clause" of such specifications as those of the A. S. T. M., for example, has no significance whatever.

14. SUMMARY AND CONCLUSIONS

The main objects of this investigation were to determine, from measurements taken in representative rail mills, the present American practice regarding the temperatures at which rails are rolled, to demonstrate the ease and accuracy with which such temperatures may be measured, to find out what the "shrinkage clause" in rail specifications really means, and finally to determine for rail steels some of the physical properties, particularly those of interest in manufacture and some of which, it would seem, are not sufficiently well known as yet. Among these last are the expansion, melting ranges, critical ranges, and temperature distribution throughout a rail section on cooling.

Among the results obtained from measurements in four mills are: Ingots for rails are rolled at temperatures ranging from 1075 to 1150° C (1965 to 2100° F), and the variation from one ingot to another in a series of 20 to 40 is only 10 to 20° C. (See Table 15.)

Rails are finished at temperatures ranging from 880° C (1615° F) to 1050° C (1922° F), but usually ranging within 50° C of 935° C (1715° F). (See Table 16.)

The finishing temperature of each rail may be measured at the hot saws. (See Tables 4 to 14.)

With uniform mill practice, the rails of 100-pound section will be finished at some 10 to 20° C hotter than 90-pound rails and about 50° C hotter than 75-pound rails. (See Table 16.)

It is possible to roll rails, all of which, of a given position in the ingot as A or B, etc., will be finished within ±10° C of the same temperature. (See Table 8.)

Chemical analyses and metallographic examinations were also made and the mechanical properties determined for a number of samples of rail the rolling of which had been observed. From a comparison of these not very numerous observations, there does not appear to be a sufficient degree of correlation to warrant associating very specifically any of the characteristics defined by these three methods of examination, either with the temperatures of rolling here observed or with each other. (See secs. 7, 9, 10, for details.)

The following thermal properties of these rail steels were determined in the laboratory:

The critical range on heating is located (maximum) to within 7° C of 732° C (1350° F) for the 10 samples of open hearth and Bessemer steels examined. On cooling, the critical range lies between the limits 680° C (1256° F) and 650° C (1202° F).

The melting or freezing range for rail steel extends from about 1470° C (2680° F) to nearly the melting point of iron, located at 1530° C (2786° F).

The expansion for open hearth and Bessemer steel is not the same. Above 800° C (1470° F) the expansion for both increases linearly with temperature and the linear coefficient per degree centigrade has the following mean values between 0° and 1000° C:

For Bessemer steel (carbon 0.40 to 0.50 per cent): $\alpha = 0.0000146$.
For open-hearth steel (carbon 0.65 to 0.70 per cent): $\alpha = 0.0000156$.
From shrinkage measurements taken in the rolling mill, open-hearth steel (C = 0.71) has a coefficient between 0° and 1000° C of ..... $\alpha = 0.0000161$.

A rail of 100-pound section cooling freely in air from a uniform temperature of 1070° C (1960° F) reaches its recalescence point at 670° C (1238° F) in about 8 minutes 30 seconds. The maximum difference in temperature between center and outside of head

during this cooling is about 85° C at 1000° C (1832° F), becoming 0° again at 670° C.

A comparison of the shrinkage clause in American rail specifications (for example that of the A. S. T. M.) with the expansion of rail steel shows that this clause permits finishing rails at 1120° C (2045° F) or 450° C (842° F) above the critical range of rail steel, and above the temperature at which many ingots for rails are actually rolled in practice. Such a shrinkage clause therefore does not serve the avowed purpose of limiting the finishing temperatures to a value slightly above the critical range.

In conclusion, it should be emphasized that the various series of observations recorded in this investigation are of but a preliminary nature and do not pretend to solve the question of the relations between temperature of rolling and the properties of rails. It would seem desirable, as herein suggested, to make a much more complete and comprehensive study of the various matters mentioned and of related questions than has hitherto been attempted, and on a scale commensurate with the importance to the community of the problem of sound rails.

The authors regret it is impossible to mention by name the several rail mills at which observations were taken, but nevertheless take this opportunity of expressing their appreciation of the facilities accorded them and are glad to acknowledge that all the four companies concerned have offered the further use of their plants for similar investigations.

Finally, it is with great pleasure that acknowledgment is made of the willing and efficient assistance rendered by H. Scott in taking and reducing observations, and also of help from members of the chemical, heat, engineering, and weights and measures divisions of the bureau.

WASHINGTON, April 28, 1914.

EXPLANATION OF FIGS. 12, 13, 14, AND 15

All photomicrographs are taken at a magnification of 100× after etching with picric acid. The samples were taken as illustrated in Fig. 5, unless stated otherwise. All represent vertical longitudinal sections.

Fig. 12, A–F, and Fig. 13, A–B, represents a medial longitudinal section of rail No. 8, a 75-pound Bessemer rail.

A=upper surface of the rail. The metal has been somewhat decarburized on the surface.

B–F (and A–B, Fig. 13). A series of samples taken about 1.5 cm apart in a medial longitudinal section beginning with the head. (Height of rail, 12 cm.) The variation in grain size may be taken as typical of rails of this kind and weight.

Fig. 13, C–F=rail No. 3, a 100-pound open-hearth rail.

C=upper surface. The outer skin has been somewhat decarburized.

D–E–F=head, web, and base, respectively.

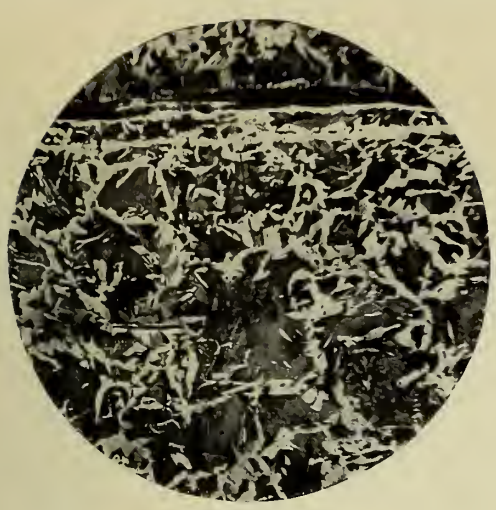
The figure illustrates the fact that microscopic examination of the surface only may give an erroneous idea of the true structure of the interior.

Fig. 14, A–B–C=head, web, and base, respectively, of rail No. 11, a 75-pound Bessemer rail. Though low in carbon (0.33) the structure is that of a steel considerably higher. The retarding effect of manganese and nickel in delaying the coalescence of the ferrite is well illustrated here.

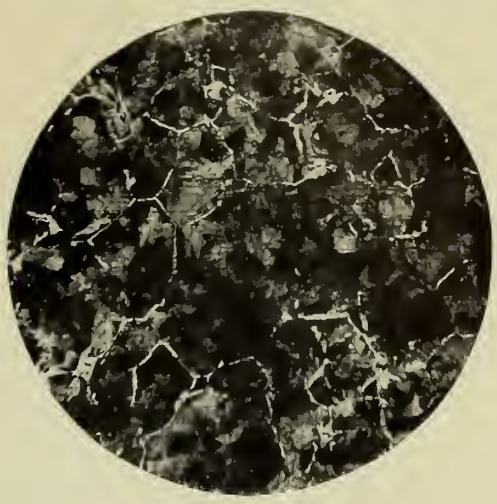
D–E–F=head, web, and base, respectively, of rail No. 18, a 72-pound Bessemer rail. The structure and grain size are typical of the small-section Bessemer rails examined.

Fig. 15, A–B–C=head, web, and base, respectively, of rail No. 25, a 100-pound Bessemer rail. Though one of the coarsest of the Bessemer rails observed, its physical properties compare very favorably with the others.

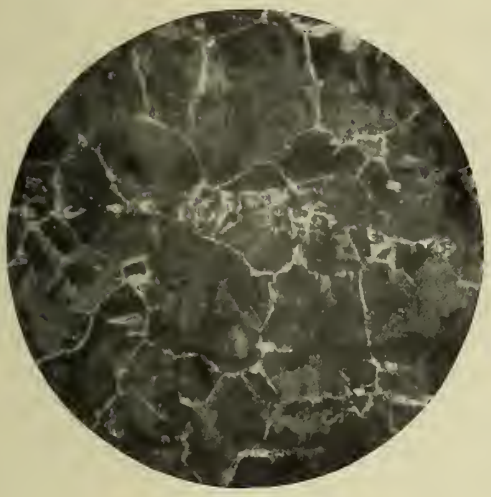
D–E–F=head, web, and base, respectively, of rail No. 32, a 100-pound open-hearth rail. The rail is typical of the large-section open-hearth rails, and shows an apparent carbon content considerably in excess of the real.



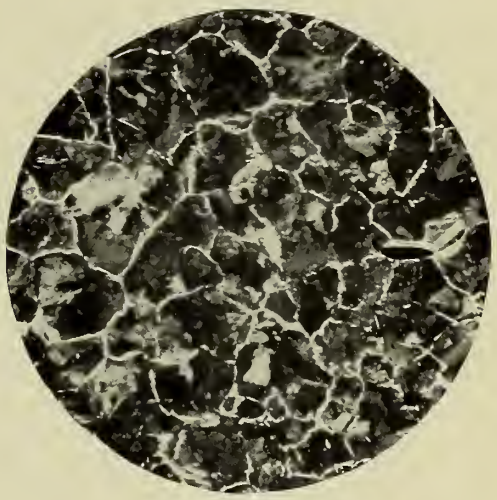
A



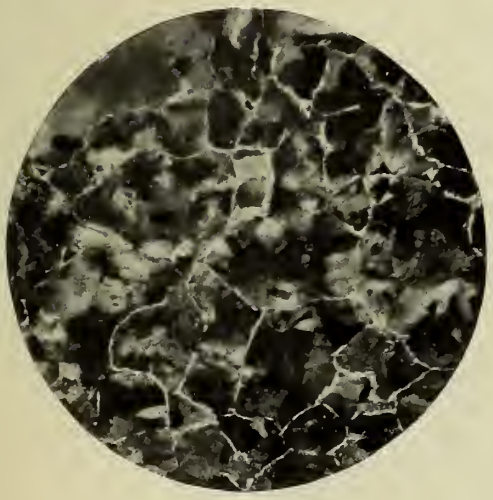
D



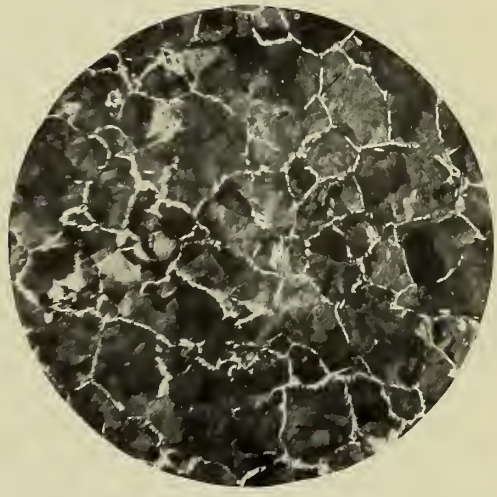
B



E



C



F

Fig. 12

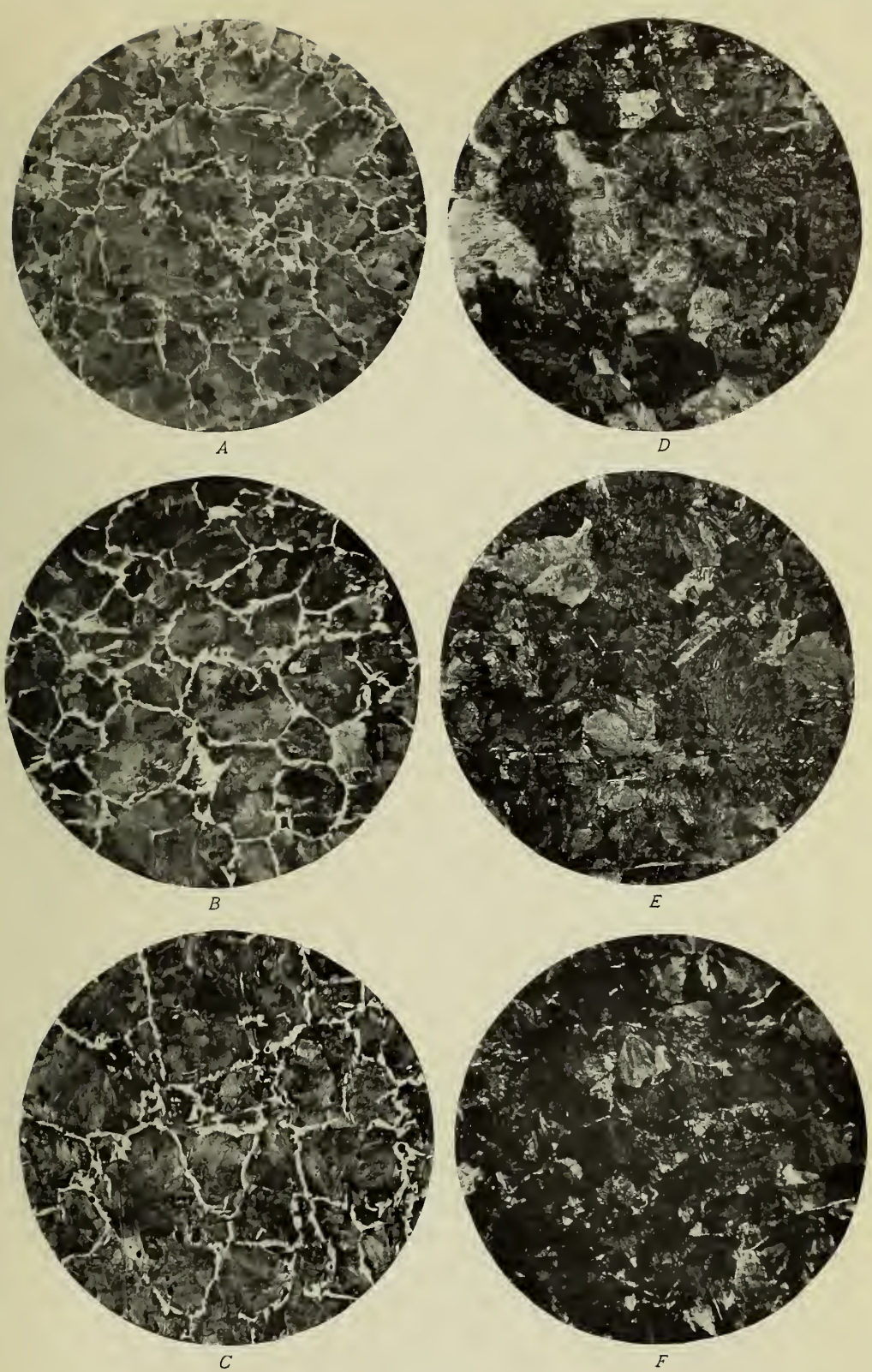
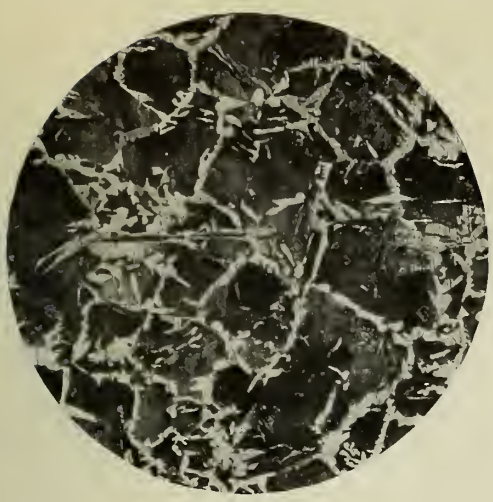
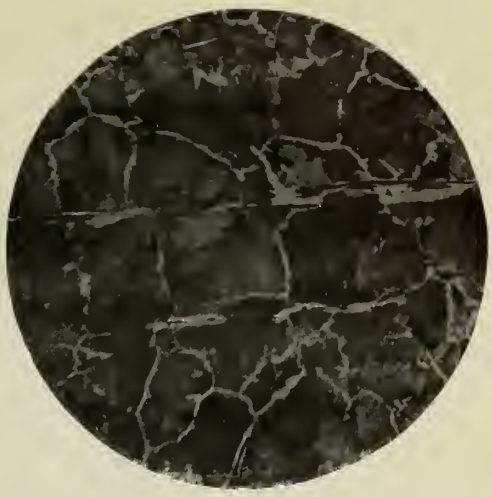


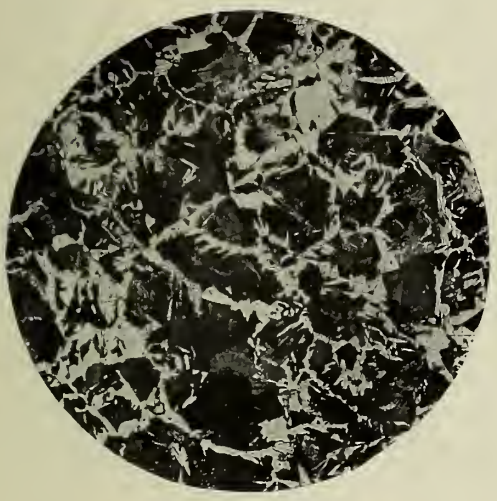
Fig. 13



A



D



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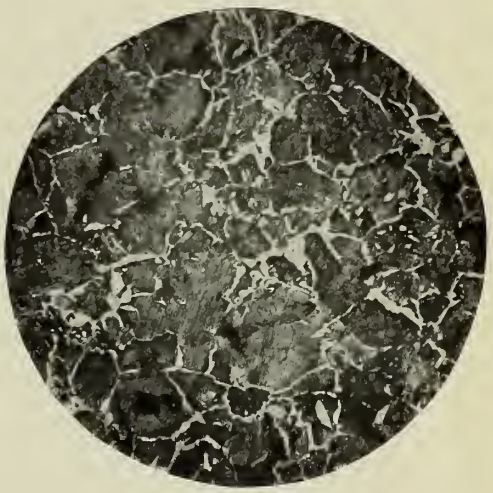
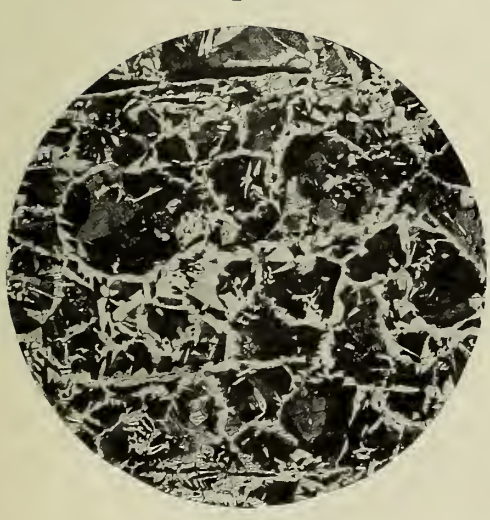


E



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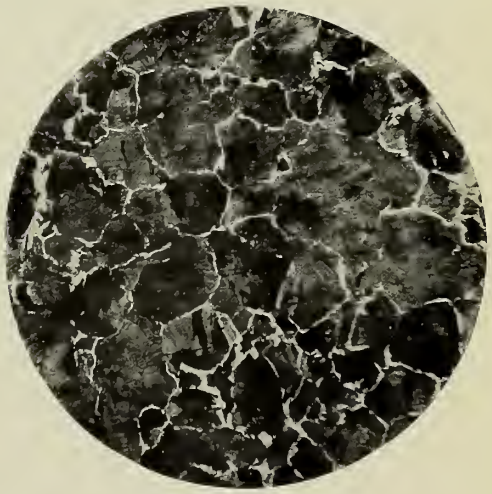
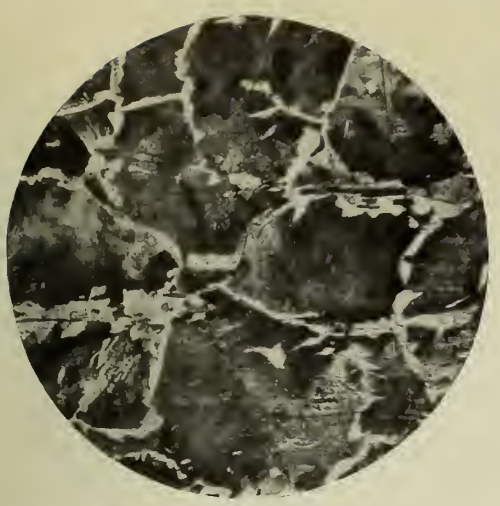
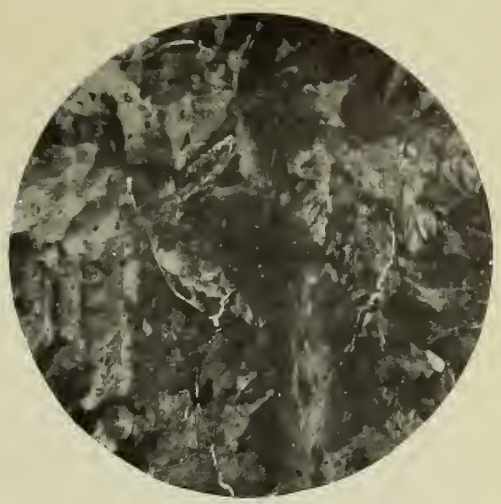


F

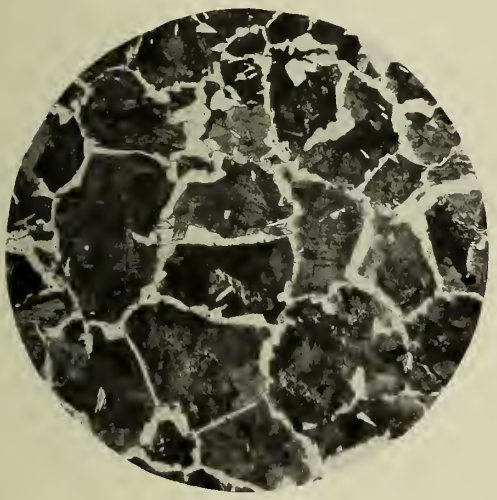
Fig. 14



A



D



B

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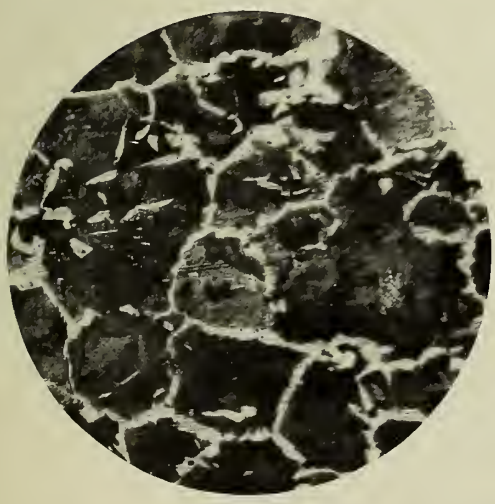

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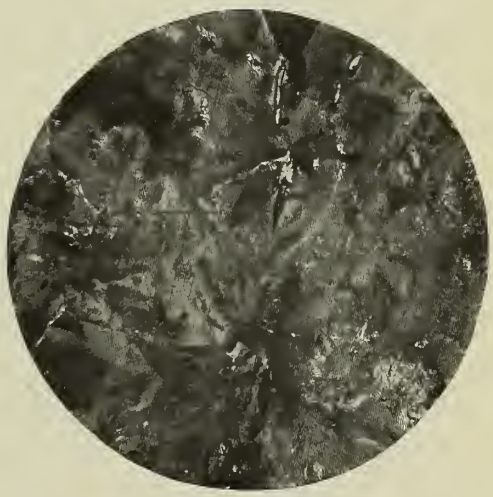

F

Fig. 15

range, it is high time to discard it, not only as useless but actually as dangerous.

R. Trimble,* Pittsburgh, Pa.—One of the most perplexing things we have had to do with in connection with the manufacture of rails is to secure their rolling at a proper temperature, and, as stated in the paper, the railroad engineers have endeavored to have rails rolled at a lower temperature, thinking that such rails would give better service, while on the other hand the mills are favorable to a high temperature, on account of the reduction in wear and tear on the mills due to rolling the rails at a higher temperature.

Although we have in our specifications a shrinkage clause, which we think should be readily met by the mills, yet one mill insists that it is impossible for it to reach our shrinkage clause, and we therefore have to make an allowance to this particular mill, which is objectionable.

William R. Webster, Philadelphia, Pa.—The authors have given us some very valuable information on temperatures at which rails are rolled at our mills in every-day practice in the execution of orders under requirements of ordinary specifications. The results of their work will, as a matter of course, lead to a very thorough and complete investigation of the whole subject. The Bureau of Standards is well fitted to undertake this work and the members of this society should co-operate with them in every way possible.

The present paper forms a very good reopening of our former discussions on the physics of steel and it is hoped that the authors will favor us with further data, from time to time, in order that definite conclusions may be arrived at on the several points they have raised, and on others they have not referred to, but which are well recognized as having an important bearing on the subject and will undoubtedly be brought out in the discussion.

The practical mill men should be consulted and their views obtained in this investigation, as it is more complicated than at first appears. For instance, the suggested plan for controlling and securing the best finishing temperatures in rolling cannot be carried out in practice, owing to the section of our **T** rails. In rolling rails direct from the ingot, the ingot is necessarily hotter than is desirable, in order to carry the heat through to the final passes and avoid finishing the flanges too cold. In rolling rails from reheated blooms, it is impossible to secure the beneficial effects of such reheating, as the blooms are heated higher than is desirable, in order to carry the heat through to the final passes. This investigation will develop that it is not merely that the manufacturer "prefers to roll

* Non-member.

his rails hot, as less power is then required to operate the mill and there is less wear and tear of the rolls," but that with the present sections he is not only compelled to roll hot, but he cannot finish the heads at temperatures low enough to produce the best structure in the steel.

It is therefore suggested that the authors repeat their observations on similar lots of rails rolled at all four mills referred to, under their own supervision, in order to see at just how low temperatures they can start with the ingot or bloom and how cold such rails can be rolled to maintain section and comply with drop-test requirements. At mills C and D, where four saws are used, the shrinkage of each rail should be measured in order to compare the variations with the observed temperatures of each rail taken by the pyrometer. It would also be well to note the amount of camber put in these rails in order to see what effect the cambering has upon the shrinkage and to determine definitely what the coefficient should be for both open-hearth and Bessemer steels.

The authors assume that their coefficient of contraction is correct and, based on it, state that the present shrinkage clause allows "rails to be finished at 1,120° C., or 450° C. above the critical range of rail steel." They also state, in connection with their own work: "From the thermal data, it follows that all these rails could have had work done on them to advantage during the rolling process down to 700° C. (1,292° F.), whereas for none of them was the actual finishing temperature lower than 880° C. (1,615° F.)." This finishing temperature of 880° C. at which some of the rails were finished corresponds to a shrinkage of about $5\frac{7}{16}$ in. in 33 ft., when figured by the same coefficient of contraction. Did the authors measure the contraction of any 100-lb. rail finished at this temperature, and if so, what was the actual shrinkage? The finishing temperature of 700° C. would only give a contraction of about $4\frac{3}{8}$ in. in 33 ft. when estimated by the same coefficient. Do the authors consider that any rails of the present sections can be rolled at low enough temperatures to give only about $4\frac{3}{8}$ in. shrinkage in 33 ft.? We have here the desired finishing temperature on the one hand and on the other the rolling difficulties owing to the present sections of rail. How are these to be brought into accord without adding metal to the web and flanges to permit the rails being finished at the proper temperatures? How much metal should be added to the web and flanges and how close would such modified sections approach to the English bull-headed rail?

The writer's views on this phase of the question were given in 1900 in an informal discussion at the annual convention of the American Society of Civil Engineers, in London, on Recent Practice in Rails. In March, 1901, he asked the Society to appoint a committee on rail sections to consider modifying the Society's sections by putting more metal in the flanges to carry the heat and allow lower rolling temperatures, and claimed that the rolling temperatures were of as much importance as the chemical

composition. His views were also given in a supplemental report to the final report of that committee in 1910, and again in his recent Discussion on Rails before the American Railway Engineering Association in March, 1913.

Too much stress cannot be placed on the influence of the finishing temperature on the quality of the steel; but formerly its effects were not well known or appreciated. The writer's attention was first called to the great influence of the initial rolling temperatures, amount of reduction in each pass, and finishing temperatures, in his investigations on The Relations between the Chemical Constitution and Physical Properties of Steel in 1891 to 1894. It was then found that the control of the rolling temperatures was the most important factor. Since that time the writer has been greatly interested in the effect of the heat treatment on all grades of steel in forging and rolling and, as far as he knows, was the first to propose the shrinkage clause in rail specifications. He has always appreciated its limitations and the force of the objections raised from time to time, but does not consider that any practical substitute has yet been offered. It was the first effort made by the purchasers of rails to systematically control and check the finishing temperatures of their rails. The rail-mill practice prior to that time has often been referred to as "hardening the steel by the addition of carbon and squirting it through the rolls in order to get increased output." It is hoped that the authors will give us further data showing how accurate a measurer of temperature the shrinkage really is, and what reductions in the present specified shrinkages can consistently be made for rails of present section.

Assuming the pyrometer can be used as suggested, in every-day practice, no explanation has yet been offered as to how the individual rails on which observations have been taken can be identified in the finishing department; but the shrinkage of the rail leaves a permanent record. All the inspector has to do at mills where four saws are used is to measure the distance between saws and the lengths of the cold rails. This check on the finishing temperature by the shrinkage is therefore automatic in every respect.

There are two problems that come into this matter: First, public safety; second, wear of our rails.

If you roll your rails of present sections too cold, endeavoring thus to secure better wear, the flanges will be finished too cold, causing the steel to tear and thus forming small fractures, many of which are covered up in rolling and are not observable on inspection. These incipient flaws in the flanges of our high-carbon rails are much more dangerous than is generally appreciated. We should therefore go very slowly in this matter before coming to any final conclusions on cold rolling of rails until sections are decidedly changed.

P. H. Dudley, New York, N. Y.—

1. *Introduction*

The periodic recurrent discussion of one or more phases of rail manufacture emphasizes:

1. That the service of rails has increased in the track in a faster ratio than generally realized.

2. The complicated problems of rail manufacture for present service in the United States are but partly encompassed by metallurgic knowledge and practice, but include those of mechanical and civil engineering, operations, climatic conditions, and a combined mill and track experience.

Page 4[1] of the Introduction states: "It is common knowledge that there are an alarming number of failures of rails in service on the railroads of the country, and, unfortunately, these failures are not on the decrease. Thus the reports of the rail committee of the American Railway Association show 36,641 rail failures, in 12,688,714 tons laid, for the year ending October 31, 1911, and 61,047 failures for 13,736,956 tons [October 31] in 1912."

The increase of failures from 36,641 in 1911, to 61,047 for an addition of only 1,048,242 more tons reported (October 31) in 1912, revealed the fact that there was some decided change in the conditions of operation which contributed to lessen the duration strain factor of the metal in the rails to a greater degree for the low temperatures in 1912, than for a milder period in 1911.

The winter of 1911 was mild for most of the northern railways, but 1912 was extremely cold, with the greatest number of broken rails in their history; 1913 was mild, with 60 per cent. reduction over 1912 of broken rails, while 1914 was again cold in the eastern portions of the United States and Canada.

November, 1911, was cool, with a range of 50° to 120° deficiency temperatures for the month of different U. S. Weather Bureau stations. December had an opposite oscillation of warm waves of 100° to 200° above normal. Rails which had contracted in the splice bars during November, were again expanded in December. The sudden excessive cold wave in the West of the last one or two days of December, and the first day of January in the East, contracted the metal in the rails and set up tensile stresses before the rails could render in the splice bars. This, combined with the stresses of the metal of the rails as girders under the moving wheels of the locomotives and cars, was the important factor in 1912 of the greatest number of breakages of Bessemer rails in the history of the railways.

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[1] *Technologic Paper No.* 38, *U. S. Bureau of Standards.*

The ordinary duration strain factor of the metal of more Bessemer rails than usual was reduced from the effects of the cold by:

1. The additional tensile stresses due to being held by the splice bars from contraction.

2. The increased tendency of the metal of Bessemer rails of 0.10 phosphorus and only 0.50 carbon to fracture under rapid distribution of the alternate unit fiber strains and balanced stresses of the moving wheel loads.

I sent out September, 1913, 450 copies of the tabulations of the accumulated excess or deficiency temperatures for the United States Weather Bureau stations on the New York Central Lines for the years 1911, 1912, and 1913 to Aug. 31, to the respective officials in charge of maintenance of way and to those of equipment.

I made the forecast September 1, that the probabilities were that the winter of 1914 would not be as mild as the winter of 1913—the broken rails not being one-half as many as in 1912 for the same locality and service.

I also sent instructions to have the maintenance of way to its highest standard in 60 days, and the equipment, as to the rotundity of the wheels, in the next 90 days, and to be maintained through the winter.

The forecast proved true, though December and the fore part of January were mild; the cold wave was severe in the latter part of January, February, and March, but from the care and attention of the officials of the respective departments, the percentages of broken rails and shelled wheels were less than in normal years.

The excess or deficiency temperatures per month for 1914, to August 31, have been added to the three preceding years, with forecast and instructions issued for the winter of 1915, and copies sent to the officials in charge of the departments of maintenance of way, of equipment, and operating. These three contribute by their care to the safety limits of the duration strain factor in the metal of the rails.

The large railway systems keep their own statistics up to date, therefore know from the comparative figures that the rail failures have decreased since the extreme cold winter of 1912, and are proportionally less than ever before for a similar service. I speak particularly for the New York Central Lines, for in some territory they often have cold waves of some days' duration of 30° and 40° F. below zero.

The introduction of basic open-hearth rails the past few years in which the phosphorus content is practically one-fourth of the former Bessemer rails, furnishes the metal of the sections as girders a duration strain factor of greater combined capacity and rapidity of distribution of the alternate unit fiber strains, balanced by equal stresses, than was possible to secure in many of the 0.10 phosphorus and only 0.50 carbon Bessemer rails.

The basic open-hearth rails for the New York Central Lines have all

been made since 1910 under the 1909 specifications of their elongation and exhausted ductility tests which were developed from the elongation tests under the drop used for Bessemer rails from 1890 and 1910. There were in the tracks of the N.Y.C. & H.R.R.R. Jan. 1, 1914:

Tons	Basis Open-Hearth Rails		Length, Miles	Broken per 100 Miles
65,297	5⅛ in.	80 lb.	519	1.93
83,268	6 in.	100 lb.	530	0.57
67,460	6 in.	105 lb.	408	0.00

There were 13 broken basic open-hearth rails from Jan. 1 to Aug. 1, 1914, and 279 Bessemer, or 1 open-hearth to 22 of Bessemer, exclusive of interior transverse fissures. February and March were extremely cold, with many continuous cold waves of 35° F. below zero and an occasional wave of 40°.

2. *Importance of Limiting Temperatures of Rolling Rails*

This is a comprehensive subject and will require many papers and discussions to state its many salient features, for application to rail manufacture for the girder and resistance to wear.

I state here that the effects of the rolling temperatures upon the duration strain factor of the metal of the basic open-hearth rails as girders, for service either in warm or cold climates, is one of the keynotes of this discussion. Investigations have shown that the transformations of all the different metallographic forms the metal should pass through from the higher temperatures of the hot set ingot to the lower of the metal of the rail in the finishing pass, did not completely occur in the metal of the section, particularly of that in the central portions of the head. It is left in a heterogeneous condition in a few rails with initial strains, and as the interior metal cannot elongate as readily as its exterior envelope of the head, is sometimes checked by the gags of the presses to straighten the rails. These develop in service from the negative strains in the wheel spacing of the passing equipment.

3. *Rolling Rails*

Rails are rolled:

1. Direct from the equalized, original heat of the ingot to the finished rail.

2. The ingots are bloomed from their equalized, original heat, then the blooms are reheated to pass through the roughing and finishing roll trains.

The investigations show that as a rule the transformations seem more complete in a greater majority of rails from the reheated blooms, than in

direct rolling. This is a difficult investigation to make direct upon the output of the rails owing to the small fraction of 1 per cent. affected. The fact is confirmed by only an occasional failed rail from the reheated blooms due to the incomplete transformations.

There have been two distinct schools of theory and practice for the manufacture of rails:

The first considers that the chemical composition should be prescribed and limited by definite proportions to make sound hot ingots, combined with rolling temperatures to secure the physical properties intended in desired sections of girders.

The second considers the chemical composition secondary, but that the rails must be rolled cold to insure good wear, as the only information to be given the manufacturer to secure a suitable product.

The first school has service tests of rails in the tracks for over two decades which proved safe and quite free from breakages in low temperatures, with fair resistance to wear. This has been of great service in the adaptation of basic open-hearth steel to replace Bessemer.

The second school had the mills remodeled for cold rolling of Bessemer rails (some were built for the purpose); and prescribed shrinkage limits for the hot saws, which have not been modified for basic open-hearth rails.

The holding the bars 40 sec. before the last pass, was abandoned many years ago, when the epidemics of broken rails in the low temperatures of 1904, 1905, and 1906 occurred. The mills which were built for direct cold rolling for wear, without the least intention of so doing, injured many rails of their output of basic open-hearth rails as girders.

The second school is no longer advocating the extreme cold rolling, for the service tests have not sustained its contention.

The metal of a rail section, as an element in the "Means of Transport" to carry and guide the passing equipment, performs two diverse functions:

1. That of a girder, to distribute in fractions of a second large alternate unit fiber strains, and which, for safety, governs the quality of metal which can be used.

2. That of resistance to wear and abrasion from the passing wheels of the equipment.

4. *Interior Transverse Fissures Due to Incomplete Transformations of Metal from the Higher Temperatures of the Ingot Metal to That of the Finished Rail*

It does not seem to matter what the distribution of metal is in the section, whether of thin or heavy bases, for each has developed interior transverse fissures in the head after more or less service. A direct con-

nection seems to be established with cold direct rolling temperatures in retarding the transformations, which must receive careful research before it can be determined what is the proper range of finishing temperatures for the combined functions of a given section and its service. It may fail from an interior transverse fissure either in a warm or cold climate.

The paper is a valuable contribution of data, and I concur with the authors that more experimental work should be done, and the rails subjected to service tests to establish the important facts as to the finishing temperatures and properties of rails.

George B. Waterhouse, Buffalo, N. Y.—The paper of Dr. Burgess and his associates is one of great interest alike to the theorist, mainly concerned with pyrometry and its application, and to the practical man whose chief interest is improvement and uniformity in his product. The comparative ease with which the temperature measurements were made is specially noteworthy, and shows that the newer types of optical pyrometers must be workmanlike instruments that can be depended upon even when subjected to the hard and exacting conditions found in steel works and rolling mills.

While the paper as a whole is valuable, several of the methods used and results obtained are open to criticism, and it is hoped that the following remarks will be accepted as a sincere effort to help in the study of this important subject of rail shrinkage and finishing temperatures.

In the first place, it seems to me that the relation between finishing temperature and shrinkage has been arrived at in a needlessly indirect way. The temperatures were taken directly in the mills, and it would have been very easy to obtain the exact shrinkage on the same rails that were observed. Instead of this, pieces were cut from rail flanges, welded together either by electricity or oxy-acetylene, and the coefficient of expansion obtained carefully and laboriously in the physical laboratory. Having obtained this coefficient, the finishing temperature corresponding to a given shrinkage was worked out. The results so obtained are questionable on account of the influence of the welded joints. It would not have been hard to get pieces from the mills of the required length, about 20 in., and it is to be regetted that this was not done.

According to these results there is quite an appreciable difference in the expansion of open-hearth and Bessemer rail steel, which would cause Bessemer rails to be finished about 100° F. hotter than open-hearth in order to have the same shrinkage. Regarding this they write: "This great difference in the shrinkage of the two classes of rails does not appear to have been considered in rail specifications, although this difference must have been detected in mill practice." As a matter of fact there is very little difference in the shrinkage of the two classes of steel. At our mill, Bessemer rails 100 lb. to the yard, 33 ft. long, require 6½ in.

at the hot saw, while open-hearth rails of the same section, rolled and finished at practically the same temperature, require as a rule from 6½ to 6⅝ in.

In regard to the temperature measurements one thing should be carefully noted, and that is that they were chiefly made on the head of the rail, which is the hottest part of the rail section. The ends of the flanges are finished much colder even with the heavy-base rails, and this difference is particularly marked with thin-flange rails such as the New York Central uses. It is obvious that the finishing temperature of every part of the rail section must be well above the critical range so as to avoid brittleness, and it is certain that this will cause the rail heads to be finished a good deal hotter than is regarded as sufficient in the paper—that is, about 1,300° to 1,350° F.

The section on microstructure is very interesting, although it is stated that no definite conclusions can be drawn as to the relation between grain size and finishing temperatures. One conclusion is arrived at, however, that appears to be definitely proved from the known evidence on the subject, and which is very valuable. The paragraph may be quoted. "It would appear probable, then, that the restoration of the crystalline arrangement which is so badly shattered by the squeezing action of the rolls is not so rapid as is generally supposed, and though the restoring process begins immediately after the rolling ceases it is not complete until at a lower temperature, which in fact is the temperature which determines the grain size of the finished product."

In other words, the effective finishing temperature as it concerns the properties of the finished rail is below the temperature as observed by the pyrometer by an amount that is not thoroughly determined, but which must be allowed for. The temperature, therefore, on leaving the rolls must be sufficiently above the critical range to allow the restoring process to get well on its way in all parts of the rail section.

The paper also lays emphasis on the influence of the amount of reduction on the grain size, and the greater the reduction the smaller the grain size. This does not refer to the number of passes but to the actual reduction from the cross-section of the ingot to that of the finished rail. In this connection it does not seem as if enough importance has been accorded to one factor governing the grain size: namely, the rate of cooling. The larger the finished rail the larger the section of the various passes from the bloom to the rail, and therefore the slower the rate of cooling on the mill tables and the hot bed. To follow this further, the slower the cooling the higher the finishing temperature, and the greater the time interval between the effective finishing temperature and the critical range. This will inevitably bring about a larger grain size in the finished rail.

Finally, in regard to the difference in temperature between the inside

and outside of the head of a rail, it is probable that the difference in practice is greater than that found by the writers in the laboratory. It must be remembered that the rail ingots are charged into the soaking pits while the interior is very little if at all below the freezing point, while the outside is usually below a good rolling temperature. Even after the customary time in the pits the interior is undoubtedly hotter than the outside, and this difference is increased during rolling because of the cooling on the tables and the water used on the rolls. This difference in temperature is important because of the shrinkage stresses that are liable to be set up, and which must be carefully considered.

M. H. Wickhorst,* Chicago, Ill.—I have made a few temperature measurements, and, although Dr. Burgess has described me as an optimist on the subject, I have not felt all the confidence in the correctness of the measurements that I would have liked, and the Bureau can, I think, do considerable toward advancing the art of measuring rolling temperatures to a point where we can accept such measurements with confidence.

I wish now to make a few remarks on the subject of the relation of the rolling temperature to the general question of rail failures. Some years ago it was customary to ascribe rail failures to too high finishing temperatures of the rail, necessitated by the thin flange, but it now seems that not many failures can be traced to this cause. Very briefly I may say that a large portion of rail failures have their origin in excessive segregation, mostly of carbon and phosphorus, in the interior and upper part of the ingot. Another large portion of rail failures have their origin in seams in the bottom of the base. Excessive segregation is to be avoided by using quiet-setting steel, well deoxidized with silicon, titanium, or aluminum; in other words, ingots with "horny" tops should not be used. Of course, such quiet-setting steel pipes deeply and successful use of such steel will then, perhaps, require a large discard, or perhaps the development of a commercially available sink-head process of casting the ingot. The surface seams, of which those at the bottom of the base are especially harmful, seem to originate in the tearing of the sides of the ingot in the early stages of blooming, and probably a full study of this part of the subject can be expected to result in the elimination of a great many of the seams.

Having obtained an ingot of fairly even composition, and having given close attention to the rolling of the bloom, it would then seem to be necessary to give attention to the matter of rolling temperature in order to still further improve the properties of the rail.

Dr. Burgess found a considerable difference in the hot shrinkage be-

* Non-member.

tween Bessemer and open-hearth rails, amounting, I believe, to something like ½ in. difference in a standard rail length of 33 ft. My own work has indicated that the shrinkage of the hot rail increases as the carbon in the steel increases and the difference between steel of average Bessemer carbon of 0.50 per cent. and steel of average open-hearth carbon of 0.69 per cent. would amount to about ¼ in. (See *Bulletin of the American Railway Engineering Association,* vol. xvi, No. 170, pp. 163 and 164, October, 1914. It is also expected that this article will appear in the *Proceedings of the American Railway Engineering Association* for 1915.)

Dr. Burgess calls attention to the point that the shrinkage of the rail is not a correct measure of finishing temperature, and this I think we can concur in. At the finishing temperature the rail shrinks at the rate of about 1/100 in. per second for a standard length of 33 ft. of cold rail, and of course the amount the rail shrinks after leaving the saws will vary according to the length of time elapsed between the finishing rolls and the saws.

As regards the question of grain size, we may ask several questions: To what extent is the grain size a function of finishing temperature; to what extent is it a function of reduction in rolling; to what extent is it a function of the length of time the ingot has been in the pit or the bloom has been in the reheating furnace; or again, to what extent is the wear of a rail a function of the grain size, or of the finishing temperature? These are some of the questions that need attention and can be finally worked out only after a considerable amount of experimental work.

James Aston,* Cincinnati, Ohio.—I have been a consistent advocate of the doctrine of the correlation of grain size and physical quality; that, other things being equal, the strength of a steel is inversely proportional to the size of grain. While it is unwise to attempt to draw conclusions from incomplete data, and in the present instance it may be somewhat unfair, I was interested in reconciling the results of the paper under discussion with the above doctrine, and was surprised and disappointed to find that the expected confirmation is lacking.

Upon arranging the data of the several tables of the paper in the order of increasing grain count, together with in each instance the carbon content, physical quality, weight of section, finishing temperature, mill practice, etc., certain conclusions seem evident. That the rails representing the materials and practice of the several mills appear to be rather promiscuously distributed, and there seems to be no regular order as to weight of section with respect to grain and temperature. And more conspicuously, that there is no concordant relation of grain size as given by the count, and the finishing temperature of rolling. Again, making due

* Non-member.

allowances for the effect of carbon, the strength does not follow the order of increasing fineness of grain; and this holds even more noticeably for the relative ductilities. Thus, of course, it is equally true that there is no correlation of physical quality and finishing temperature.

On the face of such returns we can hardly expect the mills to rush wildly into the adoption of lower temperatures of rolling; at least until more consistent and conclusive data confirming the grain-size doctrine are available.

With respect to the statement of the paper that the rolling operation produces "an 'effective finishing temperature' somewhat below the observed one" and "it would appear that the grain size of the steel is determined as much by the total amount of reduction in the rolls as it is by the finishing temperature, or any other factor," a logical answer seems to be, "Why not?" We grant that mechanical working is a factor in reduction of grain size. Consequently any reduction in the later stages of rolling, and especially that in the last or finishing pass, will break the grain down to a size less than that normal to the finishing temperature. This grain will tend to grow to normal during cooling, but will require appreciable time for its consummation; and during such interval, the temperature will be falling below that of the finishing pass. So that equilibrium will be reached with a grain growth arrested not at the finishing temperature, but at one somewhat below. The spread will be dependent primarily upon the amount of the final reductions, but to a degree also upon the speed of cooling, which in turn is influenced by weight of section, and other factors.

In view of the above, the suggestion of the authors that there may be some advantage in measuring the temperature of the blooms as they enter the rail mill, with the assumption of a constant speed of rolling, would seem open to question. For would we not have other disturbing factors varying with the amount of final reduction, weight of rail section, influence of chemical constituents, details of mill practice, and the like; all making for variations in grain size from that to be expected from temperature conditions alone?

Speaking of rail breakage, the severe winter of 1911–12 resulted in an epidemic of such failures in the Northern States. I recall an instance of the breakage by a single flat wheel of upward of 100 rails on an 85-mile stretch of as fine a piece of roadbed as there is in the country. Are we not too ready to jump at conclusions in reaching for a cause; to ascribe failure to excess of phosphorus, to incipient fissuring, to coarseness of texture resulting from high temperature of finishing, or like causes? Was not the failure in all likelihood due to the proper combination of conditions; of high phosphorus, of abnormal grain, of increased brittleness of the steel due to the low temperature, of heavy wheel load, and of excessive pounding of the flat wheel—of the above singly or in combina-

tion? And especially, was there not the important factor of unusual rigidity of frozen roadbed, which took away its power of yielding, and threw the entire resistance upon the overburdened rail?

E. F. Kenney,* Johnstown, Pa.—I read Dr. Burgess's paper, and, by the way, I was with Dr. Burgess part of the time when he made the measurements used in this paper. The thing that impressed me first, aside from the very valuable information that is included, is that, I think, the author is reasoning a little along theoretical lines without considering some of the practical lines that would appeal to those in the rail business. Two points should be determined before we lay too much stress on this question of finishing temperatures.

In the first place, have we any real evidence that lower finishing temperatures would result in betterment to the rails? We have not seen any as yet. Some years ago we rolled some rails with widely different finishing temperatures; those rails were from the same heat and were put in on Horseshoe Curve on the Pennsylvania Railroad, and very careful records of measurements were kept showing the wear. We were not able to differentiate between the hot- and the cold-finished rails in that experiment; that is, as far as wear was concerned.

As bearing on the effect of finishing temperatures on the strength of the rails we submit some recent experience. We started to roll a rail of very heavy section, weighing 125 lb. per yard, which because of its chemistry partly, and of its section, is very stiff. The drop tests required were difficult to meet because of liability to breakage. With a view to getting greater toughness we had some of the rails rolled at a temperature 100° F. lower than our ordinary finishing temperatures, or about 1,550° F., which is rather low for rails. We did not go any lower than that, because we were afraid of breaking the rolls. These temperatures were measured at the center of the base, and the edges of the base were, of course, considerably colder. Under the drop test there did not seem to be any difference between these rails and those which were finished at the ordinary temperature. We are therefore led to believe that within the limits of temperature within which the steel can be rolled, we will not get very material difference, as far as the drop test is concerned, between hot-finished rails and cold-finished rails. But let us look at the other side of this matter.

Even if we were assured that we might get some betterment from very cold-finished rails, a number of difficulties are in the way which I think would be very hard to overcome. In some of our products we strive for a very smooth finish. This is well known over the country as "Gautier Smooth Finish," and is obtained by holding the bars in the course of the rolling, so that at the finishing pass the temperature is so low that

*Non-member.

the heavy scale does not form, and the result is a bar with very smooth, black finish. Tests on those bars show that they have a finer grain and a higher elastic limit than ordinary bars, but the ductility has been reduced in the same proportion.

Even if we could roll rails under the same conditions, I think we would lose in ductility quite as much as we would increase in other qualities. This cold rolling can be done without great difficulty on simple sections such as rounds, squares, etc., but when it is attempted on any complex sections we almost invariably get into trouble. The bar is likely to twist, and this would be fatal in the case of rails, as they would not be accepted. Our present T rails are of very complex section as far as rolling is concerned.

Taking into account the doubt as to the practical effect of colder rolling and the difficulties attending it, I doubt very much if we are going to get much betterment in our rails, due to this colder finishing temperature.

A. W. Gibbs,* Philadelphia, Pa. (communication to the Secretary†). —The starting point or datum line of Dr. Burgess's paper is the critical temperature in the neighborhood of 700° C., 1,300° F. Running through the paper is the idea that rails should be finished at a temperature slightly above this critical temperature; notably at the bottom of p. 31,[2] where it says:

"From the thermal data, it follows that all these rails could have had work done on them to advantage during the rolling process down to 700° C. (1,292° F.), whereas for none of them was the actual finishing temperature lower than 880° C. (1,615° F.)."

Further on in the paper, when dealing with the question of the shrinkage clause as used in the different specifications, the excess of temperature above this critical point, as determined by the shrinkage clause together with the coefficients of expansion determined in this paper, is taken as a measure of the badness of the rolling. I would refer particularly to paragraph on page 62, reading:

"A comparison of the shrinkage clause in American rail specifications (for example that of the A. S. T. M.) with the expansion of rail steel shows that this clause permits finishing rails at 1,120° C. (2,045° F.) or 450° C. (810° F.) above the critical range of rail steel, and above the temperature at which many ingots for rails are actually rolled in practice. Such a shrinkage clause therefore does not serve the avowed purpose of limiting the finishing temperatures to a value slightly above the critical range."

While following this is the statement by the author that this is but a preliminary investigation, nevertheless I think it is unfortunate that the

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* Non-member. †Received Oct. 13, 1914.

[2] *Technologic Paper No.* 38, *U. S. Bureau of Standards.*

desirability of finishing at a point slightly above the critical range should be stated as though it were proved.

Those who are following the question of rail specifications are continually met with the statement that certain mills have rolled at finishing temperatures much below the customary ones and that the service results have not been satisfactory.

The steel people, if they will, are in the best position to offer definite proofs.

Before departing very far from the present shrinkage allowance in the rail specifications under which we are rolling, it seems necessary to have some direct evidence on the following points:

Is a greater fineness of grain than we now secure accompanied by a greater safety against shock, and against the development of that form of detail fracture concerning which so much guessing has been done of late? If we are now getting the desired fineness of grain in certain parts of the rail, such as the flange and the web, is it desirable to lower the finishing temperature still more, so that this fineness of grain will be found in the head? Will this rail of finer structure be less able to withstand the drop test? If so, are we justified in reducing the severity of the drop test, and what will be our standing in court in the event of a wreck from rail breakage, where it has been shown that the rails have been subjected to a lessened drop?

W. A. Aiken,* New York, N. Y. (communication to the Secretary†). —In a more or less detailed connection of some 15 years with the study of rail steel and the inspecting of the finished product, I have always contended, recognizing as I did the necessarily antagonistic interests involved between the producer and consumer, happily very much more marked some years ago than existent to-day, that the most important point to be definitely settled first, was the absolute necessity to secure as perfect material as possible whereon to base conclusions, arrived at from the study of its heat treatment. While it may be broadly admitted that good material may be abused during manufacturing processes and poorer material possibly improved by such processes, it is a self-evident proposition, in my opinion, that with the finished product under discussion in this paper, not to grasp the vital necessity of studying the best material obtainable is more or less a waste of time and energy and in direct opposition to the theory of the conservation of the resources.

The absolute necessity of sufficient discard from the ingot to insure sound material from which to roll the finished product has long been recognized in principle and has grown in practice; but until the two diversant interests involved become less of an *impasse* than in the past, every one is wasting energy to a certain extent in studies, no matter how

* Non-member. † Received Oct. 5, 1914.

elaborate, of material which the *ex parte* student must insist is not as good as can be procured. So that, while in no way disparaging the good work done in the past, as shown in the files of our various technical societies and markedly brought out by the present work of the associated physicists of the Bureau of Standards, no one interested in obtaining better rails, and confronted with the yearly reports of failures of this material, must close his eyes to further and continued effort to obtain better steel from which to manufacture rails. Meanwhile, of course, all study on the finished commercial product cannot be considered entirely wasted, but the value of heat treatment to prevent injury to good material strikes me as much more important than its value in improving other material, not of the best, which is offered under present commercial conditions.

That the shrinkage clause is at best a poor makeshift, cannot be ignored. That proper control of heat treatment can be accomplished instrumentally, I think is established by the present paper; though long since abstractly recognized as feasible commercially by all investigators not biased by commercial interests.

Personally, I have had sufficient experience in the use of pyrometers to have long since felt assured that their application could be effectively made for the determination of temperatures under ordinary rail-rolling conditions. And, finally, the use of such instruments of precision will, in my opinion, settle practically once for all the fact that better finished product will be obtained at much lower finishing temperatures than are now generally used by manufacturers.

It must be recognized, however, that manufacturers cannot arbitrarily be expected to void purely commercial interests for technical ones, even though these latter may be reasonably expected, if substituted, to furnish better material. There should be no question between producer and consumer thoroughly to try out commercially any method promising as good results as the practical and positive control of heat treatment of rails.

Dr. G. K. Burgess (written communication*) I wish to express my gratification at the interest expressed in the paper by so many competent authorities. The matter that appeared to be of the greatest general interest, and which it is only too apparent is still an open question, is, What are the most suitable temperatures, *all* things considered, for rolling and finishing rails? As pointed out in several communications, the answer to that question is necessarily a complex one but it is believed to be a determinable one for any given rail section. The allied question, What is the best rail section? is intimately related to the former, as stated in several of the communications, but the answer to this appears

* Answer to discussion.

to be even more complex. To neither of these questions does the paper give a reply, although more than one of the contributors to the discussion appears to have obtained the impression that there is here presented an argument for finishing rails at lower temperatures than is at present practiced. Emphasis has been placed, however, on the conclusion from this investigation that the present "shrinkage clause," which was designed to limit the upper temperature of finishing rails, does not accomplish this purpose. Statistics as to rejection of rails under this clause would be of interest. In this connection, the remarks of Professor Sauveur and of Mr. Trimble are of particular interest.

Mr. Gibbs considers "it is unfortunate that the desirability of finishing at a point slightly above the critical range should be stated as though it were proved." Of the two quotations cited by him in support to this inference, the first refers to what we consider to be a generally accepted fact, that work can be done to advantage on cooling steel to nearly the critical range; the second has to do with the inadequacy of the "shrinkage clause" to fulfill the purpose of its framers, which was to restrict the upper limit of rolling to a temperature slightly above the critical range. Whether or not rails should be rolled colder or hotter than is the present practice it was not intended to advocate in the paper, and, as Mr. Gibbs states, "the steel people, if they will, are in the best position to offer definite proofs" of the qualities of rails rolled hot or cold.

The fundamental questions asked by Mr. Gibbs regarding the relation of fineness and uniformity of grain, finishing temperatures, resistance to shock, and breakage in the track, can only be answered by experiments on an elaborate scale; and there is also implied here the underlying questions of weight and section of rail.

The comprehensive communication from Mr. Webster is most welcome and timely, and we are glad to note and acknowledge his valuable contributoins to our knowledge of the properties of rails and in particular his urging repeatedly during the past 25 years the systematic study on an adequate basis of the fundamental problems of the physics of steel.

It is of more than retrospective interest to look back at the Suggested Lines for the Discussion and Investigation of the Physics of Steel inaugurated at the Chicago meeting of this Institute in 1893, and to note how many of the queries then propounded still remain unanswered, and this in spite of the nearly boundless facilities of our many iron and steel manufacturing establishments, and the existence of not a few laboratories. One cannot help but feel that many of these questions—some of which Mr. Webster repeats to-day—might have been answered ere this without sacrificing the efficiency of our mills and probably with great economic gain in many instances.

That the government standardizing laboratory is interesting itself—within its necessarily limited sphere of activity—in some of the funda-

mental problems of the properties of railway material should, we believe, serve as an added stimulus, however slight, to others in the common endeavor to solve these oftentimes perplexing, and happily sometimes easy problems, but ones the solutions of which have been deferred.

Mr. Webster as early as 1890 to 1893 reached the conclusion from his investigations on The Relation between the Chemical and Physical Properties of Steels "that the control of the rolling temperatures was the most important factor;" and yet, to-day, it would appear that neither he nor any one else can say with certainty at what temperatures rails should be rolled.

Regarding the difficulties to be encountered, some of which Mr. Webster mentions, in the practical solution of this problem, we believe some of them to be less serious than might at first appear. There certainly will be no difficulty, for instance, in identifying individual rails the temperatures of which have been measured. Mr. Webster mentions the procedure, under the shrinkage clause, for the inspector to follow in a mill with four saws; but how about the mill with one saw? This mill also works continuously, but has no automatic shrinkage control.

Again, the question of rail section vs. temperature distribution, although undoubtedly troublesome for rails of thin flange, may perhaps be answered; and we hope to be able to contribute to its solution.

To Mr. Webster's suggestions for more work along more extended lines, for taking into account all the factors entering into the problem of rail temperatures and for co-operation with the practical mill men, we most heartily assent.

To his questions as to effect of section and the practical possibility of rolling rails colder than is the present practice, we must plead ignorance.

In view of the fact that the shrinkage measurements made in the mill and the expansion measurements made in the laboratory agree very well for the few examples given in the paper for open-hearth rails, we are inclined to the belief that these measurements are trustworthy; but much more data on shrinkage and finishing temperatures should be obtained for different kinds of steel and for rails embracing at least all the usual sections.

The communication by Mr. Waterhouse contains many useful suggestions which must be kept in mind in a comprehensive study of the subject of rolling temperatures vs. properties of rails.

Regarding his criticism of our method of determining expansion in the laboratory rather than of shrinkage in the mill, it may be stated that our original program as planned, and as carried out in the mills, involved no interference with mill practice. He appears to overlook the fact that shrinkage measurements were made, however, in one of the mills as shown on p. 55 of *Technologic Paper No.* 38. The results in shrinkage agreed with those on expansion. The effect of welding the rails can easily be

shown to be *nil* as carried out. Mr Waterhouse points out the importance of the metallographic examination indicating an effective finishing temperature lower than that given by the pyrometer. We believe this to be a field worthy of further investigation.

Mr. Aiken, in the light of his considerable experience, insists on the desirability of improving rail material, with which every one would probably agree; but we also believe in the careful study of the manufacturing processes and properties of the resulting products as carried out under present commercial and technical conditions with the materials in general use.

Mr. Wickhorst points out in a comprehensive manner what he considers to be the sequence of importance in the causes of rail failure, and emphasizes the uncertainty in practice of the effect of finishing temperatures and the need of more experimentation on this and similar questions, with all of which we agree.

Mr. Kenney's statement that 100° F. either way from the "ordinary" finishing temperature makes no material difference in the properties of rails of heavy section is of importance, as well as his account of rails from "the same heat" but rolled at "widely different" finishing temperatures not showing appreciable differences in the track. The detailed and complete account of this, and similar experiments on a more exactly determined basis, involving a sufficient quantity of material to yield "practical" results, would be of interest.

Until this is done, the question of suitable finishing temperatures will remain unsolved, for the "theoretical" man still asks, Why not roll colder? and the "practical" man admits he has no certain evidence one way or the other.

Mr. Dudley has given us in his elaborate communication what is practically a new paper on the subject of the service of rails as influenced by manufacturing, maintenance, and weather conditions. His explanation of the abnormal number of failures for the year ending Oct. 31, 1912, as due to the cold winter is undoubtedly correct. The experience of the New York Central Lines that the Bessemer rails have an overwhelming proportion of failures as compared with open-hearth—or 22 to 1—appears not to be borne out generally. Mr. Dudley does not give, however, the total number of Bessemer rails, so that a strict comparison cannot be made between the failures of the two types from his data on the New York Central Lines. For the year 1912, for the whole country, the ratio of Bessemer to open-hearth rail failures per million tons laid was 5,160 to 2,379—or roughly 2 to 1. It would appear from Mr. Dudley's figures that the present breakage of open-hearth rails on the New York Central Lines is 91 per year per million tons laid, or only about $\frac{1}{26}$ the average for the whole country in 1912; from which one would infer that the breakage is in general unnecessarily high, and one should perhaps be cautious

in attributing such wholesale failures too readily to increased train loads and high speeds. The questions of maintenance of track and quality of the rails and rolling equipment are perhaps of at least equal importance—factors which Mr. Dudley emphasizes.

Regarding the question of best rolling temperatures, Mr. Dudley appears to consider the unsatisfactory experience with the Kennedy-Morrison process of holding the rail bar 40 sec. before the last pass, to have demonstrated the practical unsuitableness of colder rolling. The fallacy involved in that pseudo-cold-rolling process was explained at the time of its introduction by Professor Sauveur. Mr. Dudley's conclusion concerning shrinkage limits prescribed by the school favoring cold rolling loses some of its force in view of the fact that the shrinkage limits have almost without exception permitted rolling at very much higher temperatures than has apparently been generally supposed.

The question of transverse fissures, also raised by Mr. Dudley, we agree is one requiring further study for their explanation and elimination. The Bureau of Standards has begun an experimental investigation of this subject—following in part suggestions from Mr. Dudley.