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ENDURANCE AND OTHER PROPERTIES OF RAIL STEEL

Part I. ENDURANCE PROPERTIES OF RAIL STEEL

BY

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Part II. COMPARATIVE TESTS OF RAIL STEEL CAST IN STANDARD AND SINK-HEAD MOLDS OF THE GATHMANN TYPE

BY

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ENDURANCE AND OTHER PROPERTIES OF RAIL STEEL

By John R. Freeman, jr., R. L. Dowdell, and William J. Berry

ABSTRACT

A series of tests on the properties of rail steel has been carried out with particular reference to their resistance to repeated stress. Eleven heats of steel were studied, some of which were cast in standard molds and others in sink-head molds. The endurance limit of steel from 100-pound rails was found to vary from a minimum of approximately 41,000 lbs./in.^{2} to a maximum of approximately 59,000 lbs./in.^{2} and the endurance ratio from 37 to 44 per cent. In general, rails rolled from sink-head ingots had higher endurance limits. It was found that the endurance limit of rail steel is decreased by overstressing and may be increased by understressing. A method is suggested whereby it may be possible to determine if rail steels in service are subjected to stresses greater or less than their endurance limits.

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Part I.—ENDURANCE PROPERTIES OF RAIL STEEL

By John R. Freeman, jr., and William J. Berry

I. INTRODUCTION

In a report [1] of the Interstate Commerce Commission in 1917 it is stated: "The continued use of rails without exact knowledge upon their resistance to repeated alternate stresses which constitutes their function in service and without exact knowledge upon the magnitude of the track stresses which they daily receive present an engineering anomaly which has extended far beyond the proper limits of time."

[1] Interstate Commerce Commission, Report of Chief of Division of Safety, Feb. 12, 1917.

It is stated further that "a finished rail is subjected to internal strains of tension and compression, respectively, and its form is so dissimilar from that of a plain cylindrical bar that the endurance of the rail to repeated alternate stresses may not be safely judged of from laboratory tests on carefully prepared cylindrical bars."

All students of transverse fissure failure agree that it is a special case of fatigue failure in which the crack starts from a nucleus inside the head of the rail and progresses from the inside to the outside, instead of from the outside to the inside, as is typical of most fatigue failures. Controversy centers about the existence of, nature of, and the causes for the nucleus of the fissure and not the method of propagation of the failure.

The Joint Committee on Stresses in Railroad Track of the American Railway Engineering Association and the American Society of Civil Engineers has published several reports of extended investigations of track stresses, but in so far as the authors are aware no extended investigations have been made of the endurance or fatigue properties of rail steels.

During the last few years the science of fatigue or endurance testing of metals has been advanced very materially and there are to-day certain fundamental principles of fatigue failures that are well established and upon which all workers in the field agree. These fundamental principles probably apply to all types of metals and alloys, but it is believed by some that rail steels are of a special type and that the same principles do not necessarily apply. In any case it is dangerous to predict the properties of a material by analogy; the properties of a material of as great importance as rail steel should be known by actual determination.

Burgess and Quick [2] reported endurance tests of rail steels, the tests being made by the Titanium Alloys Manufacturing Co., in a cooperative study of the comparative properties of steel deoxidized with titanium and silicon. In these tests the specimens were subjected at first to reversed stresses of low magnitude. After a predetermined number of cycles of stress (5,000,000) the load was increased, and the specimen again subjected to the same number of reversals of stress. This procedure was repeated with increasing increments of stress until failure occurred. At the time these tests were made the very beneficial effects of what is now termed "understressing" and discussed later in this report were not appreciated. The endurance values reported by them are therefore undoubtedly high.

The material available from the investigation of rail steels reported in detail in Part II of this paper provided an excellent opportunity for the study of the endurance properties of rail steels, the complete

[2] Burgess, G. K., Quick, G. W., A Comparison of the Deoxidation Effects of Titanium and Silicon on the Properties of a Rail Steel, B. S. Tech. Paper No. 241.

manufacturing history of which was known and the service characteristics of which were being very carefully followed. The latter fact is very important as it makes possible in the future the correlation of the endurance properties of these rail steels as determined in the laboratory with the behavior of the rails in service.

At a later date, after removal from service, because of wear or other causes, a redetermination of the endurance properties of the steel from the rails which have been in service is planned and may indicate, as discussed more fully later in this report, whether the rail when in service was being subjected to stresses greater or less than its endurance limit.

It was also thought that a better knowledge of the endurance properties of rail steel, particularly when correlated with the results of service tests, might throw some light on the problem of transverse fissures.

II. ENDURANCE TESTING EQUIPMENT

1. SELECTION OF TYPE OF TEST

The rotating beam type of fatigue or endurance test has been more generally used than any other, especially in the United States. In this type of machine, often referred to as the Sondericker or Farmer type, the specimen is a rotating beam supported near the ends and symmetrically loaded at two points thereby subjecting that portion of the beam between the points of application of the load to a uniform bending moment. At any instant during rotation the top fibers are in compression and the bottom in tension. As the specimen rotates through half a revolution the stresses on the fibers of the specimen are thus reversed.

The stress is not uniformly distributed over the entire cross section of the specimen, but varies from a minimum at the center to a maximum at the outer surface. Therefore, the relatively small section of the outer layers of the specimen determines the endurance properties, and any inequality of the material that might affect its indurance, such as an inclusion or shattered zone, which chanced to lie at or near the center of the specimen, might not make itself evident. Consequently, it would be more desirable to make an endurance test under conditions of direct tension and compression so that the stress would be uniformly distributed over the test section. Such a test would be more searching for inhomogeneities that are known to affect the endurance properties of metals. It would also be possible under the conditions of axial loading to subject a test specimen to initial tensile or compressive stresses, simulating internal stress, and determine its effect upon the endurance properties.

Endurance properties of metals have been determined under alternating axial stress. However, the relation of the endurance limit as

determined under these conditions to the endurance limit as determined under the conditions of the rotating beam, is not definitely established.

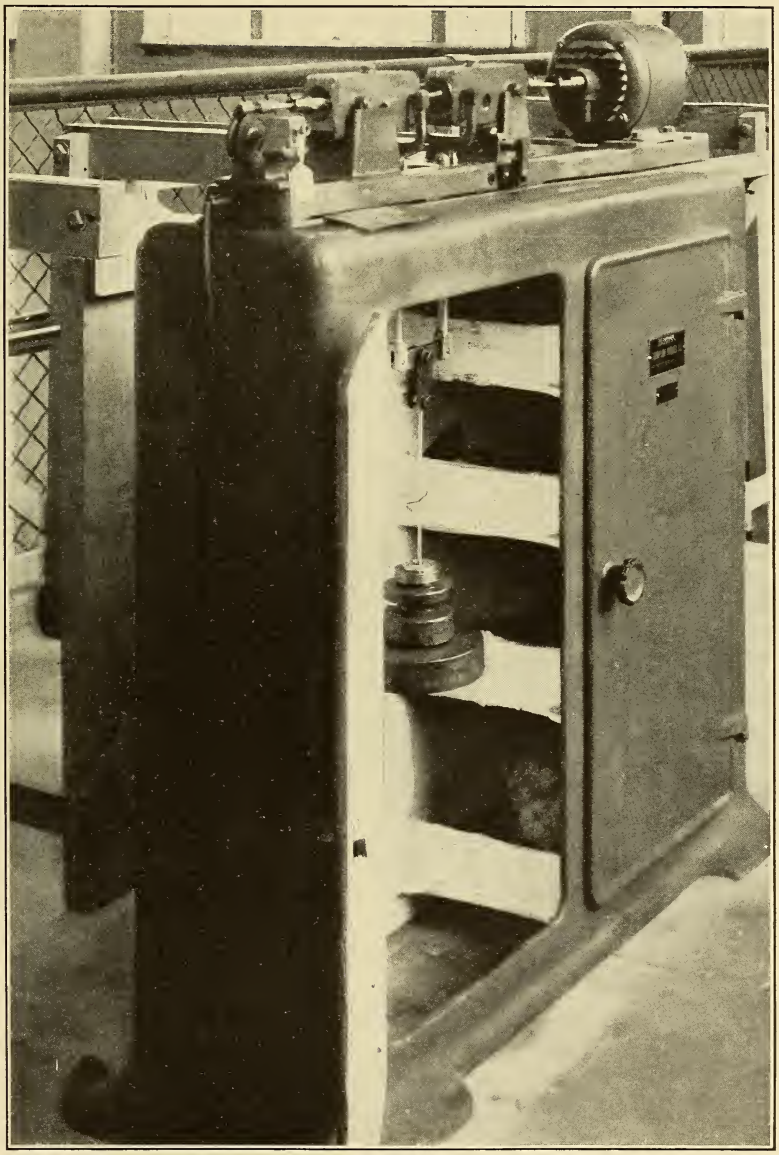

FIG. 1.—*Endurance testing machine*

It is quite generally accepted in the United States as a result of Irwin's [3] work that the endurance limits are the same for both types

[3] Irwin, Paul L., "Fatigue of metals by direct stress," Am. Soc. Test. Matls., 25, Pt. II, 1925, p. 53, and 26, Pt. II, p. 218.

of loading. However, Gough [4] is not in agreement with Irwin and gives evidence supporting his conclusions that the endurance limit as determined under the conditions of reversed axial stress may be considerably lower, depending upon the material, than under the conditions of a rotating beam.

In view of this lack of agreement and the fact that all investigators agree that the results of rotating-beam tests are strictly comparable, it was believed advisable to defer tests of rail steel under reversed axial loading until its relation to rotating-beam loading has been definitely established.[5]

The data reported here have, therefore, all been obtained on machines using the rotating-beam principle.

2. TESTING EQUIPMENT USED

Four fatigue-testing machines of the standard R. R. Moore design [6] were used for all tests. A photograph of one of the machines with specimen in place for test is shown in Figure 1. A particular advantage of this machine is the relatively short specimen required.

In all tests the machines were operated at approximately 2,000 r. p. m.

3. LOCATION, DESIGN, AND PREPARATION OF TEST SPECIMENS

The portion of the head of a rail adjoining the web may be somewhat inferior in quality to the remainder of the head because of the tendency toward a greater concentration of inclusions. Preferably enough test specimens should be taken from this position, commonly termed the "M" position, in order to determine the minimum value.

Sufficient "M" material, however, was not available to obtain the number of specimens (at least four, and preferably more) required to make an endurance test. The specimens were accordingly taken as shown in Figure 2 and given the letter designation indicated. It will be noted that the specimen from the portion (Y) of the head just above the intersection of the web is slightly above the "M" position. It is therefore termed the "Y" specimen rather than "M" throughout this report.

Where sufficient length of rail was available duplicate contiguous specimens were taken, giving in most cases a total of 12 specimens for each rail head.

The design of the test specimen is given in Figure 3a. The radius of 9⅞ inches used to obtain the minimum section has been adopted as standard by H. F. Moore and other investigators. All specimens

[4] Gough, H. J., Some comparative fatigue tests in special relation to the impressed conditions of tests, Aero. Res. Comm. Reports and Memoranda, No. 1012; April, 1926.

[5] An investigation of this question is in progress at the bureau and will be reported at a later date.

[6] Moore, R. R., Some fatigue tests of nonferrous metals, A. S. T. M., **25**, 1925, Pt. II. p. 66. Also Preprint 37; 1927.

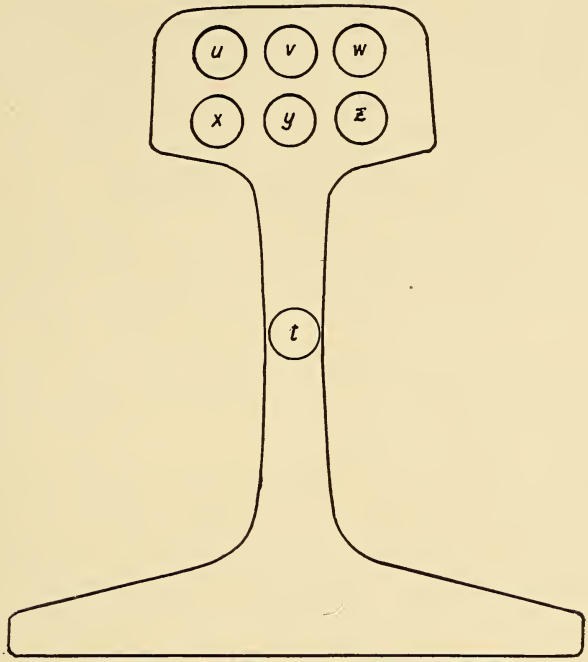

FIG. 2.—*Location of endurance test specimen*

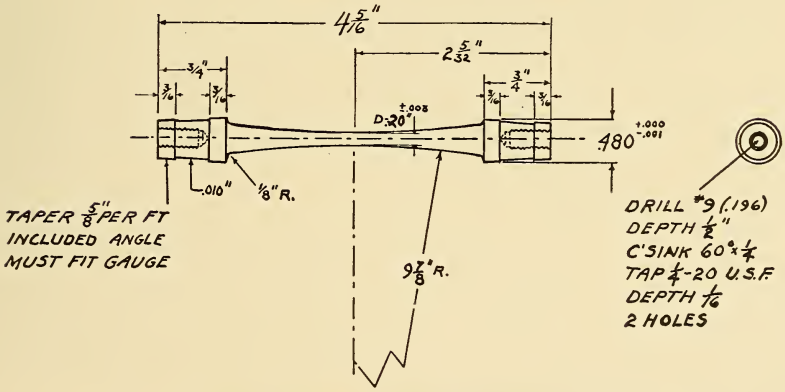

FIG. 3a.—*Design of endurance test specimen*

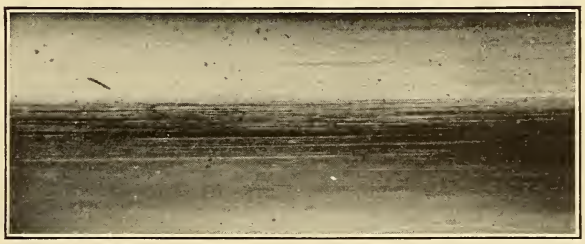

FIG. 3b.—*Typical finish of fatigue test specimen.* ×9

were finish-ground to size in a forming grinder, and then polished to remove all grinding marks. The final polishing was done in a longitudinal direction so as to eliminate all circumferential scratches which are known to affect the endurance properties. A photograph showing a representative finish is given in Figure 3b.

III. MATERIAL STUDIED

The fatigue tests were made on the A and B rails of the middle ingots from 11 heats of open-hearth rail steel. The details of the pouring and rolling of these heats, excepting one (No. 21), are given in Part II of this paper and need not be repeated here. The results of physical tests on the rails from the same ingot are also given. The same designation numbers of heats are used. The ladle analyses are given in Part II, Tables 3 and 5.

It will be noted that six of the heats, Nos. 1, 2, 3, 8, 9, and 10 were made at the Algoma Steel Co. to meet the specifications of the Canadian Pacific Railroad. The other five heats, Nos. 17, 18, 19, 20, and 21 were made at the Edgar Thompson Plant of the Carnegie Steel Co. to meet the specification requirements of the Baltimore & Ohio Railroad which are quite similar to those of the Canadian Pacific. Both are essentially the same as the 1925 specifications of the A. R. E. A. (American Railway Engineering Association.)

The melting and pouring practice for heats Nos. 8, 9, 10, and 21 was typical of present-day rail steel practice. Heats Nos. 1, 2, 3, 17, 18, 19, and 20 were of substantially the same composition, having been made to meet the same specification requirements. However, the steel for these heats was killed with aluminum and poured in sink-head molds with big end up instead of in the customary big-end-down rail ingot mold.

The rails from three of the heats, Nos. 2, 9, and 17, had been rejected; heats Nos. 2 and 9 because of failure in the drop test and heat No. 17 because of high phosphorus content. In this particular heat the specimens were cut from rails from the first ingot poured and not from the middle ingot, as was the case in all other heats except No. 21, the details of which are not known.

All test specimens were taken from rail sections cut from the rail at the hot saw before straightening (gagging), except the one B rail from heat No. 11.

IV. TEST PROCEDURE

Lucas[7] has shown from microstructural observations of armco iron what all the experience of workers in the fatigue of metals has indicated for iron and steel, namely, that inclusions exert a profound

[7] Lucas, F. F., "Observations on the microstructure of the path of fatigue failure in a specimen of armco iron," Trans. A. S. S. T., **11**, No. 4, p. 531, 1927.

influence on the behavior of metals when subjected to reversed cycles of stress, that they are a potential source of weakness, and may even act as "stepping-stones" for the propagation of a fatigue crack.

Deep etching tests (Part II) and microscopic examination of the rail sections had indicated that the fatigue-test specimens taken from that portion of the railhead nearest the junction with the web, designated the Y specimens, might contain a larger number of inclusions or other inhomogeneities than the specimens from the five adjacent positions in the head of the rail designated (fig. 2) U, V, W, X, and Z. Consequently the Y specimens might be expected to have lower endurance values.

In order to determine the validity of this hypothesis, the Y specimens were not generally used in the preliminary determination of the endurance limit of the rail steels. An endurance limit was first determined, using only the five other specimens. The Y specimens were then run at a stress approximately equal to this endurance limit. Any failure of these specimens at a relatively low number of cycles of stress, as compared with the respective endurance curves, would prove that the material in the Y position had a lower endurance value than the remainder of the head of the corresponding rail. The true value of the endurance limit of the steel of the railhead in such cases would then not be known. In some cases it was found to be less than the value determined by the five specimens, but how much less was indeterminable because of lack of material to determine its value by using only Y specimens.

The usual procedure in fatigue testing was followed in all cases. A specimen was first run at about 60 per cent of its tensile strength. According to the number of cycles required for failure at this stress, the stress applied to the second specimen was reduced and the cycles to failure determined. This procedure was repeated until a specimen ran for 25,000,000 cycles without failure.

All the remaining specimens were then run at stresses between the value which did not cause failure and the lowest stress value that had caused failure.

It is quite generally agreed that the endurance limit for steels can be determined at a value for reversals of stress of less than 5,000,000 cycles.[8] In this study, however, all tests were run on a 25,000,000 reversals basis. In no case except in understressed specimens did a failure occur beyond 5,000,000 cycles. It is therefore believed that all specimens that did not fail under 25,000,000 cycles of stress would have "infinite" life at the respective stress values. Moreover, in many cases specimens which had endured 25,000,000 cycles were tested further, but at a higher stress or stresses. As will be noted in

[8] Moore, H. F., Manual of Endurance of Metals Under Repeated Stress, Engineering Foundation Publication No. 15.

the discussion of "understressing," these specimens had in all cases longer endurance than similar bars tested initially at the higher stresses. This increased life at the higher stress substantiates further the assumption that specimens which had a life of 25,000,000 cycles at a given stress would have "infinite" life for most practical purposes at that stress.

V. RESULTS OF ENDURANCE TESTS

1. TESTS OF STEEL FROM B RAILS

The results of all tests on B rails from all heats are given in the customary S–N diagrams in Figures 4 to 11, in which the maximum fiber stress (half the stress range) is plotted as ordinate and the number of cycles for failure (N) as abscissa, the latter to a logarithmic scale for convenience. The endurance curves plotted are those obtained on the duplicate bars taken from the U, V, W, X, and Z positions in the head of the rail.

The results of tests on the Y specimens, determined later, are indicated in the plot by the letter Y beside the respective plotted values. A small arrow attached to a plotted value indicates that the specimen had not failed when the test was discontinued.

Figures 4, 5, and 6 give the results of the tests on the steel from the B rails rolled from standard ingots and Figures 7 and 8 the corresponding results from sink-head ingots. Figures 9, 10, and 11 give data on the steel from the B rails from the three rejected heats Nos. 9, 2, and 17. In Figure 10 the lowest curve represents the original condition of the material. The other curves showing higher endurance values are discussed under "understressing."

It has been established by many investigators that the endurance limit of steel is more closely correlated with the tensile strength than with any other physical property ordinarily determined. The ratio of the endurance limit to the tensile strength is commonly termed the "endurance ratio."

This value for specimens from the B rails is given, together with the tensile values in Table 1. The tensile values used for computing the endurance ratio are the average of the tensile values obtained in the longitudinal direction on the A and C rails of the respective heat and ingot as given in Tables 16 and 17 of Part II. Tensile values determined on the B rails were not available except in the two instances noted in the table.

The endurance ratio R is also given in the respective figures showing the endurance curves.

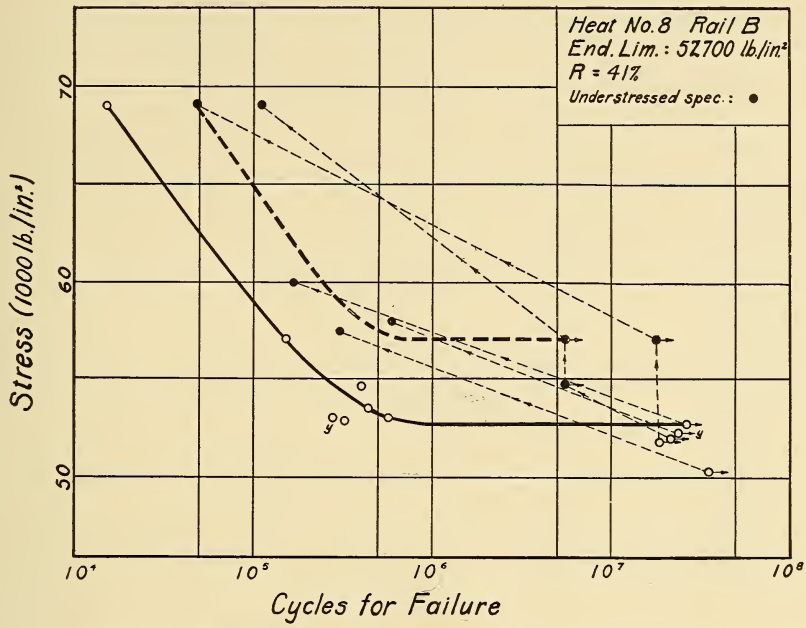

FIG. 4.—*Endurance curve of steel from "B" rail, heat No. 8*

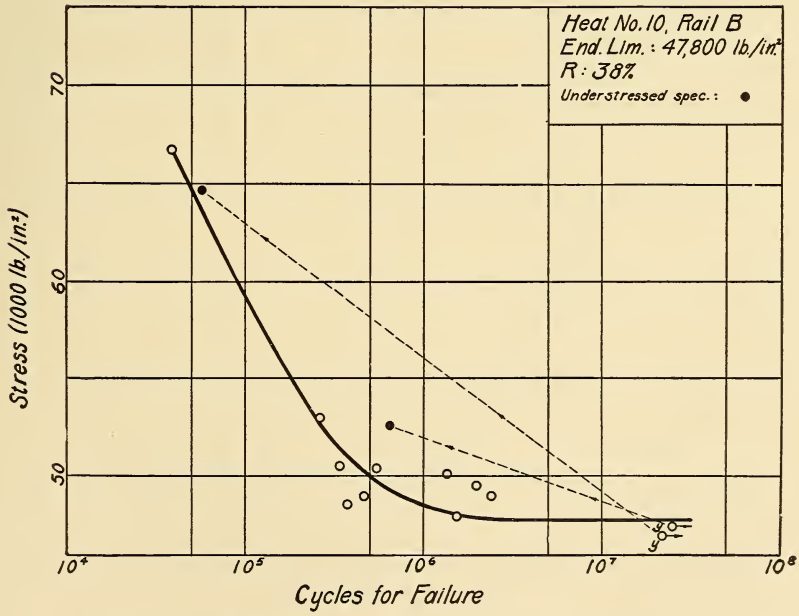

FIG. 5.—*Endurance curve of steel from "B" rail, heat No. 10*

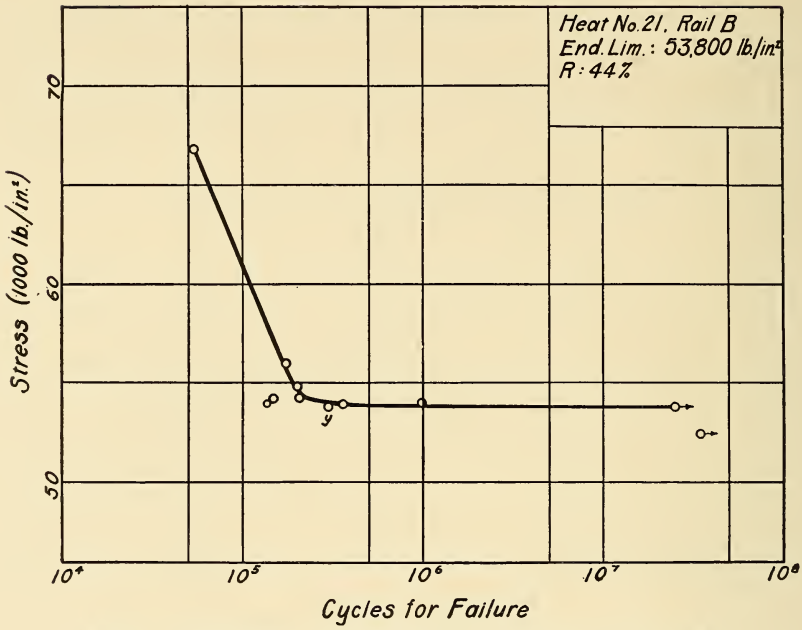

FIG. 6.—*Endurance curve of steel from "B" rail, heat No. 21*

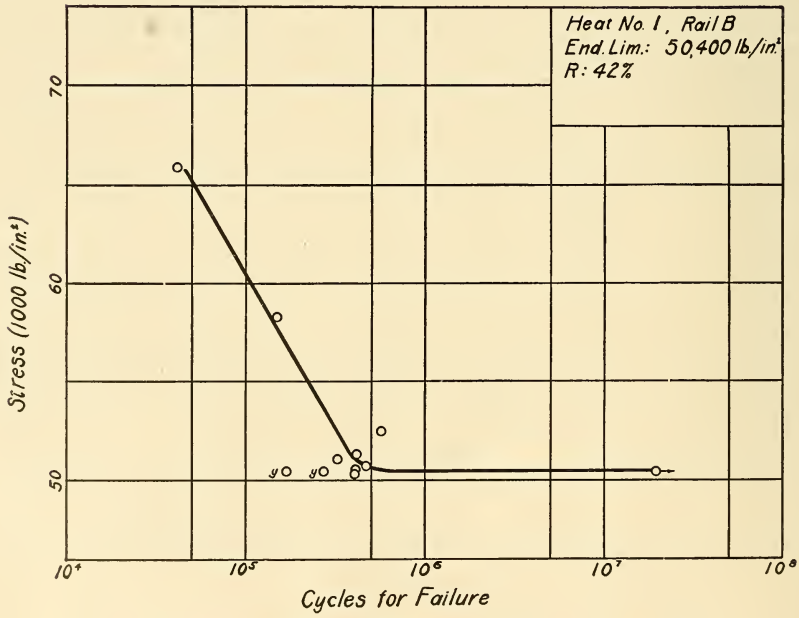

FIG. 7.—*Endurance curve of steel from "B" rail, heat No. 1*

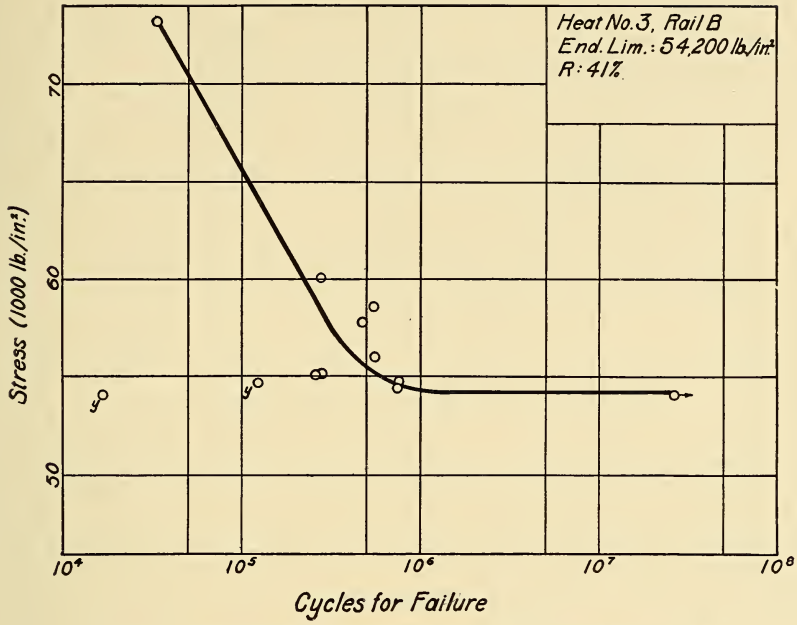

FIG. 8.—*Endurance curve of steel from "B" rail, heat No. 3*

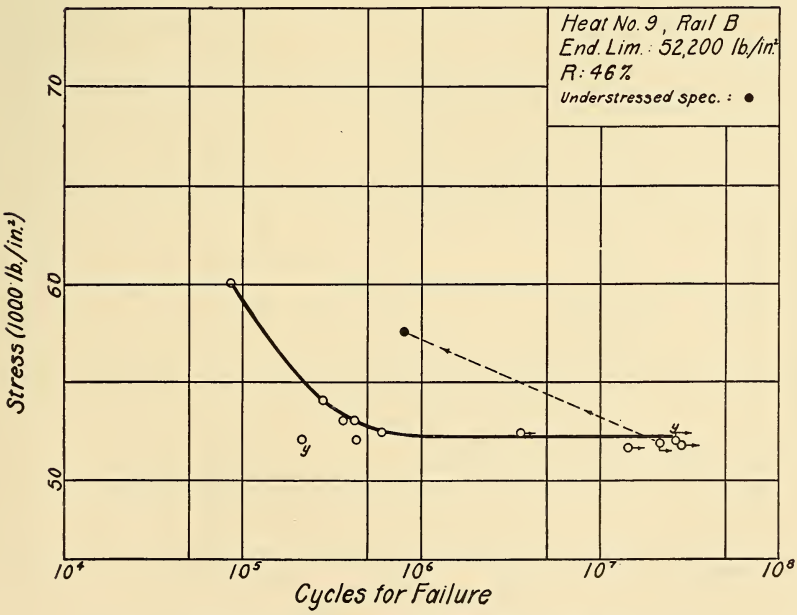

FIG. 9.—*Endurance curve of steel from "B" rail, heat No. 9*

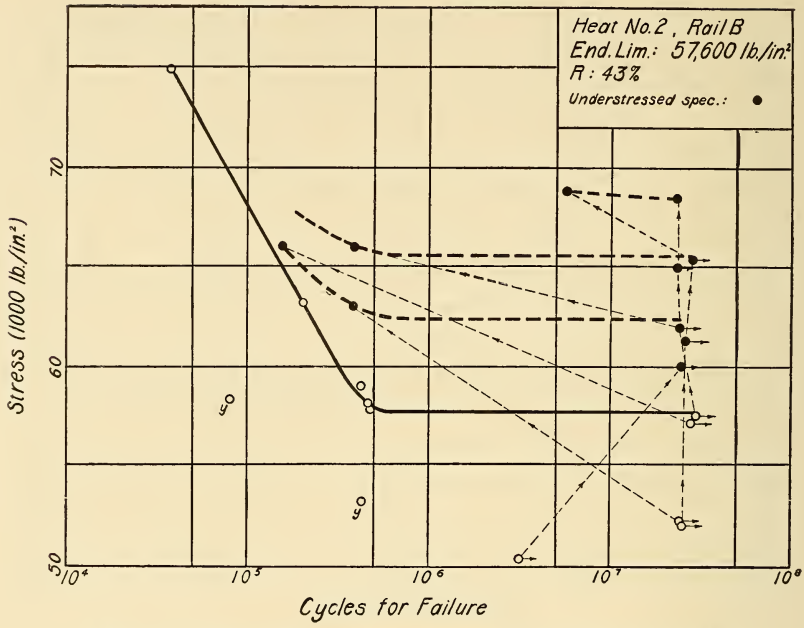

FIG. 10.—*Endurance curve of steel from "B" rail, heat No. 2*

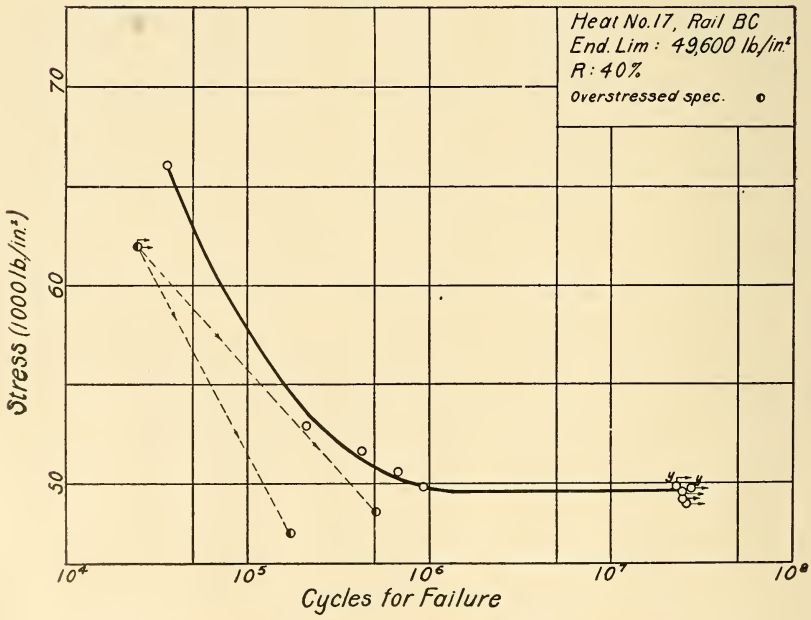

FIG. 11.—*Endurance curve of steel from "BC" rail, heat No. 17*

TABLE 1.—*Relation of endurance limit of steel from B rails to tensile strength and Rockwell B hardness*

Heat No.	Endurance limit B rail	Rockwell hardness B scale	Tensile strength		Average	Endurance ratio (R)
			A rail	C rail		
	Lbs./in.²		*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	
1	50,400	98.5	120,400	119,400	119,900	0.42
2	57,600	99.4	----------	133,200	133,200	.43
3	54,200	99.7	129,750	134,000	131,880	.41
17	49,600	95.5	----------	----------	[1] 120,250	.40
8	52,700	98.3	----------	125,750	125,750	.41
9	52,200	98.4	104,800	122,300	113,550	.46
10	47,800	97.9	132,400	118,900	125,650	.38
21	53,800	98.7	----------	----------	121,500	.44

[1] Test on B rail.

2. TESTS OF STEEL FROM "A" RAILS

The results of all tests on steel from A rails are given in Figures 12 to 18. Very little material was available for test from the A rail of heats Nos. 8 and 10, which were rolled from standard (big end down) ingots and Nos. 1 and 3 which were rolled from sink-head ingots. Four specimens only could be obtained from heat No. 8. They were cut from the top portion of the head from slightly different positions than the specimens from all of the other rails. Six specimens representing the full section of the head were obtained for heats Nos. 10, 1, and 3.

The nomenclature AB rails, used for the designation of the top rails from the sink-head ingots of heats 18, 19, and 20, is the same as was adopted in the presentation of the data for these heats in Part II. The manufacturers of these special sink-head heats marked the top rail the B rail because of the relatively large top cropping of the ingot. Inasmuch as these rails were the first rolled from the top of the ingot they would ordinarily be called the A rail. In order to keep the distinction clear they were designated the AB rails, but considered as A rails in the comparative tests.

The tensile strength, endurance limit, and endurance ratios for all tests of steels from the A and AB rails are given in Table 2.

TABLE 2.—*Relation of endurance limit of steel from A and AB rails to their tensile strength and Rockwell B hardness*

Heat No.	Endurance limit	Rockwell hardness B scale	Tensile strength	Endurance ratio (R)
	Lbs./in.²		*Lbs./in.²*	
8	([1])	101.4	----------	----------
10	46,200	98.6	132,400	0.35
1	47,800	99.2	120,400	.40
3	55,000	101.1	129,750	.42
18	57,400	98.9	----------	----------
19	59,200	98.4	134,750	.44
20	53,600	100.3	115,750	.46

[1] Less than 50,000 lbs./in.². Insufficient material to complete the test.

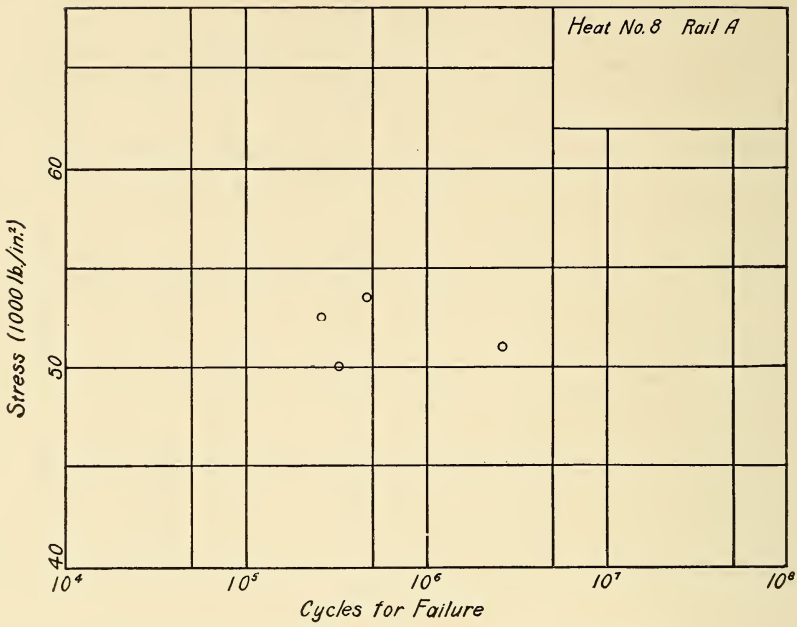

FIG. 12.—*Endurance curve of steel from "A" rail, heat No. 8*

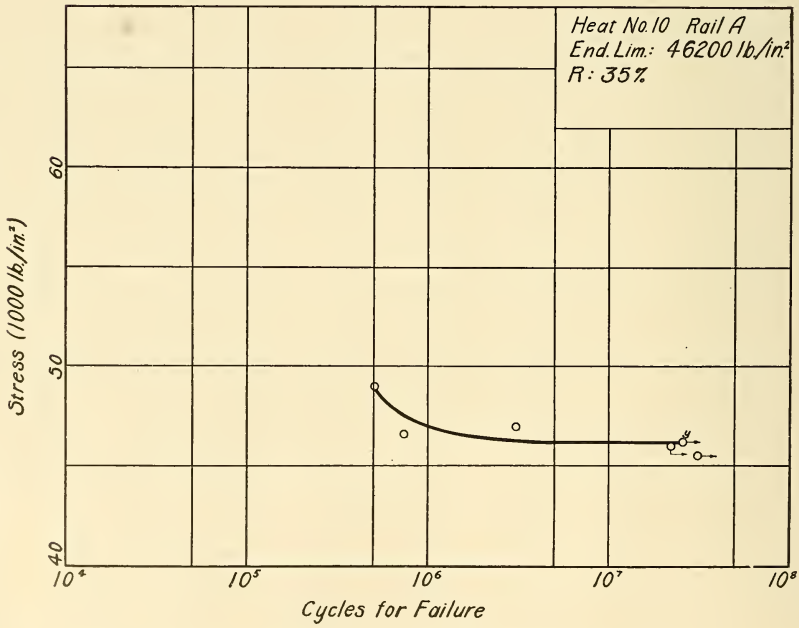

FIG. 13.—*Endurance curve of steel from "A" rail, heat No. 10*

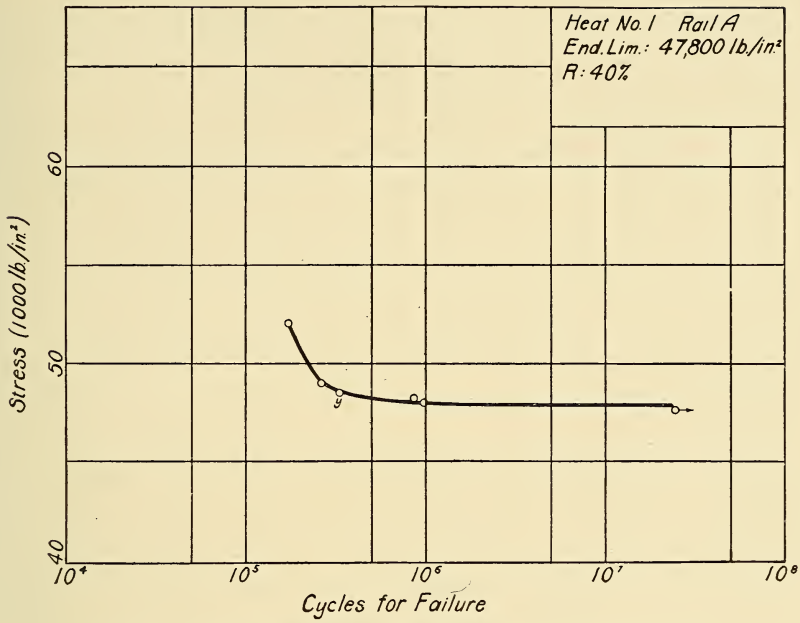

FIG. 14.—*Endurance curve of steel from "A" rail, heat No. 1*

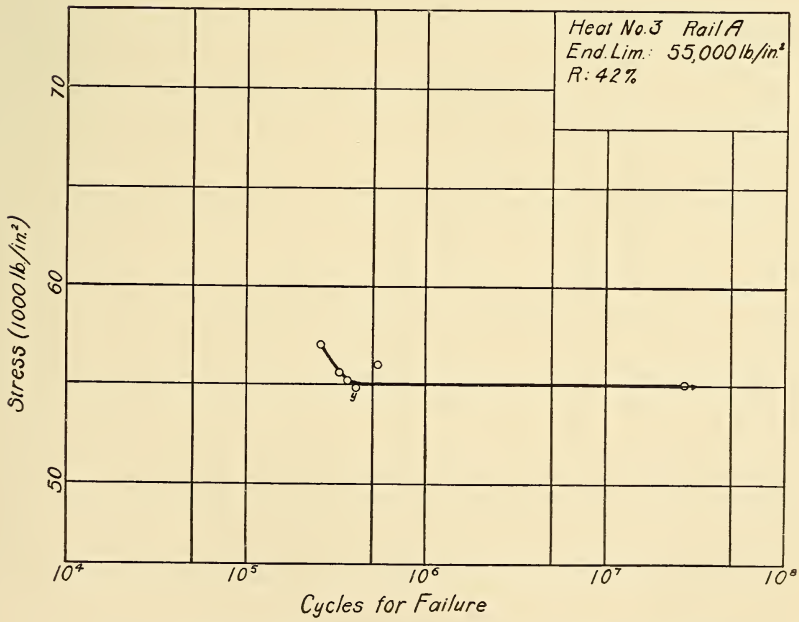

FIG. 15.—*Endurance curve of steel from "A" rail, heat No. 3*

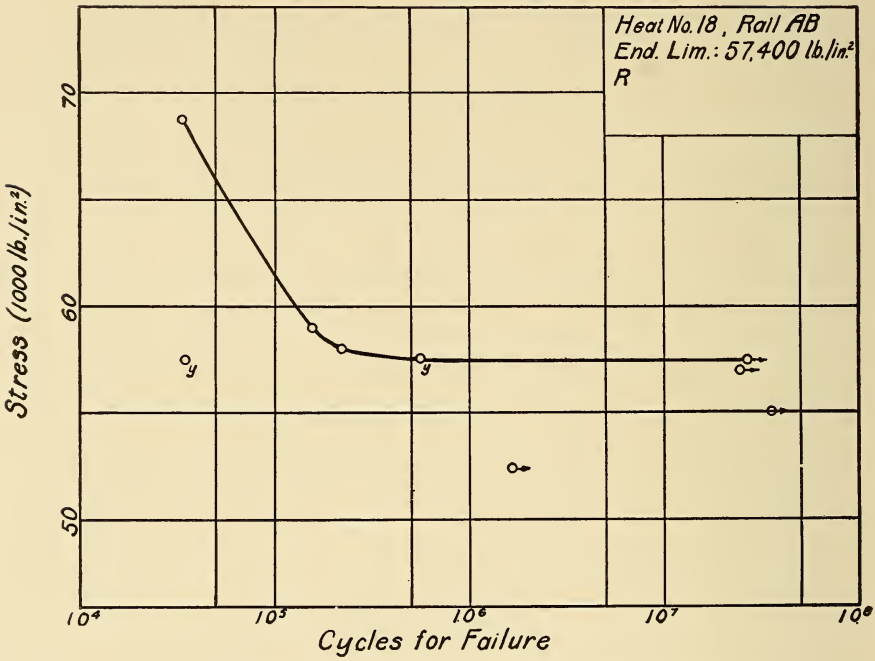

FIG. 16.—*Endurance curve of steel from "AB" rail, heat No. 18*

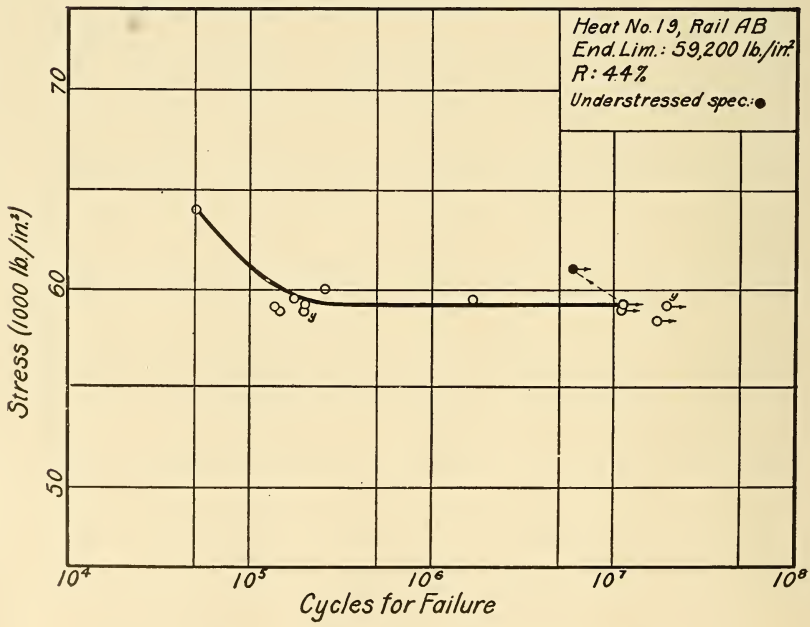

FIG. 17.—*Endurance curve of steel from "AB" rail, heat No. 19*

3. DISCUSSION OF RESULTS ON STEEL FROM A AND B RAILS

The very nature of the method of determining an endurance limit, requiring as it does at least four (preferably more) tests on individual specimens, requires that the material from which the specimens are taken be homogenous and uniform in quality. If such is the case the plotted results for steel will fall on a smooth curve asymptotic to a definite stress value, the endurance limit. If the material is not homogeneous or is nonuniform in its properties the individual tests may show more or less "scatter" from an average endurance curve according to the degree of nonuniformity of the material. Where such nonuniformity is likely to be present a relatively large number

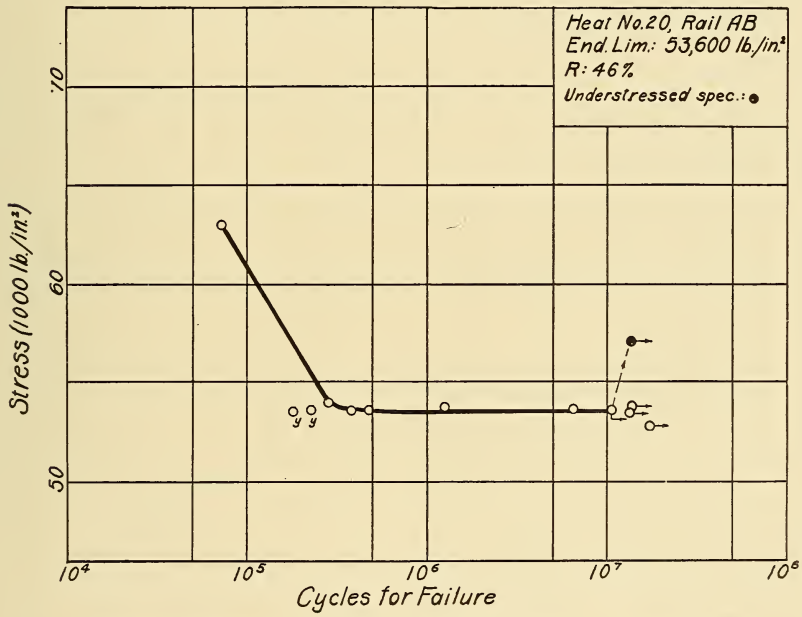

Fig. 18.—*Endurance curve of steel from "AB" rail, heat No. 20*

of tests must be made to determine the average curve although, similar to the proverbial chain, the material is no stronger than its weakest section.

In considering the tests reported here it should be borne in mind that the endurance curves as given in the figures are based upon the specimens taken from the U, V, W, X, and Z positions. (Fig. 2.) The values in Tables 1 and 2, therefore, are for the endurance limit of steel from the head of the rail excluding that portion adjacent to the web, the Y position.

However, in Figure 4 for steel from the B rail of heat No. 8, it is apparent that one Y specimen had "infinite" life at a stress only slightly below the endurance limit and the other Y specimen, tested

at a stress slightly above the endurance limit, had approximately the same life as specimens from other portions of the head. It may, therefore, be concluded that the endurance limit given, 52,700 lbs./in.^{2}, is the true endurance limit of the steel in the head of the B rail from heat No. 8.

The results of the tests on specimens from the B rail from heat No. 10 (fig. 5) show considerable scatter, indicating a lower degree of homogeneity in this rail as compared with the corresponding rail from heat No. 8. In fact, in searching for the endurance limit of this rail steel all except the Y specimens were used and had failed. The Y specimens were then tested at the lower values indicated and did not fail.

The given value of 47,800 lbs./in.^{2} represents, therefore, the true endurance limit of the steel from the head of this rail.

Similarly for the B rail from heat No. 21; inasmuch as the Y specimen showed normal life the endurance value of 53,800 lbs./ in.^{2} probably represents the endurance of steel from the full section of the railhead.

These rails, from heats Nos. 8, 10, and 21, were all rolled from standard ingots and therefore indicate that the endurance limit of steel from the head of 100-pound B rails which meet the A. R. E. A. specification requirements may vary from 47,800 to 53,800 lbs./in.^{2} and the endurance ratio from 38 to 44 per cent.

The results given in Figures 7 and 8 of the tests on the steel from the two B rails rolled from sink-head ingots (heats Nos. 1 and 3) indicate that the steels in these rails have approximately the same endurance limit as those in the rails from standard ingots. However, there is a more marked difference in the endurance properties of material taken from the Y position in the head than was apparent in corresponding specimens from the B rails rolled from standard ingots. In both heats, Nos. 1 and 3, the specimens from the Y position broke after relatively few cycles of stress. In heat No. 3 the departure of the Y specimens from the curve was particularly marked. They did not fail at the minimum section, but at a greater section about 0.47 inch (12 mm) along the axis from it. The stresses at these sections at which failure occurred were about 1,750 lbs./in.^{2} and 1,000 lbs./in.^{2}, respectively, less than the calculated stress at the minimum sections.

The causes of this low endurance of steel from the B rail of a sink-head ingot are not apparent. It should be noted, however, that the ingots of these two heats (Nos. 1 and 3) were poured with too small a hot top. A similar difference in the endurance properties of the Y specimens from the B rail of heat No. 2 was obtained. (Fig. 10.) This heat was rejected for rail service because of failure in the drop test. The hot top in this case was also considered too small. In

the other rejected heat, No. 9 (fig. 9), which was poured in standard molds, one of the Y specimens from a B rail also had a relatively low resistance to fatigue. These data indicate that any inhomogeneities that may be present in the rail are more marked in the portion of the head adjacent to the web.

The material available for endurance tests on the A rails rolled from standard ingots was not sufficient to make as extensive a study as was desirable.

The four specimens from heat No. 8 showed considerable scatter, indicating inhomogeneity. No endurance limit value was obtained. The specimen tested at approximately 51,000 lbs./in.^{2} failed at 2,673,000 cycles of stress, indicating that the stress was only slightly above the endurance limit, so that the next specimen was tested at 50,000 lbs./in.^{2}, it being expected to have "infinite" life. However, it failed in a relatively few cycles of stress.

The results of tests on specimens from the head of the A rail of heat No. 10 (fig. 13) were quite uniform and indicated an endurance limit of 46,200 lbs./in.^{2}, which is only slightly lower than that obtained on specimens from the B rail from the same ingot.

The endurance curves for steel from the A rails of heats No. 1 and 3 (sink head) gave endurance limits of 47,800 and 55,000 lbs./in.^{2}, which are approximately the same as those obtained on steel from the corresponding B rails.

In the AB rail of heat No. 18 (fig. 16) there is evidence of inhomogeneity, one of the Y specimens showing a low endurance. Both of the Y specimens of the AB rail of heat No. 20 showed a slightly but definitely lower endurance life than the specimens from other portions of the head. All specimens from the AB rail of heat No. 19 showed normal life.

The data indicate that the endurance limits of the steel from the head of the A and B rails rolled from both types of ingots are approximately the same, but there is evidence that the portion of the head adjacent to the web in rails rolled from sink-head ingots, especially with too small a sink head, may contain inhomogeneities, causing low endurance.

The result of tests on specimens from the BC rail of heat No. 17, (fig. 11), which was poured in sink-head molds and was rejected, are of interest. The endurance curve shows very little scatter and the Y specimens are of equal quality to specimens from other portions of the head. This heat was rejected, as stated in Part II, because of the high phosphorus content. Apparently the portion of the rail from which the specimens were taken was sound and relatively free from inclusions or other inhomogeneities.

The results of all tests, except for rejected heats on specimens from both A and B rails rolled from standard ingots, have been plotted

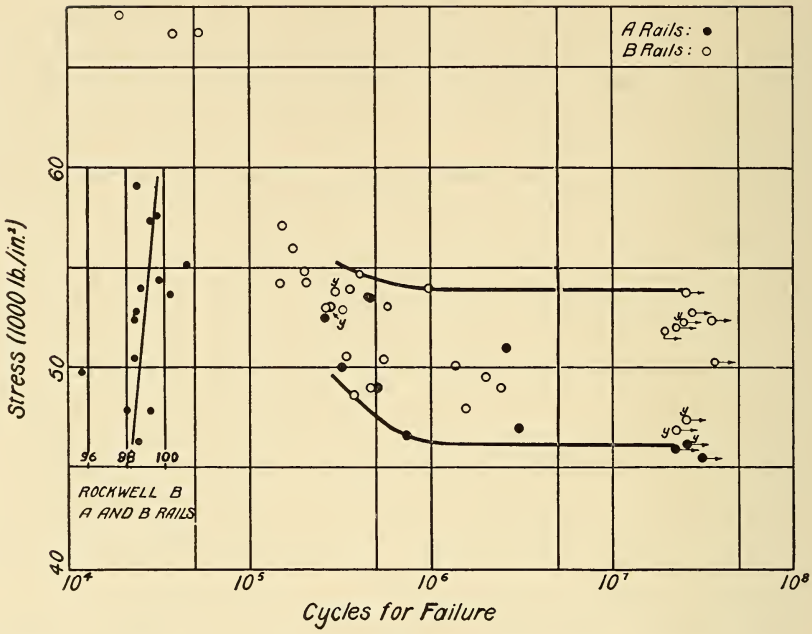

FIG. 19.—*Results of all endurance tests on steels from rails rolled from "standard" ingots*

Relation of endurance limit to Rockwell hardness

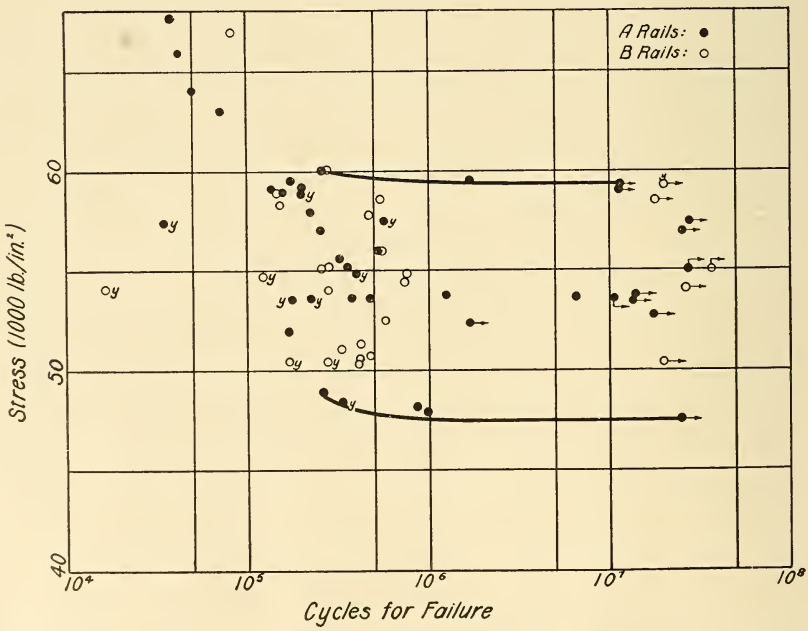

FIG. 20.—*Results of all endurance tests on steels from rails rolled from sink-head ingots*

in Figure 19, and similarly all tests of rails rolled from sink-head ingots are given in Figure 20.

These plots indicate an apparently wide variation in endurance properties of rail steels made to meet the same specification requirements. In both cases the minimum endurance values are shown by A rails. The minimum value obtained on rails rolled from standard ingots is slightly less than for rails rolled from sink-head ingots. This minimum value of approximately 46,000 lbs./in.^{2} represents the endurance limit of steel from 100-pound section rail rolled from standard ingots. It is the maximum value of repeated stress to which the steel in the head of any A or B rail of this section and composition tested in this investigation may be subjected without danger of failure by fatigue. The maximum value of approximately 53,800 lbs./in.^{2} shown by similar rail indicates what might be obtained under optimum conditions.

The rail steels tested which were rolled from sink-head ingots could not with safety be subjected to higher repeated stresses in service than the rail steels from standard ingots because of the low endurance limit shown by one of the rails. It is evident, however, that the maximum value of approximately 59,000 lbs./in.^{2} shown by these rail steels is considerably higher than was obtained on the steels from the standard ingot rails. This indicates that under optimum conditions of manufacture killed rail steel cast in sink-head ingots might have higher endurance properties than present-day standard rail made to the same specification requirements.

In view of the rather wide variation in the endurance limits of the rail steels from different heats, Rockwell hardness (B scale) tests were made on the butt ends of the broken test specimens. The results of these tests from the A and B rails of all heats have been included in Figure 19, the hardness being plotted as abscissa. The data indicate that the higher endurance limits are associated with a slightly greater hardness.

It will be noted that care has been taken to phrase the above discussion in terms of the endurance properties of "steel from" certain rails rather than that of the rails themselves. This guarded phraseology is used in order to emphasize the fact that the endurance limits given are not necessarily a complete representation of the endurance properties of the rails themselves in service.

As previously pointed out for an endurance specimen of the rotating-beam type, the volume of material that is subjected to the maximum stress is extremely small. The neutral axis might contain a serious flaw which would in no way affect the endurance of the specimen, but if subjected to stress in the rail in service might seriously reduce its endurance life. Moreover, the uniformity of the endurance limit from end to end of the rail would have to be studied exhaustively

before one could speak of the endurance limits of the rail. These tests are upon practically random samples of very small portions of a whole rail.

Internal stresses in a rail will affect its endurance properties. When specimens are cut from a rail and machined into endurance specimens, internal stresses present may be relieved or redistributed so that the endurance range of the steel in the specimen may not be the same as it would have been in the rail.

Nevertheless, it is reasonable to begin the study of the endurance properties of rails by first determining the endurance properties of the steel in the rails using the most common type of endurance test so that comparison may be made with available data on other types of steels. It may be desirable eventually to determine the endurance properties of rails, making the tests on the full section of the rail. Before such tests are made a more complete knowledge should be had of the magnitude and distribution of stresses in rails under all conditions.

It would be of interest to compare the endurance properties of steel from all of the rails from the same ingot, and from different ingots as well as from different heats. These tests show that the rail steels from different heats vary in endurance limits from 46,200 to 59,200 lbs./in.^{2}, or 13,000 lbs./in.^{2}, about 28 per cent. The tensile strength of specimens from the M position of the same rails varied from 132,400 to 134,750 lbs./in.^{2}, or 2,350 lbs./in.^{2}, about 1.8 per cent. The maximum difference in tensile strength noted, however, for all specimens from A and B rails was 29,950 lbs./in.^{2}, again about 28 per cent.

Comparison of the endurance limits of two rails from the same ingot can be made only in four instances. It will be noted (Tables 1 and 2) that the steel from the head of the rails rolled from standard ingots of heats Nos. 8 and 10 had endurance limits, at least 2,700 and 1,600 lbs./in.^{2}, respectively, greater than the steel from the corresponding A rails. The steel from the head of the B rail of one sink-head ingot (heat No. 1) was 2,600 lbs./in.^{2} greater than that from the corresponding A rail but was 800 lbs./in.^{2} less in the corresponding rails from heat No. 3.

4. COMPARATIVE TESTS FROM U, Y, AND WEB POSITIONS

As previously stated, there was not sufficient material to take more than two specimens along the length of the rails representing the several heats investigated. Since the results of the tests indicated that the endurance properties of the head of a rail might be different for different positions in the head, it was believed advisable to make tests to determine the amount of difference that might be expected in the head and web of any standard rail.

There was available a portion of a 10-foot section taken from the top end of a B rail from a heat (No. 11, Part II) cast in standard molds.

This was a typical heat of rail steel made at the same time and to the same specification requirements (Canadian Pacific) as several of the other standard heats, the endurance properties of which have been given. It may be considered typical of present-day 100-pound rail. The only known manufacturing difference between this rail and all of the others tested was that this rail was probably gagged while all other specimens were obtained at the hot saw. The amount

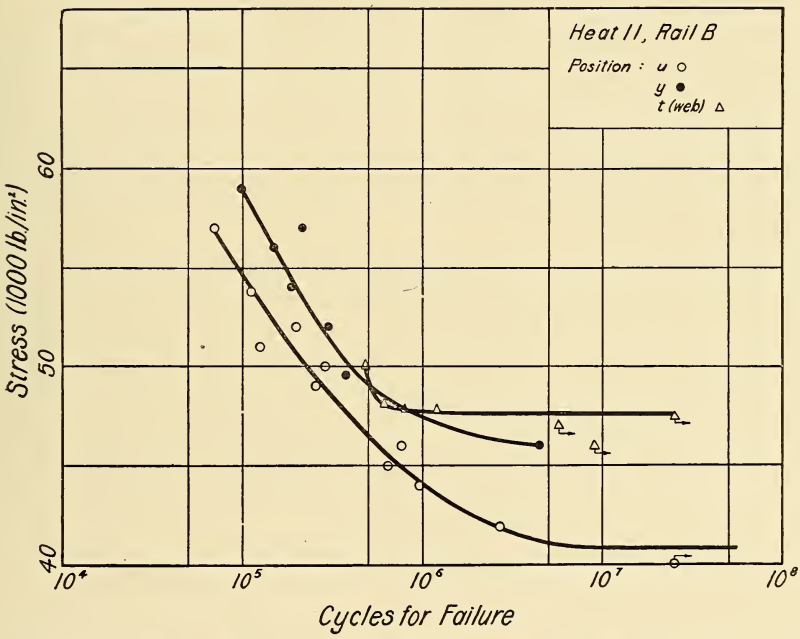

FIG. 21.—*Comparative endurance curves of specimens from the "U," "Y," and web positions*

of gagging to which it was subjected was unknown, but it was known to be not greater than permitted by specification requirements.

Specimens were cut contiguously from the U and Y positions and the center of the web, respectively.

The results of the endurance tests are given in Figure 21. The endurance limit shown by specimens cut from the U position is about 41,000 lbs./in.^{2}, which is appreciably lower than the endurance limits of 45,000 and 47,700 lbs./in.^{2} shown by specimens from the Y and web positions, respectively.

Rockwell B hardness tests were made on the butt ends of two broken specimens from each position, and the average values found to be as follows: U position, 95.4; Y position, 98.8; web position, 97.2.

The lower endurance limit for the U position is probably associated with the difference in hardness. The effect of any gagging the rail may have received is not known.

The tensile strength of specimens cut from the M position was found to be 121,750 lbs./in.^{2}. The endurance ratio based on the endurance limit of the Y position (which corresponds most nearly to the M) is then about 37 per cent.

VI. OVERSTRESSING AND UNDERSTRESSING TESTS

1. EFFECT OF OVERSTRESS

It has been shown[9] by several investigators that if a steel endurance test specimen is subjected to a number of reversals of stress above its endurance limit, but not sufficient to cause failure, the specimen will then fail in fatigue at a stress considerably below its true endurance limit. The ability of the material to withstand repeated stress has been decreased. Its endurance limit has been lowered.

Two tests were made to determine if this were true for rail steel. The results of these tests are given in Figure 11, the points representing initial stress and stresses at which tests were made later being joined by dotted lines.

Two specimens were first subjected to 25,000 cycles of stress at a stress value of approximately 62,000 lbs./in.^{2}, which stress, it was known, would eventually cause failure at about 60,000 cycles. The specimens were then subjected to cycles of stress at stresses below the endurance limit, which stress, it was known, would not cause failure were the material in its original condition.

Both specimens failed, proving that the repeated overstress had caused incipient damage sufficient to cause a distinct lowering of the fatigue resistance.

2. EFFECT OF UNDERSTRESS

It has been shown[10] that if a steel fatigue test specimen is subjected to a relatively large number of reversals of stress at a value below its endurance limit, the ability of that material to resist fatigue stresses has been increased. Its endurance limit is raised.

A series of tests was made to determine if the same effect would be found for rail steels. The results of these tests are included in Figure 10 for tests of the B rail specimens of heat No. 2 and in Figure 4 for tests on the B rail specimens of heat No. 8, which are rails from sink head and standard ingots, respectively.

In determining the endurance limit of the former, five test specimens did not fail. Four of these had been subjected to more than

[9] The Fatigue of Metals, by H. F. Moore and J. B. Kommers, p. 217.
[10] The Fatigue of Metals, by H. F. Moore and J. B. Kommers, p. 220.

25,000,000 reversals of stress and one to about 4,000,000 reversals, three of them at stresses more than 5,000 lbs./in.^{2} below the endurance limit.

These five specimens were then considered as a new material and the endurance limit redetermined.

It is apparent from Figure 10 that the endurance limit had been increased by approximately 5,000 lbs./ in.^{2}, or about 8.6 per cent, by the previous understressing. The plotted points representing retests of the same specimen are connected by dotted lines.

Three specimens remained unbroken in this second series—after 25,000,000 cycles. These were again used as a new material and a new and still higher endurance limit was obtained at approximately 65,500 lbs./in.^{2}, or about 8,000 lbs./in.^{2} higher than the original value, a total increase of 13.9 per cent. The two specimens remaining from this group were again tested. Both of these specimens failed, one after 24,000,000 cycles of stress. The slope of the curve indicates that the endurance limit was close to 68,000 lbs./in.^{2}.

By progressively increasing the stress or "coaxing" the endurance limit was raised probably more than 10,000 lbs./in.^{2}, or about 17.5 per cent.

Certain other facts of interest were brought out by these tests. This heat was rejected for rail service because of failure in the drop test. As previously discussed the endurance limit of the railhead as a whole was less than the value of 57,600 lbs./in.^{2} because of the low life of the Y specimens. The fact that the endurance limit of the other specimens could be raised so materially indicates that the steel from those sections of the head other than the Y was apparently of good quality.

Another point of general interest in fatigue testing brought out by these tests was a partial confirmation of the general belief, lacking complete experimental evidence, that the beneficial effect of understressing does not decrease with time. The specimens which were subjected to 25,000,000 cycles at approximately 52,000 lbs./in.^{2} rested in the laboratory for four months before they were used in determining the secondary endurance limits. Apparently this period of rest did not affect the beneficial effect of understressing.

As previously stated it is quite generally agreed that the endurance limit for steels may be determined at a value for reversals of stress of less than 5,000,000 cycles. Apparently this does not hold for steel specimens, the endurance limit of which has been improved by understressing, as is evident from the endurance life of 6,600,000 and 24,000,000 cycles, respectively, shown by the two understressed specimens subjected to the highest reversed stresses.

In view of this fact, it is evident that the endurance limit of understressed material should be determined on a reversals basis considerably above the 25,000,000 used.

In heat No. 8 (fig. 4) one of the test specimens which had endured 25,000,000 cycles at a stress slightly below the endurance limit was retested at 54,500 lbs./in.^{2} or about 3,000 lbs./in.^{2} above the endurance limit. It did not fail in about 6,000,000 cycles. Its stress was then increased to 57,000 lbs./in.^{2} and it endured 6,000,000 more cycles without failure. It was then subjected to a stress of 69,000 lbs./in.^{2} and failed at about 150,000 cycles of stress. Evidently because of the progressive understressing or coaxing its life at this high stress was several times greater than that of a similar specimen which had not been understressed.

It was thought that the life of this specimen at the intermediate stress (57,000 lbs./in.^{2}) might have been increased by the 6,000,000 cycles of stress to which it was subjected at 54, 500 lbs./in.^{2}. Accordingly the second understressed specimen was run at 57,000 lbs./in.^{2} and apparently had "infinite" life. Its stress was then increased to the same maximum stress (69,000 lbs./in.^{2}) as the previously understressed specimen and it failed in 500,000 cycles. This indicates that the greater number of cycles of stress at 57,000 lbs./in.^{2} was not as beneficial as the intermediate stressing at 54,500 lbs./in.^{2}, although the total number of cycles of stress was about the same.

The remaining understressed specimens were run as indicated in the figure.

The conclusion is evident that "understressing" increased the endurance limit from 52,700 to 57,000 lbs./in.^{2}, or approximately 8 per cent, which is practically the same increase as was shown by rail steel from the sink-head ingot.

3. RELATION TO SERVICE

A knowledge of the effects of overstressing and understressing on the properties of rail steel offers a possible method of determining whether rails in service are being subjected to repeated stresses greater or less than the endurance limit of the material. According to the data given above a rail that is being overstressed in service and that does not fail from fatigue before being removed from service because of wear or other causes should show a reduced endurance limit as compared with its endurance limit before being placed in service. Similarly, if the repeated stresses to which a rail is subjected in service are less than the endurance limit the material is being understressed and, therefore, after removal from service its endurance limit should be greater than before being placed in service. The amount of increase will depend, among other factors, upon the total number of repetitions of the service stresses and the magnitude of

the stresses. The relative direction of stress may be of considerable influence and also whether the stresses are of tension or of compression.

It is planned, therefore, to redetermine the endurance properties of these rail steels after their removal from service.

The results of these tests have also an important bearing on the theories of the development of transverse fissures. If it is found that the endurance limit of the rail in service has been increased the conclusion would be justifiable that the increase is the result of understressing; that the service stresses endured by that rail were, therefore, less than the endurance limit; and consequently that a transverse fissure, which is admittedly a fatigue failure, occurring in a rail of these properties and subjected to these stresses must start from a nucleus acting as a stress raiser present in the rail before laying in track.

Failure of specimens from a rail, which has been in service, to show an increased endurance limit does not prove necessarily that understressing has not occurred. All understressing experiments to date have been made on the endurance specimens per se and under the conditions of stress of the endurance test. No evidence is available to show that strengthening by understressing occurs in large masses of steel subjected to complex stresses.

On the other hand, if it is found that the endurance limit has been decreased the conclusion would be justifiable that the decrease is the result of overstress, that the service stresses are greater than the endurance limit and, therefore, a fatigue failure (transverse fissure) would ultimately develop in track in clean, sound rail free from abnormal internal defects.

When inclusions are present in any steel it is known that the endurance limit of that steel is reduced. Tests have been made on dirty steel, all of which confirm this fact.[11] An interesting example of a fatigue failure, starting from an internal defect, of a ball bearing in service, is cited by Styri.[12] In this case fatigue failure was shown to have originated at a slag inclusion inside the ball and to have then spread outward toward the surface. Its development and appearance is similar to that of a transverse fissure in a rail. Styri states, "In 60 per cent of the cases of ball failures—we can trace them to slag inclusions."

Positive experimental data on the effect of an internal crack on the endurance properties of a steel are not available.

The analogy of an external crack, however, is apparent. It has been shown [13] that the surface finish of an endurance-test specimen

[11] Gillett, H. W., and Mack, E. L., "Molybdenum, cerium, and related alloy steels," p. 158. Moore, H. F. and Jasper, J. M., Univ. of Ill. Eng. Exp. Sta. Bull. No. 142, p. 65; 1924.

[12] Discussion by H. Styri of paper on "Observations on the microstructure of the path of fatigue failure in a specimen of Armco iron," F. F. Lucas, Trans. A. S. S. T. p. 541; April, 1927.

[13] H. F. Moore, The Fatigue of Metals, p. 203.

has a considerable influence on the endurance properties. The stress concentration at the base of tool marks is sufficient to cause a lowering of the endurance limit of test specimens as much as 20 percent. Any notch or sharp fillet acts as a stress raiser and causes a consequent reduction in endurance life.

Moore and Jasper [14] say: "It seems reasonable to suppose that internal flaws act to weaken metal under repeated stress in a manner similar to the action of external notches." In a discussion [15] of the paper by Waring and Hofmann on "Deep etching of rails," Moore states that the small internal cracks noted by them "give a good illustration of material in which localized stress would be high"; that "mathematical analysis, extensometer tests of great sensitiveness, and tests with polarized light, all indicate that the stress at the edge of one of the cracks shown in those figures might be five or six times the computed stress across the rail at that section. The extension of the crack would continue the intensification of stress and fatigue failure might eventually result."

VII. SUMMARY AND CONCLUSIONS

A series of endurance tests of the rotating beam type has been made on steel from 100-pound A and B rails representing 11 heats of rail steel all made to meet approximately the same specification requirements. Some of the heats were cast in accordance with present standard practice. Others were killed with aluminum and cast in big-end-up molds with hot tops.

The endurance limit of the steel from the heads of the rails was found to vary from a minimum of 46,000 lbs./in.^{2} to a maximum of 59,000 lbs./in.^{2}. The minimum value was shown by an A rail rolled from a standard ingot, but, in general, there was no marked difference between the endurance properties of steel from A and B rails. The maximum values were shown by steel from rails rolled from sink-head ingots and, in general, their endurance limit was higher, but some rail steels from this type of ingot had endurance limits only slightly greater than the lowest value stated above. These values were determined for each rail on two contiguous sets of six specimens each, taken parallel to each other, from the head of the rail. Three sets of seven specimens, taken contiguously along the length of a standard B rail, from the O and M positions and the center of the web gave endurance limits of 41,000, 45,000, and 47,700 lbs./in.^{2}, respectively.

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[14] Moore H. F., and Jasper, J. M., "An investigation of the fatigue of metals," series of 1922. Univ. of Illinois, Bull. No. 136; 1923.

[15] Waring, F. M., and Hofman, K. E., "Deep etching of rails and forgings," Proc. A. S. T. M., **19**, Pt. II, p. 183; 1919.

It has been shown that the overstressing of rail steel reduces its endurance limit and that understressing raises it; an increase of about 10,000 lbs./in.^{2} was obtained. A method using these facts has been suggested whereby it may be possible to determine whether rails in service are being subjected to service stresses greater or less than their endurance limits.

A brief discussion is presented on the relation of endurance properties to service and their relation to the cause and development of transverse fissures.

The endurance behavior of rail steels was found to be similar to other steels. The endurance ratio is slightly lower.

Part II.—COMPARATIVE PROPERTIES OF RAIL STEEL CAST IN STANDARD MOLDS AND SINK-HEAD MOLDS OF THE GATHMANN TYPE

By R. L. Dowdell and John R. Freeman, jr.

I. INTRODUCTION

It is quite generally agreed [1] that piping, segregation, and brittleness in rail steel are among the primary causes of rail breakages. It is also stated by many [2] that transverse fissures may arise from such defects present in the steel rail before it is placed in service.

Therefore, any method of manufacture which gives promise of eliminating these defects and of producing a clean, sound, homogeneous steel free from pipe and segregation should be very carefully studied regarding its suitability and application to the manufacture of rails.

Hadfield and Burgess [3] have studied the possibilities of the application of the Hadfield type of sink-head ingot to the manufacture of rails, with particular reference to the soundness and homogeneity of the ingot produced as compared to the standard type of ingot used in the United States. Their investigation indicated a superiority of the big-end-up hot-top ingot for the manufacture of rail steel ingots free from pipe and harmful segregation.

As a result of this investigation the Pennsylvania System purchased [4] from Sir Robert Hadfield 100 tons of steel ingots cast at his works in Sheffield, England, and had them rolled, with comparison ingots, into rail at the Sparrows Point Plant of the Bethlehem (then Mary-

[1] Bulletin of the International Railway Congress, **8**, No. 3, p. 199; March, 1926.

[2] Bibliography and discussion of interior fissures in rails, W. H. Wickhorst, Proc. A. R. E. A., **23**, p. 655; 1922. Rail Report No. 92, February, 1926, A. R. E. A. Transverse Fissures, by G. L. Moore, chairman of committee on rails.

[3] R. A. Hadfield and G. K. Burgess, Sound steel ingots and rails, J. Iron and Steel Inst., No. 1, p. 40; 1915; and Trans. A. I. M. E., **51**, p. 862; 1915.

[4] G. K. Burgess, Steel Rails from Sink-Head and Ordinary Rail Ingots, B. S. Tech. Paper No. 178; 1920.

land) Steel Co. and placed in service on the Pennsylvania Railroad. Cushing [5] states: "Five of the Hadfield rails were laid in the eastward freight track on Horseshoe curve January 20, 1915, and were removed on May 15, 1915, the average abrasion being 1.16 square inches as against 0.78 square inch for the ordinary rail. None of these rails failed."

"On November 26, 1915, 46 No. 1 Hadfield and 53 No. 1 Maryland comparison rails were laid in the eastward passenger and freight track on the 5½-degree curves between Spruce Creek and Union Furnace and were removed October 23, 1916. The 61 No. 2 (seconds) Hadfield and 4 No. 2 Maryland comparison rails were laid on a 2-degree curve in the eastward freight track, Philadelphia division, and are yet in service. None of the rails of either kind have failed."

In a recent letter to the Director of the Bureau of Standards, Mr. Cushing stated that all the rails in this investigation had been removed from track on account of wear, none of them having failed.

In his conclusion to the above report, Mr. Cushing states: "The continued development of special methods in the manufacture of ingots so as to produce sound and homogeneous steel, and the treatment of the rails to bring about greater hardness and strength, without the sacrifice of toughness, is much to be desired."

Belknap, at that time the chief inspector of safety appliances, of the Interstate Commerce Commission,[6] in his discussion of the Hadfield and Burgess report, expressed the hope that the authors would continue their researches.

Kenney [7] states regarding standard molds that the pipe may be "about 50 per cent from the top of the ingot, and analyses show that there is marked segregation of impurities in the neightorhood," that "both of these features are due to the bridging of the metal above and the formation of a separate pool during the freezing of the ingot." He states further that "unfortunately, this is not an infrequent occurrence; the tendency is always present in an ingot which tapers toward the top, and then where actual piping does not develop there is frequently present a loose spongy structure which, in the opinion of the writer (Kenney), is responsible for many of the unexplained failures of steel in service."

In his concluding paragraph he states: "Some cheap method must be developed to make a larger portion of the ingot available for the new and exacting requirements, and so certain are the results which have been obtained through the use of the sink head that the writer (Kenney) believes some adaptation of it is the most promising means of achieving the desired result."

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[5] W. C. Cushing, On the Question of Special Steels, Report No. 1, Int. Rwy. Assoc. Bull., **3**, p. 635; 1921.

[6] See p. 83 of article noted in footnote 3, p. 299, of this paper.

[7] E. F. Kenney, The Commercial Production of Sound and Homogeneous Steel, Yearbook of American Iron and Steel Inst., p. 144 (see p. 161); 1915.

Cushing,[8] in his report on "breaking rails" to the International Railway Congress Association, gives further data on comparative service tests of rails made from sink-head ingots and ingots manufactured in the ordinary way, which, he states, showed that "not only does the sink-head method help to lessen head failures, but has such an effect throughout the entire ingot as to reduce the breakage as well." In a recent letter to the Director of the Bureau of Standards, Mr. Cushing states that the rails from sink-head ingots discussed in his report were the sink-head rails manufactured for them by the Cambria Steel Co., details of which have been given by Kenney. (See footnote 6, p. 300.)

More recently Cushing[9] has emphasized the desirability of the production of rail steel using the sink-head (Hadfield) ingot method because of his confidence that "it will result in a great improvement in homogeneity and strength and safety."

At a conference at the Bureau of Standards on May 2, 1926, E. Gathmann, president of the Gathmann Engineering Co., requested the Bureau of Standards to cooperate with his company in a proposed investigation of the comparative properties of rails made from rising steel in the standard big-end-down ingot molds and rails produced from fully piping (killed) steel made in the big-end-up sink-head ingot molds, known as "Gathmann ingot molds." The arrangements for making and casting of the special heats of steel were to be made by Mr. Gathmann. The cooperative work of the bureau was to be carried out through the research associate plan.[10]

The Bureau of Standards has reported on a numoer of investigations relating to the properties of railway materials.[11] This proposed investigation fitted in very well as a continuation of the study of such materials, that on rails being planned with special reference to its bearing on the problem of transverse fissures.

II. GENERAL PLAN OF INVESTIGATION

In accordance with the research associate plan,[12] Dr. R. L. Dowdell, assistant professor of metallurgy at the University of Minnesota, was appointed research associate to the Bureau of Standards from the Gathmann Engineering Co. to investigate, under the direction of the Bureau of Standards, the physical properties of rails rolled from

[8] Bulletin of the International Railway Congress, **6**, No. 10, first report, October, 1924, p. 677. (See particularly p. 743.)

[9] See p. 206 of article cited in footnote 1, p. 299, of this paper.

[10] B. S. Circular No. 296.

[11] Thermal Stresses in Chilled Iron Car Wheels, G. K. Burgess and R. W. Woodward, B. S. Tech. Paper No. 209; Thermal Stresses in Steel Car Wheels, G. K. Burgess and G. W. Quick, B. S. Tech. Paper No. 235; A Comparison of the Deoxidation Effects of Titanium and Silicon on the Properties of Rail Steel, G. K. Burgess and G. W. Quick, B. S. Tech. Paper No. 241.

[12] See footnote 9.

ingots cast in accordance with the customary practice used with big-end-down molds and rails of similar composition rolled from ingots cast in Gathmann molds.

The Gathmann Engineering Co., in cooperation with the Baltimore & Ohio Railroad and the Canadian Pacific Railway, arranged for the obtaining, at the Edgar Thompson Works of the Carnegie Steel Co. and at the Algoma Steel Co., respectively, of the samples representing the special heats of steel reported herewith.

It is the usual practice of the Bureau of Standards, in reporting upon a study of commercial products, to designate those from different makers by letters or numbers in order to preserve anonymity of the makers. Since any solution of the transverse fissure problem in rails obviously depends on being able to connect the performance of rails in service with all the variables affecting their manufacture and use, reports of rail failures made by the Interstate Commerce Commission refer to rails by the maker's name and heat number, which are rolled or stamped onto each rail. The published records of the American Railway Association are similarly specific as to failed rails. Since rails from the heats studied in this work have been laid in track and are being watched for failures, in order to allow connecting the future records of service with the properties of the specimens tested, it is necessary to give the maker's names and the heat numbers.

Doctor Dowdell, acting for the Gathmann Engineering Co., witnessed the manufacture of all heats reported herewith made at both the Algoma and Carnegie Steel Co. for the Canadian Pacific Railway and Baltimore & Ohio Railroad, respectively. All manufacturers' data regarding these heats are, therefore, those reported by him. Doctor Dowdell also selected all specimens for test and later identified and assisted in testing them at the Bureau of Standards in his capacity as research associate to the bureau.

The specifications set for the manufacture of the special heats were decided upon by the Gathmann Engineering Co. with the Baltimore & Ohio Railroad and Canadian Pacific Railway, respectively, after conference with the steel companies concerned. The rails were required to meet the specifications of the respective railroads. The requirements of the two roads are essentially the same. Direct comparison of physical properties may therefore be made.

The heats were to be cast in ingot molds as specified. Some of the ingots were to be split for examination for soundness and location of pipe and examined for segregation by chemical analysis. A definite number of ingots from each heat cast in each type of mold were to be rolled into rails. Representative sections of rails from the several heats were to be sent to the Bureau of Standards for detailed study of the physical properties.

III. MANUFACTURING PROCESSES

1. MELTING PRACTICE

(*a*) Algoma Steel Co., Gathmann Ingots.—Seven heats of full-piping steel were made in 60-ton basic open-hearth furnaces. These heats were made from about 50 per cent cold scrap with the remainder of the charge consisting of hot pig iron having a manganese content of approximately 1.60 per cent.

The deoxidation was effected by the addition of about 1,200 pounds of 15 per cent silico pig when the metal and slag had reached the proper condition. About five minutes later a recarburizer of 10,000 pounds of hot metal was added. After another five minutes all (about 900 pounds) of the ferromanganese (80 per cent) was added to the bath which was held for 15 minutes before tapping. During tapping about 300 pounds of 50 per cent ferrosilicon were added to the ladle. This ladle addition was followed, except in two heats, with about 0.85 pound of bar aluminum per ton of steel poured (about 51 pounds per heat). The other two heats were deoxidized with aluminum-silicon alloy (approximately 46 per cent aluminum, 38 per cent silicon).

(*b*) Algoma Steel Co., Standard Ingots.—Nine heats were poured in standard molds (big end down). The melting practice for the heats was essentially the same as for the heats poured into the Gathmann molds.

These heats were partially deoxidized by the addition of ferromanganese, one-fourth of which was added in the furnace and three-fourths in the ladle, together with 100 pounds of anthracite coal to recarburize. No aluminum was added to these heats.

All of these 16 heats met the specification requirements for chemical composition. One of each type, however, failed to meet the drop-test requirements and, therefore, these two heats were rejected.

Detailed data on all heats are given in Tables 3 and 4. The ladle analyses given are those reported by the company.

TABLE 3.—*Open-hearth data on rail steel cast in Gathmann and standard molds at Algoma Steel Co.*

	Data for Gathmann molds						
	Heat 5157 (B. S. 1)	Heat 5158 (B. S. 2)	Heat 5159 (B. S. 3)	Heat 5164 (B. S. 4)	Heat 5165 (B. S. 5)	Heat 5166 (B. S. 6)	Heat 5167 (B. S. 7)
Date	June 17, 1926	June 18, 1926	June 18, 1926	June 21, 1926	June 21, 1926	June 22, 1926	June 23, 1926
Limestone (bottom) ... pounds	16,300	14,600	15,900	17,500	16,100	16,100	13,000
Hot metal (mixer) ... do	72,000	70,000	72,000	72,000	70,000	58,000	68,000
Hot metal (extra) (mixer) ... do	8,000	None.	8,000	None.	None.	None.	None.
Rail scrap (ends) ... do	23,800	----------	----------	----------	20,900	----------	----------
Foreign scrap ... do	45,000	3,000	68,100	7,400	40,600	21,800	65,000
Pit scrap and skulls (iron) ... do	None.	5,600	----------	26,500	6,700	14,000 (2 molds)	6,600
Merchant scrap (bloom butts) ... do	----------	60,900	----------	34,800	----------	46,000	----------
Finish charging	10.20 p. m.	8.15 a. m.	6.35 p. m.	5.05 a. m.	3.25 p. m.	1.20 a. m.	11.20 a. m.
FURNACE ADDITIONS (AFTER MELTING)							
Iron ore 58 per cent Fe ... pounds	6,200	6,600	6,000	6,000	6,300	5,800	5,800
Iron content ... do	3,596	3,828	3,480	3,480	3,654	3,364	3,364
Silicon pig (solid) 15 per cent Si ... do	7.17 a. m. 1,200	5.06 p. m. 1,200	4.50 a. m. 1,200	2.00 p. m. 1,200	12.16 a. m. 1,200	10.29 a. m. 1,200	8.15 p. m. 1,200
Recarburizer (hot metal) (mixer) ... do	7.22 a. m. 11,000	5.12 p. m. 12,000	4.57 a. m. 10,000	2.15 p. m. 10,000	12.22 a. m. 11,000	10.35 a. m. 10,000	8.21 p. m. 11,000
Ferromanganese (80 per cent)	7.27 a.m. 900	5.15 p. m. 1,000	5.00 a. m. 750	2.18 p. m. 850	900	10.38 a. m. 900	8.24 p. m. 950
Mn analysis before tapping ... per cent	0.35	0.23	0.37 .47 .43	0.30	0.30	0.33	0.25
Time tapped	7.42 a. m.	5.30 p. m.	5.14 a. m.	2.34 p. m.	12.40 a. m.	10.52 a. m.	8.39 p. m.
Time of heat	9 hr. 25 m.	9 hr. 15 m.	10 hr. 40 m.	9 hr. 30 m.	9 hr. 15 m.	9 hr. 30 m.	9 hr. 20 m.

LADLE ADDITIONS

Ferromanganese (80 per cent) ..... pounds	None.	None.	None.	None.	None.	None.	None.
Ferrosilicon (50 per cent) ..... do	140	300	300	300	300	300	100
46 per cent Al-38 per cent Si alloy ..... do	125	None.	None.	None.	None.	None.	250
Aluminum bar 100 per cent ..... do	None.	52	54	51	51	51	None.
Coal (anthracite-pea) ..... do	None.	None.	None.	None.	None.	None.	None.
Total metallics	158,561	157,880	163,884	156,581	155,305	155,615	156,464

LADLE ANALYSIS (AT THIRD INGOT)

Carbon ..... per cent	0.67	0.72	0.66	0.71	0.68	0.70	0.72
Manganese ..... do	.74	.90	.82	.67	.75	.67	.77
Phosphorus ..... do	.022	.030	.038	.024	.024	.022	.024
Sulphur ..... do	.028	.028	.030	.021	.027	.025	.024
Silicon ..... do	.150	.164	.174	.156	.160	.102	.190

TABLE 3.—*Open-hearth data on rail steel cast in Gathmann and standard molds at Algoma Steel Co.*—Continued

	Data for standard molds								
	Heat 3178 (B. S. 8)	Heat 5156 (B. S. 9)	Heat 11142 (B. S. 10)	Heat 11145 (B. S. 11)	Heat 4141 (B. S. 12)	Heat 25098 (B. S. 13)	Heat 11148 (B. S. 14)	Heat 5168 (B. S. 15)	Heat 5169 (B. S. 16)
Date	June 17, 1926	June 17, 1926	June 17, 1926	June 21, 1926	June 21, 1926	June 21, 1926	June 21, 1926	June 22, 1926	June 23, 1926
Began charging	1.10 a. m.	1.50 p. m.	7.55 p. m.	9.10 a. m.	4.40 p. m.	6.50 p. m.	2.05 p. m.	9.15 p. m.	----------
Limestone, (bottom) pounds	15,500	13,900	20,800	20,800	17,000	20,800	20,500	14,800	----------
Hot metal (mixer) do	61,000	62,000	95,600	92,900	75,000	85,600	111,400	70,000	73,000
Hot metal (extra) (mixer) do	None.	None.	None.	None.	None.	None.	None.	None.	----------
Rail scrap (ends) do	----------	42,700	----------	18,600	----------	----------	----------	----------	----------
Foreign scrap do	----------	23,000	18,500	44,000	14,800	19,700	26,900	10,000	27,700
Pit scrap and skulls (iron) do	19,000	8,900	----------	----------	----------	----------	----------	----------	8,800
Merchant scrap (bloom butts) do	45,000	----------	53,800	7,700	40,900	49,800	44,300	60,000	43,100
Finish charging	1.35 a. m.	2.20 p. m.	8.15 p. m.	10.20 a. m.	5.10 p. m.	7.50 p. m.	2.25 p. m.	9.35 p. m.	----------
FURNACE ADDITIONS (AFTER MELTING)									
Iron ore 58 per cent Fe pounds	6,000	6,200	7,000	----------	5,500	11,300	10,800	6,200	----------
Iron content do	3,480	3,596	5,800	----------	3,190	6,554	6,264	3,596	3,480
Silicon pig (solid), 15 per cent Si do	200	200	----------	----------	----------	----------	----------	200	300
Recarburizer (hot metal) (mixer) do	10,000	10,000	12,300	12,100	12,000	12,200	12,200	11,000	----------
Ferromanganese (80 per cent)	750	----------	200	200	750	200	200	----------	----------
Time tapped	11.35 a. m.	9.35 p. m.	6.25 a. m.	7.35 a. m.	2.35 a. m.	2.50 a. m.	2.15 a. m.	4.45 a. m.	----------
Time of heat	10 hr. 25 m.	7 hr. 45 m.	10 hr. 30 m.	15 hr. 05 m.	9 hr. 55 m.	8 hr. 00 m.	12 hr. 10 m.	7 hr. 30 m.	----------
LADLE ADDITIONS									
Ferromanganese (80 per cent) pounds	None.	800	800	700	300	700	850	850	825
Ferrosilicon (50 per cent) do	300	300	450	450	200	450	500	300	400
46 per cent Al–38 per cent Si alloy do	None.	None.	None.	None.	None.	None.	None.	None.	----------
Aluminum bar 100 per cent do	None.	None.	None.	None.	None.	None.	None.	None.	----------
Coal (anthracite-pea) do	50	200	100	100	300	150	250	25	75
Total metallics	139,730	151,496	187,450	176,650	147,140	175,204	202,614	156,046	----------

LADLE ANALYSIS (AT THIRD INGOT)

Carbon ..... per cent	0.71	0.74	0.69	0.69	0.68	0.64	0.72	0.69	0.65
Manganese ..... do	.75	.78	.79	.69	.72	.68	.72	.72	.72
Phosphorus ..... do	.018	.030	.030	.026	.027	.028	.028	.026	.024
Sulphur ..... do	.018	.037	.020	.022	.026	.030	.024	.032	.022
Silicon ..... do	.166	.120	.130	.140	.162	.140	.150	.158	.154

ANALYSES OF MIXER METAL USED

Date	June 17, 1926	June 18, 1926	June 19, 1926	June 20, 1926	June 21, 1926	June 22, 1926	.....
Composition:							
Manganese ..... per cent	1.66	1.78	1.65	1.59	1.39	1.54	.....
Phosphorus ..... do	.268	.247	.265	.269	.246	.256	.....
Sulphur ..... do	.030	.025	.031	.031	.035	.034	.....
Silicon ..... do	1.14	1.75	1.49	1.14	1.08	1.14	.....

[1] Burnt lime.

NOTE.—These analyses consist of the average analyses of 12 casts per day on 2 blast furnaces making basic iron (6 casts on each furnace). Each analysis represents a time interval from 7 a. m. on the dates given above to 6.05 a. m. on the following day.

TABLE 4.—*Tapping, stripping, and soaking-pit data on rail steel cast in Gathmann and standard molds at the Algoma Steel Co.*

	Data for Gathmann molds						
	Heat 5157 (B. S. 1)	Heat 5158 (B. S. 2)	Heat 5159 (B. S. 3)	Heat 5164 (B. S. 4)	Heat 5165 (B. S. 5)	Heat 5166 (B. S. 6)	Heat 5167 (B. S. 7)
Time tapped	7.42 a. m.	5.30 p. m.	5.14 a. m.	2.34 p. m.	12.40 a. m.	10.52 a. m.	8.39 p. m.
Time furnace emptied	7.49 a. m.	5.40 p. m.	5.22 a. m.	2.41 p. m.	12.47 a. m.	11.00 a. m.	8.46 p. m.
Time of teeming (start)	7.51 a. m.	5.43 p. m.	5.25 a. m.	2.44 p. m.	12.50 a. m.	11.04 a. m.	8.49 p. m.
Finish of teeming	8.24 a. m.	6.21 p. m.	5.53 a. m.	3.19 p. m.	1.26 a. m.	11.34 a. m.	9.24 p. m.
Temperature of bath (center of furnace) °F	2,899	2,949	2,800	2,961	2,949	2,973	2,925
Temperature of ladle:							
One-half full °F	2,885	2,840	2,840	2,865	2,875	2,915	2,885
Three-quarters full °F	2,885	2,855	2,875	2,940	2,885	2,975	2,915
Full °F	2,895	2,885	2,950	2,990	2,940	3,025	2,960
Temperature of steel in teeming (average) °F	2,752	2,675	2,765	2,700	2,732	----------	2,715
Number Gathmann ingots	22	19, butt.	21, butt.	17	18, butt.	19	18
Number standard ingots	0	1	0	1	0	0	0
Ingot size:							
Gathmann, 21 by 21 inches; height of pour inches	66½	66½	66½	66½	66½	66½	66½
Standard, 20 by 22 inches; height of pour do	----------	67½	----------	67½	----------	----------	----------
Size of Gathmann ingot top do	(4½-inch fire brick) 13 by 15 by 14½			(2½-inch fire-brick lining) 18 by 19 by 14½.			
Mold and refractory, top temperature	(About 300° F. in all cases. Graphite-water wash on molds)						
Weight of ingot (average) pounds	7,077	6,915	6,966	7,415	7,376	7,170	7,361
Time stripped	10.45 a. m.	9.40 p. m.	(About 2½ hours after teeming first ingot)				
SOAKING-PIT DATA							
Time charged to pits	11 a. m.	9.55 p. m.	9.50 to 1.10 p.m.	6.30 p. m.	5.55 to 6.25 a.m.	2 p. m.	1.15 a. m.
Time drawn from pits	3.45 to 4 p. m.	2.25 to 3.15 a.m.	2.50 to 4.45 p.m.	12.10 p. m.	11.30 to 12.20 p. m.	6.50 p. m.	5.35 to 6.05 a.m.
Average time of ingots in pits	4 hr. 35 m.	4 hr. 45 m.	4 hr. 05 m.	5 hr. 30 m.	4 hr. 55 m.	3 hr. 30 m.	4 hr. 30 m.
Temperature of ingots	Soaking pits operated between 2,100 and 2,200° F. Ingots were at approximately same temperature as pits						

	Data for standard molds								
	Heat 3178 (B. S. 8)	Heat 5156 (B. S. 9)	Heat 11142 (B. S. 10)	Heat 11145 (B. S. 11)	Heat 4141 (B. S. 12)	Heat 25098 (B. S. 13)	Heat 11148 (B. S. 14)	Heat 5168 (B. S. 15)	Heat 5169 (B. S. 16)
Time tapped	11.35 a. m.	9.35 p. m.	6.25 a. m.	7.35 a. m.	2.35 a. m.	2.50 a. m.	2.15 a. m.	4.45 a. m.	1.50 p. m.
Time of teeming (start)	----------	----------	----------	----------	----------	----------	----------	4.58 a. m.	2.23 p. m.
Number of Gathmann ingots	0	1	0	0	0	0	0	0	1
Number of standard ingots	18¾	18	25	24	19½	24	27	21, butt.	18½
Ingot size: Standard, 20 by 22 inches; height of pour ... inches	67½	67½	66½	66½	67½	66½	66½	67½	----------
Mold and refractory, top temperature	(About 300° F. in all cases. Graphite-water mold wash)								
Weight of ingot (average) ... pounds	6,821	6,850	6,776	6,760	6,772	6,770	6,732	6,780	6,897
Time stripped	(About ½ hour after teeming first mold)					----------	----------	5.28 to 6 a. m.	2.37 to 2.56 p.m
SOAKING-PIT DATA									
Time charged to pits	12.40 p. m.	10.35 p. m.	7.35 to 7.55 a.m.	[1] 8.50 a. m.	4.35 a. m.	3.50 a. m.	3.20 a. m.	5.55 to 6.05 a.m.	3 to 3.10 p. m.
Time drawn from pits	2.50 a. m.	12.20 p. m.	11 to 11.45 a.m.	6.55 p. m.	8.20 to 8.45 a. m.	6.30 a. m.	5.05 a. m.	8.15 to 8.35 a.m.	4.55 to 5.15 p.m.
Average time of ingots in pits	2 hrs. 10 m.	3 hrs. 5 m.	3 hrs. 50 m.	7 hrs. 30 m. to 10 hrs.	3 hrs. 25 m. to 4 hrs. 5 m.	2 hrs. 40 m. to 3 hrs.	1 hr. 45 m. to 2 hrs. 20 m.	----------	----------
Temperatures of ingots	Soaking pits were operated between 2,100 and 2,200° F. Ingots were at approximately same temperature as pits								

[1] Mill repair.

(*c*) Carnegie Steel Co., Gathmann Ingots.—Four heats of full piping steel of 110 tons each were made in basic open-hearth furnaces. These heats have been discussed in some detail by Harden.[13]

The furnace charge consisted of about 40 per cent cold scrap with the remainder consisting of hot metal having a manganese content of about 1.80 per cent. The melting practice for the first heat (No. 209248) was similar to that used at the Algoma Steel Co.

When the melt was ready for finishing, 2,000 pounds of cold spiegel were added. About eight minutes later 2,500 pounds of 10 per cent silico pig were added and after another eight minutes 2,200 pounds of recarburizer were added from the mixer. About four minutes later a final addition of 2,000 pounds of 80 per cent ferromanganese was made.

The result of these additions was that the bath became exceptionally hot because the flame on the hearth was not cut off during the exothermic reactions.

After holding for 15 minutes the heat was tapped into the ladle. Twenty-two minutes later the first 21 ingot molds were poured with nearly a full running stopper, after which the stopper was about half running up to end of pour. The temperature of this heat was so high that no appreciable ladle skull could be found.

The ladle analysis showed a phosphorus content of 0.047 per cent, whereas before the furnace additions, it was 0.017 per cent, and the manganese 0.16 per cent. These data showed that the manganese content in the hot metal was not sufficient to maintain a high pre-manganese or residual manganese in the bath to give it the proper basicity and fluidity required for the deoxidation practice used.

Because of the results of the first heat (No. 209248) it was decided that the remaining heats should be made in accordance with the usual practice of the Carnegie Steel Co. with the following modifications:

One thousand pounds of 20 per cent cold speigel were added to the bath; 300 pounds of 50 per cent ferrosilicon were added in the ladle along with 110 pounds of bar aluminum when the ladle was between one-half and two-thirds full.

Detailed data on all heats poured at the Carnegie Steel Co. are given in Tables 5 and 6. The ladle analyses given are those reported by the company.

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[13] Sink-Head Ingots, R. S. Harden, Bull. A. R. E. A., p. 18; September, 1927.

TABLE 5.—*Open-hearth data on rail steel cast in Gathmann molds at Carnegie Steel Co.*

	Heat 209248 (B. S. 17)	Heat 203284 (B. S. 18)	Heat 203286 (B. S. 19)	Heat 206264 (B. S. 20)
Date of heat	July 12, 1926	July 18, 1926	July 19, 1926	July 20, 1926
Began charging	1.45 a. m.	8.50 a. m.	1.55 a. m.	1.35 a. m.
Limestone ... pounds	22,000	25,000	22,000	25,000
Calcined dolomite ... do	4,500	5,000	5,000	4,700
Fluorspar ... do	300	100	50	100
Hot metal (mixer):				
Initial ... do	134,000	135,200	134,000 (4.05 a. m.)	132,000 (3.15 a. m.)
Extra ... do	15,000			
Rail scrap ... do	35,000			83,800
Bloom crops ... do	73,000		20,800	
Pit scrap ... do		14,000		24,200
Ingots and butts ... do		34,000	27,400	
Miscellaneous scrap ... do		62,000	59,800	
Rods (stir) ... do	920		230	230
Ore (initial) 53 per cent Fe ... do	20,000 (10 a. m.)	None.	20,000 (11 a. m.)	17,000
Finish charging	3.40 a. m.	10.15 a. m.	4.20 a. m.	3.30 a. m.
FURNACE ADDITIONS (AFTER MELTING)				
Spiegel 20 per cent ... pounds	2,000 (11.10 a. m.)	1,000 (12.20 p. m.)	1,000	1,000
Silico pig 10 per cent ... do	2,500 (11.18 a. m.)	None.	None.	None.
Recarburizer (mixer) ... do	2,200 (11.26 a. m.)	None.	None.	None.
Ferromanganese 80 per cent ... do	2,000 (11.30 a. m.)	None.	None.	None.
Ore (hard 58 per cent Fe) ... do	2,000	15,000 (12.10 p. m.)	4,000	8,000
LADLE ADDITIONS				
Hot spiegel 5 per cent ... pounds	None.	36,200 (1.09 p. m.)	38,300	38,000
Ferrosilicon 50 per cent ... do	300 (11.52 a. m.)	300	300	300
Aluminum (bar) ... do	75	110	110	110
Total metallic charged ... do	298,220	291,700	294,630	293,130
Analysis of bath before additions:				
Carbon ... per cent	0.385	0.19		
Manganese ... do	.16			
Phosphorus ... do	.017			
Sulphur ... do	.050			
Time tapped	11.45 a. m.	1.05 p. m.	11.45 a. m.	11.05 a. m.
Time of heat	10 h. 0 m.	13 h. 0 m.	9 h. 50 m.	9 h. 30 m.
LADLE ANALYSIS				
Carbon ... per cent	0.62	0.75	0.72	0.74
Manganese ... do	.73	.793	.813	.76
Phosphorus ... do	.047	.040	.018	.020
Sulphur ... do	.050	.065	.043	.024
Silicon ... do	.15	.22	.20	.22
ANALYSIS OF BASIC PIG IRON FROM MIXER				
Date	July 17, 1926	July 18, 1926		
Silicon ... per cent	1.25	1.17		
Manganese ... do		1.12		
Phosphorus ... do	.187	.181		
Sulphur ... do	.032	.033		

TABLE 6.—*Tapping, teeming, and soaking-pit data on rail steel cast in Gathmann molds at Carnegie Steel Co.*

	Heat 209248 (B. S. 17)	Heat 203284 (B. S. 18)	Heat 203286 (B. S. 19)	Heat 206264 (B. S. 20)
Time tapped	11.45 a. m.	1.05 p. m.	11.45 a. m.	11.05 a. m.
Start of teeming	12.07 p. m.	1.21 p. m.	11.58 a. m.	11.15 a. m.
Finish of teeming	12.55 p. m.	2.12 p. m.	12.52 p. m.	12.05 p. m.
Temperature of teeming	Very hot, no ladle skull.	Good	Good	Good.
Number of ingots:				
Gathmann, 22 inches square	39	37	35	34½.
Standard, 23⅝ inches square	½	1½	1	3.
Height of pour (including sink head).—Gathmann, inches.	72	72	71	71.
	Fire-brick walls 1⅞ inches thick.			
Size of refractory top, inches	17 by 17 by 15½.	17 by 17 by 15½.	17 by 17 by 14½.	17 by 17 by 14½.
Average weight of ingot, pounds				6,950.
Time stripped:				
Gathmann	Start of stripping about 2½ hours after teeming first ingot.			
Number of stickers	None	None	None	None.
Mold and top temperature	Between 70° to 80° F. in all cases.			
Stopper condition	Running to twenty-first ingot, half running to end.	Good	Good	Good.
Ingot surfaces	Splashes and fins.	Good	Good	Good.

SOAKING-PIT DATA

Time charged	Only first ingot rolled.	6.20 to 8.50 p. m.	4.15 to 5.40 p. m.	3.20 to 3.55 p. m.
Time drawn		10.55 to 2.25 a. m.	9 to 9.50 p. m.	7.20 to 8.30 p. m.
Temperature ingots	Between 2,100 and 2,200° F. in all cases.			

(*d*) CARNEGIE STEEL CO., STANDARD INGOTS.—The standard practice of the mill presumably was used. Details of this practice for the heat from which rails were tested at the Bureau of Standards are not available.

2. DESIGN OF INGOT MOLDS

(*a*) STANDARD MOLDS.—The design of standard molds used at the Algoma and Carnegie Steel Companies is indicated in Figure 22B. That used at Carnegie was slightly larger in section, being 23⅝ inches square at the bottom and 21⅝ inches square at the top, with a 1-inch taper over the height of 76 inches, as compared to 22 inches square at the bottom and 20 inches square at the top, giving a 1-inch taper over the somewhat lower height of 72 inches. The wall thickness of the Carnegie mold was also greater, being 4½ inches at the top and 5 inches at the bottom, as compared to 4¼ inches and 4½ inches, respectively, in the Algoma mold.

In the comparison of data obtained on rails rolled from these two ingot sizes the dimensional differences of the ingot molds have been considered negligible.

(*b*) Gathmann Molds.—The design of Gathmann ingot molds and hot tops used for the so-called Gathmann heats at the Algoma and Carnegie Steel Companies is indicated in Figure 22A. The hot top used at the Algoma Steel Co. is indicated in Figure 22D. Otherwise, the mold was essentially the same.

These molds are of the big-end-up hot-top type.[14] This type of mold differs essentially from the standard type in the fact that the large end is up and the smaller end down and the latter is closed except for a conical hole through which is inserted a truncated conical plug about 5 inches in diameter that extends about 2 inches below the bottom of the mold. Bottom plates were not used to cover these plugs in the molds used at the Algoma Steel Co. This plug serves to

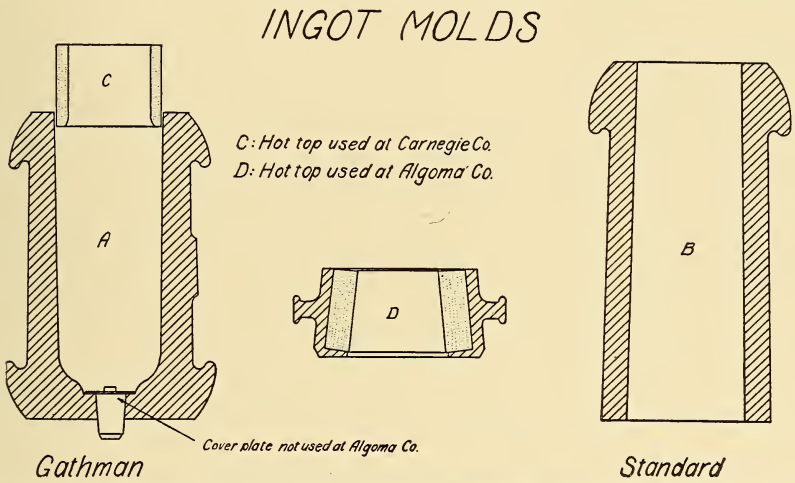

Fig. 22.—*Design of Gathmann and standard molds used at the Algoma and Carnegie Steel Companies*

loosen any possible "sticker" pushing or lifting the ingot free from the mold by the impact of the plug against the stool.

It was desirable that the standard and Gathmann molds at each plant should be of similar size and, therefore, the latter type used at the Carnegie Steel Co. was also somewhat larger than that used at the Algoma Steel Co. At the former plant the top was 22 inches square and the bottom 19 inches square with a taper of 1½ inches over the height of 50 inches, whereas at the latter plant (Algoma) the top was 21 inches square and the bottom 19 inches square giving a taper of 1 inch for the height of 53¾ inches. The wall thickness of 5 inches at the top was the same, but the bottom thickness of the mold used at Carnegie was 7½ inches as compared to 6 inches at Algoma. The

[14] Methods of preventing piping in steel ingots, E. Gathmann, Met. and Chem. Eng., **13**, p. 656; 1915; Casting and molding steel ingots, E. Gathmann, Trans. Am. Inst. Min. Engrs., **67**, p. 514; 1920–1922; Fundamental esstentials to improved quality of steel production, E. Gathmann, Trans. Am. Soc. Steel Treat., **5**, p. 158; 1924.

total heights were selected to correspond to the height of the standard molds.

The differences in dimensions were considered negligible with regard to the properties of the rails.

The inside bottom dimensions of the hot tops at the Algoma Steel Co. were 13 by 15 inches for the first three heats and were then increased to 18 by 19 inches for the remaining four heats. At the Carnegie Steel Co. they were 17 by 17 inches inside.

3. TEEMING AND STRIPPING OF MOLDS

(*a*) At Algoma Steel Co.—The mold wash for both types of molds poured at the Algoma Steel Co. consisted of graphite and water, while a lime wash was applied to the sink-head linings. Previous to teeming, the molds and hot tops were heated to approximately 300° F. (150° C.).

The Gathmann molds were teemed with a 2-inch nozzle until the hot top was filled to a height of about 14½ inches. A slight amount of molten steel occasionally leaked out at the junction of the sink head with the top of the mold, but this metal froze almost immediately and did not cause trouble. The pouring conditions for all ingots were considered very satisfactory. The ingots were left in the Gathmann molds for about two and one-half hours before stripping in order to allow time for the sink head to carry out its function of feeding the mold during solidification.

As previously stated the process of stripping this type of mold is very different from standard mold practice, it being necessary to pull the ingots out of the mold rather than to lift the mold off of the ingot.

At the Algoma plant the casing for the hot top was first lifted off. (This casing, with slight repairing, could be used for from four to six heats.) The ingot was then pulled from the mold. A few stickers were met. The ingots on removal from the mold had a dark cherry-red color. The surfaces were considered good. They were then placed in the soaking pit.

The standard ingots were poured also, with a 2-inch nozzle and were filled to a height of 66½ to 67½ inches. These standard ingots were stripped about one-half hour after pouring and as quickly as possible were placed in soaking pits.

(*b*) At Carnegie Steel Co.—The procedure of teeming of the Gathmann ingots at the Carnegie Steel Co. was to pour a mold until the molten steel began to leak out at the junction of the hot top and the mold. The next mold was then similarly poured. The hot top of the preceding mold was then filled to a height of from 14½ to 15½ inches. A 1¾-inch nozzle was used. It required from 50 to 55 minutes to complete the pouring of the heat of 37 ingots.

Except for the first heat (No. 209248) in which there was a running stopper, the pouring conditions were considered good. In order to avoid shrinkage cracks at the junction of the sink head and mold 1-inch wood blocks were placed under the lugs supporting the sink heads. After pouring, these blocks were removed in accordance with Gathmann methods so that the metal in the sink head was then better enabled to follow the volume changes of the metal in the mold and so avoid the building up of sufficient stress to form shrinkage cracks.

At the Algoma Steel Co. this difficulty was eliminated in the last four of the seven Gathmann heats by making the bottom area of the hot top the same as the top of the molds. (Heats Nos. 5164, 5165, 5166, 5167.)

As at the Algoma Steel Co. the Gathmann ingots were left in the mold for two and one-half hours after teeming before stripping.

The most satisfactory equipment for stripping the Gathmann ingots was not available at the Carnegie plant. The casings for the hot tops were removed by crushing with an "ice-tong" type of lifter which crushed through the casing and grabbed the hot top of the ingot by which it was lifted out of the mold. No difficulty was encountered with stickers. The method, however, was very unsatisfactory, causing considerable delay, the average time between the finish of the pouring and the charging of the first ingots to the soaking pit being from three and one-half to four hours (including the prescribed two and one-half hour wait).

The ingot surfaces after stripping were considered good on all the Gathmann ingots with the exception of the first heat (No. 209248) which was extra hot. The ingot from this heat showed many bad splashes and fins due to the running stopper and swinging ladle during the pouring.

Details of pouring of the standard ingot from which rails were tested are not available. Presumably the usual practice of the company was used.

4. SOAKING PIT PRACTICE

The soaking pits at both of the companies were operated at a temperature between 2,100 and 2,200° F. Before rolling, the two types of ingots were approximately in this range of temperature. The Gathmann ingots were charged with the large end down so that the ingots were resting with the sink head (top) down on the coke bottom of the pits in order to eliminate the extra amount of bottom discard which would be required if the bottom of the ingot rested on the coke bed. The standard ingots were all charged in the usual way with the large end (bottom) down.

At the Algoma Steel Co. the Gathmann ingots, being cooler on entering the pits than the standard ingots, were held there about one hour longer (between four and five hours) which was necessary in order to get the ingots to the rolling temperature without forcing the heating.

5. ROLLING-MILL PRACTICE

The rolling-mill practice on both types of ingots at the Algoma Steel Co. is shown in Table 7. Both types of ingots entered the bloomer with the small end first. The 8⅜ by 8 1/16 inch blooms were top and bottom cropped. The top crops of the sink-head blooms were usually made at the shoulder. The blooms were all cut so that the top bloom would produce three 33-foot 100-pound rails, while the bottom section would produce two 33-foot 100-pound rails. These blooms were then reheated to a temperature of 2,100 to 2,200° F. before passing to the rail stands.

TABLE 7.—*Ingot reduction and manipulation on 35-inch blooming mill at Algoma Steel Co. for 20 by 22 inch ingots (at the butt)*

Pass No.	Size in inches	Area	Reduction
		Square inches	*Per cent*
1	20 by 20	400	9.1
2	20 by 18¼, turn	365	8.75
3	18¾ by 18	337.5	7.53
4	19 by 16½	313.5	7.11
5	19¼ by 15	288.7	7.89
6	19½ by 13½	263.2	8.83
7	19¾ by 12¼	241.9	8.1
8	20 by 11, turn	220	9.1
9	11¼ by 17¾	199.7	9.23
10	11½ by 15½	178.3	10.74
11	11⅝ by 13½	156.9	11.96
12	11¾ by 11½, turn	135.1	17.06
13	11⅝ by 9¾	113.3	16.1
14	11¾ by 8, turn	94.0	17.06
15	8⅛ by 9¾	79.2	15.7
16	8¼ by 8¼, turn	68.1	14.1
17	8⅜ by 8 1/16	67.5	0.79

Pass reduction for 100-pound R. E. rail on 23½ and 28 inch rail mill

Pass No.	Stand	Position	Area	Reduction
			Square inches	*Per cent*
18	First rougher	Slab	56.84	15.2
19	do	do	48.99	13.8
20	do	do	42.04	14.18
21	do	do	35.90	14.6
22	Second rougher	Edge	32.58	9.24
23	do	Edge over	25.55	21.57
24	do	Dummy	22.78	10.84
25	do	Edge	17.2	24.5
26	Finishing	do	13.19	23.31
27	do	do	11.12	15.01
28	do	do	[1] 10.18	8.45

[1] Hot.

The finishing temperature of the rails at this plant was regulated so that the rails would not exceed a shrinkage allowance at the hot saw of more than $6\frac{11}{16}$ inches for the 33-foot rails.

All the rails at the Algoma Steel Co. were marked according to the standard nomenclature. The letters rolled on the rails from the top to the bottom of the ingot were A, B, C, D, and E, respectively. In this report the specimen from the top end of the scrap rail left after cutting off the E rail has been called the F rail. It would correspond to the top end of an F rail and is practically identical with the bottom of the E rail.

The rolling-mill practice at the Carnegie Steel Co. consisted of giving the ingots a breakdown from 22 inches square to $19\frac{1}{4}$ by $15\frac{1}{2}$ inches in four passes. This continuous "monkey mill" consisted of a tandem of two sets of two-high rolls. The small ends of the ingots entered the first two-high pass; they were then turned and passed through the second two-high stand; they were then brought back to the first two high, turned and reversed end for end and given the third pass; they were then turned and given the fourth pass through the second two-high stand. This continuous operation required approximately two minutes.

These blooms were then given seven fast passes in a three-high blooming mill to a $9\frac{1}{2}$-inch square bloom. The blooms were then cropped at the top and bottom and cut so that the first bloom would make one 33-foot and one 39-foot 100-pound rail, while the second bloom would make two 39-foot rails. These blooms were then reheated for about seven minutes to a temperature of about 2,100 to 2,200° F. They were then given 5 passes in the first rail-stand, followed by 4 passes in the second, 3 passes in the third, and 1 pass on the finisher.

The breakdown passes at the Carnegie Steel Co. were not well suited for the Gathmann ingots because the small (bottom) ends of these ingots were considerably smaller than the standard ingots, and consequently the bottom ends of the Gathmann ingots (19 inches square) were left in the unworked state until they received the fast reductions in the three-high bloomer.

After several passes in this bloomer it was noticed that considerable cracking was developed in the Gathmann ingot blooms. Some of these cracks may have been due to the above cause or the cracks may have resulted from hair cracks on the ingot surfaces produced by the tensional stresses set up when the ingots were cooling, or they may have been produced by the nonuniform stressing during the heating operation. All of the above causes would tend to promote cracks. The exact cause or causes, however, are not known.

TABLE 8.—*Rail recovery and inspection data on rail steel cast in Gathmann and standard molds at Algoma Steel Co.*

	Data for Gathmann molds									
	Heat 5157 (B. S. 1)	Heat 5158 (B. S. 2)	Heat 5159 (B. S. 3)	Average	Heat 5164 (B. S. 4)	Heat 5165 (B. S. 5)	Heat 5166 (B. S. 6)	Heat 5167 (B. S. 7)	Average	Average of all heats
	(Small hot top)				(Large hot top)					
Average ingot weight ... pounds	7,077	6,915	6,966	----------	7,415	7,376	7,170	7,361	----------	7,183
Received at shears (ingot to bloom) ... per cent	85.1	86.3	83.0	----------	79.5	81.7	84.0	81.8	----------	83.1
Received at hot saw (bloom to rail) ... do	90.4	91.7	88.4	----------	92.2	92.1	92.2	92.3	----------	91.3
Recovery of rails from ingots ... do	76.9	79.1	73.4	----------	73.3	75.2	77.5	75.5	----------	75.8
RAIL INSPECTION (FINAL)										
No. 1 rails (first quality):										
33-foot	76	(1)	53	64.5	76	73	84	79	78.0	73.5
30-foot	18	(1)	23	20.5	4	2	4	7	4.3	9.7
27-foot	2	(1)	9	5.5	9	2	1	1	3.3	4.0
Total No. 1 rails	----------	----------	----------	90.5	----------	----------	----------	----------	85.6	87.2
Per cent No. 1 rails	----------	----------	----------	84.3	----------	----------	----------	----------	93.2	89.7
No. 2 rails (second quality):										
33-foot	9	(1)	9	9.0	1	10	5	2	4.5	6.0
30-foot	0	(1)	6	3.0	0	1	1	0	.5	1.3
Total No. 2 rails	----------	----------	----------	12.0	----------	----------	----------	----------	5.0	7.3
Per cent No. 2 rails	----------	----------	----------	11.1	----------	----------	----------	----------	----------	7.5
No. 3 rails (scrap):										
33-foot	3	(1)	6	4.5	3	2	0	1	1.5	2.5
30-foot	1	(1)	0	.5	0	0	0	0	.0	.2
Total No. 3 rails	----------	----------	----------	5.0	----------	----------	----------	----------	1.5	2.7
Per cent No. 3 rails	----------	----------	----------	4.7	----------	----------	----------	----------	----------	2.8
Total	109	----------	106	107.5	93	90	95	90	92	97

	Data for standard molds									
	Heat 3178 (B. S. 8)	Heat 5156 (B. S. 9)	Heat 11142 (B. S. 10)	Heat 11145 (B. S. 11)	Heat 4141 (B. S. 12)	Heat 25098 (B. S. 13)	Heat 11148 (B. S. 14)	Heat 5168 (B. S. 15)	Heat 5169 (B. S. 16)	Average
Average ingot weight ..... pounds	6,821	6,850	6,776	6,760	6,772	6,770	6,732	6,780	6,897	6,783
Received at shears (ingot to bloom) ..... per cent	87.7	87.0	88.9	85.8	88.9	88.4	89.8	88.8	86.9	88.1
Received at hot saw (bloom to rail) ..... do	91.6	91.9	92.2	91.8	92.4	92.5	92.3	92.4	92.3	92.1
Recovery of rails from ingots ..... do	80.3	80.0	82.0	78.8	83.1	81.8	82.9	82.1	80.2	81.3
RAIL INSPECTION (FINAL)										
No. 1 rails (first quality):										
33-foot	86	(1)	114	110	81	109	125	88	84	99.6
30-foot	0	(1)	1	1	3	2	0	5	3	1.9
27-foot	0	(1)	0	0	0	0	0	0	0	.0
Total No. 1 rails										101.5
Per cent No. 1 rails										93.0
No. 2 rails (second quality):										
33-foot	3	(1)	10	3	9	7	8	2	1	5.4
30-foot	0	(1)	0	0	0	0	0	0	0	.0
Total No. 2 rails										5.4
Per cent No. 2 rails										4.9
No. 3 rails (scrap):										
33-foot	1	(1)	0	1	2	0	1	10	4	2.4
30-foot	0	(1)	0	0	0	0	0	0	0	.0
Total No. 3 rails										2.4
Per cent No. 3 rails		(1)								2.2
Total	90		125	115	95	118	134	105	92	109

[1] Rejected in drop test.

Owing to the higher percentage of top discard from the sink-head blooms (18 to 19 per cent for the killed steel) than in the case of the standard blooms (about 12 per cent for the open steel), the Carnegie Steel Co. decided to omit the letter "A" for the top rail and mark it "B." The second rail was marked "C," the third rail "D," and the fourth rail "E." Throughout this report, however, these rails have been designated as the "AB" for the "B" rail, "BC" for the "C" rail, "CD" for "D" rail, "DE" for the "E" rail.

6. INSPECTION OF RAILS

(*a*) Surface Inspection.—The data on rail recovery are given in Tables 8 and 9 for the Algoma and Carnegie Steel Companies' heats, respectively. The specified rail length at Algoma was 33 feet. At Carnegie the standard length was 39 feet.

Table 9.—*Shearing data and final inspection on rail steel cast in Gathmann molds at Carnegie Steel Co.*

SHEARING DATA

	Data for Gathmann ingots				
	Heat 203284, average of first 8 ingots	Heat 203286, average of ingot Nos. 2, 5, 8	Heat 206264		
Weight of bloom No. 2 ... pounds	2,766	2,770			
Weight of bloom No. 1 ... do	2,569	2,575			
Weight of top discard ... do	1,302	1,207			
Weight of bottom discard ... do	192	200			
Total bloom weight ... do	6,829	6,752			

FINAL RAIL INSPECTION

Quality of rail	Length				Average	Per cent
No. 1	39 feet	48 BC, CD, DE.	21 BC, CD, DE.	37 BC, CD, DE.	35.3	
	33 feet	1 AB	0 AB	0 AB	.3	25.4
No. 2	39 feet	50 BC, CD, DE.	83 BC, CD, DE.	65 BC, CD, DE.	66.0	
	33 feet	20 AB	32 AB	34 AB	28.6	67.5
Cut-off	39 feet	9 BC, CD, DE.	1 BC, CD, DE.			
	33 feet	13 AB	3 AB			
Scrap	39 feet	0 BC, CD, DE. 2 AB				
Total rails		143	140	136	140	

It is apparent from the data that the recovery of No. 1 quality rails from Gathmann ingots at the Carnegie Steel Co. of 25.4 per cent is very low and the number of No. 2 quality (67.5 per cent) correspondingly high. The data for Gathmann ingot rail recovery at the Algoma Steel Co. are in sharp contrast, with a recovery of No. 1

quality rails of 89.7 per cent and of No. 2 quality of 7.5 per cent. These figures at Algoma come close to the corresponding recovery of standard ingot rails at the same plant of 93 per cent for No. 1 quality and 4.9 per cent for No. 2 quality.

Because of variables in rolling conditions it is difficult to evaluate the effect of increasing the size of the hot top of Gathmann ingots in terms of the rail recovery data, but it is of interest to note that from the two accepted heats with small hot tops the per cent of No. 1 quality rails was 88 as compared to 92 per cent for the four heats with large hot tops.

(*b*) Drop Tests.—(1) *At Algoma Steel Co.*—A standard A. R. E. A. drop-testing machine was used with a 2,000 pound tup falling from a height of 22 feet on the base of a 4-foot long rail section (head in tension). The distance between supports was 3 feet.

The inspector of the Canadian Pacific Railway selected three test ingots from the first, middle, and last ones poured of the various heats. A 4-foot long section was cut at the hot saw from the top end of the A rail from each of these ingots for the drop test. These sections were submitted to two blows of the tups under the conditions stated.

In addition to the usual data recorded, deflection and elongation data were obtained on some heats in accordance with A. S. T. M. specification No. A1–24.

The results of these tests on rails from the Gathmann and standard ingots are given in Table 10.

TABLE 10.—*Drop-test data on rail steels cast in Gathmann and standard molds at the Algoma Steel Co.*

DEFLECTION IN INCHES AFTER ONE DROP OF TUP

[NOTE.—The standard A.R.E.A. drop-testing apparatus was used. A 2,000-pound tup was dropped from a height of 22 feet on the 100-pound rails with the rail base up (head in tension). The standard distance of 3 feet between supports was used. Black-face figures in table show the position or location of break after the second drop of tup. BK designates break, P pipe, and S segregation]

	Data for Gathmann molds							
	Heat 5157	Heat 5158	Heat 5159	Heat 5164	Heat 5165	Heat 5166	Heat 5167	Average
	Hot top 13 by 15 by 14½ inches			Hot top 18 by 19 by 14½ inches				
Test No.[1] 1 (first ingot)	1.25	BKP	1.10	1.15	1.20	1.20	1.10	1.17
Test No. 2 (middle ingot)	1.30	BKS	1.20	1.20	1.20	1.25	1.10	1.21
Test No. 3 (last ingot)	1.25	BKP	1.10	1.25	1.20	1.25	1.10	1.19
Average								1.19

PERCENTAGE ELONGATION

Test No.[1]	1 2 3		1 2 3		1 2 3	1 2 3	1 2 3	Average 1 2 3
Distance along rail:								
First inch—								
First drop	3 3 3		4 3 4		3 4 3	4 4 3	3 3 3	3.4 3.4 3.1
Second drop	5 5 5		6 5 7		3 6 5	5 6 5	3 3 4	4.4 5.0 5.2
Second inch—								
First drop	4 5 5		5 5 6		5 6 6	5 5 4	4 5 5	4.6 5.3 5.3
Second drop	7 7 7		7 7 10		7 9 9	8 8 7	5 5 6	6.8 7.2 7.8
Third inch—								
First drop	6 7 7		7 7 8		7 6 7	7 6 6	7 7 8	6.8 7.3 7.3
Second drop	9 10 11		8 9 **12**		11 **11** **11**	**11** **10** 9	8 9 9	9.4 9.8 10.4
Fourth inch—								
First drop	6 7 7		8 7 8		7 7 7	8 8 8	8 7 7	7.4 7.3 7.4
Second drop	12 **13** 13		10 12 11		**15** 11 12	12 10 **12**	**15** **19** **20**	12.8 13.0 13.6
Fifth inch—								
First drop	5 6 6		6 5 6		6 6 5	8 7 8	5 6 6	6.0 6.0 6.3
Second drop	**9** 12 **12**		8 **9** 8		12 8 9	10 8 10	7 9 14	9.6 9.2 10.6
Sixth inch—								
First drop	4 4 5		5 4 4		4 4 3	6 6 6	3 4 4	4.2 4.8 4.2
Second drop	7 9 10		7 7 6		5 4 4	7 6 8	4 6 6	6.0 6.4 6.8

TOTAL ELONGATION PER CENT

First drop	28 32 33	----------	35 31 36	----------	32 33 21	38 36 35	30 32 33	----------
Second drop	49 56 58	----------	46 49 54	----------	53 53 55	53 48 51	42 51 59	----------

DEFLECTION IN INCHES AFTER ONE DROP OF TUP

	Data for standard molds									
	Heat 3178	Heat 5156	Heat 11142	Heat 11145	Heat 4141	Heat 25098	Heat 11148	Heat 5168	Heat 5169	Average
Test No.[1] 1 (first ingot)	1.10	BKS	1.10	1.45	BKS	1.35	BKS	1.25	1.25	1.26
Test No. 2 (middle ingot)	1.05	BKS	1.10	1.35	[2] 1.30 1.20	1.40	[2] 1.25 1.25	1.30	1.25	1.24
Test No. 3 (last ingot)	1.05	BKS	1.10	1.40	1.20	1.35	1.20	1.30	1.30	1.24
Average	----------	----------	----------	----------	----------	----------	----------	----------	----------	1.25

[1] Test No. 1 was made on first 5 feet of A rail from one of first ingots. Test No. 2 was made on first 5 feet of A rail from middle ingot of heat. Test No. 3 was made on first 5 feet of A rail from one of last ingots.

[2] On account of the A rail failing in the drop test, 5 feet was taken from the top of the B rail of the same ingot.

TABLE 10.—*Drop-test data on rail steels cast in Gathmann and standard molds at the Algoma Steel Co.*—Continued

PERCENTAGE ELONGATION

	Data for standard molds									
	Heat 3178	Heat 5156	Heat 11142	Heat 11145	Heat 4141	Heat 25098	Heat 11148	Heat 5168	Heat 5169	Average
Test No.[1]	1 2 3		1 2 3							Average 1 2 3
Distance along rail:										
First inch—										
First drop	3 3 3		4 4 4							3.5 3.5 3.5
Second drop	4 5 4		5							4.0 5.0 4.0
Second inch—										
First drop	5 5 5		5 6 5							5.0 5.5 5.0
Second drop	7 7 6		8							7.0 7.5 6.0
Third inch—										
First drop	7 7 7		7 8 7							7.0 7.5 7.0
Second drop	11 10 9		11							11.0 10.5 9.0
Fourth inch—										
First drop	7 6 7		7 8 8							7.0 7.0 7.5
Second drop	14 11 **11**		**13**							14.0 12.0 11.0
Fifth inch—										
First drop	6 5 5		6 7 7							6.0 6.0 6.0
Second drop	**9** 12 7		9							9.0 10.5 7.0
Sixth inch—										
First drop	4 4 4		5 5 6							4.5 4.5 5.0
Second drop	7 7 6		7							7.0 7.0 6.0

TOTAL ELONGATION PER CENT

First drop	32 30 31		34 38 37							
Second drop	52 52 43		53							

[1] Test No. 1 was made on first 5 feet of A rail from one of first ingots. Test No. 2 was made on first 5 feet of A rail from middle ingot of heat. Test No. 3 was made on first 5 feet of A rail from one of last ingots.

Gathmann heat No. 5158, which was one of the three heats with a small (13 by 15 by 14½ inches) hot top, and one standard heat, No. 5156, were rejected because of failure of all three test specimens on first drop of tup and evidence in fracture of pipe or segregation.

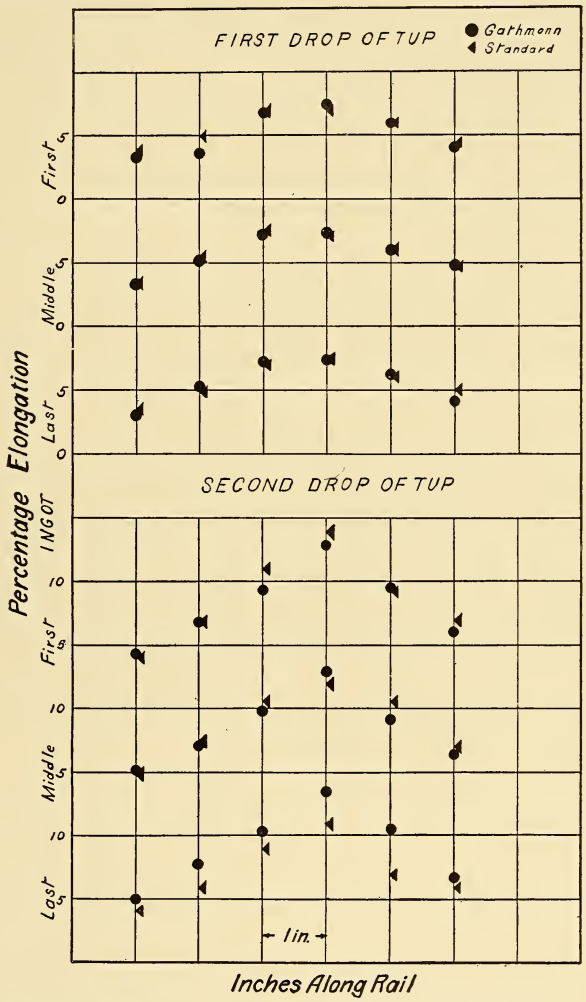

Fig. 23.—*Elongation measurements on drop test specimens at Algoma Steel Co.*

In standard heats Nos. 4141 and 11148 the A rail of the first ingot failed with evidence of segregation. A retest was made on a 4-foot section from the top end of the B rail of these ingots. These sections met requirements and heats were accepted.

All of the test sections broke on the second drop of tup. The point of fracture is indicated in Table 10. The average deflection of all specimens from Gathmann ingots is 1.19 inches as compared

to 1.25 inches for all standard ingot rail specimens, which indicates that the average A rail rolled from Gathmann ingots is apparently slightly stiffer than the A rails from standard ingots. This difference is very slight, however, as shown by the elongation measurements plotted in Figure 23. In these charts the average per cent elongation for each inch of length of test section of five Gathmann and two standard ingots has been plotted for the first, middle, and last ingots for first and second drops of tup.

It is evident from these curves that the ductility of the A rails as measured by the drop test is apparently the same for both types of ingots as cast at the Algoma Steel Co.

(2) *At Carnegie Steel Co.*—The drop tests at the Carnegie Steel Co. were made under different conditions than at the Algoma Steel Co., so that direct comparisons can not be made. A standard A. R. E. A. drop-test machine was used with 3-foot span between supports and 2,000-pound tup, but the height of fall was 19 feet as compared to 22 feet and the rail section, which was 5 feet long, was tested with the head up (base in tension) rather than base up (head in tension) as at Algoma.

The first ingot poured from the first Gathmann heat (No. 209248) was the only ingot rolled of this heat. The AB rail of this ingot was used up completely in drop tests.

Of the other three heats the first, middle, and last ingots poured were selected for the drop tests. A 5-foot test section was cut from the top end of the AB rail of each of the three ingots and subjected to one drop of the tup under the conditions stated. In addition, one of these test sections from each heat was subjected to three blows of the tup and the total elongation measured. After this third blow the specimen was nicked and broken to examine fracture, as were also those sections which were subjected to only one blow of the tup.

The results of these drop tests on Gathmann ingot rails are given in Table 11. No drop test data were available on rails from standard ingots.

It is evident from the data that the AB rail of the first heat (No. 209248) was piped and segregated. This was probably due to the fact that this heat was poured too hot and had a full running stopper.

Of the nine ingots tested from the other three heats only one (ingot No. 2, heat 206264) showed evidence of pipe, and none showed segregation in the fracture.

(*c*) Nick and Break Tests.—At the Algoma Steel Co. a nick and break test was required on the head end of the A rail from each ingot. If these fractures showed either a segregation or piped structure, the

TABLE 11.—*Drop-test data on the A rails from rail steel cast in Gathmann molds at Carnegie Steel Co.*

Heat No.	Ingot No.	Test No.	Drop No.	Permanent deflection	Percentage elongation per inch of gauge length							Character of fracture
					First	Second	Third	Fourth	Fifth	Sixth	Total	
				Inches								
209248	1	1	1	Broke.	------	------	------	------	------	------	------	Pipe.
		2	1	1.35	------	------	------	------	------	------	------	
			2	2.30	------	------	------	------	------	------	------	
			3	3.50	8	10	13	13	10	8	62	
			4	------	Twisted, nicked, and broken.						------	Segregated streak.
		3	1	1.35	------	------	------	------	------	------	------	
			2	2.45	------	------	------	------	------	------	------	
			3	3.40	9	10	12	13	12	9	65	
			4	------	Twisted, nicked, and broken.						------	Segregated streak, less than No. 2.
		4	1	1.40	------	------	------	------	------	------	------	
			2	2.45	------	------	------	------	------	------	------	
			3	3.40	8	11	13	13	11	9	65	
			4	------	Twisted, nicked, and broken.						------	Segregated streak, less than No. 3.
		5	1	1.30								
			2	2.40	------	------	------	------	------	------	------	
			3	Broke.	7	9	11	12	10	8	57	Segregation slight.
		6	1	1.40	------	------	------	------	------	------	------	
			2	2.40	------	------	------	------	------	------	------	
			3	3.30	7	10	12	12	11	8	60	
			4	------	Twisted, nicked, and broken.						------	Very slight segregation.
		7	1	1.30	------	------	------	------	------	------	------	
			2	2.30	------	------	------	------	------	------	------	
			3	Broke.	6	9	11	11	9	7	53	No segregation.
		8	1	1.45	------	------	------	------	------	------	------	
			2	Broke.	5	6	7	------	7	6	------	Do.
		9	1	1.35	------	------	------	------	------	------	------	
			2	2.35	------	------	------	------	------	------	------	
			3	3.35	7	10	13	12	10	8	60	Do.
203284	18	1	1	1.20	Nicked and broken.						------	Do.
	36	2	1	1.20	Nicked and broken.						------	Do.
	2	3	1	1.20	------	------	------	------	------	------	------	
			2	2.10	------	------	------	------	------	------	------	
			3	3.10	7	8	9	9	8	7	48	Do.
			4	------	Twisted, nicked, and broken.						------	
203286	18	1	1	1.10	------	------	------	------	------	------	------	
			2	2.00	------	------	------	------	------	------	------	
			3	2.80	7	10	11	11	10	7	56	Do.
			4	------	Twisted, nicked, and broken.						------	
	35	2	1	1.10	Nicked and broken.						------	Do.
	2	3	1	1.10	Nicked and broken.						------	Do.
206264	2	1	1	1.10	------	------	------	------	------	------	------	
			2	2.00	------	------	------	------	------	------	------	
			3	2.90	------	------	------	------	------	------	------	
			4	Broke.	------	------	------	------	------	------	------	Pipe.
	17	2	1	1.20	------	------	------	------	------	------	------	
			2	2.20	------	------	------	------	------	------	------	
			3	3.10	7	8	10	10	8	7	50	No segregation.
			4	------	Nicked and broken, base remained whole.							
	33	3	1	1.20	Nicked and broken.						------	Do.

head ends of the B rail from the same ingots were tested. These fractures were obtained by nicking the head and web and then breaking in a special shearing machine.

The results of examination of these fractures are given in Table 12 for both the Gathmann and standard ingot rails rolled at the Algoma Steel Co.

TABLE 12.—*Nick and break test data on rail steels cast in Gathmann and standard molds at the Algoma Steel Co.*

[P=pipe. S=segregation. K=good. BK=break on drop test]

	Data for Gathmann molds							Data for standard molds								
	Heat 5157	Heat 5158 [1]	Heat 5159	Heat 5164	Heat 5165	Heat 5166	Heat 5167	Heat 3178	Heat 5156 [1]	Heat 11142	Heat 11145	Heat 4141	Heat 25098	Heat 11148	Heat 5168	Heat 5169
	Hot tops 13 by 15 by 14½ inches			Hot tops 18 by 19 by 14½ inches												
Ingot [2] No. 1:																
Rail A	K	BKP	K	K	K	K	K	K	BKS	S	K	BKS	K	BKS	K	K
Rail B										K		K		K		
Ingot No. 2:																
Rail A	K	BKS	K	K	K	K	K	K	BKS	K	K	K	K	K	K	K
Rail B																
Ingot No. 3:																
Rail A	K	BKP	K	K	K	K	K	K	BKS	K	K	S	K	S	K	K
Rail B												K		K		
Ingot No. 4:																
Rail A	K	S	S	K	K	K	K	K	K	K	K	K	K	K	K	K
Rail B		K	K													
Ingot No. 5:																
Rail A	K	S	P	K	K	K	K	K	S	K	K	K	K	K	K	K
Rail B		K	K						K							
Ingot No. 6:																
Rail A	S	P	P	K	K	K	K	K	K	S	K	P	K	K	K	K
Rail B	K	K	K							K		K				
Ingot No. 7:																
Rail A	K	S	K	K	K	K	K	K	S	K	K	K	K	K	K	K
Rail B		K							K							
Ingot No. 8:																
Rail A	K	P	K	K	K	K	K	K	S	K	K	K	S	K	P	K
Rail B		K							K				K		K	
Ingot No. 9:																
Rail A	K	S	S	K	K	K	K	K	K	S	K	K	P	K	K	K
Rail B		K	K							K			K			
Ingot No. 10:																
Rail A	K	S	K	K	K	K	K	K	S	S	K	K	K	K	K	K
Rail B		K							K	K						
Ingot No. 11:																
Rail A	K	P	K	K	K	K	K	K	S	K	K	K	K	S	S	K
Rail B		K							K					K	K	

Ingot No. 12:																
Rail A	K	S	S	K	K	K	K	Scrap	S	S	K	S	P	K	P	K
Rail B		K	K						K	K		K	K		K	
Ingot No. 13:																
Rail A	K	P	P	K	K	K	K	K	K	K	K	S	K	K	K	K
Rail B		K	K									K				
Ingot No. 14:																
Rail A	S	P	S	K	K	K	K	S	S	S	K	S	K	K	P	K
Rail B	K	K	K					K	K	K		K			K	
Ingot No. 15:																
Rail A	S	S	P	P	K	K	K	K	K	S	K	K	K	S	P	P
Rail B	K	K	K	K						K				K	K	K
Ingot No. 16:																
Rail A	S	S	P	K	K	K	K	K	K	K	K	S	K	S	K	P
Rail B	K	K	K									K		K		K
Ingot No. 17:																
Rail A	K	S	K	K	K	K	K	K	K	K	K	K	K	K	P	P
Rail B		K													K	K
Ingot No. 18:																
Rail A	K	P	S		K	K	K	K		K	K	K	K	S	K	K
Rail B		K	K											K		
Ingot No. 19:																
Rail A	S		K					P		S	K	S	K	K	P	P
Rail B	K							K		K		K			K	K
Ingot No. 20:																
Rail A	K		P							K	K		K	K	P	
Rail B			K												K	
Ingot No. 21:																
Rail A	K		K							K	K		K	K	K	
Rail B																
Ingot No. 22:																
Rail A	K									S	K		P	K		
Rail B										K			K			
Ingot No. 23:																
Rail A										K	K		K	K		
Rail B																
Ingot No. 24:																
Rail A										K	K		P	S		
Rail B													K	K		
Ingot No. 25:																
Rail A										K				K		
Rail B																
Ingot No. 26:																
Rail A														K		
Rail B																
Ingot No. 27:																
Rail A														K		

[1] This heat failed in drop test and was rejected.
[2] Ingots were numbered in the order of rolling and not in the order of teeming.

It should be noted that the ingots in this table are numbered in the order of rolling, not of teeming.

In Gathmann heat No. 5158, the A rails of ingot Nos. 1, 2, and 3 broke in the drop test, causing rejection. All of the A rails of the other 15 ingots showed pipe or segregation. All of the B rails, however, showed a clean fracture. In heat No. 5157, 5 of the 22 ingots showed segregation in the A rail and in heat No. 5159, 11 out of 20 showed pipe or segregation in the A rail, but all of those ingots that showed pipe or segregation in the A rail had good clean fractures in the B rail.

The effect of increasing the area of the hot top to 18 by 19 inches from 13 by 15 inches caused a very marked improvement in soundness of the A rails. This is shown very definitely by the fact that only 1 out of 17 ingots in heat No. 5164 had a pipe in the A rail and in the three other heats poured with the larger hot top (Nos. 5165, 5166, 5167) no evidence of segregation or pipe was found in any of the A rails of the 64 ingots tested.

It is evident, therefore, that when the ratio of hot top to ingot is correct, Gathmann ingots can be poured of killed rail steel in which all of the A rails will show a clean fracture free from pipe and segregation. In this case the ratio of hot top to ingot was approximately 10.8 per cent. This tends to confirm a prediction of Kenney (see footnote 7, p. 300) based on his investigations in which he states: "There is no doubt that with a sink head of proper size there will be no question as to the piped rails being entirely eliminated."

In the nine standard heats tested one heat was rejected (No. 5156), as it had failed in the drop test. It showed segregation in the A rail of 10 of the 17 ingots tested. Only one of the nine heats (No. 11145) had no segregation in any of the A rails. Of a total of 194 ingots tested, 54, or 27.8 per cent, showed segregation or pipe in the A rails. Ten of these, or 5.4 per cent, were in the rejected heat, leaving 22.4 per cent distributed throughout all but one of the other eight heats.

These data indicate that segregation or piping is more frequent in the A rails of standard ingots than in the A rails of Gathmann ingots. The top discard from cropping of these standard ingots was approximately 12 per cent as compared to approximately 17 per cent which was made in the Gathmann ingot that gave a sound A rail.

IV. LABORATORY TESTS

1. SELECTION OF SPECIMENS

The laboratory tests may be divided into two groups, those relating to the determination of the comparative soundness of and segregation in the ingot and those relating to the comparative physical properties of the rails rolled from the two types of ingots.

The soundness and homogeneity of the ingots were determined by the usual method of splitting the ingot longitudinally through the center to determine the depth of pipe and obtain drillings for chemical analysis, from representative portions of the ingot, to determine relative segregation.

At the Algoma Steel Co. four ingots were split for examination. Two of these ingots represented a killed steel deoxidized with aluminum-silicon alloy (Algoma heat No. 5164) cast in each type of mold and the other two represented a rising steel (heat No. 5169), partially deoxidized with ferrosilicon, also cast in each type of mold.

At the Carnegie Steel Co. three ingots of the Gathmann type were split. Two of these ingots were from heat No. 209248, which was the first heat poured of killed steel, which was poured too hot and was rejected because of high phosphorus. The third ingot split was from heat No. 213281 which was a rising steel partially deoxidized with ferrosilicon.

None of the ingots poured in standard molds was split for inspection at the Carnegie Steel Co.

The rail sections selected for determining the physical properties were cut in all cases from the top end of the rails rolled from the middle ingot poured of the several heats. These sample sections generally were approximately 20 inches long.

At the Algoma Steel Co. they were cut from the rail at the hot saw and air cooled in the same manner as the drop-test specimens by resting them on their bases on a sheet-steel floor. Fractures of these test sections were obtained by nicking about 7 inches from the end and breaking off in the nick-and-break machine. All of these fractures were clean and free from pipe or segregation.

At the Carnegie Steel Co. similar test sections were obtained but were cut from the rail after cooling, on its side, on the hot bed but before straightening (gagging).

Test sections of C, D, and E rails from one standard ingot only were obtained at the Carnegie Steel Co. At a later date two 10-foot sections from the bottom end of a B rail were obtained from a Baltimore & Ohio Railroad storehouse (heat No. 206271).

All of the test sections were sent to the Bureau of Standards for preparation of test specimens and tests.

2. IDENTIFICATION OF TEST SPECIMENS

The split ingots as previously stated were examined at the mills of the respective steel companies.

The respective rail sections were selected by Dr. R. L. Dowdell. All specimens were marked by him at the plants and later identified in the Bureau of Standards laboratories.

As a matter of convenience in the laboratory new numbers were assigned to all heat numbers as given in Table 13.

TABLE 13.—*Test specimens obtained from Algoma and Carnegie Steel Companies*

[All rail sections for tests at Bureau of Standards were cut from the head end of the rails from the middle ingot of the several heats]

Heat No.	Bureau of Standards No.	Number and length of section	Specimens from Algoma Steel Co., 33-foot rails					
			Number and kind of test specimens cut from sections of rail indicated					
			A	B	C	D	E	F
5157G[1]	1 Small hot top	6, 14-inch	×2T, 2I	12E	×2T, 2I, 2W			×2T, 2I
5158G	2 Small hot top	do	×2T, 2I	12E	×2T, 2I, 2W			×2T, 2I
5159G[2]	3 Small hot top	do	×2T, 2I	12E	×2T, 2I, 2W			×2T, 2I
5164G	4 Large hot top	1, 14-inch		×2T, 2I, 2W				
5165G	5 Large hot top	do		×2T, 2I, 2W				
5166G	6 Large hot top	do		×2T, 2I, 2W				
5167G	7 Large hot top	do		×2T, 2I, 2W				
3178S[3]	8	6, 14-inch	2T, 2I	12E	2T, 2I, 2W			2T, 2I
5156S	9	do	2T, 2I	12E	2T, 2I, 2W			2T, 2I
11142S	10	do	2T, 2I	12E	2T, 2I, 2W			2T, 2I
11145S[4]	11	1, 10-foot (twelfth ingot)						
4141S	12	1, 14-inch		2T, 2I, 2W				
11148S	14	do		2T, 2I, 2W				
5168S	15	1, 8-inch		2T, 2I				
5169S	16	do		2T, 2I				

Heat No.	Bureau of Standards No.	Number and length of section	Specimens from Carnegie Steel Co.			
			B	C	D	E
			AB	BC	CD	DE
209248G	17	3, 20-inch		2T, 2I, 2W, 12E		2T, 2I
203284G	18	4, 20-inch; 2, 10-foot[5]	2T, 2I, 2W, 12E			2T, 2I
203286G	19	4, 20-inch	2T, 2I, 2W, 12E			2T, 2I
206264G	20	4, 20-inch	2T, 2I, 2W, 12E			2T, 2I
206271S	21	3, 20-inch; 2, 10-foot[6]		2T, 2I, 2W, 12E	2T, 2I, 2W	2T, 2I

[1] G signifies Gathmann ingots.
[2] One 10-foot section from top of B rail of eleventh ingot, poured of this heat was obtained after gagging.
[3] S signifies standard ingots.
[4] This section was cut from the finished rail after gagging.
[5] Two 10-foot sections from bottom of AB rail (Carnegie B rail) of twenty-sixth ingot poured and not gagged.
[6] Two 10-foot sections from bottom of B rail of eighteenth ingot obtained from B. & O. warehouse (probably gagged.)

NOTE.—T=tensile test specimens; I=impact test specimens; E=endurance test specimens; X=sections for deep etching; W=wear test specimens.

All specimens after machining from the rail section were marked with Bureau of Standards heat number and their rail letter. Since all rails tested were from the middle ingot of the heat no ingot number was given. Marking in this manner the number identifies the heat and rail from which the specimen was taken. For example, specimen No. 3B is the specimen from the head of the B rail of the middle ingot of heat No. 3 (Bureau of Standards marking) which is heat No. 5159 of the Algoma Steel Co. and was poured in a Gathmann mold. (See Table 12.)

At the Carnegie Steel Co. the first or top rail from the Gathmann ingots was always marked the "B" rail as previously stated. (No rails were marked "A" from Gathmann ingots at this company.)

In this report these rails have been called the AB rail and throughout this report they have been classed as A rails. In all data aver-

aging the properties of A rails these AB rails have been included. Similarly the C, D, and E rails of Gathmann ingots as marked at Carnegie have been called BC, CD, and DE rails, respectively, and

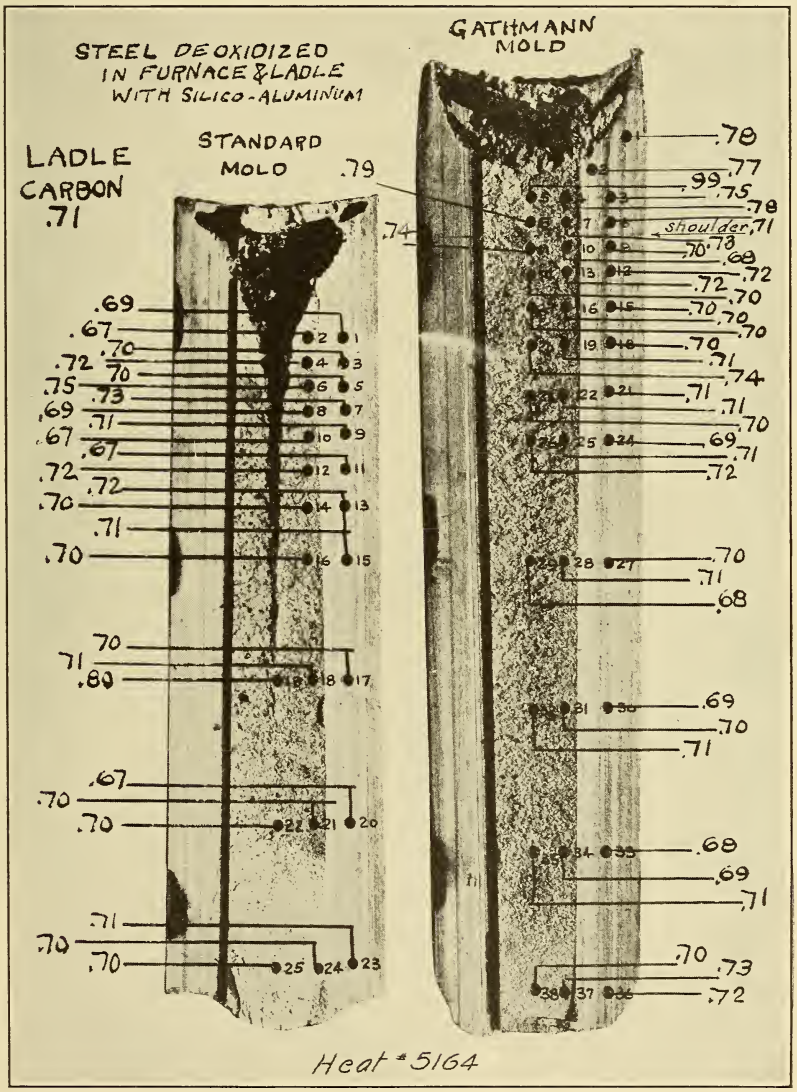

Fig. 24.—*Split Gathmann and standard ingots from Algoma Steel Co., heat No. 5164*

have been considered similarly to the AB rails, as B, C, and D rails, respectively.

3. EXAMINATION OF SPLIT INGOTS

(*a*) Algoma Steel Co.—Figure 24 shows photographs of a split ingot from heat No. 5164 which was fully deoxidized in the ladle.

The carbon distribution is shown by figures giving in per cent the carbon content of drillings taken from the points indicated. These analyses were made in the companies' laboratories.

It is obvious that in the standard mold this killed steel has formed on freezing a pipe extending down from the top of the ingot for about two-thirds of its length, whereas, in the Gathmann ingot mold, the pipe is confined almost entirely to the upper half of the hot top leaving the full length of the ingot proper apparently sound.

The average carbon contents of the upper and lower halves of the two ingots at points taken at the center of the ingot and at one-third and two-thirds the distance from the center to the outer face of ingot are given in Table 14. These analyses were made in the laboratories of the Algoma Steel Co.

TABLE 14.—*Average of carbon contents of split ingots*

HEAT NO. 5164

	Average carbon content (per cent)					
	Standard ingot			Gathmann ingot		
	Distance from center of ingot					
	0	⅓	⅔	0	⅓	⅔
Upper half of ingot	-------	0.703	0.704	0.714	0.706	0.703
Lower half of ingot	0.733	.703	.693	.707	.708	.697
Maximum difference over full length of ingot	.10	.05	.06	.06	.05	.04
Maximum difference over entire ingot section	-------	.13	-------	-------	.06	-------
Hot top	-------	-------	-------	0.71 to 0.99		

HEAT NO. 5169

Upper half of ingot	0.69	0.738	0.668	0.720	0.713	0.664
Lower half of ingot	.67	.673	.676	.663	.640	.667
Maximum difference over full length of ingot	[1].06	.17	.09	.14	.12	.04
Maximum difference over entire ingot section	-------	.17	-------	-------	.17	-------
Hot top	-------	-------	-------	0.67 to 0.90		

[1] One drilling only in upper half taken at bottom of pipe.

In calculating the averages for the Gathmann ingot the values below the hot top only have been used because in the use of this type of ingot mold the hot-top portion is always cropped as it is a primary principle of the hot-top method that the impurities will segregate into this portion and thus be eliminated in cropping together with the pipe.

The higher values for carbon shown in the analyses of drillings from the hot top indicate the truth of this principle as it is known[15] that carbon segregation is indicative of the segregation of sulphur and phosphorus.

[15] Report on the heterogeneity of steel ingots, J. Iron and Steel Inst., **113**, No. 1, p. 39; 1926.

The carbon segregation between the positions two-thirds and one-third the distance from center to face of ingot is negligible in both cases. In the standard ingot there is evidence of a marked segregation of carbon at the bottom of the pipe. In the Gathmann ingot

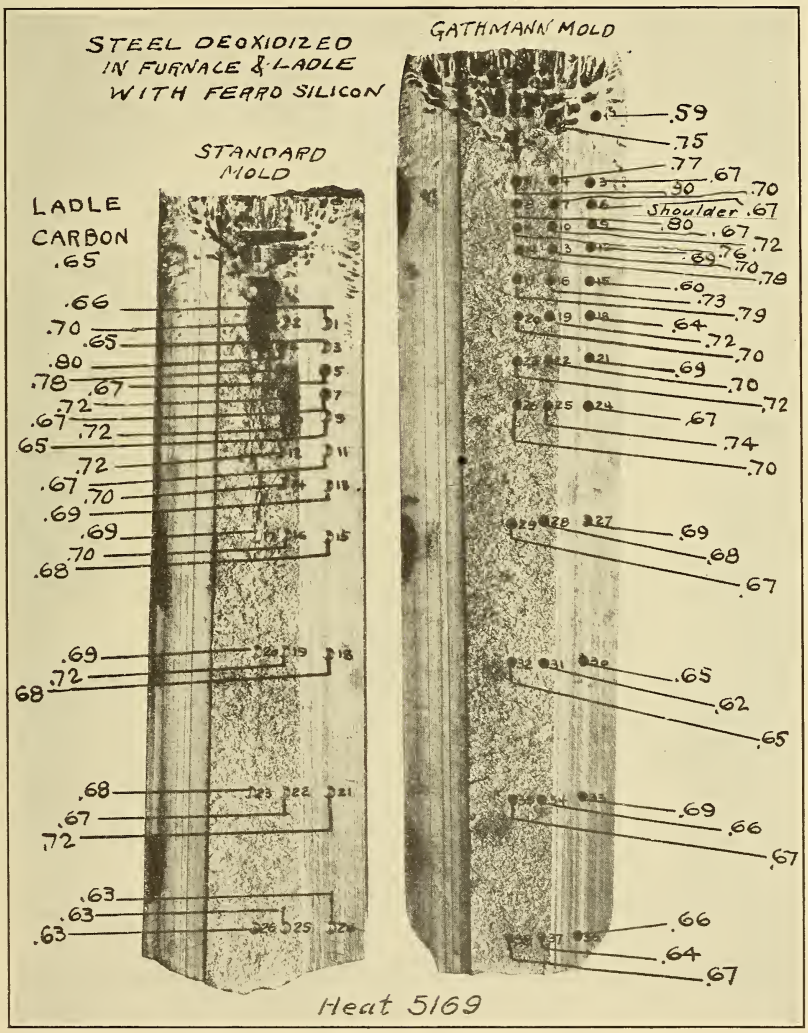

Fig. 25.—*Split Gathmann and standard ingots from Algoma heat No. 5169*

there is evidence of slight carbon segregation in the central upper portion of the ingot.

Figure 25 shows split ingots from heat No. 5169, which was a standard heat and so only partially deoxidized. The effect of the continual movement of the metal due to the evolution of gas during freezing has in the standard mold tended to prevent the formation of

a more or less symmetrical pipe, such as was formed in the killed steel. Apparently, the pipe is disseminated through the top half of the ingot. This ingot section may be considered typical of standard ingot practice for rail steels.

In the Gathmann mold the pipe is apparently confined to the hot top and as with the killed steel the full length of the ingot appears sound.

The averages for carbon content are included in Table 14. The variation of carbon in these ingots of rising steel from the outside in toward the center is more apparent, particularly in the ingot cast in the Gathmann mold, than in the killed steel ingots, and the maximum variation over the entire sections of the ingots is greater, more especially in the Gathmann ingot.

The casting of killed steel in standard molds or of rising steel in Gathmann molds is not recommended practice, so these two particular ingot sections are of relatively small practical importance, but it is of interest to note that with both types of steel, ingots apparently free from pipe were obtained in the Gathmann molds.

(*b*) At Carnegie Steel Co.—Figure 26 shows a photograph of split ingot No. 32 of Gathmann heat No. 209248 of the Carnegie Steel Co. This heat was poured very hot, had a running stopper, and was rejected because of high phosphorus. At the time this particular ingot No. 32 was poured, however, the stopper was somewhat under control.

It is evident that the pipe in this ingot is confined to the hot top and that the full length of the ingot proper is apparently sound.

In this case the drillings for survey of segregation were made along the center line of the ingot and along a line approximately one-half the distance from the center to the outer face. Phosphorus, sulphur, and silicon as well as carbon were determined in all drillings and manganese at bottom and top positions on the center line. The percentages are indicated for the respective positions in the Figure 26. All analyses of these ingot drillings were made by the firm of Pennimann & Browne, of Baltimore, Md.

An appreciable segregation of all of the elements determined is apparent along the central axis of the ingot with a minimum value at the bottom increasing to a maxmium at the top. The carbon increases from a minimum of 0.58 to 0.68 per cent at top of ingot proper, and to 0.77 per cent in the hot top. The silicon increases similarly from 0.16 to 0.19 per cent; the sulphur from 0.02 to 0.04 per cent at top of ingot, and 0.05 per cent in the hot top; and the phosphorus from 0.04 to 0.06 per cent in the ingot and also has a maximum value of 0.07 per cent in the hot top. The two analyses for manganese at the bottom (0.67 per cent) and the top (0.72 per cent) indicate a similar segregation.

The analyses of drillings along the line approximately halfway between center and outside of ingot show a segregation similar to that along the central axis, but to a less marked degree.

There is also an apparently slight but observable increase in concentration of all elements, but particularly in carbon, from the inner

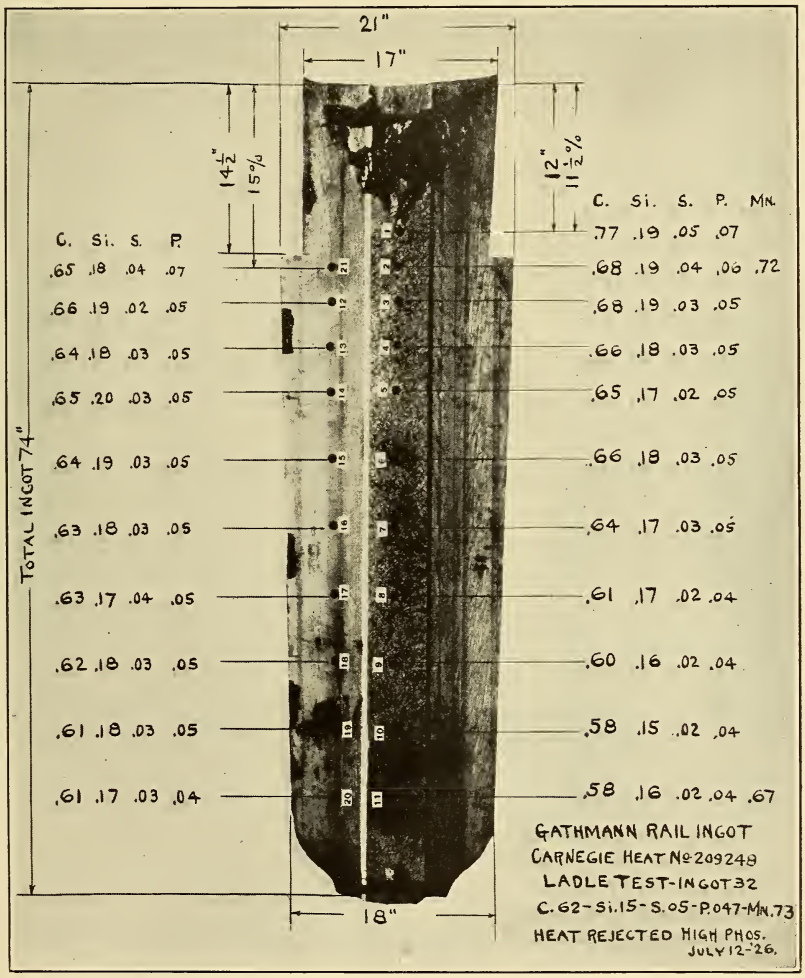

FIG. 26.—*Split Gathmann ingot (No. 32) from Carnegie heat No. 209248*

toward the outer portion of the ingot. This is more apparent in the bottom portions.

The reason for the marked segregation observed is unquestionably the excessively high temperature of teeming of the heat. Because of this high temperature the metal undoubtedly remained liquid in the mold for a considerably longer period of time than under normal conditions which gave time for the various constituents to float up toward the top of the ingot and into the hot top. The central por-

tion of the ingot is the last to solidify and the solidification in this type of mold (big end up hot top) progresses from the bottom to the top of ingot. This central portion is, therefore, fluid for a longer period than the outer portions. There is greater opportunity, therefore, for segregation toward the top central portion which explains the relative impoverishment of the lower central portion.

TABLE 15.—*Comparison of segregation in Gathmann, Hadfield, and Iron and Steel Institute ingots*

Position in ingot (see fig. 27)	Percentage of element											
	Carbon				Sulphur			Phosphorus			Silicon	
	Gathmann		Hadfield	Iron and Steel Institute	Gathmann heat 17	Hadfield	Iron and Steel Institute	Gathmann heat 17	Hadfield	Iron and Steel Institute	Gathmann heat 17	Iron and Steel Institute
	Heat 4	Heat 17										
E	140	124	150	141.8	100	125	148.8	149	129	127.4	127	107.7
G	100	105	97	112.1	60	104	115.1	106	100	110.2	127	101.8
D	101	105	104	106.8	40	76.5	114.2	106	84	106.5	113	101.8
F	100	103	94	104.6	60	90.5	101.3	106	100	103.4	112	104.2
A	99	-------	101	103.8	-------	90.5	99.0	-------	116	101.6	-------	100.7
Ladle	100 / 0.71	0.62	100 / 0.65	100.0	100 / 0.05	100 / 0.052	100.0	100 / 0.047	[1] 100 / 0.031	100.0	100 / 0.15	100.0
C	96	102	95.5	94.7	60	73	88.0	106	81	95.1	113	101.3
B	100	94.5	92.5	85.7	40	67	76.6	85	78	89.8	107	103.0

[1] No ladle analysis available; position F value used.

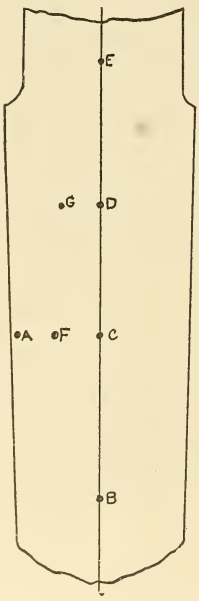

FIG. 27.—*Location of test drillings in ingots reported by Iron and Steel Institute*

A comparison of the segregation of elements in Gathmann ingots, the Hadfield ingots previously reported,[16] and the average segregation in the large number of sink-head ingots reported on by the Iron and Steel Institute Committee studying heterogeneity of steel ingots,[17] is given in Table 15. The same method of presenting the data is used as given in the above report. The figures for the various elements are expressed as a percentage of the amount of the element as determined by ladle analysis. The letters in Figure 27 represent location of test drillings.

An examination of these figures indicates that the segregation of carbon, phosphorus, sulphur, and silicon in Gathmann ingots occurs in the same manner and is no greater than in other types of sink-head ingot molds. The low percentage values for the sulphur distribution in the Gathmann ingot may be due to the ladle analysis indicating a somewhat higher sulphur content than was actually present.

4. TESTS OF RAILS AT BUREAU OF STANDARDS

(*a*) TESTS MADE.—The following tests were made on the several rail sections. Tensile prop-

[16] See footnote 4, p. 299.

[17] Report on heterogeneity of steel ingots, Iron and Steel Inst., **113**, No. 1, p. 39; 1926.

erties (tensile strength, yield point, elongation, reduction of area); comparative Rockwell B hardness of head, web and flange; endur-

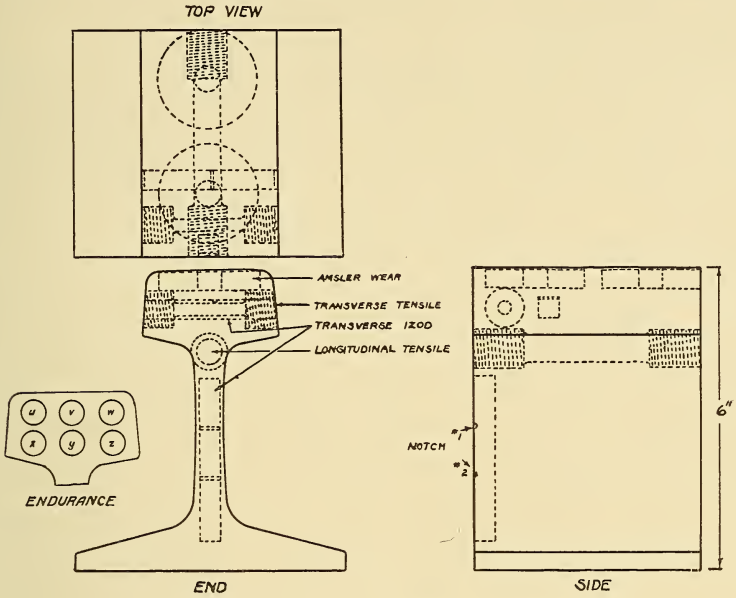

FIG. 28.—*Location of test specimens in rail*

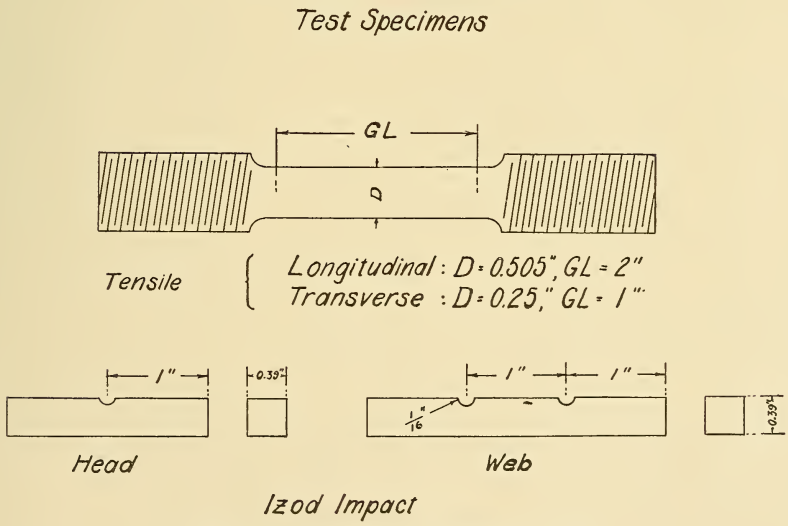

FIG. 29.—*Dimensions of test specimens*

ance properties, deep etching; microstructure; M and O analyses of rail head; and comparative total slag contents. Specimens were also obtained for future work on wear and elevated temperature tensile tests which will be reported at a later date.

(*b*) Location and Shape of Test Specimens.—The locations of the various specimens in the rail sections from which they were machined are shown in Figure 28, and the dimensions of the specimens used are given in Figure 29.

The tensile test specimens representing tensile properties parallel with the direction of rolling were taken at the junction of the web and the head. Standard 0.505 inch diameter, 2-inch gauge length specimens were used. Tensile specimens representing the tensile properties transverse to the direction of rolling were taken across the center of the head of the rail. It was obviously impossible to use a standard specimen, therefore, one with a 1-inch gauge length and 0.25 inch diameter was used. The elongation and reduction of area values for these transverse tensile tests, therefore, can not be compared directly with those obtained in the longitudinal direction.

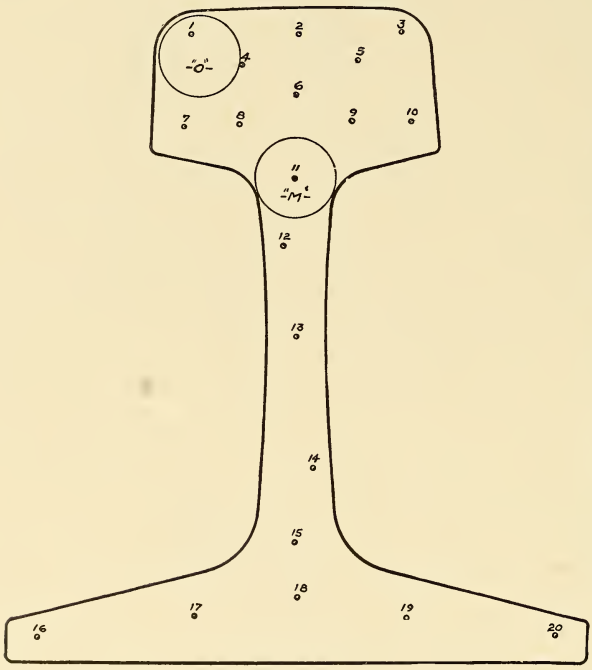

Fig. 30.—*Location of Rockwell "B" hardness tests and "M" and "O" analyses*

Two Izod impact specimens were made. One was machined transversely from the center of the head and notched on the top face so that the fracture was approximately in the middle of the head with the plane of fracture parallel to the side of the head of the rail and the second was cut from the web of the rail. This specimen was notched at two points so that the planes of fracture were parallel to the head at a point very near the center of the web and another slightly above the junction of web and flange. Because of the known low impact value of rail steel a notch smaller than standard was used. This gave the advantage of a somewhat larger area of fracture.

The hardness tests were made with a Rockwell hardness-testing machine using a one-sixteenth inch diameter ball at the 20 points indicated in Figure 30. The surfaces of the sections previous to testing were ground flat and parallel on both sides.

After the hardness tests had been made these same rail sections were used for the deep etching tests.

The total slag contents were determined on drillings (one-fourth-inch drill) taken through the butt ends of the broken tensile test bars.

The M and O analyses were made on drillings (three-fourths-inch drill) from positions also shown in Figure 30.

Microscopic examinations for distribution of nonmetallic inclusions were made on impact specimens after they had been fractured in the impact test.

5. RESULTS OF TESTS

(*a*) Tensile Tests.—The results of all tensile tests are given in Tables 16 and 17 for the Gathmann and standard ingot rails, respectively. The data have been grouped according to rail letter (position of rail in ingot) and the average values for respective rail letters determined for all heats from both companies as the specification requirements were essentially the same.

Table 16.—*Longitudinal and transverse tensile test data on rails rolled from Gathmann ingots*

Heat No.	Rail	Elongation		Reduction of area		Yield point		Tensile strength	
		Longitudinal 2-inch gauge length	Transverse 1-inch gauge length	Longitudinal 0.505 inch diameter	Transverse 0.25 inch diameter	Longitudinal	Transverse	Longitudinal	Transverse
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
1	A	11.5	11.0	17.0	13.3	55,050	60,000	120,400	117,400
2 [1]	A	(2)	2.0	(2)	3.5	[2]60,400	67,400	(2)	89,600
3	A	9.0	10.0	13.4	12.1	61,100	66,600	129,750	126,000
18	AB	(3)	5.0	(3)	6.6	[3]58,600	60,000	(3)	122,000
19	AB	12.0	6.0	13.8	8.2	54,350	64,900	134,750	125,000
20	AB	13.0	1.0	14.4	3.5	53,400	61,100	115,750	96,700
Average, A rails	--------	11.4	5.8	14.7	7.9	57,150	63,330	125,160	112,780
4	B	11.0	2.0	18.1	4.3	56,150	64,800	122,500	84,200
5	B	11.5	10.0	19.9	15.6	54,000	58,400	122,850	120,000
6	B	8.5	3.0	10.4	5.1	53,350	65,000	123,200	99,000
7	B	10.0	7.0	14.5	9.7	58,300	72,400	129,500	133,600
17	BC	14.0	--------	23.0	--------	49,750	--------	120,250	--------
Average, B rails	--------	11.0	5.5	17.2	8.7	54,710	65,150	123,660	109,200
1	C	13.0	11.0	18.1	15.6	64,600	60,800	119,400	117,600
2 [1]	C	11.0	2.0	14.1	3.5	61,750	66,800	133,200	80,800
3	C	11.0	9.0	14.4	15.6	58,100	71,000	134,000	132,700
Average, C rails	--------	11.7	7.3	15.5	11.6	61,480	66,200	128,870	110,370
17	DE	17.0	8.0	26.8	12.6	51,500	59,000	111,950	114,800
18	DE	14.0	5.0	24.0	6.6	55,400	57,000	121,450	112,800
19	DE	17.0	5.0	25.3	7.4	52,600	61,600	117,200	116,000
20	DE	11.0	7.0	18.8	7.4	56,750	65,000	129,650	126,600
Average, DE rails	--------	14.8	6.3	23.7	8.5	54,060	60,650	120,060	117,550
1	F	(4)	--------	--------	--------	--------	--------	--------	--------
2 [1]	F	13.0	(2)	19.8	(2)	56,800	60,000	128,150	(2)
3	F	10.0	9.0	11.9	12.6	52,500	62,600	126,500	124,600
Average, F rails	--------	11.3	--------	16.5	--------	54,670	61,300	127,330	--------

[1] This heat (No. 2) was rejected for rail service because of failure in the drop test.
[2] Broke in fillet due to segregated area.
[3] Broke in fillet, crystalline fracture.
[4] Specimen 1F was from section containing the mild steel inclusion. (See fig. 50 and discussion.)

TABLE 17.—*Longitudinal and transverse tensile test data on rails rolled from standard ingots*

Heat No.	Rail	Elongation		Reduction of area		Yield point		Tensile strength	
		Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
8	A	2.0	3.0	2.7	4.3	53,200	66,800	[2] 91,300	104,600
9 [1]	A	2.5	(3)	2.3	(3)	54,750	--------	104,800	(3)
10	A	9.5	(3)	13.0	(3)	53,700	60,200	132,400	(3)
Average, A rails	--------	4.7	--------	6.0	--------	53,890	63,300	109,500	--------
12	B	(3)	2.0	(3)	3.5	63,250	45,200	(3)	71,600
14	B	(3)	7.0	(3)	10.4	61,850	64,600	(3)	127,400
15	B	13.0	10.0	15.6	13.4	55,150	63,500	128,150	121,700
16	B	17.5	10.0	24.0	14.1	49,300	61,600	112,000	115,000
21	B	15.0	(4)	20.6	(4)	54,250	58,800	121,500	117,700
Average, B rails	--------	15.2	7.3	20.1	9.4	56,750	58,740	120,220	110,680
8	C	11.5	8.0	18.8	14.1	58,250	61,000	125,750	125,800
9 [1]	C	11.0	(3)	15.5	(3)	53,000	52,600	122,300	(3)
10	C	12.0	10.0	18.8	14.1	50,000	60,200	118,900	123,400
21	C	15.0	5.0	20.6	7.4	52,000	51,600	119,750	135,400
Average, C rails	--------	12.4	7.7	18.4	11.9	53,310	56,500	121,680	128,200
21	D	16.0	5.0	22.3	6.6	47,100	57,000	115,250	113,200
21	D	15.5	5.0	22.3	6.6	50,500	51,000	116,500	111,700
Average, duplicate bars	--------	15.8	5.0	22.3	6.6	48,800	54,000	115,880	112,450
8	F	10.5	10.0	17.4	15.2	59,250	67,600	123,250	124,200
9	F	13.5	9.0	23.4	12.6	51,200	54,800	118,750	118,000
10	F	12.0	11.0	19.9	15.6	45,150	79,400	117,200	117,200
Average, F rails	--------	12.0	10.0	20.2	14.6	51,870	67,270	119,730	119,800

[1] This heat (No. 9) was rejected for rail service because of failure in the drop test.
[2] Segregated fracture.
[3] Broke in fillet due to segregated area.
[4] Broke just outside of gauge mark.

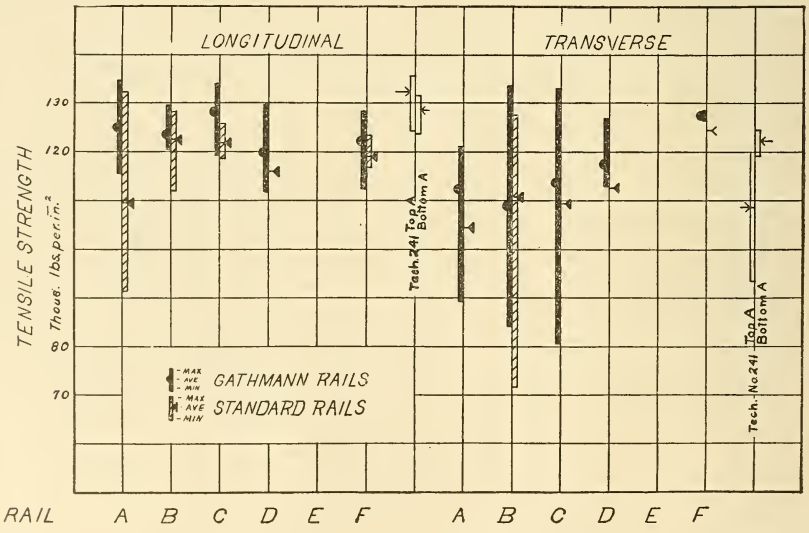

FIG. 31.—*Tensile strength of rail steels rolled from Gathmann and standard ingots*

These average values have been plotted in Figures 31, 32, and 33. In these figures, in addition to the average values, the maximum and minimum values obtained in the tests have been indicated by shaded

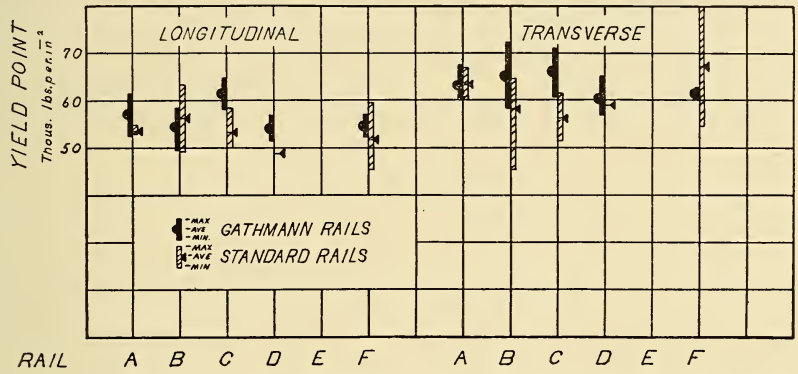

FIG. 32.—*Yield point of rail steels rolled from Gathmann and standard ingots*

areas. In cases where there was only one test reported it is indicated by a short horizontal line instead of a shaded area.

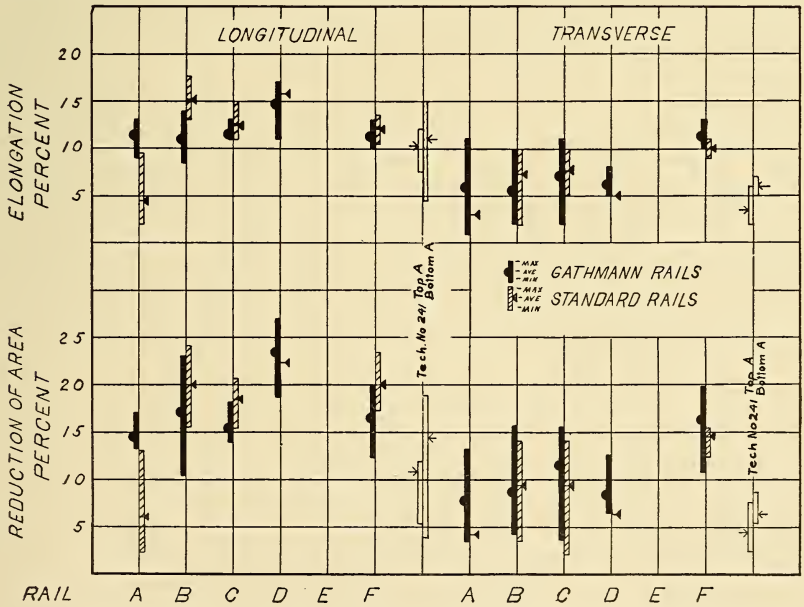

FIG. 33.—*Elongation and reduction of area of rail steels rolled from Gathmann and standard ingots*

Since all test sections were obtained from the top ends of the rails rolled from the middle ingots of the several heats, the relative length of the shaded areas is a measure of the relative uniformity of quality of the rails from the several heats.

One method of showing uniformity would be to compute the average deviations from the mean of the several tests of the physical properties of the rails. Such data, however, while showing better the generally close agreement that may exist between results, does not bring out the occasional low value which in the case of rails is the condition most likely to be the cause of failures.

A factor that should be noted is the occasional tensile test specimen that breaks in the fillet due to inclusions. The results of such tests

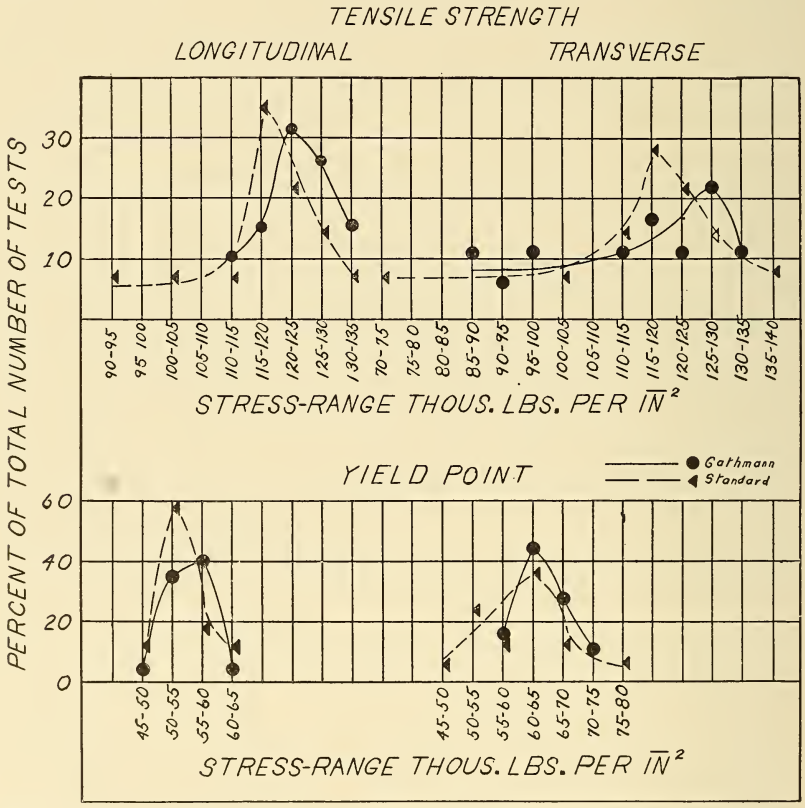

Fig. 34.—*Probability curves of some of the physical properties of the rails*

were not used in the calculation of average values, except for yield point, nor do they appear as maximum or minimum values, and yet they indicate a very definite lack of homogeneity in the steel. In this report these specimens are given in the tables. It will be noted that in some instances the number of failures in the fillet of the tensile test specimens was greater than in the reduced section. No retests were made because of insufficient material. In such cases the average value may be the result of but one satisfactory test (failure in the reduced section).

There are given in Figure 34 so-called probability curves of some of the tensile properties. These curves are obtained by plotting the per cent of the total number of test values against arbitrarily chosen but definite limiting ranges of values. The spread of the curve along the axis of the range values is indicative of the uniformity of results—the smaller the spread the greater the uniformity.

Only those probability curves which showed any differences between Gathmann and standard ingots have been included in the report.

The tensile properties of the rails from the two types of ingots are essentially of the same order of magnitude, although the Gathmann ingot rails are generally of slightly greater strength. The tensile strength in the longitudinal direction is approximately 125,000 lbs./in.^{2} and the corresponding transverse strengths about 10,000 lbs./in.^{2} lower. The yield point in the longitudinal direction is about 55,000 lbs./in.^{2} and about 60,000 lbs./in.^{2} in the transverse direction; approximately 45 and 50 per cent, respectively, of the tensile strength.

The elongation is approximately 12 per cent in the longitudinal direction and 7 per cent in the transverse direction and the reduction in area 17 and 9 per cent, respectively.

These differences in the directional properties of the rails are not unusual to material of this type, which has been rolled principally in one direction. The differences in the elongation and reduction of area values are also without doubt due in part to the differences in the diameter and gauge length of the test specimens. The longitudinal specimen, having a larger diameter and greater gauge length, would tend to give higher ductility values.

While the average tensile values of the rails from the two types of ingots are approximately the same there is evidently an appreciable difference in the uniformity of results, especially in the A rails. It is evident in Figure 31 that the average longitudinal tensile strength of the A and AB rails from the Gathmann ingots is higher than the corresponding standard rails, and that the differences between the respective maximum and minimum values are considerably less. In the A rail one longitudinal test specimen from each type of ingot failed in the fillet due to slag, but it should be noted that in both cases the specimen was from a heat which was rejected in the drop test. However, there were two failures in the fillet due to slag in standard B rails, but none from Gathmann B rails.

One transverse test specimen (2 F) of the rejected Gathmann heat (No. 2) and two (9 A and 9 C) of the rejected standard heat (No. 9) failed in the fillet due to included slag. One transverse specimen from a standard rail (10 A) likewise failed, but there were no such failures in accepted Gathmann rails.

In order to give a more general comparison of the tensile properties of the Gathmann ingot rails with standard ingot rails there has been plotted also in Figures 31, 32, and 33 the average, maximum, and minimum values of tensile strength, elongation, and reduction of area obtained on the rail specimens from a comparable position of the standard heats deoxidized with ferrosilicon reported in a previous publication of the Bureau of Standards.[18] The values for the top and bottom of the A rail are given. The values for specimens from the bottom of the A rail may be compared with specimens from the B rails in this investigation, since the bottom of the A rail and the top of the B rail are always contiguous to each other before cutting of the rails at the hot saw.

The probability curves for tensile strength given in Figure 34 indicate similarly a greater uniformity of results of tests of Gathmann rails, since the spread of standard rail tests is greater for both the longitudinal and transverse directions of test.

The curves showing average yield point and the maximum and minimum values do not indicate any marked difference in this property for the rails from different parts of the ingot, except for the F rail from standard ingots, which showed a greater range of stress values in both the longitudinal and transverse directions than the corresponding Gathmann rail. In the probability curve the rails from the standard ingots have a greater spread than the Gathmann rails, indicating greater inhomogeneity in the standard ingots.

The elongation and reduction of area of the A rail specimens from Gathmann ingots are higher than the corresponding A rail values from standard ingots, and, similar to the tensile strength, they are equal to the corresponding values of the B and other rails from portions lower down in the ingot.

It may be concluded that the tensile properties of the A (top) rails of Gathmann ingots are superior in quality to the A rails of standard ingots and that they are probably of equal quality to the B rails of both types of ingots. A similar result was noted in the study of Hadfield [19] ingots, in which there was practical uniformity of tensile strength for the sink head (Hadfield) ingots down to the E position; on the other hand, in the standard ingots an abrupt increase was noted from the A to the B position. There is apparently no appreciable difference in the tensile properties of the rails below the A rail from the two types of ingots.

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[18] See footnote 11, p. 301.

[19] See p. 44, of B. S. Tech. Paper No. 178; 1920.

TABLE 18.—*Izod impact test data of rails rolled from Gathmann and standard ingots*

[S indicates fracture segregated. SS indicates fracture slightly segregated]

ENERGY ABSORBED (FOOT-POUNDS)

Gathmann					Standard				
Heat	Rail	Web position 1	Web position 2	Head	Heat	Rail	Web position 1	Web position 2	Head
1	A	14.0	15.0	12.0	8	A	4.7S	5.7	10.3
2 [1]	A	2.4S	21.5	9.5	9 [1]	A	5.2	4.4S	2.0S
3	A	9.7	11.9	10.5	10	A	6.6	3.4	11.5
18	A	10.3	8.4SS	5.7SS					
19	A	8.7SS	10.7S	3.7SS					
20	A	12.7	11.3	4.2SS					
Average	A	9.6	13.1	7.6	Average	A	5.5	4.5	7.9
4	B	11.7	15.0	9.5	12	B	4.3S	7.2	5.8
5	B	14.3	16.9	9.8	14	B	7.1	4.1S	2.6S
6	B	9.2	8.4SS	9.3	15	B	4.0	4.0S	12.2
7	B	12.4	11.1	9.2	16	B	10.0	18.0	10.6
17	BC	13.8	10.0	8.1	21	B	12.6	13.0	6.0
Average	B	12.3	12.3	9.2	Average	B	7.6	9.3	7.4
1	C	18.8	15.5	6.0S	8	C	11.2	14.5	6.1SS
2 [1]	C	6.6S	18.0	5.9S	9 [1]	C	9.1	12.7	6.0S
3	C	12.2	10.2	9.5	10	C	8.1	3.9	10.1
					21	C	4.0	14.0	7.4
Average	C	12.5	14.6	7.1	Average	C	8.1	11.3	7.4
17	DE	16.5	13.7	8.5					
18	DE	14.3	12.6	8.1SS					
19	DE	11.7	17.2	8.5					
20	DE	13.7	11.2	8.1	21	D	18.2	14.0	--------
Average	DE	14.1	13.7	8.3	Average	D	--------	--------	--------
1	F	14.7	17.3	11.9	8	F	7.0	16.0	9.9
2 [1]	F	12.5	12.7	10.0	9 [1]	F	7.1	6.7	9.5
3	F	13.8	9.4	12.8	10	F	12.2	14.2	5.9
Average	F	13.7	13.1	11.6	Average	F	8.8	12.3	8.4
Average of all rails	--------	12.3	13.3	8.7	Average of all rails	--------	9.6	10.3	8.3
Average, all positions (63 tests)				11.4	Average, all positions (47 tests)				9.4

[1] This heat was rejected for rail service because of failure in the drop test.

(*b*) IMPACT TESTS.—The results of the Izod impact tests are given in Table 18 and Figure 35. The average impact resistance for both the No. 1 (center of web) and No. 2 position (junction of web and flange) of all rails from Gathmann ingots is greater than the corresponding values for rails from standard ingots.

It is well known that as a result of the rolling procedure the central or more segregated part of the ingot tends to go into the web of the rail. Any segregation of impurities in the web of the rails would tend to decrease the impact resistance. The lower impact values of the web of the standard ingot rails is concordant with a greater segregation of impurities in the standard ingots than in the Gathmann ingots.

There is apparently no appreciable difference in the impact resistance of specimens cut transversely from the head of the rails rolled from both types of ingots.

(*c*) Rockwell Hardness Tests.—The results of the Rockwell hardness tests are given in Figure 36. The average and the maximum and minimum values for head web and flange, respectively, have been plotted.

There is no appreciable difference in the average hardness over the entire rail section of rails from different parts of the ingot. There is apparently a somewhat greater uniformity of hardness in the flange of Gathmann ingot rails than standard ingot rails.

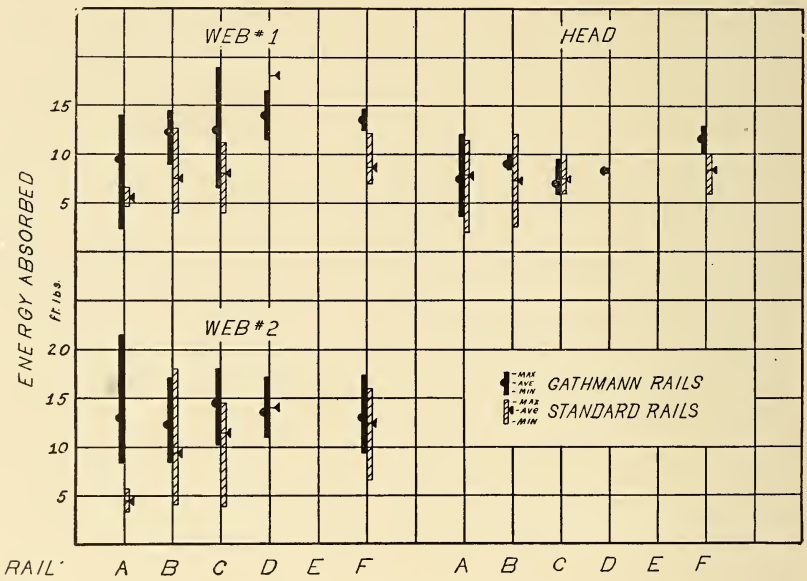


Fig. 35.—*Impact resistance of rail steels rolled from Gathmann and standard ingots*

(*d*) Chemical Analysis.—(1) *M and O analyses.*—The locations of drillings for the M and O analyses are shown in Figure 30. The usual three-fourths inch diameter drill was used for sampling. All drillings were made at the Bureau of Standards. The analyses were made by the firm of Pennimann & Browne.

The results are given in Table 19. In this table the values designated "per cent segregation" were obtained by dividing the difference in carbon content between the M and O position by the content of the respective O position. If the carbon content is higher in the M position, the segregation is considered positive, and conversely the segregation is negative if the carbon is higher in the O position. This is indicated by a minus sign.

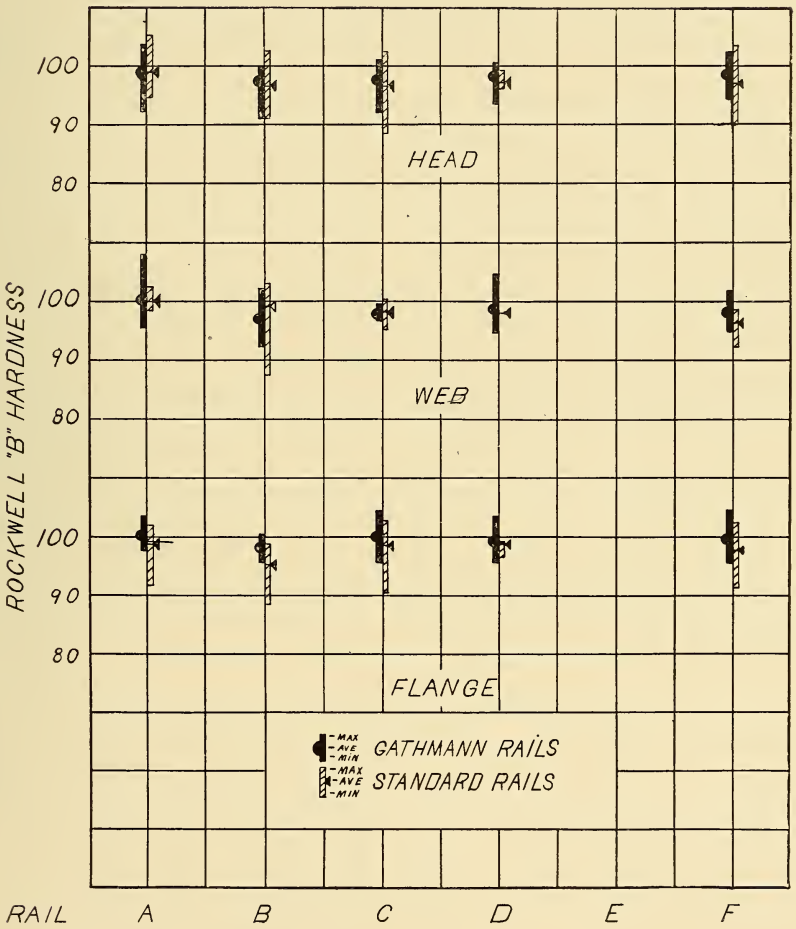


Fig. 36.—*Rockwell "B" hardness tests of rail steel sections from Gathmann and standard ingots*

TABLE 19.—*M and O analyses, total slag content, and density of rails rolled from Gathmann and standard ingots*

GATHMANN

Bureau of Standards heat No.	Rail letter	Carbon content			Total slag	Density M position	Density full section
		M	O	Segregation			
		Per cent	*Per cent*	*Per cent*	*Per cent*	*g/cm³*	*g/cm³*
1	A	0.63	0.65	−3.07	0.18	7.852	7.822
2	A	.71	.71	.00	.22	7.834	7.812
3	A	.76	.68	11.76	.23	7.846	7.819
18	AB	.74	.76	−2.63	.14	7.833	----------
19	AB	.74	.71	4.22	.22	7.835	----------
20	AB	.66	.80	−17.50	.24	7.835	----------
Average	A	.707	.718	±6.53	.21	7.840	7.818
4	B	.66	.67	−1.49	.33	7.853	----------
5	B	.67	.67	.00	.24	7.845	----------
6	B	.64	.69	−7.25	.25	7.850	----------
7	B	.71	.69	2.90	.17	7.850	----------
17	BC	.64	.56	14.29	.12	7.843	----------
Average	B	.664	.656	±5.19	.22	7.849	----------
1	C	.65	.57	14.02	.190	7.854	7.819
2	C	.67	.70	−4.28	.160	7.843	7.814
3	C	.65	.65	.00	.230	7.849	7.819
18	CD	.61	.69	−11.60	----------	----------	----------
19	CD	.69	.73	−5.48	----------	----------	----------
20	CD	.74	.76	−2.63	----------	----------	----------
Average	C	.668	.683	±6.34	.19	7.850	7.817
17	DE	----------	----------	----------	.12	7.845 1E	7.820
18	DE	----------	----------	----------	.12	7.845 2E	7.818
19	DE	----------	----------	----------	.13	7.841 3E	7.822
20	DE	----------	----------	----------	.01	7.842	----------
Average	DE	----------	----------	----------	.10	7.844	7.820
1	F	----------	----------	----------	.12	7.857	----------
2	F	----------	----------	----------	.24	7.843	----------
3	F	----------	----------	----------	.16	7.848	----------
Average	F	----------	----------	----------	.18	7.850	----------

STANDARD

8	A	0.74	0.67	10.45	0.29	7.841	7.823
9	A	.79	.70	12.86	.22	7.842	7.810
10	A	.69	.67	2.98	.23	7.845	7.828
Average	A	.740	.680	+8.76	.25	7.843	7.820
12	B	.66	.57	15.80	.29	7.840	----------
13	B	.58	.57	1.75	----------	----------	----------
14	B	.74	.72	2.78	.58	7.845	----------
15	B	.71	.63	12.70	.28	7.845	----------
16	B	.71	.64	−4.68	.46	7.847	----------
21	B	.62	.71	−12.68	.15	7.839	----------
Average	B	.653	.640	±8.39	.35	7.843	----------
8	C	.68	.63	7.94	.24	7.852	7.818
9	C	.70	.83	−15.68	.16	7.841	7.814
10	C	.64	.57	12.28	.17	7.849	7.833
21	C	.69	.63	9.52	.17	7.847	----------
Average	C	.878	.665	±11.36	.19	7.848	7.822
21	D	----------	----------	----------	.215	7.856	----------
8	F	----------	----------	----------	.17	7.848 1E	7.822
9	F	----------	----------	----------	.35	7.843 2E	7.815
10	F	----------	----------	----------	.16	7.841 3E	7.833
Average	F	----------	----------	----------	.23	7.844	7.823

The tendency toward positive or negative segregation in the Gathmann rails appears about the same; 8 of the 17 rails tested, approximately 47 per cent, showed positive segregation. There is no marked difference in this tendency in the different rails.

The rails from the standard ingots show a definite tendency toward a positive segregation, 10 of the 13 rails tested, approximately 77 per cent, having a higher carbon content in the M position.

The average percentage segregation of the Gathmann ingot rails is slightly less, in all three groups of rails tested, than in the standard ingot rails.

The 1914 specifications of the Pennsylvania Railroad required that the percentage segregation should not exceed 12 per cent. In the Gathmann heats, 3 out of 17 rails, the AB rail of heat 20, the BC rail of heat 17, and the C rail of heat No. 1 had a segregation greater than 12 per cent. Heat 17 (Carnegie 209248), however, was a rejected heat because of high phosphorous. It is noteworthy that the A rail of heat No. 1 has a small segregation value, also that heats 1, 2, and 3 were the first heats poured at Algoma Steel Co. and had hot tops which were shown by nick and break tests to be too small. The heats (4, 5, 6, 7) with larger hot tops showed low segregation values in the B rails. Unfortunately, analyses for the A rails of these heats are not available.

In the standard ingot rails 6 of the 13 rails had a segregation greater than 12 per cent.

(2) *Total slag determinations.*—The total slag content [20] was determined by the American Society for Testing Materials "Iodine method" [21] on one-fourth-inch drillings from the broken ends of the longitudinal test specimens and accordingly corresponds to the M position.

The results of the analyses are given in Table 19.

The differences noted are small and probably insignificant in so far as the relative properties of the rails are concerned.

(*e*) Density Determinations.—Density determinations [22] were made on cylinders cut from the ends of the broken tensile test specimens which were from the M position. The results are given in Table 19.

Similar determinations [23] were also made on rail sections approximately 4 to 8 inches long from some of the rails. These results are also given in Table 19.

It is apparent from the data that there is no indication of differences in average density of rails from the same type of ingot or between

[20] Made by R. L. Dowdell in the laboratories of the University of Minnesota.
[21] Proc. Am. Soc. Test. Matls., 25, pt. 1, p. 80; 1925.
[22] By R. L. Dowdell at University of Minnesota.
[23] Under direction of E. L. Peffer, Bureau of Standards.

rails rolled from Gathmann and standard ingots. There is a consistent difference in the density values as determined on the full rail section and the small specimen from the M position. This is probably due to the difference in sampling and methods of test.

6. MACROSCOPIC AND MICROSCOPIC EXAMINATIONS

(*a*) Nonmetallic Inclusions.[24]—Specimens were chosen from two representative heats of each type of steel (Gathmann heats No. 3 and 19 and standard heats No. 8 and 10) for comparison as to the number and type of inclusions. Longitudinal sections (broken impact specimens) from the centers of the heads and from the webs of A, B, and C rails of the above heats were polished for microscopic examination and surveys made of the inclusions. The micrographs, ×100, in Figures 37, 38, 39, and 40 are representative of the observations made.

As may be seen in the micrographs, both types of steel contained about an equal number of inclusions, about the usual number for this kind of steel. In both types there were more inclusions in the webs probably due to the fact that it is rolled from the central part of the ingot. The specimens from the Gathmann heats contained more alumina inclusions, some of which are indicated by arrows in the micrographs. Aluminum was used in the deoxidation of these Gathmann heats to insure complete killing of the steel. On the whole, however, it may be stated as a result of this examination that there seemed to be no decided difference between the Gathmann and the standard rails in respect to nonmetallic inclusions.

(*b*) Deep Etching Tests.—Rail sections as indicated in Table 13 were deep etched by immersion in boiling hydrochloric acid for 30 minutes in order to compare the relative segregation in the several rails from the two types of ingots.

Photographs of representative sections after deep etching are given in Figures 41 to 50, inclusive.

As may be seen in the photographs the A rail of the standard heats showed marked segregation (specimens 8 A and 10 A). There was also evidence of similar but less marked segregation in the C rails of all standard heats tested as is shown by Figures 42 and 45 of specimens 8 C and 10 C. Figure 47 of specimen 3 A is representative of the A rail of all Gathmann ingot rails.

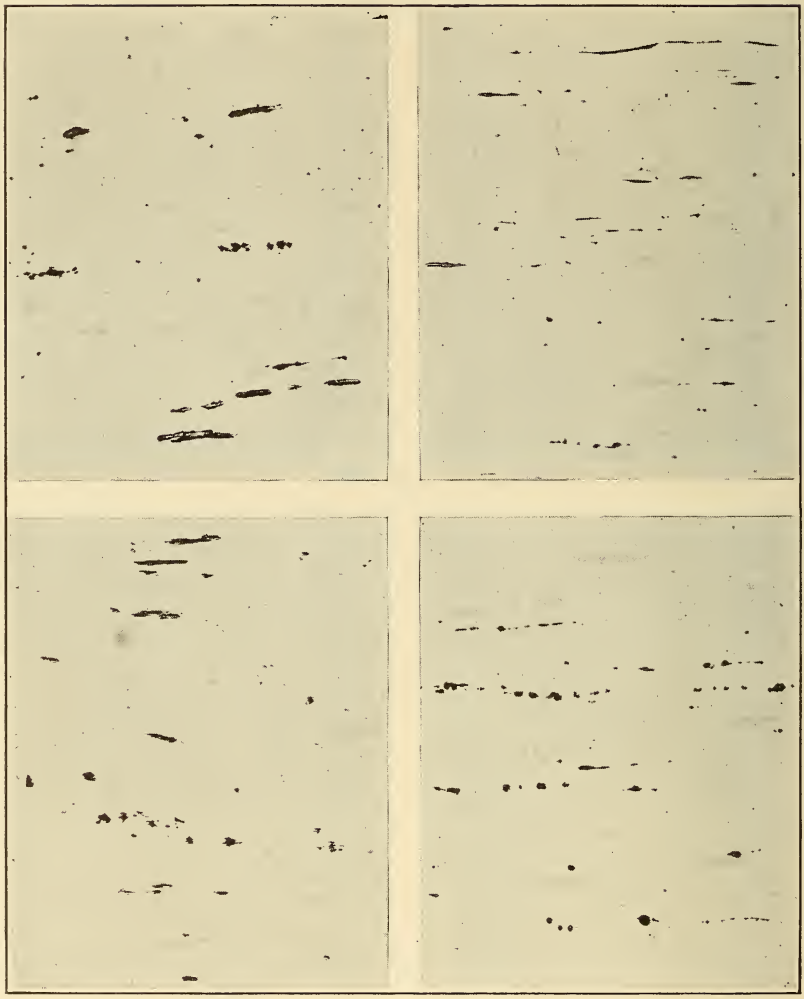
It was apparent from the examination of all deep etched sections that the segregation in the A rails from Gathmann ingots was very small and in general was less than in the C rail from standard ingots.

[24] By S. Epstein, Bureau of Standards.

FIG. 37.—*Micrographs showing type and distribution of nonmetallic inclusions in rails rolled from Gathmann ingots (heat No. 3)*

3A, head of "A" rail
3AW, web of "A" rail
3C, head of "C" rail
3BW, web of "B" rail

19AB 19ABW



20AB 20ABW

Fig. 38.—*Micrographs showing type and distribution of nonmetallic inclusions in rails rolled from Gathmann ingots (heats Nos. 19 and 20)*

19AB, head of "AB" rail, heat No. 19
19ABW, web of "AB" rail, heat No. 19
20AB, head of "AB" rail, heat No. 20
20ABW, web of "AB" rail, heat No. 20

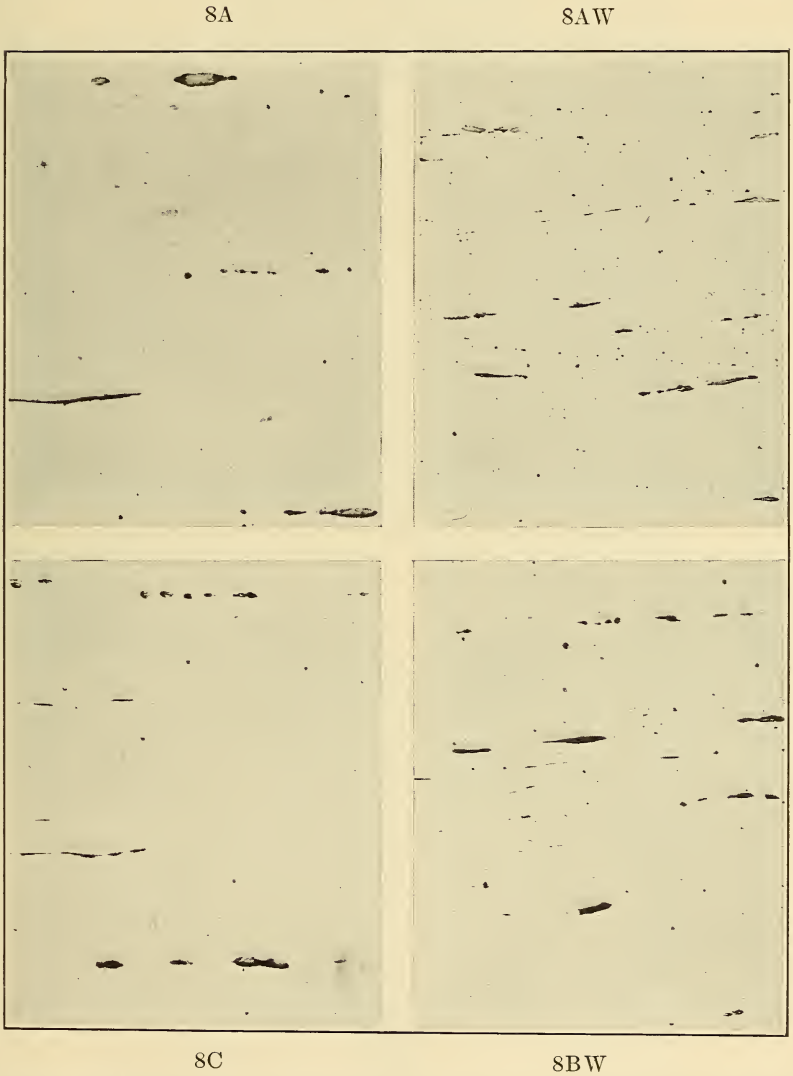
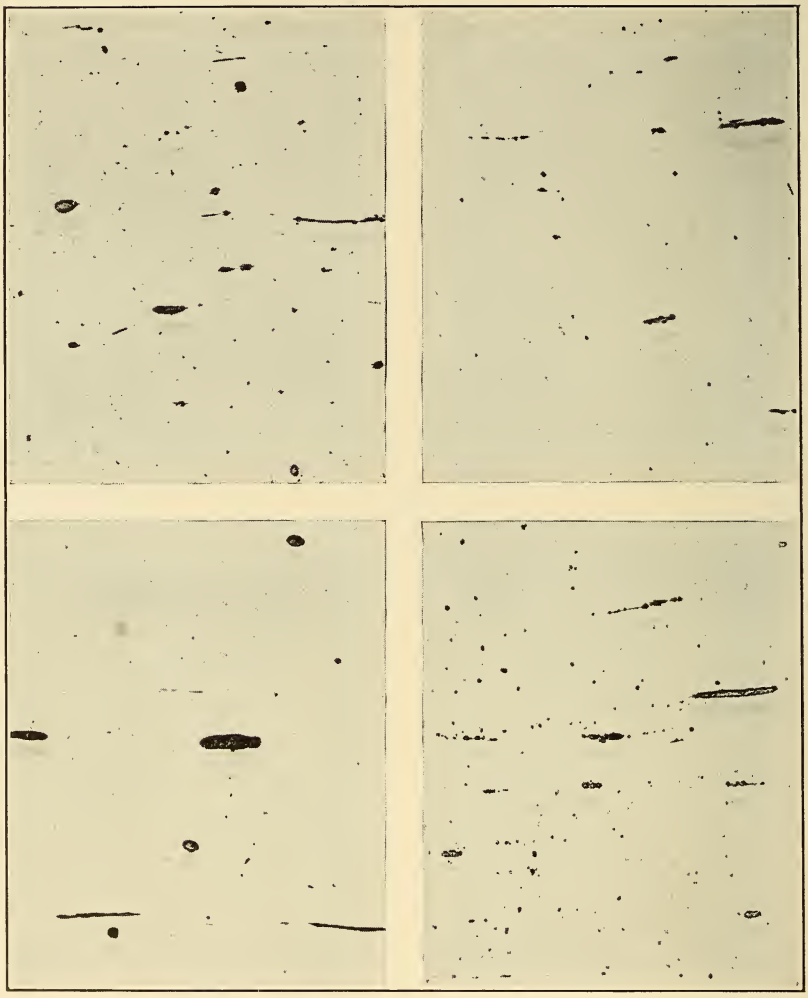


FIG. 39.—*Micrographs showing type of distribution of nonmetallic inclusions in rails rolled from standard ingots (heat No. 8)*

8A, head of "A" rail
8AW, web of "A" rail
8C, head of "C" rail
8BW, web of "B" rail

10A 10AW



10C 10BW

FIG. 40.—*Micrographs showing type and distribution of inclusions in rails rolled from standard ingots (heat No. 10)*

10A, head of "A" rail
10AW, web of "A" rail
10C, head of "C" rail
10BW, web of "B" rail

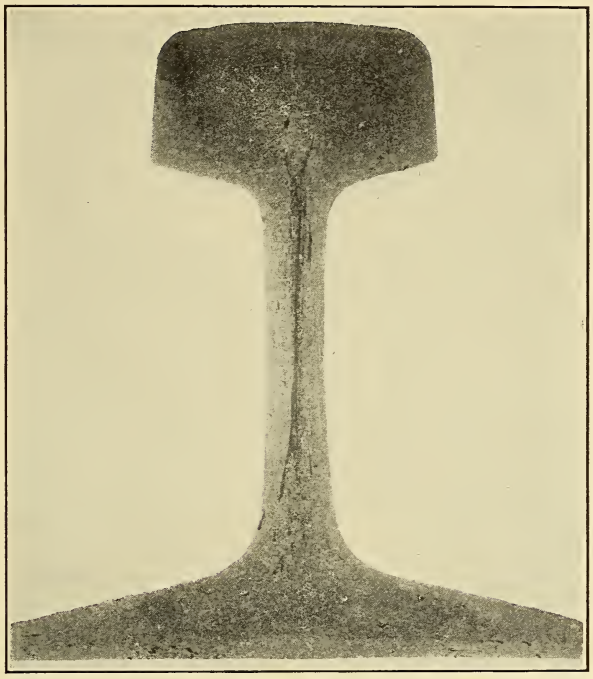


FIG. 41.—*Section of "A" rail rolled from standard ingot (heat No. 8)*

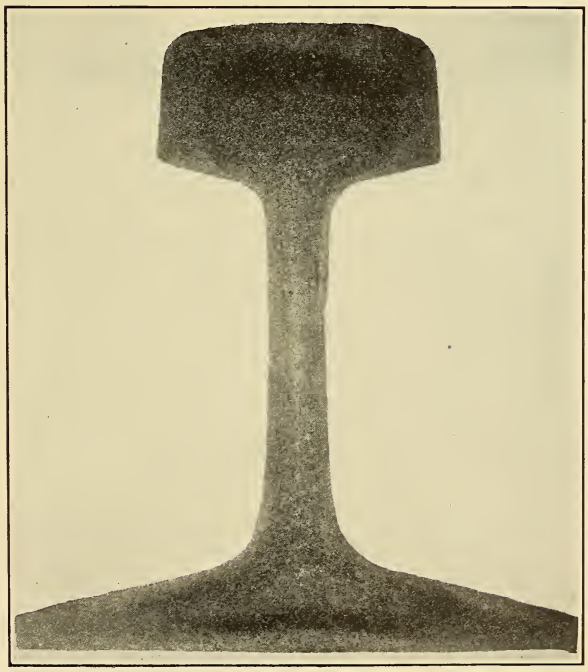


FIG. 42.—*Section of "C" rail rolled from standard ingot (heat No. 8)*

Etched with hot concentrated HCl, 30 minutes

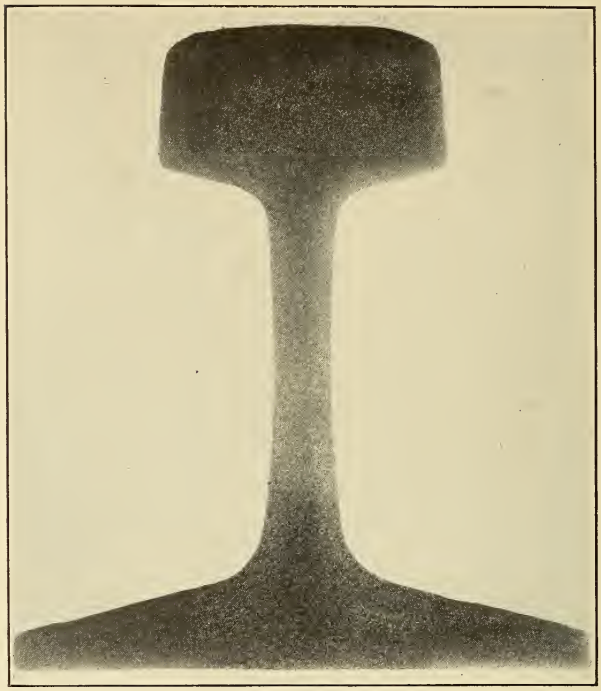


FIG. 43.—*Section of "F" rail rolled from standard ingot (heat No. 8)*

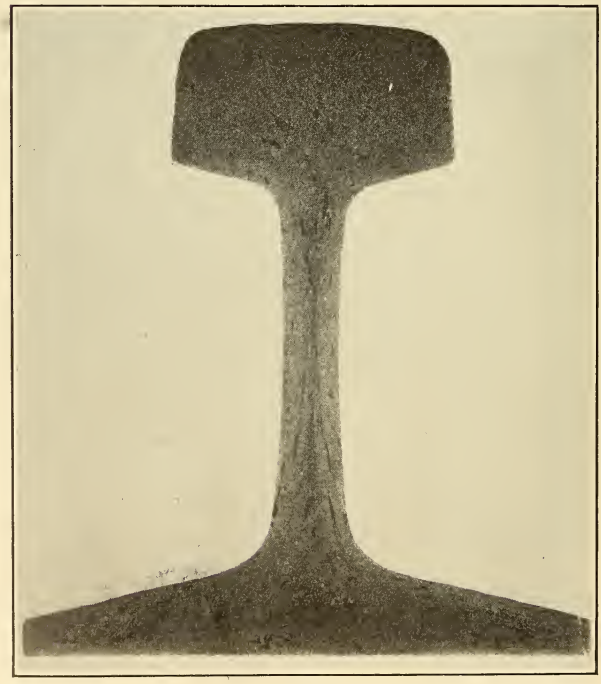


FIG. 44.—*Section of "A" rail rolled from standard ingot (heat No. 10)*

Etched with hot concentrated HCl, 30 minutes

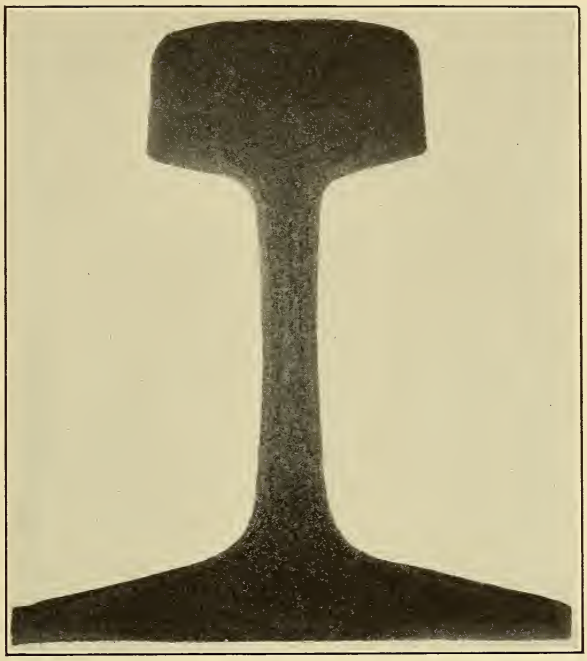


FIG. 45.—*Section of "C" rail rolled from standard ingot (heat No. 10)*

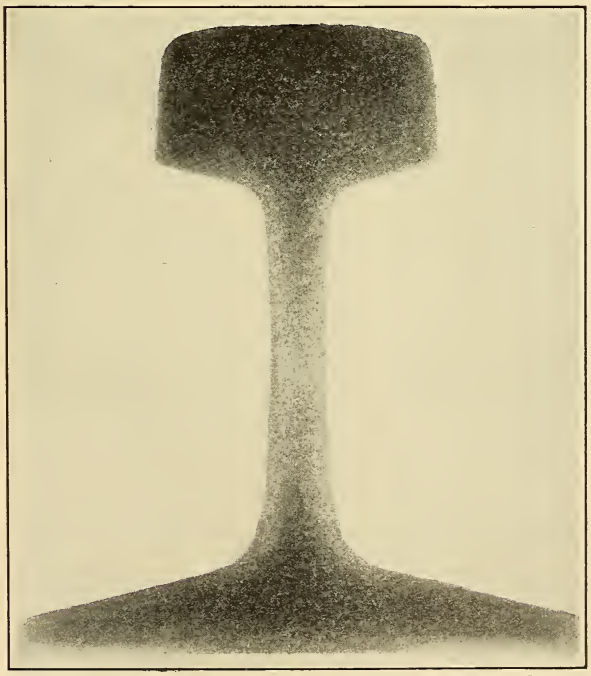


FIG. 46.—*Section of "F" rail rolled from standard ingot (heat No. 10)*

Etched with hot concentrated HCl, 30 minutes

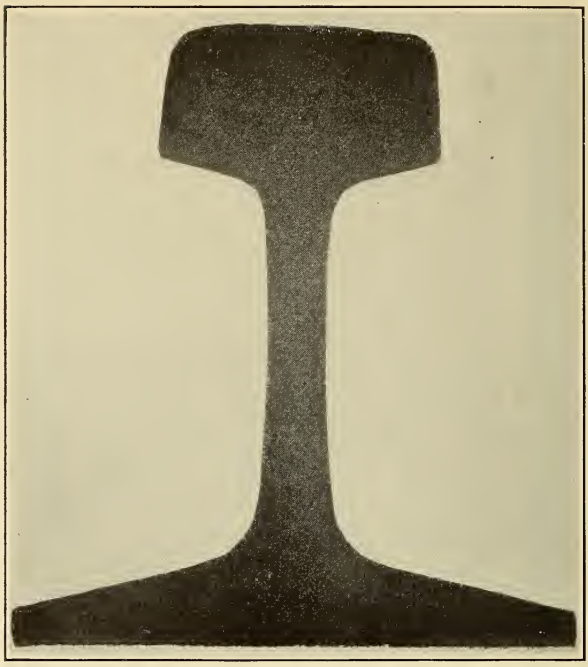


FIG. 47.—*Section of "A" rail rolled from Gathmann ingot (heat No. 3)*

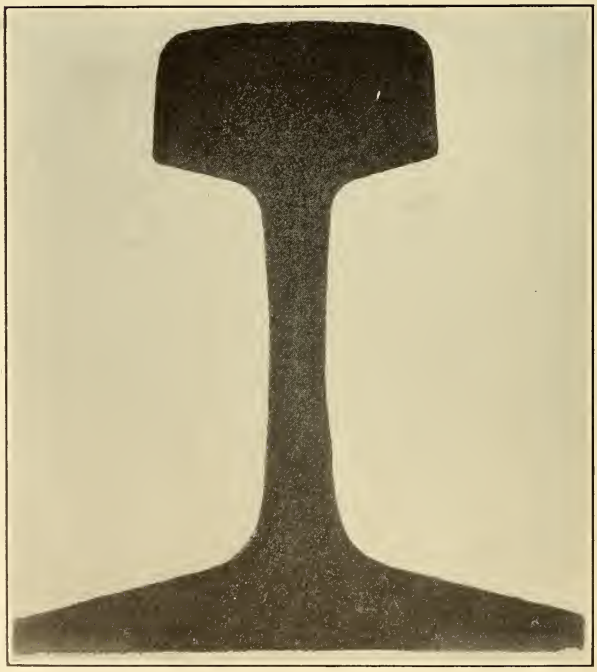


FIG. 48.—*Section of "C" rail rolled from Gathmann ingot (heat No. 3)*

Etched with hot concentrated HCl, 30 minutes

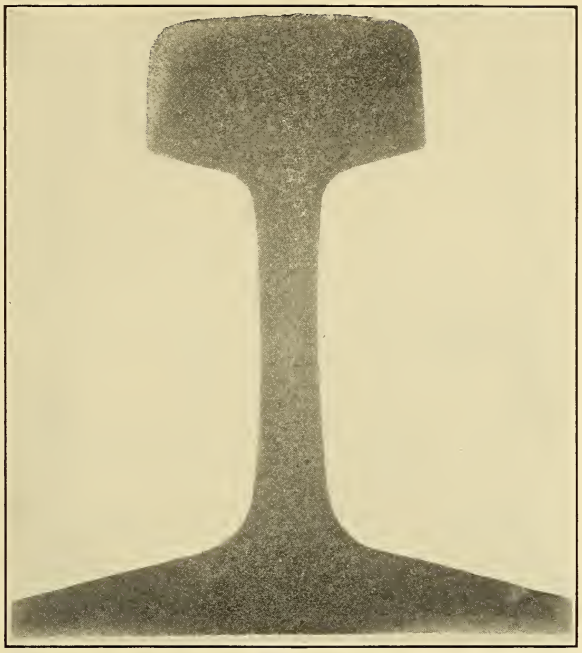


FIG. 49.—*Section of "F" rail rolled from Gathmann ingot (heat No. 3)*

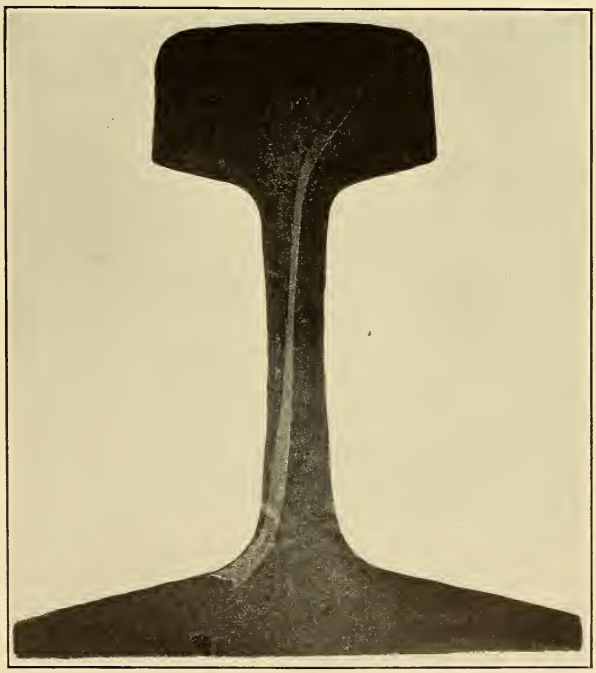


FIG. 50.—*Section of "F" rail rolled from Gathmann ingot (heat No. 1)*

Note mild steel inclusion. See discussion p. 362
Etched with hot concentrated HCl, 30 minutes

Figure 50 is a photograph of a deep etched section from the F rail of heat No. 1. The large streak running down through the web was found to be low-carbon steel. Evidently there was a piece of mild steel in the bottom of the mold when this ingot was teemed which was trapped in the bottom of the ingot and rolled into the rail. Bottom cover plates for the ejector pin were not used in the molds at the Algoma Steel Co. This mild steel inclusion, therefore, could not have been from the mold. Its presence was undoubtedly accidental and from an unknown source distinctly apart from the mold. As stated in Table 16, the tensile test values from this rail were rejected as not representative because of this inclusion.

7. INTERNAL STRESS

Two series of tests were made to determine the amount of internal stress that might be present in the head of the rails.

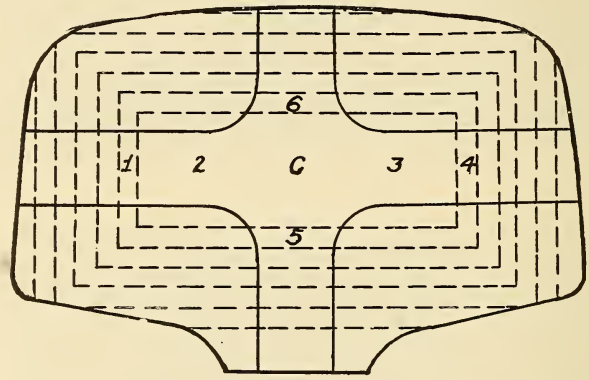


Fig. 51.—*Location of reference marks for internal stress measurements*

A section approximately 9 inches long was cut from the top end of a 10-foot section of the B rail of the middle ingot from heats No. 3 and 10 which were cast in Gathmann and Standard molds, respectively. The 10-foot section had been cut from the rail after straightening (gagging). The heads were cut off from the 9-inch sections at the junction with the web.

Both ends of the heads were then machined and indexed as indicated in Figure 51 to provide fixed reference points for measurement. The distance between corresponding points on either end was then determined. The specimen was then machined on all sides to a depth of approximately one-tenth of an inch. The distance between the reference marks was again measured. This procedure of machining off layers of metal in steps of one-tenth inch and noting the length changes was repeated until five cuts had been taken. The results are given in Table 20.

TABLE 20.—*Measurements for internal stress*

B RAIL, HEAT NO. 3. (GATHMANN)

Position	Initial length	Length between reference marks after—					Difference between initial and fourth cut×10 5
		First cut	Second cut	Third cut	Fourth cut	Fifth cut	
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	
1	8.94741	8.94738	8.94724	8.94724	8.94701	----------	−40
2	8.94742	8.94741	8.94729	8.94732	8.94721	8.94701	−21
Center	----------	8.94746	8.94732	8.94740	8.94739	8.94731	−
3	8.94740	8.94748	8.94736	8.94753	8.94752	8.94758	+12
4	8.94738	8.94749	8.94737	8.94760	8.94757	----------	+19
5	8.94751	8.94753	8.94729	8.94738	8.94730	----------	−21
6	8.94733	8.94735	8.94739	8.94744	8.94749	----------	+16
Average	8.94741	8.94744	8.94732	8.94742	8.94736	8.94730	−5

B RAIL, HEAT NO. 10. (STANDARD)

1	8.94743	8.94736	8.94708	8.94725	8.94699	----------	−44
2	8.94743	8.94742	8.94722	8.94733	8.94718	8.94700	−25
Center	----------	8.94746	8.94726	8.94745	8.94747	8.94737	−
3	8.94745	8.94749	8.94736	8.94761	8.94768	8.94774	+23
4	8.94745	8.94750	8.94739	8.94768	8.94776	----------	+31
5	8.94759	8.94768	8.94734	8.94763	8.94749	----------	−10
6	8.94731	8.94727	8.94722	8.94729	8.94742	----------	+11
Average	8.94744	8.94745	8.94727	8.94746	8.94742	8.94737	−2

The average change between the initial length and the fourth cut in both specimens is small and is within the probable observational errors but the individual changes are plus for positions 3, 4, and 6 and minus for positions 1, 2, and 5. This indicates a slight bending about a diagonal line through the center, probably due to the release of internal stress. The amount of internal stress indicated is very small.

V. SUMMARY AND CONCLUSIONS

A comparative study has been made of the physical properties of 100-pound rail rolled from ingots cast in standard molds and in sink-head molds of the Gathmann type. The work was done under the research associate plan in cooperation with the Gathmann Engineering Co. A total of 21 heats of steel were studied, all of which were made to meet specification requirements substantially the same as the 1925 A. R. E. A. specifications. Of these 21 heats, 9 were standard and 12 were killed with aluminum and cast in Gathmann molds.

Representative sections taken from the top ends of the rails from the middle ingot of each heat were sent to the Bureau of Standards for the determination of the physical properties.

The rails have been placed in track and careful service records are being kept by the respective railroads.

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In addition to the usual acceptance tests, ingots were split to determine the relative degree of pipe and segregation. The following properties of the rails have been determined: Tensile properties (ultimate strength, yield point, elongation, reduction of area) and impact resistance, longitudinal and transverse to the direction of rolling; hardness survey of rail sections; M and O analyses; total slag content; macroscopic and microscopic examination; and density. An extended study of the endurance properties was also made.

The drop tests and "nick and break" tests indicated that if the ratio of hot top to ingot is correct, sink-head ingots of the Gathmann type free from pipe and segregation can be poured of rail steel killed with aluminum. This ratio should be about 17 per cent. Examination of split ingots indicated that the distribution of carbon, phosphorus, sulphur, and silicon occurs in the same manner in Gathmann ingots as in sink-head ingots of other types. The tensile properties of rails rolled from both types of ingots are essentially the same but there is an appreciable superiority in the uniformity of results shown by rails from the Gathmann ingots especially in the A rails which also showed superior tensile properties to A rails from standard ingots. The impact resistance of rails from Gathmann ingots is appreciably greater than in standard ingot rails especially in the web. The deep etching tests indicated that rails from the top portion of standard ingots contained more inclusions and showed greater segregation than rails from Gathmann ingots. Microscopic examination indicated that both types of steel contained about an equal number of inclusions and about the usual number for this kind of steel. There was evidence in both types of a greater number of inclusions in the web than in the head. The rails from Gathmann ingots contained alumina inclusions because of the aluminum used in killing the steel. There was no appreciable difference in density of the rails rolled from the two types of ingots.

It may be concluded from the physical tests that rails rolled from sink-head ingots of the Gathmann type should show greater uniformity in their physical properties than similar rails from standard ingots.

Whether this increased uniformity and any increased freedom from rail breakage that may result therefrom warrants the extra cost involved in using sink-head ingots is outside the scope and province of this report. The results of service tests as well as the laboratory tests must be considered.

VI. ACKNOWLEDGMENTS

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