A COMPARISON OF THE DEOXIDATION EFFECTS OF TITANIUM AND SILICON ON THE PROPERTIES OF RAIL STEEL.

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ABSTRACT.

This investigation was carried out on a considerable scale with the cooperation of the Titanium Alloy Manufacturing Co., the Illinois Steel Co., the Illinois Central Railroad Co., and the Robert W. Hunt Co. on two series of heats of rail steel, one being finished with additions of ferrosilicon and ferromanganese in the ladle and the other with ferromanganese split between the furnace and the ladle, with ferrocarbon-titanium added in the ladle. The study included the following out of the manufacturing practice, tests on A rails for homogeneity by chemical analyses, sulphur printing, and deep etching; tensile, impact, hardness, and endurance tests. The titanium-treated steels were much less segregated than the others, particularly at the top ends of the A rails, and were accompanied by more pipes. These effects were roughly proportional to the amount of titanium added. Titanium in small quantities eliminates the oxygen, reducable by carbon, and in large amounts (10 to 13 pounds ferrocarbon titanium per ton) decreases the nitrogen combined with iron and manganese. A portion, at least, of the nitrogen remains in the steel combined with titanium as minute violet and orange inclusions. The titanium treatment had a tendency to scatter the sulphide inclusions, and this effect with the nitrogen content depend upon the titanium retained in the steel. As a whole, there was not as much improvement in the mechanical properties from the titanium treatment as was expected from the decreased segregation, and any improvements were confined to the upper portion of the ingot, the effects disappearing before the B rail was reached.

CONTENTS.

	Page.
I. Introduction	582
II. General plan of investigation	582
1. Manufacture of the steel	583
2. Rolling of rails	594
3. Inspection of rails	594
4. Drop tests	595
5. Material available for laboratory tests	596
III. Laboratory tests	597
1. Chemical analysis	598
(a) Test ingot drillings	598
(b) Drop test pieces	599
(c) Bottom ends of A rails	602
(d) Gas analysis	603
2. Sulphur prints and etched sections	604
3. Hardness tests	614
4. Tensile tests	617
5. Impact tests	621
(a) Izod	621
(b) Stanton	623
6. Endurance tests	624
7. Microscopic examination	625
IV. Summary and conclusions	633

I. INTRODUCTION.

Titanium is used in steel to produce sound ingots. Under the usual practice it is assumed the titanium goes into the slag, there being ordinarily no intention of producing titanium alloy steel.

In so far as we are aware titanium was first used commercially as a scavenger of steel in 1907,[1] and one of its early applications was in the production of Bessemer rails. They have been gradually superseded by the open-hearth rails, and it has been found that open-hearth steel presents similar problems of segregation as were present before. The manufacturers of ferrocarbon-titanium recommended its addition in the ladle of open-hearth rail steel, and they claim that rails so treated are more ductile without being lower in strength, slightly harder, more resistant to impact, less easily broken by simple bending or by alternating bending accompanied by impact, and greatly superior in endurance under normal loads than ordinary open-hearth rails; that they are practically homogeneous throughout and free from weak spots, such as are caused by excessive segregation of impurities. In the published rail reports of the Titanium Alloy Manufacturing Co. sulphur prints of titanium treated and untreated rails and data on the mechanical properties of the rails are given supporting these claims.[2]

In view of the importance of the claims made relative to the improvement of steel rails by suitably made additions of titanium, it seemed worth while for the Bureau of Standards to make a comparison on a considerable scale of two series of heats of rail steel, one being finished with additions of ferrosilicon and ferromanganese in the ladle without titanium additions and the other without ferrosilicon but with the ferromanganese split between the furnace and ladle and with ferrocarbon-titanium added in the ladle. The two series were otherwise as identical as commercial practice permits.

II. GENERAL PLAN OF INVESTIGATION.

The investigation was carried out with the cooperation of the Titanium Alloy Manufacturing Co., the Illinois Central Railroad Co., the Illinois Steel Co., and the Robert W. Hunt Co., and was

[1] Railway Age Gazette, Oct. 23, 1914, p. 750.

[2] Rail Reports Bulletins 1 to 8, inclusive. Titanium Alloy Manufacturing Co., Niagara Falls, N. Y.

planned on the basis of a study of manufacture, tests of A rails, and service results of 1,000 tons each of titanium-treated and silicon-treated steel.

1. MANUFACTURE OF THE STEEL.

Twenty heats of titanium-treated rail steel were made at Gary in February, 1921, for the Illinois Central Railroad Co., and within a few days 23 heats of silicon-treated steel were made in the same furnaces for the same road for comparison. Records on the practice of manufacture of this steel were taken by representatives of the Titanium Alloy Manufacturing Co. and the Bureau of Standards. The heats of titanium-treated and silicon-treated steel were distributed through the plants at Gary in practically the same way. The steel was made in 100-ton heats by the basic open-hearth process, using about 40 per cent cold steel scrap, the balance of the charge being pig iron, mostly liquid, including the recarburizer, which was added in the furnace just before tapping, in every heat.

The deoxidation practice was not the same for the two series of heats. In the titanium-treated heats about half (770 pounds, average) of the ferromanganese was added in the furnace before the recarburizer additions and the other half (920 pounds, average) was added in the ladle, with the ferrocarbon-titanium (700 to 1,200 pounds), no ferrocilicon being used in these heats. In the silicon-treated heats all the ferromanganese (1,450 pounds, average) and the ferrosilicon (600 pounds, average) were added in the ladle. The ladle additions were made partly by shoveling and partly through a chute, the titanium additions usually being divided between these methods. The ferromanganese added to the ladle in the titanium-treated heats was either shoveled in before the titanium or placed in the chute ahead of the titanium additions. The plan was to make 10 heats with about 10 pounds of ferrocarbon-titanium added per net ton of steel and 10 heats with 13 pounds per net ton, but through a misunderstanding the actual weights used were computed on a gross-ton basis, so that the heats with the smaller addition actually received 8.5 to 9.5 pounds per net ton and the other 10.5 to 12.4 pounds per net ton. One of the latter was rejected for rails because of improper chemical composition and was replaced by one of the former class, so that there were only 9 with the higher titanium additions and 11 with the lower.

TABLE 1.—Open-Hearth Furnace Data on 20 Titanium-

[Note.—Size of ingot molds 22¾ by 22¼ inches (Gary special). Teemed from 73 to 75 inches in

Heat No.	Shop No.	Furnace additions.							Time heat was tapped and date.	Ladle Additions.				
		Weight of scrap.	Weight of hot metal.	Weight of pig iron.	Weight of extra hot metal.	Weight of iron ore.	Weight of ferro-manganese.	Weight of recarburizer metal.		New or used ladle.	Weight of coke.	Weight of ferro-silicon.	Weight of ferro-manganese.	Weight of ferro-carbon-titanium.
		Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Feb. 26, 1921.		Lbs.	Lbs.	Lbs.	Lbs.
50066	4	79,400	110,000	Iron rolls 13,000	22,000	.....	.....	27,000	8.46 a. m.	.....	.....	.....	900	1,200
35087	3	86,700	104,100	.....	.....	3,500	800	27,000	9.15 a. m.	New..	.....	.....	800	900
62105	1	82,500	128,000	.....	25,000	.....	700	30,000	9.20 a. m.	Used..	200	.....	1,200	1,000
49115	4	78,000	119,200	Molds 11,000	12,000	.....	800	25,400	9.51 a. m.	.....	200	.....	900	1,170
31120	3	86,900	103,800	3,000	.....	7,000	800	26,000	10.11 a. m.	Used..	150	.....	800	900
58119	1	83,500	127,000	.....	.....	.....	700	28,000	10.12 a. m.	...do...	.....	.....	1,000	1,000
46124	4	83,900	87,400	Iron rolls 9,100	14,200	.....	800	23,700	10.24 a. m.	.....	250	.....	1,000	1,170
38110	3	96,400	87,300	10,000	Molds 8,500	3000	1,000	24,000	10.54 a. m.	Used..	50	.....	700	900
37102	3	79,700	109,500	.....	.....	3,000	1,000	26,000	11.56 a. m.	.....	.....	.....	700	900
51069	4	80,400	115,500	.....	.....	.....	800	[1] 28,000	12.16 p. m.	New..	50	.....	800	1,200
69117	1	82,600	128,000	.....	.....	.....	650	30,000	12.17 p. m.	Used..	.....	.....	1,200	1,000
43123	4	98,000	90,300	Iron rolls 10,000	.....	1,400	800	25,200	12.21 p. m.	.....	.....	.....	800	1,170
30115	3	74,400	101,100	Molds 14700	.....	6,000	800	25,000	1.05 p. m.	Used..	.....	.....	800	1170
36114	3	83,200	107,900	.....	.....	6,000	1,000	25,000	1.51 p. m.	...do...	.....	.....	800	900
59079	1	84,000	126,000	.....	.....	.....	600	30,000	2.09 p. m.	...do...	.....	.....	1,200	1,000
33106	3	74,200	116,200	.....	.....	9,000	800	24,000	3.00 p. m.	...do...	.....	.....	800	900
41113	3	50,800	80,100	Molds 34,300	.....	3,000	1,000	24,000	3.08 p. m.	...do...	.....	.....	600	1,170
54127	4	78,700	126,500	.....	.....	.....	800	[1] 30,000	3.13 p. m.	.....	100	.....	800	1,200
44120	4	77,900	115,800	.....	.....	.....	800	25,000	3.25 p. m.	.....	50	.....	800	1,170
29111	3	79,900	95,900	Molds 14,200	.....	.....	800	25,000	4.02 p. m.	Used..	100	.....	800	900
57106	1	85,900	91,000	33,200	.....	.....	.....	32,000	4.23 p. m.	...do...	.....	600	1,800	.....
50067	4	77,900	108,600	10,000	.....	.....	.....	27,200	6.40 p. m.	.....	150	600	1,400	.....
62106	1	89,200	96,500	24,300	.....	.....	.....	30,000	8.20 p. m.	Used..	350	700	1,700	.....
64091	1	85,100	92,000	33,000	.....	.....	.....	30,000	8.36 p. m.	...do...	.....	600	1,600	.....
42116	3	80,300	99,900	15,000	.....	.....	.....	35,000	9.07 p. m.	...do...	.....	550	1,300	.....
31121	3	92,700	99,600	3,000	10,500	.....	.....	32,000	9.09 p. m.	.....	.....	600	1,300	.....
58120	1	86,800	91,200	32,000 extra 4,000	15,000	.....	.....	30,000	9.13 p. m.	Used..	300	700	2,000	.....
38111	3	79,600	110,600	.....	.....	.....	.....	29,000	9.23 p. m.	...do...	.....	550	1,300	.....
49116	4	71,000	120,200	.....	.....	1,500	.....	25,500	9.38 p. m.	.....	100	600	1,400	.....
51070	4	80,600	111,000	12,500	.....	.....	.....	24,800	9.57 p. m.	.....	50	500	1,300	.....
37103	3	87,600	101,500	.....	.....	3,000	.....	28,000	10.45 p. m.	Used..	150	600	1,350	.....

[1] Estimated weight.

Treated and 23 Silicon-Treated Heats of Rail Steel.

height through a 2-inch nozzle. No internal mold wash used; stools slurried with a lime wash.]

Interval from tapping time to—						Ferrocarbon-titanium used per net ton of steel made.	Remarks.
Coke addition.	Ferrosilicon addition.	Ferromanganese addition.	Ferrocarbon-titanium addition.	Slag came.	Finish tapping.		
Min.	Min.	Min.	Min.	Min	Min.	Lbs.	
.....	.....	2	4	6	9	10.74	Ferrocarbon-titanium floater formed in ladle, but finally worked under before slag came; slag hot and wild.
.....	.....	1	3	5½	11½	8.54	Temperature hot; slag and reaction good; ladle additions good.
3	.....	2	2½	6	14	8.83	Temperature hot; slag normal; reaction mild; ladle additions good.
1	.....	4	4	.....	10	10.50	Temperature O. K.; slag normal; reaction mild.
2½	.....	2	4½	5	7	8.63	Temperature hot; slag normal; reaction mild; ladle additions good.
.....	.....	1	3	4	13	9.53	Do.
3	.....	7	7	10	13	12.00	Temperature O. K.; slag normal; reaction mild; small ferrocarbon-titanium floater in ladle.
2	.....	½	1½	2½	7½	9.33	Temperature very hot; slag thin; reaction violent; ladle additions good.
.....	.....	½	1½	3	4½	8.68	Temperature hot; slag normal; reaction mild; ladle additions good.
1½	.....	1	3	4	8	11.50	Temperature O. K.; slag lumpy in furnace; reaction mild; ladle additions good.
.....	.....	1	2	4	7	9.13	Temperature hot; slag normal; reaction mild; 100 pounds ferrocarbon-titanium floater; small boil on furnace bottom.
.....	.....	4	4	6	11	11.30	Temperature O. K.; slag normal; reaction mild; ladle additions good; heat broke out at tapping hole; part of ladle additions made before all recarburizer added.
.....	.....	1	2	4	11	11.11	Temperature hot; slag a little thin; reaction mild; 100 pounds ferrocarbon-titanium floater observed; caught by stream; was apparently all dissolved.
.....	.....	2½	3	4½	6½	9.31	Temperature hot; slag normal; reaction mild; 200 pounds ferrocarbon-titanium floater; not dissolved.
.....	.....	2	4	6	11½	9.16	Temperature O. K.; slag normal; reaction mild; ladle additions good.
.....	.....	2	4	5	7	9.31	Temperature hot; slag normal; reaction mild; ladle additions good.
.....	.....	½	2	4	7	12.38	Temperature hot; slag normal; reaction mild; 200 pounds ferrocarbon-titanium; floater undissolved.
½	.....	1	2½	3½	7	11.02	Temperature O. K.; slag good; reaction mild; ladle additions good.
5	.....	7	7	8	11	12.15	Temperature hot; slag normal; reaction mild; ladle additions good.
2	.....	2½	5	8	11	9.46	Temperature hot; slag a little thin; reaction mild; two 50-pound ferrocarbon-titanium floaters; undissolved.
.....	1½	1½	.....	3½	9	.....	Temperature hot; slag normal; reaction mild; ladle additions good.
4	5½	5	.....	11	15	.....	Temperature hot; slag normal; reaction mild; manganese floated but was dissolved by moving ladle.
2	4½	4½	.....	8	16	.....	Temperature hot; slag normal; reaction mild; ladle additions good.
.....	6½	6½	.....	12	17	.....	Temperature O. K.; slag normal; reaction mild; ladle additions good.
.....	4	4	.....	8	14	.....	Temperature hot; slag heavy; reaction mild; manganese floater observed, probably dissolved before slag came.
.....	1	1	.....	.....	8	.....	Temperature hot; slag normal; reaction mild; ladle additions good; strong reaction with recarburizer in furnace.
1	2½	2½	.....	8	14	.....	Temperature O. K.; slag thin; reaction mild; ladle additions good.
.....	2	2	.....	.....	6	.....	Temperature hot; slag good; reaction mild; ladle additions good.
1	1½	3½	.....	11	9	.....	Temperature hot; slag good; reaction mild; small manganese floater.
1	2	2	.....	4	7	.....	Temperature hot; slag good; reaction mild; ladle additions good.
8	1	6	.....	12	17	.....	Temperature very hot; slag thin; reaction mild; ladle additions good; strong reaction when recarburizer metal was added in furnace.

TABLE 1.—Open-Hearth Furnace Data on 20 Titanium-

Heat No.	Shop No.	Furnace additions. Weight of scrap.	Weight of hot metal.	Weight of pig iron.	Weight of extra hot metal.	Weight of iron ore.	Weight of ferro-manganese.	Weight of recarburizer metal.	Time heat was tapped and date.	Ladle additions. New or used ladle.	Weight of coke.	Weight of ferro-silicon.	Weight of ferro-manganese.	Weight of ferro-carbon-titanium.
		Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Feb. 26, 1921.		Lbs.	Lbs.	Lbs.	Lbs.
69118	1	86,100	93,000	31,000	28,000	.....	500	28,000	11.12 p. m.	Used..	150	700	1,700	.....
30116	3	79,200	102,300	Molds 10,700	8,500	.....	.....	30,500	11.51 p. m.	...do...	.....	600	1,300	.....
43124	4	100,400	96,000	16,400	.....	.....	.....	28,000	12.12 a. m.	.....	100	600	1,500	.....
45116	4	82,900	106,500	10,900	.....	.....	.....	26,000	1.10 a. m.	.....	50	500	1,400	.....
36115	3	88,000	101,000	.....	.....	1,500	.....	26,000	1.21 a. m.	Used..	50	600	1,300	.....
									Feb. 28, 1921.					
[2]33109	3	80,100	93,400	17,000	15,000	.....	.....	28,000	11.00 a. m.	.....	.....	500	1,400	.....
									Mar. 1, 1921.					
[2]69124	1	85,000	91,000	34,200	.....	.....	.....	28,000	10.20 a. m.	.....	350	600	1,600	.....
[2]43128	4	82,000	99,000	12,000	.....	.....	.....	28,000	10.41 a. m.	.....	150	550	1,300	.....
[2]51075	4	82,000	95,000	16,000	12,000	.....	.....	[1]28,000	11.30 a. m.	.....	100	550	1,300	.....
[2]45120	4	78,000	115,000	.....	.....	.....	.....	[1]28,000	11.35 a. m.	.....	.....	600	1,300	.....
[2]62112	1	84,900	99,000	26,300	15,000	.....	10 per cent FeSi 500	[1]28,000	11.40 a. m.	.....	.....	600	1,600	.....
[2]31126	3	75,500	98,000	16,100	10,000	.....	.....	26,500	11.45 a. m.	.....	150	500	1,400	.....

[2] Data compiled by R. W. Hunt & Co.

TABLE 2.—Teeming and Finishing Data on 20 Titanium-

[Note.—Size of ingot molds 22¾ by 22¾ inches (Gary special). Teemed from 73 to 75 inches in

Heat No.	Shop No.	Interval from tapping time to start of teeming.	Temperature of ingot molds.	Appearance of steel in molds.	Stopper shut-off and general teeming conditions.	Teeming time. Av. per ingot.	Teeming time. Total time per heat.	Total number of ingots teemed.
		Min.				Sec.	Min.	
50066	4	12 1/2	Cold...	Steel quiet; tops slightly concave.	Slight drips from stopper; small fingers of skull around nozzle.	50	22 1/2	25 1/2
35087	3	13 1/2	.....	Tops sank a little..	Incomplete shut-off from fifth to sixteenth ingots; remainder, good shut-off.	44	16 1/2	24 3/4
62105	1	15	Hot....	Twenty-sixth, twenty-seventh and twenty-eighth ingots boiled; remainder quiet, flat tops.	Light drips up to sixteenth ingot, then became heavier with spattery stream; smooth stream up to sixteenth ingot.	40	26	28 and B
49115	4	13	.....	.....	Good.....	52	18	25 and B
31120	3	13	.....	Tops good; sank a little.	Good shut-off throughout heat.....	42	20 1/2	25 and B
58119	1	16	Warm..	Last 6 ingots boiled little; remainder quiet, concave tops.	Clean shut-off and very smooth stream.	48	25	26 and B
46124	4	16	.....	.....	Good.....	58	21	22 and B
38110	3	11 1/2	Warm..	Tops good; sank a little.	Heavy drips on first 3 ingots; light drips on next 5; medium drips with light spray from eighth to fourteenth; stopper head-off at seventh; bad teeming from fifteenth; last 9 ingots rejected for rails.	45	23	23 and B

Treated and 23 Silicon-Treated Heats of Rail Steel—Continued.

Interval from tapping time to—						Ferrocarbon-titanium used per net ton of steel made.	Remarks.
Coke addition.	Ferrosilicon addition.	Ferromanganese addition.	Ferrocarbon-titanium addition.	Slag came.	Finish tapping.		
Min.	Min.	Min.	Min.	Min.	Min.	Lbs.	
1	2½	2½	.....	3½	9	.....	Temperature O. K.; slag normal; reaction mild; ladle additions good; heat broke out at tapping hole while recarburizer metal was being added.
.....	1	2	.....	.....	6	.....	Temperature hot; slag good; reaction mild; ladle additions good.
½	1	1	.....	6	7	.....	Do.
½	1	1	.....	6	9	.....	Do.
6	½	4	.....	8	15	.....	Do.
.....	.....	.....	.....	.....	5	.....	Do.
.....	.....	.....	.....	.....	11	.....	Temperature hot; slag normal; reaction mild; ladle additions good.
.....	.....	.....	.....	.....	9	.....	Do.
.....	.....	.....	.....	.....	9	.....	Temperature hot; slag good; reaction mild; ladle additions good.
.....	.....	.....	.....	.....	8	.....	Temperature hot; slag normal; reaction mild; ladle additions good.
.....	.....	.....	.....	.....	7	.....	Temperature too hot; slag normal; reaction mild; ladle additions good.
.....	.....	.....	.....	.....	9	.....	Temperature hot; slag good; reaction mild; ladle additions good.

Treated and 23 Silicon-Treated Heats of Rail Steel.

height through a 2-inch nozzle. No internal mold wash used; stools slurried with a lime wash.]

Teeming temperatures.			Skull in ladle.	Total ingot weight.	Ladle test analyses.					Number of rails rolled.	Cuts for flaws.	Seconds for flaws.	Scrap for flaws.	Number of piped rails.	Seconds and scrap for flaws.	Piped rails.
Av. of first 9 ingots.	Av. of second 9 ingots.	Av. of later part of heat.			C	Mn	P	S	Si							
°F.	°F.	°F.	Lbs.	Lbs.											P. ct.	P. ct.
.....	.....	.....	700	222,700	0.67	0.72	0.029	0.044	0.08	175	10	12	1	4	7.4	2.3
.....	.....	.....	Clean.	210,600	.74	.80	.036	.048	.08	172	9	8	1	13	5.2	7.5
.....	.....	.....	800	225,600	.68	.70	.029	.041	.05	196	8	6	0	0	3.0	0.0
.....	.....	.....	3,800	219,000	.70	.72	.026	.048	.07	175	8	9	1	3	5.7	1.7
.....	.....	2,729	Clean.	208,400	.65	.71	.035	.056	.06	175	9	12	4	3	9.1	1.7
.....	.....	.....	800	209,100	.70	.66	.026	.040	.06	182	7	22	6	4	15.4	2.1
.....	2,679	2,693	3,300	191,700	.69	.70	.018	.035	.07	154	2	6	1	1	4.5	0.7
2,776	2,780	2,720	Clean.	192,900	.73	.71	.031	.040	.05	98	6	9	1	2	10.2	2.0

TABLE 2.—Teeming and Finishing Data on 20 Titanium-

Heat No.	Shop No.	Interval from tapping time to start of teeming.	Temperature of ingot molds.	Appearance of steel in molds.	Stopper shut-off and general teeming conditions.	Teeming time. Av. per ingot.	Teeming time. Total time per heat.	Total number of ingots teemed.
		Min.				Sec.	Min.	
37102	3	9 1/2	Warm..	Tops good; sank a little.	Light drips on ingots 3, 4, 11, 12, 13, and 14; medium drips on ingots 5, 6, and 7; heavy drips on ingots 8, 9, and 10; smooth stream.	38	18	24 and B
51069	4	11	.....	Steel quiet; tops concave.....	Very slight drips from stopper; stream good.	45	22	24
69117	1	11 1/2	Warm..	Steel quiet; tops slightly concave.	Light drips up to tenth ingot; remainder ran briskly; smooth stream throughout.	45	22 1/2	26
43123	4	13	.....	Steel quiet.....	Good for first 18 ingots; remainder of heat stopper dripped.	46	21	24 and B
30115	3	12 1/2	Warm..	Tops sank a little; small spongy eruptions on surface.	Good shut-off throughout heat.....	40	19 1/2	25 and B
36114	3	11 1/2	.....	Tops good; sank a little.	Light drips from ingots 9 to 21; stopper head off at twenty-first ingot; 3 wood prickers used to open nozzle for teeming twenty-second ingot.	40	24	22 and B
59079	1	16	Warm..	Steel quiet; tops slightly concave.	Good, clean shut-off and smooth stream.	46	25	25
33106	3	12 1/2	...do....	Tops sank a little; small spongy-eruptions on surface.	Incomplete shut-off, with small drip on ingots 10 to 24.	40	17 1/2	23 3/4
41113	3	11	.....	Steel quiet; excessive concave tops.	Light running stopper throughout heat.	40	19	22 and B
54127	4	10	Warm..	Steel quiet; tops slightly concave.	Good shut-off first part; fairly strong running stopper toward end; good stream, except toward end.	46	21	24 3/4
44120	4	15	.....	.....	Good.....	51	25	23 and B
29111	3	13 1/2	.....	Ingots sank a little; with small spongy eruptions.	Incomplete shut-off, with light drips from 10th to end of heat; fifth ingot had large blister on top (center), caused by cold mold.	38	16 1/2	22 and B
57106	1	10	Warm..	First 12 ingots quiet, flat tops; remainder boiled badly.	Clean shut-off and smooth stream; last 16 ingots, bad spongy tops.	40	28	28
50067	4	20	.....	Ingots boiled a little at corners; tops flat.	Stopper head off; stream, cone shaped; first 3 ingots rejected; after third ingot stream a little better, but finger skull around nozzle.	50	23	23
62106	1	18	Warm..	All ingots boiled slightly; ingot tops convex.	Light drips throughout heat; smooth stream.	45	30	27 1/2
64091	1	18	...do....	Last 6 ingots boiled a little; remainder quiet; convex tops.	Very light drips throughout heat; smooth stream.	43	31	28 and B
42116	3	16	.....	.....	Clean shut-off from first to twenty-fourth; stopper head off on twenty-fourth ingot; 3 wood prickers used to open nozzle on twenty-fifth; this ingot rejected for rails.	45	31	25 and B
31121	3	10	.....	.....	Clean shut-off on all ingots.....	50	25	25 and B
58120	1	22	Warm..	Steel quiet; ingot tops flat.	Ladle opened up with wood pricker; very spattery stream up to fifth ingot; poor shut-off up to eighth; good shut-off from eighth to seventeenth; remainder almost full running stopper.	37	22	29

[1] Estimated weight.

Treated and 23 Silicon-Treated Heats of Rail Steel—Continued.

Teeming temperatures.			Skull in ladle.	Total ingot weight.	Ladle test analyses.					Number of rails rolled.	Cuts for flaws.	Seconds for flaws.	Scrap for flaws.	Number of piped rails.	Seconds and scrap for flaws.	Piped rails.
Av. of first 9 ingots.	Av. of second 9 ingots.	Av. of later part of heat.			C	Mn	P	S	Si							
°F.	°F.	°F.	Lbs.	Lbs.											P. ct.	P. ct.
2,734	2,736	2,724	Clean.	207,400	0.67	0.85	0.035	0.048	0.08	168	10	9	0	8	5.4	4.7
2,680	2,675	.....	2,000	206,600	.74	.83	.029	.043	.05	168	13	14	0	6	8.3	3.5
.....	.....	.....	Spots.	218,900	.73	.83	.022	.038	.05	182	14	9	2	4	6.0	2.2
.....	.....	.....	1,100	205,900	.70	.78	.033	.038	.07	168	13	23	1	2	14.2	1.2
2,709	2,712	2,687	Clean.	210,600	.68	.82	.034	.050	.07	175	10	23	0	9	13.1	5.1
.....	.....	.....	200	193,000	.66	.73	.027	.037	.05	154	8	12	2	10	9.1	6.5
2,700	2,678	2,652	1,500	217,000	.71	.77	.030	.050	.07	175	10	6	4	8	5.7	4.5
.....	.....	.....	Small.	193,200	.74	.88	.040	.055	.07	161	9	7	4	3	6.8	1.8
.....	.....	.....	1,000	188,000	.69	.76	.032	.054	.08	154	3	23	1	2	15.6	1.3
.....	.....	.....	2,700	215,100	.71	.77	.025	.040	.08	174	10	27	0	5	15.5	2.9
2,682	2,680	2,641	.....	192,600	.75	.76	.029	.041	.10	161	9	17	1	1	11.1	0.6
2,709	2,695	2,676	500	189,700	.70	.76	.027	.045	.09	154	5	9	1	4	6.5	2.6
.....	.....	.....	500	228,500	.69	.75	.031	.038	.18	195	6	15	2	0	8.7	0.0
.....	.....	.....	800	197,200	.68	.80	.033	.040	.19	140	5	11	2	0	9.3	0.0
.....	.....	.....	Clean.	230,200	.69	.67	.020	.035	.15	189	6	13	2	0	7.9	0.0
.....	.....	.....	1,000	238,900	.71	.67	.018	.045	.15	196	12	18	0	1	9.2	0.5
.....	.....	.....	1,000	206,500	.73	.80	.036	.050	.14	168	2	8	1	6	5.3	3.5
2,740	2,675	2,695	.....	213,600	.70	.76	.032	.037	.18	175	4	7	1	0	4.6	0.0
.....	.....	.....	2,000	243,100	.64	.66	.016	.037	.12	202	12	30	2	0	15.8	0.0

TABLE 2.—Teeming and Finishing Data on 20 Titanium-

Heat No.	Shop No.	Interval from tapping time to start of teeming.	Temperature of ingot molds.	Appearance of steel in molds.	Stopper shut-off and general teeming conditions.	Teeming time. Av. per ingot.	Teeming time. Total time per heat.	Total number of ingots teemed.
		Min.				Sec.	Min.	
38111	3	8	.....	Tops boiled a little from fifteenth to last.	Good.....	50	25	24 and B
49116	4	15	.....	Steel quiet; ingot tops flat.	Good shut-off; smooth stream.....	54	24	23 and B
51070	4	9 1/2	.....	Steel quiet; ingot tops convex.	.....do.....	52	25 1/2	24 and B
37103	3	20	.....	Ingot tops boiled slightly.	Clean shut-off on all ingots.....	50	25	23 and B
69118	1	10	Warm..	Steel quiet; ingot tops flat.	Light drips all through heat; smooth stream.	40	23	28 and B
30116	3	8	.....	A few of the ingots had boiled tops.	Clean shut-off on all ingots.....	55	23	23 and B
43124	4	10 1/2	.....	Steel quiet; ingot tops flat.	Good shut-off; smooth stream.....	50	26 1/2	26
45116	4	12	Cold...	.....do.....	Smooth stream up to middle of heat; after that slightly spattery stream, with fingers of skull forming around nozzle; running stopper after middle.	45	22	24 and B
36115	3	17	.....	.....	Clean shut-off on all ingots.....	50	27	24 and B
[2] 33109	3	11	.....	.....	Good; twenty-third ingot rejected for rails on account of bad teeming.	.....	24	25
[2] 69124	1	16	.....	.....	Good for first 11 ingots; remainder dripping stopper.	.....	34	27 3/4
[2] 43128	4	11	.....	.....	Good.....	.....	26	24 and B
[2] 51075	4	10	.....	.....	.....do.....	.....	23	25
[2] 45120	4	10	.....	.....	.....do.....	.....	24	24 and B
[2] 62112	1	10	.....	.....	Good for first 12 ingots; remainder light drips.	.....	28	29 3/4
[2] 31126	3	12	.....	.....	Good.....	.....	20	25

[2] Data compiled by R. W. Hunt & Co.

Treated and 23 Silicon-Treated Heats of Rail Steel—Continued.

Teeming temperatures.			Skull in ladle.	Total ingot weight.	Ladle test analyses.					Number of rails rolled.	Cuts for flaws.	Seconds for flaws.	Scrap for flaws.	Number of piped rails.	Seconds and scrap for flaws.	Piped rails.
Av. of first 9 ingots.	Av. of second 9 ingots.	Av. of later part of heat.			C	Mn	P	S	Si							
°F.	°F.	°F.	Lbs.	Lbs.											P. ct.	P. ct.
.....	.....	.....	Clean.	207,200	0.68	0.79	0.022	0.041	0.13	168	8	6	0	0	3.5	0.0
2,720	2,735	.....	Clean.	197,500	.69	.72	.024	.042	.20	161	9	13	0	1	8.1	0.6
.....	.....	.....	Clean.	201,600	.71	.69	.027	.038	.15	168	9	15	0	1	8.9	0.6
.....	.....	.....	Clean.	193,800	.72	.74	.025	.040	.17	157	11	16	2	0	11.4	0.0
.....	.....	.....	1,000	239,600	.67	.77	.028	.043	.18	193	3	5	0	0	2.5	0.0
.....	.....	.....	Clean.	194,400	.70	.73	.024	.041	.18	150	12	8	1	0	5.6	0.0
.....	.....	.....	Spots.	223,900	.67	.78	.029	.045	.17	182	4	9	1	2	5.5	1.1
.....	.....	.....	Spots.	201,300	.67	.84	.034	.056	.20	168	6	13	2	1	8.9	0.6
.....	.....	.....	Clean.	204,700	.63	.75	.024	.041	.18	77	5	4	0	0	5.2	0.0
.....	.....	.....	.....	210,700	.75	.70	.022	.044	.16	168	9	11	0	0	6.5	0.0
.....	.....	.....	.....	234,600	.65	.72	.024	.041	.19	193	5	7	1	0	4.1	0.0
.....	.....	.....	.....	206,600	.69	.74	.030	.040	.19	168	3	5	1	0	3.5	0.0
.....	.....	.....	.....	213,900	.73	.70	.026	.042	.18	175	8	7	1	0	4.5	0.0
.....	.....	.....	.....	203,600	.70	.73	.030	.042	.17	168	12	18	0	0	10.7	0.0
.....	.....	.....	.....	252,300	.63	.68	.024	.043	.16	206	15	26	0	0	12.6	0.0
.....	.....	.....	.....	208,300	.72	.67	.025	.047	.18	174	9	6	0	0	3.4	0.0

The steel of the tintanium-treated heats was held in the ladle from 8 to 12 minutes from the titanium treatment until the first ingot was poured, and the silicon-treated heats were held about the same length of time, counting from the manganese and silicon additions. None of the heats on which observations were made boiled very badly in the molds, but there were instances of slight boiling in the ingot tops, especially among the silicon-treated heats. Of the 17 observed treated heats 5, or 29 per cent, showed slight evidence of gas evolution upon solidification of the ingot tops, while of the 13 observed silicon-treated heats 7, or 54 per cent, showed more definite boiling on at least one of their ingots. In general, the conditions appeared good for all this steel.

The ingots were 22¾ inches square and 73 inches high, weighing about 8,000 pounds. It appears that the titanium-treated steel was poured slightly faster than the silicon-treated, the time per ingot averaging $44^3/_5$ seconds for the titanium-treated and 47¼ seconds for the silicon-treated ingots. Computing from the total time for teeming each heat and counting every butt and three-

fourths ingot as half an ingot, the time per ingot (including time for moving the ladle from one ingot to the next) averaged 52 seconds for the titanium-treated steel and 60 seconds for the silicon-treated. Computation of the total ingot weight poured and the total time of pouring gives a rate of 4.9 tons per minute for the titanium-treated steel and 4.2 tons per minute for the silicon-treated steel. All of these figures indicate that the titanium-treated steel was poured somewhat faster than the silicon-treated steel. Although no temperature determinations were taken on the silicon-treated steel the data on ladle skulls indicate that the silicon-treated steel, with an average skull of 400 pounds per heat, was somewhat hotter in the ladle than the titanium-treated steel, which left an average skull of 1,000 pounds per heat. The data on steel manufacture are given in detail in Tables 1 and 2.

Table 3 was constructed from the data in Tables 1 and 2, using the heats from which rails were used for physical tests. The ferrocarbon-titanium additions contain an average of 15.4 per cent titanium, and in this table the titanium content is assumed to be 15 per cent. Column A, the per cent of titanium in the heat, was computed from the actual weight of steel (the ingots and skulls) and the titanium additions. Column C is the per cent of total titanium found in the bottom ends of the A rails and is the average of the analyses from positions O and M, Figure 2. The last column, C/A, gives the per cent of titanium which remained in the steel.

TABLE 3.—Titanium Deoxidation.

Heat number.	Ferrocarbon-titanium added per ton.	Ferro-carbon-titanium added.[1]	Weight, ingots and skulls.	A	B	C	C/A
				Titanium in heat.	Titanium in test ingot.	Titanium in rail.[2]	Titanium remaining in the steel.
	Pounds.	Pounds.		Per cent.	Per cent.	Per cent.	Per cent.
62105	8–10	1,000	226,400	0.0662	0.0050	0.008	0.12
37102	8–10	900	207,400	.0651	.0117	.014	.22
37120	8–10	900	208,400	.0648	.0068	.014	.22
Average				.0654			.19
50066	10–12	1,200	223,400	.0806	.0142	.017	.21
43123	10–12	1,170	207,000	.0848	.0172	.028	.33
51069	10–12	1,200	203,600	.0863	.0145	.026	.30
49115	10–12	1,170	222,800	.0788	.0150	.034	.43
46124	10–12	1,170	195,000	.0900	.0136	.032	.36
Average				.0841			.33

[1] Assumed 15 per cent ferrocarbon-titanium is titanium.
[2] Average analyses for total titanium from positions O and M from bottom ends of A rails.

This shows that for steels treated with from 8 to 10 pounds of ferrocarbon-titanium per ton (average 0.0654 per cent titanium in the liquid) about 19 per cent of the titanium remains in the steel and 81 per cent goes into the slag; whereas for treatments of from 10 to 12 pounds per ton (average 0.0841 per cent titanium in the liquid) 33 per cent of the titanium remains in the steel and 67 per cent goes into the slag. It is seen that an average increase of 29 per cent of titanium in the ladle causes 73 per cent average increase of titanium in the steel. Thus it appears that small additions of titanium act primarily as a scavenger, while for larger amounts an appreciable portion remains in the steel. From analyses for gases (discussed later) it appears that small additions of titanium combine with the oxygen and may go to the slag, whereas for larger additions some combines with the nitrogen as a nitrogen compound of titanium and remains in the steel.

Table 4 was made from the data in Table 2 from 16 heats for which records of the amount of skulls remaining in the ladle were kept. This table shows that about 19 per cent of the silicon in the liquid steel goes to the slag and about 81 per cent remains in the finished steel.

TABLE 4.—Silicon Deoxidation.

Heat number.	Silicon (ladle analyses).	Ferro-silicon added.[1]	Weight of heat= total ingot weight and skull.	A / Silicon added.	Total silicon A+ average silicon in titanium-treated heats.[2]	Silicon to slag.
	Per cent.	Pounds.	Pounds.	Per cent.	Per cent.	Per cent.
57106	0.18	600	229,000	0.13	0.20	+0.02
50057	.19	600	198,000	.15	.22	.03
62106	.15	700	230,200	.15	.22	.07
64091	.15	600	239,900	.13	.20	.05
42116	.14	550	207,500	.13	.20	.06
31121	.18	600	213,600	.14	.21	.03
58120	.12	700	245,100	.14	.21	.09
38111	.13	550	207,200	.13	.20	.07
49116	.20	600	197,500	.15	.22	.02
51070	.15	500	201,600	.12	.19	.04
37103	.17	600	193,800	.15	.22	.05
69118	.18	700	240,600	.14	.21	.03
30116	.18	600	194,400	.15	.22	.04
43124	.17	600	233,900	.13	.20	.03
45116	.20	500	201,300	.12	.19	−.01
36115	.18	600	204,700	.14	.21	+.03
No skull record for last seven heats					av. .21	av. .04

[1] Assumed to be 50 per cent silicon.

[2] Average silicon in titanium-treated heats 0.07 per cent.

2. ROLLING OF RAILS.

The data on heating the ingots, rolling, rail inspection, and drop tests were obtained from the records of R. W. Hunt & Co. These records showed that the average time of heating the titanium-treated ingots was 3 hours and 18 minutes and the silicon-treated ingots 2 hours and 40 minutes. Thirteen of the 20 titanium-treated heats were in the pits three hours or more, while only 7 of the 23 silicon-treated heats were heated as long. This difference may have had some effect on the results.

The ingots were bloomed down to 8⅛ by 7⅞ inches in nine passes, and the top and bottom discards were then cut off and the bloom cut in two. The blooms were rolled immediately without reheating into 90-pound rails of the A. R. A. section 9020 in nine more passes. The upper bloom made the "A," "B," and "C" rails and the lower bloom the remainder. Accurate measurements were made of all discards from the thirteenth ingot of each heat, this being the ingot from which samples were taken from the ends of the A rails for testing purposes. The discard percentage, by weight, was computed for each heat and was about the same for both classes of steel, being about 13½ per cent at the top and 4½ per cent at the bottom, with variations between heats of about 1 per cent either way from these values.

Defects in blooming were reported in only two of the titanium-treated heats, Nos. 49115 and 38110, where a few of the ingots cracked and in seven of the silicon-treated heats where cracked or scabby ingots were seen. At the rail mill cobbles were made in three heats, as follows: Six on heat 50066, titanium treated; 4 on heat 37103, silicon treated; and 3 on heat 69118, silicon treated. Defects due to worn rolls were reported on 4 of the titanium-treated heats, and when the rolls were changed nearly all of the titanium-treated steel had been rolled. With practically fresh rolls available for the silicon-treated heats which followed, slightly defective sections were noted for 6 heats, and 3 others were reported a little cold when rolled. None of the A rails from these silicon-treated heats were used in physical tests. The above items were taken from the records of R. W. Hunt & Co.

3. INSPECTION OF RAILS.

The results of the inspection of rails for flaws show inferior results for the titanium-treated steel, both for surface defects and pipe. However, owing to the different conditions of the rolls and the longer period of soaking for the titanium-treated ingots, no conclusions are drawn as to the effect of titanium treatment on

the percentage of second quality rails, but a higher percentage of piped rails came from the titanium-treated than from silicon-treated steel. Although a titanium-treated steel that is thoroughly killed has a deeper pipe in the ingot than a steel which is not killed, certain other factors contribute. In Table 5 is given the average time of teeming the titanium-treated steel in the three open-hearth plants at Gary and the percentage of rails rejected for pipe.

TABLE 5.—Average Time of Teeming Titanium-Treated Steel in the Three Plants.

Plant number.	Average time of teeming one ingot.	Rails rejected for pipe.
	Sec.	Per cent.
2	41	3.7
1	45	2.2
3	50	1.9

The percentage of piped rails is seen to be less as the time of teeming increased. The higher percentages of piped rails from the titanium-treated steel, compared with the silicon-treated, appears to be due, in part, to the more rapid teeming of the titanium-treated heats as well as to its more thorough deoxidation. A comparison of the percentage of piped rails with the amount of ferrocarbon-titanium added does not show any definite relation. The heats receiving the most titanium gave the least pipe, while those receiving the least titanium gave the most pipe. Evidently variations in the amount of titanium used above the minimum in the treated heats did not affect the piping.

The pipes discussed above were those found in drilling bolt holes in the rails or visible at the ends of the rails or that caused blisters on their sides. This did not constitute a very thorough method of inspection for pipe, but the results should be fairly comparable considering the large number of rails inspected. The pipes found in drop-test fractures were not included in those discussed above.

4. DROP TESTS.

Drop tests were made according to the usual specifications on pieces cut from the top ends of the A rails from the second, thirteenth, and twenty-third (or last full) ingot of each heat. Rails from every alternate heat were tested with head or base in tension. The first test on a heat was made by repeated blows until fracture occurred, the permanent set and elongation being

measured. The second test was nicked after withstanding the first blow, so as to examine the fracture without delay. If either of these tests broke at the first blow or showed segregation in its fracture, the third test was nicked at once for fracture examination only. If pipes were discovered in the fractures, all the A rails from that heat were accepted only as "specials," and drop tests were made in the same way on the "B" rails. This occurred in only two heats, both titanium treated; all the rails except the A rails on these two heats were accepted as passing the drop test.

The results for permanent set and elongation did not show anything significant or interesting, but the summary of the other drop-test results showed superiority for the titanium-treated steel under the drop. This summary is given in Table 6.

TABLE 6.—Summary of Drop-Test Results.

Drop-test data.	Titanium-treated steel.		Silicon-treated steel.	
	No.	Per cent.	No.	Per cent.
Total number of heats	20	.....	23	.....
Total giving no breaks, unless nicked, and all clear fractures	9	45	5	22
Total number of A rails tested	60	.....	69	.....
Failures at second blow (unnicked)	4	7	11	16
Failures at third blow (unnicked)	10	17	12	17
Piped fractures	3	5	0	0
Segregated fractures	3	5	27	39

It is seen that the titanium-treated steel was harder to break and showed more uniform fractures than the silicon treated. However, none of the silicon-treated rails were segregated enough to break at the first blow, and since no penalty was attached to segregated fractures unless that occurred the actual commercial results of the drop tests were less satisfactory for the titanium-treated rails because of the three pipes found among their fractures.

5. MATERIAL AVAILABLE FOR LABORATORY TESTS.

The upper half of the broken drop-test pieces, and the A rails from the middle ingot of each heat were available. Thirteen such rails were used, 5 being treated with from 10 to 12 pounds of ferrocarbon-titanium per ton, 3 with from 8 to 10 pounds, and 5 were silicon treated. A length of 4½ feet from the top and bottom ends of the 13 A rails were used for various laboratory tests, leaving 24 feet for service tests. Sections were taken from the upper half of the broken drop-test pieces for analyses, hardness tests, and sulphur prints. The sulphur printing and chemical analysis was done by the Titanium Alloy Manufacturing Co., and the hardness survey was made on the sulphur print section later at the Bureau

of Standards. The 4½-foot sections were taken from the top ends of the A rails and used for etching, endurance, impact, tensile testing, sulphur printing, and hardness survey. The sulphur printing and endurance testing were done by the Titanium Alloys Manufacturing Co., and the etching, impact, tensile, and hardness testing were done at the Bureau of Standards. The 4½-foot sections from the bottom of these rails were used for similar tests, except that no endurance tests were made on specimens from this end of the rails and chemical analyses were made by both the Titanium Alloy Manufacturing Co. and the Bureau of Standards.

The 4½-foot pieces used for tests have been identified in all cases with letters as shown in Table 7.

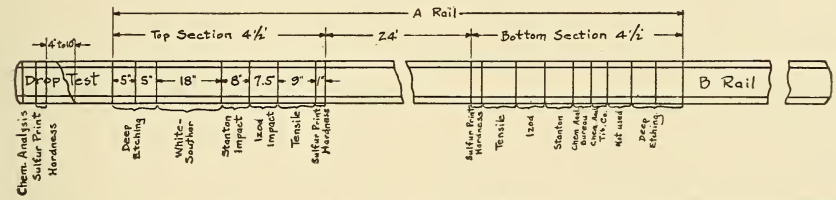


FIG. 1.—*Positions of sections from the top and bottom ends of A rails, from which samples for laboratory tests were taken as indicated; and location of drop-test samples.*

TABLE 7.—Identification of 4½-foot Samples.

Heat number.	Ferro-carbon-titanium used per ton.	Sample letter.	
		Top end of rail.	Bottom end of rail.
	Pounds.		
31121	None.	A	B
42116	None.	C	D
50067	None.	E	F
57106	None.	G	H
62106	None.	I	J
31120	8.63	K	L
37102	8.68	M	N
62105	8.83	Y	Z
43123	11.30	O	P
46124	12.00	Q	R
49115	10.50	S	T
50066	10.74	U	V
51069	11.50	W	X

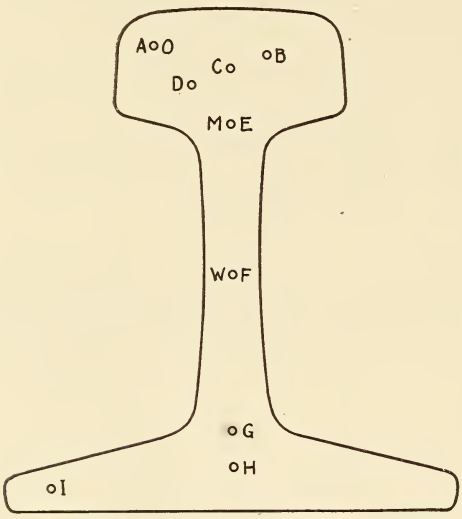
The specimens taken from the top and bottom samples of the A rails for various tests are referred to by the letters according to the plan of Table 7.

III. LABORATORY TESTS.

Sections from which the test specimens were made were taken from the top and bottom pieces of the A rails used for tests as shown in Figure 1.

1. CHEMICAL ANALYSES.

Analyses were made of test ingot drillings from all the heats for carbon, manganese, phosphorus, sulphur, and silicon by the manufacturers and for titanium by the Titanium Alloy Manufacturing Co. Analyses were made by the Titanium Alloy Manufacturing Co. of the drop test pieces, the drillings being taken at the O, M, and W positions, as indicated in Figure 2; the first two were taken with a ⅝-inch drill and the last with a ½-inch drill. Complete analyses, including titanium, were made of all samples from the heats used for physical tests, except that manganese, silicon, and titanium were not determined upon the web samples. The drop-test pieces from the other heats were anlayzed for carbon and titanium at the O and M positions and for carbon only in the web. The samples taken from the drop-test pieces were considered near enough to the top end of the A rails, so that the results of the analyses represent sufficiently the composition of the top ends.



BRINELL IMPRESSIONS—A, B, C, D, E, F, G, H, I
CHEMICAL ANALYSIS—O, M, W

FIG. 2.—*Location of positions where hardness tests and chemical analyses were made.*

Complete analyses were made by the Titanium Alloy Manufacturing Co. and the Bureau of Standards of drillings from the bottom ends of all the A rails used for mechanical tests.

(*a*) TEST INGOT DRILLINGS.—The average results of the analyses of the test ingot drillings for titanium-treated and silicon-treated steel, with the maximum and minimum values, are given in Table 8.

TABLE 8.—Average Analyses of Test Ingot Drillings.

	C			Mn			P			S			Si		
	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.
Titanium treated	0.70	0.75	0.65	0.76	0.88	0.66	0.030	0.040	0.018	0.045	0.056	0.035	0.07	0.10	0.05
Silicon treated	.69	.75	.63	.73	.84	.66	.026	.036	.016	.042	.050	.035	.17	.20	.12

These two average analyses for the titanium-treated and silicon-treated heats are nearly identical, except for silicon. All of the other elements averaged a little higher in the titanium-treated heats.

(*b*) Drop-Test Pieces.—Table 9 gives the results of carbon determinations on each drop-test piece from the A rails at the O, M, and W positions. The percentage of segregation was computed by dividing the difference between the O value and the M or W (whichever showed the greater difference) by the O value.

TABLE 9.—Carbon Determinations on Drop-Test Pieces From Top of A Rails.

Titanium-treated heats.						Silicon-treated heats.				
Heat number.	Titanium average at O and M.	Carbon at positions—			Segregation of carbon.	Heat number.	Carbon at positions—			Segregation of carbon.
		O	M	W			O	M	W	
					Per cent.					Per cent.
29111 [1]	0.0136	0.75	0.80	0.73	6.7	30116	0.75	0.83	0.81	10.7
31120 [1]	.0086	.70	.69	.67	−4.3	31121	.73	.80	.90	23.3
33106 [1]	.0154	.75	.83	.77	10.7	33109	.75	.76	.80	6.7
35087 [1]	.0083	.72	.69	.70	−4.2	36115	.67	.68	.70	4.5
37102 [1]	.0096	.73	.71	.64	−12.3	37103	.75	.91	.90	21.3
38110 [1]	.0072	.76	.72	.70	−7.9	38111	.68	.76	.80	17.7
58119 [1]	.0044	.74	.74	.78	5.4	42116	.74	.87	.84	17.6
59079 [1]	.0065	.77	.79	.78	2.6	43124	.71	.73	.72	2.8
62105 [1]	.0042	.69	.77	.73	11.6	43128	.72	.75	.77	6.9
69117 [1]	.0076	.75	.81	.80	8.0	45116	.68	74	.75	10.3
Average	.0085	.736	.755	.730	7.37	49116	.71	.79	.78	11.2
						50067	.73	.82	.82	12.3
Average of O, M, W			.740		.....	51070	.72	.79	.85	18.1
						51075	.73	.88	.86	20.5
30115	.0192	.71	.75	.72	5.7	57106	.70	.76	.78	11.4
41113	.0151	.75	.76	.72	4.0					
43123	.0244	.75	.77	.79	5.3	58120	.63	.67	.71	12.7
44120	.0172	.78	.71	.72	−9.0	62106	.67	.87	.85	29.8
46124	.0226	.72	.71	.72	−1.4	64091	.73	.81	.82	12.3
						69118	.69	.74	.72	7.2
49115	.0233	.73	.74	.73	1.4	69124	.64	.77	.78	21.9
50066	.0145	.71	.70	.71	−1.4					
51069	.0180	.78	.75	.79	−3.8					
54127	.0167	.70	.70	.69	−1.4					
Average	.0190	.737	.732	.732	3.71		.706	.786	.789	13.96
Average of O, M, W			.734		.....			.760		.....

[1] Less than 10 pounds ferrocarbon-titanium per ton was used in these heats.

TABLE 10.—Chemical Composition of Rails Tested Physically.

Heat No.	Ferrocarbon-titanium per ton.	Position.	Drop-test pieces representing top ends of A rails.						Bottom ends of A rails.							Segregation of C.	
			C	Mn	P	S	Si	Ti (insoluble).	C	Mn	P	S	Si	Ti (insoluble).	Ti (total).[1]	Bottom.	Top.
																Per ct.	Per ct.
31121	None	O	0.73	0.79	0.018	0.030	0.155	.....	0.76	0.75	0.030	0.033	0.132	0.0025	.....	11.8	23.3
		M	.80	.79	.018	.028	.164	.....	.85	.79	.035	.039	.137	.0015			
		W	.90	.....	.036	.044	.....	.....	.83	.....	.033	.035	.....	.....			
42116	do	O	.74	.81	.024	.033	.178	.....	.74	.79	.035	.043	.186	.0030	.....	9.5	17.6
		M	.87	.85	.033	.041	.198	.....	.81	.82	.039	.045	.186	.0030			
		W	.84	.....	.036	.041	.....	.....	.80	.....	.036	.033	.....	.....			
50067	do	O	.73	.79	.021	.050	.183	.....	.71	.77	.023	.037	.178	.0010	.....	14.0	12.3
		M	.82	.84	.019	.050	.190	.....	.79	.80	.024	.043	.183	.0015			
		W	.82	.....	.021	.038	.....	.....	.81	.....	.026	.036	.....	.....			
57106	do	O	.70	.83	.028	.040	.183	.....	.70	.79	.027	.034	.186	.0015	.....	10.0	11.4
		M	.76	.83	.029	.038	.174	.....	.75	.80	.023	.035	.180	.0015			
		W	.78	.....	.027	.044	.....	.....	.77	.....	.034	.030	.....	.....			
62106	do	O	.67	.68	.010	.020	.127	.....	.72	.68	.018	.037	.117	.0010	.....	15.3	29.8
		M	.87	.73	.022	.043	.113	.....	.83	.69	.023	.045	.118	.0010			
		W	.85	.....	.016	.033	.....	.....	.77	.....	.024	.034	.....	.....			
	Averages		.792	.794	.0239	.0382	.1665	.....	.776	.768	.0287	.0373	.1603	.00165	.....	12.12	18.5
31120	8 to 10 pounds	O	.70	.73	.028	.053	.071	0.0090	.71	.74	.035	.048	.077	.0090	0.0150	5.7	4.3
		M	.69	.72	.024	.051	.084	.0082	.75	.77	.036	.060	.077	.0090	.0140		
		W	.67	.....	.023	.054	.....	.....	.71	.....	.036	.044	.....	.....	.....		
37102	do	O	.73	.89	.030	.046	.098	.0100	.72	.87	.038	.042	.096	.0080	.0150	6.9	12.5
		M	.71	.89	.028	.043	.094	.0090	.77	.86	.041	.045	.103	.0075	.0120		
		W	.64	.....	.029	.034	.....	.....	.77	.....	.033	.041	.....	.....	.....		
62105	do	O	.69	.73	.019	.024	.065	.0051	.69	.71	.024	.034	.070	.0050	.0110	17.4	11.6
		M	.77	.75	.015	.030	.071	.0032	.81	.73	.023	.043	.071	.0025	.0060		
		W	.73	.....	.028	.031	.....	.....	.79	.....	.017	.033	.....	.....	.....		
	Averages		.703	.785	.0250	.0407	.0805	.00742	.747	.780	.0315	.0433	.0824	.00683	.0122	10.0	9.4

43123	10 to 13 pounds	O	.75	.85	.026	.020	.117	.0255	.74	.82	.028	.032	.115	.0215	.028	5.3	5.3
		M	.77	.85	.020	.027	.110	.0233	.79	.84	.027	.037	.113	.0190	.028		
		W	.79	.....	.028	.042	.....	.....	.81	.....	.029	.044	.....	.....	.....		
46124	do	O	.72	.69	.012	.035	.056	.0235	.69	.70	.014	.031	.050	.0205	.033	14.5	1.4
		M	.71	.69	.015	.032	.061	.0216	.76	.69	.016	.033	.061	.0205	.032		
		W	.72	.....	.011	.027	.....	.....	.79	.....	.016	.027	.....	.....	.....		
49115	do	O	.73	.76	.018	.029	.089	.0241	.74	.74	.023	.041	.110	.0205	.035	4.1	1.4
		M	.74	.75	.018	.028	.095	.0225	.76	.75	.030	.046	.092	.0220	.032		
		W	.73	.....	.017	.031	.....	.....	.77	.....	.018	.035	.....	.....	.....		
50066	do	O	.71	.71	.023	.045	.079	.0148	.71	.69	.028	.039	.076	.0140	.022	5.6	1.4
		M	.70	.73	.023	.048	.074	.0142	.74	.71	.029	.042	.078	.0090	.012		
		W	.71	.....	.024	.040	.....	.....	.75	.....	.026	.035	.....	.....	.....		
51069	do	O	.78	.83	.028	.038	.081	.0180	.76	.80	.021	.041	.082	.0175	.026	11.8	3.8
		M	.75	.84	.018	.040	.084	.0180	.85	.82	.031	.044	.082	.0155	.026		
		W	.79	.....	.016	.034	.....	.....	.79	.....	.032	.038	.....	.....	.....		
	Averages		.740	.770	.0197	.0344	.0846	.02055	.763	.756	.0245	.0377	.0859	.01800	.0274	8.26	2.66

[1] Determinations for total titanium were made only on samples from the bottom ends of rails tested physically.

These results show that titanium reduces segregation in the drop-test pieces taken from the tops of the A rails, for only 1, or 5.3 per cent, of the titanium-treated rails showed as much as 12 per cent segregation of carbon, while 11, or 55 per cent, of the silicon-treated showed more than that amount. Only 1, or 11.1 per cent, of the heats treated with over 10 pounds ferrocarbon-titanium per ton showed over 6 per cent segregation, while all but 2, or 90 per cent, of the silicon-treated heats showed more than this amount. It should also be noted that the small segregation, 3.71 per cent on the average, for heats treated with 10 to 13 pounds of ferrocarbon-titanium per ton is distributed about equally between positive and negative values, as compared with an average of 13.86 per cent, all positive, for segregation in the drop-test pieces of the silicon-treated heats.

(*c*) Bottom Ends of A Rails.—Complete analyses were made on rail sections used for mechanical tests. These samples came from the drop-test pieces, representing the top ends of A rails, and from the bottom ends of the A rails. Table 10 gives these analyses and the per cent of carbon segregation in samples from the top and bottom ends of these rails.

The effect of titanium is very marked in reducing segregation near the top of the ingot, and this improvement is approximately proportional to the titanium addition (see Table 9), but this effect of titanium appears to fall off very rapidly, as shown by a comparison of carbon segregation at the top and bottom of the A rails (see Table 10). Thus it is seen that there is not as much difference in the segregation of carbon between the titanium-treated and silicon-treated heats at the bottom of the A rails as there was at the top, represented by the drop-test pieces. The average segregation at the bottom for the silicon-treated heats is 12.1 per cent, for heats treated with less than 10 pounds of ferrocarbon-titanium per ton 10 per cent, and for heats treated with over 10 pounds per ton 8.3 per cent; whereas at the top the respective percentages are 18.9, 9.4, and 2.7. The other elements did not segregate as much as the carbon, and the titanium treatment appears to influence their segregation but little more than the silicon treatment.

The phosphorous contents for titanium-treated and silicon-treated steel were consistently higher at the bottom ends than at the top ends of the A rails. The titanium content was usually higher

at the O position than at the M position and generally slightly higher in the drop-test piece than in the bottom of the A rails, or in the ladle-test ingots, indicating that this element tends to rise to the top of the ingot, but does not segregate toward the center of the section. Nickel was looked for in these analyses, but none was detected. The analyses from the bottoms of the A rails show that there were no important differences in composition between the three classes of samples used for mechanical tests. The silicon-treated samples were, of course, considerably higher in silicon, and the samples treated with from 8 to 10 pounds ferro-carbon-titanium per ton were slightly lower in carbon and higher in phosphorus and sulphur than the others.

(*d*) Gas Analysis.—Samples from the top ends of the 13 A rails tested mechanically were analyzed for nitrogen by the Allen method,[3] and some of these specimens were checked by the use of hydrofluoric acid in the solution of the steel samples. Specimens from both the top and bottom ends of one rail of each type were analyzed for oxygen and hydrogen by the graphite fusion method [4] instead of the Goerens antimony-tin alloy vacuum fusion method, because the latter is not satisfactory for steel having as high carbon content as these rails. These results, together with the per cent of residual insoluble titanium at positions O and M (fig. 2) from both the top and bottom ends of the A rails and the total titanium from the bottom ends, are given in Table 11. The table is arranged in the order of increasing total residual titanium.

In general, the nitrogen determined by the Allen method decreased as the residual titanium in the steel increased. This may be interpreted as meaning that less nitrogen is combined with iron and manganese in the steel as the residual titanium becomes greater. It does not mean that the nitrogen has been eliminated from the metal, since tests made in the course of these determinations have shown that any nitrogen combined with either titanium or silicon is not detected by the usual method of analysis.

The use of hydrofluoric acid in the solution of the steel samples does permit the determination of at least a part of the nitrogen combined with titanium and silicon. Analysis of the titanium-treated rails by such a method shows them to contain much more nitrogen than is determined by the Allen method.

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[3] B. S. Sci. Paper No. 457.

[4] Recently developed at the Bureau of Standards and will be published shortly.

The addition of ferrocarbon-titanium to these rail steels has decreased the amount of nitrogen combined with iron and manganese. The nitrogen thus taken up by titanium is apparently in part retained in the metal as a nitrogen compound of titanium. The total amount of combined nitrogen in steel treated with 8 to 9 pounds of ferrocarbon-titanium per ton is as high as the silicon-treated steel. Steels treated with 10 to 12 pounds per ton contain less total combined nitrogen than the silicon-treated steels or those treated with the smaller amounts of ferrocarbon-titanium.

As stated above, the values for oxygen and hydrogen were obtained by fusion of the steel samples in vacuo in graphite crucibles. This method probably determines oxygen of silica inclusions in a steel in addition to oxides of iron, manganese, and carbon. It is doubtful whether the method at the temperature employed—namely, 1,450° C.—does reduce oxygen in titanium oxide inclusions, and at present it is possible to assume that any apparent reduction of oxygen in the steel by the additions of titanium is due to the formation of titanium oxides at the expense of the oxygen of iron, carbon, manganese, and silicon oxides, but that this oxygen may still be present in the metal as titanium oxide inclusions.

The results for oxygen in Table 11 show there is an immediate and appreciable drop in the amounts of oxides reducible by carbon on the addition of ferrocarbon-titanium in the proportion of 8 to 10 pounds per ton. After the addition of ferrocarbon-titanium in amounts of 10 to 12 pounds per ton, oxides reducible by carbon are entirely lacking. The effect of titanium additions on the oxygen content of the steels is apparently more immediate than is the effect of the same additions on the nitrogen. Addition of 10 to 12 pounds of ferrocarbon-titanium completely absorbs the oxygen, but still leaves 0.001 to 0.002 per cent nitrogen determinable by the Allen method.

2. SULPHUR PRINTS AND ETCHED SECTIONS.

Sulphur prints were made of cross sections of all the drop-test pieces near the crop end of the rail bar and of the top and bottom ends of the A rails, as shown in Figure 1. The outstanding features revealed by the sulphur prints of sections of all the drop-test pieces and sections from the top and bottom of the A rails used for mechanical tests are summarized in Table 12.

TABLE 11.—Residual Titanium and Gas Content of A Rails Used in Laboratory Tests.

A rail specimens.		Ferro-carbon-titanium added per ton.	Residual titanium.									Nitrogen, top of rail, Allen method.	Nitrogen, top of rail, hydrofluoric method.	Oxygen.		Hydrogen.	
			Top insoluble.			Bottom insoluble.			Bottom total.								
Top end.	Bottom end.		Position M.[1]	Position O.[1]	Average.	Position M.	Position O.	Average.	Position M.	Position O.	Average.			Top.	Bottom.	Top.	Bottom.
		Lbs.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
A	B	None.	0.0015	0.0020	0.0018	0.0015	0.0025	0.0020	.....	.....	.....	0.0036	0.0038	.....	.....	.....	.....
C	D	None.	.0014	.0019	.0016	.0030	.0030	.0030	.....	.....	.....	.0045	.0104	.....	.....	.....	.....
E	F	None.	.0020	.0020	.0020	.0015	.0010	.0012	.....	.....	.....	.0046	.....	.....	.....	.....	.....
G	H	None.	.0015	.0020	.0018	.0015	.0015	.0015	.....	.....	.....	.0046	.....	.....	.....	.....	.....
I	J	None.	.0010	.0015	.0012	.0010	.0010	.0010	.....	.....	.....	.0046	.....	0.0027	0.0048	0.0003	Nil.
Y	Z	8.83	.0032	.0051	.0042	.0025	.0050	.0038	0.0060	0.0110	0.0085	.0049	.0098	.....	.....	.....	.....
M	N	8.68	.0092	.0100	.0096	.0075	.0080	.0078	.0120	.0150	.0135	.0028	.....	.....	.....	.....	.....
K	L	8.63	.0082	.0090	.0086	.0090	.0090	.0090	.0140	.0150	.0145	.0028	.....	.0020	.0010	.0002	Nil.
U	V	10.74	.0142	.0148	.0145	.0090	.0114	.0102	.0120	.0220	.0170	.0034	.0064	.....	.....	.....	.....
W	X	11.50	.0180	.0180	.0180	.0155	.0175	.0168	.0260	.0260	.0260	.0017	.....	Nil.	Nil.	Nil.	Nil.
O	P	11.30	.0233	.0255	.0244	.0190	.0215	.0203	.0280	.0280	.0280	.0016	.....	.....	.....	.....	.....
Q	R	12.00	.0216	.0235	.0225	.0205	.0205	.0205	.0320	.0330	.0325	.0011	.0031	.....	.....	.....	.....
S	T	10.50	.0225	.0241	.0233	.0220	.0205	.0212	.0320	.0350	.0335	.0012	.....	.....	.....	.....	.....

[1] See Fig. 2.

TABLE 12.—Summary of Results Shown by Sulphur Prints.

Ferrocarbon-titanium used per ton.	Location of section.	Total samples.	Segregation shown on sulphur prints.							
			Serious.		Slight.		None.		Negative.	
		No.	No.	Per cent.	No.	Per cent.	No.	Per cent.	No.	Per cent.
None	Drop-test piece	20	8	40	11	55	1	5	0	0
	Top of A rail	5	3	60	1	20	1	20	0	0
	Bottom of A rail	5	0	0	3	60	2	40	0	0
8 to 10 pounds	Drop-test piece	10	0	0	2	20	4	40	4	40
	Top A rail	3	0	0	1	33	0	0	2	67
	Bottom A rail	3	0	0	0	0	3	100	0	0
10 to 13 pounds	Drop-test piece	9	0	0	0	0	3	33	6	67
	Top A rail	5	0	0	0	0	3	60	2	40
	Bottom A rail	5	0	0	0	0	5	100	0	0

As indicated in Table 12, none of the titanium-treated samples and none of the samples from the bottoms of the A rails were seriously segregated and none of the silicon-treated samples showed negative segregation of sulphur. All of the samples from the bottom ends of the A rails gave uniform sulphur prints except three out of five silicon treated which showed slight segregation at this distance below the top of the ingot. Figures 3 to 14, inclusive, are sulphur prints from the drop-test pieces and pieces from the top and bottom ends of the A rails. There is a decided difference between the prints of the titanium-treated and silicon-treated rails. Of all the silicon-treated samples, 87 per cent showed serious or slight segregation, while 91 per cent of all the titanium-treated samples, or 100 per cent of those treated with over 10 pounds of ferrocarbon-titanium per ton, showed either uniform sulphide distribution or negative segregation.

Horizontal sections for etching were cut parallel to and one-half inch below the top of the head of pieces from the top and bottom ends of the A rail samples only, none of the drop-test pieces being tested in this way. The sections were first etched in copper ammonium chloride. The only defects revealed were slight longitudinal streaks in silicon-treated samples G, I, and J and in titanium-treated samples W and Y. From the sulphur prints such streaks would be expected in all these samples except W. Sample Y was from a heat that received less than 10 pounds of ferrocarbon-titanium per ton. It showed low titanium content on analysis and slight segregation in its sulphur print. Figure 15 shows macrographs of some sections etched in this manner.

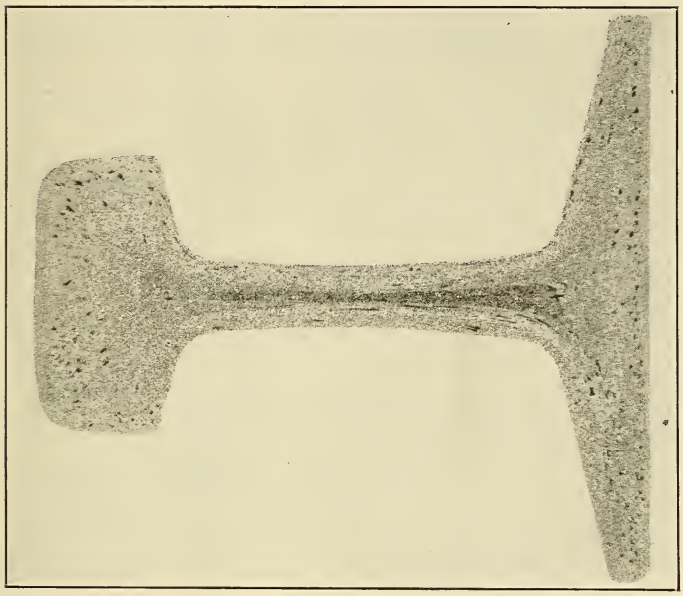

FIG. 4.—*Sulphur print of drop-test piece, showing slight segregation, from the middle ingot of a silicon-treated heat.*

Carbon: Position O (fig. 2), 0.75 per cent; position M, 0.83 per cent; segregation M over O=10.7 per cent.

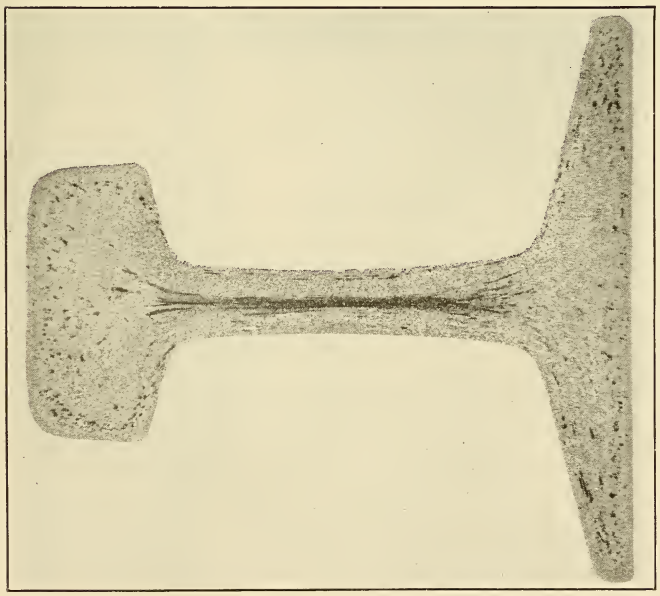

FIG. 3.—*Sulphur print of drop-test piece, showing serious segregation, from the middle ingot of a silicon-treated heat.*

Carbon: Position O (fig. 2), 0.73 per cent; position W, 0.82 per cent; segregation W over O=12.3 per cent.

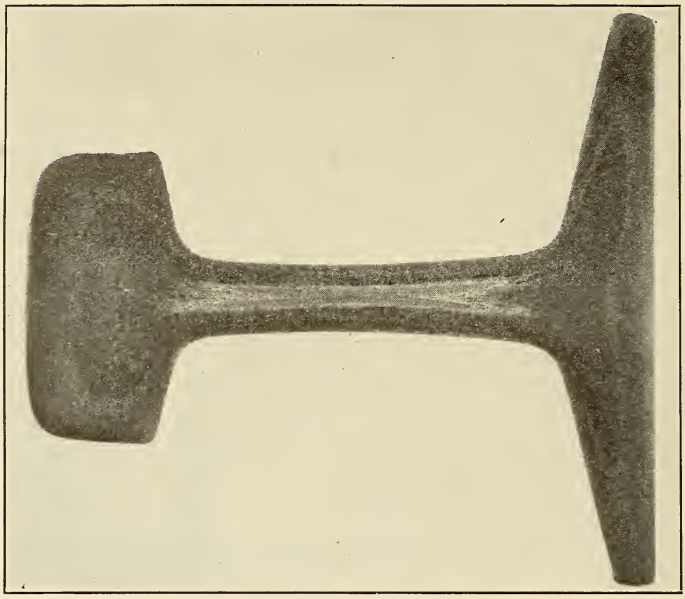

FIG. 6.—*Sulphur print of drop-test piece, showing negative segregation, from middle ingot of heat treated with 8.63 pounds F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.70 per cent; position M, 0.69 per cent; segregation M over O= −4.3 per cent.

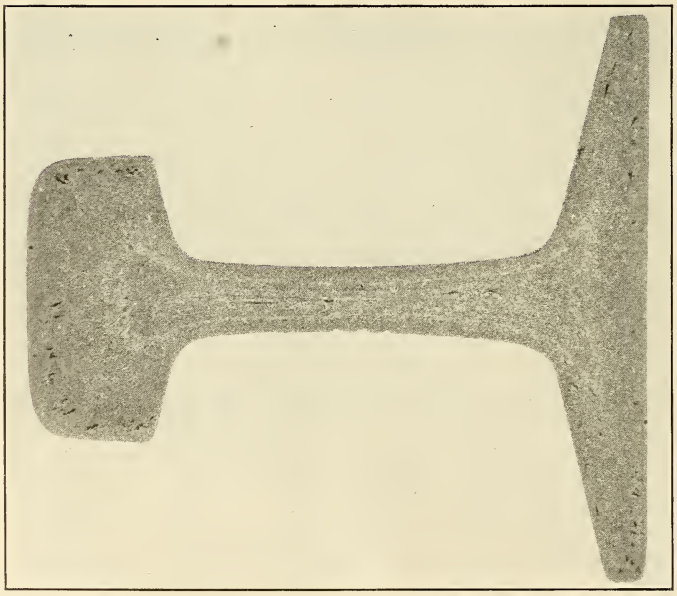

FIG. 5.—*Sulphur print of drop-test piece, showing slight segregation, from the middle ingot of heat treated with 9.53 pounds F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.74 per cent; position W, 0.78 per cent; segregation W over O=5.4 per cent.

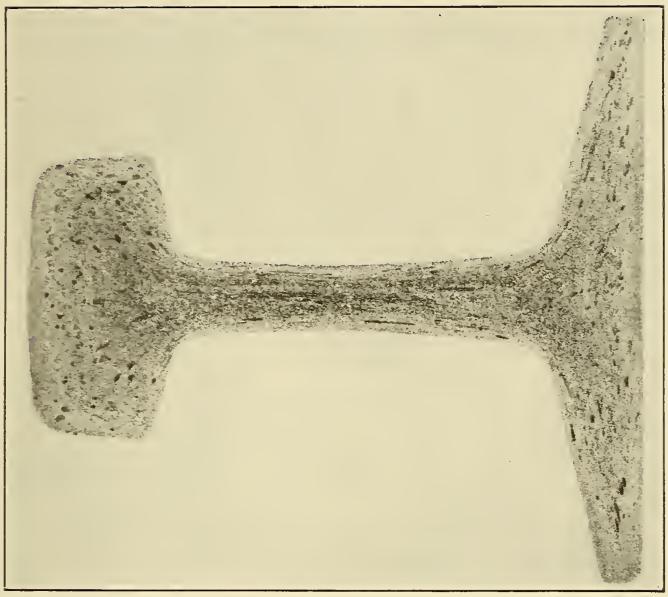

FIG. 8.—*Sulphur print of Section I from top end of A rail, showing serious segregation, from the middle ingot of silicon-treated heat 62106.*

Carbon: Position O (fig. 2), 0.67 per cent; position M, 0.87 per cent; segregation M over O=29.8 per cent.

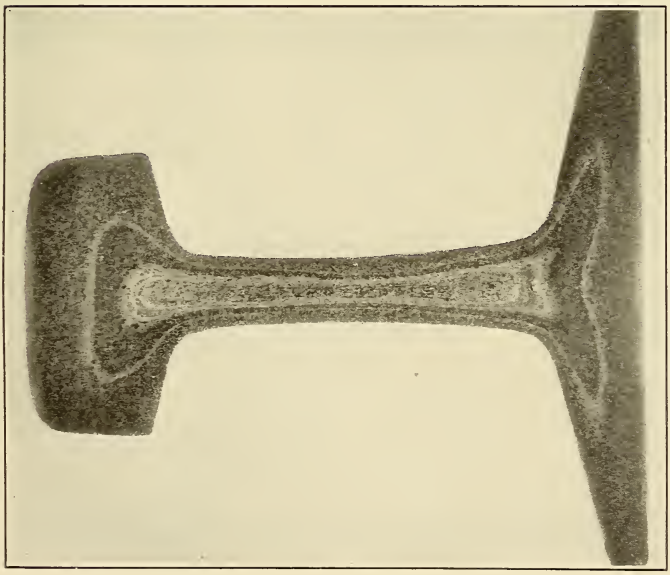

FIG. 7.—*Sulphur print of drop-test piece, showing negative segregation, from middle ingot of heat treated with 12.15 pounds F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.78 per cent; position M, 0.71 per cent; segregation M over O= −9.0 per cent.

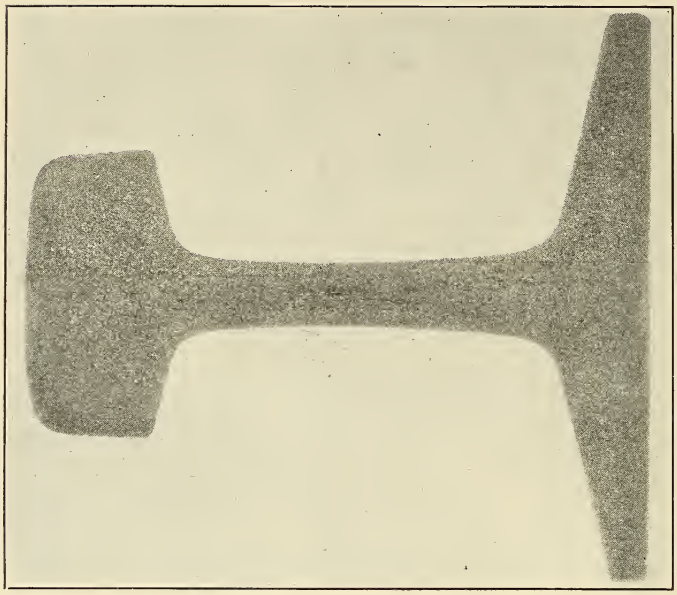

FIG. 10.—*Sulphur print of Section Y from top end of A rail, showing slight segregation, from the middle ingot of heat 62105 treated with 8.83 pounds of F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.69 per cent; position M, 0.77 per cent; segregation M over O=11.6 per cent.

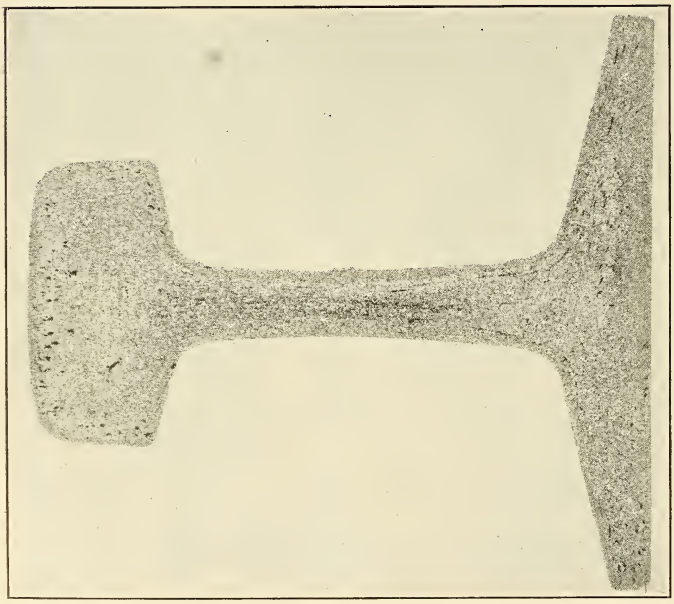

FIG. 9.—*Sulphur print of Section A from top end of A rail, showing slight segregation, from the middle ingot of silicon-treated heat 31121.*

Carbon: Position O (fig. 2), 0.73 per cent; position W, 0.90 per cent; segregation W over O=23.3 per cent.

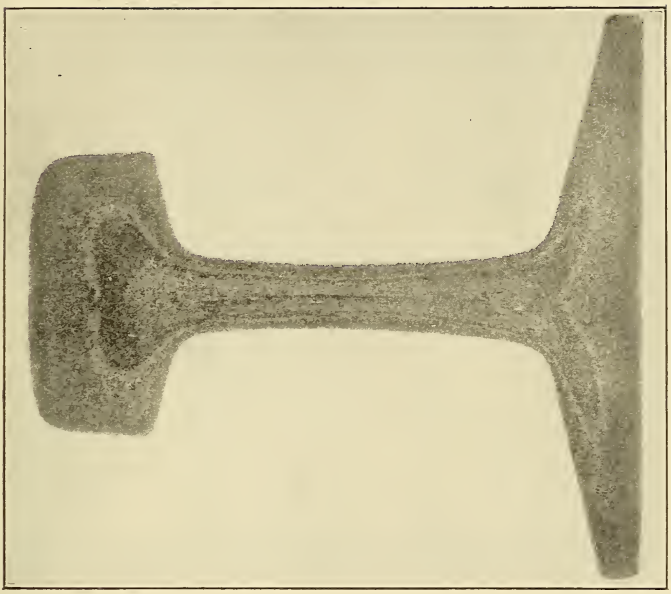

FIG. 12.—*Sulphur print of Section W from top end of A rail, showing negative segregation, from the middle ingot of heat 51069 treated with 11.5 pounds F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.71 per cent; position M, 0.70 per cent; segregation M over O= −3.8 per cent.

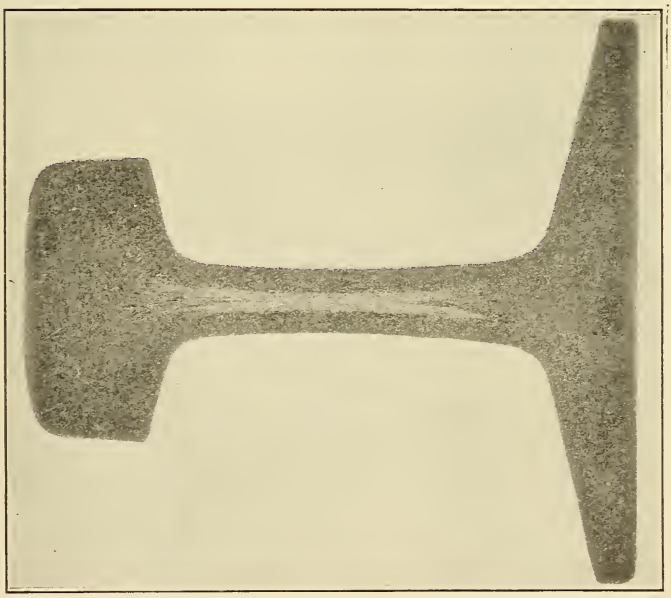

FIG. 11.—*Sulphur print of Section M from top end of A rail, showing negative segregation, from the middle ingot of heat 62105 treated with 8.68 pounds F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.73 per cent; position W, 0.64 per cent; segregation W over O= −12.3 per cent.

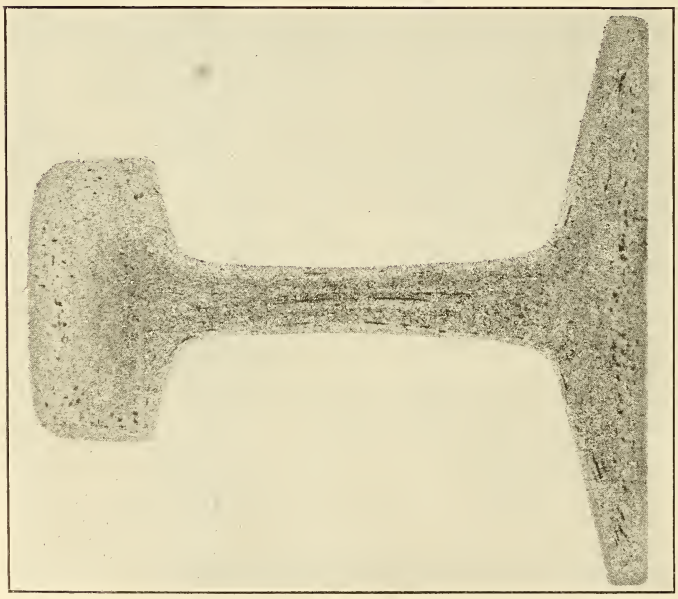

FIG. 13.—*Sulphur print of Section J from bottom end of A rail, showing slight segregation, from the middle ingot of silicon-treated heat 51069.*

Carbon: Position O (fig. 2), 0.67 per cent; position M, 0.87 per cent; segregation M over O=15.3 per cent.

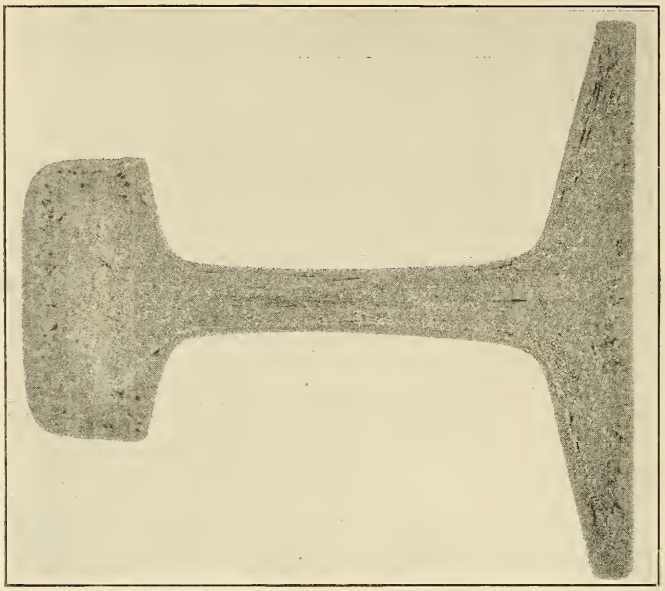

FIG. 14.—*Sulphur print of Section R from bottom end of A rail, showing no segregation, from the middle ingot of heat 46124, treated with 12.0 pounds of F. C. T. per ton.*

Carbon: Position O (fig. 2), 0.72 per cent; position M, 0.71 per cent; segregation M over O=1.4 per cent.

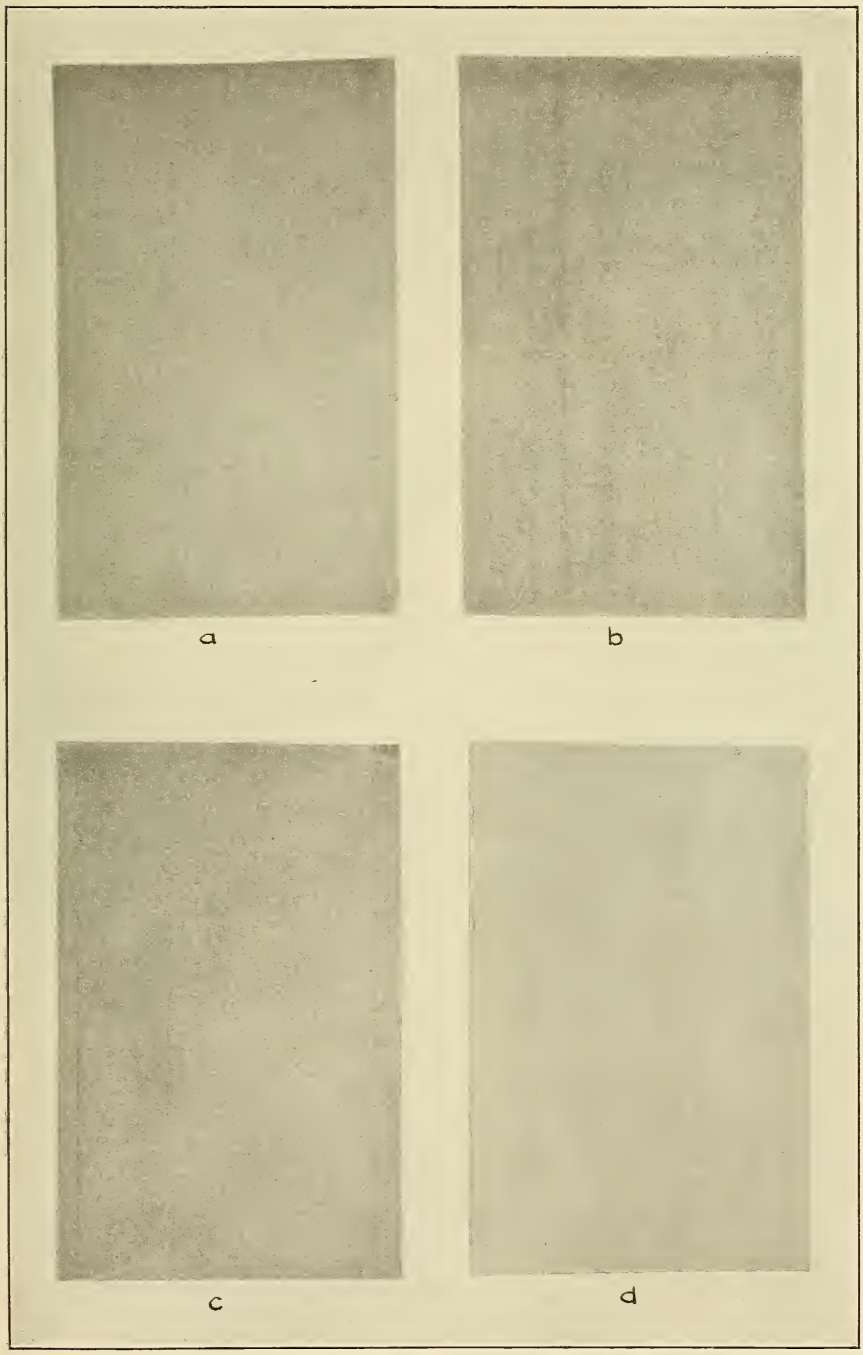

FIG. 15.—*Macrographs of specimens taken longitudinally one-half inch below the tread, from sections of A rails. Etched with copper ammonium chloride (15 applications, two minutes each).*

(*a* and *b*) From the top end of silicon-treated A rails (Sections E and I, Table 7). (*c*) From the bottom end of silicon-treated A rails (Section J, Table 7). (*d*) From top end of titanium-treated A rail (Section Y, Table 7). This and specimen from Section W were the only titanium-treated specimens to show streaks after this etching.

These sections were then etched in boiling concentrated hydrochloric acid for half an hour. This etching developed longitudinal streaks along the horizontal face and transverse pits on the ends of the half-inch sections in all the samples from the top ends of the silicon-treated A rails and in some of the silicon-treated samples from the bottom ends. In none of the titanium-treated samples, except Y (which was low in titanium), were such streaks developed. Figure 16 shows macrographs of some of the silicon-treated sections etched in this manner and Figure 17 is macrographs of some etched sections of titanium-treated rails. The results agree quite closely with the sulphur prints in showing the influence of titanium treatment on the soundness of A rails.

3. HARDNESS TESTS.

Hardness tests were made by the Brinell method, using 3,000 kg load, on all sulphur print sections at 13 positions as shown in Figure 2. A summary of the average results at these positions on the sections from the drop-test pieces and the pieces from the top and bottom ends of the A rails treated with different amounts of titanium is given in Table 13.

TABLE 13.—Average Brinell Hardness for Samples Treated with Different Amounts of Titanium.

Ferrocarbon-titanium, per ton.	Positions of sections (see fig. 2).									Average Brinell number.	Maximum difference.	Number averaged.	Positions.	
	A	B	C	D	E	F	G	H	I				Maximum.	Minimum.
DROP-TEST PIECES.														
None	260	257	256	259	272	286	264	251	255	262.2±7.8	35	20	F	H
8 to 10 pounds	255	253	252	253	268	257	267	256	260	257.6±4.4	16	10	G	C
10 to 13 pounds	251	249	247	252	249	258	257	251	253	251.9±3.0	11	11	F	C
TOP ENDS, A RAILS.														
None	240	240	246	253	266	272	251	236	238	249.1±9.0	36	5	F	H
8 to 10 pounds	233	236	239	242	247	244	244	237	242	240.4±3.7	14	3	E	A
10 to 13 pounds	237	235	236	244	250	261	243	243	241	243.3±5.5	26	5	F	B
BOTTOM ENDS, A RAILS.														
None	245	246	249	255	261	265	255	242	248	251.8±6.4	23	5	F	H
8 to 10 pounds	237	238	240	243	262	256	252	241	236	245.0±6.7	26	3	E	I
10 to 13 pounds	239	238	243	249	255	267	248	243	243	247.3±6.7	29	5	F	B

These results show less variation in hardness in the titanium-treated sections from the drop-test pieces and the top ends of the A rails but slightly greater variation over sections at the bottom ends of the A rails. The average hardness over the entire section of the silicon-treated pieces was higher than for the sections of the titanium-treated pieces, which is consistent with the higher

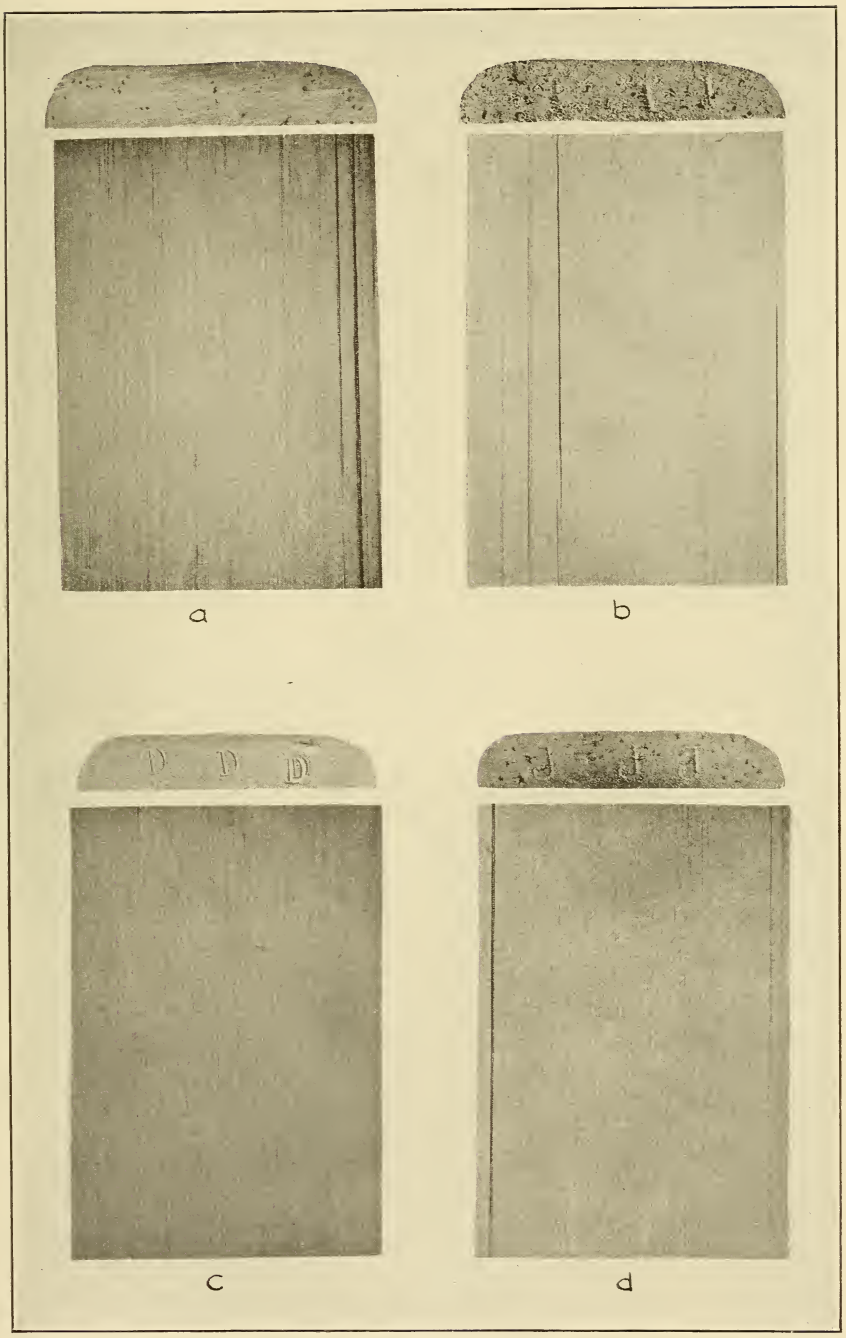

FIG. 16.—*Macrographs of specimens taken longitudinally, one-half inch below the tread, from sections of silicon-treated A rails. Etched in boiling concentrated hydrochloric acid for one-half hour.*

(*a* and *b*) From top ends of silicon-treated A rails (Sections G and I, Table 7). (*c* and *d*) From bottom ends of silicon-treated A rails (Sections D and J, Table 7).

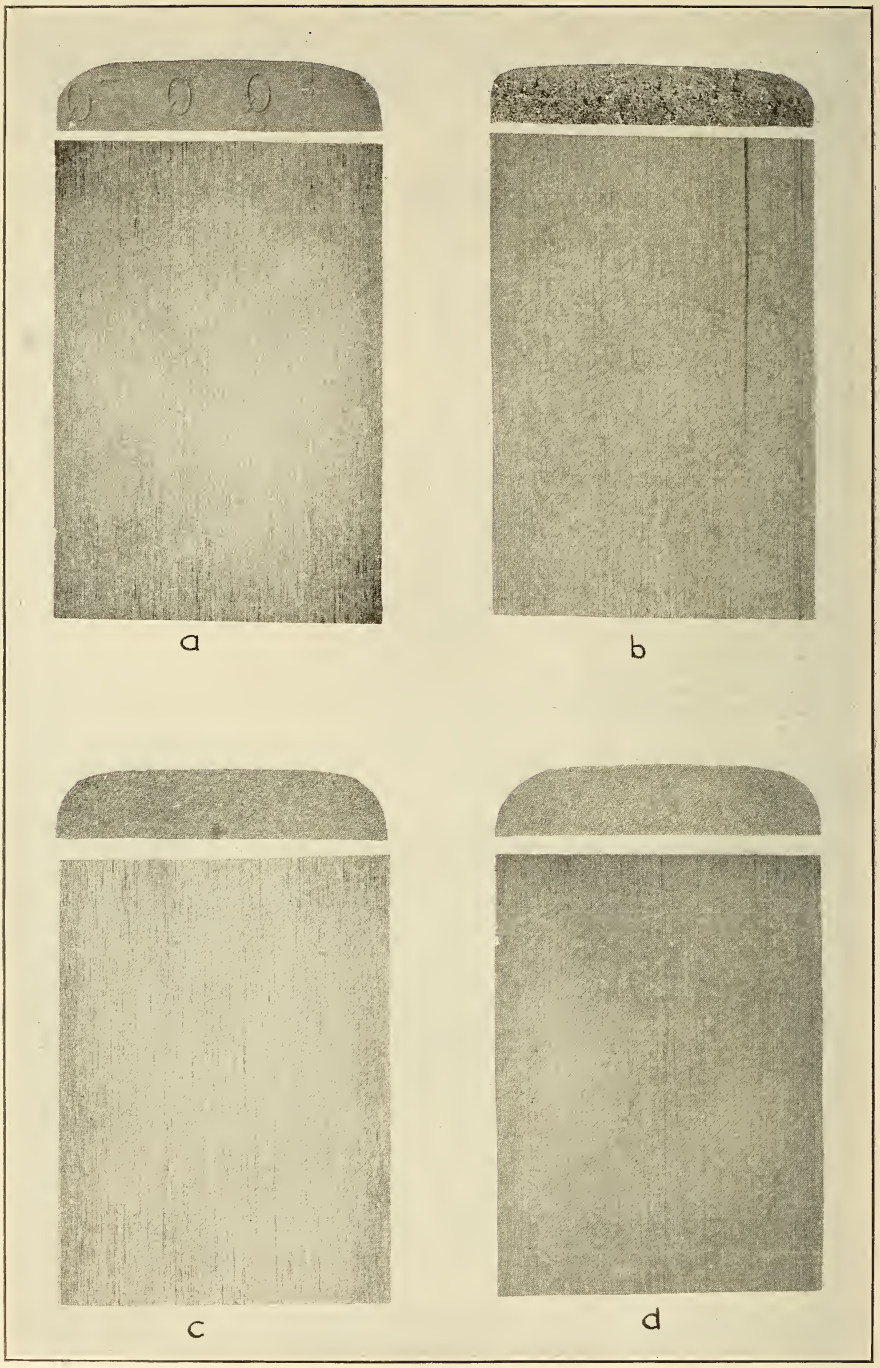

FIG. 17.—*Macrographs of specimens taken longitudinally from sections of titanium-treated A rails. Etched in boiling hydrochloric acid for one-half hour.*

(*a*) From the top end of A rail (Section Q, Table 7) treated with 12 pounds F. C. T. per ton. (*b*) From the top end of A rail (Section Y, Table 7) treated with 8.83 pounds of F. C. T. per ton. (*c*) From the bottom end of A rail (Section R, Table 7) treated with 12 pounds F. C. T. per ton. (*d*) From the bottom end of A rail (Section Z, Table 7) treated with 8.83 pounds F. C. T. per ton.

carbon and silicon contents (Tables 9 and 10) of the former. At certain positions on the silicon-treated sections the hardness exceeded any part of the titanium-treated sections on account of segregation in the former. The hardest part was in the web in all classes. The highest web values were in the drop-test pieces from heats silicon treated and treated with less than 10 pounds of ferrocarbon-titanium per ton, while from heats treated with over 10 pounds ferrocarbon-titanium per ton the hardest point was in the web of the sections from the bottoms of the A rails. The hardness survey shows also another similar result to the chemical analyses, namely, that the effect of the titanium additions is practically no better at the bottom ends of the A rails than the effect of silicon additions.

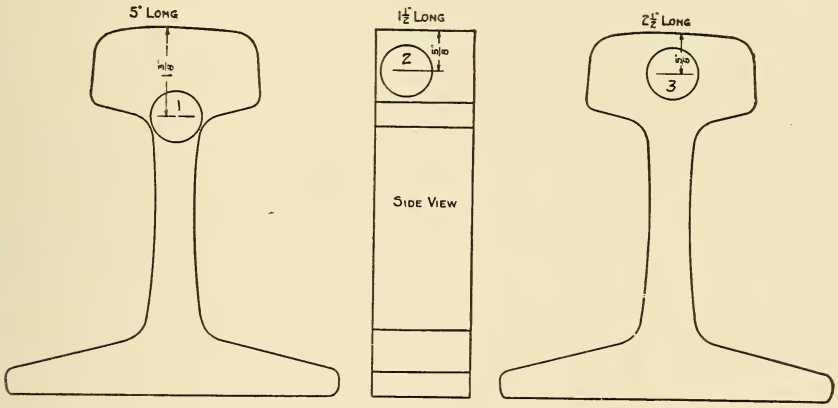

Fig. 18.—*Showing positions where tensile specimens were taken from the top and bottom ends of all 13 of the A rails used in physical tests.*

4. TENSILE TESTS.

Tensile tests were made on specimens cut from pieces from both the top and bottom ends of the A rails. Three specimens, two of them taken longitudinally from the center of the head and the junction of the head and web, respectively, and one transversely across the center of the head, were tested from all the A rails used for mechanical tests (see fig. 18). Additional specimens were cut from the top and bottom ends of one A rail for each class of steel. Heat 62106 (samples I and J) was chosen to represent the silicon-treated steel for this purpose, heat 31120 (samples K and L) was chosen for steel treated with from 8 to 10 pounds of ferrocarbon-titanium per ton, and heat 51069 (samples W and X) for steels treated with 10 to 12 pounds per ton. Besides specimens from positions shown in Figure 18 the additional specimens were

taken from positions shown in Figure 19. Some of these specimens were long enough to make standard 2-inch gauge length bars 0.505 inch in diameter and others were too short and were machined into 1-inch gauge length 0.252-inch diameter test bars. For testing the 1-inch specimens a special 1-inch strain-gauge was made.

Figures 20 and 21 give graphically the average results of tensile tests on specimens taken from the nine positions in the top and

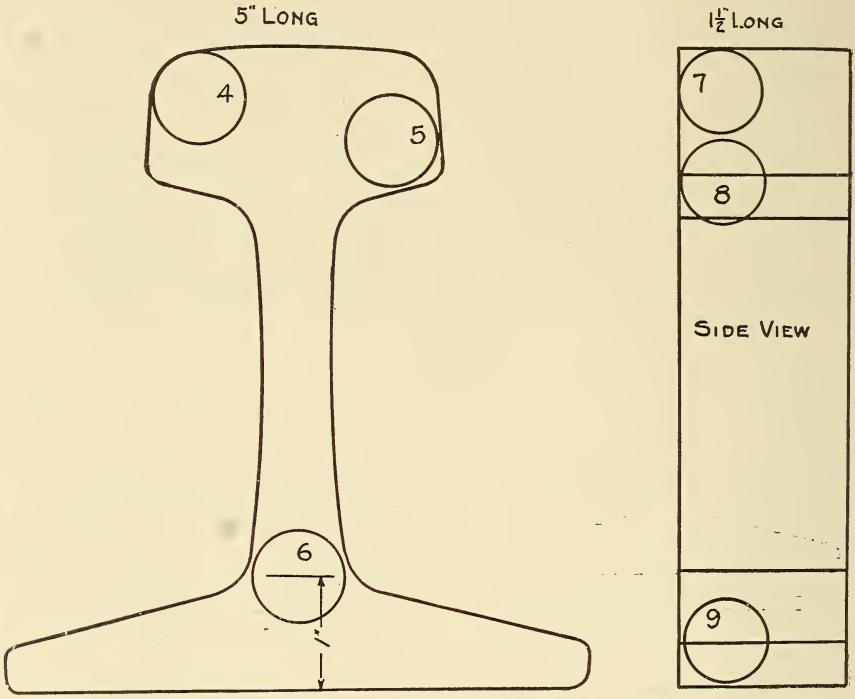

FIG. 19.—*Positions from where additional tensile specimens were taken from three A rails.*

bottom ends of A rail sections. The average values of the tensile strength, proportional limit, elongation, and reduction of area of specimens from the top ends for the three treatments are given on the left of the vertical lines marked positions 1 to 9, inclusive, and the values for test specimens taken from the bottom of the A rails are given on the right of the vertical lines. The number of tests averaged in each case for each type of steel from the top and bottom ends of the rails, the diameter of the specimens, and whether they were taken longitudinally or transversely, are also indicated in the figures. The average results of all longitudinal and transverse tests are given in the last two columns. In practically every case

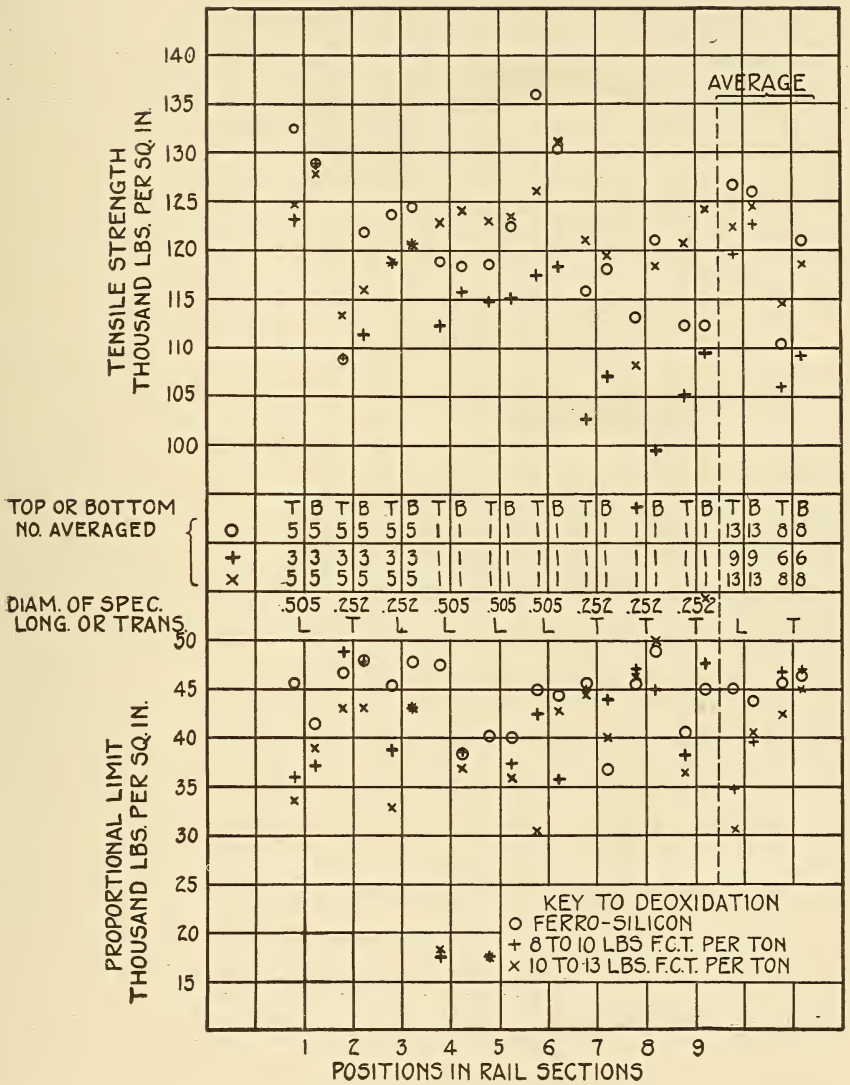

FIG. 20.—*Diagram showing average tensile strength and proportional limit of specimens.*

Specimens were taken from the nine positions from the top and bottom sections of A rails for the three treatments, the number of tests averaged from top and bottom ends for each treatment with the diameter of specimens, and whether they were taken longitudinally or transversely. Also the average of all of the results of all the tests on longitudinal and transverse specimens, respectively.

the steels treated with from 8 to 10 pounds of ferrocarbon-titanium per ton were lower in tensile strength and higher in ductility longitudinally than either the steel treated with from 10 to 12 pounds ferrocarbon-titanium per ton or the silicon-treated steels. For the steel treated with ferrosilicon and with from 10 to 12 pounds ferrocarbon-titanium per ton the highest tensile strength

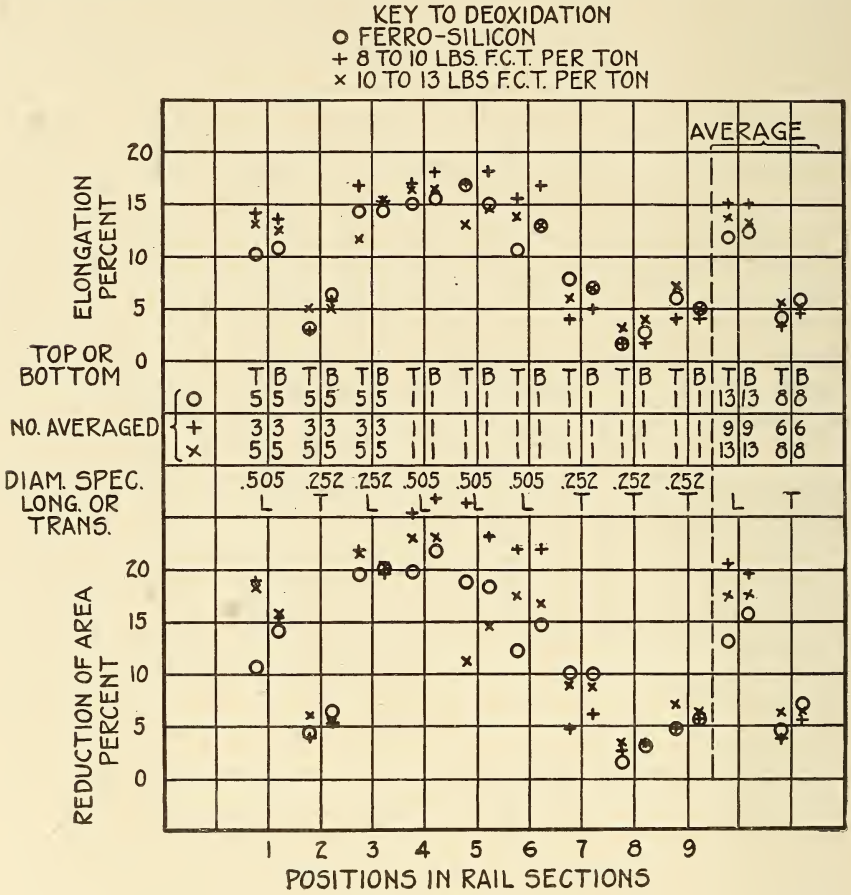

FIG. 21.—*Diagram showing the average results for elongation and reduction of area in tensile tests.*

Arranged similarly to results in Figure 20.

was about equally divided between these two types for specimens from the various positions. The proportional limits of the titanium-treated specimens were irregular, some of them being as high as those of the silicon-treated specimens and others much lower. The average of the results for proportional limit shows that of the longitudinal specimens the silicon treated gave the highest values, and of the specimens taken transversely the ones

that received from 8 to 10 pounds ferrocarbon-titanium per ton gave slightly higher average values. It is also seen from Figure 21 that all of the transverse specimens were decidedly deficient in ductility. The titanium-treated samples averaged somewhat more ductile but less strong and stiff than the silicon treated.

The greater ductility of specimens from steel treated with the smaller amount of titanium and the greater strength of specimens treated with ferrosilicon and the larger amounts of titanium are probably affected more by the carbon content of these steels than by the deoxidation practice. Table 10, which gives the chemical composition of the rails tested mechanically, shows that the average carbon content for the three types of steel at the top and bottom ends of the A rails to be as follows:

Ferrocarbon-titanium used per ton.	Average carbon content.	
	Top ends.	Bottom ends.
	Per cent.	Per cent.
None	0.79	0.78
8 to 10 pounds	.70	.75
10 to 12 pounds	.74	.76

The transverse pieces were low in ductility and somewhat low in tensile strength and relatively high in proportional limit, with no pronounced differences between the titanium-treated and silicon-treated steels.

As a whole the results from the tensile tests did not show as much difference between the titanium-treated and the silicon-treated rails as was expected from the difference in segregation. There was, however, somewhat more uniformity in tensile properties between different parts of the section in the titanium-treated rails than in those treated with silicon. In general, the proportional limit and tensile strength was lower with higher ductility for specimens from titanium-treated rails. These effects were more pronounced in tests on samples taken longitudinally than in those taken transversely.

5. IMPACT TESTS.

Impact tests were made on samples from the top and bottom ends of the A rails, both by the Izod and the Stanton repeated impact methods.

(*a*) Izod.—These tests were carried out at the Bureau of Standards with specimens 1 cm square with a 45° notch 0.079 inch deep and 1.1 inches from the end, using the Izod type machine

of 120-foot-pound capacity, built by F. H. Bultman. The test specimens were cut from the rails at exactly similar positions as the tensile test specimens (see figs. 18 and 19). Most of the Izod impact tests were made in duplicate, and in some cases four tests were made. All of the specimens broke off completely, leaving a coarse crystalline fracture.

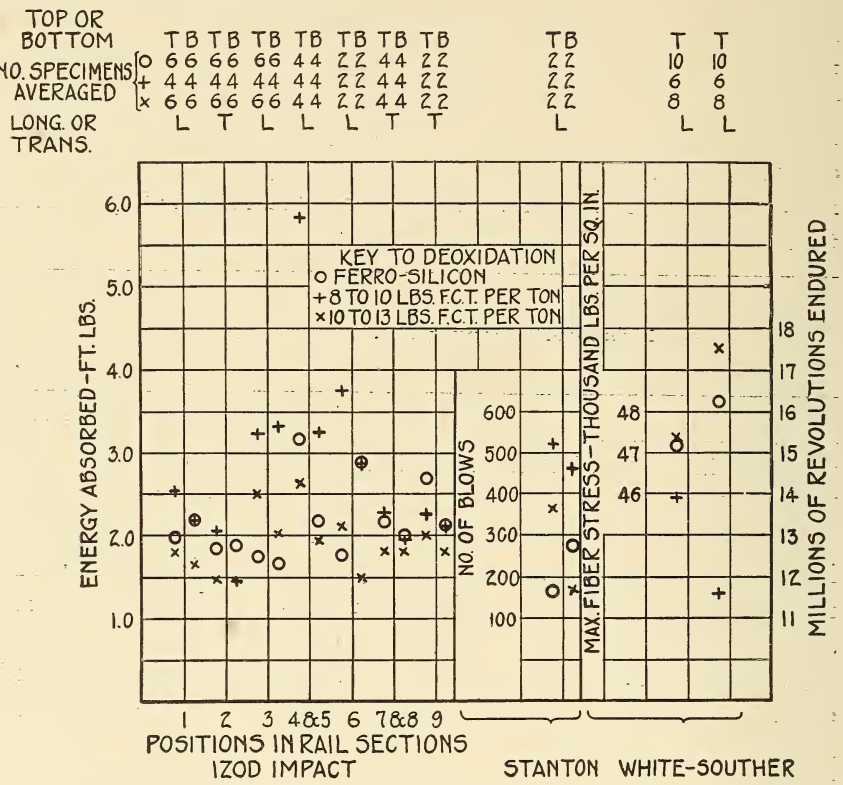

FIG. 22.—*Gives average energy absorbed in the Izod tests for specimens from each position indicated and in a similar manner the number of blows endured in the Stanton test, the maximum fiber stress and the millions of revolutions endured in the White-Souther tests.*

Figure 22 gives the average results of the Izod impact tests on specimens taken longitudinally and transversely for the three types of steel from the various positions in the top and bottom ends of the A rails. The average results of the tests are arranged similarly to the tensile results in Figures 20 and 21. The average energy absorbed by specimens from the top ends of A rails of similar steels is indicated on the left of the vertical lines, representing the various positions in the rail, while for specimens from the bottom ends the energy absorbed is indicated on the right of these lines. It is seen that for silicon-treated steels from po-

sitions 1 and 6 at the upper and lower portions of the web, where segregation is more pronounced, more energy was absorbed by specimens taken from the bottom ends of the rails than by those taken from the top ends; whereas the specimens from the top ends of the titanium-treated rails absorbed the most energy. This shows that the titanium treatment has, by decreasing the segregation, improved the top end of the A rails at these points and makes very little change in the ability of the bottom ends to resist impact. The specimens from rail samples treated with less than 10 pounds of ferrocarbon-titanium per ton gave the best values longitudinally from both the top and bottom ends of the rails. The higher values for specimens from steels treated with the smaller amounts of titanium is probably due to the lower carbon content in these rails, as was pointed out above under the head of tensile properties. The steel treated with the larger amounts of titanium gave better results in tests on longitudinal specimens from the middle and edges of the head from the top ends of the rails than the silicon-treated steels and as good as the silicon-treated steel from the bottom ends; whereas the tests on specimens from position 1, where negative segregation was so prevalent, gave poorer values.

The results of tests on transverse specimens from both the top and bottom ends of the rails, excepting the head positions from the top ends, gave poorer results for the titanium-treated steel than the silicon-treated steels, indicating that the negative segregation is as injurious to transverse impact resistance as the average amount of positive segregation in the silicon-treated rails.

(*b*) STANTON.—These tests were made on a Stanton repeated impact machine made by the Cambridge Scientific Instrument Co., of Cambridge, England. The specimens were round bars of one-half inch diameter with a 45° notch in the middle, having a diameter of 0.397 inch. They were supported on knife edges 114 mm (4.488 inches) apart and the hammer, weighing 4 pounds, fell from a height of 1¾ inches, striking across the notch alternately on opposite sides of the specimen at a rate of about 100 blows per minute.

Tests were made only on the rails used for additional tensile and Izod tests or one heat from each class of steel. Two bars were tested from samples from both ends of these three rails. These bars were cut longitudinally from the center of the head and junction of the head and web, respectively. Figure 22 shows

graphically the average number of blows received by the two specimens before failure from the top and bottom ends of the rails from the three types of steel. For the rails treated with titanium a greater number of blows was required to produce fractures in specimens from the top ends than in those from the bottom ends, while for the silicon-treated rails the specimens from the bottom ends required the greater number of blows to produce fracture. The samples treated with less than 10 pounds of ferrocarbon-titanium per ton, as in the Izod tests, gave the best results. This condition probably is due to the greater segregation in the silicon-treated samples and the negative segregation in samples treated with more than 10 pounds of ferrocarbon-titanium per ton and the slightly lower carbon content in the samples treated with less than 10 pounds ferrocarbon-titanium per ton.

6. ENDURANCE TESTS.

These tests were made with two White-Souther machines operating on the rotating cantilever beam principle. The test specimens were cut longitudinally from the lower central part of the head near the junction with the web from each of the top end samples of the A rails. Duplicate results were obtained from each specimen with two exceptions, both among the titanium-treated rails. The test on sample Q was spoiled because the power was shut off from the machines one night when this test was running and the specimen became bent, since the load was not removed before stopping the machine. One end of the specimen from sample W was probably broken prematurely by a rough bearing in the machine, and it gave such a divergent result from that of the other end that it is not included in the average results. The tests were all started with a maximum fiber stress of 42,400 lbs./in.^{2}, and this was increased every 5,000,000 revolutions by about 1,750 lbs./in.^{2} up to 51,200 lbs./in.^{2} at 25,000,000 revolutions. No test was continued beyond 30,000,000 revolutions, and no specimens were wholly unbroken after this number, although one end of each of two silicon-treated and two titanium-treated specimens endured the full test without failure. The average number of revolutions endured and the average of the maximum fiber stresses at the ends of the tests for specimens from rail samples of the three types of steel are shown graphically in Figure 22, with the Izod and Stanton impact results. These results show a very slight superiority

in endurance for the samples treated with over 10 pounds of ferrocarbon-titanium per ton over the silicon-treated ones, while the samples from rails treated with less titanium show inferior endurance. This may be because of their lower carbon content and agrees with their better showing in the Izod impact and Stanton repeated impact tests.

7. MICROSCOPIC EXAMINATION.

The purpose of this examination was to make a comparison of the number and type of inclusions in silicon-treated and titanium-treated A rails.

It has been noticed by Comstock[5] that in titanium-treated steel that the sulphide inclusions were smaller and more evenly distributed, and that steels so treated contained hard, pink inclusions which were never found in steel that had not been treated with titanium. Comstock, by incorporating compounds of titanium sulphide, carbide, and nitride in samples of steel that had not been treated with titanium, concluded that the pink inclusions are probably composed largely if not entirely of titanium nitride, since this was the only compound added that produced these inclusions. It is, however, uncertain whether this compound is a nitride or a cyanide. Spiegel[6] states that copper-colored cubes found in blast-furnace "bears," which simulate in appearance the pink inclusions in titanium-treated steels, are a cyanide of the composition $Ti_{10}C_2N_8$, and Stead[7] states that probably no blast-furnace "bears" are free from copper-colored crystals of this composition.

The survey of the number and type of inclusions was made on specimens taken longitudinally and transversely from samples of A rails treated with ferrosilicon and different amounts of titanium. Care was taken to choose a representative spot for each micrograph. Figures 23 to 25, inclusive, show the relative number of inclusions in the titanium-treated and silicon-treated rails in longitudinal and transverse sections and from different positions in the rail. The number of inclusions is seen to be least for the silicon-treated rails and increased with the titanium additions. In rail sections Y and Z (figs. 23 to 25, inclusive), in which only a small amount of titanium was retained in the steel, the number of inclusions were about equal to that in the silicon-treated steel.

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[5] Titanium nitride in steel, George F. Comstock, Met. and Chem. Eng., **12**, pp. 577–580; 1914.

[6] L. Spiegel, Nitrogen and Its Compounds, pp. 732–734.

[7] Blast-furnace bears, J. E. Stead, Iron and Steel Inst., **97**, 170; 1918.

FIG. 23.—*Inclusions in cross sections from center of head of top ends of titanium-treated and silicon-treated rails.* ×100.

(*a*) Rail Section A, silicon treated. (*b*) Rail Section Y, 8.83 pounds F. C. T. per ton 0.0042 per cent insoluble titanium retained. (*c*) Rail Section M, 8.68 pounds F. C. T. per ton 0.0096 per cent insoluble titanium retained. (*d*) Rail Section Q, 12.00 pounds F. C. T. per ton 0.0226 per cent insoluble titanium retained. It can be seen that there are more inclusions in the titanium-treated than in the silicon-treated rails. Rail Section Y treated with the lower amount of ferrocarbon-titanium, and in which very little titanium was retained in the steel contains about the same number of inclusions as rail Section A not treated with titanium.

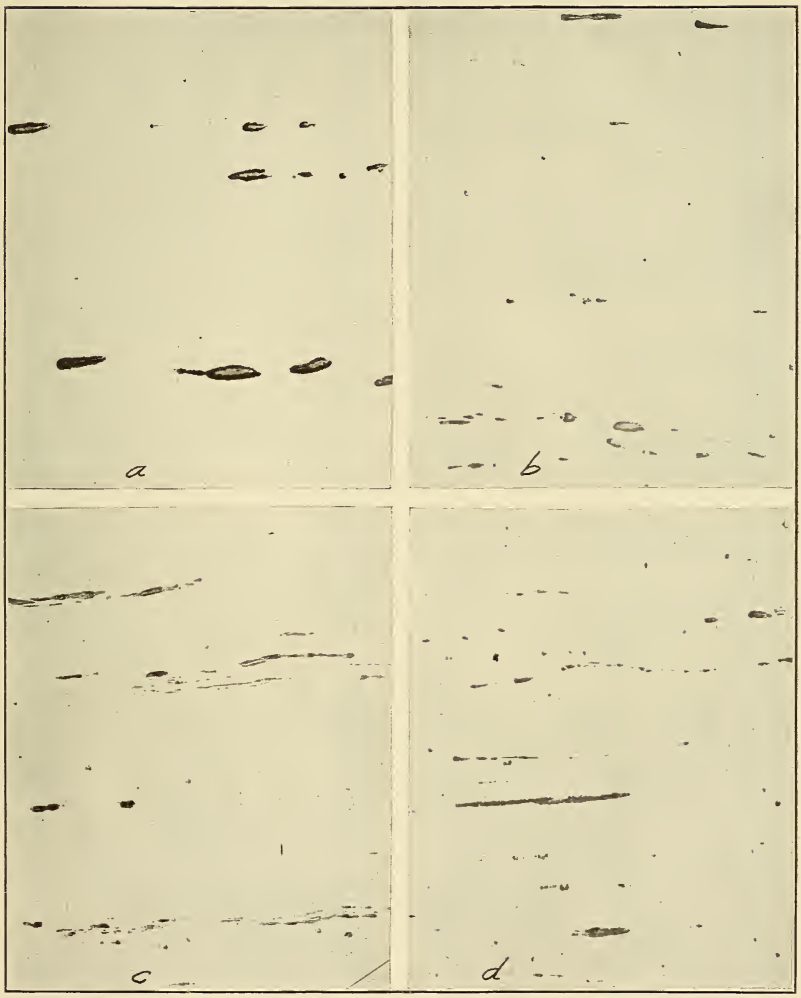

FIG. 24.—*Inclusions in longitudinal sections from center of head.* ×100.

(*a*) Rail Section A, silicon treated. (*b*) Rail Section Y, 8.83 pounds F. C. T. per ton 0.0042 per cent insoluble titanium retained. (*c*) Rail Section M, 8.68 pounds F. C. T. per ton. 0.0096 per cent insoluble titanium retained. (*d*) Rail Section Q, 12.00 pounds F. C. T. per ton 0.0226 per cent insoluble titanium retained.

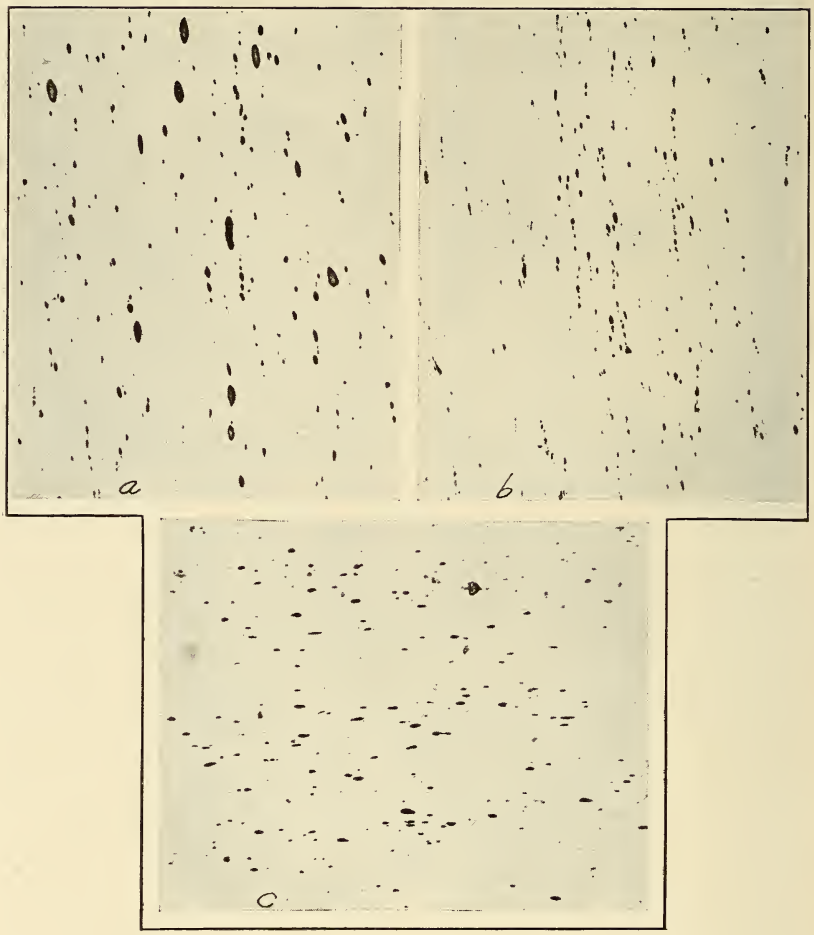

FIG. 25.—*Cross section from web of top ends of titanium-treated and silicon-treated rails.* ×100.

(*a*) Rail Section G, silicon treated. (*b*) Rail Section K, 8.63 pounds F. C. T. per ton 0.0086 per cent insoluble titanium retained. (*c*) Rail Section S, 10.5 pounds F. C. T. per ton 0.0233 per cent insoluble titanium retained. There are more inclusions in the web than in the head of the rail. Silicon-treated rail Section G, which was segregated in the web, did not contain any more inclusions than titanium-treated rail Section S, which was not segregated.

The distribution of the inclusions through the head of both types of rails was fairly uniform. Increases in the number of inclusions in segregated spots, such as were indicated by the sulphur prints, although present, were not very conspicuous. For instance, there was no particularly noticeable variation in the number of inclusions along the lengths of the specimens which passed transversely through the centers of the heads of the rails to the sides of the heads; also there was no marked increase in the numbers of inclusions at the junctions of the head and web. In the webs, however, the number of inclusions was very much greater in both the silicon and titanium treated rails (compare figs. 23 and 25). It is perhaps worthy of mention that rail section G, silicon treated, which was segregated in the web, did not contain any more inclusions in the web than rail section S, titanium treated, which was not segregated (see fig. 25). There did not seem to be any pronounced difference between the top and bottom ends of the rails in regard to the number of inclusions.

The increase in the number of inclusions with titanium treatment appears to be due, in large measure, to the curious effect titanium has of breaking up and scattering the manganese sulphide which composes the majority of the inclusions in steel. Thus, in a titanium-treated steel a large number of small sulphide inclusions are found, while in silicon-treated steel the inclusions are larger and fewer in number (see fig. 26). This effect has been described before.[8] It was noticed also in the examination that the sulphide inclusions in titanium-treated steel were associated with the titanium inclusions; that is, very often the sulphide inclusions would have titanium inclusions inside of or beside them (see fig. 27 *c*). Another reason for the increased number of inclusions resulting from titanium treatment is that the titanium inclusions themselves were found to be far more numerous than the silicate inclusions, which may be considered as due to the ferrosilican deoxidizer.

It should be noted (see micrographs of longitudinal sections, fig. 24) that, although titanium breaks up and scatters the sulphide inclusions, the effects are not so widespread as to distribute the inclusions evenly throughout. The streaks or threads of inclusions in the longitudinal sections were present in both the titanium-treated and silicon-treated steels. These streaks shown in the micrographs are somewhat distinct from the larger streaks

[8] See footnote 5, p. 625.

brought out by deep etching. They are a result of secondary or microsegregation in the dentritic crystals of the ingot, while the large streaks revealed by deep etching result from the primary or gross segregation.

The titanium inclusions were of two types, orange and violet, of lighter and darker shades (see fig. 27). They were generally very small, and even the largest of them were magnified to appreciable size only at 500 diameters. The orange ones in cross section were always square or sharp cornered, and so were some of the violet inclusions, which were often found very near to the orange inclusions or even superimposed upon them. There were other violet-colored inclusions which were rounded in shape. The angular inclusions, both of the orange and violet varieties, usually showed considerable pitting on polishing. The round violet inclusions polished smoothly, however. The orange inclusions were so characteristic in color that they were very easily identified. The violet ones also could be recognized without difficulty, although there is a possibility of confusing them with the silicate inclusions which are of a grayish purple color. However, there were fewer in number of the silicate inclusions, and usually they contained white, needle-like crystals by which they could be distinguished from the violet inclusions (see fig. 27 *d*). In the steels treated with the lower amounts of titanium there were very few of the orange inclusions, whereas they were quite numerous in the steels treated with the higher amounts. The number of violet inclusions in the steel treated with the lower and higher amounts of titanium were about equal. In the steels treated with the higher amounts of titanium there were approximately twice as many orange inclusions as violet inclusions.

It was found on analysis for gases that in the steels treated with the lower amounts of titanium containing the violet inclusions the nitrogen combined with the iron and manganese was still quite high, and that the steels treated with higher amounts of titanium, containing the orange inclusion also, the nitrogen remaining in combination with the iron and manganese was very low. It seems, therefore, very probable that the difference in shape and polishing characteristics between the square and the round violet inclusions indicates a difference in compositions. The square violet inclusions, so intimately associated with the orange inclusions and so similar in shape and polishing characteristics, are possibly a lower nitrogen compound of titanium. The round

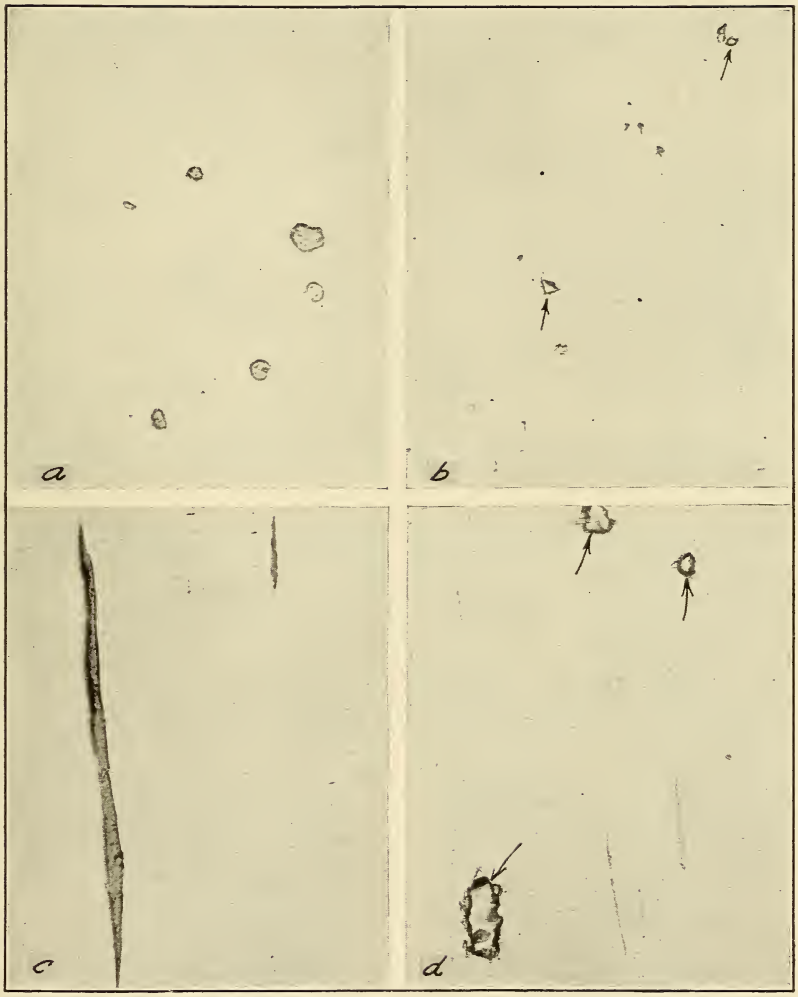

FIG. 26.—*Comparative size of manganese sulphide inclusions in titanium-treated and silicon-treated steels.* ×500.

(*a*) Large sulphide inclusions in cross section of silicon-treated steel. (*b*) Smaller sulphide inclusions in titanium-treated steel. Cross section. (*c*) Silicon-treated steel. Longitudinal section. (*d*) Titanium-treated steel. Longitudinal section.

The inclusions indictead by arrows are compounds of nitrogen and titanium. The rest are sulphide inclusions.

FIG. 27.—*Types of inclusions in titanium-treated rails.*

(*a*) 1, Orange inclusions of nitrogen compound of titanium; 2, violet titanium inclusion. Of the violet inclusions, some were angular and others were rounded in shape. It appeared probable that the angular violet inclusions were of a lower nitrogen compound of titanium and the orange inclusions of higher nitrogen compound of titanium, while the rounded violet inclusions were, perhaps, a titanium oxide; 3, a group of broken up sulphide inclusions, characteristic of the titanium-treated rails. (*b*) Rounded violet inclusions and a square violet inclusion. (*c*) Violet inclusion surrounded by sulphide. (*d*) Silicate inclusion. It can be distinguished from the violet-titanium inclusions by the white needle-like interior markings.

violet inclusions appear to be some other compound, perhaps titanium oxide, which, if it is not reducible under the conditions of the vacuum fusion method of analyses—namely, at 1,450° C. in contact with graphite—may explain the immediate and appreciable drop found by oxygen analysis in the amounts of oxides reducible by carbon in steels treated with the lower amounts of titanium. This conclusion seems in harmony with the results of the gas analyses. (See III, 1 *d.*)

The probable reactions of titanium may be summarized as follows: A certain large proportion of the titanium used slags out either after combining with the gases in the steel or as a loss. With the use of the lower amounts of ferrocarbon titanium (8 to 10 pounds per ton) there is only a small amount of titanium retained in the steel, largely in the form of round violet inclusions, possibly of titanium oxide, and some of the square violet inclusions probably of a lower nitrogen compound of titanium. With the use of the higher amounts of ferrocarbon titanium (10 to 12 pounds per ton) a relatively much larger amount of titanium is retained in the steel. This is present in the form of similar violet inclusions and, in addition, in the form of orange inclusions probably of a titanium compound higher in nitrogen than the square violet inclusions. It seems as if the violet inclusions are the first to form, and then, if there is an excess of titanium, the orange inclusions appear. Apparently a large part of the nitrogen removed by the titanium from the iron in the steel is combined in the orange inclusions. The effect of titanium in breaking up the sulphide inclusions depends, according to reasons given, on the retention of titanium in the steel. This effect on the sulphide inclusions is hardly noticeable in rail sections Y and Z, in which very little titanium was retained.

IV. SUMMARY AND CONCLUSIONS.

A cooperative investigation with the Titanium Alloy Manufacturing Co., the Illinois Central Railroad Co., the Illinois Steel Co., and the Robert W. Hunt Co. to study the effect of titanium additions in open-hearth rail steel as compared with steel treated with ferrosilicon as a deoxidizer has been carried out. This investigation included the following out of the manufacturing processes of melting, teeming, and rolling of rails for 20 titanium-treated and 23 silicon-treated heats; tests on samples from the top and bottom ends of A rails from the middle ingots of 13 heats for chemical homogeneity, soundness, and uniformity of

mechanical properties. The remaining portion of the rails were laid in the track for service observations. Although it is difficult to draw definite conclusions from the relative small number of tests on rails from the various heats where slight differences in practice and chemical analyses introduce variables, the results point to the following general conclusions.

1. A higher percentage of piped rails come from titanium than from silicon treated rails, but the time of teeming affects the number of pipes. The greatest number of pipes were in rails from steel treated with the smaller amount of ferrocarbon titanium per ton, and variations in the amount above this did not seem to affect the pipe.

2. The titanium-treated rails were harder to break and showed more uniform fractures in the drop test than those treated with ferrosilicon.

3. The titanium additions compared with the silicon additions had a marked effect in reducing the segregation of carbon at the top of the ingot. This improvement was approximately proportional to the titanium additions, but the effect falls off rapidly at the bottom ends of the A rails.

4. Nitrogen determined by the Allen method decreases as the residual titanium in the steel increases. This indicates that less nitrogen is combined with iron and manganese, not that the nitrogen has been eliminated, but that it probably is combined with titanium or silicon.

5. The addition of from 8 to 10 pounds of ferrocarbon titanium per ton causes an immediate and appreciable drop in the amount of oxides reducible by carbon, while for additions of more than this amount the oxides reducible by carbon are entirely lacking.

6. Titanium treatment is shown by sulphur prints to lessen segregation of sulphur, particularly in the drop-test pieces, and in samples from the top ends of the A rails, where this segregation is most prevalent in the silicon-treated rails. This condition was checked by etching specimens in boiling hydrochloric acid, which showed streaks in many of the silicon-treated pieces, whereas the pieces treated with titanium remained practically free from streaks.

7. Rail sections from the top of the ingots from titanium-treated heats were more uniform in hardness than those from similar positions in silicon-treated heats. This effect had entirely disappeared at the bottom of the ingot.

8. The results of tensile, impact, and endurance tests did not show as much improvement from the titanium treatment as was expected from the decreased segregation. There was somewhat more uniformity in mechanical properties at the top ends of A rails from titanium than from silicon treated heats. At the bottom ends of A rails not much improvement was shown by titanium treatment.

9. Steel treated with from 8 to 10 pounds of ferrocarbon titanium per ton retains about 19 per cent of the titanium and steel treated with from 10 to 13 pounds about 33 per cent, whereas the silicon-treated steel retains about 81 per cent of the silicon. The smaller amount of titanium remaining in the steel treated with from 8 to 10 pounds of ferrocarbon titanium per ton is retained in the form of violet inclusions, perhaps of titanium oxide and some of a lower nitrogen compound of titanium, and for treatments with larger amounts much more titanium is retained as similar violet inclusions, and, in addition, in the form of orange inclusions, probably a higher nitrogen compound of titanium.

10. In the titanium-treated steel the sulphide inclusions were more broken up and scattered than in the silicon-treated steel, and this effect is dependent upon the retention of titanium in the steel.

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