ORIGINAL PAPERS

TITANIUM AND ITS EFFECTS ON STEEL¹

By GEORGE F. COMSTOCK

Titanium is one of the chemical elements which is widely distributed in the earth's crust in small quantities but is not especially abundant. It has a very strong affinity for oxygen, and is always found in nature as an oxide, its principal ores being rutile, the fairly pure dioxide, and ilmenite, a mixture of iron and titanium oxides. One of the element's chief peculiarities is the readiness with which it combines with nitrogen. It is one of the very few elements which will "burn" in an atmosphere of nitrogen. Its dioxide is one of the most stable compounds known, and the expenditure of great energy is required to decompose it. Thus it follows that when titanium is separated from its oxygen, it will readily re-combine with it and energy will be evolved again in the form of heat.

The value of titanium in the steel industry is due largely to the fact that its dioxide is so much more stable than iron oxide that its action in robbing melted steel of its oxygen, or "deoxidizing" it, is very powerful. In order to obtain titanium in a form useful for this purpose, it is necessary to reduce the oxides found in nature to some metallic state. There are two known ways of doing this: (1) by reduction with carbon under the intense heat of the electric arc, forming a carbide of titanium; (2) by an aluminothermic reaction, whereby aluminum is oxidized at a high temperature at the expense of the titanium, and an alloy of titanium, aluminum and iron is produced. The carbide of titanium is the form most generally used, for reasons that will be explained below.

Before proceeding to consider the effects of titanium on steel, it may be well to explain more clearly the relation of the element to the compounds mentioned above. Arranged in the order of increasing stability we have the series:

Titanium,
Titanium carbide,
Titanium nitride,
Titanium oxide.

Each member of this series tends under favorable conditions to be converted into one of the following members. Thus metallic titanium when heated to redness in pure nitrogen forms titanium nitride, but when heated in air only, the oxide is formed. The nitride when heated to redness in air is slowly converted to the oxide, but the carbide burns vigorously in air, forming titanium dioxide. The reverse reaction, driving the oxide back to carbide, takes place only at very high temperatures and with the expenditure of great energy. Even at the temperature of the blast furnace titaniferous ores do not give more than 1 per cent of titanium in the pig iron. This is probably present partly as carbide and partly as cyanonitride, a mixture of carbide and nitride. Although in the

blast furnace titanium nitride is sometimes formed, it is not present in the titanium-carbide alloy used in treating steel, for at the temperature of the electric arc furnace and with the reducing atmosphere and excess carbon used, the nitride is dissociated in favor of the carbide.

Besides titanium, there are other elements that are used more or less frequently to deoxidize steel. Among these are aluminum, manganese and silicon. The comparative efficiency of these elements as "corrective agents" for defects in steel ingots was thus tabulated by Prof. Bradley Stoughton in an article appearing in the *Railway Age Gazette*, Feb. 7, 1913, the elements being given in the order of their effectiveness:

	1	2	3	4	5
Prevention of blowholes.....	Al	Ti	Si	V	Mn
Removal of oxides of Fe and Mn.....	Ti	Si (weakly)			
<i>Hindering this removal.....</i>	Al	Mn			
Removal of all oxides and slag enclosures.....	Ti				
<i>Hindering this removal.....</i>	Al				
Removal of nitrogen.....	Ti	V(?)			
Breaking up and removal of iron sulfide.....	Mn	Ti(?)			
Causing a pipe.....	Al	Si	Ti	V	Mn
Hindering segregation.....	Al	Ti	V		
<i>Promotion of segregation.....</i>	Mn	Si (sometimes)			

A general outline of the influence of titanium on steel is given above and at the same time it is shown that for general effectiveness titanium is the best of the various deoxidizers used. For these purposes the carbide is at least as valuable as the pure metal in regard to the results obtained. As to expense there is a very great difference in favor of the carbide, as this can be obtained in carload lots for 8 cents per lb. with a titanium content of 15 to 20 per cent, while the cost of metallic titanium would be prohibitive. The material sold at this price is known as "Ferro Carbon-Titanium," and is made at Niagara Falls, N. Y. It consists of microscopic particles of titanium carbide held in a matrix similar to gray cast iron. When added to melted steel the matrix dissolves quickly, and the particles of titanium carbide are rapidly diffused throughout the bath, where they react with great vigor on the oxygen present.

The aluminothermic alloy, which contains very little carbon, is of course an alloy of both aluminum and titanium in iron, and hence its use produces the above-mentioned effects of both these elements. The chief objection to the use of aluminum is its harmful effect in hindering the removal of oxide and slag enclosures. Aluminum oxide, which is formed when steel is deoxidized by this element, is exceedingly infusible, and its tendency toward making all metallurgical slags infusible and viscous is notorious. Hence these particles of alumina (more or less pure) solidify in steel as soon as they are formed, and have no tendency to rise into the slag at the top of the ladle or mold. Moreover, by mixing with other small slag inclusions in the steel, the alumina makes them more viscous, and helps to keep them back in the metal. In the same way when silicon alone is used to deoxidize steel, the metal is filled with small inclusions of iron and manganese silicates, which do not remove themselves before solidification.

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Titanium oxide, however, acts as a flux for silicates and other slags that may be in the steel, making them fluid enough to rise to the top of the metal and pass into the slag under conditions that might otherwise have held them back in the metal. Various researches

aluminum, *i. e.*, in the form of the carbide. The aluminothermic alloy should be used only in the few rare cases where the carbon of the ferro carbon-titanium alloy could not be tolerated in the steel. In soft steels the increase in carbon content

FIG. 1—SULFUR PRINTS OF UNTREATED "A" RAILS
The black spots indicate where small sulfide inclusions are thickly segregated.

FIG. 2—SULFUR PRINTS OF TITANIUM-TREATED "A" RAILS
The small size and uniform distribution of these spots are characteristic of titanium-treated rails.

have demonstrated this action of titanic oxide in rendering slags more fluid, when added in not too large amounts. Thus it is seen that the best cleansing action is obtained when the titanium is added without

from this addition as usually practiced would not be more than about 0.01 per cent so that the cases where this would make any material difference are very few indeed. Practically all the titanium used in steel in

this country at the present time is in the form of ferro carbon-titanium, and a large percentage of this is used for rail steel, although its use in other steels is growing steadily.

"Titanium steel," properly speaking, is not made commercially at present. Such a title naturally implies a steel whose properties are dependent to an appreciable extent on a certain content of titanium. But the advantages of the titanium-treated steels as made today are due to greater soundness, cleanness, and less segregation, and not, as far as we know at present, to the small amount of titanium left in the solid metal. In no case has over 0.025 per cent of titanium been found in any sample of titanium-treated

titanium, but most of this element is used in Open-Hearth steel on account of the greater tonnage of this material manufactured. The alloy is furnished in various sizes, from lumps of about 1 inch diameter to powder, according to the quantity of steel to be treated at one time. For the best results it must be added to the melted steel as it flows from the furnace to the ladle. The addition must of course be entirely completed before the slag has begun to flow out on top of the metal. After the addition, the steel must be held in the ladle for from 3 to 10 minutes, depending on the size of alloy used and the mass of steel treated, to allow the titanium to become thoroughly diffused, the deoxidizing reactions to take place, and the titanium

FIG. 3—TYPICAL UNTREATED (UPPER) AND TITANIUM-TREATED (LOWER) "A" RAILS $\times 100$; REDUCED BY ONE-FOURTH

The above samples (etched with picric acid) show dark crystals of pearlite with light streaks of ferrite between, except in the web of the untreated rail. This rail was badly segregated, and had a very hard and brittle spot in its web. Part of this spot is shown above, mostly pearlite with one long, light crystal of cementite or iron carbide. Note the seams at the top of the head of the untreated rail, and the scarcity of pearlite at its upper and lower edges.

steel analyzed at our laboratories. Of course it is possible that this very small titanium content is in some way associated with impurities so as to distribute them uniformly, thus preventing segregation, but we do not know that there is any such association and hence are not justified in considering titanium-treated steel as a true alloy steel. Under the usual conditions of manufacture it is very difficult to make steel absorb more titanium than the 0.025 per cent noted above and no use that would warrant the commercial production of a real "titanium steel" has yet been found for a product containing larger quantities.

Steels made by the Bessemer, Open-Hearth, or Crucible processes may be, and are, treated with ti-

and other oxides to rise out of the metal into the slag. Then the steel is teemed as usual into the molds where no further additions should be made.

The amount of alloy recommended for use in rail steel is 13 lbs. per ton, which means, since the ferro carbon-titanium is guaranteed to carry over 15 per cent titanium, an addition of 0.1 per cent of metallic titanium. A higher grade alloy is not used because its rate of solution in the melted steel would be slower. The price of rails treated in this way is about 5 per cent above the price of ordinary rails. For castings and soft steels a smaller amount of alloy may be added, but in every case it is important to allow time for the reaction to take place completely in the ladle, before

the steel gets into the molds. The heat of the reaction will usually prevent the formation of a skull in the ladle, and it is not necessary to tap the steel hotter from the furnace to allow for cooling while the ladle is being held.

Smaller amounts of titanium have been tried in rail steel, with the usual precautions of holding in the ladle, etc., but the best results have not been obtained. This indicates not only that it is not safe to skimp the amount added, but also that merely holding the steel in the ladle will not give the cleanness and homogeneity that result from the titanium treatment.

these gas bubbles are trapped in the freezing metal before they can escape, blowholes are formed, and these holes may be welded together when the steel is rolled or forged. Low-carbon steels, even if treated with titanium, always contain blowholes, but, the steel being normally cleansed by the titanitic oxide, they are free from slag and are closed up when the ingots are worked. If they become oxidized, however, or contain slag, they will open up as seams or remain as slag inclusions in the metal. It is well known that if steel is completely deoxidized, and no blowholes are formed, a large shrinkage cavity, or

FIG. 4—TITANIUM CARBIDE $\times 100$
Reduced by One-fourth

Made in laboratory. Large rounded grains are light violet color. Network is yellowish white, probably iron carbide. Black spots are pits caused by grinding. Not etched.

FIG. 5—TITANIUM CARBIDE $\times 200$
Reduced by One-fourth

Near top, dissolving into steel below with particles of carbide scattered through the steel. Not etched.

FIG. 6—FERRO CARBON-TITANIUM $\times 100$
Reduced by One-fourth

Black streaks are graphite. Rounded grains standing out in relief are titanium carbide. Not etched.

FIG. 7—Fe-Ti-Al ALLOY $\times 100$
Reduced by One-fourth

Titanium about 12 per cent, aluminum about 6 per cent and carbon about 0.5 per cent. Etched with HNO_3 .

FIG. 8—Fe-Ti-Al ALLOY $\times 400$
Reduced by One-fourth

Alloy of Swedish iron with aluminothermic ferrotitanium, showing inclusions of alumina. Not etched.

FIG. 9—Fe-Ti-Al ALLOY $\times 200$
Reduced by One-fourth

Pink crystal of titanium nitride in aluminothermic ferrotitanium. The black spots are pits caused by grinding. Not etched.

The two great advantages of well-deoxidized steel are (1) soundness, or freedom from blowholes, and (2) absence of excessive segregation. The making of both Bessemer and Open-Hearth steel is essentially an oxidation process, the carbon being burned out of pig-iron in each case, and the steel necessarily contains a considerable quantity of oxide when first made. If this is not removed before solidification begins, the iron oxide in the steel continues reacting with the carbon, forming carbon monoxide, a gas which passes up continually in small bubbles to the surface of the metal, where it burns with a bluish flame. If some of

"pipe," will form in the center of the upper part of the ingot. Titanium may cause piping, as well as other deoxidizers, but by properly designing the molds piping may be controlled so as not to give much trouble.

The dependence of segregation on deoxidation is less obvious than that of soundness. Primarily, of course, segregation is due to selective freezing. The freezing-point diagram of the iron-carbon alloys shows that with ordinary steel the first metal to freeze is of lower carbon content than the remaining liquid, and the last liquid to freeze is of higher carbon content than the already frozen solid. But with well-deoxidized steel this

selective freezing takes place in a quiet mass of pasty material, and the higher carbon liquid is so intricately entangled in the lower carbon solid that it does not have a chance to collect in the center of the ingot to any great extent, and is finally frozen together with the lower carbon material. The action is somewhat like that of a sponge holding water. But assume that this steel is not well deoxidized, but is giving off gas, produced by the reaction $\text{FeO} + \text{C} = \text{Fe} + \text{CO}$, during solidification. This gas, being of course much

will be excessive segregation. Phosphorus is subject to this action in the same way as carbon; sulfur, existing in the steel as small non-metallic globules composed of a mixture of iron and manganese sulfides with a freezing point not much, if any, higher than that of the metal, is even more affected. [For this explanation of the relation between segregation and oxides in steel, the writer is indebted to Mr. N. Petinot, Metallurgist of the Titanium Alloy Manufacturing Co.]

Aluminum, and probably also vanadium and silicon,

FIG. 10—TITANIUM NITRIDE $\times 100$
Reduced by One-fourth

Made in laboratory. The rounded gray grains are bright yellow and are probably fairly pure nitride. The white substance is probably carbide, and the black, oxide. Not etched.

FIG. 11—STEEL CONTAINING TITANIUM NITRIDE $\times 400$
Reduced by One-fourth

Pink crystal in longitudinal section from web of titanium-treated steel rail. Not etched.

FIG. 12—STEEL CONTAINING TITANIUM NITRIDE $\times 200$
Reduced by One-fourth

The three larger spots are pink crystals in cross section of web of titanium-treated steel rail. Not etched.

FIG. 13—ALUMINA SEGREGATION IN UNTREATED RAIL $\times 200$
Reduced by One-eighth

Inclusions in the cross section of the web of an untreated rail. These are dark bluish gray in color. By chemical analysis 0.003 per cent of alumina was found here. Not etched.

FIG. 14—SILICATE SEGREGATION IN UNTREATED RAIL $\times 200$
Reduced by One-eighth

Silicate, or slag, inclusions in a cross section of the web. Not etched.

lighter than the metal, has a strong tendency to rise; in rising while the metal is in a pasty condition, part liquid and part solid, it opens up passages through the steel, and each bubble of gas will take with it a little of the higher carbon liquid toward the top and center of the ingot leaving the solid lower carbon material behind. This action, multiplied many times by the millions of gas bubbles given off, will result in the formation of a large body of higher carbon material in the upper part of the ingot, or in other words, there

have an effect on segregation similar to that of titanium, but with vanadium the cost of this effect would be higher, and with the cheaper agents, silicon and aluminum, not only would the cleansing action of the titanium dioxide be lacking, but impurities (silicates or alumina) would be added to the steel. In this connection it should be noted that in most rail steel that has been properly treated with titanium, very small, hard, angular, pink inclusions can be found with the microscope. These are titanium nitride, possibly

contaminated with carbide, and show that the titanium has combined with some of the nitrogen dissolved in the steel, and separated it in this form. An average of many nitrogen determinations made in our laboratories by an improved method on titanium-treated rails shows a distinctly lower amount present in solution in the metal, than in untreated rails. No method is known for determining nitrogen that is combined with titanium in this form. Thus the dif-

this form than any other non-metallic inclusions of the same size. As the titanium nitride inclusions are never found segregated in groups or streaks, as are alumina and silicates, but are always very small, scarce, and thinly scattered, their weakening effect on the metal is practically negligible. They have been found in titanium-treated steel axles as well as rails but not in steel castings nor soft steels, where smaller amounts of titanium have been used.

FIG. 15—SULFIDE SEGREGATION IN UNTREATED RAIL $\times 200$

Reduced by One-eighth

Inclusions in a cross section of the web. A group like this would appear as a pure black spot on a sulfur print. Not etched.

FIG. 16—SULFIDES IN TITANIUM-TREATED RAIL $\times 200$

Reduced by One-eighth

Typical inclusions with one small dark slag inclusion (right). This shows the dirtiest spot found in the cross section of the web of a treated rail. Not etched.

FIG. 17—BADLY SEGREGATED UNTREATED RAIL $\times 100$

Reduced by One-twentieth

Cross section of the upper part of the web showing very brittle structure. The dark constituent is cementite or iron-carbide and the light constituent is pearlite. Etched with boiling alkaline sodium picrate.

FIG. 18—TYPICAL TITANIUM-TREATED RAIL $\times 400$

Reduced by One-twentieth

Center of head, showing normal structure: laminated pearlite, sorbite, and considerable ferrite, with a few gray sulfide globules. Etched with picric acid. (Bessemer steel.)

ference in nitrogen content of the metal may be due merely to the locking up of some nitrogen by titanium in the pink inclusions, or also partly to the actual removal of nitrogen from the liquid steel bath. At any rate, if it is assumed that nitrogen has an injurious effect on steel, the lower amount found by analysis must be an advantage, for even if the whole amount removed from the metal itself is still present in the pink inclusions, it could have no more ill effect in

It is an unfortunate fact that some so-called "titanium-treated" steels have not been any better in regard to segregation than the average untreated steel. These have constituted, however, an insignificant percentage of the total number examined in our laboratories. In every case these segregated "treated" rails have not shown a titanium content of over 0.005 per cent (the average treated rails are well above this figure) and the pink nitride inclusions have also been

absent from them. These facts indicate that not enough titanium was actually added in these heats to produce the usual effects; either the heats were badly oxidized, and needed more than the usual amount of titanium, or some of the alloy was lost or wasted in the slag. It is well known that chemical reactions do not in most cases proceed rapidly to completion when only the theoretical amount of reagent is applied, but an excess of greater or less amount is usually needed. In the case of deoxidation of steel with titanium, the excess necessary is probably at least 0.005 per cent, which, it will be admitted, is a very small amount.

Having now explained the reasons for the addition of titanium to steel, and its general effects thereon, it may be of interest to give some concrete examples of the improvement, shown by testing machines and in actual service, of titanium-treated steel as compared with plain untreated steel of the same general composition. It must be emphasized again that as the amounts of titanium found in treated steels are entirely negligible, so no change in microstructure of the steel is caused by it, and the physical properties are no better than are theoretically possible with perfectly clean and sound steel of the given composition. Our most complete knowledge on this subject has been acquired with rail steel, and forty-two samples of plain and treated Open-Hearth steel rails have been exhaustively tested, physically and chemically, in our laboratories. For this purpose the samples have all been taken from the "A rails," or first rails rolled from the ingots, after the usual discards from their tops, thus representing in each case metal from the top part of an ingot, which would show the greatest amount of segregation and impurities. The "A" rails from which samples were to be taken were chosen at random from the products of various mills and at different times by the manufacturer's or the purchasing railroad's representatives, but the samples were always taken in pairs, one treated and one untreated from each rolling, so that in the final comparison the influence of the conditions of manufacture could be as far as possible eliminated. All samples submitted were tested impartially, with the same care and by the same methods, and the results have been published in our Rail Report Bulletins. The final averages of all the results are given on page 94.

Chemical analyses were made at four places on each rail: top of head, center of head, web, and flange. The lowest and highest figures for each rail were averaged, giving the average low and high results here reported.

The Landgraf-Turner endurance machine bends a thin test-bar backward and forward through a small angle by quickly alternating blows, and the results

are expressed as alternations endured before fracture. The stresses applied to the test-piece are above its elastic limit.

The White-Souther endurance machine holds a test-bar in the middle, turning it very fast like an axle, while weights are suspended from its ends. The stresses applied are below the elastic limit, and the failure is thus due to fatigue. The results are expressed as revolutions endured, but many test-bars were removed unbroken after thirty or forty million revolutions.

As the above figures represent tests on twenty-one untreated rails, and twenty-one treated rails, with all other conditions kept as nearly alike as possible, it is believed that they possess real value for showing the improvement to be expected in "A" rails when properly

FIG. 19.—TYPICAL TITANIUM-TREATED RAIL $\times 400$: NOT REDUCED
Center of head showing normal structure: laminated pearlite, sorbite, and traces of ferrite. Etched with picric acid. (Open-Hearth steel.)

treated with titanium. The improvement in other rails, from lower positions in the ingots, would be much less marked, but the rails that give most of the trouble in service are the segregated "A" rails; these are rendered practically as uniform and homogeneous as other rails by treatment with titanium. Titanium-treated rails are not better, probably, than the best possible untreated rail, but by this treatment the general standard of quality is unquestionably raised, uniformity is more nearly attained, and the bad heats of dangerously segregated or dirty steel are avoided.

In order to acquire still more positive data on the effect of titanium on segregation in rails, seventy-nine "A" rails from different untreated heats and thirty-one similar rails from different treated heats were examined recently by means of sulfur prints and chemical analyses for carbon made on each at an upper corner

of the head and at the junction of head and web. The average difference between these two prints was 17 per cent for the untreated rails, and the worst rail showed 40 per cent, while only 29 of these 79 rails showed less than 12 per cent. For the treated rails the average difference was 3.1 per cent, and the worst one gave 11.5 per cent, none of the 31 showing over this amount.

CHEMICAL ANALYSES PERCENTAGES	UNTREATED RAILS		TREATED RAILS	
	LOW	HIGH	LOW	HIGH
Carbon.....	0.58	0.82	0.63	0.76
Manganese.....	0.71	0.78	0.75	0.79
Phosphorus.....	0.016	0.026	0.018	0.023
Sulfur.....	0.032	0.058	0.031	0.040
Silicon.....	0.117	0.131	0.090	0.099

TENSILE TESTS	UNTREATED RAILS		TREATED RAILS	
	HEAD	FLANGE	HEAD	FLANGE
Elastic limit.....	56,071	55,961	59,738	60,338
Ultimate strength.....	118,138	119,385	124,857	125,690
Elongation, per cent.....	12.8	15.4	13.1	14.4
Reduction of area, per cent.....	14.3	18.5	15.4	18.2

	UNTREATED RAILS			TREATED RAILS		
	Head	Web	Flange	Head	Web	Flange
White-Souther.....	16,550,920			23,923,628		
Brinell hardness.....	220	248	216	226	235	227
Impact resistances.....	1.47	1.08	1.23	1.58	1.21	1.43
Endurance						
Landgraf-Turner....	1312	1001	1324	1280	1084	1270

The impact resistances were measured with a Fremont machine, and are expressed as kilogram-meters expended in breaking a test-piece 7 by 10 mm. in cross-section.

The railroads have been acquiring data for some time in regard to the wear of titanium-treated rails in track, as compared to that of ordinary Open-Hearth rails. The results have been uniformly favorable to the treated rails, in some cases very decidedly so. For instance, on a sharp curve on the Boston Elevated Railway, titanium-treated rails laid alternately with plain rails of practically the same composition showed 41 per cent less wear after 214 days' service. In a test made by the Rock Island Railroad, titanium-treated rails in 17 months had 0.014 sq. in. abraded from their sections, on the average, while electric steel rails showed under the same conditions a loss of 0.058 sq. in., and ordinary rails 0.075 sq. in. Other instances of the same general type might also be given, but enough has surely been said to show clearly the advantages following the use of titanium in rail steel.

In axle steel it has been found similarly advantageous to use titanium for purifying the metal and preventing segregation. In steel castings the use of titanium as a deoxidizer has usually been successful and satisfactory, and in soft steel for plates and thin sheets much titanium is used. This element is preferred to any other deoxidizer because it does not leave any product of its oxidation in the steel as do aluminum and silicon, and the ingots therefore roll out smoother and the finished sheets have a better surface. Small defects on the surface of a sheet are very serious in galvanizing, so that the smoother surface of titanium-treated sheets, due to cleaner ingots, is much appreciated.

A few photomicrographs and sulfur prints are submitted to illustrate some of the points mentioned in this paper, though of course they are not intended to prove much in themselves, but merely to serve as illustrations. It is hazardous to draw conclusions from two or three trials or instances, but an average from forty or eighty tests should surely be trustworthy.

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MANGANESE STEEL¹

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COMPOSITION AND CHARACTERISTICS

Manganese steel was discovered in the early eighties, and since that time has found a place for itself wherever a steel is required that is highly resistant to wear. In the original experiments, the steel was made by mixing molten ferromanganese and carbonless Bessemer blown metal in such amounts as to give various proportions of manganese in the finished product; as a consequence the ratio of the manganese to the carbon was practically fixed, the carbon content decreasing as the manganese was diminished. With less than a certain amount of manganese, the metal proved to be extremely brittle, and in practice the manganese was seldom less than 9 per cent, the steel as generally made containing from 10 to 14 per cent manganese and from 1 to 1.5 per cent carbon. The silicon is generally from 0.2 to 0.5 per cent, the sulfur always very low (about 0.001 per cent), the phosphorus averages from 0.08 to 0.1 per cent. Small variations in the silicon and phosphorus have little effect on the properties of the steel. The sulfur is invariably low, because the manganese of the steel eliminates it by

flotation as MnS . By heating this steel to between 1000 and 1100° C., it can be made, if not of too heavy a section, to consist entirely of the metallographic constituent known as austenite.

More recent researches, in some of which the author has participated, have shown that if the carbon content of the metal is maintained at about 1 per cent, the steel will be austenitic after quenching, even if the manganese content is as low as 5 per cent or even a little less, the range of carbon content within which pure austenite can be obtained being narrow with low manganese content, and widening as the manganese content increases. This can be more readily understood by reference to the accompanying diagram showing part of the manganese steel series, in which the carbon content is plotted as abscissa and the manganese content as ordinate. Within the area WXYZ the steel consists of pure austenite when quenched. Steels immediately to the left of the line $C = 1.075 - 0.04 \text{ Mn}$ are more or less martensitic when quenched; steel immediately to the right of the line $C = 1.075 + 0.1/3 \text{ Mn}$ contain free cementite

¹ Presented before the New York Section of the Society of Chemical Industry, Chemists' Club, November 20, 1914.