PREPARATION AND PROPERTIES OF PURE IRON ALLOYS:

I. EFFECTS OF CARBON AND MANGANESE ON THE MECHANICAL PROPERTIES OF PURE IRON.

By Robert P. Neville and John R. Cain.

ABSTRACT.

This paper describes the preparation and mechanical properties of an extensive series of very pure alloys of electrolytic iron, carbon, and manganese whose compositions were so chosen as to bring out the specific effects on pure iron of additions of manganese, additions of carbon, and additions of carbon and manganese together in varying relative proportions. The maximum content each of carbon and manganese in each series is about 1.6 per cent; the minimum, o per cent, or pure iron.

Three-pound ingots of the alloys were made by melting electrolytic iron under vacuum in an electric furnace in a crucible of pure magnesia to which the carbon and manganese were added after fusion of the iron. From these ingots tensile specimens were made and tested in the annealed state. The data were tabulated in the order of increasing carbon for comparison and interpretation of results. The effects of carbon are shown by grouping the specimens according to manganese contents and plotting curves for each group, with values from tests for ordinates and carbon contents for abscissas. The effects of manganese are shown in a similar manner by regrouping the specimens according to carbon contents.

CONTENTS.

Ι.	Introduction	4I2
II.	Investigations of the effects of carbon and manganese on the mechanical	
	properties of steel	413
III.	Preparation of the alloys	418
	1. Fusion in vacuo	418
	2. Materials used	419
	(a) Iron	419
	(b) Manganese	419
	(c) Carbon	419
	3. Furnaces	420
	4. Crucibles	421
	5. Melting procedure	422
	6. The ingots	424
IV.	Preparation of specimens for testing	425
	1. Mechanical work	425
	2. Samples for chemical analyses	425
	3. Heat treatment	426
	v	

	Page.
V. Properties of the alloys	426
1. Mechanical tests	426
2. Microexamination	427
3. Mechanical properties of pure iron	427
4. Chemical analysis	428
5. Data	429
VI. Interpretation of data	433
1. Effects of carbon	433
2. Effects of manganese	436
3. Combined effects	438
VII. Summary	440

I. INTRODUCTION.

While many of the specific effects of carbon and manganese on the properties of iron are well known and the knowledge is being usefully employed in the processes of manufacture, there remains in spite of many investigations much that is not thoroughly understood. Manganese is known to affect the properties of steel in at least three well recognized ways: (1) When present in sufficient amount it eliminates the red-shortness due to the presence of sulphur, thereby enabling the metal to be worked hot; (2) it deoxidizes or helps deoxidize the steel, thereby eliminating the harmful effects of oxides and gases which in some cases cause brittleness on forging or rolling; (3) it confers definite physical properties. There still remains, however, a lack of knowledge as to the amount of manganese needed for each function. In the hope of adding to the available information concerning this question the Bureau of Standards is conducting investigations on the effects of deoxidizers and alloying elements on iron.

The investigation described in this paper was planned to show the properties of alloys of electrolytic iron, pure carbon, and manganese. The alloys of this series were chosen so as to bring out the specific effects on pure iron of additions of manganese, carbon, and manganese and carbon together in varying relative proportions. Following this investigation of the effects of carbon and manganese on the mechanical properties of the annealed alloys further work is to be undertaken on the effects on the heat treatment of the alloys.

Other phases of the work in progress deal with the rôle of manganese in deoxidation and in reducing or eliminating redshortness. Much of the preliminary work of this investigation and the preparation of the first ingots were done by Dr. A. W. Owens, formerly associate chemist of this bureau.

412

Neville Cain

II. INVESTIGATIONS OF THE EFFECTS OF CARBON AND MANGANESE ON THE MECHANICAL PROPERTIES OF STEEL.

A review of the literature failed to reveal any investigations conducted in a manner similar to the method employed by the bureau which attempted to determine the effects of manganese and carbon on the mechanical properties of pure iron and alloys with carbon and manganese, but for comparison a very brief review of investigations purporting the effects of these two elements on steels of compositions similar to those of our alloys seems essential here.

The investigation by A. Stadeler ¹ makes the nearest approach in similarity to ours of any reviewed. Its scope is restricted to the effects of manganese between the limits of 0.35 and 0.70 per cent. This investigation was on seven series of low carbon basic openhearth steels of very high purity, each of the series with carbon constant within the series (each series varying by 0.01 per cent C. from 0.08 to 0.14 per cent) and manganese in each series varying from 0.3 to 0.7 per cent. The impurities in these steels were the lowest of any steel used in any of the investigations found. Sulphur was from 0.004 to 0.009 per cent, phosphorus from 0.010 to 0.043 per cent, and silicon from 0.004 to 0.009 per cent.

In these series manganese increased the ultimate strength from 149 to 284 lbs./in.² for each 0.01 per cent manganese. There seems to be no relation between this variation in the effects of manganese and the difference in carbon contents of the series. Elongation and reduction of area were not influenced by manganese.

An investigation with a similar purpose by Lang² covers a wider range of manganese, from 0.28 to 2.47 per cent. He prepared a series of 11 alloys by drawing small ladles from a heat of low carbon electric steel, to which he added varving amounts of manganese before pouring in sand molds.

The impurities in this steel were very much greater than those in the former steel—Si, 0.286 to 0.324 per cent; S, 0.045 to 0.059 per cent; P, 0.04 to 0.11 per cent; Cu, 0.123 to 0.167 per cent. Although the conditions which obtained in this investigation were more favorable for comparison than those of many investigations of a similar nature, the manganese used contained phosphorus as an impurity in sufficient amounts to make the increase in phosphorous content with the increase in manganese quite noticeable.

¹A. Stadeler, Einfluss des Mangans auf die Mechanischen und Strukturellen Eigenschaften Niedriggekohlten Flusseisens Gewohnlicher Handelsqualität Zeitschrift für anorganische chemie, 81, p. 61, 1913.

² George Lang, Über den Einfluss des Mangans auf die Eigenschaften des Flusseisens, Metallurgie, 8, p. 15 and p. 49, 1911.

Scientific Papers of the Bureau of Standards.

[Vol. 18

Lang concluded that the effect of manganese was not constant. Up to a content of 3 per cent its average strengthening effect was 220 lbs./in.² for each 0.01 per cent. In amounts below 1.5 per cent it raised the Brinell hardness numbers about 0.5 for each 0.01 per cent. Reduction of area and elongation were practically uninfluenced by manganese in amounts below 1.5 per cent, and above this both were very rapidly reduced by increasing amounts. Likewise, in amounts below 1.5 per cent, manganese increased the resistance to shock. Up to 1.8 per cent its effect was less, and in amounts above 1.8 per cent it decreased the resistance to shock.

No other references were found in which the investigator made the steel used in his work. Some investigations take the form of tabulations from numerous routine tests from which attempts were made to deduce formulæ and construct curves. Sometimes attempts were made to eliminate as far as possible the effects of elements not under consideration by the manner in which the data were tabulated. In other cases some degree of control over these variables was attempted. The specimen to be used in the comparison were selected from the mills' output in the manner most favorable for bringing out the influence of the elements under consideration. Other investigators used formulated corrections for elements present, but not under consideration, in determining the effects of carbon and manganese. Some were measurably successful in securing from the mills specimens of specified compositions to be tested specifically for their purpose.

A study or comparison of investigations of this nature for steels is rendered more difficult not only by the fact that the chemical compositions of the specimens used were usually not well controlled and the different investigations were on ranges of compositions frequently widely separated, but also in that there were often variations other than those of composition within a series such as method of manufacture (basic open hearth, Bessemer, etc.), mechanical working, heat treatment after working, and various other factors.

Of the investigations following the method of tabulating data from routine mill tests in such a manner as to bring out the specific effects of the elements Webster's is the most extensive.³ According

³ W. R. Webster: Observations on the Relations Between the Chemical Constitution and the Physical Character of Steel. Trans. Amer. Inst. Min. Eng., 21, p. 766, 1892-3; Further Observations on the Relations Between the Chemical Constitution and the Physical Character of Steel, Trans. Amer. Inst., Min. Eng., 23, p. 113, 1893; Observations on the Relations Between the Chemical Constitution and Ultimate Strength of Steel, Iron and Steel, Inst., 45, p. 328, 1894, No. I; Application in Rolling of Effects of Carbon, Phosphorus and Manganese on the Mechanical Properties of Steels, Blast Furnace and Steel Plant, 9, p. 555, 1921; Abstract, Iron Age, 107, p. 982, 1921.

to his observations, extending over a period of many years, in basic open-hearth steel, carbon, within the limits of 0.10 and 0.40 per cent, increases the ultimate strength from 782 to 1,054 lbs./in.² for each 0.01 per cent carbon. The first value worked out for the limits of 0.07 to 0.18 per cent carbon was 800 lbs./in.² for each 0.01 per cent. In acid Bessemer steels he found carbon to increase the ultimate strength 1,000 lbs./in.² for each 0.01 per cent.

At first only manganese contents below 0.65 per cent were considered. In amounts under 0.20 per cent manganese increased the ultimate strength 240 lbs./in.² for each 0.01 per cent, and above 0.20 per cent, as its content increased, its strengthening effect gradually decreased until a value of 100 lbs./in.² for each 0.01 per cent was reached at 0.50 per cent, after which it was constant. A later investigation on steels containing manganese between 0.34 and 0.58 per cent found manganese to increase the ultimate strength at a fairly constant rate of 170 lbs./in.² for each 0.01 per cent.

From a tabulation of data from nearly 2,000 tests on steels from the Pennsylvania Steel Works, H. H. Campbell⁴ found the increase in ultimate strength of acid steels due to carbon to be 1210 lbs./in.² and of basic steels, 950 lbs./in.² for each 0.01 per cent carbon. For the basic steels he found manganese to increase the ultimate strength 85 lbs./in.² for each 0.01 per cent.

After a second and more extensive investigation⁵ on both acid and basic steels (manganese under 0.60 per cent, carbon between 0.10 and 0.50 per cent), in which more precautions were taken to eliminate the effect of variables, his conclusions were: In acid steels carbon increases the ultimate strength 1,000 lbs./in.² and manganese 80 to 400 lbs./in.² (the increase is with the increase in the carbon content) for each 0.01 per cent. Small amounts of manganese with very low carbon decrease the ultimate strength. In basic steels carbon increases the ultimate strength 770 lbs./in.² and manganese 130 to 250 lbs./in.² for each 0.01 per cent.

Brinell⁶ found the average rate of increase in the ultimate strength, due to carbon, of 1,500 heats of open-hearth steel to be 1,032 lbs./in.² for each 0.01 per cent up to 0.80 per cent. The average for manganese was 197 lbs./in.² for each 0.01 per cent.

⁴H. H. Campbell, The Manufacture and Properties of Structural Steel, Hill Pub. Co. New York, 1891. ⁵H. H. Campbell, The Influence of Carbon, Phosphorus, Manganese, and Sulphur on the Tensile Strength of Open-Hearth Steel, Trans. Amer. Inst. Min. Eng., 35, p. 772, 1904. Also Iron and Steel Inst., 66, p. 21, 1904, No. II.

⁶ Axel. Wahlberg, Brinell's Method of Determining Hardness and Other Properties of Steel, Iron and Steel Inst., 59, p. 243, 1901, No. I, and 60, p. 234, 1901, No. II.

The mean rate of increase in hardness due to manganese was 0.04 Brinell hardness numbers for each 0.01 per cent. Variations in the influence of the elements at different contents can be seen in Figures 1 and 2.

In an investigation by J. H. Nead⁷ 12 ordinary commercial steels from regular mill stock were used. These steels, received



FIG. 1.—Curves from foremost investigations on the effects of carbon on the ultimate strength of steels.

as 1-inch bars, were carefully selected as to compositions and treatment, and all the work of testing carried out in the manner most favorable for bringing out the effects of carbon. An attempt was made to have the manganese constant throughout the series. In this investigation for the annealed specimens the

[Vol. 18

⁹ J. H. Nead, The Effect of Carbon on the Physical Properties of Heat-Treated Carbon Steel, Bull. Amer. Inst. Min. Eng., 1915, p. 2341.

Neville Cain

average rate of increase in ultimate strength due to carbon between the limits of 0.14 and 0.7 per cent was 1,000 lbs./in.² for each 0.01 per cent. Curves in Figure 1 show the variation of this rate with the increase in carbon.



FIG. 2.—Curves from foremost investigations on the effects of manganese on the ultimate strength of steels.

J. O. Arnold⁸ first attributed to carbon an increase in ultimate strength of 860 lbs./in.² for each 0.01 per cent. A later investigation⁹ gave values of from 950 to 1,025 lbs./in.² Cunningham,¹⁰ working on Campbell's data, found carbon to increase the ulti-

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⁸ J. O. Arnold, The Physical Influence of Elements on Iron, Iron and Steel Inst., 45, p. 107, 1894, No. I. ⁹ J. O. Arnold, The Influence of Carhon on Iron, Proceedings Inst. Civil Eng., **123**, p. 127, 1895-6, No. 1.

¹⁰ A. C. Cunningham, The Relation of Tensile Strength to Composition in Structural Steel, Papers Amer. Soc. Civil Eng., 23, p. 231, 1897.

mate strength at a rate of 1,000 lbs./in.² for each 0.01 per cent. Deshayes¹¹ found manganese under 0.50 per cent increased the ultimate strength from 255 to 285 lbs./in.² for each 0.01 per cent. Vosmaer,¹² Salom,¹³ and Harbard found rates of increase for carbon in low carbon steels to be from 800 to 1,000 lbs./in.² for each 0.01 per cent. Gatewood¹⁴ got values somewhat lower, from 420 to 665 lbs./in.²

After an extensive compilation of data and comparative study of many similar investigations, H. M. Howe emphasized principally that the specific effects of elements can not be quantitatively expressed. However, he placed limits. In low carbon steels the ultimate strength is increased at a rate falling between 665 and 1,000 lbs./in.² for each 0.01 per cent carbon and by manganese at an average rate of 197 lbs./in.² for each 0.01 per cent.

J. E. Stead ¹⁵ has made an excellent review of investigations of the effects of the elements on steel. After this survey of the literature he was of the opinion that carbon raised the ultimate strength of steel a little less than 900 lbs./in.² for each 0.01 per cent.

Figures 1 and 2 are curves constructed for all these investigations in which sufficient data were given. These serve to show how the effects of carbon and manganese vary for different contents and to compare the results of investigations.

III. PREPARATION OF THE ALLOYS.

1. FUSION IN VACUO.

Since the purpose of the work was to study the specific effects on iron of carbon and manganese uninfluenced by other elements, it was necessary to exercise great care to have conditions such that other influences would be reduced to a minimum. This not only required that the impurities in the alloys be the lowest possible, but also that especial consideration be given the method of fusion.

The influence of gases on the properties of metals are being more and more recognized to be of importance. Metals are known to contain relatively enormous amounts of gases either dissolved, occluded, or in chemical combination which are known to very

¹¹ H. M. Howe, The Metallurgy of Steel, 1, p. 14.

¹² Vosamer, The Mechanical and Other Properties of Iron and Steel in Connection With Their Chemical Constitution, p. 17.

¹³ P. G. Salom, Physical and Chemical Tests of Steel for Boiler and Ship-Plate for the United States Government Cruisers, Trans. Amer. Inst. Min. Eng., **12**, p. 661, 1883-4.

¹⁴ Report of Naval Advisory Board on Mild Steel, 1885, p. 184.

¹⁵ J. E. Stead, Influence of some elements on the mechanical properties of steel, Iron and Steel Inst., 94 p. 5; 1916, No. II.

greatly affect their properties. On this account, in order that these influences might be obviated, the melting of the alloys were all conducted in vacuo.

2. MATERIALS USED.

(a) IRON.—If the alloys were to have the desired minimum impurity, only the very purest of materials could be used. The iron from which the alloys were made was purified by the electrolytic method regularly practiced at this bureau for obtaining very pure iron. This method has been previously described.¹⁶ Minor modifications of the method have been developed in practice.

The anodes used now are 1-inch plates of "Armco" ingot iron. The cathodes are rolled sheets of the same material of about one-eighth inch thickness. The electrolyte is a 25 to 30 per cent solution of ferrous chloride made by dissolving "Armco" iron in 1:1 chemically pure hydrochloric acid. When the deposit of electrolytic iron is about 5 mm thick, it is stripped from the cathode, washed, and dried as quickly as possible. Washing in hot water then twice in alcohol and igniting the alcohol covered pieces has proved the best method. Even after careful drying electrolytic iron oxidizes slowly in air. However, it may be kept bright and free from oxide if stored in a dessicator over calcium chloride. The iron as deposited is brittle, a feature which is undoubtedly the result of occluded hydrogen, and has a more or less spongy structure, depending on the speed of deposition. Hence, it may be easily broken into small pieces.

As deposited the iron normally contained the following percentages of impurities: C, 0.004; S, 0.004; Si, 0.001; Cu, Ni, and Co together, 0.014. When fused into ingots, the impurities were slightly increased with maximum values: C, 0.02; S, 0.008; Si, 0.008; Cu, Ni, and Co together, 0.014 per cent. The carbon entering during fusion came from the graphite resistance heater of the electric furnace employed for melting the iron.

(b) MANGANESE.—Manganese of 98.75 per cent purity was used. The 1.25 per cent impurity in the manganese consisted mainly of iron, with a very small per cent of carbon. The nature and amount of these impurities were such as to make them of no consequence.

(c) CARBON.—The carbon used was powdered Acheson graphite. It was not, however, added in this form. The method employed

¹⁶ J. R. Cain, E. Schramm, and H. E. Cleaves, Preparation of Pure Iron and Iron-Carbon Alloys, B. S. Sci. Papers, No. 266.

was to prepare a saturated iron carbon alloy by melting pure electrolytic iron with as much graphite as it would dissolve. For this a No. 20 plumbago crucible was lined with a half-inch coating of powdered graphite moistened with a 1:1 solution of glucose in water. This was done by tamping the moistened graphite around a mandrel frequently turned a little so it might be easily removed. The lined crucible was dried several hours in an oven at about 150° C., after which it was ready for the charge. The graphite liner served to prevent contact of the melt with the walls of the plumbago crucible, thereby preventing contamination. It also insured the complete saturation of the iron, for if insufficient carbon had been added or that added was burned out in the gas furnace more would be absorbed from the graphite walls of the container.

Crushed electrolytic iron was placed in the crucible as compactly as possible, through which was sprinkled an amount of the pure powdered graphite equivalent to 4.75 per cent of the weight of the iron. The charge was then melted in a gas-fired crucible furnace, kept molten long enough to insure complete saturation and allowed to cool with the furnace. The carbon content was in all cases very close to 4.45 per cent. Variations from this never amounted to more than a few hundredths per cent either way. These high carbon ingots were then sawed into small pieces of such sizes as were required for securing desired carbon contents in the alloys. This method was advantageous both in convenience and in facilitating the obtaining of ingots of definite carbon percentages.

3. FURNACES.

Experiments previously conducted at this bureau ¹⁷ indicated the Arsem type of vacuum furnace to be the best of the available furnaces for preparation of pure iron alloys. It imparted the least amounts of impurities (provided suitable crucible material was used and proper precautions taken) and permitted the melting to be conducted under vacuum, which was to be a special feature of the present work. Melting in vacuo was not only important in the removal of gases for the sake of having gas-free alloys, but also was necessary in order to secure ingots sufficiently free from blowholes without the use of deoxidizers.

All ingots prepared in this investigation were melted in Arsem furnaces of 25-kilowatt capacity, capable of attaining a tempera-

¹⁷ See note 16.

Neville Cain

ture of 1,800° C., although the temperature used was usually not over 1,700° C. The maximum power used was 21 kilowatts. The only impurity usually imparted in any significant amount during this procedure was carbon, which for the greater portion of the ingots was a normal constituent. By keeping the vacuum as high as possible the carbon in the ingots was usually not increased more than 0.01 per cent. It was necessary to use first quality Acheson graphite for the helical heaters to avoid contamination from volatilization by sulphur and silicon contained in other forms of carbon.

For the calcination of crucible material and for melting the high-carbon alloy gas furnaces were used. These furnaces were lined with zirkite brick and equipped with air-injector burners, so that a temperature of 1,600 to 1,700° C. could be attained.

4. CRUCIBLES.

Difficulties in obtaining suitable crucibles in which to melt the alloys led to special investigations on making refractory materials and methods of molding crucibles, details of which it may be possible later on to publish. In the previous work on the preparation of pure iron and iron-carbon alloys it was found that chemically pure magnesia was the most easily available material that would meet all requirements. Crucibles used in the work just mentioned were satisfactory enough for melting the small ingots then used, but since larger ingots were desired for the present investigation the difficulties were very greatly increased. The size and shape of the melting chamber of the furnace made it necessary for the crucibles to be very tall with thin walls if ingots of the desired size were to be secured. This made the matter much more difficult; so much so that the question of refractory crucibles was no little one in itself.

After many varied and always unsuccessful attempts at molding crucibles the following method was developed: Graphite shells of dimensions adapted to the size of the heating chamber of the furnace were turned on the lathe from solid pieces of Acheson graphite. These shells were then lined with the magnesia refractory. This was done by tamping the finely ground moistened material around a mandrel. The mandrel was removed and the magnesia-lined graphite crucible dried in an oven at about 120° C. After this it was calcined in the Arsem furnaces at a temperature higher than that to which it would be subjected during the melting of the alloy. This calcination caused the magnesia liner to shrink

[Vol. 18

away from the graphite shell. The method of taking care of this shrinkage is described below.

Electrically fused magnesia most satisfactorily met the requirements of a refractory for this investigation, but it has been found very difficult to fuse pure magnesium oxide without its taking up an excessive amount of silicon. The magnesia used in the preparation of the first ingots was prepared by the method¹⁸ devised in the former investigation.

A new method for the preparation of refractory magnesia was developed during the course of the investigation which entirely replaced the old acetate method. U. S. P. magnesium sulphate was dehydrated in a gas-fired semimuffle furnace, after which it was calcined at 1,700° C. for about five hours in alumina-lined plumbago crucibles in a large gas furnace. The magnesium sulfate is almost completely converted to MgO by this treatment and the residual magnesium sulfate is removed by washing in hot water. Briquetting magnesium carbonate with a solution of glucose in water, drying and firing for several hours in a gas furnace at about 1,700° C., also served satisfactorily.

Magnesia prepared by any of these methods sinters much better when some other material is mixed with it to serve as a binder. A mixture of one part pure calcined alumina to nine parts of magnesia was found satisfactory. Later it developed that magnesium fluoride in small proportions served even better.

5. MELTING PROCEDURE.

Since ingots approximating in size the capacity of the crucibles were desired and the charges before fusion occupied a much larger volume, it was necessary to use a chimney to contain the excess iron which, as it melted, settled down into the crucible below.

A magnesia crucible was placed inside the graphite shell in which it was made and calcined. Then the intervening space between the walls of the shell and crucible was filled with powdered graphite to support the magnesia against the pressure of the molten iron, since magnesia is very frail at the temperature at which iron melts. The crucible thus supported was filled with a weighed portion of the crushed electrolytic iron. A similar crucible, but without a bottom, was inverted over this one to serve as a chimney. This chimney was almost entirely out of

¹⁸ Grecian magnesite was dissolved in acetic acid, the solution evaporated to dryness, and the solid magnesium acetate converted to the oxide and shrunk by successive calcinations in the gas and Arsem furnaces. See note 16.

the heating zone, but the lower portion became quite hot, due to its proximity to the crucible containing the melt, just below. The remainder of the weighed portion of iron was loosely placed in the chimney, so that it would sink as the iron below melted. Sometimes trouble was caused by the iron bridging across the top of the crucible, due to partial fusion at this point and failing to sink down.

The first method employed for the addition of the high-carbon alloy and manganese consisted in suspending pieces of calculated weights by a fine iron wire from a small iron cross wire between two binding posts set in the top of the furnace.¹⁹

After all the iron was melted and ready for the addition of the manganese and high-carbon alloy, the iron-supporting wire was fused by the passage of an electric current, which allowed the charge to drop into the crucible. In our work it was found that the dropping of this charge upon the molten iron produced a splash that often caused part of the melt to be lost unless the molten metal was allowed first to solidify superficially. Invariably there was a strong ebullition when the carbon alloy dissolved, but this violence was lessened when the carbon and manganese were added after the beginning of solidification. The method subsequently employed was to place the manganese and carbon additions in the chimney on top of the iron, so they would sink into the molten metal last, thus remaining in the cooler part of the furnace until the larger portion of the charge was melted.

During melting the furnace was evacuated to 0.5 to 1 cm mercury, which was as good a vacuum as could be had with the pumps and furnaces used. The power was turned on in increments of 5 kilowatts until a maximum of 20 kilowatts was reached. The iron melted in about an hour's time. If the additions were not added by placing in the chimney on top of the loose iron, the furnace was allowed to cool to the desired temperature and the charge dropped. After the manganese and carbon had been added the melt was held at a temperature of 50 to 100° C. above its melting point to insure thorough diffusion, as no stirring was possible.

Chemical analyses of samples from different parts of the first ingots prepared showed the manganese and carbon contents were lower in the bottom part of the ingot because of poor diffusion due to insufficient fluidity of the melt. This difficulty was over-

¹⁹ This method was taken from Yensen and Gatward's paper, "Magnetic and other properties of Iron aluminum alloys melted in vacuo," University of Illinois, Eng. Exp. Station Bull. No. 95, p. 11.

come by keeping the charges well above their melting points for about 30 minutes after fusion. Ingots prepared in this way were entirely homogeneous, with no signs of segregation. Unless the melt was carefully watched at this stage disastrous results were liable to follow. If the temperature was allowed to go too high, strong agitation set in, which, unless the temperature was decreased, would become so violent as to eject a large portion of the melt. If this happened, the graphite heater of the furnace was damaged or the magnesia crucible was liable to break and the melt be lost. Since the range between the minimum temperature for thorough diffusion and the temperature at which this agitation became violent was rather narrow, many melts were lost in this way. The temperature at which this agitation began was quite definite for each composition, being lowered as the carbon increased. This agitation was advantageous in securing thorough mixing. However, its advantageous utilization was hindered by the difficulties of control. This phenomenon, whether actual boiling or escaping of gases, was observed in melts of all compositions from pure iron to the alloys of the highest carbon and manganese content. It had the characteristics of real boiling and it would repeatedly begin or stop at a definite point as the temperature increased or decreased. After the charge had been kept molten about 30 minutes the power was cut off and the vacuum maintained while the furnace cooled down.

After an average of about 25 runs, including both crucible calcinations and melts, the furnace had to be taken apart and a new heater installed. Heaters were in nearly every case broken through accident rather than burned out. Owing to accidents due to causes just described and others, the preparation of the ingots was a long and tedious task. Successful runs constituted about 45 per cent of those attempted ("successful" meaning ingots low enough in impurities and suitable for rolling).

6. THE INGOTS.

The ingots were about $1\frac{3}{4}$ inches in diameter at the top, $1\frac{3}{8}$ inches at the bottom, and about $8\frac{1}{4}$ inches long, except in cases where part of the melt was lost by too much agitation. The ingots were all free from blowholes and sound, except that there was in the majority of them either a pipe with a small pinhole near the top opening into a larger cavity inside or else a contracted area all around the ingot near the top like a neck. Whenever there was a "neck" there was never an interior pipe, and

[Vol. 18

vice versa. A few ingots had neither this contracted "neck" area nor a pipe with an external opening. One of these was split longitudinally, and an internal pipe was found near the top, but not opening to the outside. Evidently there is always a certain amount of shrinkage on solidification which may take place in any one of these three ways.

As a check on the work during preparation of the ingots samples were taken from the bottoms of the ingots for carbon and manganese determinations to see if the compositions of the ingots compared with those calculated. The compositions given in Table 2 were from analyses of samples taken as described later.

IV. PREPARATION OF SPECIMENS FOR TESTING. 1. MECHANICAL WORK.

The ingots were hot rolled.²⁰ The starting temperature was $1,100^{\circ}$ C. and the finishing temperature approximately 900° C. The first passes were longitudinal, the reduction being 10 per cent until a length of 10 or 12 inches was reached, after which the remainder of the rolling was crosswise, with 7 per cent reductions, to a minimum thickness of one-half inch. After the end discards had been made the plates were approximately 9 inches long and 2 inches wide. The majority of the ingots rolled well with no flaws, but occasionally pipes in some ingots caused flaws which made it difficult and in some cases entirely impossible to get bars from the rolled specimens for tension tests. The first eight ingots were forged to $\frac{3}{4}$ -inch round bars, but because of better facilities all of the rest were rolled.

Bars $\frac{3}{4}$ by $\frac{1}{2}$ by 6 inches from which the test specimens were to be turned were cut from these plates. Two bars were cut from each plate (in a few cases defects in the plate permitted only one) in order that there might be a check on each composition. It was necessary to anneal some of the plates before they could be machined, but usually they could be worked without thermal treatment. These bars were turned down to tensile test specimens with a gauge length of 2 inches and 0.38 inch diameter, with threaded ends. After heat treating, as described below, the specimens were ground down along the entire length of the reduced section to a diameter of 0.357 inch.

2. SAMPLES FOR CHEMICAL ANALYSIS.

The last of the lathe turnings from cutting the reduced section down to the required diameter were saved as a sample for chemical

Neville Cain]

²⁰ We wish to thank R. G. Waltenberg and A. T. Derry, associate physicists, for rolling the ingots. 111637°-22-3

[Vol. 18

analysis. The turnings from the two bars made from the same plate were collected as one sample, thoroughly mixed, and analyzed.

3. HEAT TREATMENT.

It was considered advisable to subject all samples to a preliminary annealing in order to compensate for possible ingotism. Accordingly, the test bars were divided in three groups, according to the carbon content, irrespective of the manganese content. The first group contained those with carbon percentages from 0.0 to 0.09; the second group, 0.10 to 0.29; the third group, 0.30 to 1.50. The bars were heated in a mixture of magnesite and a small amount of charcoal to a temperature of 940° C. for the first group, 900° C. for the second, and 840° C. for the third, held at these respective temperatures for two hours, then cooled in the furnace to below 500° C.

Since it was desired to use an annealing temperature of approximately 30° C. above the end of the Ac₃, the bars were grouped as shown in Table 1.

Range of C.	Temperature for speci- mens of 0-0,79 per cent Mn. Temperature for speci- mens of 0.80-1.50 per cent Mn.		Range of C.	Temperature for speci- mens of 0-0.79 per cent Mn.	Temperature for speci- mens of 0.80-1.50 per cent Mn.
0.0 -0.09 .1019 .2029 .3044	°C. 940 915 885 845	°C. 915 885 860 830	0,45–0.59 .60– .74 .75–1.50	°C. 815 785 770	°C. 800 785 770

TABLE 1.-Normalizing Temperatures.

The specimens of each group as listed in the table were then heated in an electric muffle furnace containing burning charcoal to the temperature designated in the column corresponding to that group, held at that temperature for 20 minutes, removed from the furnace, and cooled in still air.²¹

V. PROPERTIES OF THE ALLOYS.

1. MECHANICAL TESTS.

The tension tests were made on a 50,000-pound Amsler hydraulic testing machine which has 10,000, 25,000, and 50,000 pound ranges.²² A Ewing strain gauge was used to obtain the data for stress-strain curves. The specimens were the threaded-end type

²¹ We are indebted to H. J. French, physicist, for thermal analyses and heat treatment.

²² We wish to acknowledge the valuable assistance of J. R. Freeman, jr., associate physicist, in performing the tension tests.



Scientific Papers of the Bureau of Standards, Vol. 18

FIG. 3.—Typical microstructures representative of the alloys of the lowercarbon half of the series.

Scientific Papers of the Bureau of Standards, Vol. 18



FIG. 4.—Typical microstructures representative of the alloys of the highercarbon half of the series.

whose reduced sections were 0.357 inch in diameter and 2 inches long. The method of conducting the tests was according to the usual standard practice.

Brinell hardness determinations were made upon each broken tension specimen, the side of which had been previously ground to a flat surface and slightly polished. Three impressions made under standard conditions were used for each bar. The averages of these values are the points shown in the curves.

2. MICROEXAMINATION.

All the bars were examined under the microscope to detect any discrepancy in heat treatment or irregularity of structure.²³ In order that the surface examined might be as near the fracture as possible and yet not in the strained portion of the test bar, the fractured ends were sawed in two at the shoulder and the microexaminations made on this cross section. Photomicrographs were made of a sufficient number of specimens to include all compositions included in the series. There were a few specimens very closely approximating others in composition, wherefore it seemed superfluous to photograph both; but to assure that nothing had been overlooked in any instance all specimens not photographed were examined visually.

The microstructures of the alloys will be treated in Part III; however, a few photographs are included here to show the structures of the compositions included in the series. Figures 3 and 4 are 11 photomicrographs of 6 specimens so selected as to represent the entire range of compositions included in the series. These are the structures of the specimens after final heat treatment, the condition in which they were tested.

3. MECHANICAL PROPERTIES OF PURE IRON.

Owing to the numerous estimations of the mechanical properties of pure iron and the very few actual determinations, attention is called here to values obtained for the specimens of pure iron. The ultimate strengths of the two specimens were 41,700 and 42,200 lbs./in.² The elongations in 2 inches were 40.0 and 41per cent, the reductions of area were 80.0 and 85.0 per cent (0.357-inch specimen), and the Brinell hardness numbers 70.

Vensen²⁴ obtained for six pure iron specimens ultimate strengths of 35,500 to 41,600 lbs./in.² whose average was 38,100 lbs./in.²

Neville Cain]

²³ We are indebted to H. S. Rawdon, physicist, for microexamination and photomicrographs.

²⁴ T. D. Yensen, Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo, University of Illinois, Eng. Exp. Station Bull. No. 72, p. 29.

428

The average elongation in $1\frac{1}{2}$ inches was 51.8 per cent. The average reduction of area was 87.4 per cent (diameter of reduced section 0.3 inch). The heat treatment of these specimens included a more drastic annealing than our normalizing treatment.

Escard ²⁵ has reported an ultimate tensile strength of 42,000 lbs./in.² for the electrolytic iron made at Grenoble, while Goerens and Fischer ²⁶ have given 43,000 lbs./in.² for the ultimate strength of a Swedish "soft iron" containing C, 0.057; Mn, 0.097; S, 0.02; Si, 0.01; P, 0.01 per cents. The elongation of the Grenoble iron was 40.3 per cent; that of the Swedish iron 47.0 per cent.²⁷ The reduction of area of the latter was 80 per cent. Escard did not give the reduction of area for the Grenoble iron.

4. CHEMICAL ANALYSIS.

Since the iron was all from the same source and there was little chance for contamination by elements other than carbon, sulphur, and silicon, analyses²⁸ for only these three elements and for manganese were made on every sample. The samples were the lathe turnings taken as previously described. Analyses on samples from the broken specimens were also made later, as will be described below. Carbon was determined by the direct-combustion soda-lime absorption method, manganese by the bismuthate method, silicon by Drown's method, and sulphur by evolution. Phosphorus was determined on a few representative samples but was never found in determinable quantities. Since the anodes used in the electrolytic purification method contained small amounts of copper, cobalt, and nickel, analyses for these were made of two or three samples.

Even though the samples used in these analyses were the last of the lathe turnings obtained in cutting the reduced section of the tension specimens down to measurement, and therefore the farthest from the surface, slight decarburization was thought possible in some instances, since the plates from which the specimens were cut were little thicker than the specimens themselves, thereby making it possible for warping of the plate to have caused some of these turnings to have been from very near the surface. Also, although all tests for inhomogeneity of the ingots prepared after the technique of melting had been worked out indicated no

[Vol. 18

J. Escard, Fabrication et Properties Industrielle du Fer Electrolytique, Le Genie Civil, 75, p. 199, 1919.
P. Goerens and F. P. Fischer, Über Weicheisen, Electrochem. Zeit., No. 27, p. 1, 1920.

²⁷ Gauge length not stated.

²³ H. A. Bright and W. C. Fedde, associate and assistant chemists, respectively, of the chemistry division, collaborated in the carbon determinations.

Neville Cain

appreciable differences in composition in different parts of the ingot, all possibilities of variances in composition in all instances were not foregone. Therefore a small sample was milled from the fractured end of each bar after testing, on which carbon and manganese determinations were made.

This additional analysis served practically only as a precautionary measure, as there were appreciable differences in results in only a few cases, and in these the differences were very slight. Although the differences were slight, in instances of disagreement these latter values were considered to more nearly represent the true compositions of the specimens, so they were substituted for the values formerly obtained. Some of these disagreements were between the two companion specimens from the same ingot. Whenever their differences were enough to be perceptible on the curves, the two companion specimens were both plotted instead of the average for the two.

5. DATA.

The chemical compositions of the alloys, determined in the manner just described, are given in Table 2.

Carbon.	Manganese.	Sulphur.	Silicon.	Carbon.	Manganese.	Sulphur.	Silicon.
Per cent. 0.001 .02 .02 .02 .02 .02	Per cent. Nil 0.15 .55 .85 1.39	Per cent. 0.011 .006 .011 .008 .009	Per cent. 0.004 .005 .034 .029 .05	Per cent. 0.46 .47 .52 .54 .54	Per cent. 1.25 .87 1.12 Nil .59	Per cent. 0.009 .004 .007 .008 .005	Per cent. 0.013 .010 .030 .017 .005
.03 .05 .07 .08 .09	.50 .05 .55 .24 .35	.007 .006 .009 .006 .012	.04 .004 .017 .005 .005	.54 .59 .59 .59 .61	.99 Nil .35 1.10 .59	. 005 . 007 . 004 . 005 . 005	.015 .039 .006 .017 .005
.09 .10 .11 .13 .16	.64 .53 .86 1.07 .59	.009 .009 .006 .007 .008	.03 .014 .003 .004 .024	.62 .63 .63 .67 .67	. 20 . 35 . 48 . 37 . 86	.004 .004 .005 .003 .007	. 024 . 006 . 007 . 012 . 027
. 20 . 21 . 21 . 21 . 21 . 21	. 39 Ni1 . 03 . 26 . 69	. 006 . 02 . 006 . 006 . 007	.002 .006 .009 .003 .011	.67 .68 .69 .70 .70	1.17 Nil .96 .20 .97	.006 .009 .009 .006 .006	. 007 . 002 . 03 . 002 . 011
. 25 . 25 . 30 . 31 . 31	. 19 . 55 1. 55 Nil 1. 03	.007 .008 .009 .004 .011	.007 .037 .037 .005 .028	.72 .73 .73 .76 .81	. 28 . 33 . 84 1. 20 Nil	.007 .008 .006 .009 .012	.051 .014 .010 .008 .003
. 32 . 33 . 36 . 40 . 41	Nil 1.29 1.07 .43 .24	.009 .003 .011 .004 .014	.007 .015 .028 .004 .03	.81 .83 .84 .86 .89	1.59 .31 .04 .82 .01	.007 .007 .007 .006 .011	.004 .009 .010 .005 .018
. 41 . 42 . 44 . 45 . 45	.87 .34 .46 Ni1 1.09	. 004 . 003 . 004 . 014 . 006	.01 .01 .014 .003 .03	.93 .96 .98 1.00 1.01	1.25 .43 1.42 1.20 .29	.009 .006 .006 .006 .006 .011	.008 .010 .015 .009 .011

TABLE 2.- Results of Chemical Analyses.

Carbon.	Manganese.	Sulphur.	Silicon.	Carbon.	Manganese.	Sulphur.	Silicon.
Per cent. 1.01 1.02 1.07 1.08 1.00	Per cent. 0.91 1.59 .33 .49 .37	Per cent. 0.005 .007 .004 .006 .009	Per cent. 0.005 .004 .009 .009 .008	Per cent. 1.26 1.28 1.28 1.28 1.28 1.29 1.20	Per cent. 1.71 Nil .24 .77 Nil 55	Per cent. 0.005 .008 .005 .012 .009	Per cent. 0.017 .025 .008 .007 .006
1.09 1.09 1.09 1.11 1.12	.24 .51 .96 Ni1 .38	.004 .009 .012 .004	.038 .010 .019 .004 .004	1.29 1.29 1.34 1.35 1.38	.94 .91 .51 .60	.008 .016 .009 .009 .004	.007 .008 .050 .007 .005
1.13 1.16 1.16 1.19 1.20	.33 .43 .84 .78 .85	• 005 • 006 • 005 • 004 • 006	.008 .011 .012 .009 .006	1.39 1.39 1.44 1.44 1.44	.46 1.43 .95 1.31 1.43	.006 .007 .008 .007 .007	.009 .014 .022 .017 .014
1.21 1.22 1.24 1.24 1.24 1.25	. 40 . 38 . 31 . 51 . 82	.004 .004 .009 .004 .006	.007 .004 .008 .008 .009	1.50 1.50 1.54 1.54 1.54	.97 1.16 Nil 1.60 Nil	.008 .004 .003 .005 .005	.022 .003 .004 .009 .005

TABLE 2.-Results of Chemical Analyses-Continued.

The values obtained for the mechanical properties of each alloy may be read from the curves of Figures 5 to 10 or 11 to 16. The data are presented in the form of curves, since this offers the best means of showing the effect of successive additions of carbon and manganese to iron. Two sets of curves are shown in which the values for mechanical properties have been plotted against chemical compositions in two different ways: First, to show the effects of carbon, and, second, to show the effects of manganese.

The specimens were arbitrarily grouped, first for comparing the data in such a manner as to bring out the effects of carbon, then similarly regrouped for studying the effects of manganese. Since constant manganese is needed for the comparison of data so as to bring out the effects of carbon on iron, the specimens were grouped in six classes according to manganese contents. The first group are the iron-carbon alloys, containing no manganese; the second contains those with manganese percentages from 0.15 to 0.30; the third, 0.31 to 0.59 per cent; the fourth, 0.60 to 1.00 per cent; the fifth, 1.01 to 1.35 per cent; the sixth, 1.36 to 1.55 per cent. The ideal condition for comparison would be to have a number of specimens of identical manganese contents and varying carbons, but there were not enough specimens with exactly the same amounts of manganese. However, by having the manganese within the limits given above, it is improbable that its influence is greater than differences due to experimental errors of testing. The effects on the tensile properties of variations in manganese between these limits is very small in comparison with those of carbon.

[Vol. 18

Neville Cain

The points on the curves are the averages of the values for the two companion specimens of the same ingot except for the few specimens which had no mates and in cases where there were great variations in the results of the two, in which cases the erratic appearing one was discarded. The yield points were not plotted, because their detection was practically impossible in many cases, assigned values being scarcely more than approximations. They were very definite for the specimens of low carbon contents, but those for specimens of higher carbons were almost impossible of



FIG. 5.—Effects of carbon on alloys of pure iron and carbon.

detection, and stress-strain curves had gradual slopes from the proportional limit to point of rupture.

The specimens were then regrouped according to carbon contents to bring out the effects of manganese. The first group contains the specimens of iron-manganese alloys with negligible amounts of carbon. By comparing data of the specimens of no carbon with variations in manganese content the effects of manganese on pure iron can be shown. If there were a sufficient number of specimens of the same carbon contents to have series with identical carbon contents within each series, the influence of manganese could be more easily shown; but since there were not, the alloys were

grouped according to limits of carbon content in per cents, as follows: 0.05 to 0.45, 0.46 to 0.75, 0.76 to 1, 1.01 to 1.25, and 1.26 to 1.55.

In studying the effects of carbon the influence of differences in manganese contents within a group of no wider limits of manganese than those chosen was so small that it was altogether ignored, but since in studying the effects of manganese the much greater effects of carbon would completely obscure the lesser effects of man-



FIG. 6.—Effects of carbon on iron-carbon-manganese alloys; manganese limits, 0.15 to 0.3 per cent.

ganese unless the carbon contents of the alloys compared were exactly the same throughout the whole series, and since there were an insufficient number of specimens of exactly the same carbon content to make such a series these had to be grouped so that each group contained the alloys of a certain range of carbon and corrections made for differences in carbon contents within the group. The values of the specimens within each group were corrected before plotting to a certain specific carbon content designated to each group. The narrow range of manganese contents within the

[Vol. 18

Iron-Carbon-Manganese Alloys.

Neville Cain

groups and the slight effect of the variable made corrections unnecessary in considering the effects of carbon; but in studying the effects of manganese any variances in carbon at all would obscure the effects of the manganese. Corrections were made on the basis of the influence of carbon for alloys of the composition under consideration as observed from the curves plotted according to the first grouping. A definite carbon content was designated to each group to which all data were corrected before plotting. After the data of each group had been plotted in this manner all the



FIG. 7.—Effects of carbon on iron-carbon-manganese alloys; manganese limits, 0.31 to 0.59 per cent.

specimens within the group were considered to be of the same carbon content. The curves then show how manganese effects each of the properties of the alloys of that range of carbon. Figures 11 to 16 present the data according to this method of grouping.

VI. INTERPRETATION OF DATA.

1. EFFECTS OF CARBON.

The effects of carbon on iron and the alloys may best be seen from the curves. Figure 5 shows how additions of carbon influence the mechanical properties of iron. Figure 6 shows how the mechanical properties of iron with manganese between 0.15 and 0.30 per

[Vol. 18

cent were influenced by additions of carbon, and so on, with increasing amounts of manganese up to 1.50 per cent.

The points of mechanical test data do not fall with sufficient regularity for a smooth curve to pass through all points. Smooth curves were constructed so as to represent a mean of all the points. Values for ultimate strengths fall more regularly than those for any other of the five properties plotted. Up to carbon contents of about 1 per cent they are nearly all almost on the line, with only exceptions explained by the data. All values tended to become



FIG. 8.—Effects of carbon on iron-carbon-manganese alloys; manganese limits, 0.60 to 1.00 per cent.

more irregular when the carbon contents became greater than 1 per cent. This was especially noticeable when the manganese contents also began to be high.

Though it seems unlikely that the effects of carbon on ultimate strengths are exactly quantitative, a better comprehension of its influence can be had if average quantitative values are calculated from the curves. In the series containing no manganese the average rate of increase in ultimate strength with increase in carbon is 875 lbs./in.² for each 0.01 per cent. Above contents of about 0.70 per cent this rate decreases until the maximum ultimate strength is had at approximately the eutectoid composition. Iron-Carbon-Manganese Alloys.

Neville Cain

Further increase in carbon above this amount decreases the ultimate strength. These average rates of increase in ultimate strength with increases in carbon for each of the groups up to approximately 0.70 per cent are in the order of increase in manganese, 875, 885, 900, 915, 965, and 1150 lbs./in.² for each 0.01 per cent carbon.

The curves for Brinell hardness numbers are very similar to those for ultimate strengths. The points fall less regularly, but the curves drawn as means of the points are almost parallel to those



FIG. 9.—Effects of carbon on iron-carbon-manganese alloys; manganese limits, I.OI to I.35 per cent.

for ultimate strengths. The relation of Brinell hardness numbers to ultimate strengths as the latter increases has been noticed in steels. The thing of particular interest here is the marked drop in Brinell hardness numbers as the carbon content increases above the eutectoid composition.

Elongations and reductions of area rapidly decreased with the increase in carbon. These decreases are fairly regular up to about the eutectoid compositions, where the values become very small and decrease only slightly with further carbon increases. The curves for the six groups are very much alike. However,

[Vol. 18

as the manganese increases in the succeeding groups there is a tendency toward a greater steepness of slope, with possibly a minimum ductility reached at lower carbon contents.

The proportional limit values are so irregular that about the most that can readily be determined from them is that carbon increases the proportional limit less than it does ultimate strength, a maximum value being reached at a lower carbon content but with a maximum influence extending over a wider range of carbon.



FIG. 10.—Effects of carbon on iron-carbon-manganese alloys; manganese limits, 1.36 to 1.55 per cent.

2. EFFECTS OF MANGANESE.

It will be noticed, first, that the effects of manganese on all five of the properties are straight-line ratios, which is quite in contradistinction to the effects of carbon. The points in some instances are rather widely scattered but not in such a manner as to indicate that they represent any other than straight-line ratios.

Manganese in the absence of carbon seems to have only a slight effect on the properties of the iron (Fig. 11). Ultimate strength, hardness, and proportional limit in the no-carbon group are slightly increased, but there appears no obvious relation between variations in ductility values and differences in manga-

Neville Cain

nese content. This latter condition also holds when carbon is present. Throughout all the groups the lines for elongation and reduction of area are parallel to the abscissa. The lines for ultimate strength, proportional limit, and Brinell hardness are practically parallel within the group, and, in fact, with the exception of the first two groups the slopes of all the groups are about the same. It will be noticed, too, that while carbon affected the proportional limit much less than the ultimate strength and Brinell



FIG. 11.—Effects of manganese on alloys of pure iron and manganese.

hardness, manganese affects it at about the same rate as it does the other two properties.

When carbon is added, or in iron-carbon-manganese alloys, ultimate strength, proportional limit, and hardness are each more rapidly increased with a manganese increase; or, in the presence of carbon, manganese has more influence. This may be seen by comparing Figure 12, which has 0.25 per cent carbon, with Figure 11, which has no carbon. A comparison of the curves of all the groups, Figures 11 to 16, will reveal that manganese affects

438

elongation and reduction of area not at all, and that the rate of increase of ultimate strength, proportional limit, and Brinell hardness with increase in manganese content becomes higher as the carbon content of the succeeding groups increases. Quantitatively expressed, so that comparisons may be made with values of other investigations previously mentioned, the rate of increase in ultimate strength and proportional limit is about 90 lbs./in.² for each 0.01 per cent manganese in the absence of carbon, which



FIG. 12.—Effects of manganese on iron-carbon-manganese alloys; carbon limits, 0.05 to 0.45 per cent.

increases to about 230 lbs./in.² for each 0.01 per cent manganese toward the upper limits of carbon content. Similarly, the rate of increase in Brinell hardness numbers increase from about 0.2 Brinell hardness numbers per 0.01 per cent manganese for no carbon to about 0.5 Brinell hardness numbers per 0.01 per cent manganese for higher carbon contents.

3. COMBINED EFFECTS.

It will be noticed that both carbon and manganese have more influence on the mechanical properties of iron according

[Vol. 18

Iron-Carbon-Manganese Alloys.

to the amount of the other element present. Manganese in the absence of carbon affects the properties of iron very little. As soon as carbon is added this influence becomes more marked. Likewise, the same variation in carbon content of an alloy of low or no manganese and one of higher manganese does not produce the same effect. The same difference in carbon has more effect when manganese is present than when the alloy contains no manganese. The influence of carbon is increased



FIG. 13.—Effects of manganese on iron-carbon-manganese alloys; carbon limits, 0.46 to 0.75 per cent.

accordingly as the manganese content becomes greater. Reference to the curves will show the extent to which each element influences the effect of the other.

A comparison of the effects of manganese on steels with its effects on pure alloys fused in vacuo is of particular interest. According to other investigations in some steels, especially those prepared by the Bessemer process, the first additions of manganese cause a decrease in tensile properties as the manganese content increases until its content amounts to about 0.35 per cent,

[Vol. 18

after which further increase has a strengthening effect. In our pure vacuum-fused alloys the effect of manganese was continuously positive from the lowest to the highest contents.

This seems in accordance with the theory that with steels the first additions of manganese serve to deoxidize the steel, forming oxides which tend to separate the grains, thereby decreasing its strength. Any excess of manganese then added over the amount required for deoxidation forms combinations beneficial to tensile properties. In the case of the "psuedo"



FIG. 14.—Effects of manganese on iron-carbon-manganese alloys; carbon limits, 0.76 to 1.00 per cent.

steels of this investigation, absence of oxygen prevents the formation of weakening oxides when the first manganese is added. Accordingly, the first additions of manganese are available immediately to combine in a manner beneficial to mechanical properties.

VII. SUMMARY.

1. Over a hundred alloys with negligible amounts of impurities were prepared from electrolytically purified iron, carbon, and manganese of very high purity by fusion in vacuo in crucibles of magnesia prepared especially for the purpose to prevent contam-

ination during melting. The compositions were so chosen as to bring out the effects on pure iron of additions of small amounts of carbon, additions of small amounts of manganese, and additions of carbon and manganese together. The ranges in chemical composition of the alloys include from o to 1.6 per cent carbon and o to 1.6 per cent manganese. Ingots of 3 pounds were made and rolled to half-inch plates from which specimens for testing were made. Ultimate strength, proportional limit, yield



FIG. 15.—Effects of manganese on iron-carbon-manganese alloys; carbon limits, 1.01 to 1.25 per cent.

point, elongation, reduction of area, and Brinell hardness determinations were made and photomicrographs taken.

2. In amounts below approximately I per cent the ultimate strengths of the alloys were increased by carbon. The ratio of this strengthening effect to carbon content was not constant, but was within the limits of 875 and 1,150 lbs./in.² for each 0.01 per cent carbon between the limits of 0 and 0.70 per cent. This strengthening effect was greater in the alloys of higher manganese contents. An approximate average of the rate was 1,000 lbs./in.² for each 0.01 per cent carbon.

3. The hardness of the alloys was influenced by carbon in about the same manner as was the ultimate strength. The increase in hardness due to carbon was from 1.8 to 2.6 Brinell numbers for each 0.01 per cent carbon, the rate being larger as the manganese contents increased.

4. Reduction of area and elongation of pure iron were 82.5 and 40.5 per cent, respectively. With the addition of carbon these values were rapidly and regularly decreased with the increase in carbon until values little greater than zero were reached



FIG. 16.—Effects of manganese on iron-carbon-manganese alloys; carbon limits, 1.26 to 1.55 per cent.

around I per cent. Increase in carbon beyond this point had little effect on ductility. These minimum values were reached at lower carbon contents when the manganese was increased.

5. Carbon influenced the proportional limits of the alloys less than the other properties. Although the effects on proportional limits were less easily discernible, it could be seen that the maximum values were reached at lower carbon contents than maximum values for ultimate strengths and remained at its maximum value over a wider range of carbon composition.

[Vol. 18

6. Manganese increased the ultimate strengths of the alloys only slightly, particularly with very small amounts of carbon present. Expressed quantitatively, this rate of increase was about 90 to 250 lbs./in.² for each 0.01 per cent manganese.

7. Manganese influenced the proportional limits in about the same manner it did the ultimate strengths.

8. Brinell hardness numbers were increased about 0.5 by each 0.01 per cent manganese when carbon was present. This rate was lower in the alloys of lower carbon contents.

9. Manganese had very little effect on the ductility of the alloys.

10. The effects of manganese and carbon on the mechanical properties of the alloys were each influenced by the other. The presence of carbon augmented the influence of manganese and vice versa.

WASHINGTON, May 11, 1922.

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