July 5, 1960 P. R. WHITE ET AL 2,943,932

BORON-CONTAINING FERROUS METAL HAVING AS-CAST COMPACTED GRAPHITE

Filed June 10, 1957 3 Sheets-Sheet 1

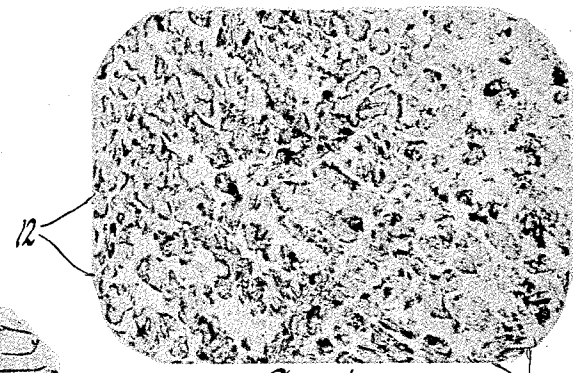


Fig. 1

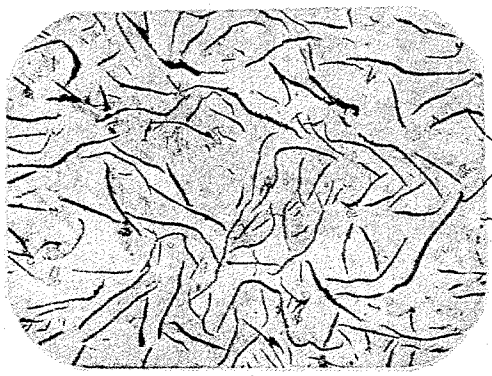


Fig. 2

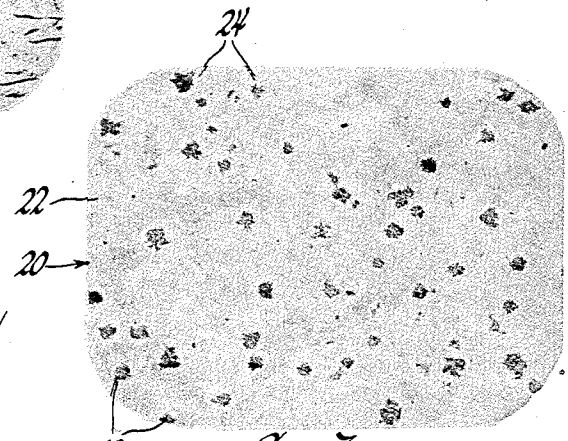


Fig. 3

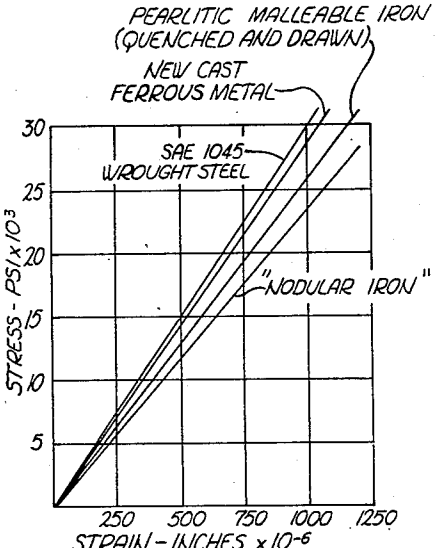


Fig. 4

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Filed June 10, 1957 3 Sheets-Sheet 2

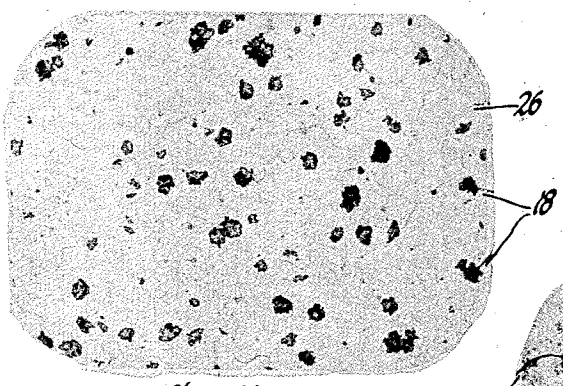


Fig. 5

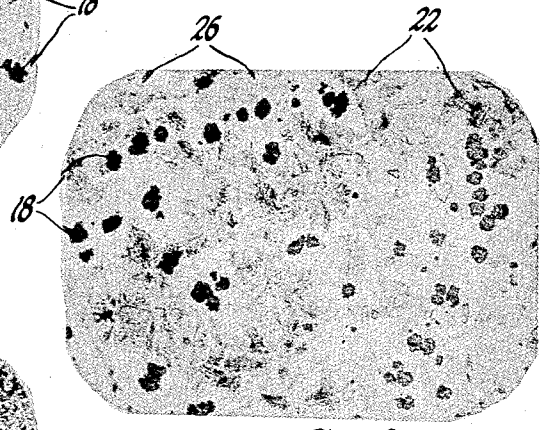


Fig. 6

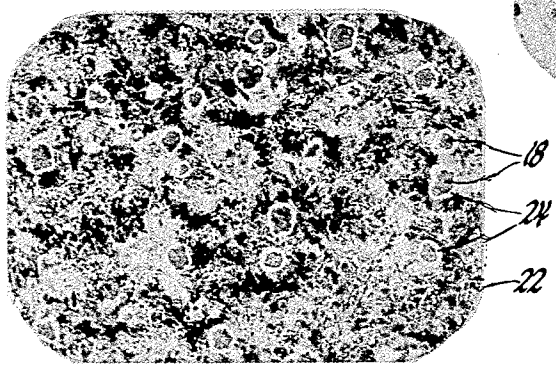


Fig. 7

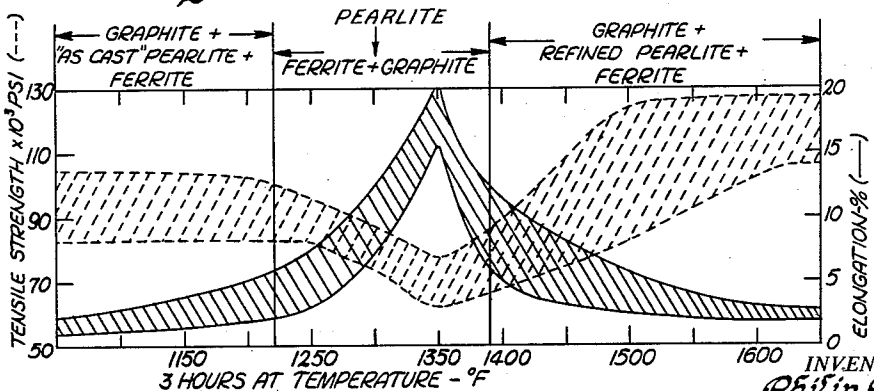


Fig. 8

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BORON-CONTAINING FERROUS METAL HAVING AS-CAST COMPACTED GRAPHITE

Filed June 10, 1957 3 Sheets-Sheet 3

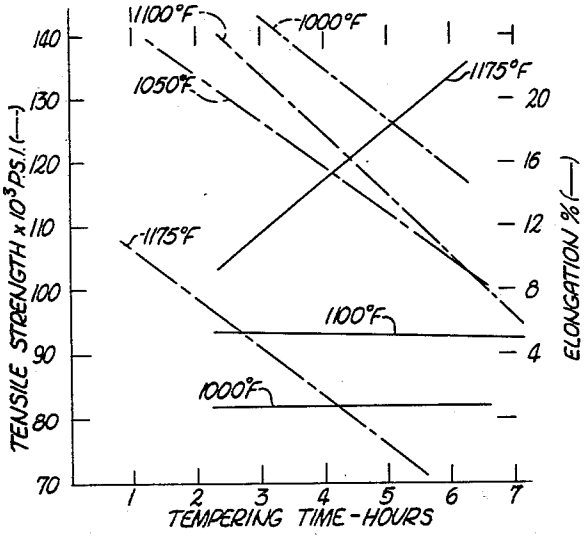


Fig. 9

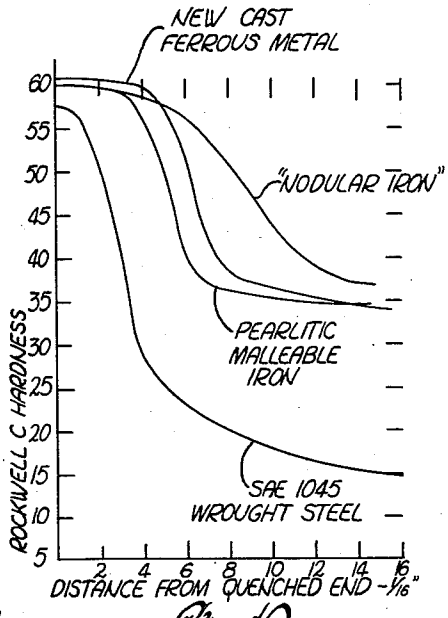


Fig. 10

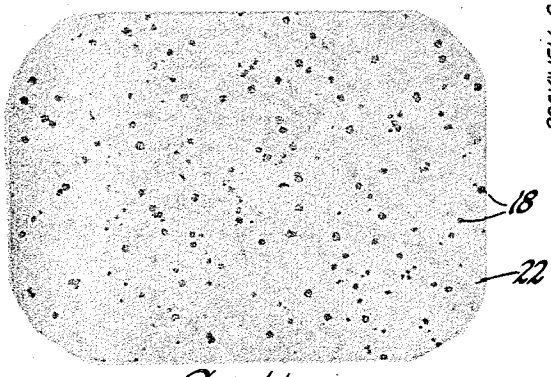


Fig. 11

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2,943,932

BORON-CONTAINING FERROUS METAL HAVING AS-CAST COMPACTED GRAPHITE

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Filed June 10, 1957, Ser. No. 664,727

14 Claims. (Cl. 75—123)

This invention relates to a ferrous metal and a method of producing the same. More particularly, the invention pertains to a cast ferrous metal product, which may be described as "as-cast" malleable iron or "high modulus malleable iron," characterized by a combination of properties heretofore unobtainable in any one metal composition. This new material possesses an unusually high modulus of elasticity in both the as-cast and heat-treated conditions, as well as high tensile strength and yield strength.

In the manufacture of a conventional malleable iron casting, there is first produced a white iron casting which is extremely brittle due to the fact that all, or substantially all, of the carbon in the iron is in the combined form. This white iron casting is subsequently given a long and expensive annealing treatment at an elevated temperature in order to break down combined carbon and deposit carbon in the free form. The free carbon, formed at a multiplicity of points throughout the casting, constitutes what is commonly referred to as "temper carbon." Malleable iron has considerably higher tensile strength and ductility than gray cast iron which, upon solidification, contains carbon in the form of elongated flakes.

Malleable iron may have all, or substantially all, of the iron carbide broken down into free carbon or may retain about 0.85% carbon in the combined form, resulting in what is known as pearlitic malleable iron. However, a relatively long and expensive annealing cycle is required to produce conventional malleable iron castings. Hence, it would be highly desirable to form products which, in the "as-cast" condition, possess the desirable characteristics and general microstructure of malleable iron without the necessity of employing an extended annealing treatment. Moreover, it would also be very advantageous to produce an as-cast malleable iron having a modulus of elasticity which is considerably higher than the elastic modulus of conventional malleable iron and which approaches the elastic modulus of steel. Such a material could replace plain carbon steel forgings for many applications, and at the same time, permit a manufacturer to take advantage of the flexibility of design inherent in the production of castings.

Accordingly, a principal object of the present invention is to provide an improved ferrous metal composition in the "as-cast" condition which has physical properties and microstructure which compare favorably with those of conventional pearlitic malleable iron. A further object of the invention is to provide an improved cast ferrous metal and a rapid, inexpensive method for producing the same in which the resultant product has a considerably higher modulus of elasticity than any conventional malleable iron or so-called "nodular iron."

These and other objects are attained in accordance with this invention with a ferrous metal composition having a substantial amount of compacted graphite in the as-cast condition. This new steel-like material contains controlled amounts of carbon, silicon, boron and iron. The composition is such that the metal normally would

solidify as a white cast iron if no boron were present; that is, in the absence of boron, the carbon will be present in the combined form rather than as free carbon. Optimum results are obtained when the product also contains a small amount of tellurium and/or bismuth. At the present time tellurium is preferred over bismuth as an inoculant not only because tellurium produces superior results but it may be used effectively in smaller amounts.

One of the significant features of this new cast ferrous metal is the fact that substantially all of the hypereutectoid carbon is present as free graphite in compacted form with no hypereutectoid iron carbide being present, thus producing a ferrous metal product having high tensile strength which can be used in the as-cast condition. Inasmuch as this new material also has an exceptionally high modulus of elasticity, it may be employed in applications for which most of the presently available cast materials are unsatisfactory.

Furthermore, it should be noted that, in addition to its outstanding as-cast physical properties, this new ferrous metal can be heat treated to provide it with a wide combination of desirable physical properties. Consequently it is an extremely versatile metal, and the same base composition may be employed in the production of numerous different types of articles. As hereinbefore indicated, this "as-cast malleable iron" has steel-like physical properties. Despite this fact, however, its castability is superior to steel, and hence it cannot be considered in the class of steel from the standpoint of foundry operations.

Of course, since no heat treatment of our new ferrous base metal is normally necessary and, when employed, can be of very short duration, the cost per casting is considerably less than that of conventional malleable iron. When compared with similar steel parts, the cost of a finished article formed of the new ferrous metal is appreciably lower because of its superior machineability as well as its lower initial cost.

Other objects and advantages of the present invention will more fully appear from the following detailed description of preferred embodiments thereof, reference being made to the accompanying drawings, in which:

Figure 1 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, showing the etched microstructure of conventional white cast iron;

Figure 2 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, showing the etched microstructure of conventional gray cast iron;

Figure 3 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, showing the etched as-cast microstructure of ferrous base metal formed in accordance with the present invention;

Figure 4 is a graph showing stress-strain curves comparing the modulus of elasticity of ferrous metal formed in accordance with this invention with the elastic moduli of various other ferrous base materials.

Figure 5 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, of the etched microstructure of the cast ferrous base metal shown in Figure 3 after heat treatment for three hours at approximately 1350° F.;

Figure 6 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, of the etched microstructure of the cast ferrous base metal shown in Figure 3 after heat treatment for three hours at about 1300° F.;

Figure 7 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, of the etched microstructure of the cast ferrous metal shown in Figure 3 after normalizing at approximately 1500° F.;

Figure 8 is a graph illustrating the effects of heat treatment on the tensile strength, ductility, and microstructure of the cast ferrous base metal shown in Figure 3;

Figure 9 is a graph showing the effects of tempering

time and tempering temperature after oil quenching on the strength and ductility of the cast ferrous base metal formed in accordance with the present invention;

Figure 10 is a graph comparing the end quench hardenability curves for various ferrous base metals which had been austenitized for one hour at approximately 1600° F.; and

Figure 11 is a reproduction of a photomicrograph taken at a magnification of 100 diameters, of the etched microstructure of a thin-sectioned portion of a casting formed from the ferrous base metal shown in Figure 3.

The various constituents in the novel cast ferrous metal of this invention are so balanced that free carbon separates out of the cast product in compacted form, generally similar to the temper carbon of conventional malleable iron, rather than in flake form as in normal gray cast iron. In general, the ingredients of this new cast material are present in amounts to provide a ferrous base metal comprising approximately 1% to 2.5% carbon, 1.5% to 3.2% silicon, manganese not in excess of 1.15%, 0.001% to 0.02% boron and the balance substantially all iron. For optimum results, the carbon content should be between about 1.5% and 1.9% and the silicon should constitute approximately 2.4% to 2.9%. In instances where a particular application permits the use of a ferrous metal casting having a moderate amount of hypereutectoid iron carbide in its microstructure, the boron content may be as high as about 0.05%. Generally such a casting will contain roughly 5% to 10% by volume of carbide. However, the aforementioned lower boron range is normally preferred for reasons hereinafter set forth.

As hereinbefore explained, most satisfactory castings are produced when the above composition also contains tellurium. This element should not be present in quantities greater than about 0.01%, a tellurium addition of approximately 0.003% to 0.008% being preferred. In the case of small castings, however, it is often desirable to use a tellurium content as low as 0.002%. If bismuth rather than tellurium is employed, as much as 0.02% of this material may be used. Although both tellurium and bismuth may be present at the same time, the total amount of these constitutents should not exceed approximately 0.02%.

Of course, sulfur is normally always present in cast iron and steel, and this constituent is not detrimental to the resultant product in quantities even as large as 0.5%, provided the metal also contains a sufficient amount of manganese. Usually, however, about 0.3% is the maximum amount of sulfur normally found in such ferrous metals. The manganese counteracts the detrimental effects of sulfur by combining with it to form manganese sulfide.

Accordingly, it is desirable to have a sufficient amount of manganese present to combine with the sulfur, but an excess of either of these constituents is detrimental since it results in undesirable carbide stabilization. The preferred manganese content should approximately satisfy the equation $Mn=1.7(\text{percent sulfur})+0.2$. Practically, sulfur always will be present, and the sulfur content usually is at least 0.02% unless a special procedure is employed for reducing the amount of sulfur. However, it appears that the presence of sulfur may somewhat improve the fluidity of the molten cast metal. From the standpoint of the present invention manganese does not appear to be necessary if no sulfur is present.

A cast ferrous base metal having the following composition appears to possess optimum physical properties: 1.5% to 1.9% carbon, 2.4% to 2.9% silicon, 0.3% to 0.5% manganese, 0.05% to 0.15% sulfur, 0.005% to 0.015% boron, 0.003% to 0.008% tellurium and the balance iron. However, for some applications it may be desirable to use tellurium in amounts as small as 0.001% or as large as 0.01%. If bismuth is substituted for tellurium, the preferred range is between 0.005% and 0.01%. Excellent results have been obtained using an as-cast malleable iron consisting essentianlly of 1.7% carbon, 2.6% silicon, 0.4% manganese, 0.1% sulfur, 0.01% boron, 0.005% tellurium or 0.008% bismuth, and the balance iron.

Of course, the impurities normally found in cast iron may be present in the usual small amounts. In addition to the elements listed above, the ferrous base product of the present invention also may contain one or more of the various elements which are frequently present in cast iron either as impurities in small quantities or as intentional additives in larger, controlled amounts when particular properties are desired. These elements include chromium, nickel, copper, phosphorus, titanium, aluminum, vanadium, molybdenum, tin, etc. The phosphorus content generally is in the order of about 0.05%.

It should be noted that the high silicon content and the low carbon content of this new ferrous base material are just the reverse of the proportions of these elements normally used in cast irons. It is this unique combination, particularly in conjunction with inoculation with boron and preferably also tellurium or bismuth, which imparts to the resultant product its high modulus of elasticity and outstanding versatility.

While it is possible to produce compacted graphite in castings having compositions within the broader ranges recited above, the narrower ranges are preferred in order to produce optimum results. The low carbon, high silicon composition, such as one containing 1.80% carbon and 2.80% silicon, has been found to be perculiarly susceptible to the formation of compacted graphite when treated with boron and tellurium and/or bismuth. Deviations from the preferred analysis may result in useful but less favorable structures. For example, in some instances section sensitivity is encountered with compositions outside the preferred ranges listed above. Moreover, the use of higher carbon or lower silicon levels which approach those of conventional malleable iron produce a corresponding increase in hypereutectoid iron carbide. Although this carbide may be substantially eliminated by raising the silicon content or by inoculation with various graphitizers, such procedures produce flake graphite, particularly in heavy sections of the casting. As is true with conventional pearlitic malleable iron and so-called "ductile cast iron" or "nodular iron," the presence of flake graphite or hypereutectoid iron carbide reduces the strength and ductility of the metal. Tensile tests of our new cast material indicate, however, that the presence of some small hypereutectoid carbide particles randomly distributed throughout the metal is much less detrimental to physical properties than the presence of flake graphite. Acceptable strength and ductility can be obtained with the new metal in both the as-cast conditions and in the heat-treated condition even when some carbide is present in this form. While we have found that the presence of approximately 5% by volume of AFS–ASTM type D graphite may lower tensile strength by 20,000 p.s.i. and reduce the ductility drastically, we have also found that the presence of stubby flakes or "quasi-flake" graphite is in small amounts generally has no detrimental effects on either tensile strength or ductility.

If both tellurium and bismuth are omitted, there is a likelihood that some residual flake graphite will be present in the cast product. Therefore, in order to provide the metal with uniformity and reproducibility, it is preferable to employ tellurium or bismuth in the foregoing amounts. It appears that if the initial base iron is a type which would solidify as only white iron with no free carbon being present, the inoculation with boron alone would produce a structure having 100% of the free carbon in the form of compacted graphite and which contains no residual hypereutectoid iron carbide. The addition of tellurium along with the boron, however, insures such a structure regardless of the structure of the base iron without these additives.

If, after inoculation, the retained boron is present in

a quantity greater than approximately 0.02%, some stabilized hypereutectoid carbide will be produced. Consequently, the addition of excess boron does not compensate for the deleterious effects produced by too high a carbon content. Chemical analysis has indicated that when the preferred compacted graphite structure is obtained, more than 90% of the total boron is present as acid-insoluble boron, while an increased amount of AFS–ASTM type D flake graphite with less compacted graphite is associated with an increase in acid-soluble boron. It therefore appears that the formation of compacted graphite in the new ferrous metal is correlated with the presence of an acid-insoluble boron compound. The acid solubility of the boron in the metal was determined by standard analyses using a solution of 20% sulfuric acid or phosphoric acid.

Although boron is the essential ingredient which produces compacted graphite in the composition described herein, the presence of tellurium insures against the formation of flake graphite. As indicated above, optimum physical properties are obtained with the use of approximately 0.003% to 0.008% tellurium, and no apparent variations in results have been observed when tellurium is present in amounts within this range. However, if the tellurium content greatly exceeds 0.008% there is a tendency to produce chill in thin sections. This result of using higher tellurium contents is of particular interest since the preferred composition set forth above is not highly section sensitive in that there is only a slightly greater tendency for hypereutectoid carbide formation in thin sections than in heavy sections. As hereinbefore indicated, it is frequently advantageous to use somewhat less tellurium in small castings.

With respect to the amount of the hypereutectoid iron carbide present in the cast ferrous metal, it is generally desirable to reduce the amount of this compound to less than 1% of the volume of the metal, although for some applications the carbide content may range up to 5% or higher. However, it is much more difficult to machine the cast product when it contains more than about 2% hypereutectoid iron carbide. Nevertheless, the presence of this carbide contributes measurably to the wear resistance of the metal, and consequently a hypereutectoid carbide content as high as even 10% by volume may be desirable in applications where high wear resistance is an important factor. As indicated above, the preferred composition consistently produces a cast ferrous base metal which contains less than 1% hypereutectoid carbide.

The cast ferrous metal of this invention may be prepared by various melting processes employed in making conventional iron castings. Direct arc melting and high-frequency induction melting are among the specific procedures which have been successfully used. Likewise, either batch-type or continuous cupola-direct arc duplexing operation may be employed. The process of making the new ferrous base metal appears to be independent of the furnace lining used. Heats have been successfully melted in furnaces lined with SiO_2 (acid), MgO (basic) and zirconium silicate (neutral). Tapping and pouring temperatures of 2750° F. to 2850° F. and 2600° F. to 2700° F., respectively, provide satisfactory results. These temperatures are consistent with current malleable iron practice. However, the tapping temperature may range from about 2700° F. to 3000° F. under particular conditions, and the pouring temperature may be as high as approximately 2750° F.

Apparently because of the low carbon content of the new cast ferrous metal, melting in direct arc furnaces frequently results in some porosity due to an occluded gas. This condition can be avoided by melting metal under a protective slag.

The optimum carbon content of approximately 1.8% may be obtained by a mixture of plain carbon steel and conventional white iron, such as an iron containing 2.6% carbon, 1.4% silicon, 0.4% manganese and 0.1% sulfur.

When melting in induction furnaces, it is convenient to mix white iron scrap with the steel and to melt these two metals together. On the other hand, when a direct arc furnace is used it appears desirable to transfer the cupola hot metal to a direct arc furnace and to subsequently add an appropriate amount of slag. The molten steel, which has previously been melted in a second direct arc furnace, is then mixed with the cupola metal. Such a procedure provides consistent chemistry control due to minimum oxidation loss and also constitutes a convenient means of preventing gas pickup.

Cold melting by direct arc is also possible, but the higher carbon content white iron should be melted and a fluid slag obtained prior to adding steel. In either direct arc or induction melting, silicon and manganese may be added to the metal at any stage.

We have also found the new cast ferrous composition having the desirable carbon content may be produced by employing an oxygen jet converter type of arrangement to reduce the carbon content of conventional cupola melt malleable iron. A refractory-lined vessel and a water-cooled copper lance may be used. By carefully controlling the chemistry and quantity of the hot charge and metering the oxygen, it is possible to predict the carbon content of the melt at any time during the blow. Silicon and manganese can be added to the receiving ladle upon tapping of the melt in order to compensate for losses which occur during the blow and to maintain proper amounts of these elements in the melt. These additions also serve to deoxidize the metal. The boron and tellurium inoculants may then be added while tapping from the receiving ladle to a transfer ladle. However, such a practice does not appear to be as economical as a normal cupola diretc arc duplexing operation at the present time.

The importance of a microstructure which is substantially free of hypereutectoid iron carbide and flake graphite is well recognized in the "nodular" iron and malleable iron industries. To produce such a microstructure in accordance with the present invention, it is necessary to use the aforementioned amount of boron. However, it is generally found that the base metal will contain some boron, and therefore the amount of the inoculant used may be somewhat less than the total boron content. For example, a residual boron content of approximately 0.001% to 0.003% normally can be obtained from white iron scrap used in the base charge. A small amount of free graphite can readily be observed in controlled castings made from a metal which was not inoculated with the boron due to the retained boron present in the white iron and the base charge.

Ladle additions of boron and bismuth and/or tellurium are adjusted according to the composition of a base iron, melting conditions, etc. The boron inoculation may be made with a number of boron-containing compounds. Among the inoculants which can be employed are ferroboron, boron carbide, calcium boride, nickel-boron, pure boron metal, and borax, preferably anhydrous. The tellurium also may be added in various forms, such as pure tellurium, ferro-tellurium or copper-tellurium, for example; and bismuth can be introduced as substantially pure bismuth metal. Of course, the addition agents which may be employed are not restricted to the metals or compounds listed above.

Laddle additions may be made to the molten iron stream, the bottom of the ladle prior to tap, by plunging, or by any method which assures thorough mixing of the additives with the melt. It is convenient to introduce the aforementioned additives simultaneously by attaching them to a steel rod and plunging the rod into the ladle while tapping from a furnace or transfer ladle. However, in large production quantities where considerable turbulence is generated, the additive or additives may be placed in the bottom of the receiving ladle or introduced into the stream.

The following are specific examples of melting and casting practices which further indicate the importance of the composition of the new ferrous metal described herein. In one instance an induction melted heat was made from white cast iron scrap having a residual boron content of 0.001% to 0.003%, iron punchings, manganese metal (96% Mn), and ferrosilicon (48% Si). On analysis, this heat showed a composition of 1.78% carbon, 2.80% silicon, 0.45% manganese, 0.05% phosphorus, 0.10% sulfur and the balance iron. The heat was divided into three equal parts at a tapping temperature of approximately 2840° F. No additions were made to one portion, while the second portion had about 0.045% boron added to the ladle in the form of calcium boride (48% boron) and about 0.01% bismuth added to the stream as bismuth metal. It should be noted that this boron figure refers to the amount of boron added rather than to the final analysis. The third portion was inoculated in the same manner as the second portion except that approximately 0.007% tellurium was added to the stream in place of the bismuth. The three portions thus formed were then poured at a temperature of approximately 2660° F. into separate dry sand molds each having a casting cavity of 1⅝" x 1⅝" x 2⅝". All the castings were subsequently cooled to room temperature in the molds.

The first portion of the heat, which had not been inoculated with boron, tellurium or bismuth, contained a small amount of flake graphite, no compacted graphite and was principally a white iron. The second portion, to which boron and bismuth had been added, had a microstructure which showed that the free carbon was approximately 50% compacted graphite and 50% flake graphite and that there was some hypereutectoid iron carbide present.

The third portion, which had been inoculated with both boron and tellurium, contained only traces of flake graphite and hypereutectoid carbide in a matrix of "bull's eye" ferrite and pearlite. About 95% to 100% of the free carbon was present as compacted graphite of generally spheroidal shape.

A second heat contained approximately 1.65% carbon, 3.07% silicon, 0.46% manganese, small amounts of sulfur and phosphorus, and the remainder iron. In this instance an appropriate amount of 90% ferrosilicon was used in the charge. After tapping the molten metal, about 0.045% boron (as 48% calcium boride) was added to the ladle and about 0.006% tellurium metal was introduced into the stream. The resultant metal was then cast as a one inch Y block in a green sand mold. The microstructure of this casting showed that approximately 10% to 15% of the free carbon was present as flake graphite and that it contained about 5% hypereutectoid iron carbide. The compacted graphite was the same type as in the third portion of the heat described above in the first example and likewise contained "bull's-eye" ferrite and pearlite.

Another heat was prepared in the same manner as the aforementioned second heat except that a suitable quantity of 48% ferrosilicon was used in the charge and a ladle addition of about 0.045% boron and 0.007% tellurium was employed. The resultant metal also was cast in a green sand Y block mold. Examination of the microstructure of the one-inch section of this casting showed that the metal contained approximately 10% hypereutectoid carbide and that 100% of the free graphite was in compacted form.

The following Table I lists a series of pertinent heats of our new cast ferrous metal. This table indicates under "remarks" variations in procedure and points out the effects of composition and processing on the microstructure of the castings produced:

TABLE I

Heat No.	Size	Crucible	C	Si	Mn	S	P	Remarks
C-1079	16#	SiO_2	1.78	2.80	.45	.10	.05	No additions to tap #1. Structure was all hypereutectoid carbide and pearlite. 0.045% B and 0.01% Bi to tap #2 resulted in 50% of free carbon as flake and 50% as compacted graphite with trace of hypereutectoid carbide. 0.045% B and 0.007% Te to tap #3 resulted in 95% of free carbon as compacted graphite and a trace of hypereutectoid carbide. All taps poured in 1⅝" x 1⅝" x 2⅝" mold cavities.
C-1082	16#	SiO_2	1.65	3.07	.46	.11	.03	Entire melt poured into Y block casting having a 1" base. Ladle addition was 0.045% B and 0.006% Te. Microstructure had 90% of free carbon as compacted graphite and about 5% hypereutectoid carbide.
C-1086	16#	SiO_2	1.85	3.02	.44	.10	.03	Entire melt poured into Y block mold. Ladle addition was 0.045% B and 0.007% Te. Microstructure 100% of free carbon as compacted graphite and 10% hypereutectoid carbide.
C-1107	16#	SiO_2	1.90	1.45	.45	.10	.03	Entire melt poured into step block mold. 0.006% Te plus 0.045% B added to ladle. All graphite compacted. 15% hypereutectoid carbide.
C-1141	100#	SiO_2	2.28	1.49	.43	.10	.03	Three taps made. All poured into step block molds. 0.006% Te and 0.045% B added to ladle. All graphite compacted. More free graphite than heat No. C-1107. 20% hypereutectoid carbide.
C-1142	100#	SiO_2	2.24	2.15	.45	.10	.04	Same procedure as heat No. C-1141. All graphite compacted. Aggregates larger than in heat No. C-1141. 25% hypereutectoid carbide.
C-1143	100#	SiO_2	2.25	2.81	.48	.09	.03	Same procedure as heat No. C-1141. Graphite compacted (very ragged) to star shaped. 20% hypereutectoid carbide.
C-1144	100#	SiO_2	2.88	2.69	.48	.10	.03	Same procedure as heat No. C-1141. Graphite mostly type D flake. Some isolated flake and compacted graphite. 5% hypereutectoid carbide.
C-1152	100#	SiO_2	2.65	2.07	.44	.10	.03	Same procedure as heat No. C-1141. Essentially a white cast iron structure. Some isolated patches of compacted graphite.
C-1155	100#	SiO_2	2.61	2.38	.45	.10	.03	Same procedure as heat No. C-1141. All graphite compacted and 30% hypereutectoid carbide. In heats C-1107 through heats C-1155, thin sections (less than ½ inch thick) were almost entirely white iron.
C-1139	100#	SiO_2	1.78	2.86	.44	.09	.03	Same procedure as heat No. C-1141. All graphite compacted. Less than 1% hypereutectoid carbide. Heavy and light sections (2" to ¼") very similar except for size of graphite aggregates.

The new steel-like material described above, which contains compacted or spheroidal graphite in the as-cast condition, is outstanding in that it possesses a modulus

of elasticity between 27.5 and 28.5 million pounds per square inch. Thus, it will be seen that although the castability of the new material appears to be generally comparable to that of conventional pearlitic malleable iron, it can be considered competitive with steel for many applications because of its high elastic modulus. Hence, it can be successfully used for highly stressed parts such as automotive crankshafts.

With regard to castability, the feeding characteristics of our new cast ferrous base metal are only very slightly inferior to those of white cast iron of the compositions commonly used in making conventional malleable iron. The relatively high silicon content of the new metal undoubtedly measurably contributes to the satisfactory feeding characteristics. As a result, sound castings of various shapes and sizes can be formed of this material. In casting some articles the "cast-to-clean" ratio can be made equal to that of conventional malleable iron by the addition of small quantities of exothermic riser compound. Pouring temperatures, preferably in the range of 2650° F to 2700° F., are approximately the same as for white cast iron.

Referring more particularly to the drawings, the photomicrograph of Figure 1 shows the microstructure of white cast iron which consists of approximately 2.5% carbon, 1.4% silicon, 0.4% manganese, 0.1% sulfur, 0.003% boron, a small amount of bismuth, and the balance iron. It will be noted that the white cast iron is composed solely of hypereutectoid iron carbide **10** in a pearlite matrix **12** and, as is well known, contains no free carbon. Figure 2 shows the microstructure of gray cast iron consisting of about 3.25% carbon, 2.25% silicon, 0.35% manganese, 0.1% sulfur, 0.05% phosphorus, and the remainder iron. This material contains free carbon in a pearlite matrix **14**. However, this graphite is in the form of relatively large flakes **16** rather than in the form of nodules or spheroids. As a result, gray cast iron has relatively poor physical properties, particularly with respect to strength and ductility. Generally, it possesses an ultimate tensile strength of approximately 40,000 p.s.i., a modulus of elasticity of only 15×10^6 p.s.i., and exhibits less than 1% elongation in two inches. White cast iron likewise is extremely brittle.

The specimens used to prepare all of the photomicrographs shown in the drawings were etched with a solution of about 4% nitric acid in ethyl alcohol, each photomicrograph being taken at a magnification of 100 diameters.

As pointed out above, inoculation of the base metal of the present invention with a combination of boron and tellurium produces the compacted graphite structure necessary to provide excellent physical properties. A typical as-cast microstructure of our new ferrous metal is shown in Figure 3. The specimens used to prepare this photomicrograph and the other photomicrographs of the new metal shown in the drawings were composed of approximately 1.7% carbon, 2.6% silicon, 0.4% manganese, 0.1% sulfur, 0.05% phosphorus, 0.01% boron, a small amount of tellurium, and the balance substantially all iron. It will be noted that all but the eutectoid carbon is present as graphite having a compacted or roughly spheroidal structure, as indicated at **18**. The matrix **20** is essentially medium-to-fine pearlite **22** with some "bull's-eye" ferrite **24** being present.

The properties of our new ferrous base metal product, particularly its high modulus of elasticity and susceptibility to various heat treatments, permit it to be used in a wide variety of applications in both the as-cast and heat-treated conditions. Even when no heat treatment is employed, however, the physical properties of this metal are outstanding, as can be seen from Table II which compares its as-cast properties with those of other cast ferrous base metals. The "nodular iron" listed is a type produced by the use of metallic magnesium and is composed of approximately 3.75% carbon, 2.84% silicon, 0.51% manganese, 0.048% magnesium, less than 0.02% sulfur, and the balance iron. This nodular iron is in the as-cast condition. The malleable iron set forth in Table II is a pearlitic malleable iron which has been air cooled and tempered. It consists of about 2.45% carbon, 1.31% silicon, 0.36% manganese, 0.09% sulfur, 0.05% phosphorus, 0.04% nickel, and the remainder iron. In evaluating the yield strength of these ferrous metals, measurements were taken by a standard test at 0.2% offset.

TABLE II

As-cast properties of new ferrous metal compared with those of other cast ferrous products

	Minimum Tensile Strength (p.s.i.)	Minimum Yield Strength (p.s.i.)	Elongation in 2 inches, percent	Modulus of Elasticity ($\times10^6$ p.s.i.)
New Ferrous Metal	80,000	60,000	1–3	27.5–28.5
"Nodular Iron"	80,000	60,000	1–10	20.0–24.0
Pearlitic Malleable Iron (air cooled and tempered)	80,000	60,000	1–3	24.0–26.0

The useful engineering properties of the subject ferrous base metal in the as-cast condition result from the almost complete absence of hypereutectoid carbide and flake graphite. While the ductility of the new material is not as high as the ductility sometimes obtained in "nodular iron" its strength is equivalent to that of either as-cast nodular iron or pearlitic malleable iron. More important, however, is the fact that its average elastic modulus of approximately 28 million pounds per square inch is measurably superior to the elastic modulus of the other cast iron products and is very nearly equal to that of steel. In no instance does the new ferrous metal exhibit an elastic modulus less than 27 million p.s.i. This high modulus of elasticity, which is not altered by heat treatment of the new metal, is essentially a function of the quantity of graphite in the microstructure.

Precise determinations of moduli of elasticity were obtained by an American Society of Testing Materials' bending beam method using S.R.–4 electrical resistance strain gages. The differences in the elastic moduli of the above-described cast ferrous metals can be clearly seen by comparing the slopes of the stress-strain curves of Figure 4. These curves show variations in slope due to differences in moduli of elasticity.

As hereinbefore indicated, although our new ferrous metal possesses outstanding physical properties in the as-cast condition, it may be readily heat treated to provide it with a wide variety of physical properties. Table III shows the properties which result from heat treating our new material, "nodular iron," pearlitic malleable iron and SAE 1045 wrought steel. All test specimens were standard 0.505 inch diameter tensile bars and, except for the steel, were machined from bars having a one inch square cross-section after heat treatment. The SAE 1045 wrought steel tensile bars were machined from heat treated stock having a circular cross-section of one inch diameter. The data regarding the steel was obtained from Hoyt, S. L., Metals and Alloys Data Book, Reinhold, 1943. The compositions of the nodular iron, pearlitic malleable iron and the new ferrous metal are set forth above, while the steel consists of about 0.47% carbon, 0.65% manganese, 0.04% sulfur, 0.04% phosphorus, and the balance iron.

TABLE III

Physical properties resulting from various heat treatments of new ferrous metal and other ferrous base materials

	Minimum Tensile Strength (× 1,000 p.s.i.)			Minimum Yield Strength (× 1,000 p.s.i.)			Percent Elongation in 2 Inches			Modulus of Elasticity ($\times 10^6$ p.s.i.)
	Annealed	Normalized @ 1,650 ° F.	Oil Quenched and Tempered @ 1,200 ° F.	Annealed	Normalized @ 1,650 ° F.	Oil Quenched and Tempered @ 1,650 ° F.	Annealed	Normalized @ 1,650 ° F.	Oil Quenched and Tempered @ 1,200 ° F.	
New Ferrous Metal	60	100	120	45	70	80	15–20	2–6	1–4	27.5–28.5
"Nodular Iron"	60	100	120	40	70	80	10–25	3–10	1–7	20–24
Pearlitic Malleable Iron	50	80	100	32	60	80	10–15	2–3	1–2	24–26
SAE 1045 Steel (Wrought)	90	98	103	55	65	70	20–28	20–27	20–24	29–30

In comparing the physical properties of these various materials it will be noted that the cast ferrous base metal disclosed and claimed herein can be heat treated to provide it with a minimum tensile strength and a minimum yield strength which are as high as the best values of the other materials to which it is compared. Moreover, the new material, when annealed, possesses ductility which compares with that of SAE 1045 wrought steel and annealed "nodular iron." Of course, the modulus of elasticity of our new cast ferrous metal is exceeded only by the elastic modulus of the steel. If the new metal were judged only on the basis of elastic modulus it would be considered more closely related to steel than to nodular iron or conventional malleable iron.

Low-temperature stress relief anneals increase the ductility of the new cast metal to a minimum of 3% with essentially no effect on its tensile strength or its microstructure. It appears that the minimum time for this treatment is approximately three hours at 1250° F.

If maximum ductility is desired, an elongation of 15% to 20% can be obtained by heating the new cast ferrous base metal for three hours at about 1350° F. At the same time, the tensile strength is correspondingly decreased to approximately 70,000 p.s.i. Such a heat treatment results in the decomposition of pearlite to graphite and ferrite. Graphite from the pearlite is deposited onto existing graphite nodules **18** and produces a matrix **26** which is 100% ferritic. The microstructure of our new ferrous base metal which has been heat treated in this manner is shown in the photomicrograph of Figure 5.

The aforementioned heat treating procedure is a time-temperature relationship, and consequently the process may be arrested at low temperatures, thus producing considerable ductility of the metal with less sacrifice in tensile strength. The effect on the microstructure of the new material after heat treatment for three hours at 1300° F. is shown in the photomicrograph of Figure 6. It will be seen that the pearlite decomposition is incomplete after this heat treatment, and consequently high strength is obtained in combination with less than maximum ductility. The matrix of the resultant structure is a mixture of pearlite **22** and ferrite **26**.

A pronounced increase in the tensile strength of the new ferrous metal can be obtained by a normalizing treatment at 1500° F. to 1600° F. This treatment produces a refinement of the pearlite in the metal, thereby increasing its minimum tensile strength to approximately 100,000 p.s.i. The retention of small amounts of ferrite, presumably at austenite grain boundaries, together with the homogenization of the pearlite matrix which results from the normalizing procedure, increases the ductility of the metal. The amount of this increase in ductility is inversely proportional to the temperature employed. The microstructure of the new ferrous metal after normalizing at 1500° F. is shown in Figure 7. Tensile strengths as high as 125,000 p.s.i. have been obtained by such a normalizing heat treatment.

One of the most significant features of our new ferrous base metal, as indicated by the foregoing examples, is that a very wide range of physical properties can be obtained in a relatively short period of time at heat treatment temperature. The graph of Figure 8 illustrates the effects of heat treatment on the tensile strength, ductility, and microstructure of this metal with heat treatments involving no more than three hours at temperature. Air cooling was employed in each instance.

Maximum physical properties of the new material can be produced by quenching and tempering. The graph of Figure 9 indicates the effects of tempering time and temperatures on the strength and ductility of the metal. One inch square bars, which were oil quenched from 1600° F. were used. The susceptibility of the new metal to low-temperature heat treatment is further illustrated by extending the tempering times. In this manner varying degrees of ductility up to the maximum amount may be obtained.

The end quench hardenability curves shown in the graph of Figure 10 indicate that the hardenability of our new ferrous base metal is superior to that of either pearlitic malleable iron or SAE 1045 steel. "Nodular iron" possesses somewhat greater hardenability than the new cast metal for most portions of the quenched specimens. However, this difference in hardenability resulted only because the nodular iron contained a negligible amount of sulfur and the manganese was in solution rather than being present as MnS inclusions. In each instance the bars used to produce the end quench hardenability curves shown in Figure 10 were austenitized for one hour at approximately 1600° F.

Castings of the new cast ferrous base metal can be successfully produced in green sand molds, dry sand molds, and shell molds with no apparent variation in results. Unlike white cast iron, the metal exhibits no tendency to "mottle" when poured into shell molds. Also, the prevention of flake graphite formation is not a serious problem. Another very important consideration is the fact that the condition of cope side segregation of graphite nodules, which frequently is present in nodular iron castings, does not occur in the ferrous metal described herein. Homogeneous microstructures are obtained in casings of all sizes.

When the new metal was made into test castings having section thicknesses ranging from one-fourth inch to several inches, there was little greater tendency for carbide to form in the thin sections than in the larger sections even though the size of the graphite nodules was somewhat reduced. This can be seen from the photomicrograph of Figure 11, which shows the microstructure of a one-fourth inch section of a step plate casting having sections ranging from one-fourth inch to two inches in thickness.

Moreover, the machinability of the new ferrous base metal, either in the as-cast condition or after heat treatment, appears to be entirely satisfactory. When compared

with pearlitic malleable iron, it was found that identical turning speeds and feed rates may be used while drilling speeds should be reduced slightly. The latter practice is advisable because the quantity of free graphite in the new cast metal is somewhat less than in pearlitic malleable iron.

Since the new cast metal may be annealed at temperatures in the order of 1350° F. to produce a ferritic matrix, it is possible for a single foundry using the same base iron to produce all of the parts currently formed from both ferritic and pearlitic malleable iron. Moreover, the increased strength resulting from normalizing and quenching and tempering treatments, as well as the high elastic modulus of the metal, permits it to be used in forming articles which are conventionally forged from plain carbon steel.

It should be noted that our new cast ferrous metal requires no costly or explosive addition agents, injection apparatus, or extensive heat treatment. Of course, there is no problem with regard to plugging of injection tubes or controlling feed rates of injected material. Also, since an injection operation is not used there is no reduction in temperature caused by such a procedure, and speed in the preparation of the metal is not an important factor. Late ferrosilicon additions are not required to reduce the chill of the metal. Furthermore, unlike some of the upgraded cast irons heretofore made, a dry, granular slag is not formed during production of the metal and hence does not present any removal problems.

Likewise, it is unnecessary to desulfurize the metal or to use a base metal having a very low sulfur content. It is also not necessary to employ a basic or neutral-lined ladle. Despite these facts, however, the physical properties of the new metal may be varied appreciably by short and inexpensive heat treating procedures to provide a diversity of useful products.

While the present invention has been described by means of certain specific examples, it will be understood that the scope of the invention is not to be limited thereby except as defined in the following claims.

We claim:

1. A ferrous metal having high tensile strength and a modulus of elasticity of at least 27 million p.s.i., said metal comprising approximately 1% to 2.5% carbon, 1.5% to 3.2% silicon, 0.001% to 0.05% predominantly acid-insoluble boron and the balance substantially all iron, said metal being characterized in the "as-cast" condition by a microstructure having carbon in the form of compacted graphite and in the absence of boron having a white iron "as-cast" microstructure.

2. A ferrous metal having high tensile strength and a modulus of elasticity of at least 27 million p.s.i.. in the "as-cast" condition, said metal comprising approximately 1% to 2.5% carbon, 1.5% to 3.2% silicon, manganese not in excess of 1.15%, sulfur not in excess of 0.5%, 0.001% to 0.05% predominantly acid-insoluble boron and the balance substantially all iron, said metal being characterized in the "as-cast" condition by a microstructure having free carbon principally in the form of compacted graphite and in the absence of boron having a white iron "as-cast" microstructure.

3. A ferrous metal having high tensile strength and a modulus of elasticity of at least 27 million p.s.i., said metal comprising approximately 1% to 2.5% carbon, 1.5% to 3.2% silicon, 0.001% to 0.05% predominantly acid-insoluble boron, a small amount not in excess of about 0.02% of an additive selected from the class consisting of tellurium and bismuth, and the balance substantially all iron, said additive being present in an amount sufficient to insure that said ferrous metal has an "as-cast" microstructure with free carbon substantially all in the form of compacted graphite, said ferrous metal in the absence of boron having a white iron "as-cast" microstructure.

4. A ferrous metal having high tensile strength and a modulus of elasticity of at least 27 million p.s.i. in the "as-cast" condition, said metal consisting essentially of about 1% to 2.5% carbon, 1.5% to 3.2% silicon, 0.001% to 0.05% predominantly acid-insoluble boron, 0.3% to 1.15% manganese, sulfur not in excess of 0.5%, a small amount not in excess of approximately 0.02% tellurium, and the balance substantially all iron, the amount of said tellurium being sufficient to insure that said ferrous metal has an "as-cast" microstructure with free carbon substantially all in the form of compacted graphite, said ferrous metal in the absence of boron having a white iron "as-cast" microstructure.

5. A cast ferrous metal having a high tensile strength and a modulus of elasticity of at least 27 million p.s.i., said metal comprising approximately 1% to 2.5% carbon, 1.5% to 3.2% silicon, manganese not in excess of 1.15%, sulfur not in excess of 0.5%, 0.001% to 0.02% predominantly acid-insoluble boron, 0.005% to 0.01% bismuth, and the balance substantially all iron, said metal being characterized in the "as-cast" condition by a microstructure having free carbon predominantly in the form of compacted graphite and having a white iron "as-cast" microstructure in the absence of said boron.

6. A cast ferrous metal having a high tensile strength and a modulus of elasticity of at least 27 million p.s.i. in the as-cast condition, said metal consisting essentially of about 1% to 2.5% carbon, 1.5% to 3.2% silicon, 0.3% to 1.15% manganese, 0.05% to 0.5% sulfur, 0.001% to 0.02% predominantly acid-insoluble boron, 0.001% to 0.01% tellurium, and the balance substantially all iron, said ferrous metal being characterized in the "as-cast" condition by a microstructure having free carbon in the form of compacted graphite and containing less than 10% by volume of hypereutectoid iron carbide, said ferrous metal in the absence of boron having a white iron "as-cast" microstructure.

7. A high strength ferrous metal having a modulus of elasticity of at least 27 million p.s.i. in the "as-cast" condition, said ferrous metal consisting essentially of about 1.5% to 1.9% carbon, 1.5% to 2.9% silicon, manganese not in excess of 1.15%, sulfur not in excess of 0.5%, 0.005% to 0.015% predominantly acid-insoluble boron, 0.003% to 0.01% of a metal selected from the class consisting of tellurium and bismuth, and the balance substantially all iron, said ferrous metal being characterized in the "as-cast" condition by a microstructure having free carbon predominantly in the form of compacted graphite and having a white iron "as-cast" microstructure in the absence of boron.

8. A high strength ferrous metal having a modulus of elasticity of at least 27 million p.s.i., said ferrous metal consisting esesntially of about 1.5% to 1.9% carbon, 2.4% to 2.9% silicon, 0.3% to 0.5% manganese, 0.05% to 0.15% sulfur, 0.005 to 0.015% predominantly acid-insoluble boron, 0.003% to 0.008% tellurium and the balance substantially all iron, said ferrous metal being characterized in the "as-cast" condition by a microstructure having carbon predominantly in the form of compacted graphite and containing less than 1% by volume of hypereutectoid iron carbide, said ferrous metal in the absence of boron having a white iron "as-cast" microstructure.

9. A ferrous metal having a pearlitic matrix and a modulus of elasticity of at least 27 million p.s.i. in the "as-cast" condition, said metal comprising approximately 1% to 1.9% carbon, 1.5% to 3.2% silicon, 0.001% to 0.02% acid-insoluble boron and the balance substantially all iron, said metal being characterized in the "as-cast" condition by a microstructure having free carbon predominantly in the form of compacted graphite and containing less than 5% of free carbon as AFS–ASTM type D flake graphite, said metal in the absence of said boron having a white iron "as-cast" microstructure.

10. A ferrous metal comprising approximately 1.5% to 1.9% carbon, 1.5% to 2.9% silicon, manganese not in

excess of 1.15%, sulfur not in excess of 0.5%, 0.001% to 0.02% boron and the balance substantially all iron, said metal having in the "as-cast" condition a modulus of elasticity of at least 27×10^6 p.s.i. and a microstructure having free carbon principally in the form of compacted graphite, at least 90% of said boron being acid insoluble, said metal in the absence of boron having a white iron "as-cast" microstructure.

11. A ferrous metal consisting essentially of about 1.5% to 1.9% carbon, 2.4% to 2.9% silicon, 0.3% to 0.5% manganese, 0.05% to 0.15% sulfur, 0.005% to 0.015% predominantly acid-insoluble boron, 0.003% to 0.01% of a metal selected from the class consisting of tellurium and bismuth, and the balance substantially all iron, said ferrous metal having in the "as-cast" condition a modulus of elasticity of at least 27×10^6 p.s.i., a minimum tensile strength of at least 80,000 p.s.i. and a minimum yield strength of at least 60,000 p.s.i. at 0.2% offset, said ferrous metal having an "as-cast" microstructure in which the free carbon is predominantly in the form of compacted graphite and which contains less than 1% by volume of hypereutectoid iron carbide, said ferrous metal in the absence of boron having a white iron "as-cast" microstructure.

12. A method of producing a ferrous metal casting having a high modulus of elasticity, tensile strength and yield strength in the "as-cast" condition, said method comprising melting together a mixture of steel and white cast iron in a proportion such that the resultant melt contains approximately 1% to 2.5% carbon and 1.5% to 3.2% silicon and would solidify with a white iron microstructure, thereafter tapping said melt into a ladle at a temperature of about 2700° F. to 3000° F., inoculating the melt with boron and an additive selected from the class consisting of tellurium and bismuth in amounts such that boron and said additive each constitutes approximately 0.001% to 0.02% of the melt, and subsequently pouring said inoculated melt at a temperature of about 2600° F. to 2750° F. into a mold to form a ferrous metal casting having an "as-cast" microstructure with free carbon substantially all present in the form of compacted graphite.

13. A method of producing a ferrous metal casting characterized by a modulus of elasticity of at least 27×10^6 p.s.i. and having free carbon predominantly in the form of compacted graphite in the "as-cast" condition, said method comprising melting together a mixture of plain low-carbon steel and white cast iron in a proportion such that the resultant melt consists essentially af about 1.5% to 1.9% carbon, 2.4% to 2.9% silicon, manganese not in excess of 1.15%, sulfur not in excess of 0.5% and the balance substantially all iron and would solidify with a white iron microstructure, tapping said melt into a ladle at a temperature of about 2750° F. to 2850° F., inoculating the tapped melt with boron and tellurium in amounts such that boron and tellurium respectively constitute approximately 0.001% to 0.02% and 0.001% to 0.01% of the melt, and subsequently pouring said inoculated melt at a temperature of about 2600° F. to 2700° F. into a mold.

14. A method of producing a ferrous metal casting having a modulus of elasticity of at least 27×10^6 p.s.i. and being substantially free of hypereutectoid carbide and AFS–ASTM type D flake graphite in the "as-cast" condition, said method comprising melting together a mixture of plain low carbon steel and boron-containing white cast iron, the ratio of said steel to said white cast iron being such as to provide a melt which in the absence of boron would solidify with a white iron microstructure, said melt consisting essentially of about 1.5% to 1.9% carbon, 2.4% to 2.9% silicon, 0.001% to 0.02% predominantly acid-insoluble boron, manganese not in excess of 1.15%, sulfur not in excess of 0.5% and the balance substantially all iron, tapping said melt into a ladle at a temperature of about 2750° F. to 2850° F., inoculating the tapped melt with tellurium in an amount equal to approximately 0.001% to 0.01% of the weight of the melt, and subsequently pouring said inoculated melt at a temperature of about 2600° F. to 2700° F. into a mold to form a ferrous metal casting having an "as-cast" microstructure with free carbon substantially all present in the form of compacted graphite.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 2,943,932 July 5, 1960

Philip R. White et al.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 4, line 29, for "perculiarly" read -- peculiarly --; column 6, line 18, after "desirable" insert -- low --; line 34, for "diretc" read -- direct --; columns 11 and 12, TABLE III, heading to column 7 thereof, for "1,650° F." read -- 1,200° F. --; column 12, line 62, for "casings" read -- castings --.

Signed and sealed this 6th day of December 1960.

(SEAL)

Attest:

KARL H. AXLINE
Attesting Officer

ROBERT C. WATSON
Commissioner of Patents