March 7, 1961 R. H. T. DIXON ET AL 2,973,564

METHOD OF GRAPHITIZING CAST IRON

Filed April 29, 1958 5 Sheets-Sheet 1

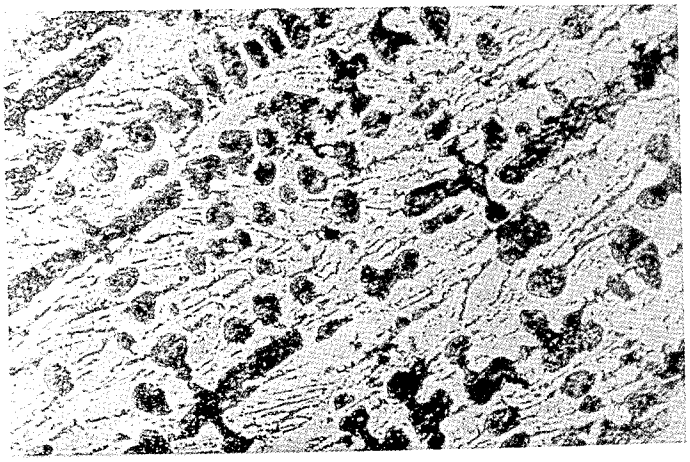


FIGURE 1

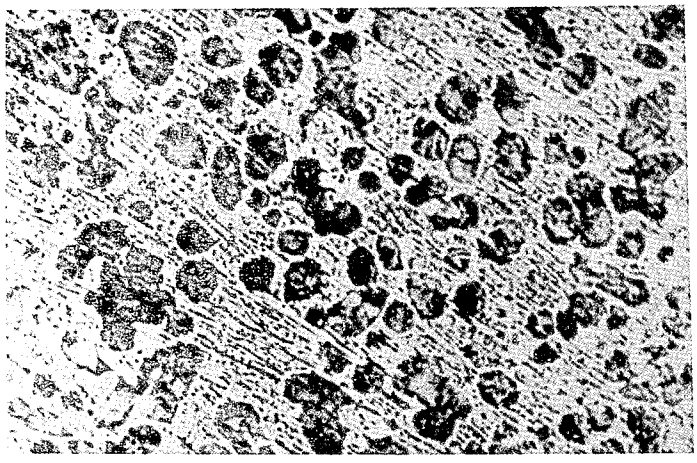


FIGURE 2

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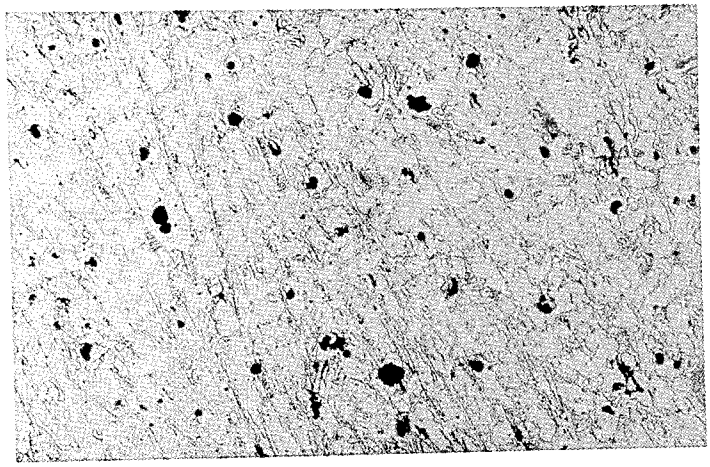


FIGURE 3

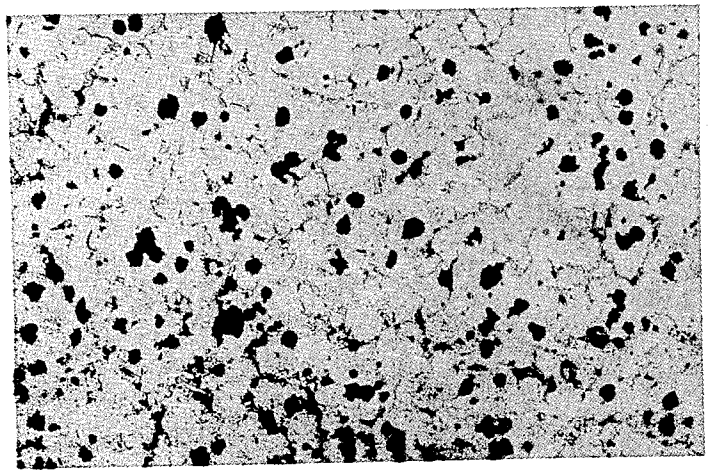


FIGURE 4

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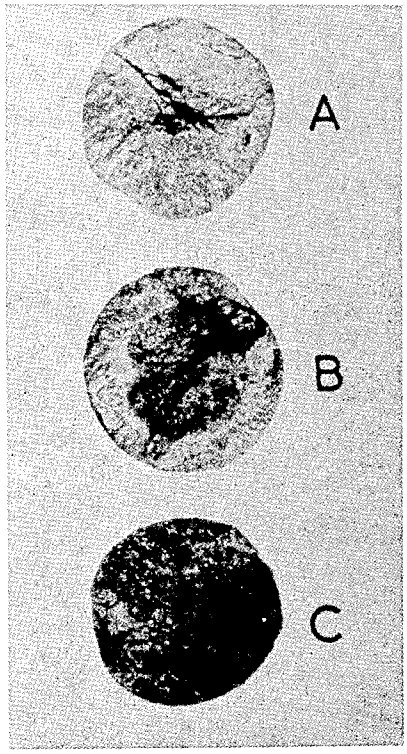


FIGURE 5

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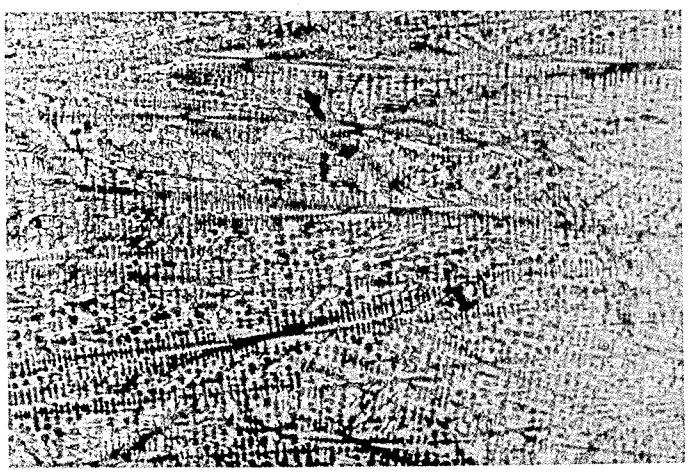


FIGURE 6

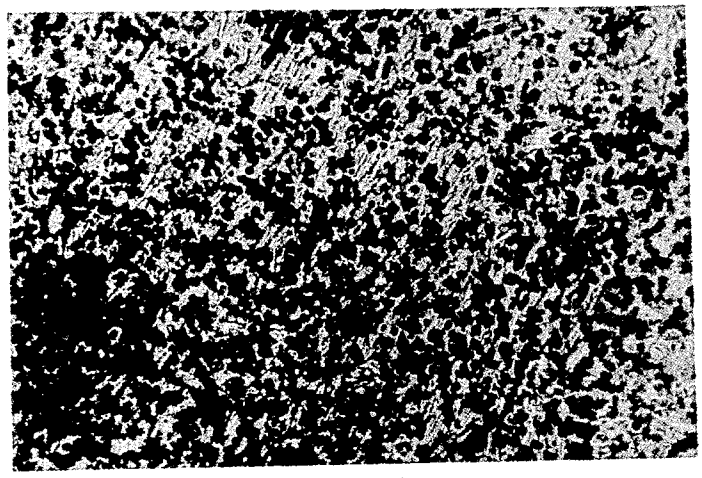


FIGURE 7

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Filed April 29, 1958 5 Sheets-Sheet 5

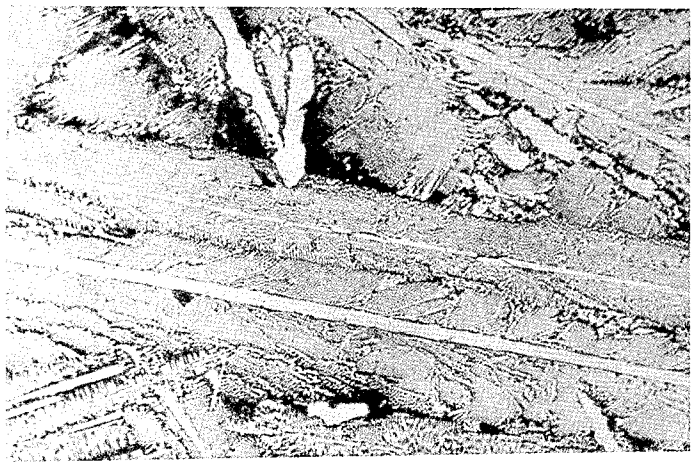


FIGURE 8



FIGURE 9

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United States Patent Office 2,973,564 Patented Mar. 7, 1961

2,973,564

METHOD OF GRAPHITIZING CAST IRON

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Claims priority, application Great Britain May 2, 1957

5 Claims. (Cl. 22—200)

This invention relates to a method for producing gray cast irons and white cast irons having improved metallurgical quality.

A typical example of a ferrous casting containing eutectic and possibly also hyper-eutectic carbides is white cast iron. White cast iron is commonly made for one or other of two principal purposes, namely:

(*a*) For use where its hardness and consequent resistance to abrasion are useful. An example is the use of white cast iron balls in grinding mills; and

(*b*) For conversion to malleable iron by an annealing process. Components produced by annealing white iron have good ductility, strength and shock resistance because the annealing operation produces aggregates or spheroids of graphite which do not weaken the casting to the same extent as do the graphite flakes in gray cast iron.

By means of the present invention, white cast iron for both these purposes can be improved.

We have now discovered an improved and simple method whereby the properties of white cast irons may greatly be improved and whereby the properties of gray cast irons produced from cast iron compositions which would otherwise cast white are also improved.

It is an object of the present invention to provide a method for producing white iron castings having improved metallurgical quality.

It is another object of the invention to provide a method for producing from cast irons which would otherwise cast white a gray cast iron casting having improved metallurgical quality.

It is a further object of the invention to provide a method for graphitizing cast iron castings without changing the composition thereof.

Another object of the invention is to provide an improved method for producing alloyed or unalloyed white or gray cast irons having improved metallurgical quality.

Other objects and advantages of the invention will become apparent from the following description taken in conjunction with the accompanying drawings, in which:

Figure 1 is a reproduction of a photomicrograph taken at 100 diameters depicting the structure of a white cast iron ball chill cast in a static mold;

Figure 2 is a reproduction of a photomicrograph taken at 100 diameters depicting the structure of a chill cast white iron ball made of cast iron having a composition identical with that of the iron shown in Figure 1 but treated in accordance with the invention;

Figure 3 is a reproduction of a photomicrograph taken at 200 diameters depicting the structure of a highly alloyed white cast iron casting produced in a static sand mold;

Figure 4 is a reproduction of a photomicrograph taken at 200 diameters depicting the structure of a cast iron having a composition identical with the iron depicted in Figure 3 but which had been treated in accordance with the present invention;

Figure 5 is a reproduction of a photograph taken at about ½ size depicting the fractured surfaces of three cast iron balls cast from the same melt and cast in the same type of mold but wherein ball A was cast into a static mold, ball B was allowed to solidify for 30 seconds prior to treatment in accordance with the present invention and ball C was produced entirely in accordance with the treatment contemplated by the present invention;

Figure 6 is a reproduction of a photomicrograph taken at 60 diameters depicting the structure of a nickel-chromium white cast iron ball about 2½ inches in diameter which was cast in a static sand mold;

Figure 7 is a reproduction of a photomicrograph taken at 60 diameters depicting the structure of a 2½ inch diameter cast iron ball having the same composition as that of the iron depicted in Figure 6 but treated in accordance with the present invention;

Figure 8 is a reproduction of a photomicrograph taken at 60 diameters depicting the structure of a nickel-chromium alloy white cast iron cast into a stationary mold; and

Figure 9 is a reproduction of a photomicrograph taken at 60 diameters depicting the structure of a cast iron similar to that of the iron depicted in Figure 8 but cast in accordance with the present invention.

According to the invention, a process of modifying the eutectic structure in the as-cast condition of ferrous metals containing carbon that would otherwise contain hyper-eutectic or eutectic carbides as cast comprises subjecting the metal to vibration before or during solidification.

The invention is particularly concerned with castings which contain a proportion of eutectic carbides and possibly also hyper-eutectic carbides when cast without vibration.

We have found that by vibrating such castings, during their solidification, surprising, novel and useful modifications in structure and properties can be produced.

The principal effect of vibration upon white iron castings is to modify the hyper-eutectic and eutectic carbides. In particular by vibrating a casting which would normally be free from eutectic and hyper-eutectic graphite and which would normally contain eutectic and hyper-eutectic carbides, graphitization can be induced during solidification. If the composition of the casting and the conditions under which it is produced are modified so as to prevent the production of hyper-eutectic and eutectic graphite by vibrating the casting during solidification, then the vibration produces a marked alteration in the appearance and structure of the hyper-eutectic and eutectic carbides. These carbides commonly form a brittle network throughout a white iron casting and seriously lower its shock resistance by providing a continuous path for the propagation of cracks. Vibration causes the continuous carbide network to be replaced by a discontinuous pattern of carbide needles or plates. Since these carbide needles do not form a continuous network, they do not form a continuous path for the propagation of cracks and the shock resistance of the casting is conspicuously improved. In an ordinary white iron casting, produced without vibration, fracture occurs through the brittle carbide network. In vibrated white iron castings, where the carbide is discontinuous, fracture must take place through both the carbide and the other constituents which are present. The other constituents can be made tough and fracture resistant by the use of suitable alloying elements and heat treatments and in this way the fracture resistance of the casting is substantially improved.

This is illustrated in Figures 1 and 2. Figure 1 shows the etched microstructure of a static chill cast white iron

ball, while Figure 2 shows the microstructure of a ball, identical in every way to that of Figure 1, save for the fact that the mold was vibrated at 100 cycles per second with an amplitude of 0.04 inch. The modification of both the primary dendrites and the eutectic is clearly shown.

Furthermore, the discontinuous carbide structure produced by vibrating white iron castings during their solidification is more readily annealed to produce malleable iron than is the continuous carbide network in white iron cast in the conventional manner.

Thus, for example, white iron castings which are commonly graphitized at about 900 to 1000° C. for the purpose of producing malleable iron may be so graphitized much more rapidly if the carbide has been modified by the application of vibration.

As stated above, by a suitable choice of casting conditions and metal composition, vibration can be applied to promote graphitization during solidification in castings which would otherwise be free from graphite. Similarly, vibration can be used to increase the amount of graphite which forms during the solidification of castings which would normally only contain a proportion of graphite, in addition to hyper-eutectic and eutectic carbides. Here, vibration has an effect similar to that of inoculation of the liquid metal with ferro-silicon, calcium silicide or other graphitizing inoculants prior to casting. Vibration can be used in addition to or instead of such inoculants and makes possible a hitherto unobtainable degree of graphitization during solidification in conditions under which partially carbidic castings would otherwise be produced.

Thus, for example, iron may be cast into metal molds in a way which would normally produce white castings containing eutectic and hyper-eutectic carbides. If the molds are vibrated during the solidification of the castings, graphitization is induced and gray iron castings are produced.

This is particularly useful in the production of cast iron pipe by centrifugal casting in metal molts, where the metal would normally cast white. Vibration of the mold during solidification enables a gray iron to be produced as cast and also enables an iron of lower silicon content to be used with consequent improvement in the properties of the pipe. For example, the silicon content of cast iron used to make centrifugally cast pipe in accordance with the invention may be as low as about 0.2% and will usually not exceed about 1.5%, whereas the silicon level of cast irons previously used for this purpose has been at least about 2.0%. These irons contain about 3.0% to about 3.6% carbon.

Again, vibration can be substituted for, or allied with, the inoculation commonly employed as one of the steps for the production of spheroidal graphite during the solidification of metal which has been treated with magnesium, cerium or any other spheroidizing agent. In the production of spheroidal graphite in iron, as hitherto performed, a spheroidizing agent is added to liquid iron with the result that the whitening or carbide-stabilizing tendency of the iron is increased. Castings made in iron so treated frequently contain some hyper-eutectic and eutectic carbides and it has previously been necessary, in such cases, to make an addition of a graphitizing inoculant such as ferro-silicon to the liquid metal before casting and after treatment with the spheroidizing agent. The inoculant favors the formation of spheroidal graphite instead of carbides, during solidification, and according to the present invention a similar effect can be produced by the application of vibration.

The following series of experiments illustrates the use of vibration as graphitizing means in the production of spheroidal graphite cast iron.

Three taps were poured from a bath of molten cast iron containing approximately 3.6% carbon, 1.3% silicon and 0.3% manganese, and each tap was treated with 1% of an alloy of 85% nickel–15% magnesium. From each tap two similar cylindrical castings each approximately 2¼ inches in diameter and 6 inches long were cast in sand molds bonded by the CO_2-sodium silicate process. One mold of each pair was rigidly clamped to a table that was caused to vibrate at 100 cycles per second by means of an electromagnet energized by a solenoid, while the other molds were not vibrated. The vibration was applied while the metal was being poured and was continued until the casting had cooled to about 500° C. The amplitude of vibration of the table could be varied by varying the voltage applied to the solenoid, a voltage of 250 volts giving an amplitude of 0.04 inch and smaller voltages giving smaller amplitudes.

When the castings had cooled they were removed from the molds and sectioned, and the sections were analyzed and examined under the microscope. The results are shown in the following table in which castings 1, 2 and 3 were not vibrated and 1A, 2A and 3A were vibrated.

Table I

Casting No.	Analysis					Structure				
						Edge		Center		Voltage
	Percent C	Percent Si	Percent Mn	Percent Mg	Percent Ni	Cementite* percent	Graphite, percent	Cementite* percent	Graphite, percent	
1	3.6	1.35	0.29	0.065	0.66	40	t. of S.G.	40	t. of S.G.	
1A	3.6	1.35	0.29	0.065	0.66	0	much S.G.	0	much S.G.	250
2	3.6	1.45	0.35	0.071	0.54	30	t. of S.G.	40	t. of S.G.	
2A	3.6	1.45	0.35	0.071	0.54	0	much S.G.	0	much S.G.	200
3	3.5	1.20	0.33	0.063	0.52	30	t. of S.G.	35	t. of S.G.	
3A	3.5	1.20	0.33	0.063	0.52	0	much S.G.	0	much S.G.	150

*Estimated by microscopic analysis of microspecimens.
S.G.=Spheroidal graphite.
t.=Trace.

It will be seen that the castings that were not vibrated during solidification all contained considerable amounts of cementite (iron carbide) and only very small amounts of spheroidal graphite, while those that were vibrated were almost completely graphitized.

To obtain a completely graphitic structure in similar castings without the use of vibration would in our experience have required the addition of about 0.5% silicon as an inoculant immediately before casting.

Another example of the use of vibration to graphitize eutectic carbides is provided by high alloy cast irons containing approximately 22% nickel, 2% chromium, and 3% carbon that are used for applications requiring a combination of toughness with high resistance to corrosion. When such irons are inoculated in the conventional manner, for example, with 0.5% of silicon (added as ferro-silicon) and are cast into unvibrated sand molds, they contain carbides. If, however, the molds are vibrated, the amount of carbide is reduced, while use of both vibration and conventional inoculation resulted in irons completely free of carbide. Figures 3 and 4 illustrate the use of vibration to reduce the amount of eutectic carbide present in such an alloy cast iron. Figure 3 shows the microstructure of static cast bar while Figure 4 shows the microstructure of an exactly similar bar poured under the same conditions into a vibrating mold. The melt used to produce these two bars was not inoculated with ferro-silicon. The foregoing demonstrates that these irons when cast in sand molds without vibration contain small amounts of free eutectic carbide. Vibration of such castings during solidification graphitizes this carbide with corresponding improvement in the properties.

The graphitizing effect of vibration may also be used to produce localized effects, to provide greater precision in the control of chill depth and to prevent inverse chill. Thus, by vibrating a casting during initial stages of solidification, a shell of gray iron can be formed adjacent to the mold surface. If the vibration is stopped before solidification is complete, the interior of the casting (provided this is of suitable composition) may then solidify white. Alternatively, a casting having a carbidic exterior and a graphitic interior may be produced by applying vibration after the initiation of solidification in castings of suitable composition. The foregoing is illustrated in Figure 5 which depicts the fractured surface of three 2¼ inch diameter balls which were all cast from the same melt. All were uninoculated. Ball A was unvibrated, ball B was allowed to solidify for 30 seconds prior to vibrating and ball C was produced by pouring into a vibrating mold and allowing vibration to proceed until solidification was complete. A further advantage of the use of vibration-inoculation is that conventional inoculation effects "fade" with the passage of time, while vibration-inoculation is effective so long as the vibrations are maintained. It has been found that in heavy section castings (i.e., castings having an included section of at least about 6 inches), which take a very long time to solidify, the effect of ferro-silicon inoculation "wears off" or "fades" with the passage of time so that the center of castings of this type may show an uninoculated type of structure. If, however, vibration is applied using for instance a vibrating probe inserted in the feeder head of the casting, it is possible to maintain a very strong inoculating influence until the last metal has solidified.

Tests have also shown that it is possible to make gray irons from compositions which would normally solidify white even though they were conventionally inoculated. For example, this range includes gray spheroidal graphite cast iron of the following composition:

Percent C	Percent Si	Percent Mn	Percent S	Percent P	Percent Mg
3.2	0.2	0.3	0.01	0.03	0.08

Such an iron would normally solidify completely white even if all of the silicon (i.e., 0.2%) was added as inoculant. Vibration-inoculated castings have, however, been produced in this composition which are almost completely gray. Irons of this composition and such a structure as cast have never previously been reported. Such castings were found to have superior ductility and impact strength after a subsequent ferritizing heat treatment.

It was also found possible to produce heavy section castings with a definite chill rim in magnesium-treated cast irons of low silicon content (0.01 to 0.5%). The castings were allowed to solidify to give a definite chill rim and they were then vibration-inoculated, using a vibrating probe immersed in the feeder head, so that the central portions of the castings were gray and thus shock resistant. Structures of this description are impossible to produce by any other existing technique.

In a further experiment, a series of irons were produced and from each melt two 2½ inch diameter balls were cast in sand. One ball of each pair was vibrated during solidification and the other was not. The irons had the following composition:

Table II

Iron No.	Composition				
	Percent T.C.	Percent Si	Percent Ni	Percent Mn	Percent Cr
4	3.2	0.52	4.15	0.60	1.55
5	3.1	0.52	3.95	0.64	2.25
6	3.1	0.55	3.75	0.61	3.0
7	3.2	0.56	3.8	0.51	3.2

T.C.=Total carbon.

All the unvibrated balls contained carbide in the form of a continuous brittle network (Figure 6). This structure is well known in alloy cast irons of this type which are used extensively when great resistance to abrasion is required, for instance in grinding balls, and its presence is a limiting factor on the shock resistance.

The balls made in molds that were vibrated during pouring and solidification (100 cycles per second at approximately 0.04 inch amplitude) had modified eutectic structures.

Iron No. 4, with the lowest chromium content, was inoculated by the vibration and the casting contained substantial amounts of flake graphite. Iron No. 5, with a chromium content of 2.25%, had no free graphite in its structure as cast but there was some evidence of modification of the structure of the carbide towards discontinuous needles. Further increase in the chromium content led to a more pronounced change in form of the carbide to discontinuous needles, and this change was complete at the highest chromium content in Iron No. 7, which had a completely acicular carbide structure. This structure is known to confer increased toughness upon castings which exhibit it.

This effect is also observed in nickel-chromium alloy white cast irons with primary carbides (hyper-eutectic carbide). Figure 8 shows the structure of an unvibrated casting with massive primary carbide, while, in the vibrated casting produced from the same melt, the structure was found to be as illustrated in Figure 9. The massive carbides are broken up and eutectic modification has occurred.

According to a further feature of the invention, in the production of iron castings containing eutectic carbide as cast, the metal is vibrated before or during solidification and subsequently annealed. As a result of the vibration, graphitization occasioned by the subsequent annealing heat treatment is accelerated. Thus, in the production of malleable iron, both the first and second

stages of anneal may be accelerated. Again, in the production of spheroidal graphite iron castings from an iron that has been treated with magnesium or some other spheroidizing agent, vibration that is insufficient completely to graphitize the iron during solidification may give an iron that is still wholly or partly white as cast but which can be graphitized by a shorter anneal than would otherwise be needed. Where the vibrated magnesium-treated iron contains spheroidal graphite in a pearlitic matrix as cast, subsequent ferritization is accelerated.

Vibration of the metal before solidification may take place immediately before, during or after pouring the casting. To affect hyper-eutectic carbide the metal is preferably vibrated before and during eutectic solidification but the eutectic structure is affected by vibration both during and before its solidification.

The invention is not limited to the use of any particular method of vibration or of any particular amplitudes and frequencies. The vibration must however be such as to supply a substantial amount of energy to the metal being treated. The frequency is preferably at least 50 cycles per minute but preferably does not exceed 20,000 cycles per second, as it becomes more difficult to obtain sufficient amplitude of vibration as the frequency increases.

The metal may suitably be vibrated by vibrating the mold, for example, by attaching it firmly to a plate that is vibrated electromagnetically, as described above, or a vibrating probe may be immersed in the metal in the mold. In practice the vibrating probe, which is made of either metal, e.g., mild steel, or non-metal, e.g., graphite, is usually inserted in the feeder head of the casting and it has been found that such an arrangement is effective in producing "gray" iron castings from uninoculated cast iron which would otherwise have solidified "white." In the case of a soluble probe, such as mild steel, the probe may be fed into the feeder head of the casting as it is dissolved in order to maintain complete metallic contact with the liquid metal of the casting throughout the solidification period. The vibration may be produced mechanically, hydraulically, pneumatically, or in any other manner. The method known as electromagnetic pulse stirring may also be used.

Cast irons which may be treated for their general betterment in accordance with the invention contain about 1½% to about 4½% carbon, about 0.05% to about 5% silicon, up to about 7% manganese, up to about 35% nickel, up to about 30% chromium, up to about 0.5% of an agent from the group consisting of magnesium and cerium, and the balance essentially iron. The usual impurities phosphorus and sulfur found in cast iron may be present in the usual amounts up to a total of about 1.5%, with the proviso that cast irons of the invention which contain either of the special graphite spheroidizing agents magnesium and cerium will not contain sulfur in amounts exceeding about 0.02%.

White cast irons treated in accordance with the invention for the production of malleable iron will contain about 2% to about 3.5% carbon, about 0.05% to about 2.0% silicon, up to about 3% nickel, up to about 0.5% of an agent from the group consisting of magnesium and cerium, and the balance essentially iron.

Production of graphite on cooling of a cast iron melt is dependent upon the summation of the graphitizing factors which are operative in a particular casting. Thus, the principal factors involved are the composition of the casting, particularly the carbon and silicon contents of the casting, and the cooling rate applied thereto. Cooling rate in turn is affected, as those skilled in the art know, by the section size of the casting and the type of mold into which the molten metal is poured. Thus, those skilled in the art know that metal molds and baked resin-bound sand molds such as those used in carrying out the "C" process provide more rapid cooling rates than the usual foundry sand molds and thus provide a greater whitening or carbide-forming or carbide-stabilizing effect in cast iron castings produced therein than is the case when the usual foundry sand mold is used. It is also known that elements such as chromium, manganese, etc., produce a whitening or carbide-forming effect in cast iron whereas other elements such as carbon, silicon, aluminum and, to a lesser extent, nickel tend to produce a graphitizing effect in cast iron.

The art is also aware that a late addition to molten cast iron of a graphitizing inoculant, which usually is silicon or a silicon-containing agent, is employed shortly before casting to produce an enhanced, but relatively short-lived, graphitizing effect. Such additions are widely employed with beneficial results although they alter the composition of the cast iron generally by way of increasing the silicon content thereof.

The method contemplated in accordance with the invention is of wide applicability in the production of both white and gray cast irons and may be employed in place of, or in conjunction with, the usual and widely employed graphitizing inoculation of cast iron. The method when applied to a white cast iron composition designed to prevent graphitizing produces a refinement of the eutectic constituents and in particular of the eutectic cementite. The treatment aparently causes a reduction in the size and an increase in the number of eutectic cells, with resultant refinement of the eutectic constituents. The method is also applicable to the graphitization of irons which would cast white if not vibrated during solidification. A particular example of this occurs when the carbide-stabilizing element added is magnesium. If sufficient magnesium is added to the cast iron melt to produce a whitening effect, but insufficient to prevent graphitization from occurring when the casting is vibrated, then spheroidal graphite is produced.

It has been found out hereinbefore that vibration of magnesium-containing cast iron produces an effect which resembles that produced by conventional inoculants such as ferro-silicon. It is to be pointed out that, in fact, the inoculating or graphitizing effect of vibration is much more powerful than that of the conventional ferro-silicon inoculant. Thus, vibration has been found to produce graphitization in a chill-cast magnesium-containing cast iron ball containing not more than about 0.2% silicon. In hyper-eutectic iron which solidified too rapidly for graphitization to be produced, vibration has been found to confer a random orientation upon the hyper-eutectic carbides.

Tests which have been conducted demonstrate and confirm the foregoing. These tests employed castings made of magnesium-containing cast iron having varying carbon and silicon contents. The castings were made in the form of 2¼ inch diameter balls supplied with a feeding head. The molds were either machined from graphite electrodes or were rammed up in silica sand bonded by the CO_2/sodium-silicate process. Vibration was supplied directly to the mold using a solenoid which delivered a maximum amplitude of 0.050 inch at an applied voltage of 250 volts. Lower voltages applied to the apparatus gave smaller amplitudes. The vibration was conducted at 100 cycles per second. Certain of the castings were given an annealing treatment comprising an 8-hour heating at 900° C., followed by a 16-hour heating at 690° C. and a slow cool to room temperature. Brinell hardnesses on the castings were measured at a distance of one inch from the edge of the ball.

In the first test, a melt of cast iron containing about 3.5% carbon and about 1.25% silicon was prepared and was treated with a nickel-magnesium alloy to provide a retained magnesium content sufficient to produce spheroidal graphite. Three taps were taken from the melt and in each case two sand-molded ball castings were produced, one of which was vibrated and the other of which was not. A vibrator voltage of 150, 200 and 250 volts was employed, respectively, to the vibrated casting produced from each tap. The analyses of the resulting casting are shown in the following table:

Table III

Casting Number	Analysis						
	Chemical			Spectrographic			
	Per-cent T.C.	Per-cent S	Per-cent P	Per-cent Mg	Per-cent Ni	Per-cent Mn	Per-cent Si
8	3.50	0.005	0.04	0.125	0.80	0.32	1.25
8V							
9				0.081	0.65	0.24	1.30
9V							
10				0.12	0.89	0.22	1.15
10V							

The vibrator voltage applied, the resulting Brinell hardnesses and microstructures of the castings are shown in the following table:

Table IV

Casting Number	Vibrator Voltage	B.H.N. As cast	B.H.N. Annealed	Microstructure As cast
8	0	415		White iron + a few graphite spheroids.
8V	150	412		Do.
9	0	415		Do.
9V	200	263	123	Gray iron with S.G.*
10	0	367		White iron + a few graphite spheroids.
10V	250	257	132	Gray iron with S.G.*

*S.G. = Spheroidal graphite.

The foregoing data demonstrate that all of the unvibrated balls were substantially free from graphite as would be expected from the fact that retained magnesium in the amounts given is a powerful graphite stabilizer. It was found that the balls which were vibrated by applying 200 volts or 250 volts to the solenoid were completely graphitized and had good spheroidal graphite structures.

A further series of tests was made in a similar manner upon a magnesium-containing cast iron containing about 4% carbon and less than about 0.2% silicon. In this test, both sand and graphite molds were employed to produce the 2¼ inch diameter balls. In some cases, the metal was inoculated immediately before casting either with ferro-silicon or crushed electrode carbon or with both materials simultaneously. Two ball castings were made from each tap, one of which was vibrated and the other of which was not. The following table contains the analyses of the resulting castings:

Table V

Casting Number	Analysis						
	Chemical			Spectrographic			
	Per-cent T.C.	Per-cent S	Per-cent P	Per-cent Mg	Per-cent Ni	Per-cent Mn	Per-cent Si
11	4.20	0.007	0.04	0.037	0.38	0.14	0.13
11V							
12				0.048	0.79	0.15	0.80
12V							
13	4.15	0.007	0.04	0.044	0.75	0.16	0.12
13V							
14				0.115	0.68	0.14	0.64
14V							
15				0.051	0.74	0.13	0.15
15V							
16				0.035	0.62	0.19	0.60
16V							

The type of inoculant employed, the vibrator voltage and Brinell hardnesses and microstructures obtained in the foregoing castings are shown in the following table:

Table VI

Casting Number	Type of Inoculant	Vibrator Voltage	B.H.N. As cast	B.H.N. Annealed	Microstructure As cast
11	Nil	0	545	256	White iron. No graphite.
11V	do	250	202	102	3/16" white iron rim. Gray iron core with S.G.*
12	0.625% FeSi**	0	278	194	Slight white iron rim. Gray iron core with S.G.*
12V	0.625% FeSi**	250	238	122	Do.
13	1.2% graphite	0	514	378	White iron. No graphite.
13V	1.2% graphite	250	309	177	5/8" white iron rim. Gray iron core with S.G.*
14	1.2% graphite + 0.625% FeSi**	0	283	146	Slight white iron rim. Gray iron core with S.G.*
14V	1.2% graphite + 0.625% FeSi**	250	233	115	Do.
15	Nil	0	508	185	White iron. No graphite.
15V	do	250	332	130	½" white iron rim. Gray iron core with S.G.*
16	0.625% FeSi**	0	497	150	White iron. No graphite.
16V	0.625% FeSi**	250	375	139	½" white iron rim. Gray iron core with S.G.*

NOTE.—Castings 11 through 14V were made in sand molds and castings 15 through 16V were made in graphite molds.
*S.G. = Spheroidal graphite.
**80% silicon, balance substantially iron.

The foregoing data demonstrated that despite the low silicon content of the castings vibration has produced a very substantial graphitizing effect as will be noted particularly in the case of ball 11V and again in the case of ball 15V. A comparison of ball 15V with similar ball 16 demonstrates that in this case vibration is much more effective as a graphitizer than was the ferro-silicon inoculant. It may be noted that the result obtained in the case of ball 15V indicates that by means of vibration it is possible to produce chill molded spheroidal graphite iron castings having substantially graphitic structures in the as-cast condition even through the silicon content is less than about 0.2%.

A still further series of 2¼ inch ball castings made of magnesium-containing cast iron was made in graphite molds using a base iron containing about 4.4% carbon and about 1.7% silicon. Again, in each case, one ball from each tap was vibrated using the full 250 volt vibrator voltage. A nickel-magnesium alloy was again employed to introduce magnesium into the molten cast iron. The analyses of the resulting castings are shown in the following table:

Table VII

Casting Number	Analysis						
	Chemical			Spectrographic			
	Per-cent T.C.	Per-cent S	Per-cent P	Per-cent Mg	Per-cent Ni	Per-cent Mn	Per-cent Si
17							
17V	4.45	0.009	0.038	0.076	0.66	0.36	1.7
18							
18V				0.071	0.59	0.31	1.95
19							
19V	4.42	0.008	0.037	0.081	0.73	0.26	1.6
20							
20V				0.054	0.60	0.35	1.75

The Brinell hardness, number of spheroids per square millimeter and the microstructure as cast are shown in the following table, together with the amount and type of graphitizing inoculant, where employed:

Table VIII

Casting Number	Type of Inoculant	B. H. N. As Cast	B. H. N. Annealed	Spheroids per Sq. mm. Annealed	Microstructure As cast
17	Nil	405	143	163	White iron. Some S. G.* at center.
17V	do	287	148	720	3/16" white iron rim. Gray iron core with S.G.*
18	0.625% FeSi**	331	158	360	Mottled iron.
18V	0.625% FeSi**	274	155	750	1/8" white iron rim. Gray iron core with S.G.*
19	1.20% graphite	459	139	150	White iron. Some S. G.* at center.
19V	1.20% graphite	302	150	760	3/16" white iron rim. Gray iron core with S.G.*
20	1.20% graphite + 0.625% FeSi**	361	159	480	Mottled iron.
20V	1.20% graphite + 0.625% FeSi**	276	152	870	1/8" white iron rim. Gray iron core with S.G.*

*S.G.=spheroidal graphite.
**80% silicon, balance substantially iron.

In the foregoing table, the suffix "V" denotes that the casting was vibrated with a vibrator voltage of 250 volts.

The results in the foregoing table demonstrate that vibration acts as a powerful inoculant producing balls consisting of gray iron cores and thin white iron rims. The foregoing data again demonstrate that vibration is a more powerful inoculant than the conventional addition of ferro-silicon which was employed.

Further information regarding the inoculating effects of vibration and ferro-silicon was obtained by counting the number of spheroids per square millimeter of a zone approximately one inch from the edge of each annealed ball. The figures so obtained are proportional to the rates at which eutectic cells (each of which has, as its center, a graphite spheroid) were nucleated during solidification. Since the principal effect of inoculation, in spheroidal graphite iron, is to increase the rate at which the iron-graphite eutectic is nucleated, the efficiency of an inoculant may be measured by a spheroid count: at fixed levels of all other variables, the more potent the inoculant, the greater will be the number of spheroids which it produces. On this basis, the spheroid counts listed in the foregoing table clearly confirm that vibration has been a more powerful inoculant than the ferro-silicon addition. An increase in the number of spheroids was accompanied by a decrease in their size.

In the as-cast condition, the vibrated balls exhibited four distinct structural zones. Near to the mold was a layer of equiaxed white iron about 0.10 inch thick. This structure is typical of chill molded cast irons cast in stationary molds. Further from the mold wall, a band of hyper-eutectic white iron occurred which had a columnar structure. In the vibrated balls, this structure gave place to a randomly oriented white iron structure while in the unvibrated balls this structure extended to the center of the casing. The center region in the vibrated balls exhibited a graphitic structure as a result of vibration.

Although the present invention has been described in conjunction with preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention, as those skilled in the art will readily understand. Such modifications and variations are considered to be within the purview and scope of the invention and appended claims.

We claim:

1. The method for producing a gray iron casting having improved metallurgical quality which comprises establishing a bath of cast iron having such a composition that it tends to freeze as a white cast iron containing carbides when poured into a mold, casting metal from said bath into a mold, and graphitizing said metal by applying vibration at a frequency of at least about 50 cycles per minute to said metal during the solidification thereof to form a casting having substantially no retained carbides and having improved metallurgical quality.

2. The method for producing a gray iron casting having improved metallurgical quality which comprises

establishing a bath of cast iron containing about 1.5% to about 4.5% carbon and not more than about 1.5% silicon, and being characterized by a strong tendency to freeze as a white cast iron when cast without a graphitizing inoculation, casting metal from said bath into a mold, and graphitizing said metal during the solidification thereof by applying vibration thereto at a frequency of at least about 50 cycles per minute until solidification is substantially complete to form a gray iron casting containing not more than about 1.5% silicon having improved metallurgical quality and having improved ductility as compared to a similar casting produced with a graphitizing inoculation.

3. The improved method for producing malleable iron using a short annealing cycle which comprises establishing a bath of molten white cast iron containing about 2.0% to about 3.5% carbon, up to about 2.0% silicon, up to about 1.0% manganese, up to about 0.3% sulfur up to about 3.0% nickel, up to about 0.5% of a carbide-stabilizing agent from the group consisting of magnesium and cerium, and the balance essentially iron, casting metal from said bath into a mold, vibrating said metal during solidification at a frequency of at least about 50 cycles per minute to provide a white iron casting containing not more than about 1% of uncombined carbon, and annealing said white iron casting to produce a malleable iron casting after a shorter period of time at the annealing temperature than would be required to malleablize a white iron casting of similar composition which had not been vibrated during solidification.

4. The process for producing an improved nickel-chromium alloy abrasion-resisting white cast iron normally characterized by a continuous brittle carbide network which comprises establishing a molten bath of such a cast iron, pouring metal from said bath into a mold and applying vibration to said metal at a frequency of at least about 50 cycles per minute during solidification thereof to provide an acicular carbide structure in the resulting solidified metal.

5. The method for producing improved spheroidal graphite cast iron which comprises establishing a bath of molten cast iron containing a small but effective amount up to about 0.5% of metal from the group consisting of magnesium and cerium and having a composition such that metal from said bath when cast without a graphitizing inoculation would be substantially a white cast iron containing carbides, casting metal from said bath into a mold and applying vibration to the cast metal at a frequency of at least about 50 cycles per minute during solidification thereof to provide a graphitized casting containing at least a substantial amount of spheroidal graphite and which is substantially free from carbides.

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UNITED STATES PATENT OFFICE

CERTIFICATION OF CORRECTION

Patent No. 2,973,564 March 7, 1961

Ronald H. T. Dixon et al.

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

Column 3, line 40, for "molts" read -- molds --; column 8, line 32, for "aparently" read -- apparently --; line 43, for "found" read -- pointed --; column 11, line 12, for "through" read -- though --; line 39, for "hardness" read -- hardnesses --; column 12, line 28, for "casing" read -- casting --.

Signed and sealed this 15th day of August 1961.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents