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3,155,498

DUCTILE IRON AND METHOD OF MAKING SAME
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 No Drawing. Filed Dec. 27, 1961, Ser. No. 162,558
 13 Claims. (Cl. 75—130)

This invention relates to the manufacture of ductile iron and more particularly to ductile iron which can be subsequently formed into semi-finished and finished ductile iron products by various methods of working, i.e., rolling, forging, or hammering, which can be used in many applications instead of the more costly mild steels.

Among the principal difficulties in producing a ductile iron ingot which can be deformed and converted to useful semi-finished and finished products by subsequent working processes is the prevention of the precipitation of large areas of free primary graphite, and free massive carbides usually referred to as cementite which render the ingot brittle and thus susceptible to rupture during the hot-working processes.

It is a well known fact that graphite in itself possesses no appreciable strength. It is obvious, therefore, that the form of the graphite in a cast iron ingot is important in the sense that it determines the shape of the discontinuities which the graphite forms in the matrix of the ingot. The mechanical strength of the ingot is dependent upon the manner in which these discontinuities interrupt the continuity of the essential matrix or mass of the ingot.

The formation of numerous large free primary graphite flakes in grey iron castings interrupt the matrix in such a manner that any applied stresses are resisted by small areas of the matrix between the graphite flakes. These areas are usually of insufficient strength to resist large concentrations of stresses and are bridged quite readily by these stresses, thus rendering the castings brittle and susceptible to fracture by applied static or dynamic forces.

The formation of nodular or spheroidal free primary graphite in ductile iron castings inoculated with magnesium, cerium or the like increases the strength and ductility of these castings as compared to the strength and ductility of grey iron castings. These ductile iron castings, however, are also susceptible to brittle rupture at low stress levels due to the large nodules formed during the solidification of the castings.

Malleable iron castings can be hot worked but as a practical matter are limited to small sizes and must be subjected to lengthy and costly annealing cycles to obtain the necessary microstructures. They are chill cast in small cross-sectional molds to prevent the formation of any form of free primary graphite. This procedure favors the formation of free massive carbides which upon lengthy annealing at the proper temperatures decompose into ferrite and spheroids of graphite called temper carbon. Since any free primary flake graphite formed in the initial casting is not converted to the spheroidal form on heating, malleable iron castings must be relatively small so that the entire mass is cooled rapidly in the chill molds in order to insure that only carbides are formed.

The free massive carbides formed in malleable castings are hard and brittle and are not conducive to hot-working operations so that it is necessary to decompose these carbides to ferrite and graphite. If comparatively large castings, e.g. large ingots, were made, the heat treatment required to make them suitable for subsequent hot-working operations would be of such duration as to make it economically unfeasible to produce such castings. The decomposition of the massive carbides to graphite is sluggish and requires holding times of many hours at temperatures exceeding 1200° F. and as high as 1850° F., and these massive carbides decompose into relatively

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large graphite particles, which, as hereinbefore stated are not conducive to working operations.

It is the primary object of this invention to provide a new method for the manufacture of ductile iron which can be worked hot or cold by known methods into semi-finished and finished articles.

Another object of this invention is to produce a new article of manufacture which comprises ductile iron which can be readily transformed into semi-finished and finished products by the usual working operations, i.e., rolling, hammering, forging, etc., and a method of producing same.

Another object of this invention is to produce a new article of manufacture which comprises ductile iron, the microstructure of which as-cast comprises primarily fine widely-dispersed unstable complex carbides in a substantially pearlitic or ferro-pearlitic matrix in which free primary graphite is substantially absent, and a method of producing same.

Another object of this invention is to produce a new article of manufacture which comprises ductile iron, the microstructure of which as-cast comprises primarily fine widely-dispersed unstable complex ferro-magnesium carbides in a substantially pearlitic or ferro-pearlitic matrix in which free primary graphite is substantially absent and a method of producing same.

Still another object of the invention is to produce a new article of manufacture which comprises ductile iron having improved mechanical properties, particularly good ductility, high impact strength, low transition temperatures, good corrosion resistance, high damping capacity, and good machinability, and a method of producing same.

A further object of the invention is to produce a new article of manufacture comprising ductile iron, the microstructure of which as-cast comprises primarily fine widely-dispersed carbides in a pearlitic or ferro-pearlitic matrix which, upon heating to the hot working temperature, comprises fine well-dispersed nodular graphite in an austenitic matrix, and a method of producing same.

I have found that by controlling the chemical composition of iron, particularly the carbon, sulfur, silicon and magnesium contents, and by pouring the molten iron into a chill mold of any size or type, an ingot can be produced which comprises mainly fine, well-dispersed, unstable complex carbides and has practically no free primary graphite in any form, but if some be present it will be in the form of minute, very widely-dispersed nodules or spheroids as the constituents of its microstructure. The said microstructure makes it possible to heat the castings to a temperature of about 1850° F. and hold for a very short time, e.g. 1 to 2 hours, to decompose the carbides to fine well-dispersed graphite nodules and austenite so that the ingot can be subsequently hot-worked by such methods as rolling, hammering, or forging. Should it be desired to cold work the ingot, it can be slowly cooled from the annealing temperature to produce a structure retaining the said graphite nodules, but which below the critical will be in a matrix of ferrite or pearlite according to the cooling rate to give properties desired in the worked product. The time required at temperature to decompose the fine carbides to fine graphite is much shorter than that required to decompose the free massive carbides present in malleable iron castings.

The broad composition ranges permissible in the final product made by the method of this invention comprise by weight a total carbon content of about 1.20% up to about 3.60%, a silicon content of about 1.00% up to about 2.00%, a phosphorus content not over 0.06%, a sulfur content not over 0.035%, and about 0.005% up to about 2.00% of well-known nodularizing elements such as magnesium, tellurium, cerium, calcium, lithium, sodium and potassium. The preferred chemical compo-

sition ranges of the final product made by the method of the present invention comprise a total carbon content of from about 2.40% to about 2.80%, silicon from about 1.50% to about 2.00%, phosphorus up to about 0.06%, sulphur up to about 0.025%, and magnesium from about 0.04% up to about 0.08%.

A normal cast iron is melted to a manganese range of about 0.60% up to about 0.80% primarily to provide sufficient manganese to desulfurize the iron and to a lesser degree to add to the hardness of the iron. The nodularizing elements used in the manufacture of ductile iron are also powerful desulfurizers making it unnecessary to have a higher manganese than up to 0.35%. The hardness and brittleness of the iron are reduced, thus increasing the workability of the ductile iron of the present invention. However, it has been found that if a harder ductile iron is desired an increase of the manganese content up to 1.50% will not greatly affect the workability of the iron of the invention.

The melting of the iron can be accomplished in any suitable melting apparatus such as a cupola furnace, blast furnace, open-hearth furnace or electric furnace using the usual ore mixtures, fuels and other necessary additives, although the preferred equipment is the cupola furnace familiar to all foundries, and the preferred charge is steel scrap.

The ductile iron embodying the present invention can be produced, for example, by melting a suitable charge, preferably 100% selected steel scrap such as structural channel shapes, having a low content of residual elements such as copper, bismuth, tin, lead, titanium, so as to produce a heat of molten iron at tapping comprising a chemical content of, for example, carbon from about 2.50% up to about 4.20%, silicon about 2.00% max., manganese from about 0.05% up to about 1.00%, phosphorus about 0.06% max., sulfur up to about 0.30% max. and the balance iron.

The aforementioned molten iron is tapped into a ladle and the carbon and silicon contents are reduced by subjecting the said molten iron to the action of an oxidizing agent, preferably pure gaseous oxygen blown under pressure through a pipe onto the surface of the said molten iron. The oxygen unites with the silicon in the iron resulting in the removal of substantially all of the silicon before the carbon is oxidized to the required ranges of 1.20% to 3.60%. The silicon is replaced in the iron in subsequent deoxidation and inoculation steps to a level of 1.00% to 2.00%. The carbon and silicon contents are required at this level so that large nodules of free primary graphite are not formed during the solidification of the metal in the mold as occurs in normal ductile iron and which would render the metal unworkable.

The said molten iron is now deoxidized by the addition of silicon preferably in amounts which will also provide a silicon content of 0.20–0.50%. Small amounts of aluminum may be added to insure complete deoxidation, but this is not essential to the practice of the invention, as deoxidation can be accomplished by the silicon alone.

After deoxidation, a nodularizing agent consisting of one or more elements of the group magnesium, tellurium, cerium, calcium, lithium, sodium, potassium, preferably magnesium ferro silicon alloy, is placed in a second ladle. The said dioxidized molten iron is reladled into the ladle containing the aforementioned nodularizing agent to reduce the sulphur and to provide the final residual content of nodularizing agent necessary to provide nuclei for the formation of fine well-dispersed unstable complex carbides as cast and later the formation upon heating of small graphite nodules or spheroids and to inhibit the formation of any flake graphite in the final product.

The silicon added in the deoxidation step and with the nodularizing agent should be sufficient to promote graphitization in the heating or annealing step.

An example of a final composition of the iron of the

invention comprises carbon about 2.40–2.80%, silicon about 1.50–2.00%, manganese about 0.15–0.40%, phosphorus about 0.06% max., sulfur about 0.025% max. and magnesium about 0.04–0.08%.

Following the inoculation step, it has been found that the addition of silicon in a post inoculation treatment is sometimes desirable. This additional silicon has been found effective in shortening the heating times required to break up the unstable carbides. Although this has been found to be advantageous, it is not essential to the invention.

The above treated molten iron is teemed into chill molds of any desired size or shape and allowed to remain for a period of time long enough to solidify the ingot. The resultant ingot will have a structure comprising fine well-dispersed unstable complex carbides in a ferrous matrix and little if any graphite, such graphite if present being in the form of minute, well-dispersed nodules.

The solidified ingot is removed from the mold as soon as possible and charged into a holding chamber or furnace at 1500° F. to 2000° F. and preferably 1850–1950° F. prior to any working operation. Holding the ingot within this temperature range will result in the dissolution of all the carbides within a period of 1 to 2 hours resulting in a structure comprising small well-dispersed nodules of free graphite in an austenitic matrix. If for any reason the solidified ingot is allowed to become cold, it is preferred that the said cold ingot be charged into a preheat chamber or furnace at approximately 1000°–1300° F., preferably about 1200° F., heated for a sufficient length of time to assure that the casting is at a uniform heat, then transferred to a heating chamber at 1500° F. to 2000° F., preferably 1850°–1950° F. and held for a sufficient length of time to assure a uniform heating prior to the final hot-working operations of rolling, hammering, or forging necessary to form the said ingot into semi-finished and finished products. It will be understood that the semi-finished and finished products referred to in the present invention include such articles as blooms and billet stock for secondary conversion by rolling, hammering or forging, bar stock both round and flat as used in the industry for further processing by machining, drawing cold-working and the like, and finished hammered or forged materials such as steam traps, gear blanks and the like. These finished products may be used as rolled, or annealed or in the heat-treated condition. If the ingot is to be directly cold worked, the heating is followed by slow cooling to the cold working temperature.

By careful control of the chemical composition of ductile iron, particularly the carbon and silicon contents, and by careful hot metal procedures, it is possible to manufacture a ductile iron which can be worked hot or cold by any of the conventional methods, rolling hammering, forging, into semi-finished and finished products which have better mechanical properties, particularly ductility, and higher impact strengths than grey cast irons, malleable cast irons or normal ductile irons; and lower transition temperatures, better corrosion resistance and higher damping capacity than mild steels.

A specific example of my process is as follows:

A molten iron bath containing by weight a total carbon content of about 3.40%, a manganese content of about 0.35% and a silicon content of about 1.30% was obtained by melting a charge of 6,000 pounds of selected steel scrap, 1,000 pounds of coke, 150 pounds of 50% ferro-silicon alloy and 60 pounds of limestone in a cupola-type furnace. The molten metal was tapped at a temperature of approximately 2600° F. into a ladle which contained 90 pounds or purite (Na_2CO_3) which desulfurized the cupola iron and resulted in a sulfur content of below .03%. In order to insure satisfactory desulfurization and the "floating out" of the manganese sulfides thus formed, the molten metal was agitated with pure gaseous nitrogen for approximately 3 minutes.

The molten metal was then oxidized by blowing 1650

cu. ft. of pure gaseous oxygen onto the surface of the iron. The total carbon content was reduced to 2.70%, the silicon content to 0.20%, the manganese content to 0.10%.

The molten metal was then deoxidized by adding 9 pounds of 85% ferrosilicon as a deoxidizing agent, bringing the silicon content of the metal to 0.50%. After the deoxidation step 18 pounds of 75% ferro-manganese were added to the molten metal in order to bring up the manganese content to a level which would insure a 0.35% content in the final product to provide hardenability to the iron.

The molten metal in the ladle was then inoculated with 211 pounds of a nodularizing alloy containing 47.0% silicon, 9% magnesium, 10% cerium, 10% calcium, the balance iron, and 9 pounds of 85% ferrosilicon. The inoculated bath was then allowed to stand for several minutes, after which time the slag was removed and the molten metal teemed into two 13-inch round ingot molds. The metal was allowed to solidify in the molds for one hour. The molds were stripped from the ingots which were placed in a box and covered with sand to cool. Microscopic examination of test specimens cut from the cold ingot revealed the microstructure to be fine, well-dispersed unstable complex ferro-magnesium carbides, and a very few small nodules of free primary graphite in a pearlitic matrix.

The ingots were charged into a preheat furnace held at 1100° F. and soaked for 5 hours. One ingot was transferred to a furnace at 1900° F. and was soaked at this temperature for 5 hours. The structure of the hot ingot at 1900° F. comprised fine nodules of well-dispersed free graphite in an austenitic matrix. The ingot was then forged into 6-inch round billets which were rolled in a conventional bar mill to 2-inch round bars finishing at a temperature of 1550° F. and air cooled to room temperature. Samples were cut from the roller bars and were mechanically tested at the Physical Laboratory. The results of the mechanical tests follow:

	Y.S. (p.s.i.)	T.S. (p.s.i.)	Elong. (percent)	R.A. (percent)	BHN
As-rolled.....	76,000	145,000	8.0	8.9	262
Annealed.....	55,000	96,750	16.0	19.2	163

The second ingot was transferred to a furnace at 1850° F. and was held for a total time of 12 hours, after which it was furnace cooled to 900° F. The ingot was removed from the furnace and air cooled. Blanks weighing 74 pounds each were cut from the ingot, were heated to 1900° F. at which time said blanks had a microstructure comprising small nodules of well-dispersed free graphite in an austenitic matrix, and were forged into sixteen inch gear blanks. The finished pieces were allowed to cool in air. Specimens cut from the finished cold blanks revealed a microstructure of fine nodules of well-dispersed free graphite in a pearlitic matrix. Test specimens were removed from the forged blanks and tested at the Physical Laboratory. Results of the tests showed:

	Y.S. (p.s.i.)	T.S. (p.s.i.)	Elong. (percent)	R.A. (percent)	BHN
As-Forged:					
Tangential.....	73,500	132,500	5.0	5.5	248
Radial.....	71,500	127,000	4.5	4.7	241
Normalized:					
Tangential.....	72,500	131,000	5.5	5.5	248
Radial.....	70,500	125,500	5.0	3.5	248

A chemical analysis was conducted on the broken test specimens and revealed the ductile iron to be comprised of 2.98% total carbon, 1.61% silicon, .26% manganese, 0.35% sulfur, .047% phosphorus, .06% magnesium.

Although I have described the process of manufacture and product in considerable detail, I am aware that altera-

tions and changes may be made without departing from the spirit of the invention and scope of the claims.

I claim:

1. A method of manufacturing a workable ductile iron alloy having a total carbon content of from about 1.20% up to about 3.60%, a silicon content of from about 1.00% up to about 2.00%, a sulfur content of 0.035% max. and a content of from about 0.005% up to about 2.00% of a nodularizing agent, said method comprising:

(a) tapping from a furnace into a ladle a molten iron alloy containing carbon, silicon and sulfur,

(b) treating the molten iron alloy in the ladle by oxygen injection for a period of time to effect substantially complete removal of all the silicon,

(c) adding a deoxidizing agent comprising silicon to the molten iron alloy in the ladle to produce a silicon content of about 0.20% up to about 0.50%,

(d) adding silicon and a nodularizing agent to the molten iron alloy in the ladle, said nodularizing agent consisting of at least one of the elements of the group magnesium, tellurium, cerium, calcium, lithium, sodium, potassium, thereby imparting to the said molten iron alloy a final silicon content of from about 1.00% up to about 2.00% and 0.005% up to about 2.00% of said nodularizing agent,

(e) teeming the molten iron alloy into a chill mold and allowing the said molten iron alloy to solidify.

2. A method as claimed in claim 1 in which the nodularizing agent in step (d) is magnesium in an amount of .04% to .08%.

3. A method as claimed in claim 1 in which the solidified metal alloy in the mold in step (e) consists essentially of a total carbon of about 2.40% up to about 2.80%, a silicon content of about 1.50% up to about 2.00%, a manganese content of about 0.15% up to about 0.40%, a phosphorus content up to about 0.05%, a sulfur content up to about 0.025%, a magnesium content of about 0.04% up to about 0.08%, and the balance iron.

4. A method as claimed in claim 1 in which the nodularizing agent utilized in step (d) consists essentially of a ferrosilicon magnesium alloy.

5. A method as claimed in claim 1 in which the solidified iron alloy is subjected to heating above the upper critical temperature of the alloy.

6. A method as claimed in claim 2 in which the solidified iron alloy is subjected to heating above the upper critical temperature of the alloy.

7. A method as claimed in claim 3 in which the solidified iron alloy is subjected to heating above the upper critical temperature of the alloy.

8. A method as claimed in claim 4 in which the solidified iron alloy is subjected to heating above the upper critical temperature of the alloy.

9. A method as claimed in claim 5 in which the iron alloy after heating is subjected to working.

10. A method as claimed in claim 6 in which the iron alloy after heating is subjected to working.

11. A method as claimed in claim 7 in which the iron alloy after heating is subjected to working.

12. A method as claimed in claim 8 in which the iron alloy after heating is subjected to working.

13. A method of manufacturing a workable ductile iron alloy having a total carbon content of from about 1.20% up to about 3.60%, a silicon content of from 1.00% up to about 2.00%, a sulfur content of 0.035% max. and a content of from about 0.005% up to about 2.00% of a nodularizing agent, said method comprising:

(a) tapping from a furnace into a ladle a molten iron alloy containing carbon, silicon and sulfur,

(b) treating the molten iron alloy in the ladle by oxygen injection for a period of time to effect substantially complete removal of all the silicon,

(c) adding a deoxidizing agent comprising silicon to

the said molten iron alloy in the ladle to produce a silicon content of about 0.20% up to about 0.50%,
 (d) adding silicon and a nodularizing agent thereto,
 (e) teeming the molten iron alloy into a chill mold and allowing said molten iron alloy to solidify.

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