

Nov. 29, 1949

L. F. WHITNEY

2,489,839

PROCESS FOR CARBURIZING COMPACTED IRON ARTICLES

Filed April 30, 1946

2 Sheets-Sheet 1

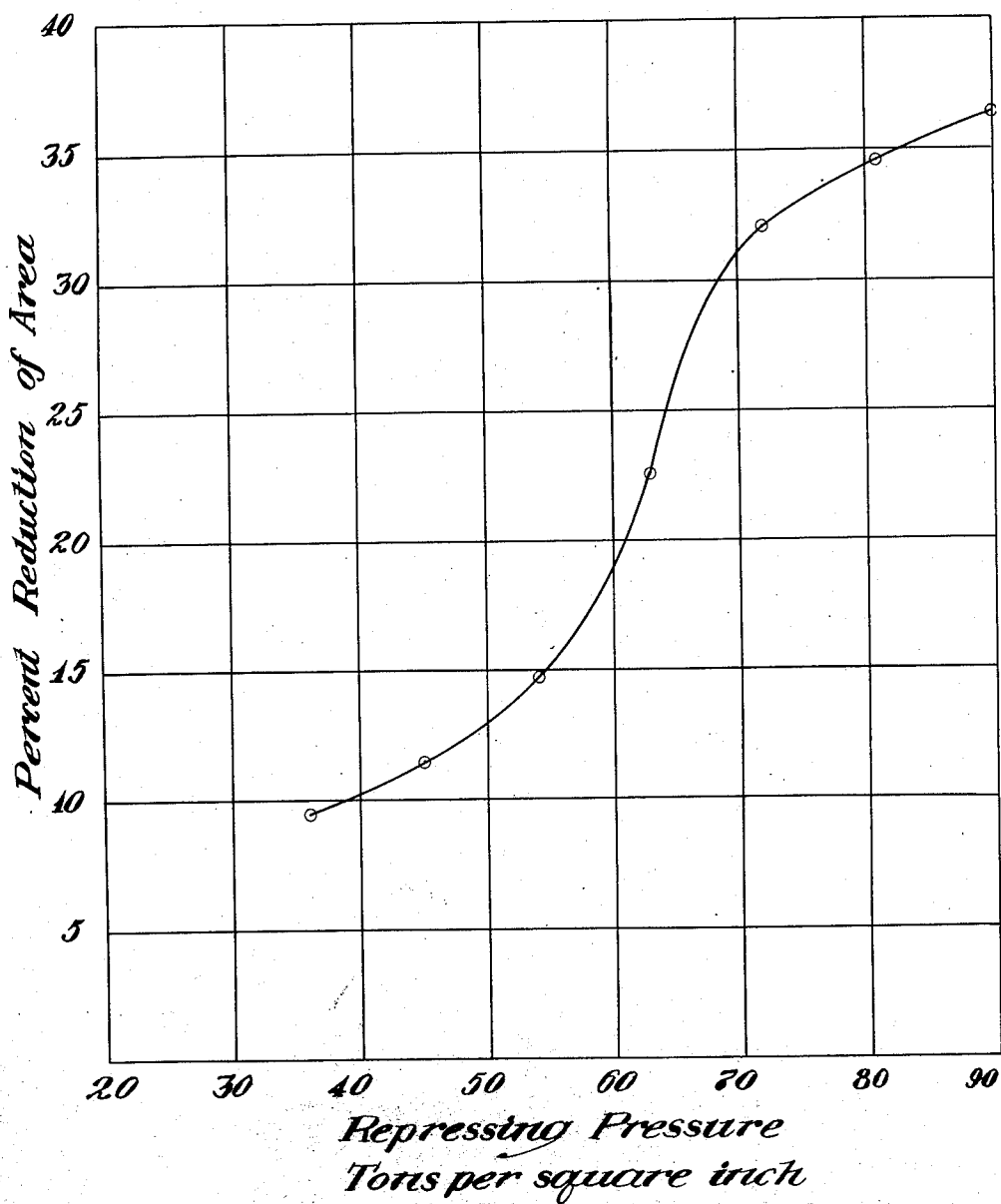


Fig. 1.

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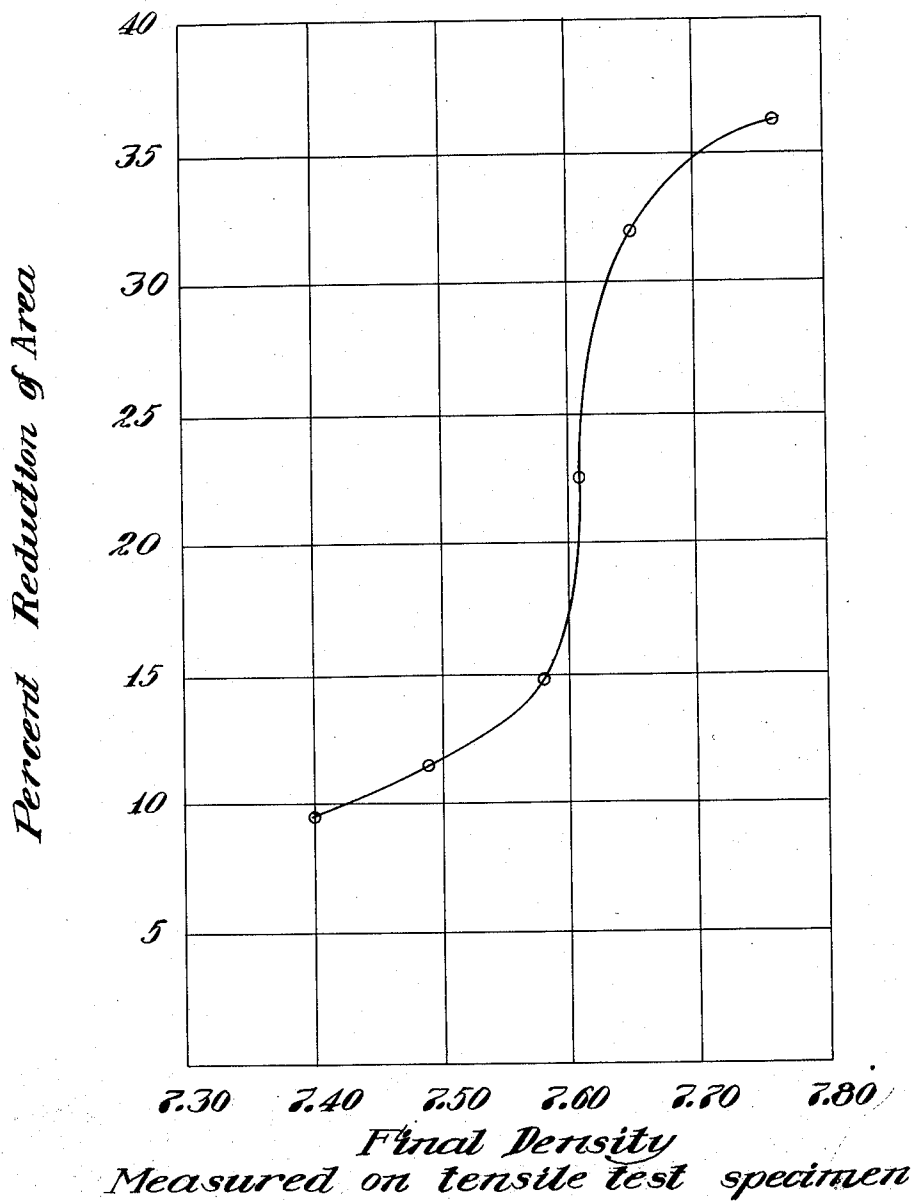


Fig. 2

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UNITED STATES PATENT OFFICE

2,489,839

PROCESS FOR CARBURIZING COMPACTED
IRON ARTICLES

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Application April 30, 1946, Serial No. 636,034

4 Claims. (Cl. 148—16.5)

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This invention relates to powder metallurgy processes for producing steel parts.

Heretofore it has not been practicable to produce steel having simultaneously high densities of 7.60 and over, and high carbon, by powder metallurgy methods.

The chief object of the invention is the production of small steel parts of unusually good physical properties from iron powders.

Another object is to produce by powder metallurgy methods, steel of high density, and consequently with high physical properties, without the use of excessive pressures and/or temperatures.

Another object is to produce steels by powder metallurgy methods which, during the pressing operations, are unusually soft and ductile and consequently cause relatively little wear on the dies and punches.

Another object is to produce steel parts by powder metallurgy methods which at an intermediate stage of manufacture are substantially free from carbon and are of great softness and ductility thereby allowing a certain degree of flow of the metal to take place during pressing or coining operations. Other objects of the invention will appear from the following disclosure.

In the drawings, Figure 1 shows a curve of repressing pressures as abscissae plotted against percent reduction of area as ordinates. Figure 2 shows a curve of final densities as abscissae plotted against per cent reduction of area as ordinates.

It is well known to produce steel parts by powder metallurgy methods either by pressing and sintering steel powder which already has its carbon dissolved in it, or by mixing iron powder with graphite or other carbonaceous material, compressing the mixture, and sintering to dissolve the carbon in the iron and bond the particles together simultaneously. Such methods produce compacts of relatively high porosity and poor physical properties. To produce better compacts, a second pressing and a second sintering may be used to increase the density and produce somewhat better physical properties. However, even when only moderate amounts of carbon are used the material is too hard to compress or coin to high densities. For example, when 0.5% carbon is used, practical pressures and temperatures do not produce densities higher than about 7.6 even when the purest of iron powders are subjected to two or even more pressings and sinterings. Furthermore, the pressing of steel powders or compacts, and the pressing of powders containing

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graphite, at high pressures, causes a substantial wearing of the die surfaces.

I avoid these difficulties by pressing pure iron powder, which may contain desired amounts of powdered metallic alloying ingredients, in two or more pressing operations not exceeding about 100 tons per square inch and preferably not exceeding 90 tons per square inch with intervening sinterings at temperatures preferably above about 1600° F. In this way I achieve extraordinarily high densities of about 7.70 or higher without the use of excessive pressures or temperatures. I then introduce carbon into the piece in any desired amount by a heat-treatment in a rapidly carburizing atmosphere, following which I cause the carbon to become distributed in the piece, at least to a substantial depth, by an equalizing heat-treatment in an atmosphere or other medium which is in equilibrium with the predetermined final carbon content at the equalizing temperature.

As a starting material, or as a component thereof, I prefer to use pure iron powder such as electrolytic iron, which has an apparent density of substantially 2.3, and which, aside from water and other sorbed gases (as well as from carbon and the common alloying metals) contains no more than 0.2% of impurities. In general I prefer that such iron powder, when heated in dry hydrogen for 2 hours at approximately 1800° F. does not lose in weight more than 0.6 to 0.8%, and preferably not more than 0.4%. Normally, electrolytic iron powder which has been annealed sufficiently to be suitable for most ordinary powder metallurgy operations loses from 0.6% to 0.8% in weight after heating for 2 hours at 1800° F. in dry hydrogen or cracked anhydrous ammonia. Such powder may be further annealed, however, in dry hydrogen or cracked anhydrous ammonia at approximately 1350° F. for about 3 hours, and left in suitable powdery condition for pressing. After such heat-treatment the weight loss of the powder when heated as above for 2 hours at 1800° F. is reduced from 0.6% to 0.8% to about 0.2%. This weight loss may result from the elimination of sorbed water, sorbed gas which is largely oxygen, and other impurities and the reduction of iron oxide (or any of them) due to the high temperature employed and the reducing power of the hydrogen.

For many applications of my invention the weight loss of the iron powder may be from 0.6% to 0.8%, but under some circumstances, and for best and most consistent results I prefer to use an iron powder whose weight loss does not ex-

ceed 0.2%. The presence of large proportions of sorbed water or sorbed gases in the iron component of a starting material results in a tendency for cracks to be present in the final product and in difficulty in always obtaining uniformly high physical properties in such products.

Where manganese or other alloying agent having a high affinity for oxygen is an ingredient of the starting material, there is a tendency for oxygen in whatever form it exists in the starting material to combine with such ingredients to form an oxide thereof. Such alloying agents when combined with oxygen are present in the powder compacts as inclusions, and therefore cannot contribute hardenability and strength to the final product.

If the starting material contains some carbon, for example 0.3%, the use of a low weight loss iron component is not as important, because deleterious impurities may be removed by combining with the carbon and escaping as gases during the first sinter operation so that the final product has consistently high physical properties. Furthermore, if alloying agents, such as manganese, having relatively high affinity for oxygen, are present in the starting material, and carbon is added in appropriate amounts the carbon will combine with oxygen in preference to such oxidizable metals and thus prevent their oxidation and the presence of their oxides in the final product.

In connection with the use of carbon for removing deleterious materials (principally sorbed oxygen), as described above, it is a surprising fact that the amount of carbon required is much less than the amount required to combine chemically with all of the oxygen from the powder. For example, assuming that there is 0.6% to 0.8% sorbed oxygen in the iron powder, 0.3% carbon in the starting material gives the necessary stabilizing effect and insures a final product which has consistently high physical properties, although only about $\frac{2}{3}$ of this carbon is driven off as gas in the sintering operation, leaving a sintered compact containing 0.1% carbon. The addition of carbon to the starting material is also effective to reduce metallic oxides which may be already present therein and to prevent subsequent oxidation. It thus overcomes all of the deleterious effects of oxidation upon the charge during and after the first sintering treatment.

My starting material may include a lubricant, for example stearic acid, and alloying agents if desired.

According to my invention the starting material is subjected to a first pressing operation at a pressure of less than 40 tons per square inch, but sufficient to form a coherent, unitary compact. The minimum pressure which will permit easy handling of compacts prior to sintering without excessive breakage may be about 15 tons per square inch. The preferred density of the compact after such pressing operation is 6.3 to 6.8. If carbon is incorporated in the starting material some of the carbon combines with oxygen which may be present by itself or in combination in the starting material and the reaction products are expelled as CO and CO₂. In addition, hydrogen in the sintering atmosphere may combine with some more of the carbon and the reaction product be expelled as CH₄, so that at the end of the sintering operation the carbon may have been reduced to 0.1% or less. In the sintering operation it is important to reduce the carbon to a small percent if it is desired, on repressing, to obtain a compact having a density of 7.65 to 7.7 or

over. A carbon content of say 0.5% makes it very difficult to repress to obtain densities of these magnitudes.

This sintering operation also has the beneficial effect of causing certain alloying agents which may have been intentionally added to the starting material to dissolve substantially completely in the iron and become quite uniformly distributed throughout the compact. Some of my preferred alloying materials and the amounts in which I prefer to add them are as follows; manganese metal up to 1%; ferro-manganese (containing approximately 80% Mn) up to 1.15%; manganese silicon eutectic (consisting of 90% Mn and 10% Si) up to 0.55%; silicon up to 1%, molybdenum up to 1%; ferro-vanadium up to 0.8%; and ferro-chromium up to 4.5%. The quantities of these alloying agents may of course be varied, depending upon the particular properties desired. Other alloying agents which diffuse to varying extents include chromium, vanadium, molybdenum, cobalt, tungsten, silicon, titanium, aluminum, etc. Since most of these alloying materials have a very high affinity for oxygen, I prefer, when using them to include, as previously mentioned, a small amount of graphite to reduce such oxides of such metals as may have formed and to prevent their oxidation. Such use of graphite with powders of high oxygen content in the sintering operation overcomes and prevents the oxidation of alloying materials.

Following the aforesaid sintering operation the compacts are repressed using pressures of 60 tons per square inch or greater, to produce high densities. Depending on the particular alloying materials added and the amount of such materials used, with pressures of 60 tons per square inch or over, these densities may be approximately 7.65 to 7.70 or over. The advantages of the above described sequence of steps, viz. an initial pressing at less than 40 tons per square inch, a sintering in a reducing atmosphere, and a repressing at pressures of 60 tons per square inch and over, are set forth in detail in my copending application Ser. No. 549,807, filed August 16, 1944, now Patent No. 2,411,073.

After the repressing operation the compacts are of high density but contain either substantially no carbon or only a small amount of carbon. I then increase the carbon content of the compacts as follows:

The compacts are heat-treated at a temperature of about 1700° F. in an atmosphere which consists of a gas such as dry hydrogen, or cracked anhydrous ammonia, to which is added a small amount of a hydrocarbon. This atmosphere is preferably one which would be in equilibrium with steel of a carbon content which is higher than that desired in the final product. For example, I may use cracked anhydrous ammonia containing 0.2% to 1.0% of propane. During this heat-treatment a predetermined amount of carbon, supplied by the propane in the atmosphere, is dissolved in the surface of the iron. This takes the form of a high carbon case, whose carbon content decreases fairly rapidly from the surface inward toward the center.

In general, I prefer that the amount of carbon which is rapidly introduced during this carburizing step be reasonably close to that required in the final article, so that in the equalizing step described below only a small amount of carbon will have to be either removed or introduced in order to reach the finally desired carbon content. In general, I prefer that the carbon introduced in

the carburizing step should be more rather than less than the finally desired amount.

Following the carburizing, I use an equalizing step to cause the carbon to become uniformly distributed throughout the piece by subjecting it to an equalizing heat-treatment at approximately 1700° F. in an atmosphere which may be similar to that used for carburizing, except that the quantity of hydrocarbon present is so regulated as to be in equilibrium with the finally desired steel composition at the equalizing temperature. During this equalizing cycle the carbon diffuses inward from the high carbon case and becomes substantially uniformly distributed throughout the piece. During the first part of the cycle, the carbon at the surface is initially of higher concentration than the final uniform concentration, and consequently a small amount of carbon will always be removed from the piece by reaction with the equalizing atmosphere. But if it is desired to reduce this loss of carbon, e. g. for the sake of obtaining an unusually high degree of uniformity, the composition of the atmosphere may be varied during the course of the equalizing cycle so as to be always in approximate equilibrium with the carbon concentration of the surface of the piece.

I prefer to introduce the carbon into the piece by the two heat-treatments described above, viz. carburizing and equalizing, rather than by a single heat-treatment in an atmosphere which is in equilibrium with the final carbon concentration. Since the atmosphere which I use for carburizing contains a concentration of the carburizing hydrocarbon which is sufficient to be in equilibrium with steel of substantially higher carbon content than that finally desired, it introduces into the piece the total amount of carbon necessary in a shorter time than would an atmosphere in equilibrium with steel of the desired carbon content. Therefore the total time for producing a uniform carbon content can be substantially shortened when the two (rather than one) heat-treating steps are used.

For example, a carburizing heat-treatment at 1700° F., for 13 hours in an atmosphere of hydrogen containing 1% propane, followed by an equalizing heat-treatment also at 1700° F. for 19 hours in an atmosphere of hydrogen containing 1% methane (a total of 32 hours), produced a substantially uniform carbon distribution, the average carbon content being 0.96%. At the same temperature, a single heat-treatment in an atmosphere of hydrogen containing 1% methane had to be continued for 61 hours before comparable uniformity of carbon content was produced, and the average carbon content was 0.83%.

At 2000° F., a carburizing heat-treatment of 2½ hours in hydrogen containing 1% propane, followed by an equalizing heat-treatment also at 2000° F. for 5½ hours in hydrogen containing 0.2% methane (a total heat-treating time of 8 hours) produced good uniformity of carbon, the carbon content being 0.93%. At the same temperature, a single heat-treatment in an atmosphere of hydrogen containing 0.2% methane had to be continued for 32 hours to produce comparable uniformity of carbon, and the carbon content was 0.73%.

In the above comparisons all of the pieces heat-treated were 2 inches long by ¼ inch square, and all were between 7.80 and 7.82 in density. The hydrogen used was deoxidized and dried to a dew-point of between -49° C. and -53° C. The

compacts were prepared by compressing at 27 tons/in.² a starting material consisting of -100 mesh electrolytic iron powder mixed with 0.63% of ferro-manganese powder and 1.0% of stearic acid powder. The compacts were preheated for 1 hour at 900° F. in hydrogen to eliminate the stearic acid, and then were sintered for 3 hours at 2000° F. in dry hydrogen. The pieces were then repressed at 90 tons per square inch, dry soap being used as a lubricant to reduce die-wall friction. The pieces were then carburized as described above.

In a porous compact, in which the density is low enough so that the voids are interconnecting, carburizing in an atmosphere which is in equilibrium with the desired final uniform carbon content may be done in shorter times than those described above, because the carburizing atmosphere penetrates the compact by way of the interconnecting voids, and carburizes the interior surfaces of the compact. Under these conditions the distances which the carbon must diffuse through solid iron in order to achieve uniformity of carbon distribution are greatly decreased, and the time correspondingly shortened.

I use temperatures for carburizing and equalizing which do not exceed the melting point of carbon eutectic composition (approximately 2100° F.) in order to minimize distortion of the pieces and to prevent too rapid deterioration of the metal parts of the furnace which are exposed to the atmospheres. Temperatures much above 1700° F. are avoided commercially because of higher maintenance costs of the heat-treating equipment, even though the times involved can be considerably shortened if higher temperatures are used. For that reason my preferred temperature for carburizing and equalizing is approximately 1700° F. and for the two heat-treating operations the temperatures employed should not go much above 1900° F. and should not be much below 1600° F.

In certain cases it may be desired to make parts in shapes which cannot be ejected from the pressing dies (as for example on account of re-entrant angles). Parts having knurls on surfaces adjacent to the die wall, for example, could not be ejected from the die by conventional powder pressing techniques. I can, however, produce such parts by substituting smooth surfaces throughout the first and second pressing operations. Following the second pressing operation I may anneal the parts and the material will then, in the absence of any substantial amount of carbon, be very soft and ductile. Then by a cold coining operation, during which only certain parts of the piece may be supported in a die, I may impress the knurling into the surface of the piece by means of a punch. When the punch has been removed, the piece may be withdrawn from the die. It may then be made into steel of the desired carbon content by the method described elsewhere herein.

If, instead of using a starting material containing 0.3% graphite as previously cited, I use more than a 0.3% graphite, say 0.6% graphite, and in the first sintering operation reduce the carbon to approximately 0.4% instead of 0.1% or less, I still can reach densities of 7.65 and over by employing a re-pressing pressure of less than 100 tons per square inch if no alloying ingredients are present. With 0.9% manganese added, densities of 7.5 and over can be obtained at re-pressing pressures of less than 100 tons per square inch.

It is possible by my method to obtain a rather substantial degree of flow in the second pressing operation during which the piece is densified to its final high density of approximately 7.65 to 7.7 or more. For example I compressed one of my preferred starting materials in a die in a first pressing operation into the shape of a stick of cross section approximately 0.25" x 0.28" and 2" long. I then cut off a piece approximately $\frac{3}{8}$ " long from one end of the stick. After a sintering operation as described above the piece was put back into the same die and repressed at 90 tons per square inch. During this repressing operation the material flowed, while being densified, to reduce the 0.28" dimension of the piece and fill the die cavity entirely, and completely closed up the $\frac{3}{8}$ " space which was unfilled in the length of the cavity before the repressing operation. This property of the material is extremely useful in making relatively complex shapes. It has hitherto been impossible by powder metallurgy processes producing steel parts to achieve such high degrees of flow but it is possible by my method when I retain the great softness and ductility characteristic of very pure iron by having little or no carbon present throughout the pressing operations and introduce the carbon component of the steel after the final shaping operation has been performed.

As a specific example of my invention I may take an electrolytic iron powder containing 0.6% to 0.8% oxygen, and mix it with 0.5% to 0.9% manganese metal powder or preferably sufficient ferromanganese to be equivalent in manganese content, and with 0.3% powdered graphite and about 1% of a lubricant such as stearic acid. I press this mixture at about 15 to 40 tons per square inch to form a coherent compact, and sinter the compact in dry hydrogen at 2000° F. until the remaining carbon does not exceed 0.15%. This requires in the case of pieces $\frac{1}{4}$ " thick, approximately three hours. I then repress the piece, (using at least 65 tons per square inch) to final dimensions. The density of the compact will now be at least approximately 7.65 if I use about 75 tons per square inch, and at least approximately 7.6 density if I use 65 tons per square inch pressure. I then carburize the piece at approximately 1700° F. in an atmosphere of hydrogen containing 0.4% to 1.0% of propane for a period of time, determined by the dimensions of the piece, which will introduce into the piece slightly more total carbon than will be present in the finished article. In some instances the amount of carbon introduced will be approximately the same as that required in the finished article. This carbon is confined largely to regions near the surface. I then equalize by heat-treating the piece at approximately 1700° F. in an atmosphere of hydrogen containing 0.30% of methane for a period of time which is also determined by the dimensions of the piece. During the first part of this equalizing a slight amount of carbon may be lost to the equalizing atmosphere, while the remaining carbon diffuses toward the center and by the end of the equalizing period is substantially uniformly distributed throughout the piece. The amount of methane is so chosen that the atmosphere will be in equilibrium with the desired final steel composition at the equalizing temperature. Therefore, if the total amount of carbon contained in the piece after the carburizing treatment is less than that ultimately required on the article, this deficiency in carbon content and the

subsequent initial loss in the equalizing treatment may be made up during the latter part of the equalizing treatment.

As another example of the utilization of my invention I have produced pieces of square cross section $\frac{1}{4}$ " x $\frac{1}{4}$ " and 2" long having final uniform carbon content of 0.8%. Annealed electrolytic iron powder, finer than 100 mesh, containing approximately 0.7% oxygen was mixed with 1% stearic acid lubricant, 0.63% ferromanganese powder, finer than 400 mesh, and 0.3% graphite. The mixture was given an initial pressing at 27 tons per square inch, followed by a sintering for 3 hours at 2000° F. in dry hydrogen. The compact was then given a final pressing at 90 tons per square inch. The compact was then carburized for 10 hours at 1700° F. in dry hydrogen containing 1.0% propane. It was then equalized for 22 hours at 1700° F. in hydrogen containing about 0.30% methane. After cooling from this heat treatment the piece was reheated to 1500° F., oil quenched, and drawn at 1100° F. Its physical properties were then found to be: density 7.78, tensile strength 131,400 lbs. per square inch, elongation 18.7%, reduction of area 36%, and Rockwell B hardness 99.

Other sintering media may be substituted for hydrogen or cracked anhydrous ammonia if desired. Gases which I can successfully use include the conventional partially combusted types of heat-treating atmospheres, completely burned atmospheres of the type consisting of CO, N₂, and H₂ in various proportions, and inert gases such as nitrogen alone. Where methane or other hydrocarbon is required to be used with any of the above gases during the equalizing cycle, the proportion of methane or other hydrocarbon may be so regulated as to be in equilibrium with the carbon of the final desired steel composition at the equalizing temperature.

Carbon may be introduced into the piece in ways other than those described above. For example, instead of gaseous carburizing atmospheres I may use a pack, or I may use liquid carburizing salt baths. For an equalizing medium, I may substitute inert liquids such as lead or inert salt baths. Since the compact is of high density, for example 7.65 to 7.70, the pores in the compact are not interconnecting and the liquids do not penetrate to the interior of the compact.

As previously noted, I have chosen 60 tons per square inch as a preferred minimum pressure for the second pressing operation. I have chosen this pressure because when the process described herein is followed, the physical properties, especially the per cent reduction in area, (at the point of rupture by tensile elongation) show a very sharp improvement beginning at 60 tons per square inch. To be comparable in quality with conventional steel products, the steel made by powdered metallurgy methods must show a per cent reduction in area comparable to that obtained with conventional steel of the same kind. For example, a steel containing approximately 0.7% carbon and 0.5% manganese made according to this invention, shows a very sharp improvement in the per cent reduction in area as, with all other factors kept constant, the pressure used in the second pressing operation is increased, starting with 60 tons per square inch. In a second pressing operation of 36 tons per square inch, the per cent reduction in area of the final material is approximately 9%; at 55 tons per square inch the reduction in area is increased to 15%; while at 65 tons per square inch the reduction

in area had jumped to 26%. A curve of second pressures as abscissae plotted against per cent reduction of area as ordinates first rises slowly and then, at approximately 60 tons per square inch rises sharply, and then tends to flatten out again.

This is a very important and surprising result as it naturally would be assumed that the per cent reduction in area would increase roughly in proportion to the pressure employed.

In the re-pressing operation the degree of compression may be governed in terms of the density attained, instead of in terms of the pressure applied. From this standpoint, I prefer that in the re-pressing operation the compact be re-pressed to a density of approximately 7.6 or higher because this is shown to be the critical density at which the per cent reduction of cross-sectional area rises very abruptly to values which are characteristic of steel of excellent physical properties. The per cent reduction of cross-section is shown to be more than doubled when the final density of the compact is increased from 7.58 to 7.65 by the re-pressing operation. A curve of final densities as abscissae plotted against per cent reduction of area as ordinates rises slowly and then at approximately 7.6 density rises almost vertically and then tends to flatten out again.

While I have referred to the use of a mixture of pure iron powder and one or more of my preferred alloying agents as a preferred starting material or as one component thereof, I could equally well use an iron powder in which one or more such alloying agents is dissolved, but containing aside from oxygen and other sorbed gases other impurities to the extent of not over 0.2%.

From the foregoing it will be understood that a characteristic feature of my invention consists in using a rich carburizing medium and then changing the medium to reduce its carburizing effect, thereby to equalize the distribution of carbon in the article. The degree of richness of the initial medium may be varied to suit different conditions but it is always greater than the equilibrium concentration, that is the concentration of carbon in the medium at which the medium would be in substantial equilibrium with the finished article. The change of richness may be made abruptly, as by replacing a rich atmosphere by a lean atmosphere, or it may be made gradually, as by drawing off rich atmosphere and feeding in lean atmosphere. The change may be carried to or below the equilibrium point. Indeed the richness may be reduced to zero, as by replacing the carburizing atmosphere with an inert atmosphere. If the richness is carried below the equilibrium point it may be brought back to this point either gradually or abruptly. In equalizing the distribution of carbon in the article by changing the medium, the equalization may be carried as far as desired and throughout all or only part of the article. For example, in many cases it is necessary to carry the equalization only to the point where the distribution is partly equalized and only throughout a limited depth adjacent the surface of the article.

The above-mentioned extraction of sorbed material from the compact during the first sintering by means of carbon is fully disclosed and claimed in the copending application of George Warren Webb, Serial No. 666,171, filed on even date herewith, and that disclosure is incorporated herein by reference.

I claim:

1. The process of making a steel article of a

desired final carbon content from powdered iron and containing non-ferrous solid impurities in an amount not exceeding 0.2%, sorbed material including oxygen not exceeding 1%, all percentages being by weight, which has been compacted at less than approximately 40 tons per square inch, sintered, and repressed at a pressure of at least approximately 60 tons per square inch, comprising the steps of introducing carbon into the surface region of the compact in a concentration in excess of the predetermined final carbon content of the desired steel by raising the temperature of the article to between about 1600° F. and about 2100° F., soaking the article at said temperature range in a carburizing medium having a carburizing potential substantially higher than that in equilibrium with the desired final carbon content of the steel, and then redistributing the carbon concentrated in the surface of the article substantially uniformly throughout the article by further soaking at said temperature range in a medium having a carburizing potential which is in equilibrium with the desired carbon content of the steel.

2. The process of making a steel article of predetermined final carbon content from powdered iron containing non-ferrous solid impurities in an amount not exceeding 0.2%, sorbed material including oxygen not exceeding 1%, and free carbon, which has been compacted at less than approximately 40 tons per square inch, sintered to remove substantially all of the oxygen and to leave not more than 0.4% carbon, all percentages being by weight, and repressed at a pressure of at least approximately 60 tons per square inch to its ultimate shape and dimensions, comprising the steps of introducing carbon into the surface region of the article in a concentration in excess of the predetermined final carbon content in the article by raising the temperature of the article to between about 1600° F. and about 2100° F., soaking the article in said temperature range in a carburizing medium having a carburizing potential substantially higher than that in equilibrium with said predetermined final carbon content, and then redistributing the carbon concentrated in the surface substantially uniformly throughout the article by further soaking the article while at said temperature range in a medium having a carburizing potential which is in equilibrium with said predetermined final carbon content of the steel.

3. The process of making a steel article of a desired final carbon content from powdered iron including carbon and containing non-ferrous solid impurities in an amount not exceeding 0.2%, sorbed material including oxygen not exceeding 1%, all percentages being by weight, which has been compacted at less than approximately 40 tons per square inch, sintered to remove substantially all of the oxygen and to leave not more than 0.4% carbon and repressed at above approximately 40 tons per square inch to a density in the order of at least 7.5, comprising the steps of introducing carbon into the surface region of the article in a concentration in excess of the predetermined final carbon content in the article by raising the temperature of the article to between about 1600° F. and about 2100° F., soaking the article in said temperature range in a carburizing medium having a carburizing potential substantially higher than that in equilibrium with said predetermined final carbon content, and then redistributing the carbon concentrated in the surface substantially

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uniformly throughout the article by further soaking the article while at said temperature range in a medium having a carburizing potential which is in equilibrium with said predetermined final carbon content of the steel.

4. The process of making a steel article of a desired final carbon content from powdered iron including carbon and containing non-ferrous solid impurities in an amount not exceeding 0.2%, sorbed material including oxygen not exceeding 1%, all percentages being by weight, which has been compacted to a density up to about 6.8, sintered to remove substantially all of the oxygen and to leave not more than 0.4% carbon and repressed to a density in the order of at least 7.5, comprising the steps of introducing carbon into the surface region of the article in a concentration in excess of the predetermined final carbon content in the article by raising the temperature of the article to between about 1600° F. and about 2100° F., soaking the article at said temperature range in a carburizing medium having a carburizing potential substantially higher than that in equilibrium with said predetermined final carbon content, and then redistributing the carbon concentrated in the surface substantially uniformly throughout the article by further soaking the article while at said tem-

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perature range in a medium having a carburizing potential which is in equilibrium with said predetermined final carbon content of the steel.

LYMAN F. WHITNEY.

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