

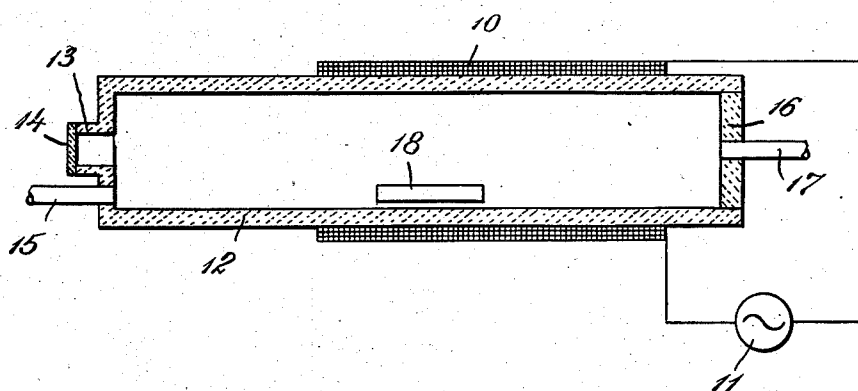
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POWDER METALLURGY

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POWDER METALLURGY

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This invention is concerned with powder metallurgy and particularly with promoting diffusion of metals across grain boundaries in a metal powder aggregate or "briquette" with a view to bonding the grains together. The invention aims to shorten the time necessary to accomplish such bonding and to bring it about with expenditure of less energy than employed heretofore. The invention also aims to reduce distortion of powder metal briquettes during the bonding operation.

In powder metallurgy it is customary to press a body of metal powders, with or without a binder, to form a coherent mass or briquette. The body usually is compressed in a relatively cold condition in a mold, and thereafter the resulting briquette is removed from the mold and subjected to heat treatment in a relatively unsupported or unconfined condition, in order to bring about a bonding of the metal grains or particles which form the briquette. The briquette may be heated to the point of incipient fusion so that grain boundaries are destroyed, but under such conditions great distortion of the unsupported briquette is likely to occur. Distortion of an unsupported briquette generally is less if incipient fusion is avoided and the briquette merely heated to a relatively high temperature but below its melting point, under which conditions metal tends to diffuse across grain boundaries while the grains remain in a relatively solid state. However, this procedure (which is known as diffusion welding) is relatively slow and in many instances must be prolonged for several days in order to secure an adequate bond between particles. The longer treatment time affords an opportunity for some distortion to occur. Hence, diffusion welding does not eliminate distortion. Since powder metallurgy finds its principal application in the manufacture of articles of accurate configuration and competes with die-casting processes and the like, distortion even when relatively slight presents a serious problem.

As indicated above, diffusion welding as employed heretofore in powder metallurgy is a slow process. The briquette usually is heated by introducing heat from an exterior source, for example, by placing a briquette in a furnace in the presence of a gaseous atmosphere or solid packing. Under such conditions a long time is consumed in bringing the briquette up to the necessary temperature. A more rapid rise in temperature results when a briquette is immersed in a molten bath of metal or a thermally stable salt, such, for example, as a cyanide. Such heating, however, involves industrial hazards, especially when cyanides are em-

ployed, and is likely to result in contamination of the product. The immersed briquette almost always has a certain degree of porosity and the molten material of the bath tends to impregnate the pores. Removal of the impregnant from the briquette is difficult and, if it is allowed to remain, frequently causes sweating, corrosion, etc. Moreover, the problem is not merely one of raising the temperature of the briquette rapidly. Even after the briquette has been raised to an appropriate temperature, the diffusion of metals across the grain boundaries in heretofore customary practice is slow. Frequently it is necessary to maintain the briquettes at an elevated temperature for several days. Under such circumstances, heat consumption is high, furnace capacity is low and consumption of gas such as hydrogen or nitrogen employed to maintain a protective non-oxidizing or reducing atmosphere is excessive and costly.

In the course of my investigations I have found that generally speaking, the lower the melting point of a metal the lower is its rate of diffusion in the solid state under the influence of heat at ordinary pressures. Thus, briquettes of lead or tin powder must be heated for days to bring about diffusion welding between the powder particles unless a high degree of pressure is employed simultaneously. Aluminum and copper diffuse in the solid state at a higher rate than lead or tin, but still relatively slowly. Metals having a very high melting point such as tungsten tend to diffuse relatively rapidly at temperatures in the neighborhood of 2000° C. but below their melting points. Certain metals, such, for example, as chromium, appear at first to be exceptions to the above enunciated rule, because diffusion from grains of chromium under the influence of heat ordinarily is very slow. This, however, appears to be due to the skins of oxidation products on the chromium grains and diffusion is fairly rapid when care is taken to use chromium powder having absolutely clean surfaces.

As a result of my investigations I have discovered that internally induced eddy currents of high frequency (i. e., of a frequency of at least 50,000 cycles per second) not only bring about a rapid rise in temperature of a briquette of metal powder, but also, if maintained in the briquette after an appropriate temperature is attained stimulate greatly the rate at which diffusion welding occurs, so that strong metal bodies can be formed from metal powders in but a small fraction of the time and with but a small fraction of the energy consumed in prior practices and with minimum distortion, even though the briquette be relatively

unsupported. These results appear to be due to two factors: (1) an actual carrying of metals across grain boundaries in the briquettes by the eddy currents and (2) a tendency for the eddy currents to cause non-metallic impurities in the briquettes to "ball up" or coalesce and so to reduce the resistance to migration of metal across the grain boundaries. As will appear more fully hereinafter, the operation of these factors in the process of my invention is confirmed by comparative energy measurements and by microscopic examination of specimens which have been made by the process. But whatever be the explanation, the fact remains that I have succeeded in accelerating markedly the rate of diffusion in an apparently solid state of even such low melting metals as tin and lead and such relatively high melting point metals as chromium, which heretofore have required both long time periods and much energy for diffusion welding. When the briquette is formed of a single metallic constituent, either a metal or an alloy, bonding of the particles proceeds under the influence of the internally induced eddy currents at a temperature below the melting point of the constituent but preferably in excess of two-thirds of the temperature at which melting would occur. To take a concrete instance, tin melts at 232° C., and in the practice of my invention a briquette containing no other metal than tin preferably is subjected to internally induced high frequency currents while it is maintained at a temperature ranging from about 154° C. to slightly below 232° C. for a short time, during which a thorough bonding of the particles results. When the briquette to be treated contains a plurality of metallic ingredients, for example 20% by weight of particles of elemental nickel (melting point 1452° C.) and 80% by weight of particles of elemental iron (melting point 1530° C.), it is subjected to the internally induced eddy currents while maintained at a temperature below the weighted average of the melting points (in this example 1514° C.) but above a temperature that is about two-thirds of such weighted average (in this example 1010° C.). Under such conditions alloying and bonding proceed almost instantaneously, and the treatment time becomes a matter of minutes as compared with hours or days in heretofore customary practice. Accordingly, my invention contemplates the acceleration of diffusion welding in a coherent mass of metal powder by internally inducing eddy currents of high frequency within the coherent mass while maintaining it at a relatively elevated temperature (so that diffusion welding tends to occur) but below the weighted average of the melting points of its metallic constituents, and preferably below the melting point of any of its metallic constituents but above a temperature that is about two-thirds of said weighted average. (In the case of a briquette containing only one metallic constituent, the "weighted average" referred to above is, of course, its own melting point.) In most instances, because of the heat economies obtained, it is also advisable to raise the temperature of the mass to a point within the treatment range by means of the internally induced eddy currents. In this manner, the whole heat treatment is enabled to take place in such a short time that the briquettes, even though relatively unsupported, suffer a minimum distortion.

In the practice of my invention, superior results are obtained by placing the aggregate or briquette in a field of a high frequency current so that currents of correspondingly high frequency are in-

duced within it. Metal powder briquettes thus treated rapidly attain high temperatures. I attribute the rapid heating to the fact that a myriad of eddy currents are set up in the individual particles or small and perhaps partially insulated groups of particles. In this way heat is generated throughout the powder metal body and no time is lost in conducting heat into the mass. Rapidity of heating, however, does not explain completely the fact that diffusion is accomplished more rapidly in the practice of my invention and, as indicated hereinbefore, I believe that the currents induced within the mass actually carry metal from one particle to another (even though the mass remains at a temperature below the melting point of any of the particles), and thus aid in diffusion and bonding. In any event, the process of my invention by accelerating and improving diffusion across grain boundaries in briquettes of metal powders produces objects which are comparable in hardness, malleability, tensile and compressive strengths, and other desirable properties with those obtained heretofore by other methods such as casting, and does so in but a mere fraction of the time and at a mere fraction of the cost of prior powder metallurgical processes. My invention is particularly advantageous in the treatment of briquettes containing metals which are difficult to bond by diffusion welding either by reason of an inherently low rate of diffusion as in the case of lead and other low melting point metals or by reason of skins of oxidation products as in the case of chromium. To illustrate, a compressed mass of iron, nickel, and chromium powders may be heat treated to produce excellent stainless steel in from 2 to 4 hours by inducing high frequency currents in the mass, whereas equivalent treatment by conducting the heat into the mass from an outside source requires in the neighborhood of 96 hours.

Powder metal aggregates or briquettes formed by compressing a loose mass of the powders in a relatively cold state are not homogeneous. Individual powder particles may be distinguished in the aggregate, which has a granular structure. The grain boundaries are characterized by the presence of films of occluded or adsorbed gas or by solid oxidation products. The heterogeneous character of the mass is probably responsible for the intensity of eddy currents induced therein. In commercial practice, metal powders almost inevitably are contaminated at their surfaces by such adsorbed or occluded gases or by thin films of oxides, carbonates, sulphates, etc. Consequently, it is, in general, unnecessary to actually add an insulating media to assure the desired heterogeneous structure. However, no attempt should be made to remove completely films of occluded or adsorbed gases from the metal particles which form the briquettes and, in certain instances, it may be desirable to assure that the particles are not too clean and to employ small amounts of a binder of insulating character to assure adequate intensity of induced high frequency eddy currents. The presence of a considerable proportion of foreign material at the grain boundaries may be tolerated in the practice of my invention because under the influence of the high frequency eddy currents, these tend to segregate or "ball up" and thus isolated do not weaken the resulting structure substantially. Microscopic examination of briquettes bonded together in accordance with my invention shows this "balling up" of impurities very clearly, but this phenomenon does not appear in comparable sam-

pies which have been bonded by mere heat treatment.

Other factors being equal, the higher the frequency of the internally induced currents, the more rapid will be the heating and the more thorough the welding together of the particles in unit time. Some advantage accrues to employing internally induced currents of relatively low frequency, but for commercial work a source of current having a frequency of about 100,000 cycles per second is recommended. However, good results may be obtained with currents having a frequency ranging from 50,000 cycles to 200,000 cycles per second, and in general, high frequency induction furnaces of the type employed heretofore for melting cast metal ingots, etc., may be employed in the practice of my invention with satisfactory results. It should be noted, however, that the temperature rise of powder metal aggregates in such furnaces is much more rapid than has been obtained heretofore in melting cast metal bars and other relatively homogeneous metal masses and that it is unnecessary and in fact undesirable to raise the powder metal aggregate to a point at which substantial fusion occurs.

In the operation of my invention, powder metal briquettes of desired configuration are formed by compression in a mold with or without the use of a binder, and are disposed within the field of a high frequency induction coil. Alternating current, preferably of a frequency of about 100,000 cycles per second, is passed through the coil and results in the induction of a plurality of high frequency eddy currents in the briquette. Coherent masses made from the powders of any metal or combination of metals may be so treated, but the invention finds its greatest application in promoting diffusion welding of metals which have relatively low melting points or for some other reason have inherently low diffusion rates.

It is desirable to carry on the treatment of the aggregate in a non-oxidizing or reducing atmosphere or in vacuo. This may be done conveniently by placing the object to be treated within a refractory container disposed within the coil. Proper atmosphere within the container may be maintained by means of a solid packing or by introducing therein non-oxidizing or reducing gas such as nitrogen, hydrogen, or carbon monoxide, or the container may be wholly or partially exhausted.

These and other features of my invention will be more thoroughly understood in the light of the following, detailed description of presently-preferred practices of my invention taken in conjunction with the accompanying single figure which shows schematically apparatus adapted to the practice thereof.

Referring now to the figure, it will be seen that the apparatus comprises an induction coil 10 connected to a suitable source of high frequency alternating current 11 such, for example, as a generator or converter. The coil preferably is in the form of a helically wound copper tube of low ohmic resistance, and water or other cooling fluid may be passed through it. Disposed within the coil and spaced therefrom is a tubular muffle 12 made of refractory and substantially non-conductive material such as quartz. The two ends of the muffle extend well outside of the ends of the coil, one end of the muffle being provided with an observation port 13 closed by a quartz window 14. Below the observation port is an integrally formed nipple 15 communicating with the interior of the muffle so that a suitable gas such as

hydrogen, nitrogen or carbon monoxide may be introduced to maintain the desired non-oxidizing or reducing atmosphere within the muffle. The other end of the muffle is closed by a tightly fitting but removable plug 16. An outlet nipple 17 is provided in the plug for withdrawing gas from the muffle or for introducing a thermocouple thereinto, if desired. A briquette or group of briquettes 18 to be treated is introduced into the muffle and the plug is then inserted. Current is introduced into the induction coil and heat treatment ensues.

In the following tests, the induction coil was helical in form, made of $\frac{3}{8}$ " diameter copper conductor and had approximately 15 coils about $2\frac{3}{4}$ " square. The length of the coil was about 6 inches. The coil was connected to a Lepel high frequency spark gap converter (type C-6), which converted ordinary commercial alternating current at 220 volts and 60 cycles per second to current having a frequency of approximately 100,000 cycles per second for the induction coil. The input into the apparatus was approximately 6 kilowatts in most of the tests.

Comparative test No. 1

In this test, electrolytic iron powder having relatively clean surfaces and of a particle size ranging from 100 to 200 mesh, Tyler scale, was compressed with a force of 50 tons per square inch into small bars about $\frac{1}{2}$ inch square and 4 inches long. The resulting bars were then placed in the muffle in the field of the induction coil and current was applied. In approximately one minute at a temperature of 1100° C., adequate diffusion welding was accomplished and the resulting metal object was sufficiently malleable that it could be reduced to one-tenth of its original thickness by hot forging before any signs of cracking appeared.

In a comparative test in which identical aggregates were heated indirectly in a muffle wound with an electric resistance element, the same degree of welding was not obtained until the aggregates had been maintained at the same temperature (1100° C.) for longer than thirty minutes, the powder consumption in this comparative test being approximately 6 k.w. Energy consumption in this comparative test was, therefore, from 30 to 60 times that employed in the practice of my invention.

Comparative test No. 2

In a second test, electrolytically produced iron powder having an average particle size of 150 mesh and with some iron oxide on its surfaces was mixed with 3½% of relatively clean nickel powder of comparable particle size obtained from nickel carbonyl. The resulting mixture was compressed into bars $\frac{3}{8}$ inch square in cross-section and 3 inches long. These bars were also placed in the muffle within the induction coil as described hereinbefore and subjected to treatment at 1100° C. for one minute. The resulting objects were sound in all particulars and resembled billets obtained by casting molten metal. Microscopic examination of the resulting objects indicated a high degree of homogeneity and excellent diffusion. The same degree of diffusion could not be obtained by indirect heat treatment of identical bars in a muffle in less than 2 hours. The iron oxide present in the finished material was in very small amount and appeared as somewhat spherical segregations. The nickel present aided diffusion.

Comparative test No. 3

Heretofore stainless steel has been particularly difficult to form by powder metallurgical processes because of the long time required to attain adequate diffusion welding. Certain alloy ingredients in a powder mixture for manufacture of stainless steel, particularly chromium, oxidize rapidly at elevated temperatures and consequently require careful maintenance of a non-oxidizing or reducing atmosphere throughout the entire period of heat treatment, which adds considerably to the cost of the operation.

In the practice of my invention, the manufacture of stainless steel by powder metallurgical practice becomes relatively simple as will be apparent from the following description.

A powder mixture having a particle size ranging from 100 to 200 mesh, Tyler scale, was made by mixing 74% by weight of iron powder, 8% by weight of nickel powder, and 18% by weight of chromium powder having a thin skin of chromium oxide on its surface. The resulting mixture was compressed under a force of about 70 tons per square inch to form bars about $\frac{3}{8}$ inch square and about 3 inches long. The bars were then placed in the muffle in the field of the induction coil and current was turned on. In 15 minutes they had reached a temperature of 1350° C. as indicated by observations taken with an optical pyrometer. They were maintained at this temperature for about 1 hour. Thereafter, 45 minutes was required to bring the muffle and the heat treated bars to a temperature at which the aggregates might safely be withdrawn from the muffle. During this 2-hour period, an atmosphere of dry hydrogen was maintained within the muffle. Subsequently the bars were subjected to an annealing treatment in the muffle disposed in the coil. The annealing treatment consumed two hours during which the bars were heated to about 1000° C., held at this temperature for 60 minutes, and then cooled to a temperature of about 30° C. when they were withdrawn from the muffle.

For comparative purposes identical bars were placed in a muffle disposed within an electrical resistance furnace and subjected to primary heat treatment and annealing at the same temperature as employed in the foregoing tests. The furnace employed was wound with a molybdenum resistance element and the power consumption of this element was approximately 6 k.w. To raise the temperature of the aggregates to a temperature of 1350° C., required 8 hours. An additional 44 hours was required to bring about adequate bonding. Thereafter, it was necessary to let the muffle cool for 36 hours before the aggregates reached room temperature and could be removed without running risk of damage. The time consumption for primary heat treatment in this operation was, therefore, 88 hours as compared with 2 hours by induction heating. Annealing in the resistance furnace in the muffle required an additional 8 hours, so that the total operation consumed 96 hours as compared with 4 hours to produce the same result in the practice of my invention.

The following tests illustrate presently-preferred practices of my invention with a variety of metals:

Practice with briquettes of iron powder

Iron powders made by any of the heretofore customary methods may be employed in the practice of the invention. Thus, iron powder ob-

tained by reducing iron oxide with hydrogen or iron powder obtained from iron carbonyl is suitable. This is demonstrated by the following tests:

12 bars each $\frac{3}{8}$ inch square and about 3 inches long were made from iron powder obtained by hydrogen reduction of iron oxide. The powder was minus 150 mesh, Tyler scale, and was briquetted under a pressure of 50 tons per square inch. The resulting 12 briquettes were placed in the muffle separated from each other by thin layers of alundum powder. The current was applied to the induction coil and in 8 minutes with a 6 kilowatt power input they reached a temperature of approximately 1100° C. They were held at this temperature for approximately 10 minutes in an atmosphere of dry hydrogen and then were permitted to cool to room temperature. Cooling took 30 minutes. The resulting solid bars were homogeneous in all respects and had all the desirable characteristics of iron bars obtained by casting processes.

Four bars approximately $\frac{3}{8}$ of an inch square and 3 inches long were made from iron powder obtained from iron carbonyl. The powder was minus 200 mesh and was pressed under a force of 70 tons per square inch. The resulting briquettes were placed in a muffle and insulated from each other by layers of alundum powder. Current was applied to the induction coil and with a 6 kilowatt power input the bars reached a temperature of approximately 1200° C. in 11 minutes. They were held at this temperature for 10 minutes in an atmosphere of dry hydrogen and then cooled to room temperature in the muffle in 35 minutes. The resulting bars were solid and resembled those produced from the hydrogen reduced iron.

Practice in manufacture of binary ferrous alloys

Binary ferrous alloys may be produced very easily in the practice of the invention. The presence of alloying ingredients, particularly nickel, in the briquettes to be formed into alloys by diffusion welding has a favorable influence upon the treatment time, as will be apparent from the following tests:

Iron powder obtained by hydrogen reduction of iron oxide (96 parts by weight) and 4 parts by weight of nickel powder obtained from nickel carbonyl were made into briquettes. The powder mixture was all minus 150 mesh, Tyler scale, and was thoroughly mixed in the dry state for a period of about 8 hours prior to being compressed into briquettes under a force of 50 tons per square inch. The briquettes were placed in the muffle and heated in an atmosphere of dry hydrogen for approximately 8 minutes at a power input of 6 kilowatts. At the end of 8 minutes, the temperature had risen to approximately 1100° C. and they were maintained at this temperature for 10 minutes. Current was then turned off and the briquettes cooled at room temperature within the muffle in 30 minutes. These briquettes were solid, free from pores and from all standpoints could be considered excellent. It was found, however, that the same results could be obtained with an even lower period of heat treatment. The following test was comparable in all respects to that described immediately above, except that after an 8 minute heating period the briquettes were held for only one minute at 1100° C. This time was sufficient to accomplish a thorough bonding together of the particles and microscopic examination of the resulting bars showed them to be as satisfactory as those obtained by holding the briquettes for 10 minutes at 1100° C.

Practice in manufacture of ternary iron alloys

That the bond obtained between particles in the practice of my invention is strong, is indicated by the fact that stainless steel made in the practice of my invention may be subjected to a water quenching from a relatively high temperature without harmful effect. To demonstrate the excellent character of the stainless steel made in the practice of my invention, a powder mixture containing about 74% iron, 8% nickel, and 18% by weight of chromium was made from hydrogen reduced iron powder, finely-divided low carbon ferrochromium containing 70% chromium, and nickel powder obtained from nickel carbonyl. The size of the powder ranged from 100 to 200 mesh. It was mixed in dry condition for 12 hours, then pressed into briquettes under a force of 70 tons per square inch and placed in a muffle under the influence of the high frequency currents and in an atmosphere of dry hydrogen. In 12 minutes, with a power input of 6 kilowatts, the briquettes attained a temperature of 1375° C. at which temperature they were held for one hour. They were then allowed to cool in the muffle for 40 minutes and at room temperature were repressed under a force of 70 tons per square inch. Following repressing they were annealed in the muffle for 9 minutes where an input of 6 kilowatts raised the temperature of the repressed bars to approximately 1000° C. The bars were held at this temperature for one hour in an atmosphere of dry hydrogen and they were withdrawn from the muffle and quenched immediately in water.

In another test, the conditions were identical with those described immediately above except in the following particulars: The heat treatment took place in a vacuum. The pressure within the muffle was kept under 1 mm. of mercury and the cooling after the first heat treatment consumed about 35 minutes. After repressing the bars, they were annealed in the high frequency induction furnace for one hour in an atmosphere of carbon monoxide and carbon dioxide. From the high temperature (approximately 1000° C.) prevailing at the end of the annealing period, the bars were cooled immediately to room temperature by water quenching.

In both of these tests, the bars suffered no ill effects in the water quenching and were entirely satisfactory from all metallurgical standpoints.

Practice with non-ferrous metal briquettes

The bonding together of non-ferrous metal briquettes in the practice of my invention is well illustrated by the following examples.

12 bars of aluminum about $\frac{3}{8}$ inch square and 3 inches long were made of aluminum powder having a mesh size minus 150 under a pressure of 50 tons per square inch. The resulting briquettes, separated from each other by thin layers of aluminum powder, were placed in the muffle and raised to a temperature of 600° C. in 4 minutes with a power input of 4.5 k.w. The briquettes were held at a temperature of 600° C. for 10 minutes, the atmosphere in the muffle being one of dry hydrogen. At the end of the 10 minute period, current was turned off the induction coil and the bars were allowed to cool in the muffle for 15 minutes, at the end of which time they were approximately at room temperature. These bars, like all the others described herein, were entirely satisfactory.

Twelve copper bars of the same size as those made from aluminum were made from electrolytically-produced copper powder of minus 150 mesh under a pressure of 50 tons per square inch.

The bars were separated from each other by layers of aluminum powder and were heated in the muffle for 6 minutes with a power input of 4.5 k. w. At the end of the 6 minutes, the bars had reached a temperature of approximately 800° C. At this temperature they were held for 5 minutes in a dry hydrogen atmosphere and, of course, in the presence of the induced eddy currents. They were then allowed to cool for 20 minutes. Microscopic examination of the bars thus formed showed them to be comparable in structure to bars made by heretofore customary casting operations, except that the non-metallic impurities such as copper oxide were more segregated and not so completely distributed throughout the mass.

Manufacture of non-ferrous alloy objects

Twelve bars containing 90% copper and 10% tin were made as follows:

Tin powder and copper powder of a mesh size minus 150 were mixed in the dry state for 8 hours and then pressed into briquettes about $\frac{3}{8}$ of an inch square and 3 inches long under a pressure of 50 tons per square inch. The resulting briquettes were heated as described hereinbefore in the muffle for 5 minutes with a power input of 4.5 k. w. In the five minutes the briquettes attained a temperature of 725° C. and they were held at this temperature for 10 minutes in the atmosphere prevailing in the muffle, namely, one of dry hydrogen. At the end of 10 minutes, the current was turned off and the resulting bronze bars were allowed to cool for 20 minutes to approximately room temperature, when physical tests and microscopic examinations were made. Results were excellent.

In another test, similar bars were raised in 6 minutes to a temperature of 825° C. and held at this point for 10 minutes. It was found, however, that the bars thus treated were not superior to those obtained at the lower temperature.

I claim:

1. In a process in which metal powder particles are formed into a coherent mass and bonded together by diffusion welding, the improvement which comprises accelerating the diffusion of metal between the powder particles by inducing alternating currents having a frequency of at least 50,000 cycles per second within the mass while maintaining the mass in a relatively unsupported condition at an elevated temperature but below the weighted average of the melting points of its metallic constituents.

2. In a process in which metal powder particles are pressed into a coherent mass which is subjected to heat treatment to bond the particles together, the improvement which comprises heating said mass by inducing eddy currents therein and maintaining said mass in a relatively unconfined condition at an elevated temperature but below the melting points of its metallic constituents while maintaining therein eddy currents having a frequency of at least 50,000 cycles per second, whereby diffusion of the metal between the particles is accelerated.

3. In a process in which metal powder particles are formed into a coherent mass and bonded together by heat treatment, the improvement which comprises subjecting such a mass containing metal particles having skins of solid oxidation products thereon in a relatively unsupported condition to the action of high frequency eddy currents induced within the mass until the mass reaches a temperature ranging between the weighted average of the melting points of the

metallic constituents of the mass and a temperature that is about two-thirds of said weighted average and maintaining the mass in said temperature range in said relatively unsupported condition while inducing eddy currents having a frequency of from 50,000 to 200,000 cycles per second therein until the particles have become bonded together, whereby diffusion welding of the particles is accelerated and the distortion of the mass during heat treatment is inhibited.

4. In a process in which metal powder particles are formed into a coherent mass and bonded together by heat treatment, the improvement which comprises disposing said mass in the field of an alternating current of high frequency and inducing eddy currents of a frequency ranging from 50,000 to 200,000 cycles per second within the mass while maintaining the mass in a relatively unconfined condition at a temperature below the melting point of any of its metallic constituents but above a temperature that is about two-thirds of the weighted average of the melting points of the metallic constituents of the mass.

5. In a process in which a coherent mass of metal powder particles is subjected to heat treatment to cause the particles to bond together, the improvement which comprises forming said mass of metal powders having films of gas and solid oxidation products upon them so that the particles in the mass are at least partially insulated from each other, and heating the mass in a relatively unsupported condition thus formed to a point in a range below the weighted average of the metallic constituents in the mass but above a temperature that is about two-thirds of said weighted average by inducing eddy currents having a frequency of at least 50,000 cycles per second within the mass, and maintaining said mass at a temperature within said range while inducing said currents therein until the particles become bonded together.

6. In a process in which a coherent mass of metal powder particles is subjected to heat treatment to cause the particles to bond together, the improvement which comprises forming said mass of metal powders having solid oxidation products of the metallic constituents of the powder upon the surfaces thereof so that the particles in the mass are at least partially insulated from each other and heating the mass thus formed to a point in a range below the weighted average of the metallic constituents in the mass but above a temperature that is about two-thirds of said weighted average by inducing eddy currents having a frequency ranging from 50,000 to 200,000 cycles per second within the mass, and maintaining said mass in a relatively unconfined condition at a temperature within said range while inducing said currents therein until the particles become bonded together.

7. In a process in which metal powder particles having solid non-metallic constituents on the surfaces thereof are formed into a coherent mass and subjected to heat treatment to bond the particles together, the improvement which comprises coalescing and segregating the solid non-metallic constituents in said mass to facilitate diffusion of metal between the powder particles by inducing in said mass high frequency eddy currents having a frequency ranging from 50,000 to 200,000 cycles per second while maintaining the mass in a substantially unsupported condition at an elevated temperature but below the melting point of any of its metallic constituents.

8. In a process in which a bronze object is formed by heat treatment of a coherent mass of metal powder containing tin and copper, the improvement which comprises inducing within such a mass containing metal particles having skins of solid non-metallic impurities thereon high frequency eddy currents having a frequency of at least 50,000 cycles per second and of an intensity sufficient to raise the temperature of the mass to a temperature of about 725° C., and maintaining in the mass at about said temperature in a relatively unconfined condition while inducing said currents therein for a relatively short time.

9. In a process in which stainless steel is formed by heat treatment of a coherent mass of metal powder containing iron, nickel, and chromium, the improvement which comprises inducing within such a mass containing metal particles having thin skins of solid oxidation products thereon high frequency eddy currents having a frequency of at least 50,000 cycles per second and of an intensity sufficient to raise the temperature of the mass to about 1350° C., and maintaining the mass at about said temperature in a relatively unconfined condition while inducing said currents therein for a relatively short time.

10. In a process in which a coherent mass of metal powder particles containing chromium powder having a skin of oxidation products on the surface thereof is subjected to heat treatment to bond the metal powder particles together, the improvement which comprises heating said mass to an elevated temperature but below the melting point of chromium by inducing currents of a frequency of at least 50,000 cycles per second within the mass, whereby the oxidation products tend to be removed from the chromium particles and coalesced, and maintaining the mass in a relatively unsupported condition at said elevated temperature while inducing said currents therein so as to promote diffusion of the chromium throughout said mass.

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