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METHOD OF EXPLOSIVELY COMPACTING POWDERS TO FORM A DENSE BODY

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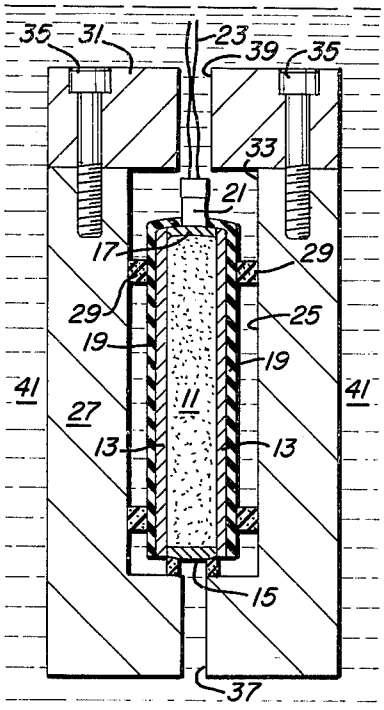

FIG. 1

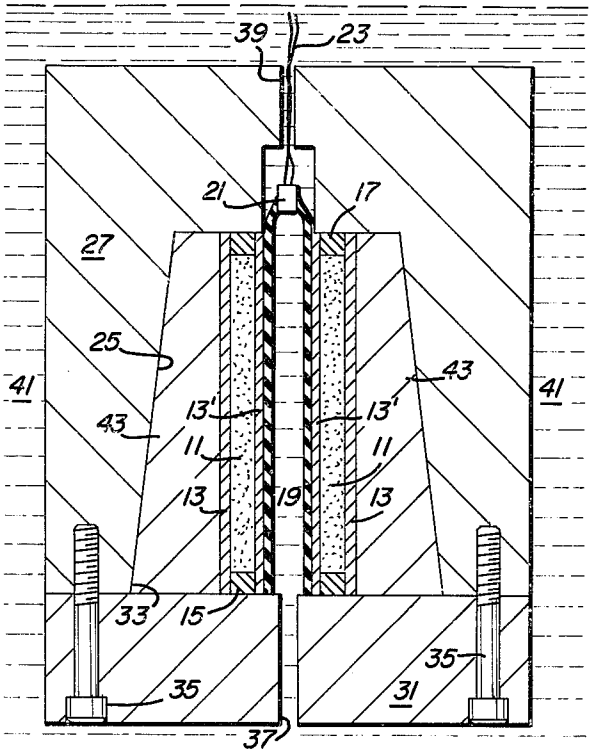

FIG. 2

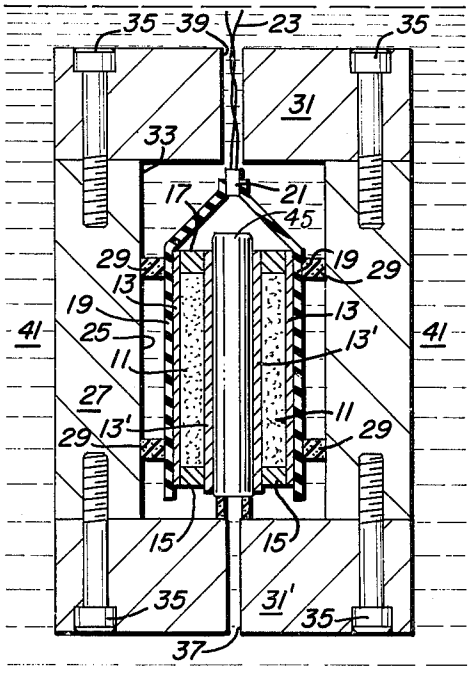

FIG. 3

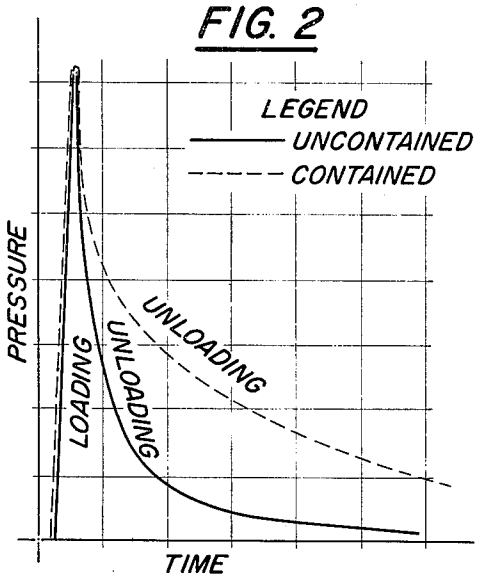

FIG. 4

INVENTOR...

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METHOD OF EXPLOSIVELY COMPACTING POWDERS TO FORM A DENSE BODY

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This invention relates to the method of explosively forming solid bodies from powder. More particularly, it relates to compaction of powder materials to a dense condition by using the energy generated by the detonation of a high explosive charge.

The art of consolidating small particles or powders into a massive component has been known and used for many years. In the early history of metallurgy, powder metallurgy was simply a technique which was used if a metal could not be melted. Today powder metallurgy is utilized to produce materials that cannot be easily made by other methods and also to produce materials that could be made by another method but for which powder techniques are cheaper or more convenient.

For many years powder metallurgists used only the sintering techniques. Sintering involves heating loose or compacted powders to the point where the compacted powders adhere and bond to each other in order to reduce surface energy, or where one component melts and the surface of the liquid phase draws the remaining solid particles together to form a massive body. More recently, however, many varied processes have come into use. At the present time, almost every known metalworking process is used to consolidate powders, including rolling, forging, and extrusion. Even the arts of the ceramists, such as slip-casting and shaping of metal-binder claylike mixtures have been borrowed by powder metallurgists. Among the more recent developments is the explosive compaction of powders.

The major advantages of powder metallurgy are close compositional control, uniform dispersion of secondary phases, control over grain size, and ability to produce complex shapes. The major disadvantages are frequent inability to remove porosity and occasional difficulty in removing impurities. The problem of porosity still persists with recently developed methods that use explosive techniques. The explosive compaction method of this invention eliminates porosity in the finished article.

Compaction by explosive may be accomplished in two general ways—by the contact method and by the stand-off system. In the stand-off system, the explosive is detonated at some distance from the powder compact to drive a die punch onto the powder. An example of the contact method is the use of an explosive sheet which is wrapped around a powder-filled container. Detonation of the explosive deforms the container and compacts the powder. This invention uses the contact method as the basis for compacting powders.

Explosive compaction by the contact method is a process which incorporates the high-velocity shock waves and pressures developed by the detonation of explosive charges for densifying powders. Compaction of the powder is caused by the passage of a shock wave producing a compression front. The exact pressure developed by the explosion has not been determined but borders on or reaches 12 million p.s.i. The quality of the compacted specimen depends on the procedure used for the explosive compaction technique. Many powder metallurgists have abandoned explosive compaction because of porosity and cracking. If the explosive charge is too small, the finished product is too porous. If the charge is too large, the product develops numerous small cracks or

central voids. This invention includes methods that allow an explosive charge to be used that is sufficient to eliminate porosity and still prevent cracking. One test of the success of any method for compacting powders is the density of the final product and how closely that density approaches the theoretical density of the final product desired. The density must also be uniform throughout the finished product. Many conventional explosive compaction methods will produce a product with some portions having good density in part of the specimen but not throughout. Tungsten powder compacted by the method of this invention has a density of greater than 95 percent of the theoretical density of tungsten throughout the finished product.

Briefly described, this invention includes the steps of confining a powder in a container, placing an explosive charge closely adjacent to the surface of the container detonating the explosive charge and delaying the reduction of pressure generated by the explosion and thus prolonging the unloading of stresses from the powder in the container.

In conventional explosive compaction methods, a large pressure is generated by the explosion, and this pressure is lost almost instantaneously. One advantage of the present invention is that the stresses caused by the explosion are unloaded more gradually, and cracking of the product is eliminated. Porosity is also eliminated. In explosive compaction methods where an insufficient charge is used because the product cracks, the center of a rod, for example, will be porous. This cannot be corrected by sintering after compaction, since the outer surface of the product is more dense and the product does not shrink uniformly during sintering. Nonuniform shrinkage produces voids in the product which are, of course, undesirable. Many explosive compaction processes are usable with simple materials having great ductility but are completely useless with refractory materials, ceramic materials, or metallic oxides have low ductility.

Present powder-metallurgical techniques require three to four steps to produce a finished product. For example, producing tungsten requires pressing and presintering, followed by a consolidation sinter and/or several hot-working steps. Explosive compaction eliminates the need for large presses and expensive hot-pressing dies. In many instances, actual production costs may be reduced as much as 25 times or more.

In the drawings:

FIG. 1 is a sectional elevational view of explosive compacting apparatus including a specimen prepared for compacting to a rod shape;

FIG. 2 is a sectional elevational view of explosive compacting apparatus, including a specimen prepared for compacting to a tube shape;

FIG. 3 is a sectional elevational view of explosive compacting apparatus also including a specimen prepared for compacting into a tube shape; and

FIG. 4 shows two curves comparing conventional unloading after an explosive impact with unloading on the specimen according to this invention.

In the drawings, the same reference numerals are applied to identical parts in all embodiments and such identically numbered parts are substantially identical in structure, function, and operation.

Referring to FIG. 1, the powder 11 is placed inside of a tube 13 having a closure 15 at one end. After the powder 11 has been packed or tamped inside the tube 13, a cap or closure 17 is used to close and seal the tube 13. A sheet of explosive 19 containing PETN (pentaerythritol tetranitrate) is placed around the exterior of the tube 13 and closed over one end of the tube 13. A cap 21 is then attached to the explosive 19 having electric

leads 23–23. The tube 13, wrapped with explosive 19, is then lowered into a central cavity 25 of a housing 27 and centrally positioned in the cavity 25. Small positioning blocks 29–29 made from a light material such as polystyrene foam are used to keep the tube 13 centrally located in the cavity 25. An end plate 31 is used to close off the open end 33 of the cavity and fastened in place by suitable means such as bolt 35–35. At least one opening (37 and 39) communicates between each end of the cavity 25 and the exterior of the housing 27. The electric leads 23–23 pass out through the opening 39. The vent openings 37 and 39 may also be positioned in the walls of the housing 27, depending on the shape and size of the specimen and pressure-unloading effect desired.

The housing 27, with the explosive wrapped tube 13 in the cavity 25 is placed in a pressure transmitting medium. Preferably it is lowered into a pit or body of water and the pressure transmitting medium, in this instance the water 41, enters the openings 37 and 39, filling the spaces of cavity 25 surrounding the tube 13. The explosive 19 is detonated and the housing 27 removed from the pressure transmitting medium and the tube 13 removed from the housing 27. Other pressure transmitting mediums can be used such as sand or other non-inflammable liquids.

FIGS. 2 and 3 show the formation of a tube instead of a rod. In FIG. 2, an inner tube 13′ is used and the explosive 19 is placed in the inside diameter of the tube 13′. A tapered split die 43 is placed around the tube 13 and fits snugly in the cavity 25 of the housing 27.

The tapered split die 43 allows the specimen to be removed from the housing 27 and the die 43 after impacting. The housing 27 may have two end plates 31 but is shown in FIG. 2 with only one.

In FIG. 3, a mandrel 45 is inserted into the inside diameter of tube 13′, and the explosive 19 is placed on the outside of tube 13 as in FIG. 1. Also, in FIG. 3 the housing 27 is shown with a second end plate 31′ providing access to either end of the cavity 25. The mandrel 45 may be solid metal or made up of another powder.

The specimens are exploded under water and a tremendous pressure occurs almost immediately in the cavity 250. This pressure from the explosion approaches or reaches 12 million p.s.i., depending on explosive charge size, specimen size, and housing dimensions. When the explosion is unconfined, the pressure is released rapidly and is believed to account for cracking of the specimen. If the pressure is unloaded slowly, cracking does not occur. Thus the vents or holes 37 and 39 are provided in the housing 27 to allow the explosive pressure to be released but with some delay. Referring to FIG. 4, the conventional unloading curve shown by a solid line drops off rapidly after the explosion. The method of this invention delays the pressure drop, reducing the slope of the unloading curve as shown by the dotted line. The total time shown by the curves is only a few microseconds, but these few microseconds are sufficient delay in the unloading to prevent cracking especially in materials having low ductility.

Although other means can be used to delay the pressure release in the vicinity of the specimen, a housing such as shown is the preferred apparatus for this purpose. Preferably such housing is relatively thick and is fabricated from stainless steel. Such a housing will withstand the shock of the explosion and may be re-used many times.

The tubes 13 and/or 13′ may be left in place after compaction if the product obtained from the compacted powder material is to be clad. If only the product resulting from the powder material 11 is desired, the tubes 13 and/or 13′ may be removed by acid leaching, pickling or by mechanical means.

The drawings indicate two very general shapes that

can be formed by explosion compacting. Other shapes are also easily formed including rings, crucibles, and fluted cylinders. The type of apparatus shown in FIG. 2 is especially adaptable to produce a variety of shapes. The method of this invention has also been used successfully to form nose cones and tungsten rocket nozzles.

In order to illustrate further the present invention, reference is now made to the following examples.

Example 1

A seamless tube of annealed mild steel 2.5 inches long with an inside diameter of 0.3125 inch, a wall thickness of 0.0625 inch, and an end plug of 0.25 inch was filled with 2.7 grams of reactor grade graphite. A 0.25-inch end plug was inserted in the open end and electron-beam welded in place. A sheet of explosive having a charge density of 2 grams per square inch was cut 1.375 inches by 3.75 inches and wrapped around the specimen with 0.75 inch extending beyond one end of the specimen. This 0.75-inch extension was then cut into a tent shape and an electric detonating cap was attached. The charged specimen was then placed in a pressure retaining housing (27). This assembly was then lowered into an explosion pit full of water and the charge detonated (9.91 grams PETN).

The compacted specimen had a compacted density of over 95 percent of theoretical as compared to a density of 47.8 percent before compaction. In fractures appeared in the specimen which had a uniform density throughout.

Example 2

A seamless tube of annealed mild steel 3.0 inches long with an inside diameter of 0.3125, a wall thickness of 0.0625 inch, and an end plug of 0.25 was filled with 9.13 grams of a mixture of 30 percent −100 +200 mesh uranium dioxide and 70 percent −325 mesh reactor grade graphite. A 0.25-inch plug was inserted in the open end and electron-beam welded in place. A sheet of explosive having a charge density of 2 grams per square inch was cut 1.375 inches by 4.5 inches and was wrapped around the specimen with 0.75-inch extending beyond one end of the specimen. An electric detonating cap was attached as in Example 1. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit and the charge detonated (13.26 grams PETN).

The compacted specimen had a compacted density of over 95 percent of theoretical as compared to a density of 60 percent before compaction. The graphite packed very well around the UO_2. The UO_2 and graphite were not fractured and the specimen had a uniform density throughout.

Example 3

Into a seamless tube of annealed mild steel 7 inches long, with an inside diameter of $\frac{13}{16}$ of an inch, wall thickness of $\frac{1}{16}$ of an inch, and an end plug of 0.5 inch, strips of .02 tungsten wire were inserted lengthwise and the tube was then filled with beryllium powder. A 0.5-inch end plug was inserted and electron-beam welded in place. A sheet of explosive having a charge density of 3 grams per square inch was cut 3.125 inches by 8 inches, wrapped around the specimen and an electric detonating cap attached as in Example 1. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit and the charge detonated (75 grams PETN).

The original density of the powder was 54 percent and the compacted specimen had a density of over 95 percent of theoretical. The beryllium powder was well compacted around the tungsten wire. The density was uniform throughout.

Example 4

A seamless tube of annealed mild steel 5 inches long, with an inside diameter of $\frac{5}{16}$ of an inch, a wall thickness

of 1/16 of an inch, and an end plug of 0.5 inch was first loaded with 2.79 grams of beryllium and then filled with 23.64 grams of tungsten. The powders were maintained in two separate layers. A 0.5 inch plug was electron-beam welded in place. A sheet of explosive having a charge density of 2 grams per square inch was cut 1.375 inches by 5.5 inches, wrapped around the specimen and an electric detonating cap attached as in Example 1. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit, and the charge detonated (15.12 grams PETN).

The above Example 4 was performed to form a beryllium-tungsten transition joint. The formation of this joint successfully occurred. Density of the compact was greater than 95 percent of theoretical. The two powders (Be and W) locked together very well at the interface and the density was uniform throughout.

Example 5

The tube and explosive charge were the same size as in Example 4, but the tube was filled with 31.76 grams of a 50–50 percent mixture of tungsten and beryllium. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit, and the charge detonated (15.12 grams PETN).

The original powder density of 54 percent was increased to over 95 percent of theoretical density. The density was uniform and a good dispersion was produced.

Example 6

A seamless tube of annealed mild steel 4.5 inches long, with an inside diameter of 0.875 inch, a wall thickness of 0.125 inch, and an end plug of 0.75 inch was filled with 254.9 grams of tungsten powder. A 0.75-inch plug was electron-beam welded in place to seal the tube. A sheet of explosive having a charge density of 6 grams per square inch was wrapped around the specimen and an electric detonating cap attached as in Example 1. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit and the charge detonated (135.9 grams PETN).

The original density of the powder was 44.5 percent and the compacted density was over 95 percent of theoretical. The compacted specimen was very dense throughout having excellent green strength. Photomicrographs of the specimen showed a large degree of cold work in the structure throughout the compacted bar of tungsten.

Example 7

A seamless tube of annealed mild steel 4.0 inches long, with an inside diameter of 0.3125 inch, a wall thickness of 0.625 inch, and an end plug of 0.25 inch was loaded with a mixture of 25 percent −100 +200 mesh copper powder and 75 percent −200 +270 mesh nickel. A 0.25-inch plug was electron-beam welded in place to seal the tube. A sheet of explosive having a charge density of 2 grams per square inch was cut 1.375 inches by 5.5 inches, wrapped around the tube, and an electric detonating cap attached as in Example 1. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit, and the charge detonated (15.13 grams PETN).

The compact had a density greater than 95 percent of theoretical. The density of the finished rod was uniform throughout. Photomicrographs of the compacted specimen showed that alloying or diffusion between the Cu and Ni had occurred.

Example 8

A seamless tube of annealed mild steel 3.0 inches long having an inside diameter of 0.4375 inch and wall thickness of 0.0625 inch was concentrically centered in a tube of annealed mild steel 3.0 inches long, having an inside diameter of 0.6562 inch and a wall thickness of 0.0938 inch. An annular ring or plug 0.125 inch long closed off one end of the space (0.1562 inch wide) between the two tubes. The annular cylinder or space between the concentric tubes was filled with 6.69 grams of beryllium powder. An annular ring or plug 0.125 inch long was used to close off the opposite end of the powder-filled space between the tubes and electron-beam welded in place. The central hole of the smaller, center tube was then loaded with 22.18 grams of nickel powder and two 0.25 inch-plugs were welded in place at each end of the nickel powder-filled central opening. A sheet of explosive having a charge density of 2 grams per square inch was cut 2.5625 inches by 3.75 inches, wrapped around the specimen, and an electric detonating cap attached as in Example 1. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit, and the charge detonated (20 grams PETN). The specimen was then removed from the housing and sintered in a vacuum for 2 hours at 1650° F.

The original beryllium powder had a density of 55.5 percent. The above procedure produced a solid tube of beryllium having a density greater than 95 percent of theoretical. The photomicrograph showed that particle bonding of the beryllium had occurred. The nickel powder core had also been compacted and had a fine small grain size.

Example 9

The specimen was prepared by centering a 4-inch-long 0.25 outside-diameter tube inside a 4-inch-long 0.5 inside-diameter fluted tube; both tubes were made from annealed mild steel. The flutes were approximately 0.15 inch deep. The annular space between the two tubes was filled with 2.5 grams of a powder made up of a mixture of 75 percent of BeO and 25 percent UO_2 and annular 0.5-inch end plug rings were electron-beam welded in place to close off the powder-filled space. This assembly was then centered in an annealed mild steel tube having a length of 5.5 inches, an inside diameter of 0.6562 inch, and an end plug of 0.5 inch. Iron powder was then loaded into the large tube around and through the center core of the BeO-UO_2 specimen. A 0.5-inch plug was then inserted and welded in place. A sheet of explosive having a charge density of 2 grams per square inch was cut 2.5625 inches by 7.0 inches and wrapped around the 0.6562 inch inside-diameter tube. The charged specimen was then placed in a pressure retaining housing (27), lowered into a water-filled explosion pit, and the charge detonated (36.76 grams PETN).

The compact was a fluted tube of 75 percent BeO and 25 percent UO_2 having a density of 96 percent of theoretical as compared to an original powder density of 68.3 percent. The photomicrograph showed a densely compacted structure of uniform density throughout.

Example 10

Two stainless steel tubes 12 inches long, having outside diameters of 1 inch and .875 inch, and each having a wall thickness of 0.010 inch were positioned concentrically and one end of the space between the tubes closed off with a 0.25-inch ring. The tubes were then cleaned in a mixture of 88 percent water, 10 percent nitric acid and 2 percent hydrofluoric acid after which they were air-blown dry. The space between the tubes was then filled with 780 grams of a mixture of 70 percent stainless steel (type 347) and 30 percent spherical uranium dioxide. A second 0.25-inch ring was electron-beam welded in place to seal off the powder-filled space. The tubes were then placed in a split die that fitted snugly around the outer surface of the outside tube. A sheet of explosive was placed around the inside diameter of the inside tube and an electric detonating cap attached to the explosive. The charged assembly was then placed inside a tapered die housing of the pressure retaining type (27 of FIG. 2), lowered into the water and the explosive charge detonated (10.86 grams PETN).

The resulting compact was a stainless steel clad tube of 70 percent 347 stainless steel and 30 percent uranium

dioxide having a density of 95 percent of theoretical. The photomicrograph showed a structure having uniform density throughout. Some of the UO_2 particles had agglomerated and the structure had a sintered appearance.

The following table lists other powder materials that were explosively compacted by the process of this invention with good results. The specimens had high densities that were uniform throughout.

Powder Composition (percent)	Weight of Powder in Grams	Explosive Charge in Grams PETN	Shape	Initial Density, percent of Theoretical	Final Density, percent of Theoretical
75TiC-25UN	12.16	12.56	Rod	59.5	96.2
80$MoSi_2$-20ZrB_2	8.8	11.88	Rod	57.5	95.3
$MoSi_2$	8.9	11.88	Rod	58.2	98.1
80ZrB_2-20$MoSi_2$	8.7	10.31	Rod	56.8	95.6
3ThO_2-97Ta	29.13	14.63	Rod	56.4	97.0
347 Stainless Steel in Aluminum Tube.	6.07	10.22	Aluminum Clad S/S Rod.	30.2	95+
70W-30UO_2	22.665	10.22	Rod	51.1	95+
Haynes Stellite 25	7.713	10.23	Rod	44.4	94.6
Haynes Stellite 31	5.629	10.23	Rod	34.7	96.4

Haynes Stellite 25 is an alloy composed of C 0.15% max., Cr 19.0–21.0%, Ni 9.0–11.0%, W 14.0–16.0%, Si 1.0% max., Mn 1.0–2.0%, Fe 2.0 max., and the balance Co.

Haynes Stellite 31 is an alloy composed of C 0.45–0.6%, Cr 23.0–28.0%, Ni 9.0–12.0%, W 6.0–9.0%, Fe 2.0% max., and the balance Co.

The electron-beam welding mentioned in the examples is a convenient way of evacuating and closing the powder containers simultaneously. Electron-beam welding is performed at or near vacuum conditions. The container is placed in an enclosure with the pressure greatly reduced and an electron-beam focused on the edge of the container and the plug.

The container may also be evacuated by other means. For example, one of the end plugs may be provided with a tube. The gas in the container may then be removed with a vacuum pump. In the case of some ceramic powder material which have dissolved gases in them, the container having a tube in one end plug may be heated to drive off the gas in the powder and then further evacuated with a pump.

The dispersion of uranium dioxide in carbon produced in Example 2 is unique in that a product having a density of such magnitude (95 percent of theoretical) cannot be produced by other known methods. Compacted carbon is usually produced by mixing graphite or carbon powder with pitch. The specimen is then heated to change the pitch to carbon. The temperatures required for this change are quite high and at such temperatures the uranium dioxide would be destroyed.

It will be understood, of course, that, while the forms of the invention herein described constitute the preferred embodiments of the invention, it is not intended to herein illustrate all the ramifications of the invention. It will also be understood that the words used are words of description, rather than limitation, and that various changes and arrangement of steps may be substituted without departing from the spirit or the scope of the invention herein disclosed.

What is claimed is:

1. A process for compacting powders comprising the steps of:
   (a) confining the powder in a container;
   (b) evacuating the gases from said container;
   (c) positioning an explosive charge closely adjacent to the surface of said container;
   (d) compacting said powder by detonating said explosive charge; and
   (e) delaying the reduction of pressure generated by the explosion in accordance with the relationship shown in the graph of FIG. 4.

2. A method for compacting powders to form a predetermined shape comprising the steps of:
   (a) loading powder into a container of said predetermined shape;
   (b) surrounding said container with a die having said predetermined shape;
   (c) positioning an explosive charge closely adjacent to said container in such a manner that when the explosive charge is detonated the container will be impacted against said die;
   (d) compacting said powder by detonating said explosive charge; and
   (e) delaying the reduction of pressure generated by the explosion for a period of at least about ten microseconds.

3. A method for forming a tube of compacted powder comprising the steps of:
   (a) loading the annular space between two concentric tubes with powder;
   (b) evacuating the gases from the powder-filled space;
   (c) sealing said powder-filled space;
   (d) providing closely fitting retaining means around the outside surface of said two concentric tubes;
   (e) positioning an explosive charge in the inside opening of said two concentric tubes, said explosive charge being sufficient to eliminate porosity in the tube formed from the compacted powder;
   (f) compacting said powder by detonating said explosive charge in the presence of a pressure transmitting medium; and
   (g) delaying the reduction of pressure generated by the explosion for a period of at least about ten microseconds.

4. A method for forming a tube of compacted powder comprising the steps of:
   (a) loading the annular space between two concentric tubes with powder;
   (b) evacuating the gases from the powder-filled space;
   (c) sealing said powder-filled space;
   (d) positioning a mandrel in the inside opening of said two concentric tubes;
   (e) positioning an explosive charge closely adjacent to the outside surface of said two concentric tubes, said explosive charge being sufficient to eliminate porosity in the tube formed from the compacted power;
   (f) compacting said powder by detonating said explosive charge in the presence of a pressure transmitting medium; and
   (g) delaying the reduction of pressure generated by said explosion for a period of at least about ten microseconds.

5. A process of compacting powders comprising the steps of:
   (a) loading the powder into a container;
   (b) evacuating the gases from said container;
   (c) sealing said container;
   (d) generating a pressure of about 12 million pounds per square inch on the exterior surface of said container;
   (e) delaying the total reduction of said pressure to a time of greater than about 10 microseconds.

6. The process of manufacturing a coherent refractory body comprising the steps of:
(a) packing the constituent refractory material in a finely ground state in a collapsible mold;
(b) enclosing said mold in a sheath of explosive, said sheath of explosive being of sufficient potential to eliminate porosity in the coherent refractory body;
(c) compacting said powder by detonating said explosive in a pressure transmitting medium; and
(d) delaying the reduction of pressure generated by said explosion for a period of at least about ten microseconds.

7. A process for compacting powders to form a dense body comprising the steps of:
(a) confining the powder in a container;
(b) positioning an explosive charge closely adjacent to the surface of said container; said explosive charge being sufficient to prevent porosity in the dense body formed by the compaction of said powder;
(c) compacting said powder by detonating said explosive charge; and
(d) delaying the reduction of pressure generated by the explosion in accordance with the relationship shown in the graph of FIG. 4 thereby preventing cracking of the dense body.

8. In the method of compacting powders to form a dense body which comprises surrounding a mass of powder with high-velocity detonating explosive and initiating said explosive, the improvement of delaying the reduction of pressure generated by the explosion in accordance with the relationship shown in the graph of FIG. 4 thereby preventing cracking of the dense body.

9. A method of making a product consisting of a dispersion of uranium dioxide particles in graphite having a density in excess of ninety-five percent of theoretical density produced by the process of:
(a) loading a mixture of graphite and uranium dioxide powders into a container;
(b) evacuating the gases from said container;
(c) sealing said container;
(d) positioning an explosive charge closely adjacent to the surface of said container;
(e) compacting said powder by detonating said explosive charge in the presence of a pressure transmitting medium; and
(f) delaying the reduction of pressure generated by the explosion for a period of at least about ten microseconds and thereby prevent cracking of the compacted product.

10. A method of forming a body of a first material clad with a second material different from said first material comprising the steps of:
(a) loading a first material in a finely ground state into a container fabricated from a second material;
(b) enclosing said material in a sheath of explosive;
(c) compacting said powder by detonating said explosive in a pressure transmitting medium; and
(d) delaying the reduction of pressure generated by the explosion in accordance with the relationship shown in the graph of FIG. 4 thereby preventing cracking of the compacted material.

11. A method of forming an alloy from metals in powder form comprising the steps of:
(a) mixing at least two powdered metals together to form a substantially homogeneous powder mixture;
(b) loading said powder mixture into a container;
(c) evacuating the gases from said container;
(d) delaying the reduction of pressure generated by the explosion in accordance with the relationship shown in the graph of FIG. 4 thereby preventing cracking of the compacted powders.

12. A method of compacting powders to form a dense body comprising the steps of:
(a) loading the powder into a first container;
(b) evacuating the gases from said first container;
(c) sealing said first container;
(d) positioning an explosive charge adjacent to the surface of said first container;
(e) positioning the sealed powder-filled container and explosive charge in a second heavy-walled container having openings opposite one another, said second container being constructed to withstand the explosive force of said explosive charge;
(f) immersing said first and second containers in water; and
(g) compacting said powder by detonating said explosive charge whereby the reduction of pressure generated by the explosion is delayed by said water and second container in accordance with the relationship shown in the graph of FIG. 4 thereby preventing cracking of the compacted powder.

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WHITMORE A. WILTZ, *Primary Examiner.*
THOMAS H. EAGER, *Examiner.*

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,220,103 November 30, 1965

Charles C. Simons

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

Column 3, line 45, for "250" read -- 25 --; column 4, line 28, for "In" read -- No --.

Signed and sealed this 20th day of September 1966.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents