

[54] **ELECTRICAL SINTERING UNDER LIQUID PRESSURE**

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[22] Filed: Mar. 4, 1968

[21] Appl. No.: 710,219

[30] **Foreign Application Priority Data**

Mar. 3, 1967	Japan.....	42/13622
June 16, 1967	Japan.....	42/38574
June 19, 1967	Japan.....	42/39214
June 21, 1967	Japan.....	42/39830
June 23, 1967	Japan.....	42/40342
Aug. 19, 1967	Japan.....	42/53378
Sept. 4, 1967	Japan.....	42/56661
Sept. 7, 1967	Japan.....	42/57482
Sept. 16, 1967	Japan.....	42/59554
Sept. 18, 1967	Japan.....	42/59766
Sept. 20, 1967	Japan.....	42/60322
Sept. 22, 1967	Japan.....	42/61037
Sept. 30, 1967	Japan.....	42/62898
Dec. 12, 1967	Japan.....	42/82280
Feb. 22, 1968	Japan.....	43/11524

[52] U.S. Cl.....75/226, 75/200, 75/214, 219/117

[51] Int. Cl.....B22f 3/14

[58] **Field of Search**.....75/200, 214, 226; 219/117

[56] **References Cited**

UNITED STATES PATENTS

2,725,288	5/1955	Dodds.....	75/226
3,182,102	5/1965	Simnad.....	75/226 X
3,241,956	3/1966	Inoue.....	75/200 X
3,317,705	5/1967	Inoue.....	75/206 X
3,356,495	12/1967	Zima.....	75/226 X
3,383,208	5/1968	Corral.....	75/226 X

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[57] **ABSTRACT**

A method of electrical sintering of a mass particles of conductive or nonconductive powder in which the powder is compacted between the electrode by means of liquid pressure applied through a flexible membrane. The fluid pressure may be supplied within the body or from the outside and may follow the shrinkage of the mass which can be spark sintered or fused by resistance heating. An elongated element can bridge the electrodes for retention in the mass to form a reinforcing member or can serve as an auxiliary heating element. The body thereby sintered can be surrounded by a lightly compacted, porous layer of a heat resistant material (e.g., graphite) to form a force-transmitting medium between the membrane in the sinterable mass.

19 Claims, 27 Drawing Figures

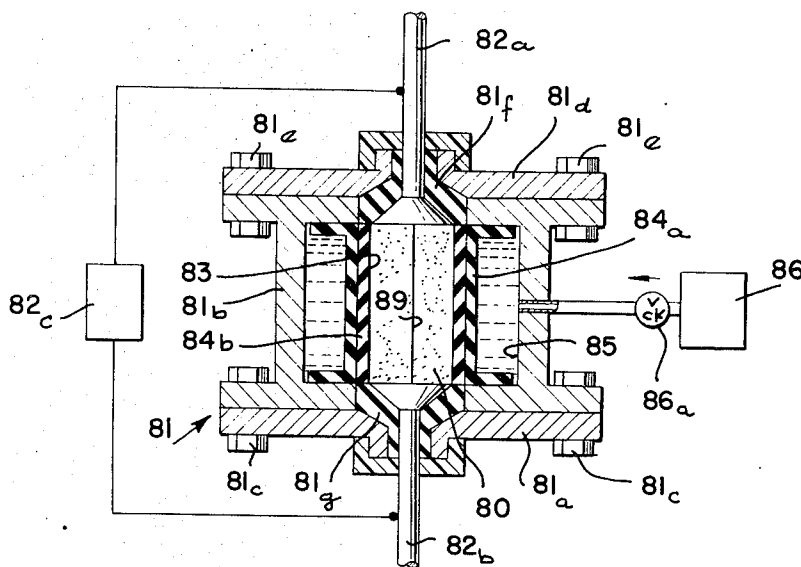


FIG. 1

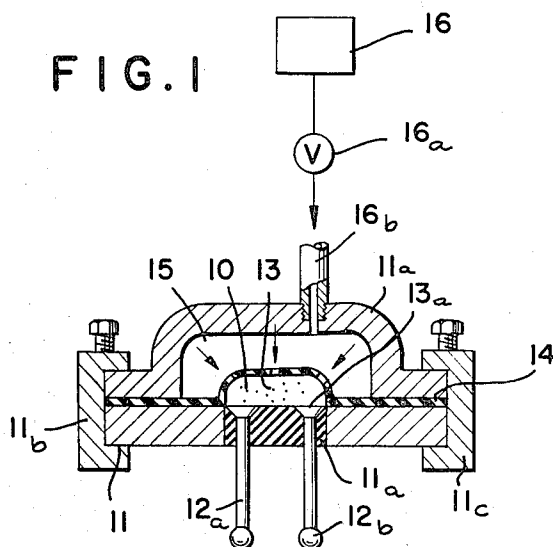


FIG. 2

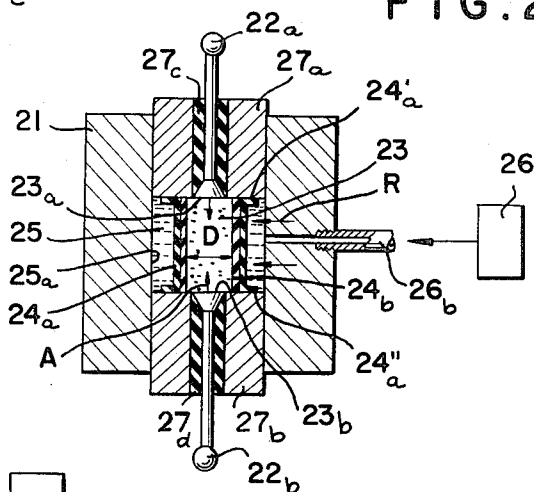
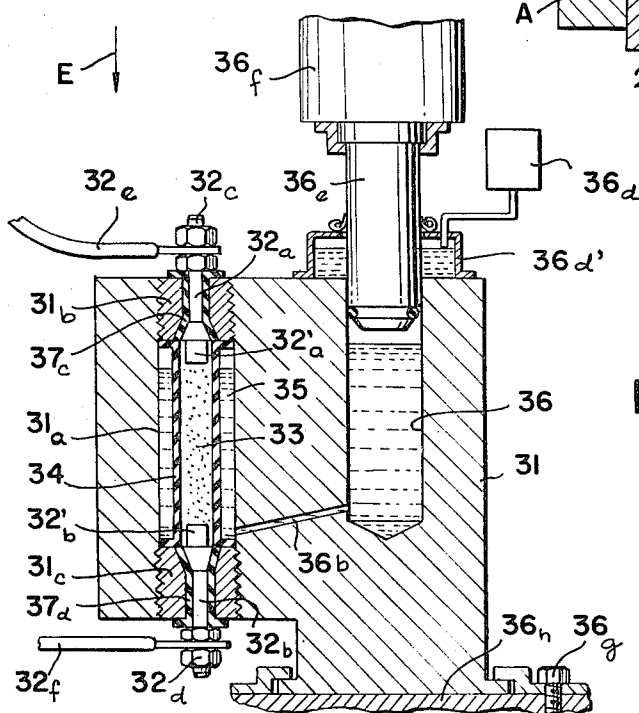


FIG. 3

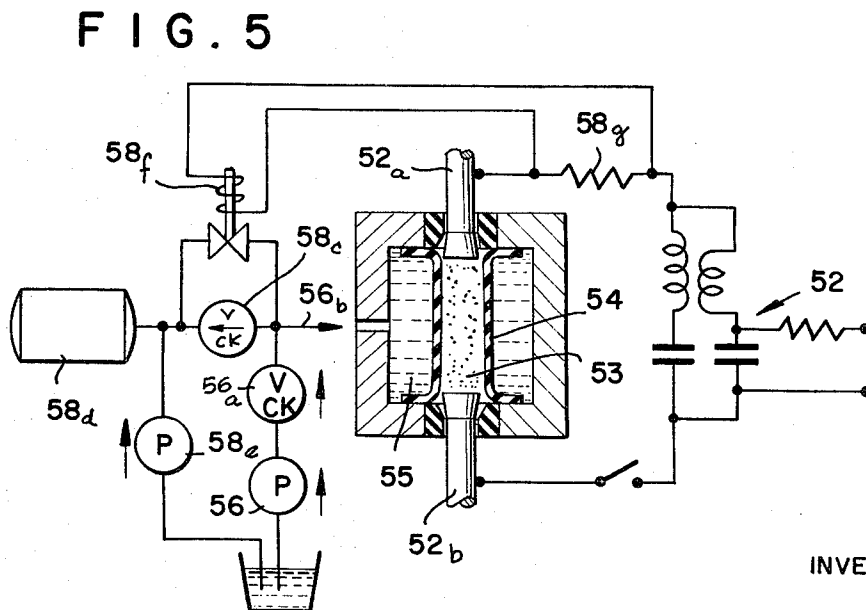
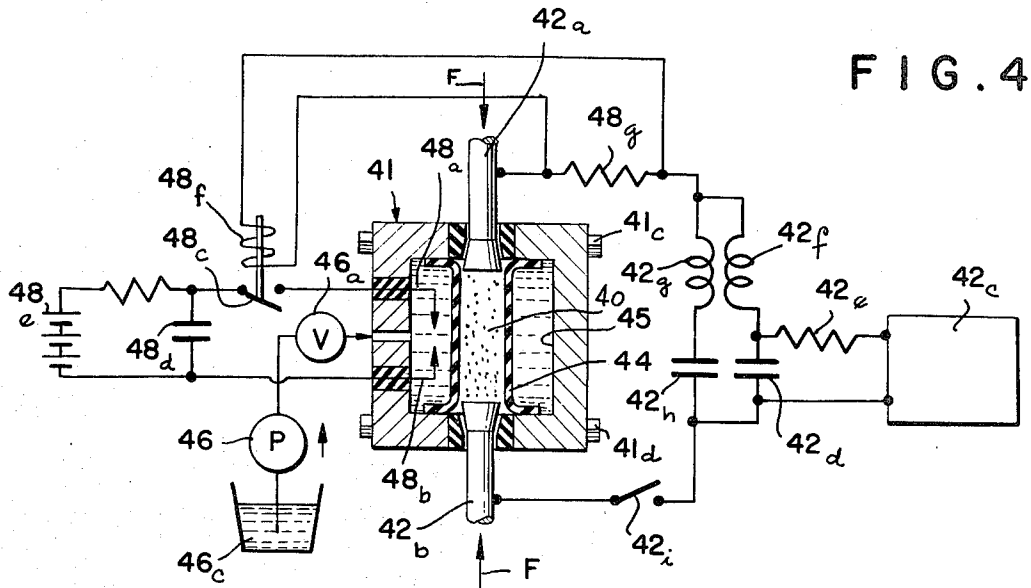


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FIG. II

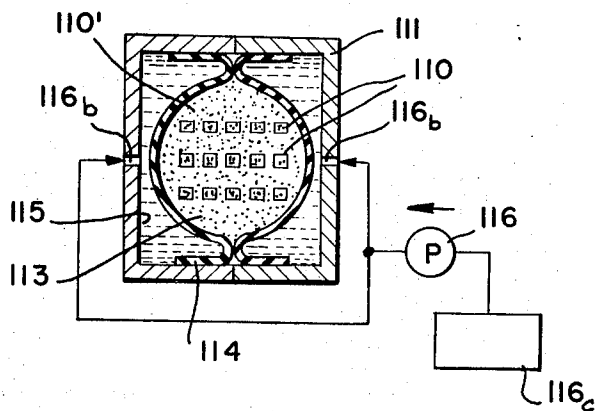


FIG. II-C



FIG. II-D

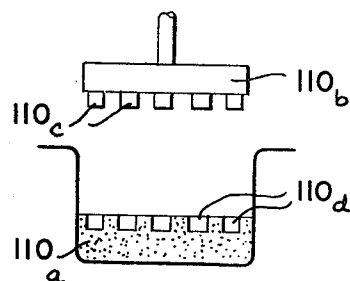


FIG. II-A

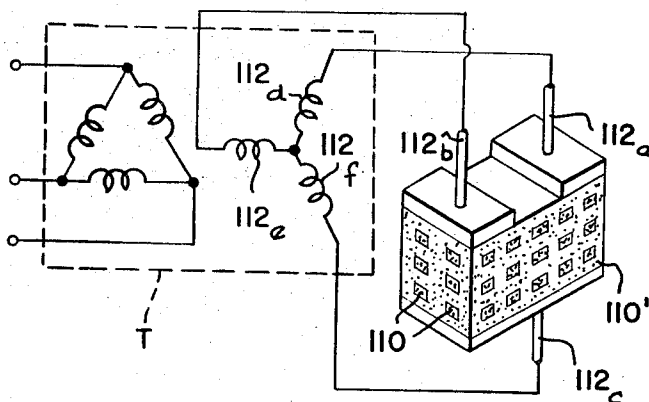


FIG. II-E

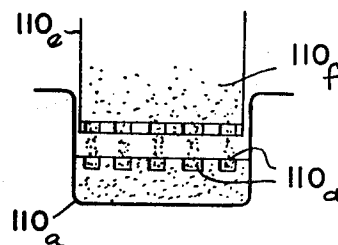


FIG. II-B

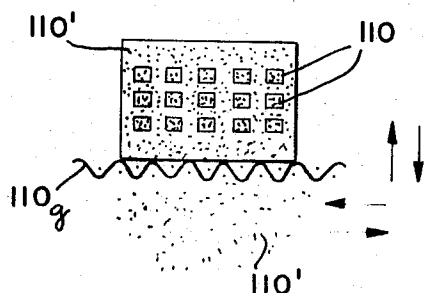
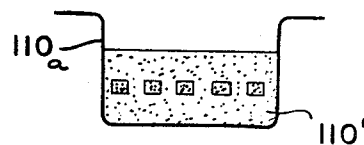


FIG. II-F



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FIG. 12

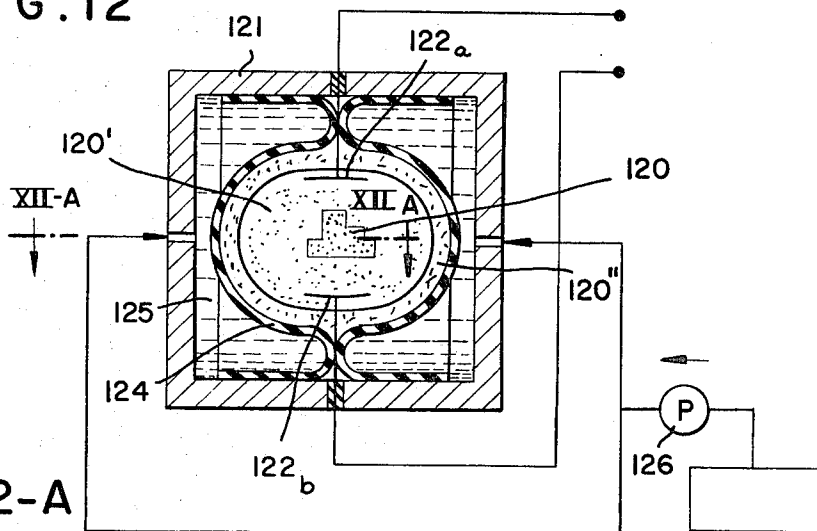


FIG. 12-A

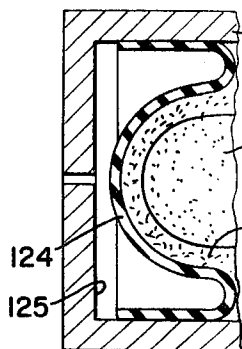
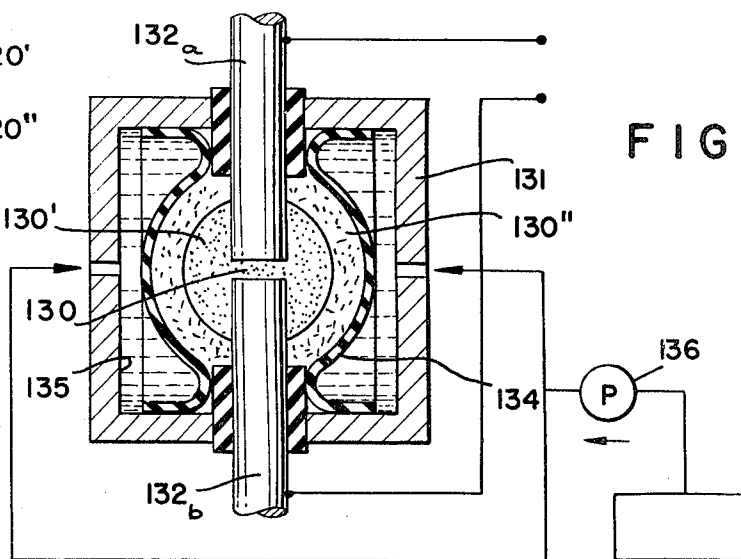


FIG. 13



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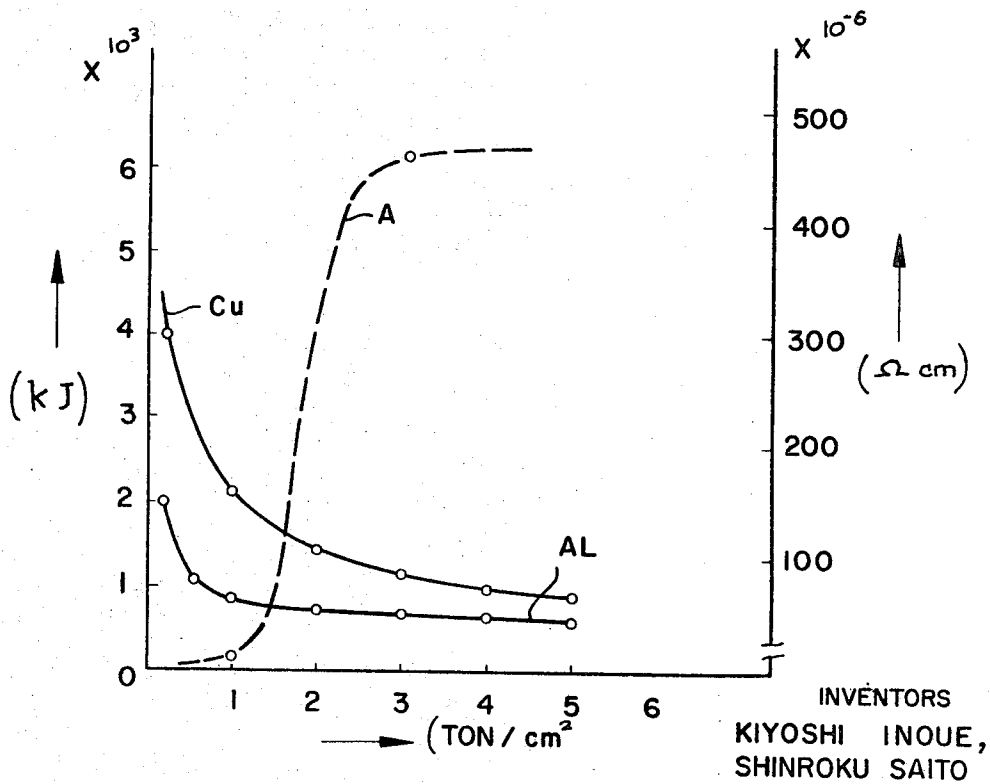
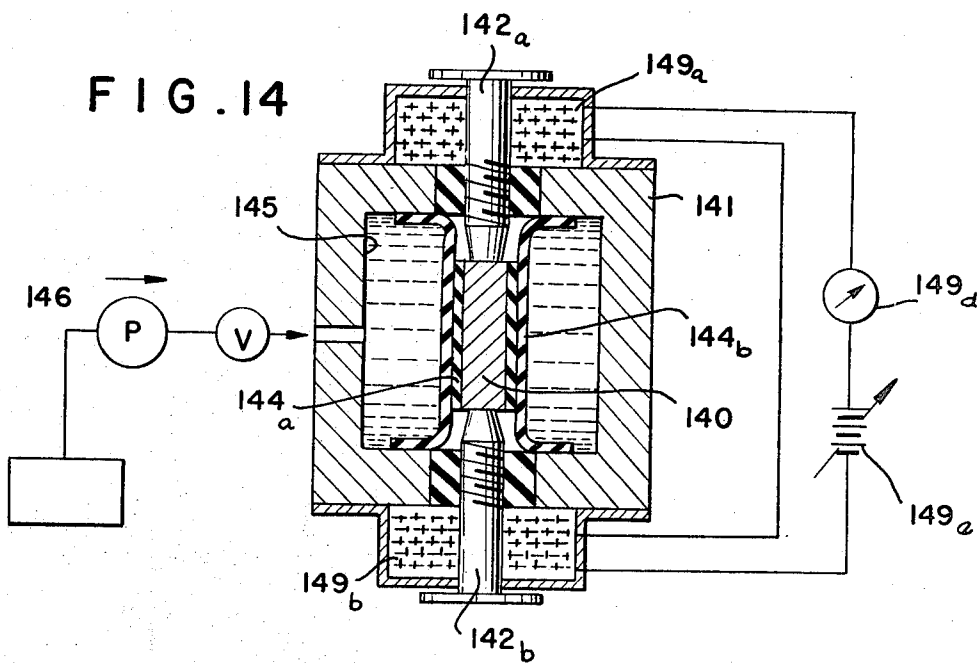
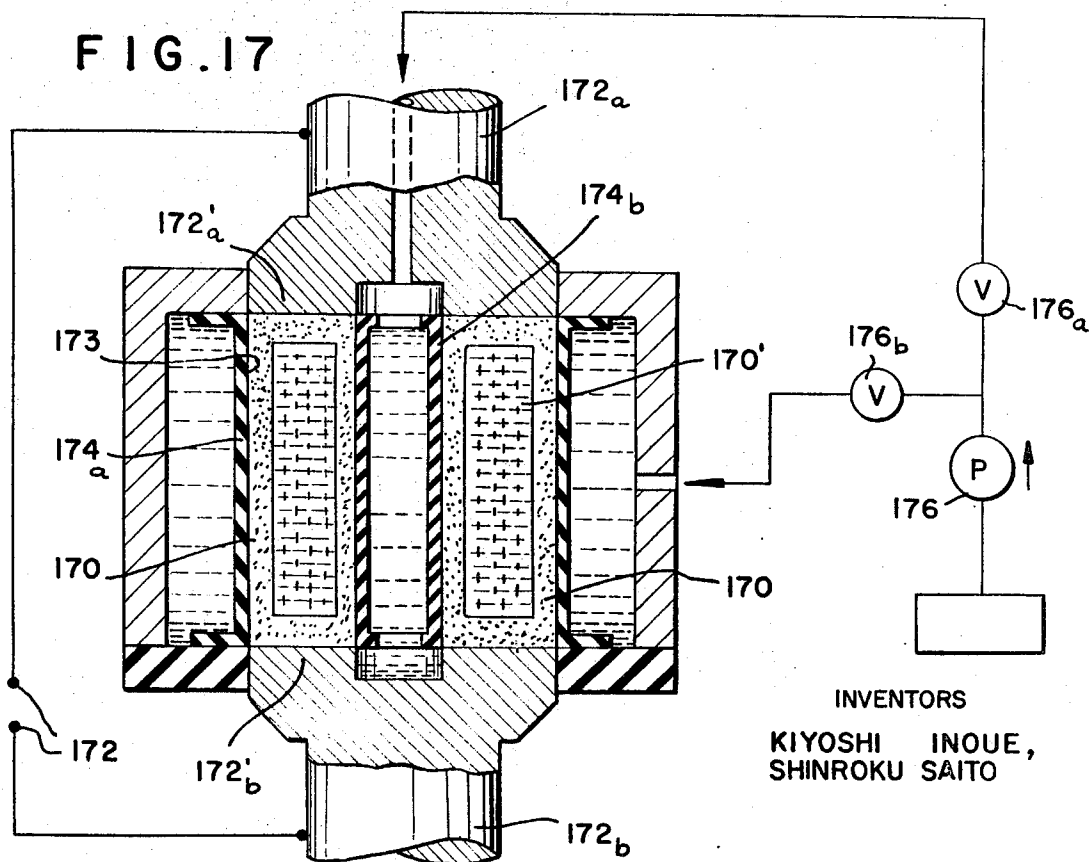
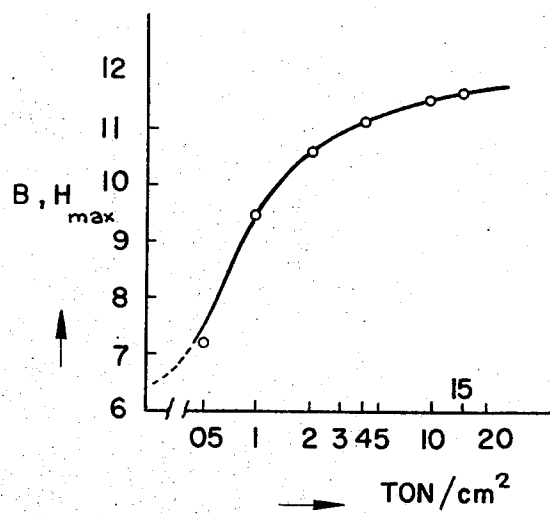


FIG. 16

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ELECTRICAL SINTERING UNDER LIQUID PRESSURE

Our present invention relates to electrical sintering with increased externally-applied-pressure uniformity.

In applications Ser. No. 611,497 filed 30 Nov. 1966 and Ser. No. 652,561 filed 11 July 1967 (U.S. Pat. No. 3,508,029) by Kiyoshi Inoue, one of the present joint inventors, and in earlier U.S. Pats. No. 3,241,956, No. 3,250,892, No. 3,317,705, No. 3,340,052 and No. 3,364,333, there are described improved methods of electrically sintering conductive particles and mixtures of conductive and nonconductive particles wherein a spark discharge is applied across the particle mass to bond the particles together under the impulsive force of the discharge, with interparticle heating at the interface promoted by the discrete sparks bridging them, with resistance heating after initial bridge formation, and with the application of pressure to condense the particles further subsequent to the initial sintering and, possible, during such sintering. In these applications and the aforementioned patents, it has been pointed out that the improved technique differs from earlier systems in that compacted bodies or so-called "green compacts" of particles were, in the earlier systems, subjected to resistance heating under conditions designed to fuse the particles together. The latter technique requires relatively high-static pressure during or prior to the sintering operation at least in part because the method is devoid of the kinetic force of impulsive spark discharge. Both systems, however, use principles which may be generically referred to as "electrical sintering" to bond the particles together.

It has been found that these systems do not always produce perfect results because of the purely uniaxial or unidirectional application of pressure by the pistons almost invariably employed to compact the sintered-particle mass. Thus, an important principle arising in this connection is the inhomogeneity of internal stress and the nonuniform compaction of the mass.

It is the principal object of the present invention to provide an improved method of electrically sintering particles in which the internal stresses may be eliminated or more uniformly distributed.

Another object of this invention is to provide a method of electrical sintering of particles in which pressure is applied more uniformly throughout the body.

Another object of our invention is the provision of a method of welding metallic bodies together with the intermediary of a sinter-particle layer which has improved stress characteristics and uniformity.

Still another object of the instant invention is the provision of a method of producing uniform sintered-particle bodies which may consist of conductive particles, mixtures of conductive and nonconductive particles and even exclusively of nonconductive particles.

Our present discovery resides in the fact that it is possible, in spite of common belief that axial pressure in line with the electrodes of a sintering system is necessary for satisfactory electric (spark plus resistance, or purely resistance) bonding of particles and the further discovery that electrical, especially spark, sintering when used in conjunction with more or less isostatic pressure applied by a pressure liquid over at least a major portion of this periphery of the particle mass results in synergistic improvement in the quality of the body. Thus, we have found that it is possible to carry out electrical sintering of a particle mass by disposing this mass between a pair of spaced-apart electrodes and enclosing the mass, in whole or a substantial part, in a flexible-wall force-transmitting membrane defining the chamber in which the particle mass is located, in applying pressure to the particle mass by introducing a fluid (i.e. a liquid or a gas) into a plenum chamber surrounding the membrane. The pressure thereby imparted to the mass tends to compact the latter in a direction perpendicular to its surface or periphery regardless of the contours thereof, thereby increasing the uniformity of the externally applied pressure, compaction and internal stress of the resulting body. The improved system represents a marked advance over conventional ram-and-mold shaping of the particle mass and permits a saving in equipment cost and energy.

As indicated above, the isostatic pressure, as here applied to electrical sintering, produces a boundary effect which is not to be found in isostatic methods used to compact a mass for heating in a furnace or the like. While applicants do not wish to be bound by any theory in this regard, it has been found that a boundary-layer effect appears to be produced by the isostatic pressure upon the particle subjected to electrostatic sintering and especially the spark-discharge fusion of the particles. Thus, whereas uniaxial pressures fail to compact the mass at locations remote from the piston and ram surfaces so that nonuniform electric-current passage through the mass results, the present system causes practically uniform particle-to-particle pressure at all locations within the body, thereby permitting the resistance-heating effects within the particles and at their interfaces to be more uniformly and homogeneously distributed and, of course, allows uniform distribution of the space discharge between the electrodes among the particles. Of course, these principles are not in point when, as in conventional isostatic systems, externally applied heating sources are used. The combination of electrical sintering, especially spark sintering with isostatic pressure therefore can be considered synergistic because of the distribution of fusion sites in the interior of the body which results from the spark action and the significantly more homogeneous pressure with which particle-to-particle contact is promoted.

According to a more specific feature of this invention relatively low isostatic or semisostatic pressure (e.g. 10 kg./cm.² to several hundred kg./cm.²) may be employed initially, i.e. prior to or during electrical, preferably spark, sintering, and can be followed by compaction of the initially sintered mass at a pressure (externally applied by the liquid) of 1 to 20 tons/cm.², preferably of the order of several tons/cm.²). Alternatively, a high-isostatic pressure may be used to effect green packing of the mass, followed by electrical sintering with automatic expansion of the plenum chamber under liquid pressure to follow the shrinkage of the sintered mass during the sintering process. When a gas serves as the pressure medium, the plenum chamber thus constitutes an expandable pressure accumulator which allows expansion and pressure reduction of the gas in the plenum to follow the shrinkage of the particle mass. Such pressure reduction may be used to measure the shrinkage and the nature of the sintering process and thereby allow servocontrol of an electric or other parameter of the sintering system.

According to still another aspect of this invention, a non-conductive particle mass can be sintered by the present method with the intermediary of a conductive force-transmitting powder filling the space between the particles to be fused and the surrounding membrane. To this end, the force-transmitting powder may be a particulate material which will not sinter under the electrical conditions applied thereto, graphite powder or carbon powder being used for this purpose. In accordance with this principle, the body to be sintered may consist of refractory particles capable of fusion by the generation of heat therearound, with the heat being produced by the resistance heat generated by the current flow through the force-transmitting powder. When spark-discharge techniques are employed, the space discharge between the electrodes is also propagated through and in the region of the nonconductive body to generate a compact force assisting in the densification of the body.

When conductive particles constitute the body, however, it is sintered by the passage of electrical current therethrough or the generation of a spark discharge within the body in addition to externally developed heat in the surrounding particle mass. The latter method has been found to be particularly suitable for the sintering or tungsten carbide, beryllium, aluminum and magnesium powders or refractory materials such as aluminum oxide, silica or boroncarbide powders. The body of particles to be sintered may be subjected initially to green compaction with the force-transmitting powder relatively loosely compacted therearound to conform to the shape of the green compact. Alternatively, the force-transmitting powder may define the shape of the finished body when, as in conventional sand-

mold casting, the force-transmitting powder is compacted about a pattern and the particles to be sintered are then filled into the compartment formed by removal of the pattern.

This principle may also be used in the welding of two bodies together with an intermediate layer of sintered particles; in this case, the sinter particles are retained in place by a mass of force-transmitting powder which here forms the mold. Certain aspects of these features are clear from Kiyoshi Inoue application Ser. No. 652,560. The latter system has the significant advantage that the force-transmitting powder may be loosely compacted and thereby forms a porous mold allowing the escape of gases generated upon electrical sintering of the body.

We have also found that the present method is able to form bodies of particulate materials with physical properties quite different from those normally attributed to the materials used. For example, it is possible to electrically sinter aluminum particles by the present method with a density of more than 99 percent of its solid specific gravity and yet form a body whose resistivity may be 10 or more times greater than the resistivity of an aluminum body formed by sintering aluminum particles by conventional techniques. It has also been found that there are certain pressure at which powders of various materials may be compacted at high pressure and sintered with expansion of the plenum chamber to follow the sintering and thereby yield bodies of maximum cohesiveness and mechanical properties. For example, aluminum and aluminum alloy powders should be initially compacted at a pressure of about 1 ton/cm.² while powdered copper and titanium and alloys thereof may be compacted at 2 tons/cm.², iron and iron alloy powders at 2.5 tons/cm.², powdered beryllium nickel and their alloys at 3 tons/cm.², tungsten powder at 5 tons/cm.², and copper, zinc, lead and synthetic resin powders at about 1 ton/cm.².

The above and other objects, features and advantages of the present invention will become more readily apparent from the following description, reference being made to the accompanying drawing, in which:

FIG. 1 is a vertical cross-sectional view diagrammatically illustrating an apparatus for electrically sintering a conductive powder mass;

FIG. 2 is a vertical sectional view through a similar apparatus for the formation of a cylindrical body;

FIG. 3 is a vertical cross-sectional view of an apparatus for the formation of cylindrical bodies in accordance with the principles of FIG. 2 but adapted to be used in a conventional press;

FIG. 4 is a vertical section through an apparatus in which the pressure applied to the particles is pulsed synchronously with the application of spark-discharge energy;

FIG. 5 is a view similar to FIG. 4 illustrating another embodiment of this aspect of the invention;

FIG. 6 is a vertical section through a system in which ultrasonic vibrations are applied to the powder via the pressurization fluid;

FIG. 6A is a sectional view through another apparatus for applying the vibration waves to the powder;

FIG. 7 is a cross-section taken along the line VII — VII of FIG. 6;

FIG. 7A is a cross-sectional view similar to FIG. 7 but illustrating a system for the formation of tubular cylindrical bodies;

FIGS. 8 and 8A are axial cross-sectional views through other embodiments of our invention;

FIG. 9 is a view, partly in diagrammatic form, of an apparatus for controlling the pressure applied to the powder;

FIG. 10 is an axial cross-sectional view through another apparatus of this character;

FIG. 11 is a cross-sectional view through an apparatus using the principles of the present invention to form a multiplicity of sintered bodies simultaneously and wherein a force-transmitting powder is provided;

FIG. 11A is a perspective view of the electrical circuitry for a system of this latter type;

FIG. 11B is a diagram illustrating the removal of the force-transmitting powder;

FIGS. 11C — 11F show successive steps in the preparation of the powder mold for the systems of FIGS. 11a and 11B;

FIG. 12 is a vertical cross-sectional view through a system illustrating another aspect of this invention;

FIG. 12A is a cross-section along the line XII — XII of FIG. 12;

FIG. 13 is a vertical section through an apparatus for the welding of a pair of rods together in accordance with the principles of this invention;

FIG. 14 is a diagrammatic cross-sectional view of an apparatus for making a magnetic body in accordance with this invention;

FIGS. 15 and 16 are graphs illustrating Examples of this invention; and

FIG. 17 is a cross-sectional view through a device for making a motor stator of this invention.

In FIG. 1, we show an apparatus for semi-isostatically forming a powder mass 10 into a coherent body. The apparatus comprises a base 11 having an insulating body 11a in which a pair of electrodes 12a and 12b are received such that their inner faces, formed on a frustoconically enlarged terminus of a rod, lies flush with a wall 13a of a chamber 13 containing the powder. An elastomeric membrane 14 overlies the powder and can be composed of an elastomer such as urethane rubber, butadienestyrene rubber, natural rubber, silicone rubber, a film-forming lattice or neoprene. The membrane 14 is clamped between the base 11 and a housing head 11a which defines with the membrane 14 a plenum chamber 15 to which fluid may be supplied from a source 16 (e.g. a pump) via a valve 16a and a dust 16b. A pair of clamps 11b and 11c hold the assembly together. The base and housing members 11 and 11a may be composed of cast iron, steel or other relatively rigid material. In accordance with the present invention, fluid under pressure is supplied to the chamber 15 from the pump 16 via a valve 16a to bear upon the powder semi-isostatically, with isostatic fluid pressure applied over all walls of the chamber 13 with the exception of the wall portions formed by the electrodes. The electrodes are preferably connected to a spark discharge source (see Kiyoshi Inoue applications Ser. Nos. 611,497 and 652,561) or to a resistance-welding source of conventional character. Prior to introduction of the powder 10 and the mold formed by the membrane 14, the powder may be precompact or green-compact. It has been discovered that this arrangement results in a denser product with a pressure between a pair of coaxial electrodes as will be apparent from the specific Examples given below. The pressure fluid may be a liquid or a gas and can be oil, glycerin or mercury, or common air or another gas (e.g. nitrogen).

In FIG. 2, there is shown a system for the formation of cylindrical bodies which comprises a cylindrical housing 21 forming a cylinder bore 25a which, between a pair of pistons 27a and 27b forms a plenum chamber 25 in which a pair of annular cylindrical membranes 24a and 24b are coaxially disposed. The outer membrane 24a has a pair of outwardly extending annular flanges 24a' and 24a'' which are urged outwardly by the fluid supplied to the plenum chamber 25a through an inlet 26b from the fluid source 26. The piston 27a and 27b are respectively formed with insulating bushings 27c and 27d in which the electrode rods 22a and 22b are disposed. The diameter D of the chamber 23 receiving the powder is approximately equal to the diameters of the faces 23a and 23b of the electrodes which form the only walls of the chamber 23 which are not elastomeric. Here again, a spark-discharge power supply may be connected across the electrodes 22a and 22b and can be constituted of the type shown in Kiyoshi Inoue applications Ser. Nos. 611,497 and 652,561. The pistons 27a and 27b may be urged toward one another by hydraulic means (see FIG. 9, for example) and compact the powder mass with substantially the same axial pressure A as the radial pressure R. The result is a substantially isostatic compression of the powder mass concurrently with electrical sintering (see Example II).

While the pressure sources in the systems of FIG. 1 and 2 have included substantially any hydraulic supply, it is possible to use the pressure of a ram, e.g. of a press which may or may not drive the pistons as well, as the fluid pressure source. Such an embodiment is illustrated in FIG. 3. In this Figure, the housing 31 is formed with a bore 31a closed by plugs 31b and 31c to form a plenum chamber 35 adapted to be charged with hydraulic fluid from a pressurization cylinder 36 via the bore 36b. The plenum chamber 35 surrounds an elastic membrane 34 which, upon pressurization, is forced inwardly to hug cylindrical bosses 32a' and 32b' formed on respective electrodes 32a and 32b constituting the end faces of a compartment 33 containing the powder to be sintered. The electrodes are received in insulating sleeves 37c and 37d and are provided with terminals 32c and 32d to which the leads 32e and 32f of a spark discharge sintering circuit or an electrical resistance sintering circuit are connected. The chamber 36 is supplied with hydraulic fluid from a reservoir 36d which is connected to an annular compartment 36d' surrounding the plunger 36e which can be withdrawn by the head 36f of the press to allow liquid to fill the bore 36. The housing 31 is held by bolts 36q upon the bed plate 36h or anvil of the press. When the head 36f is driven in the usual manner in the direction of arrow E, the plunger 36e drives fluid from bore 36 via passage 36b into the chamber 35 surrounding the membrane 34, thereby substantially isostatically compacting the particles within the membrane in the radial direction. In FIG. 9 below, we describe a system whereby the pressure applied to the particle mass is controlled by a servomechanism so as to transmit pulses through the pressurizing medium to the particles. When the assembly of FIG. 3 is used, the hydraulic line to the interior of the chamber 35 need not be pulsed independently from the pulsing of the ram or head 36f of the press. Furthermore, the ram 36f may be coupled with a piston replacing either of the plugs 31b and 31c for simultaneous mechanical compaction of the particles by direct piston action and hydraulic compaction of the particles by the development of pressure in chamber 35.

According to another aspect of the invention alluded to earlier, we prefer to combine the isostatic or substantially isostatic pressure applied to the particles via a flexible membrane with other energy systems involving ultrasonic or low-frequency pulsation of the particle mass concurrently with spark or electrical-resistance sintering, involving substantially simultaneous pulsation of the pressurizing medium with spark generation across the sintering electrodes, involving the transmission of ultrasonic vibrations and shock waves through the fluid-pressurizing means, and applying magnetic pulses or static magnetic field concurrently with spark sintering. The advantages of such steps, taken individually or in combination have been adequately demonstrated in the Kiyoshi Inoue applications and patents mentioned earlier. In FIG. 4, for example, we show a system for imparting shock pulses to the sintering mass concurrently with the generation of the sintering pulses. In this embodiment, the housing 40 is bipartite and can be held together by a pair of tie bolts 41c and 41d running perpendicularly to the vertical axis of the cylindrical bore 45a defined between the two housing parts when they are secured together. The housing parts 41 also clamp a pair of electrodes 42a and 42b slidably in place so that axial forces may be applied to the electrodes via a hydraulic press or piston arrangement as described in connection with FIG. 3 above and FIG. 9 below; the axial pressures are represented by the arrows F. This system makes use of principles described in Kiyoshi Inoue applications Ser. No. 508,487 of 18 Nov. 1965 (U.S. Pat. 3,512,384), No. 574,056 of 22 Aug. 1966 and No. 696,757 of 10 Jan. 1968 and prior U.S. Pats. No. 3,208,255, No. 3,232,086 and No. 3,267,710. One of the principles of these latter disclosures is that a high-energy shock wave can be generated by an impulsive spark discharge between a pair of electrodes in a fluid, preferably a nonconductive liquid, to generate waves of ultrasonic, sonic or subsonic frequency. In this embodiment, a pair of wire-like electrodes 48a and 48b extend through respective insulating sleeves into the liquid

containing plenum chamber 45 whose fluid pressure is maintained by a check valve 46a in series with a pump 46 and a reservoir 46c. The sparking electrodes 48a and 48b are connected in series with a switch 48c across a discharge capacitor 48d which in turn can be charged by DC source 48e represented as a battery. Switch 48c is of the relay type and has a coil 48f connected across a current-flow detector formed as a resistor 48g in series with the spark-sintering electrodes 42a and 42b. A pulse source of the type described in Kiyoshi Inoue application Ser. Nos. 611,497 and 652,561 is connected at 42c across a discharge capacitor 42d via a charging resistor 42e. The capacitor 42d forms a series circuit with one winding 42f of a coupling transformer whose secondary 42g is connected in series with capacitor 42h across the electrodes 42a and 42b via the switch 42i. When switch 42i is closed, capacitor 42e discharges through the primary 42f and the electrodes 42a, 42b across the powder mass 40 therebetween to effect spark sintering of the powder as described in the last-mentioned copending applications. The current surge through primary winding 42f induces a surge in secondary 42g which, with capacitor 42h, increases the duration of the discharge. A pulsing rate of about 0.1 millisecond to about 1 second is preferred (see Example III below). The current flow through the detecting resistor 48g generates a potential thereacross sufficient to operate the relay 48c, 48f and discharge the capacitor 48d across the gap 48h between electrodes 48a and 48b. In accordance with the principles set forth in applications Ser. Nos. 508,487, 574,056 and 696,757, the resulting shock wave augments the pressure sustained in chamber 45 around the membrane 44 separating this chamber from the powder 40. As a consequence, the impulsive spark discharge which sinters the particles together is co-ordinated with a substantially instantaneous increase in the pressure within chamber 45, which pressure increase is uniformly applied radially to the membrane and, by the membrane, to the powder. The circuitry thus provides a servocontrolled synchronization of pressure pulses with sintering pulses.

In FIG. 5, we show an analogous system in which fluid pressure pulses are supplied to the chamber 55 surrounding the membrane 54 which encloses, with electrodes 52a and 52b, the chamber 53 retaining the sinterable powder. In this embodiment, a current surge delivered by the network 52c (which corresponds to the network 42c through 42h) is applied to the electrodes 52a and 52b through the resistor 58g and generates a potential sufficient to operate an electromagnetic valve 58f and shunt hydraulic fluid rapidly across a check valve 58c. The latter connects a hydromechanical or hydropneumatic accumulator 58d to the inlet line 56b of the fluid-supply means. The accumulator 58d may be of any of the types shown in "Fluid Power," U.S. Government Printing Office, 1966, pages 86 - 89, or any other conventional type. To charge the accumulator, we may provide a pump 58e behind the check valve 58f which is oriented to prevent fluid from flowing to chamber 55c when the valve 58f is closed. Another pump 56 may be provided to maintain, via a check valve 56a, a normal fluid pressure within the chamber 55. In this system, the spark sintering surges of electrical current through the resistor 58g upon the valve 58f to momentarily apply a high-pressure pulse from the accumulator 56d to the fluid chamber 55. The valve 58f then closes and any reverse surge of pressure may be absorbed, via check valve 58c, by the accumulator 58d. Otherwise, the system of FIG. 5 operates in the manner previously described in connection with FIG. 4.

FIG. 6 shows a system in which ultrasonic vibrations are superimposed upon the high pressure serving to compact the powder 60 within the chamber 63. The annular membrane 64, surrounding the powder 60, is formed with an annular flange 64a' and 64a'' at its opposite extremities as described in connection with FIG. 2. The housing 61 is formed with a base 61a to which a cylinder 61b is attached by bolts 61c. The interior wall 65a of this cylinder defines a pressurizable plenum chamber 65 with the membrane 64. A cover plate 61d is affixed to the cylinder 61b by bolts 61e and has an opening 61f

formed with a thread adapted to receive the plug 67 after the powder 60 has been introduced. Plug 67 may constitute a plunger which, as it is threaded into its bore 61f, axially compacts the powder.

In this embodiment, a circulating liquid stream or a static liquid may constitute the pressurizable medium. The fluid pressure source may be constituted as a pump 66 drawing fluid from the reservoir 66c and circulating it via a line 66b to the chamber 65. From the latter, liquid may return via line 66d and a valve 66e to the reservoir 66c. The pressure is regulated by a shunt valve 66f which bypasses fluid from the high-pressure side of the pump 66 to the reservoir. When valve 66e is open, a dynamic liquid medium flows through the chamber 65 and can constitute a coolant as well as the pressure medium. When valve 66d is closed, a static pressure is maintained in chamber 65. When it is desired to release the sintered body, valve 66e is opened, pump 66 is cut off and plug 67 withdrawn. A pair of terminals 62a and 62b is connected to the plug 67 and the plate 61a to constitute these members as the electrodes for spark discharge or electrical sintering.

In accordance with the principles of this invention, a chamber 68 is formed along the line 66b and has a converging nozzle 68a opening into the chamber 65 within the chamber 68, we provide a magnetostrictive ultrasonic vibrator 68b which is energized by an ultrasonic-frequency a.c. source 68c whose frequency output and amplitude may be varied. The ultrasonic vibrations transmitted by the liquid to the isostatically pressurized powder 63 gives rise to a sharp increase in the mechanical properties of the spark or resistance-sintered objects (see Example IV). From FIG. 7, it is apparent that only radially inward pressure is applied by the liquid in chamber 65 to the membrane 64 and the powder 60. It is also possible, however, to support the powder between a pair of membranes as shown in FIG. 7A at 74 and 75', the powder being disposed in the compartment 73 between these membranes. Surrounding the outer membrane 74' and within the inner membrane 74, we provide the plenum chamber 75' and 75, respectively, which are supplied with fluid under pressure so that radially inward and radially outward pressure is applied to the powder.

The ultrasonic vibration source may be a spark discharge generator as shown in FIG. 6A in which the chamber 68' is provided with a pair of electrodes 68b' which may be advanced toward one another and away from one another alternately by the rollers 68c' to initiate spark discharge across the electrodes. The supply circuit comprises a battery 68d' connected across a capacitor 68e' and a spark gap 68f' in series with the electrodes 68b' and the capacitor. As the electrodes 68b' are advanced toward one another, the breakdown voltage developed at the capacitor 68e is attained and a discharge produced in the liquid within chamber 68' which may be substituted for the chamber 68 of FIG. 6. The resulting shock waves are transmitted to the liquid in chamber 65. The system of FIG. 6A may be used as a substitute for the spark system of FIG. 4 and vice versa depending upon the spark energy and frequency desired. With respect to ultrasonic vibration, it has been found that best results are obtained when the vibrations are in the frequency range of several hundred cycles/second to 5 megacycles/second.

FIG. 8 represents another principle of the present invention according to which we provide filamentary or rod-like members extending through the sinter-powder mass and, advantageously bridging the electrodes. The elongated element may be straight or bent to conform to the contours of the mass and may be conductive or nonconductive as will be apparent hereinafter. For example, one or more elongated elements may be provided of a nonconductive material, e.g. glass fiber or ceramic fiber, asbestos or other refractory material to form a reinforcing element remaining intact within the sintered body. Alternatively, a resistance-heating wire composed of, for example, nichrome may be provided between the two electrodes and can have a total resistance somewhat in excess of that of the porous mass between the electrodes when resistance fusion of the particles is desired. In this case, a portion

of the heating current passes through the mass while the balance of the current flows through the wire to heat the central area to a greater extent or, when the wire is bent into the contours of a body of intricate configuration (FIG. 8A) to heat the portions remote from the straight-line current path which dominates the welding operation. The same technique may be employed when the particles are composed at least in part of nonconductive materials and are admixed with a thermosetting binder which is activated by the heat generated in the nichrome wire. We have also found that it is possible to exploit principles described in connection with the shockforming of materials as described in Kiyoshi Inoue applications Ser. Nos. 508,587, 574,056 and 696,757 to create internal outward shock forces which supplement the fluid pressure applied from the exterior to the sintered powder. In the latter instance, the elongated element bridging the electrodes may be a fusible wire which is explosively destroyed by the application of a spark-sintering electrical pulse across the electrodes. Still another alternative provides that the elongated element constitutes a catalyst for reaction with a bonding agent or for promoting such reaction, or to constitute the bonding agent itself. Thus, when the primary heating current flows through the powder, the wire may be composed of a thermoplastic which is rendered flowable during the spark or resistance sintering operation to assist in the adhesion of the particles.

The system of FIG. 8, therefore, provide a housing 81 whose base plate 81a supports the cylindrical housing body 81b to which it is secured by bolts 81c. A cover 81d is attached to the cylindrical body 81b by bolts 81e. Insulating members 81f and 81g forms supports for the electrodes 82a and 82b which are connected to a source of electric pulses 82c of the spark-sintering type previously described. Within the interior of the cylindrical housing 81b, a pair of rubber membranes 84a and 84b subdivide a liquid-filled plenum chamber 85 from the outer chamber 83. The plenum chamber is supplied with the pressure fluid from a source 86 via a check valve 86a. Within the powder mass 80, we provide a centrally extending elongated element 89 which may remain within the sintered body as a reinforcing element, which may be destroyed by these spark-sintering current surges to increase the compaction force, which may serve as a heat source, or which may act as a catalyst for or as part of the bonding agent, all as described above. Otherwise the device functions in the manner previously described. When the body has irregular or intricate contours with portions remote from a straight line connecting the electrodes, heating may be provided in these remote portions by bending wire to conform thereto as shown in FIG. 8A. In this embodiment, the dot-dash lines represent the straight line current paths between the electrodes 82a' and 82b' so that the powder portions 80' and 80'' are to be considered as remote from the straight line paths to produce heating in these regions, the core wire 89' is bent to pass through the portions 80' and 80'' as indicated in FIG. 8A. The membrane 84', of course, also conforms to the contours of the green-compacted mass of particles.

As more generally described above, it has been found to be advantageous to provide servocontrol of the fluid pressure and the mechanical pressures upon the body to maintain the isostatic pressure during the sintering step and/or to pulse the externally applied pressure concurrently with spark-sintering of the mass.

FIG. 9 represents, in generalized form, a servomechanism for carrying out this modification of the present process. In this system, the housing 91 co-operates with a fixedly positioned electrode 92a and an electrode 92b which is axially shiftable by a hydraulic cylinder 92b' to axially compact the powder mass 90 within the membranes 94a and 94b composed of elastomeric material. The electrodes 92a and 92b can be connected across an impulsive spark-sintering source as represented by the terminals 98 and are adapted to sinter the particles in the manner previously described. In this embodiment, however, the fluid-pressure source is a pump 96 which draws fluid from the reservoir 96c and supplies it to a three-

position electromagnetic valve 96a whose function is described in greater detail below. A return line 96d connects the valve 96a with the reservoir 96c, which line 96b conducts fluid from the valve to the plenum chamber 95 of the housing 91 surrounding the membranes. A bypass line 92c with a throttle valve 92d connects the output side of valve 96a with the electrode-displacing hydraulic cylinder 92b'. A servosensor is constituted by a resistor 98q in the supply network to the electrodes 92a and 92b and is connected to the servoamplifier 96e whose output supplies one coil 96f of the magnetic valve 96a. The oppositely effective coil 96g is supplied with current from a network establishing a reference voltage and shown as a DC source 96h bridged by a voltage-dividing potentiometer 96i. A timing mechanism or programming control 96j may also be provided for resetting the potentiometer to step up or step down the pressure applied to the particles during a subsequent stage of sintering in accordance with principles previously discussed. It will be apparent that, whenever a current stage is applied across the electrodes 92a and 92b to induce a sintering operation, the surge is sensed by the detector 98q which, via amplifier 96e energizes coil 96f when the level is sufficient to overcome coil 96g. The valve is shifted from its position I in which the fluid within the chamber 95 is at relatively low pressure corresponding to the low level of the current surge detected at 98q, to position II in which the pressure in chamber 95 is sustained. As the current flow across the electrodes, which passes from impulsive to continuous during the transition from spark sintering to the final resistance heating, increases, the valve is shifted to position III in which a high-pressure buildup in chamber 95 and in cylinder 92b' is carried out, thereby developing high radial and axial pressures upon the body. As long as pulses are sustained across the electrodes, the valve 96a shifts in the cadence of these pulses between positions II and III to synchronously apply both axial and radial impulsive pressure to the mass. When the electrodes are disconnected, coil 96g shifts valve 96a into its position I to relieve the pressure within chamber 95. The timer 96j permits the rate of pressure build up in chamber 95 and the ultimate level of this pressure to be adjusted or to be established in accordance with a predetermined program.

In FIG. 10, we show another servomechanism using some of the principles previously described. In this embodiment, the electrodes 102a and 102b are composed of graphite and are axially shiftable in the housing 101 by a pair of pistons 102c and 102d whose cylinders are represented at 102e and 102f, respectively. The pulsating power supply for spark sintering is connected across the electrodes 108 while pressurization of the outer chamber 105 is carried out via a throttle valve 106c and a check valve 106d from the pump 106 whose electromagnetic control valve is represented at 106a. A porous cylinder 104c is disposed within the chamber 105 to physically support the elastomeric membrane 104a and 104b surrounding the powder mass 100. In this apparatus, a high-initial pressure is sustained and an accumulator is provided to permit the liquid to follow the shrinkage of the particle mass under pressure. The accumulator 108d is connected via a valve 108f (operated by timer 106g) with the chamber 105, a cut-off valve 108f' being provided in the feed line for accumulator 108d. From the pump 106, fluid may be supplied under pressure to a conventional intensifier accumulator 108e by way of a check valve 108c which is shunted by pressure-relief valve 108b. The intensifying accumulator may be of the type described in "Fluid Power" (supra). A pressure-relief valve 106f shunts check valve 106d.

During the initial stages of sintering, valves 106a, 108f and 108f' and 106c are open to permit circulation of fluid through the chamber 105 but to maintain high axial and radial pressure upon the powder mass 100 between the electrodes. Spark sintering is then carried out with shrinkage of the mass 100, this shrinkage being followed by the fluid-chamber 105 as supplied by the accumulator 108d. Upon termination of the shrinkage-following stage, a final high pressure is applied by opening valve 108f' closing valve 108f and valve 106c via the timer

106g. Otherwise, the apparatus functions in the manner previously described.

In accordance with still another aspect of this invention, certain aspects of which have been described above, we provide a force-transmitting pulverulent mass between the membrane and the body to be sintered, this mass advantageously consisting of particles of low bondability. The concept of "low bondability" depends, of course, upon the operational parameters of the system although graphite and other carbon powders have been found most satisfactory for the present purposes. Note also that by the use of the combination formed by the membrane in conjunction with electrical sintering (preferably with a spark discharge carried out throughout this compartment) and a force-transmitting powder medium, it is possible to simultaneously sinter a multiplicity of bodies and to sinter bodies of different configurations in a single operation. Furthermore, the system also permits the use of the force-transmitting medium as a powder mold in which the sinter powder is given its shape and constitutes a porous body which permits gases evolved in the sintering operation to diffuse away from the body formed in the sintering step. According to another feature of this invention, particularly applicable in a system in which a plurality of bodies is formed simultaneously, the electrical supply is a polyphase alternating-current source and has n -phases while $n \times m$ electrodes are provided in spaced-apart relationship around the bodies to be sintered and in engagement with the force-transmitting electrically conductive mass. Each group of m electrodes thus constitutes a set connected to one phase of the source so that between each two sets of electrodes, a sinusoidal wave may be applied across the respective zone of the sintering chamber, the waves being out of phase with one another.

FIG. 11 diagrammatically shows an apparatus in accordance with this aspect of the invention. The apparatus comprises a housing 111 whose chamber 115 is supplied with the pressurizing fluid via inlets 116b from a pump 116 and a reservoir 116c. A two-part membrane 114 is disposed within the housing 111 and defines the sintering space 113 which is filled with a force-transmitting powder (graphite) represented at 110'. Within this porous body of loosely packed powder, there are dispersed a plurality of green-packed bodies 110 to be sintered, the green-packed bodies being composed of tungsten carbide, beryllium, aluminum, magnesium, aluminum oxide, silicon dioxide or boron carbide powder. An electrode arrangement for the system of FIG. 11 is represented in FIG. 11A where the mass 110' of force-transmitting particles and the bodies 110 are received between three spaced-apart electrodes 112a, 112b and 112c connected respectively to the output terminal 112d, 112e and 112f of a three-phase transformer represented at T. The input side of this transformer may be connected to any three-phase line. Instead of a transformer, the source may be a three-phase generator. Thus, a sinusoidal resistance-heating current will be applied between electrodes 112a and 112b, between electrodes 112b and 112c and between electrodes 112c and 112a, all three current flows being out of phase with one another by about 120°. In place of green compacts, it is possible to constitute the sinter powder bodies 110 in situ as represented in FIGS. 11C - 11F. Thus, the force-transmitting powder 110' is placed in a receptacle 110a to form an initial layer which, via a piston 110b (FIG. 11D) is compressed. The piston 110b has pattern formations 110c which produce cavities 110d in the layer of powder previously formed. From a vessel 110e containing the sinter powder 110f, the latter is deposited in the cavities 110d without compaction and a further layer of powder 110' is built up over the filled cavities (FIG. 11F). The process is repeated until the entire mass is formed and a final compaction renders the mass sufficiently coherent to enable it to be placed in the housing 111. Sintering is carried out with the system in the manner previously described and, as can be seen from FIG. 11B, the bodies 110 are released by abrading the lightly coherent force-transmitting powder 110' with a grater, rasp or similar tool 110g. The powder 110' can, of course, be reused.

In FIGS. 12 and 12A, we show a further modification of this basic system wherein the housing 121 forms a plenum chamber 125 surrounding the membrane 124 and adapted to be filled with the pressurizing liquid delivered by a pump 126. A pair of electrodes 122a and 122b are imbedded in a conductive mass of force-transmitting powder 120' (e.g. graphite) surrounding the green-compacted body 120 of conductive or nonconductive powder. To prevent terminal distortion of the membrane 124, we provide a further layer 120'' of force-transmitting powder around the powder mass 120' and between the layer and the membrane, the powder 120'' being of low-terminal conductivity and high refractivity (e.g. asbestos). Sintering is carried out by passing an electric current through the mass 120' to generate heat sufficient to bond the particles of the body 120 and sinter same. Gases released in the sintering process diffuse through the porous masses 120' and 120'' while the latter layer prevents deterioration of the membrane 124. External pressure is supplied isostatically by the fluid in chamber 125. The same principles may be applied in the welding of a pair of rods 132a, 132b together via a bonding layer 130 of sinterable particles. A welding system of this nature has been broadly described in the Kiyoshi Inoue application Ser. No. 652,561. Problems in degassing and nonuniform pressure have characterized earlier systems and can be removed by sintering the layer 130 with a substantially spherical layer 130' of porous force-transmitting particles (e.g. graphite) less capable of bonding to the rod 132a and 132b. An outer porous layer 132'' of particles of lower thermal conductivity are disposed between the mass 130' and the rubber membrane 134 which is isostatically compressed inwardly by a pressurizing fluid supplied to the surrounding chamber 135 in the casing 131. The refractory powder 130'' may be magnesium oxide or aluminum oxide. A resistance-welding source may be connected across the terminals 132c while a pump 136 supplies the fluid under pressure as previously described.

A further feature of this invention resides in the provision of a magnetic field across the powder mass to be sintered in order to orient the particles and, if desired, form a permanent magnet of high-energy product (see FIG. 15 and Example VI). In this embodiment, the magnetic field is supplied by a pair of oppositely wound coils 149a and 149b surrounding the magnetically permeable electrodes 142a and 142b which retain a body of magnetic material 140 between them. The electrodes 142a and 142b may be threaded into the housing 141 and can serve to electrically sinter the body 140 in situ by the systems previously described under the pressure applied to the membranes 144a and 144b by a liquid delivered to pump 145 under the pressure of pump 146. Alternatively, the members 142a and 142b may merely hold the body 140 for the concurrent application of high semi-isostatic pressure and magnetic field. In the latter case, the body may be formed as described in connection with FIG. 2. The coils 142a and 142b are energized by an adjustable DC source 149c in series with an ammeter 149d.

In FIG. 17, we show a device for making a motor stator (Example VII) wherein a pair of electrodes 172a and 172b have annular faces 172a' and 172b' bearing upon a cylindrical mass of iron particles 170 in an annular compartment 173 between an outer membrane 174a and an inner membrane 174b which define plenum chambers within the housing 171 to which fluid is supplied from the pump 176 via a valve 176a and 176b. An electrical sintering source is connected to the electrodes at 172. The stator coils are imbedded in the motor winding as shown at 170'. Similar systems may be used for forming the armature of the motor.

The following Examples represent the best mode known to us for carrying out the various aspects of the present invention in practice.

EXAMPLE I

In a silicone-rubber mold (FIG. 2) having an internal diameter of 5 mm., a thickness of 1.5 mm. and a length of 10 mm.,

94 percent by weight of tungsten carbide and 6 percent by weight of cobalt powder were placed, the powder having a particle size of 2 - 3 microns. The internal diameter of the cylindrical vessel 21 was 10 mm. and the rubber membrane was centrally located. The sintering power was an alternating current (30 percent) superimposed upon direct current (70 percent), the alternating current having a frequency of 1 kilocycle/second. The electrodes 22a and 22b were composed of graphite, the initial pressure of the fluid was 3 to 30 kg./cm.², resistive heating was carried out for 1.2 seconds and the pressure chamber 25 was then raised to 2,000 kg./cm.². The density of the sintered body was found to be 99.98 percent of the solid density. Densities of 99 percent or above could not be economically made by other electrical sintering processes.

EXAMPLE IIa

Using the apparatus illustrated in FIG. 10, 100 mesh aluminum powder (100 g.) were formed into a rod having a diameter of 15 mm. and a length of 200 mm. by spark-discharge sintering at a DC applied voltage of 3 - 10 volts. The initial pressure was 300 kg./cm.² and with shrinkage of the mass followed by expansion in the accumulator, the final pressure was 100 kg./cm.². In FIG. 16, in which electrical energy consumption is plotted along the ordinate in kilojoules, the pressure required for a density in excess of 99 percent is plotted along the abscissa in tons/cm.², this high-initial pressure being permitted to lower with shrinkage of the mass during sintering the resulting aluminum body at a tensile strength of 78 kg./cm.² and an elongation (at break) of 10.2 %.

EXAMPLE IIb

Using the same apparatus aluminum powder of Example IIa, it was possible to make an aluminum with unusually high resistivity using a DC current flow for 3 seconds at 2.5 volts of 300 amp. under the conditions represented by the broken line A of FIG. 16, the resistivity of the body being represented along the right-hand abscissa in ohm-cm. The current was terminated for a period of 3 seconds, permitted to flow for 3 seconds, and cycled in this manner. The aluminum body had the same dimensions as the body of Example IIa and a density of 99.6 percent of solid aluminum density. At initial pressures between 1 and 3 tons/cm.², it was possible to increase the resistivity of the body at least tenfold.

EXAMPLE IIc

Using the apparatus and technique of Example IIa, 330 g. of 100 mesh copper powder was sintered into a rod of 15 mm. diameter and 200 mm. length. The operating parameters in terms of electrical energy consumption and pressure were plotted in FIG. 16 for the copper curve and the resulting body at a density of more than 99 percent solid copper density. Otherwise the same parameters were used as in Example IIa.

EXAMPLE III

Using the device illustrated in FIG. 4, 400 g. of 150 mesh copper was subjected to an initial pressure of 4 tons/cm.² by the rubber membrane. A low-melting-point rubber constituted the membrane. Impulsive discharges with an energy of 20 kilojoules were supplied at the electrodes with pulse widths of 0.1 micronseconds to 1 second. A discharge at capacitor 48d was carried out with 200,000 mfd. capacity. The density of the resulting body was 8.82.

EXAMPLE IV

Using the apparatus of FIG. 6, ultrasonic vibrations with a power of 500 watts and a frequency of 18 kHz. was applied to the fluid in chamber 65 which was maintained at a static pressure of 3,000 kg./cm.². The particles were carbon black and they were shaped to a cylinder of 5 mm. diameter and 10 mm. length. To test the effectiveness of the compaction, three samples were used as follows:

Sample A was merely cold-pressed in a rubber mold using the apparatus of FIG. 6 without ultrasonic vibration or shock impulse;

Sample B was formed as in sample A with superimposition of 500 watts 18 kHz. ultrasonic vibrations;

Sample C was formed as sample A with superimposition of 10 shock-wave pulses at 5,000 joules.

All three samples were subjected to furnace sintering at a temperature sufficient to yield a resistivity of 2,100 microhm-cm. The temperature required for sintering sample A was 1,100° C. and yielded a body with a density of 1.62, the temperature required for sintering sample B was 580° C. and yielded a body with a density of 1.8 and the temperature required for sintering the sample C was 410° C. and yielded a body with a density of 1.88. When spark sintering was used (Example II), less power was required by approximately corresponding amounts and substantially higher densities were obtained.

EXAMPLE V

Using a rubber mold with a diameter of 12 mm. and a length of 150 mm., titanium powder of 99.99 percent purity was cold-pressed. Under a pressure of 200 kg./cm.², applied by fluid, the titanium powder was subjected to spark and resistance sintering at 5 volts DC (4,000 amp.) upon which 6 volts AC (1 kHz. at 500 amp.) is superposed. The process was carried out under two separate sets of conditions, condition A being a continuous increase in the pressure to 1,600 kg./cm.² during sintering with both current flow and pressure increase terminating after 6.5 seconds. The body resulting from this procedure had a tensile strength of 67 kg./cm.² and an elongation at break of 14 percent. Condition B corresponded except that the higher pressure was maintained until the body had cooled to 180° C. This body has a tensile strength of 78 kg./cm.² and an elongation at break of 26 percent. The procedure of condition B was also found to be suitable for beryllium of 99.8 percent purity and it has also been observed that best results are obtained when the body is permitted to cool to a temperature at least 100° C. below the melting point before the terminal pressure is cooled off. When beryllium and tungsten powders are used, it is desired to increase the pressure in steps with the period between steps being equal substantially to the duration of the steps. For aluminum and nickel powder continuous pressure increase is preferred.

EXAMPLE VI

A magnetic body is formed by spark sintering and is subjected to high-pressure treatment in the device of FIG. 14 under fluid pressure. The body is composed of equal parts by weight platinum and cobalt. In FIG. 15, we have plotted the maximum energy product of the body along the ordinate against the applied pressure along the abscissa, the latter being a logarithmic plot.

EXAMPLE VII

A motor stator was produced by the device of FIG. 17 using a 100 mesh iron powder and a pressure of 1,500 kg./cm.² in both the inner and outer chambers. The sintering current flow was 550 amp/cm². The iron-powder body had a resistivity of 3.4×10⁻⁸ ohm/cm., an eddy current loss less than one-tenth that of conventional iron cores and mechanical properties similar to those of solid iron. The iron powder was a silicon steel, sintering was carried out for a period of 10 seconds and the particles size was 0.3 mm. The temperature rise of the stator, operated at 20° C. for a period of 3 hours, was 22° C. for the stator of the present invention and 65° C. for a conventional motor stator used solid steel of the same composition.

The invention described and illustrated is believed to admit of many modifications within the ability of persons skilled in the art, all such modifications being considered within the spirit and scope of the appended claims.

We claim:

1. A method of sintering a mass of particles, comprising the steps of enclosing said mass in a chamber formed at least in part by a membrane of flexible material; passing an electric current through said chamber of an intensity sufficient to initiate spark discharge in said mass and to fuse the particles of said mass together with shrinkage thereof; applying a liquid pressure of about 10 kg./cm.² to 20 tons/cm.² to the mass through said membrane to compact said mass during the passage of electric current therethrough, said pressure being at least sufficient to force said membrane to follow the shrinkage of the mass.

2. The method defined in claim 1 wherein a relatively high-liquid pressure of substantially 1 to 20 tons/cm.² is applied to said membrane during initial passage of electric current through said chamber and the pressure is reduced to a relatively low pressure of substantially 10 to several hundred kg./cm.² during subsequent passage of electric current through said chamber.

3. The method defined in claim 1 wherein a relatively low-initial pressure of substantially 10 to several hundred kg./cm.² is applied by said liquid to said membrane and said mass during initial passage of said electric current through said chamber and the pressure is increased to a relatively high pressure of substantially 1 to 20 tons/cm.² during subsequent passage of electric current through the chamber.

4. The method defined in claim 3 wherein said mass is heated by the passage of electric current through said chamber and the relatively high pressure subsequently applied to said mass is sustained during cooling of the mass.

5. The method defined in claim 1, further comprising the step of pulsing the pressure of the liquid for transmission of pressure pulses by said membrane to said mass by applying ultrasonic vibrations transmitted through said liquid to said membrane.

6. The method defined in claim 1, further comprises the step of pulsing the pressure of the liquid for transmission of pressure pulses by said membrane to said mass by effecting spark discharge in said liquid.

7. The method defined in claim 1, further comprising the step of pulsing the pressure of the liquid for transmission of pressure pulses by said membrane to said mass by storing liquid under pressure and intermittently releasing stored pressure into the liquid acting upon said membrane.

8. The method defined in claim 1 wherein said electric current is passed through said chamber in surges, further comprising the step of pulsing the pressure of the liquid for transmission of pressure pulses by said membrane to said mass in the cadence of said current surges.

9. The method defined in claim 1, further comprising the step of imbedding in said mass an elongated element in the form of a refractory filament retained in the mass as a reinforcing member subsequent to sintering.

10. The method defined in claim 1, further comprising the step of imbedding in said mass an elongated element in the form of a conductor, at least part of the electric current traversing said chamber passing through said element.

11. The method defined in claim 10 wherein said element is fusible and is explosively disintegrated by the passage of electric current therethrough to apply an internal shock wave to said mass.

12. The method defined in claim 10 wherein said element is a heating wave generating heat upon passage of electric current therethrough to facilitate bonding of the particle mass.

13. The method defined in claim 1, further comprising the step of disposing a porous layer of refractory material between said mass and said membrane, said layer constituting a force-transmitting medium transferring the liquid pressure on said membrane to said mass.

14. The method defined in claim 13 wherein said porous layer is composed of electrically conductive particles of lesser cohesiveness than said mass.

15. The method defined in claim 13 wherein said porous layer is composed of carbon particles.

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16. The method defined in claim 15, further comprising a refractory layer of nonconductive particles surrounding said layer of carbon particles.

17. The method defined in claim 13 wherein said mass of particles is disposed between a pair of metallic members bondable thereto, said members being welded together via said mass by said electric current.

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18. The method defined in claim 13 wherein said mass is green-compacted prior to being surrounded by said porous layer.

19. The method defined in claim 13 wherein said porous layer forms a mold imparting shape to said mass.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTIONPatent No. 3,656,946 Dated April 18, 1972Inventor(s) Kioshi INOUE et al

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the cover page, change the name of the inventors at line 2 to read -- INOUE et al -- ;

In line 72, identifying the inventors, read the surname of the first inventor as -- Inoue -- ;

Signed and sealed this 19th day of February 1974.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents

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