United States Patent

Inoue

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[54] KINETIC DEPOSITION OF PARTICULATE MATERIALS

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Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 574,056, Aug. 22, 1966, Pat. No. 3,416,617, and a continuation-in-part of 629,633, Apr. 10, 1967, Pat. No. 3,461,268, and a continuation-in-part of 696,757, Jan. 10, 1968, Pat. No. 3,552,653.

[52] **U.S. Cl.** **29/421,** 72/56

[51] **Int. Cl.** **B21d 26/12**

[58] **Field of Search** ..... 29/421 E, 421; 228/6; 72/56

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[57] **ABSTRACT**

Method of high-energy-rate deposition of particulate materials upon a receiving surface whereby the particles are propelled against the receiving surface with sufficiently high kinetic energy to effect bonding between the particles and the surface. The high-kinetic-energy propulsion of the particles is effected by impulsive spark discharge. Apparatus for the repeated propulsion of unit masses of such particles whereby a belt having a series of encapsulated particle masses is passed intermittently between the discharge source and surface, the belt forming one of the discharge electrodes.

6 Claims, 13 Drawing Figures

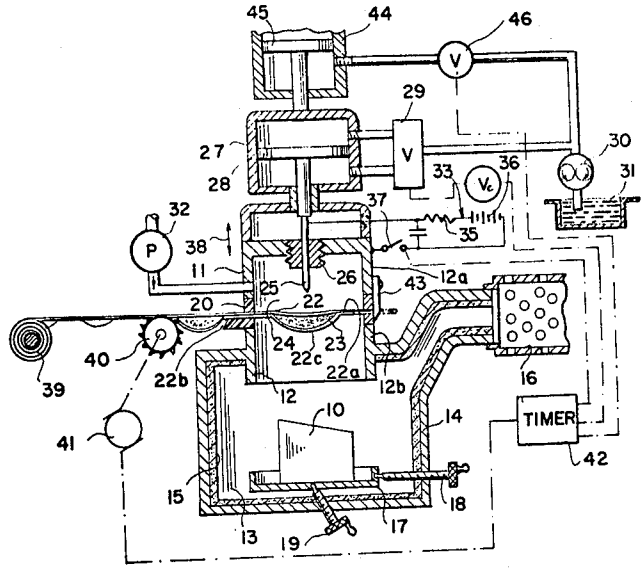


FIG. 1

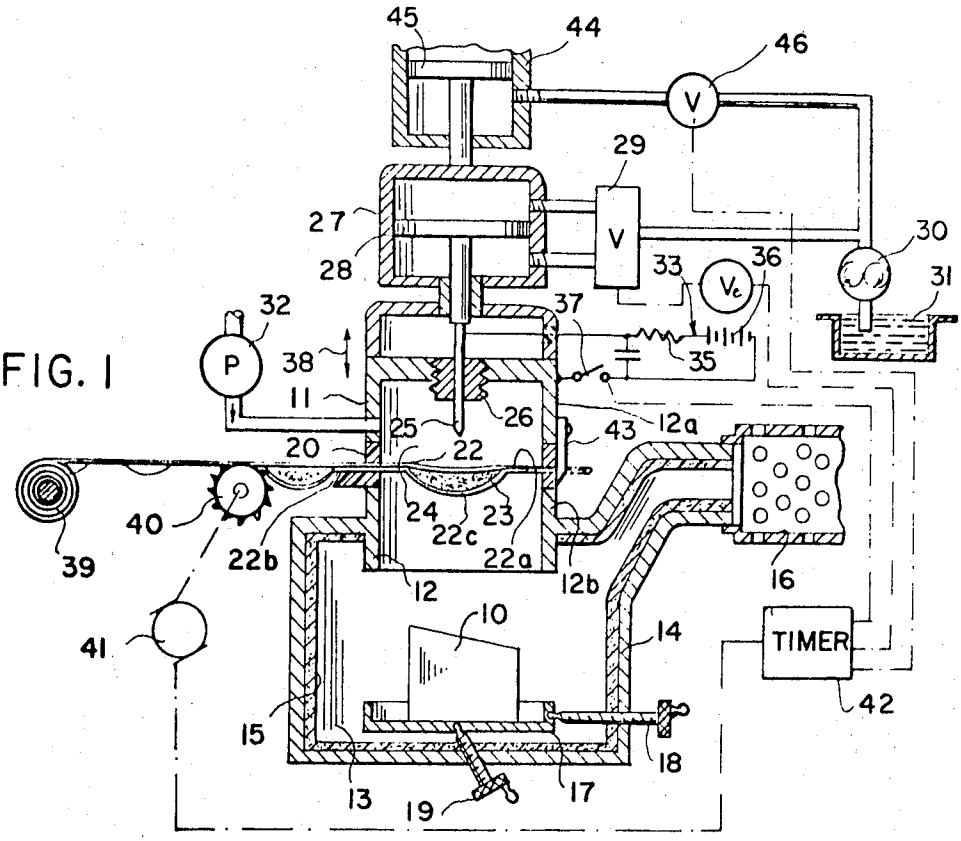
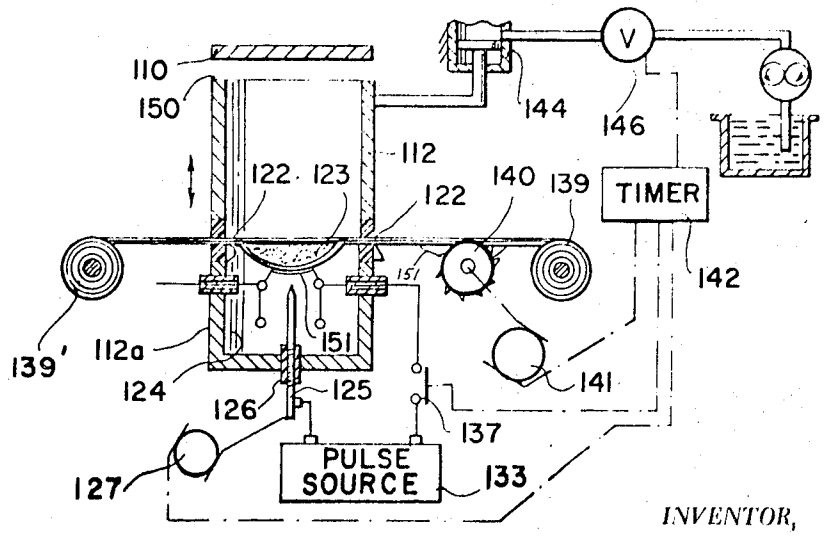


FIG. 2



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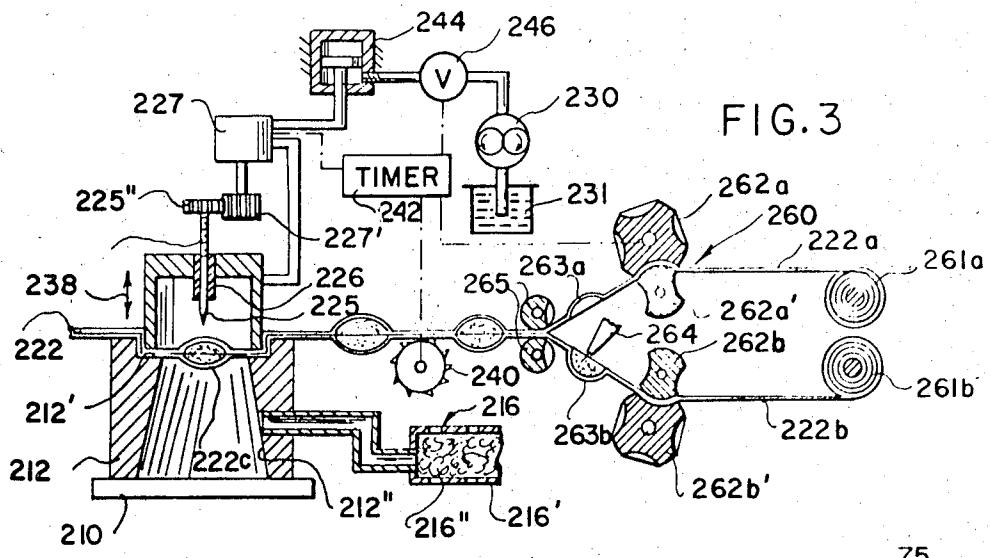


FIG. 3

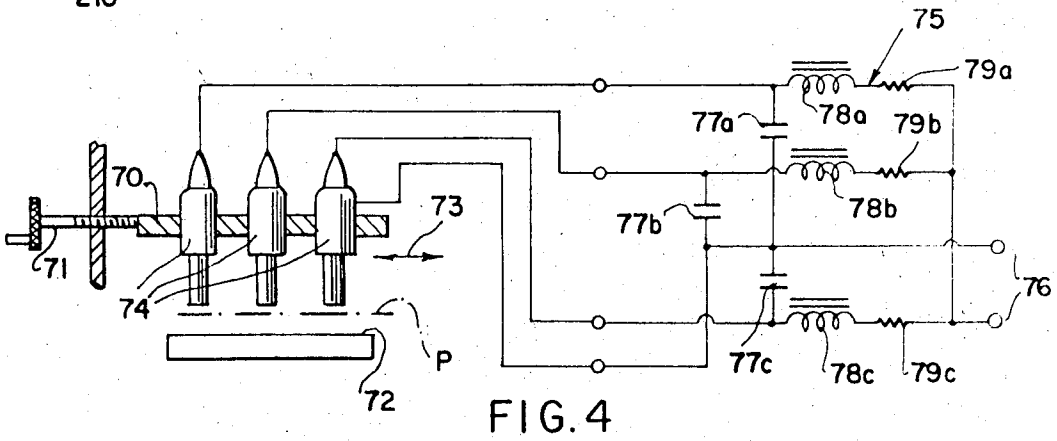


FIG. 4



FIG. 5

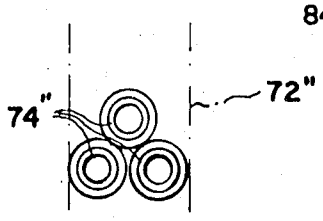


FIG. 6

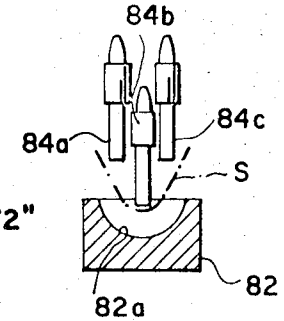


FIG. 7

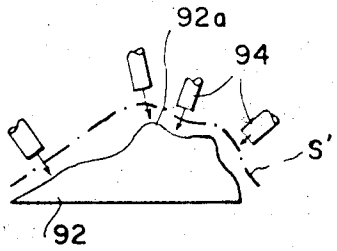


FIG. 8

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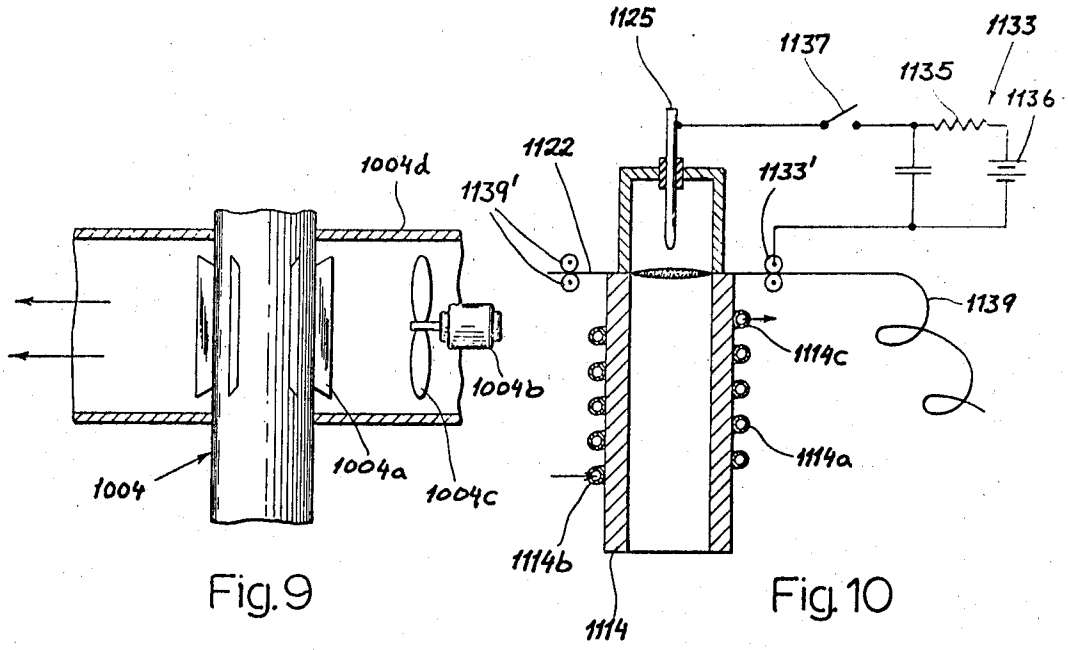


Fig. 9

Fig. 10

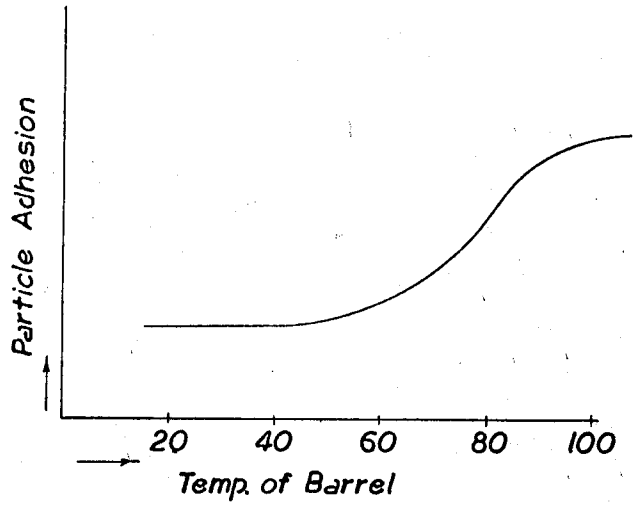
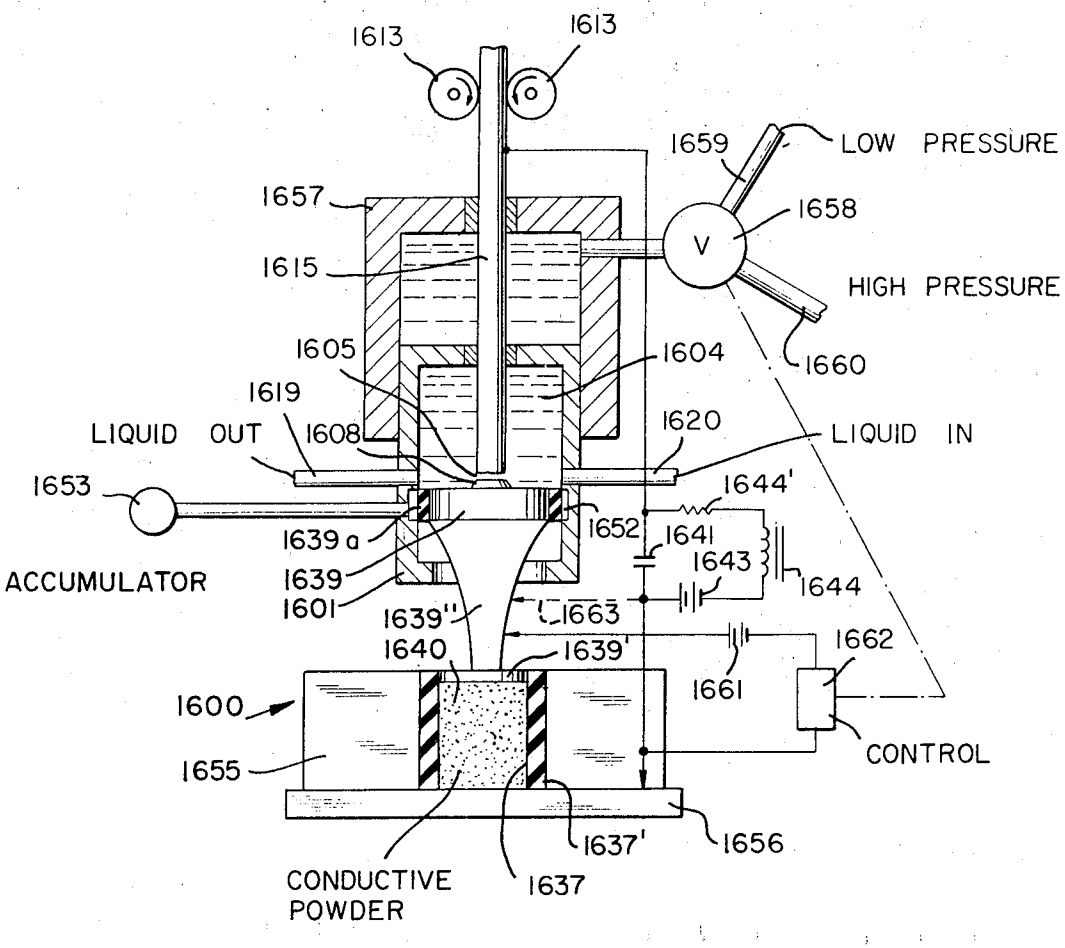


Fig. 11

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FIG. 12

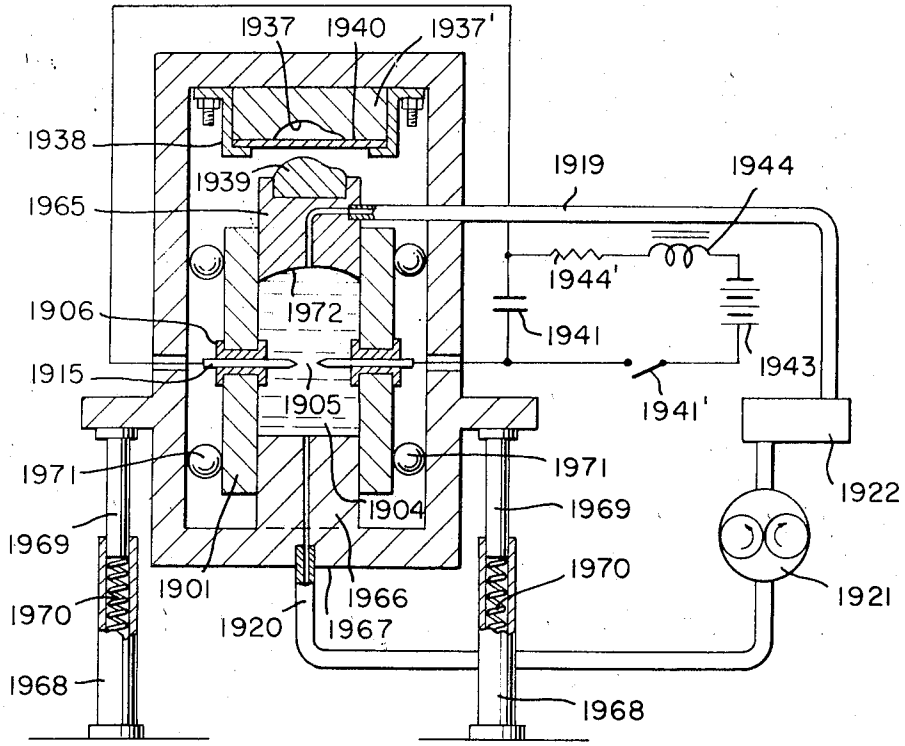


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FIG. 13



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KINETIC DEPOSITION OF PARTICULATE MATERIALS

This application is a continuation-in-part of my copending applications Ser. No. 574,056 filed 22 Aug. 1966, now U.S. Pat. No. 3,416,617, Ser. No. 629,633 filed 10 Apr. 1967, now U.S. Pat. No. 3,461,268, and Ser. No. 696,757 filed 10 Jan. 1968, now U.S. Pat. No. 3,552,653.

In my application, Ser. No. 574,056, which is a continuation-in-part of application, Ser. No. 311,061, now U.S. Pat. No. 3,267,710, and application Ser. No. 508,487 filed 18 Nov. 1965, now U.S. Pat. No. 3,512,384, as a continuation-in-part of application, Ser. No. 41,080 (now U.S. Pat. No. 3,232,085), I have pointed out that metallic substrates and other surfaces may be coated with surface layers of a pulverulent material in a convenient economical and satisfactory manner when a source of detonation-type impulsive wave is juxtaposed with a surface of the body to be coated and between this body and the source, a mass of pulverulent material is placed (preferably in proximity to the detonation source).

The pulverulent material can have a hardness greater than that of the substrate and may even be nonbondable thereto by conventional methods. The detonation-type wave described in that application was generated by a impulsive, intermittent spark discharge and apparently projected the particles onto the substrate with a velocity and kinetic energy sufficient to overcome the rebound tendency at the surface and cause the particles to lodge thereon with a firm bond to the substrate.

The technique is particularly advantageous when applied to the bonding of particles of a hard-facing material (e.g., tungsten-carbide) or hard-alloy steels to metallic, synthetic-resin or like substrates.

In the last-mentioned application, a particularly advantageous system was described wherein the particulate material was a layer of powder disposed upon or in a frangible foil, film or sleeve juxtaposed with the surface to be coated and forming a rupturable diaphragm retaining the particle layer and separating a discharge chamber from the workpiece chamber or propulsion path. The latter chambers vented to the atmosphere via a sound-damping muffler to prevent the development of substantial outward pressure within the workpiece chamber which might resist the high-velocity movement of the particles as well as to destroy the violent sound wave which such discharges have a tendency to generate.

The use of a frangible diaphragm to retain the particles in this manner facilitates the uniform deposition of the particles upon the surface, especially when the diaphragm is generally parallel to the surface of the substrate to be coated or conforms to the latter. Moreover, the diaphragm constituted the counterelectrode for the spark-discharge system forming the detonation source. The other discharge electrode was a needle spaced from and perpendicular to the frangible diaphragm. The apparatus preferably made use of a discharge chamber in the form of a "gun" or shock tube whose barrel was trained upon the workpiece and received, at an intermediate location therealong, a mass of particles which were propelled against the surface of the substrate upon triggering of a spark-type discharge at the closed end of the barrel. In the horizontal position of the barrel, the particles were introduced substantially continuously, i.e., as a cloud at least partly suspended by the gaseous environment within the barrel, between the discharge chamber and its mouth while a train of pulses was supplied in across the electrodes so that the resulting sequence of discharges imparted intermittent but repeated high-energy-rate forces to the particles and impelled them toward and against the workpiece surface. In upright positions of the barrel. I provided frangible, foil-type diaphragms as supports for the pulverulent material, the latter merely resisting upon the diaphragm. The needle electrode was constituted of aluminum, zirconium, magnesium or copper, (in this order of preference) since these materials appeared to impart greater kinetic energy to the particles when used as discharge electrodes. Correspondingly, foils of aluminum, zirconium, magnesium, copper and nickel have been found to be effective as counterelectrodes.

It was also pointed out there that means can be provided to heat the particles to temperatures less than their fusion point but relatively elevated by comparison with ambient temperature and, if possible, above the softening temperature of the substrate, thereby ensuring the improved bond between the coating material and the substrate. The heating means there described provided for the passage of a heating current through the mass of particles in advance of the discharge, the use of externally operable electric heating means, the mixing with the particles of a reducing agent capable of promoting an oxidation-reduction reaction with the particles during the impulsive propagation of the mass in the direction of the substrate. It was found that the incorporation of a reduction-oxidation reaction system in the particulate mass was highly effective, since the reactants tend to remain in the quiescent state until the generation of a spark discharge; the quiescent state terminates very shortly after the discharge and the heating reaction is initiated slightly before or concurrently with acceleration of the particles and their dispersion so that they are heated without significant interparticle fusion.

In both of the parent applications of my Ser. No. 696,757 filed 10 Jan. 1968, now U.S. Pat. No. 3,552,653 I have emphasized the fact that a surprisingly firm and durable bond results from the use of spark generators as the source of impulsive energy. The surprising results apparently derive from the stripping of oxide layers from the surfaces of the particles or the destruction of bond-resistant surface skins thereon and on the workpiece against which the discharge is propagated. Thus, practically all metalic particles having an oxide or other bond-resistant skin limiting interparticle bonding as well as particle-to-substrate adhesion can be joined together by the high-energy-rate process in which a spark-type detonation source not only propels the particles in the direction of the substrate but also appears to eliminate the oxide layers and to pierce the bond-resistant surface skins.

In the aforementioned application, Ser. No. 311,061 issued 23 Aug. 1966 as U.S. Pat. No. 3,267,710, I have described an arrangement wherein the impulsive spark pressure of a discharge in a liquid is exploited to bond a mass of particles together and to shape the mass with or without bonding the same to a substrate. The spark pressure generating the shock wave in the liquid medium is supplemented by electrical discharge through the powder. This application, in turn, extends principles originally disclosed in my application, Ser. No. 247,387 of 26 Dec. 1962, since issued as Pat. No. 3,250,892. An apparatus for the simultaneous bonding and shaping of materials of this type can include a fluid receptacle in which a pair of electrodes are adapted to sustain a spark discharge. The force transmission takes place in this system via a piston or plunger which applies its energy to the powder as indicated.

It is thus an important object of the present invention to provide an improved system for the bonding and shaping of materials which extends principles already described in the aforementioned copending applications, and their parent applications.

Various methods of initiating the discharge can be employed according to my prior discoveries in connection with deposition with high kinetic energies, the preferred method involving changes in the electrical parameters of the discharge system. Thus, the needle electrode can be advanced toward the foil to reduce the wheel of the discharge gap and, effectively, reduce the voltage needed for breakdown thereof. In this system, an external pulse source is not required for the generator and the discharge capacitor may merely be charged to a potential which is sufficient, upon advance of the needle, to effect breakdown in the gap when the desired width is attained.

Alternatively, or in addition, the ionization condition within the discharge compartment may be simply modified to reduce the potential required for breakdown in the gap. This may be done by directing a stream of compressed air into the chamber to produce a cloud of conductive particles, or by evacuating the region of the gap to lower the breakdown potential.

The system can be used to deposit tantalum or titanium upon an aluminum foil to form capacitor plates, to deposit gold or aluminum upon a silicon wafer to form semiconductive components, and to deposit lead sulfide or cadmium sulfide upon conductive or semiconductive substrates to produce photoconductive cells.

Another main object of the present invention, therefore, is to provide a method of kinetic deposition of particles and the coating of substrates, which represents an improvement over and an extension of the principles of my above-mentioned copending applications and the patents issuing thereon.

A more specific object of this invention is to provide an improved method for the impulsive coating of various substrates whereby the character of the bond formed between the coating and the substrate is improved, the energy efficiency (in terms of quantity of coating material bonded per unit of energy consumption) is increased, and greater control over the deposition process and the nature of the deposit can be obtained.

Another object of this invention is to provide an improved technique for the coating of substrates with particulate material at high energies, whereby the apparatus is rendered less complex, a higher deposition rate can be obtained, and the system employed for coating surfaces at various locations.

Yet another object of the present invention is to provide an improved method of for the high-energy-rate deposition of particulate material on relatively complex contoured surfaces.

I have observed that, when the particulate material is to be applied to the substrates by a high-energy-rate deposition apparatus or gun, according to the invention, there is frequently a loss of efficiency and control by virtue of the fact that the particulate materials often are dispersed by the shock wave prior to rupture of the foil. Consequently, the particles may be dispersed within the shock-generating chamber and be partly propelled in directions other than that which is intended. To avoid this disadvantage, and to increase the rate at which the shock-wave chamber can be supplied with the particulate material and the reproducibility of such supply, I advantageously provide a foil with a multiplicity of pockets, each enclosing a predetermined quantity of the particulate material, the pockets being successively aligned with the shock-wave generator and supplied to the latter in the form of a belt.

According to a further feature of this invention, the particulate material is pocketed between a pair of metallic foils which thus form a laminate as well as counterelectrodes for juxtaposition with a needle electrode. The apparatus thus may be provided with a barrel portion and a shock-wave generator portion, these portions being separable to receive the pocketed foil between them. Advantageously, the portions are provided at their junction with sealing means cooperating with the foil so that the latter simultaneously forms a pressure-retaining and self-locking sealing joint.

I have found further that it is advantageous to employ as the pocketing foil or foils, one or more materials which are intended to be found subsequently upon the coated surface. It is particularly desirable to use for the foil material a substance which is readily bondable both to the particles and to the substrate inasmuch as a substantial portion of this foil is present at the interface between the particles and the substrate.

For example, it has been found to be advantageous to employ a nickel foil when tungsten carbide or like hard-facing material is to be bonded to steel or the like. It appears that the nickel acts as a bonding layer between particles of the hard-facing material and of the substrate and derives from the foil originally employed to retain the particles. While loose masses of such particles have been proposed as being retained within a pair of foil layers in respective pockets, it is also conceivable to lightly sinter or adhesively bond respective masses of particles in molded masses along a continuous foil and to the latter. The interparticle bond should, of course, have as little strength as possible so as to conserve the shock-wave energy and utilize the maximum energy for implanting the particles in the substrate.

Accordingly to a further feature of this invention, a contoured cavity or other surface is coated with particulate materials by juxtaposing with this surface an array of shock tubes or guns, extending transversely to the surface regions confronting them, but oriented so that their mouths define a surface generally parallel to that of the workpiece.

The invention also involves a method of cladding and shaping a member whereby a member to be clad is supported adjacent a shaping means of predetermined shape. A cladding material is disposed on the surface of the member to be clad and a working fluid medium is provided above the cladding material. Using the principles set forth above, an intense pressure is generated in the fluid medium against the cladding material at sufficient intensity to cause a cladding material to become molecularly bonded to the surface of the member, while simultaneously the cladding material and member are deformed to a predetermined shape. The method also applies to the use of metal as the member to be clad and a system wherein the cladding material is a particulate material. Of course, the intense fluid pressure is constituted by a shock wave which is directed against material disposed on the member to effect the cladding of the member as it is simultaneously deformed to its predetermined shape.

Applying the principles of this concept to the systems previously described, it will be evident that a particulate material disposed on a substrate within a mold has at least a lower layer, which can be considered a member to be clad, supported adjacent a shaping means of predetermined shape. Upper particles on the mass are then a cladding material disposed on the surface of the member to be clad. When a piston, plunger, membrane or other force-transmitting member is disposed between a fluid in which a shock wave can be generated and the cladding material, in force-transmitting relationship therewith, a working fluid medium is provided above the cladding material within the purview of the presently disclosed subject matter. An electrical discharge in the medium of sufficient intensity to bond the mass together causes the cladding material to be molecularly bonded to the member and simultaneously imparts the desired shape to the cladding material and member to be deformed.

The system also includes an arrangement whereby a metal plate is cladded and simultaneously worked with its cladding to deform same to a predetermined shape. In this system, a metal plate member to be clad ans shaped is supported with one surface thereof in alignment or registry with a forming die of predetermined shape. A cladding material is disposed against the other surface of this metal plate and a shock wave is generated and directed against the cladding material at sufficient intensity to cause said cladding material to become molecularly bonded to the surface of the plate and to simultaneously deform and change the shape of the cladding material and plate to conform to the predetermined shaft as defined by the shape of the die.

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

FIG. 1 is a diagrammatic cross-sectional view illustrating an apparatus for the coating of surfaces according to the present invention;

FIG. 2 is an axial cross-sectional view of another embodiment of a coating apparatus according to this invention;

FIG. 3 is a view generally similar to FIG. 1 of a system wherein the doses of particles may be formed concurrently with the coating;

FIG. 4 is a diagrammatic elevational view, with accompanying circuit diagram, of an apparatus for uniformly coating relatively broad flat surfaces according to this invention;

FIG. 5 is an elevational view of a multitube array of the type shown in FIG. 4;

FIG. 6 is a view similar to FIG. 5 of another array;

FIG. 7 is an elevational view in diagrammatic form of a system for the coating of a convex surface;

FIG. 8 is a diagram illustrating a further modification of an apparatus for coating convex surfaces of complex configuration;

FIG. 9 is an enlarged detail view, partly in cross section, of the cooling means for an impact deposition barrel according to an aspect of this invention;

FIG. 10 is a diagrammatic cross-sectional view of another apparatus for practicing this invention using other cooling means;

FIG. 11 is a graph showing the relationship between barrel temperature and particle adhesion to the barrel;

FIG. 12 is a diagrammatic axial cross-sectional view of an apparatus for the simultaneous compression and spark sintering of a conductive powder; and

FIG. 13 is a cross-sectional view showing another system according to this invention.

As described in the aforementioned application, Ser. No. 574,056, the basic apparatus for the high-energy-rate coating of a workpiece **10** comprises a shock tube or gun **11** whose barrel **12** extends into a coating chamber **13** of a housing **14**, the coating chamber **13** being lined with a sound-damping elastomeric material **15** such as foam rubber. The chamber **13** is vented through a muffler **16** of the automotive vehicle or internal combustion engine type for limiting the intensity of the sound wave transmitted to the atmosphere. Chamber **13** is, moreover, provided with a crossfeed carriage **17** for the workpiece **10**, designed to position the workpiece **10** selectively in the path of the particles emerging from the barrel **12**. The crossfeed **17** includes spindles **18** and **19** for the longitudinal and transverse displacement of the carriage **17** and the workpiece **10** from locations outside the chamber **14**.

The upper part of the barrel **12** is separable at the insulating seat **21** of the lower barrel portion **12***b*. The foil **22** carrying the particulate material **23** is disposed within, and partly defines, the spark chamber **24** in which the shock wave is generated. For this purpose a needle electrode **25** passes through an insulating bushing **26** and is connected with a pulse-generating electric-current supply network as illustrated only diagrammatically here but as is fully described in the aforementioned application, Ser. No. 574,056. The firing control of the system may be regulated by a hydraulic motor **27** (i.e., a piston-and-cylinder arrangement) whose piston **28** is connected with the electrode needle **25** for hydraulically advancing same toward the foil. A distributing valve **29** in a fluid circuit with the pump **30** and a reservoir **31** provide the necessary regulation of the position of the motor **27**.

Upon the application of a static voltage across the foil **22** and the needle **25**, the latter can be advanced until the gap is so narrow that the potential suffices to break down the gap and a spark discharge bridges same. The discharge results in rupture of the foil diaphragm **22** and the propagation of the particles **23** against the workpiece **10**.

The discharge can also be initiated by a compressed-air source **32** designed to blow a high-velocity stream of air-entrained particles into the chamber **24** to effect the breakdown between the electrode **25** and foil **22** without advance of the needle electrode.

The energizing circuit **33** includes a discharge capacitor **34** connected between the electrode **25** and the housing portion **12***a* which makes electrical contact with the foil **22**. The condenser **34** is charged through a resistor **35** via a battery **36** and may be discharged across the gap via a switch **37**. The latter may represent any electronic breakdown device (e.g., thyratron or solid-state-controlled rectifier) or other switching means capable of sustaining the capacitor potential and current surge. When the hydraulic motor **27** is inactivated and air is not blown into the chamber **24** to initiate discharge, the spark may be produced on closure of this switch **37**.

The separable barrel **12** has its lower portion **12***b* integrally formed or affixed to the housing **14** while the upper portion **12***a* is shiftable in the direction of arrow **38** alternately toward and away from the lower barrel portion **12***b*. In its lower position, the upper barrel portion **12***a* clamps the foil **22** against the bottom barrel portion so that the upper chamber **24** is hermetically sealed and substantially all of the shock-wave energy in this chamber is transmitted axially to the frangible diaphragm **22**. The latter consists of a generally flat upper layer **22***a* and a pocketed lower layer **22***b* in which longitudinally spaced pouches or pockets **22***c* are formed.

When the pockets **22***c* are filled with a pulverulent material **23** to be deposited, the foils are brought together and may be thermally fused (e.g., by welding) or may have their longitudinal edges rolled together to fully retain the respective doses of the particulate material. In this embodiment, the upper layer **22***a* is shown to be concave toward the discharge needle **25** and convex toward the workpiece **10**, although of a radius of curvature substantially greater than that of the pocket **22***c*. The convexity described above appears to promote sufficient transfer of shock-wave energy to the particulate material within the pouch.

The foil **22** is carried upon a supply roll **39** and can be intermittently advanced into the barrel **12**, when the upper barrel **12***a* is raised, by a sprocket **40** whose motor **41** is operated for predetermined intervals by a timer **42**. Thus, when the upper barrel portion **12***a* is raised, the motor **41** and sprocket **40** advance a predetermined length of the foil **22** into the barrel and shift any remnant of the ruptured pocket of the foil out of the system. On the discharge side of the system, the upper barrel portion **12***a* is provided with a blade **43** which severs the damaged portion of the foil from that remaining.

In operation, the upper barrel portion **12***a* is removed, and a workpiece **10** mounted upon the carriage **17** and positioned in axial alignment with the fixed lower barrel portion **12***b* via the spindles **18** and **19**. An initial length of foil **22**, from the supply roll **39**, is placed on the lower barrel portion **12***b* with its convex pocket side turned downward. The upper barrel portion **12***a* is thereupon replaced and the source **33** is reconnected. Timer **42** can thus close switch **37**, while the upper barrel portion **12***a* is clamped tightly against the foil **22** and produces a spark discharge between the needle **25** and the upper foil layer **22***a*. The resulting impulsive wave ruptures, in short order, the upper and lower layers **22***a* and **22***c*, while propelling the particulate material **23** at high velocity and high kinetic energy against the surface of the body **10** to be coated. Thereafter, timer **42** deenergizes the electrode **25** and activates the valve **46** to raise the upper barrel portion **12***a* and cause the sprocket **40** to advance the foil by a corresponding length to receive a successive filled pocket of the foil. It will be understood that, instead of, or in addition to, the switch **37**, the motor **24** or the valve **29** for the air jet may be activated to initiate the breakdown.

In the system of FIG. **2**, the barrel **112**, trained upon the sprocket **110** with a clearance **150** to prevent excess static pressure buildup in the barrel, is provided with feed means including a supply roll **139** for a foil **122** of a conductive or nonconductive material. Pockets **123** are formed in the foil as described with respect to FIG. **1** with longitudinal equispacing. The discharge chamber **124** is formed, at least in part, by a barrel portion **112***a* which can be advanced by a hydraulic motor (see FIG. **1**) or an electric motor as represented at **127**. Here, the pockets **123** can rest upon a basket-shaped counterelectrode **151** just behind the foil **122** and contacting the latter. A bracket electrode of this type is fully described in application, Ser. No. 574,056.

When a current source **133** of the type shown in FIG. **1**, for example, is connected across the needle electrode **125**, which is shiftable in its sleeve **126**, closure of switch **137** will apply a current surge across the gap and effect spark discharge between the needle electrode **126** and the basket electrode **151**. Switch **137** also is controlled by a timer **142** which operated a valve **146** of a hydraulic cylinder **144**. The piston of this cylinder is connected to the upper barrel portion **112***a* so that this member can be raised and lowered to release and clamp the foiled sections **122**. Motor **127** is likewise operated at a cadence determined by the timer **142**. In this system, a sprocket **140** and drive **141**, likewise controlled by timer **142**,

advance the foil **122**, while a takeup roll **121'** collects the ruptured portions of the foil for salvage, if desired. The foils preferably are of a thickness no greater than 0.01 and 0.02 mm.

EXAMPLE I

Using an apparatus of the type illustrated in FIG. **2**, a pocketed foil **122** was formed from a pair of foil layers having a thickness of about 0.006 mm., with the pocket sufficient to enclose 5 grams of a particle mixture per pocket (see FIG. **3**). The mixture was made of equal proportions, by weight, of 300-mesh tungsten carbide and 600-mesh synthetic diamond. The gun **112** was held stationary, while a carbon steel band **110** was moved above the barrel, the workpiece being composed of carbon steel (0.55 percent by weight carbon) of the designation S55C. The surface to be coated was located at a distance of 12 mm. from the foil. Discharge energies of about 8,000 joules per pocket were applied and the foil advanced at an intermittent rate identical to the intermittent rate of advance of the workpiece. The coated surface was found to consist of approximately 80 percent by weight of all of the particles employed in a highly adherent layer. Corresponding results were obtained when the particles were composed of silicon carbide, aluminum nitrate, boron nitrate and titanium carbide. When the workpiece was an aluminum foil, it was found that titanium and tantalum particles could be readily applied to the surface of this foil with the same discharge energy and device. There was no deed for any binder in the particle mass and the coating was found to be more uniform and of greater strength than that produced when the particles were merely placed upon the foil and not encapsulated therein.

A somewhat greater penetration of the particles was observed when stoichiometrically equivalent quantities of chromic oxide (oxidant) particles and cellulose particles (reducing agent) were incorporated in the mass within each pocket in an amount up to 10 percent by weight. It appears that the exothermic chemical reaction between the chromic oxide and the cellulose generates sufficient heat to increase the surface energy of the particles and the degree to which they are bonded to the substrate.

In FIG. **3**, I show a modified system for the high-rate coating of a substrate **210**. In this system, the barrel or tube **212** is generally cylindrical and is formed with a seat **212'** at its upper end at which a frustoconical inner bore **212''** terminates. The barrel **212** is provided with an exhaust muffler **216** of the type illustrated and described with respect to FIG. **1** and advantageously consisting of a tube **216'** filled with a packing **216''** of stainless steel wool or other sound-damping material. An upper member **224** forms a shock wave generator and is provided with a needle electrode **225** in an electrically insulated ceramic sleeve **226**. The needle electrode **225** is threaded at its upper extremity **225'** and engages a nut **225''** whose toothed periphery meshes with a pinion **227'** of an electric motor **227**. The housing **224** and motor **227** are connected together and are shifted in the direction of arrow **238** by a hydraulic cylinder **244**. The latter is operated by a valve **236** and receives hydraulic fluid from a pump **230** and a reservoir **231**. A timer **242** is provided to operate the valve **246** and lift the barrel **224** from the seat **212'** against which it clamps the foil **222**. Timer **242** also is coupled with the sprocket **240**, representing the means for advancing the foil **222** intermittently to dispose the pockets **222***c* in the barrel.

The foil **222** may be paid off a supply roll as described in connection with FIGS. **1** and **2** or can be formed concurrently by an encapsulating device **260**. This apparatus can, of course, be employed independently of a coating apparatus to prepare the foil for coiling and subsequent use. The system basically comprises a pair of supply rolls **261***a* and **261***b* from which nickel, aluminum or other metal foil having a thickness ranging between substantially 0.005 and 0.02 mm. and a width slightly in excess of that of the seat **212'** of the apparatus in which the pocketing band is to be used, the foil layers passing between forming rolls **262***a*, **262***a'* and **262***b*, **262***b'*, respectively, in which pockets **263***a* and **263***b* are respectively formed in the foils **222***a* and **222***b* to register and open toward one another. When the apparatus **260** is to be employed for the production of pocketed foils of the type illustrated in FIGS. **1** and **2** only, a single set of forming rollers is necessary and the rollers **262***b* and **262***b'* may be dispensed with.

A feed means **264** with any conventional metering device deposits the particulate material in the pockets thus formed as the foils are brought together and encapsulates the masses via a pair of sealing rollers **265**. The sealing rollers **265** may be heated to weld the foils together about the pocket or may merely apply sufficient pressure to laminate them together. It is also possible to use a crimping arrangement at these rollers to fold the edge portions of one foil around the other and thereby encapsulate the particulate material. The metering device **264** and the rollers **262***a* etc., are operated in the cadence of the foil-advancing means **240** and the barrel **224** by the timer **242**. Otherwise, the apparatus operates in the manner previously described with reference to FIG. **1**.

FIGS. **4** through **8** illustrate various modifications and arrangements of the spark-activated coating gun of the present invention. In FIG. **4**, for example, three guns of the general type illustrated in FIGS. **1** through **3**, supplied with foil-encapsulated pockets of particulate material from respective supply rolls and energized in succession, are mounted upon a carriage **70** which may be shifted by a spindle **71** parallel to the workpiece surface **72** in the direction of arrow **73**. All of these deposition guns or tubes **74** have similar spark chambers and, when the surface **72** is flat, have their mouths lying along a plane P parallel to the receiving surface of the substrate. The means for energizing the coating gun **74** can include a circuit such as that illustrated at **75**. This circuit, whose terminals **76** are supplied with direct current, include a respective capacitors **77***a*, **77***b* and **77***c* energized respectively via chokes **78***a*, **78***b* and **78***c* and charging resistors **79***a*, **79***b* and **79***c*. The parameters of this network can be such that the left-hand tube **74** (FIG. **4**) is energized an instant prior to the energization of the intermediate tube which, in turn, is energized shortly in advance of the right-hand tube **74** as the workpiece **72** is shifted to the left. In this manner, it is possible to move the workpiece with considerable rapidity and apply a relatively thick coating in short order. FIGS. **5** and **6** show several modifications of the orientation of tubes **74**. In the system of FIG. **5**, the tubes **74'** are aligned in a common vertical plane and thus may extend over the full width of a body such as that diagrammatically illustrated at **72'**. In the system of FIG. **6**, the shocktubes **74''** are arrayed at the vertices of a triangle and may serve to coat a narrower workpiece **72''**.

When, however, the workpiece **82** has a relatively complicated contoured surface **82***a* to be coated with the particulate material, I have found that it is most desirable to employ a number of spark-operated deposition guns **84***a*, **84***b* and **84***c* energized by a circuit such as that shown in FIG. **4**, and disposed so that the mouths of these guns lie along an imaginary surface S which is generally parallel and complementary to the surface **82***a*.

In the modification of FIG. **8**, the contoured surface **92***a* of the workpiece **92** has a positive curvature for the most part, i.e., is convex, the deposition guns **94** being disposed along axes perpendicular to tangents to the surface and thus are perpendicular to these surfaces as well. The guns are spaced as closely together as possible with the illustrated spacing being somewhat exagerated. Moreover, the mouths of the guns are at identical distances from the confronting surface portions so that they lie generally along an imaginary complementary surface S'. When more than three guns are employed, the energization circuit can include a delay line for firing the guns in any desired sequence or rate at each cycle. Furthermore, while a timer means has been described in connection with FIGS. **1** through **3** and is of course employed in the circuit of each of the guns of FIGS. **4** through **8**, it will be understood that such timer means can be triggered by a previous

discharge in the shock wave chamber with a predetermined delay time controlled by the charging of the condensers to their respective capacities.

According to another aspect of this invention, the impact deposition barrel is provided with cooling means to promote the transfer of powdered materials to the substrate and minimize particle adhesion to the barrel. Thus, in FIG. **11**, there is plotted the temperature of the barrel along the abscissa in degrees centigrade while the percent particle adhesion to the internal surface of the barrel is plotted along the ordinate. From this relationship it will be apparent that particle adhesion remains relatively low at temperatures up to about 60° C. but lies sharply between 70° and 80° C., prior to leveling off at relatively high values at still more elevated temperatures. Since particle adhesion to the internal surface of the barrel is inversely proportional to the number of particles delivered to the surface to be treated and to the period of time for which the device can be used effectively without cleaning, it will be evident that operation of the system at lower temperatures produces considerable advantages and promotes efficient operation especially when repeated discharges are to be produced.

Therefore, I have found it to be advantageous to provide cooling means along the barrel for promoting the dissipation of heat therefrom. While this cooling means can include a heat sink in contact with the metallic barrel, i.e., of relatively large heat capacity and high thermal conductivity or a radial surface making use of convection currents to effect fluid-solid heat transfer, I prefer to provide a forced fluid transfer of heat since the amount of heat energy generated by the high-energy-rate deposition apparatus requires relatively high heat transfer efficiency and capability.

In FIG. **9** I show a system in which the barrel **1004** of a deposition device of the type illustrated in FIGS. **2–8** is provided with radial fins **1004***a* around which a fan **1004***b* displaces a forced stream of air. Any air displacement means can be used for this purpose although the fan **1004***b* is here shown to have a propeller-type blade **1004***c*. I have found it to be advantageous to confine the cooling fluid in a duct **1004***d* which encloses the finned region of the barrel **1004** and prevents the high-velocity cooling-air stream from inconveniencing the particle deposition system of this barrel or any adjoining barrels (see FIGS. **4–8**).

A modified arrangement with the same purpose is illustrated in FIG. **10** in which the barrel **1114** of a thermally conductive material is in contact with a cooling coil **1114***a* whose inlet and outlet **1114***b* and **1114***c*, respectively, are connected in a fluid-circulation system of any convenient type. The foil **1122**, into which the particles are pocketed, may be passed through the system via the displacement means **1139′** as shown in greater detail in FIGS. **1–3**, while the central electrode **1125** effectuates discharge between the foil and itself. The pulse-supplying source **1133** includes a pair of roller contacts **1133′** engaging the foil **1122** downstream of the supply coil **1139**. The source comprises a battery **1136** which charges the capacitor through a resistor **1135** while the switch **1137**, upon closure, applies the impulsive discharge to the electrode. The cooling means of FIGS. **9** and **10** are dimensioned to maintain the barrel temperature below 80° C. and preferably below 60 °C.

It has been found that in addition to the foil materials described above and illustrated in FIGS. **1–3** and **10** to form pocketed magazines for the particles, it is possible to make use of cobalt, copper-nickel alloys and iron foil materials with thicknesses as previously indicated. When, however, the discharge is produced between a pair of electrodes independently of the foil, e.g., as described in the above-identified applications, the foil material can be a synthetic resin such as polyethylene or polyvinyl resin.

In FIG. **12**, I show an apparatus **1600** for the sintering of conductive as well as nonconductive particles which can carry out the simultaneous cladding (bonding) and shaping of a metal body as previously described. In the aforementioned application 247,387 of 26 Dec. 1962 and 311,061 of 24 Sept. 1963, I disclose the advantages of spark sintering of discrete bodies. In accordance with the principles of this invention, discrete particles of a conductive material or a mixture of conductive and nonconductive particles are disposed in a relatively light contacting relationship so that the interfacial resistance is substantially greater than the internal resistance of the particles.

When the capacitor is then discharged across the mass of particles, spark discharges develop in the interfacial arrays and eventually merge so that the entire mass is penetrated by an electrical space discharge which apparently ionizes the material of the particles at the interfacial zones and causes the formation of conductive bridges.

Subsequent passage of electric current is concentrated at these bridges, thereby heating the particles further and permitting their consolidation. While this method is highly suitable for the production of porous bodies and relatively low density nonpermeable structure, the formation of high-density particles from particulate material has been found to require an increase in the pressure applied to the particles upon conclusion of the bridge-forming stage.

In FIG. **12**, therefore, I show an apparatus for the simultaneous cladding and bonding of members which can obtain the aforementioned results. The device **1600** comprises a fluid receptacle **1601** which itself constitutes the piston by a hydraulic cylinder **1657**. Inlet and outlet tubes **1619** and **1620** circulate the liquid medium **1604** within vessel **1601** via a filter for removing particles formed by discharge in the liquid **1604**.

A piston **1639** is slidable within vessel **1601** and is provided with an insulating lining **1639***a*. Piston **1639** carries a deposit **1608** of electrode material and thus constitutes one of a pair of electrodes forming a spark gap **1605**, the other electrode of the pair being a rod or wire **1615** adapted to be fed into vessel **1601** by rollers **1613** in response to an alteration in the size of the spark gap. A thin-wire electrode can be assumed to pass through the interior of electrode **1615** for juxtaposition with the electrode **1608** to serve as a consumable electrode.

A vibratile bar **1639″** whose resonant frequency is approximately equal to the frequency of the discharge to be applied across the gap **1605**, connects the piston **1639** with a plate **1639′** in force-transmitting relationship with a conductive powder **1640** retained within the cavity **1637** of a mold in the form of an electrically insulating sleeve **1637′** which is reinforced by ribs **1655** and mounted upon the metal plate **1656**.

A two-position valve **1658** is connected in series with the hydraulic cylinder **1657** and is supplied by a high-pressure conduit **1660** and a low-pressure conduit **1659**. Valve **1658** is operated by a control circuit **1662** in response to the voltage drop across the mass of particles **1640**. A battery **1661**, in series with the control circuit **1662**, provides the necessary current for the latter. The discharge energy is supplied by a capacitor **1641** connected between plate **1656** and electrode **1615**, capacitor **1641** bridged by a charging battery **1643**, an inductance **1644** and a charging resistor **1644′**. Vessel **1601** is provided with an annular recess **1652**, normally blocked by piston **1639** but which communicates with a high-pressure accumulator **1653**.

When conductive particles are employed, capacitor **1641** discharges to develop simultaneously sparks at gap **1605** and through the particle mass **1640**, thereby forming conductive bridges among the particles.

The shock wave within vessel **1601** is applied to the particles via piston **1639** so that the powder is compressed at the conclusion of the electrical discharge. Simultaneously, control **1662** senses the decreased voltage drop across the mass of particles and energizes valve **1658** to close off the low-pressure fluid supply at cylinder **1657** and terminates the gradual supply of fluid to this cylinder which enabled vessel **1601** to follow the shrinkage of the particle mass; the valve **1658** also cuts in the high-pressure conduit **1660**. The conductive powder, now sintered into a porous mass but still in a plastic

state, is thus subjected to the additive pressure of source **1660** and the shock wave within vessel **1601**. When nonconductive particles are used, capacitor **1641** is connected with the piston **1639** as indicated by the dot-dash conductor **1663**, whereupon the pressure of the discharge at gap **1605** is applied to the particles without initial formation of bridges across them by electrical discharge.

EXAMPLE II

A mass of polytetrafluorethylene particles of **200** mesh are disposed in a nonconductive sleeve having a diameter of 15 mm. and a length of 2 cm. Light pressure was applied at hydraulic cylinder **1657** to compress the particles (approximately 1 kg./cm.^{2}) while a discharge in silicone oil within vessel **1601** was created. Electrodes composed of an aluminum-copper alloy were used while the single discharge pulse had a duration of 150 microseconds and an energy of 1,500 joules. The resulting coherent body had all of the characteristics of a body molded at elevated temperatures although the powder was held at room temperature for the duration of the process.

EXAMPLE III

The procedure of Example II was followed, except that nickel particles and a spark energy of 5,000 joules was used between plate **1656** and electrode **1615**. The pressure applied by cylinder **1657** to the particles was 1 kg./cm.^{2}, this pressure being followed upon reduction of the voltage drop across the mass of particles to a value of 500 kg./cm.^{2}, the discharge terminating concurrently with the increase in pressure. The resulting body had the density of greater than 90 percent of that of the solid mass.

EXAMPLE IV

It is well known that so-called "shot-peening" and shot-blasting techniques make use of spherical bodies which are used in large numbers and directed against an article to be treated at high velocity in an air stream. I have found that the efficiency of shot peening and shot blasting can be materially increased when the spherical shot is provided with sharp edges and uniform deformities. Heretofore, however, it has been difficult to provide uniform deformities upon bodies of this type in an inexpensive manner. Utilizing a device of the type illustrated in FIG. **12** however, it has now become possible. Five hundred steel balls having a diameter of 0.5 mm. were stacked in a cavity **1637** and subjected to pressure derived from an arc discharge having an energy of 5,000 Joules; the pulse duration was 100 microseconds. An initial vibration of plate **1656** settled the balls into a close-packed structure so that the resulting deformation had hexagonal character. A machining efficiency upwards of 50 percent above that attainable with the smooth surface balls was realized.

EXAMPLE V

The method of Example IV was followed except that, in addition to the steel balls, approximately 10 percent by weight of the balls of a chromium oxide powder (Cr_2O_3) of 10–30 microns particle size was added to the cavity. Approximately 70 percent of the chromium oxide particles were bonded to the balls and another increase in machining efficiency was attained.

FIG. **13** shows an arrangement wherein the pressure vessel **1901** is formed as an open-ended cylinder within which a piston **1965** is slidably displaceable. A further piston **1966** is disposed in the opposite end of vessel **1901** and is formed with an inlet tube **1920** while piston **1965** has an outlet tube **1919** for circulation of the dielectric liquid **1904** by pump **1921** via filter **1922**. Piston **1965** carries a forming die **1939** adapted to drive a synthetic-resin plate **1940** into the cavity **1937** of a die **1937'** secured at **1938** to a housing **1967**. The latter is integral with piston **1966** and thus movable therewith and is mounted upon a plurality of legs **1969** resiliently supported by springs **1970** on pedestals **1968**. Vessel **1901** is shiftable with respect to the housing **1967** on antifriction bearings **1971** and is provided with a pair of insulating bushings **1906, 1907** through which pass the electrodes **1908, 1915** to form the spark gap **1905**. A capacitor **1941** is connected across the electrodes **1908, 1915** and in parallel with a battery **1943** via switch **1942**, an inductor **1944** and a resistor **1944'**. The inner surface **1972** of piston **1965** is concave in the direction of spark gap **1905** to reduce kinetic rebounding of the pressure wave. Vessel **1901** can be held stationary by a support not shown or floatingly displaceable within housing **1967**.

The shock wave developed at spark gap **1905** radiates circularly in a symmetrical manner about the axis of the discharge. Thus, only that portion of the shock wave intercepted by surface **1972** is directly acted upon by this wave. The diametrically opposite component of the shock wave is, in the apparatus of FIG. **13** transferred to die **1937'**, as this member of the die moves toward the head **1939** with approximately twice the velocity with which forming the workpiece was done heretofore. In addition, the effective energy transfer is more than twice the energy derivable from diametrically opposite locations of a spherical shock wave as a consequency of the flattened configuration of the wave produced by the spark discharge between electrodes **1908** and **1915**.

I claim:

1. A method of cladding and shaping a member comprising:

a. supporting a member to be clad adjacent a shaping means of predetermined shape,

b. disposing a cladding material on the surface of said member to be clad and providing a working fluid medium above said cladding material,

c. generating an intense pressure in said fluid medium against said cladding material at sufficient intensity to cause said cladding material to become molecularly bonded to the surface of said member and simultaneously causing said cladding material and member to be deformed to said predetermined shape.

2. A method in accordance with claim **1** wherein said member to be clad is metal and said cladding material is a particulate material.

3. A method in accordance with claim **1**, whereby said intense fluid pressure is composed of a shock wave, said method further comprising directing said shock wave against material disposed on said member to effect the cladding of said member as it is simultaneously deformed to said predetermined shape.

4. A method of cladding metal plate and simultaneously working said plate and cladding to deform same to a predetermined shape comprising:

a. supporting a metal plate member to be clad and shaped with one surface thereof in alignment with a forming die of predetermined shape,

b. disposing a cladding material against the other surface of said metal plate.

c. generating a shock wave and directing said shock wave against said cladding material at sufficient intensity to cause said cladding material to become molecularly bonded to the surface of said plate and to simultaneously deform and change the shape of said cladding material and plate and cause same to conform to said predetermined shape as defined by the shape of said forming die.

5. A method in accordance with claim **4** including generating a plurality of shock waves to clad and deform said plate.

6. A method in accordance with claim **4** whereby said forming die has a curved shape and the force of said shock wave is operative to cause said clad metal plate to conform to said curved shape.

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