United States Patent [19]

Inoue

[11] **3,825,064**

[45] **July 23, 1974**

[54] **HEAT EXCHANGER**

[76] Inventor: **Kiyoshi Inoue,** 16-8 3-Chome, Kamiyoga, Setagaya-ku, Tokyo, Japan

[22] Filed: **Oct. 12, 1971**

[21] Appl. No.: **187,988**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 10,090, Feb. 16, 1970, which is a continuation of Ser. No. 611,497, Nov. 30, 1966, abandoned, which is a continuation-in-part of Ser. No. 356,714, April 2, 1964, Pat. No. 3,340,052, which is a continuation-in-part of Ser. No. 247,387, Dec. 26, 1962, Pat. No. 3,250,892.

[30] **Foreign Application Priority Data**

Dec. 26, 1961 Japan 36-47409

[52] **U.S. Cl.** ..... **165/179,** 29/157.3 R, 165/10, 165/165, 165/148, 165/180, 165/181

[51] **Int. Cl.** **F28f 1/22**

[58] **Field of Search** 165/133, 179, 184, 180, 165/181

[56] **References Cited**

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Primary Examiner—Albert W. Davis, Jr.
Attorney, Agent, or Firm—Karl F. Ross; Herbert Dubno

[57] **ABSTRACT**

A heat exchanger is formed by compacting metallic particles, especially of materials of high thermal conductivity to form the heat exchange surfaces, preferably against a substrate such as thermally conductive tube. The compaction involves electrical sintering, with the particle-particle interfaces and the particle-substrate interfaces metallurgically homogenized to form a monolithic structure free from corrosion sites.

1 Claim, 47 Drawing Figures

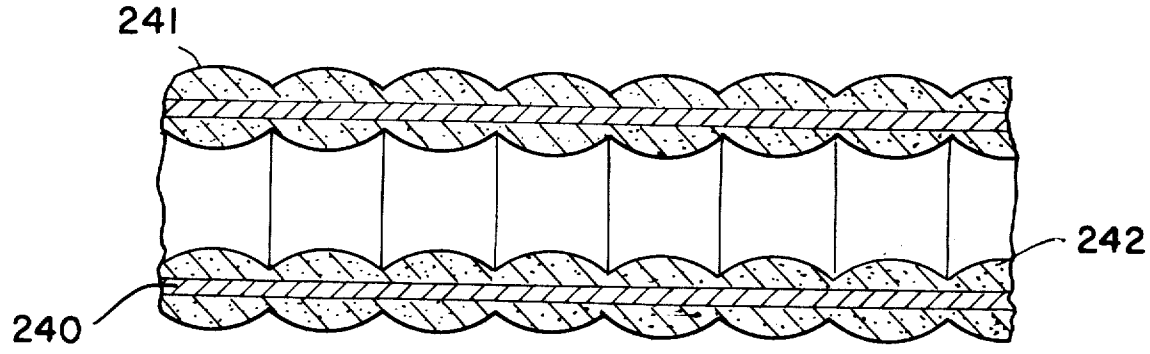


FIG. 1

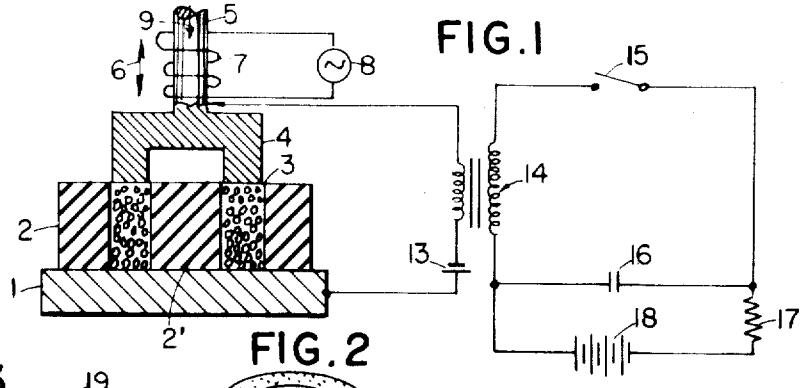


FIG. 2

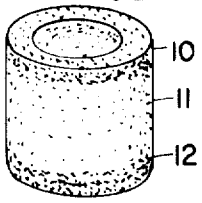


FIG. 3

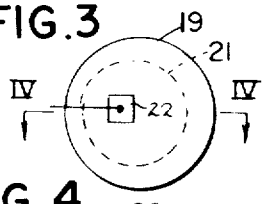


FIG. 4

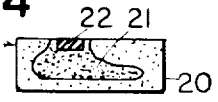


FIG. 5

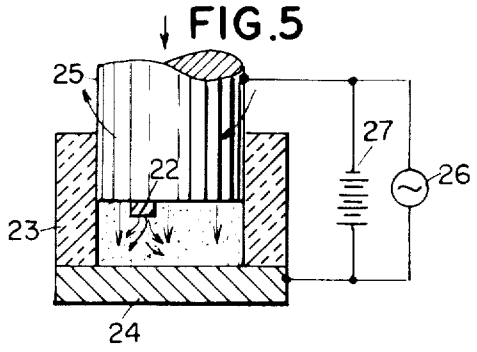


FIG. 6

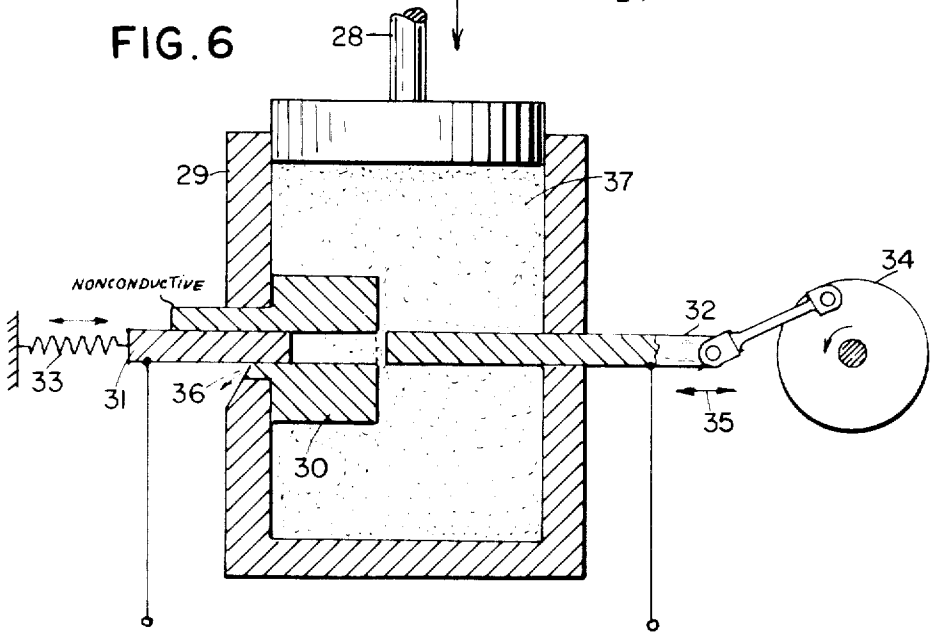


FIG. 7

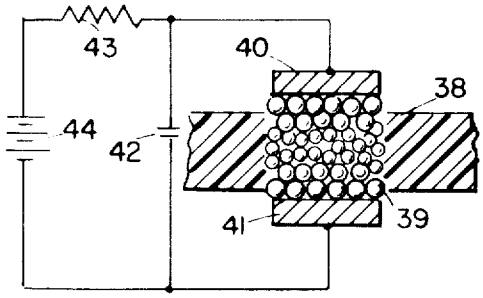


FIG. 8

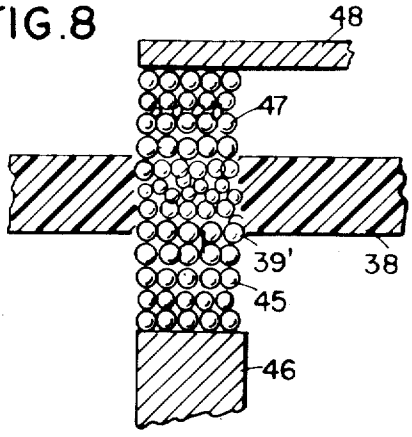
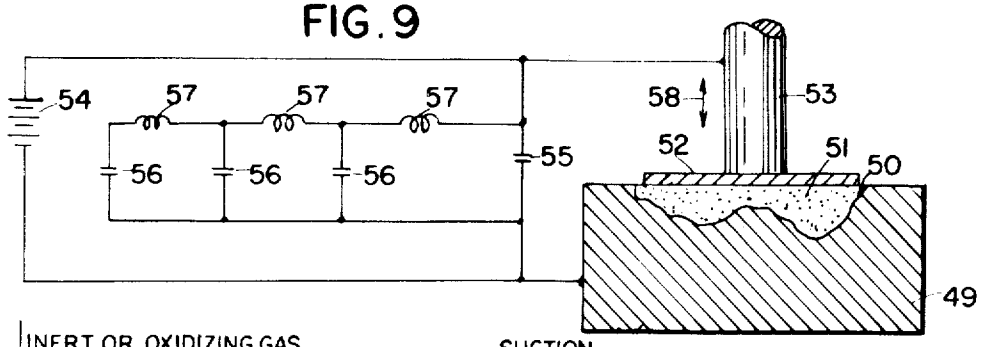


FIG. 9



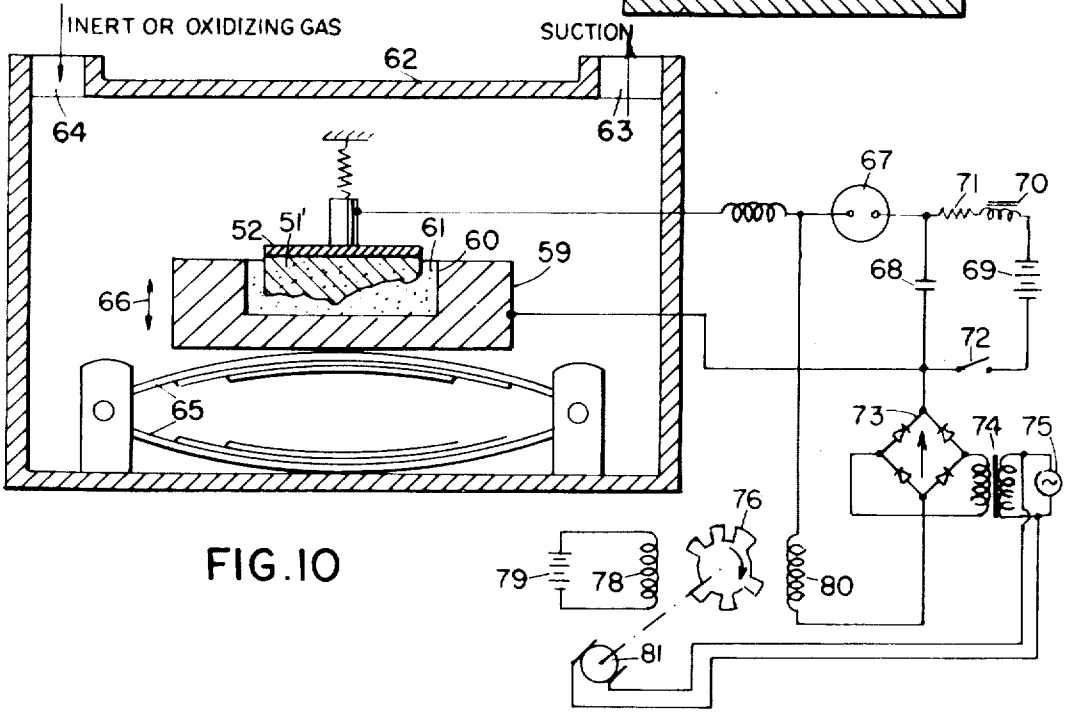


FIG. 10

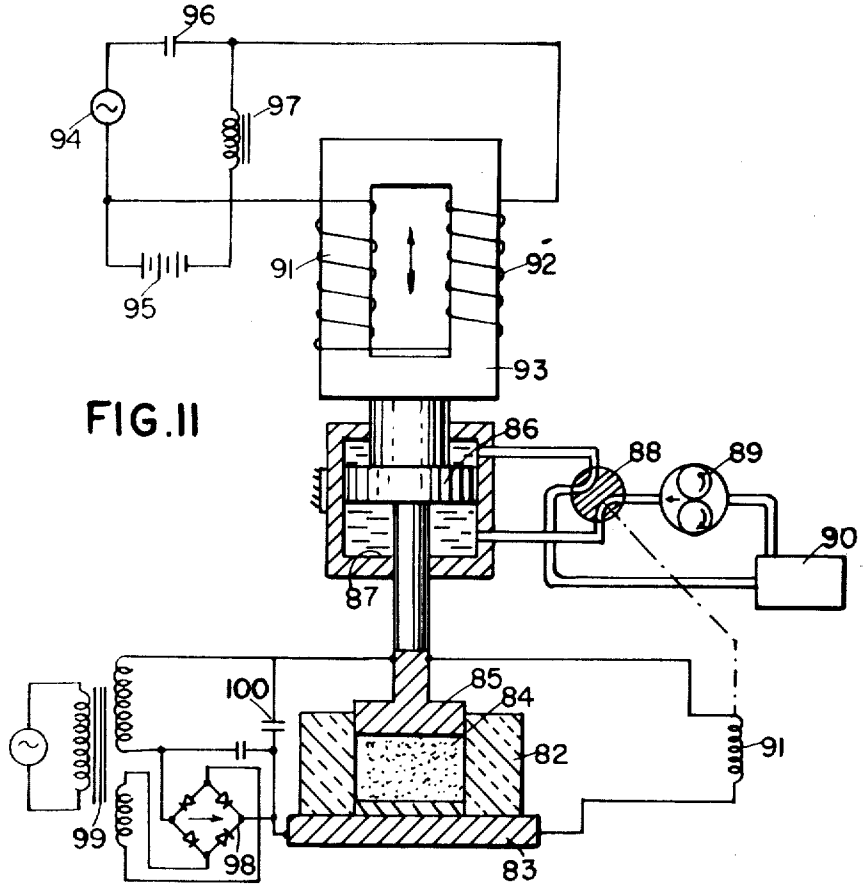


FIG.11

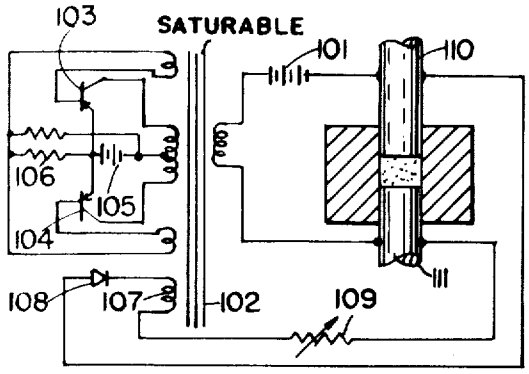


FIG.12

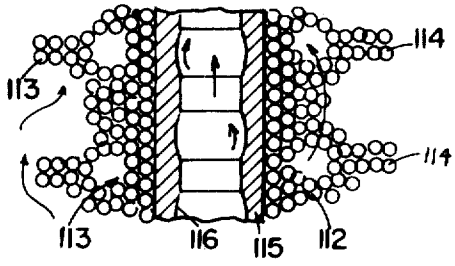


FIG.13

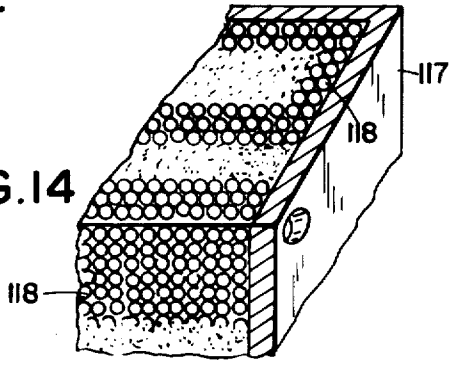


FIG.14

FIG.15 FIG.16

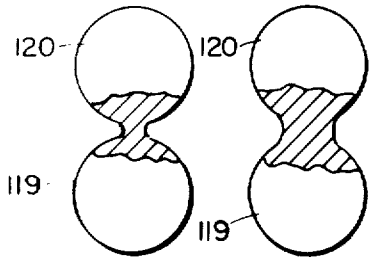
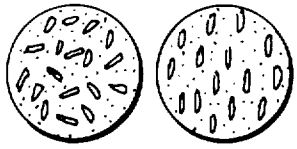


FIG.17 FIG.18



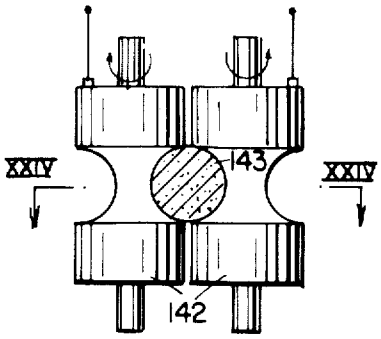


FIG.23

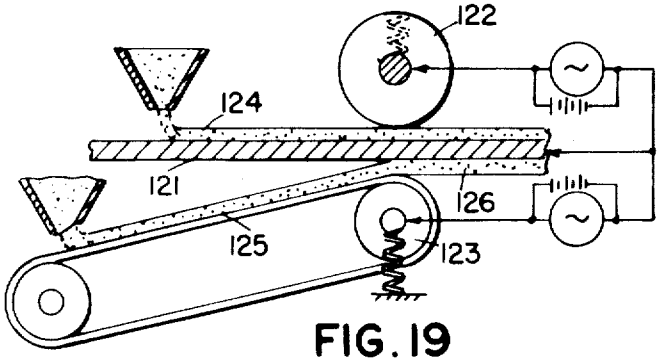
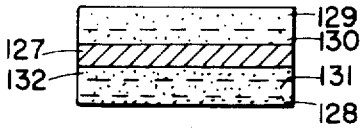


FIG.19

FIG.20



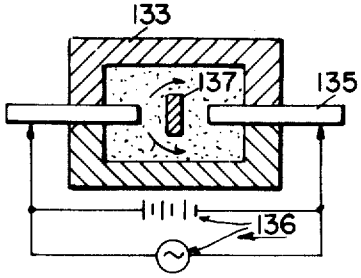


FIG.21

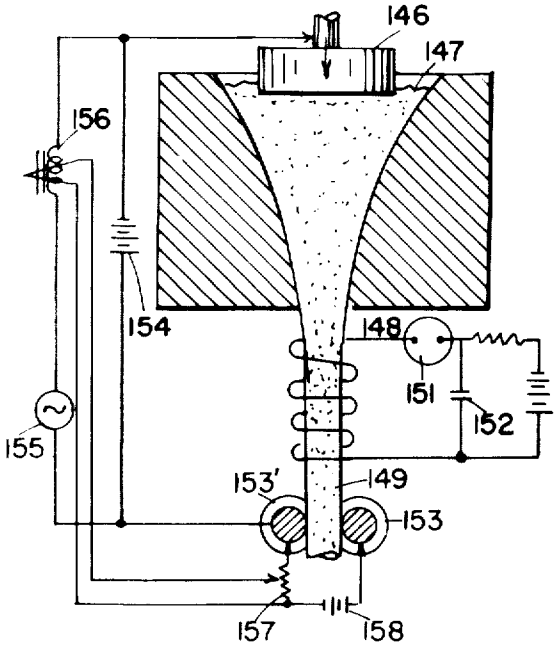


FIG.25

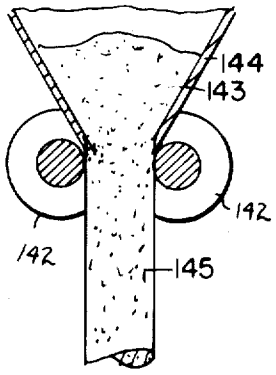


FIG.24

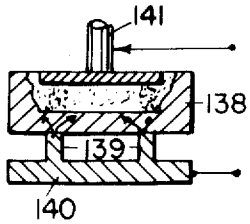
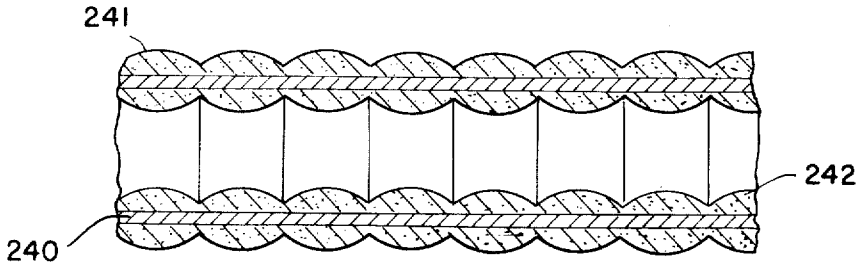


FIG.22

FIG. 26



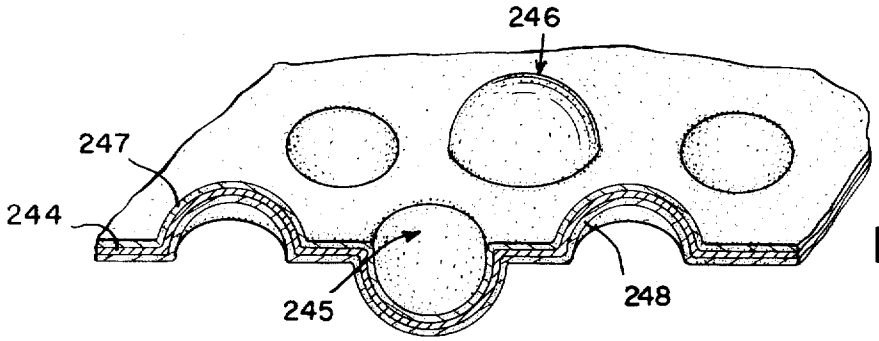


FIG. 27

FIG. 28

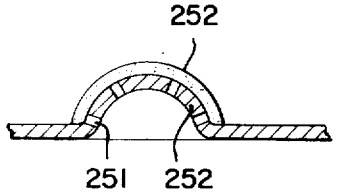
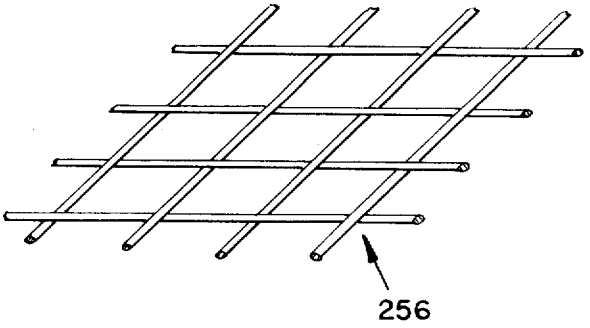


FIG. 30



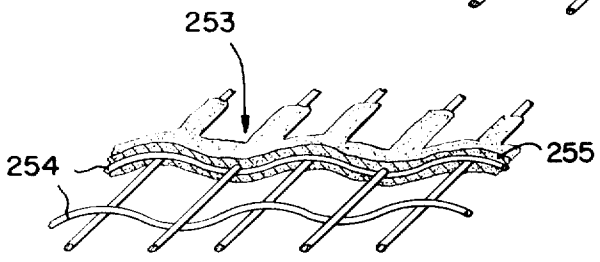
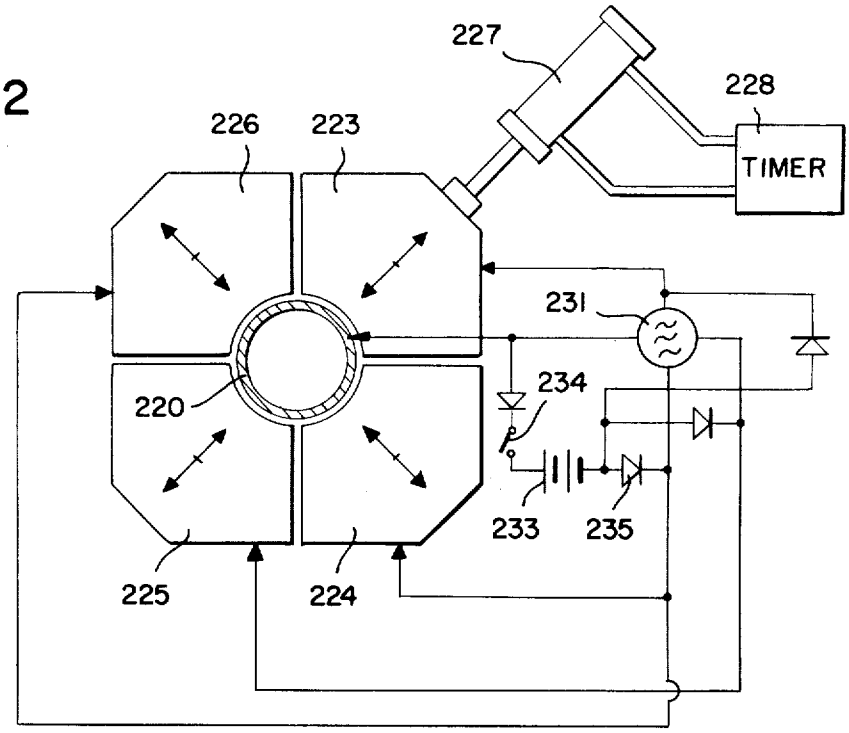


FIG. 29

FIG.32


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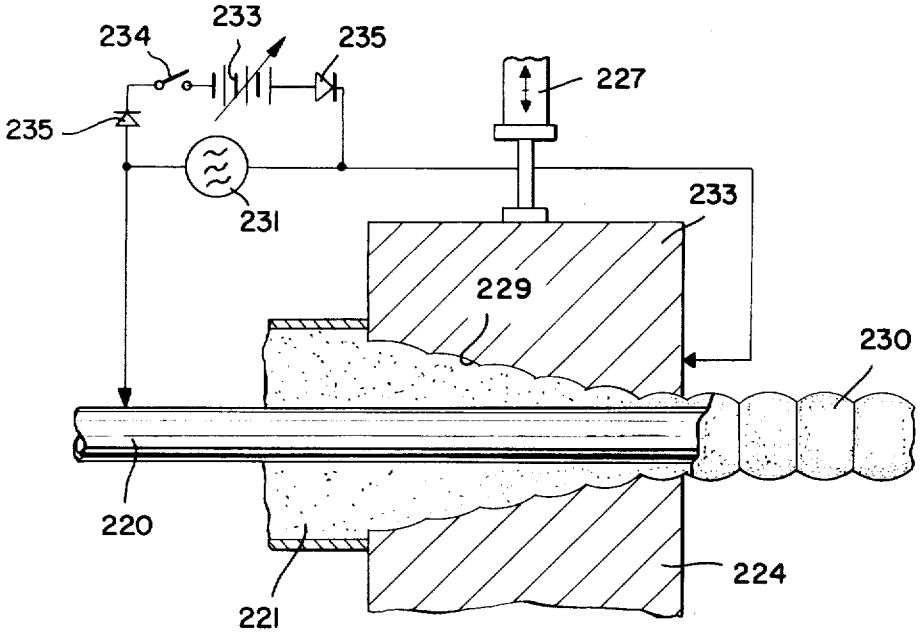

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FIG.31

FIG. 33

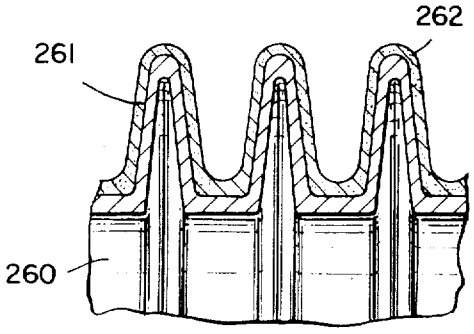


FIG. 34

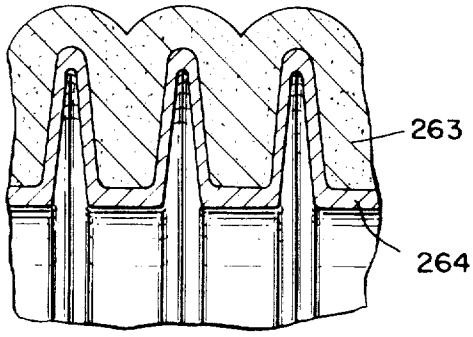


FIG. 35A

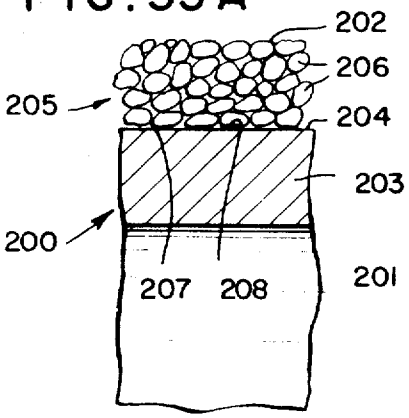
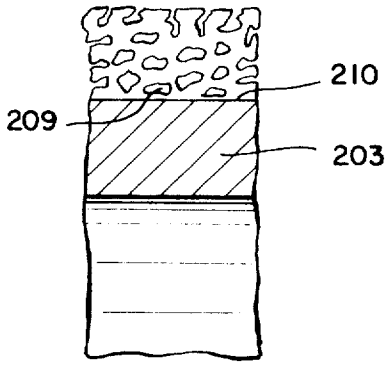


FIG. 35B



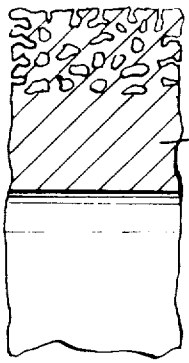


FIG. 35C

FIG. 36A

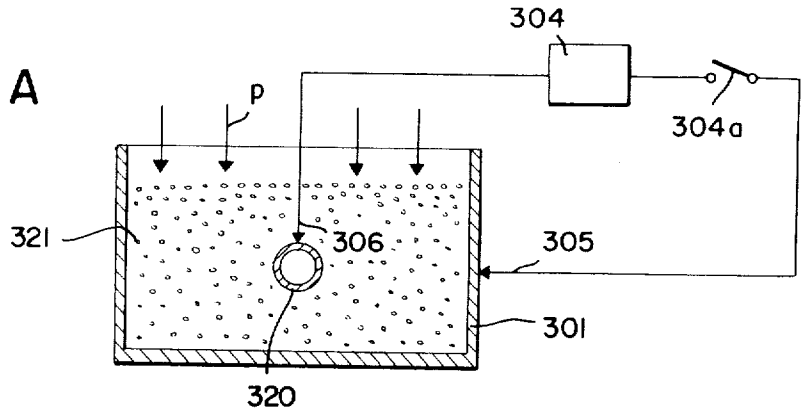
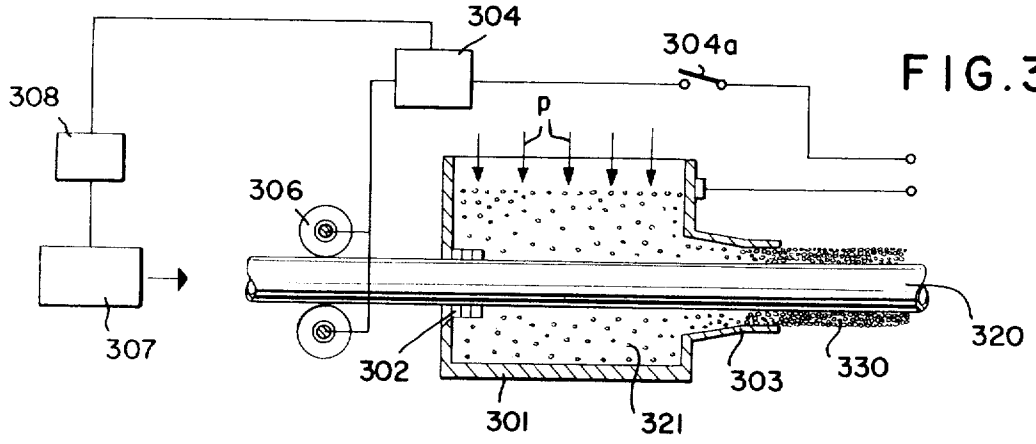


FIG. 36B



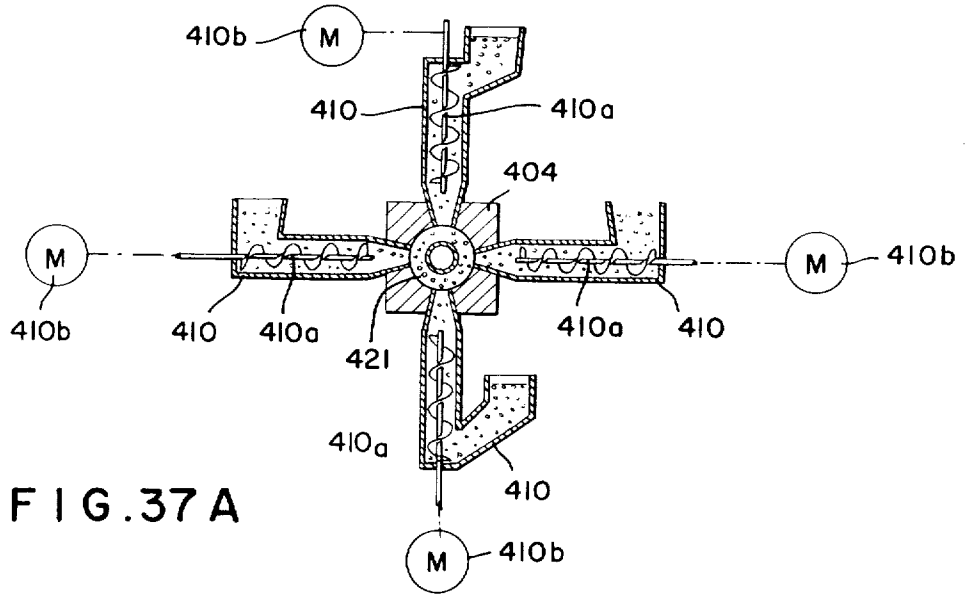
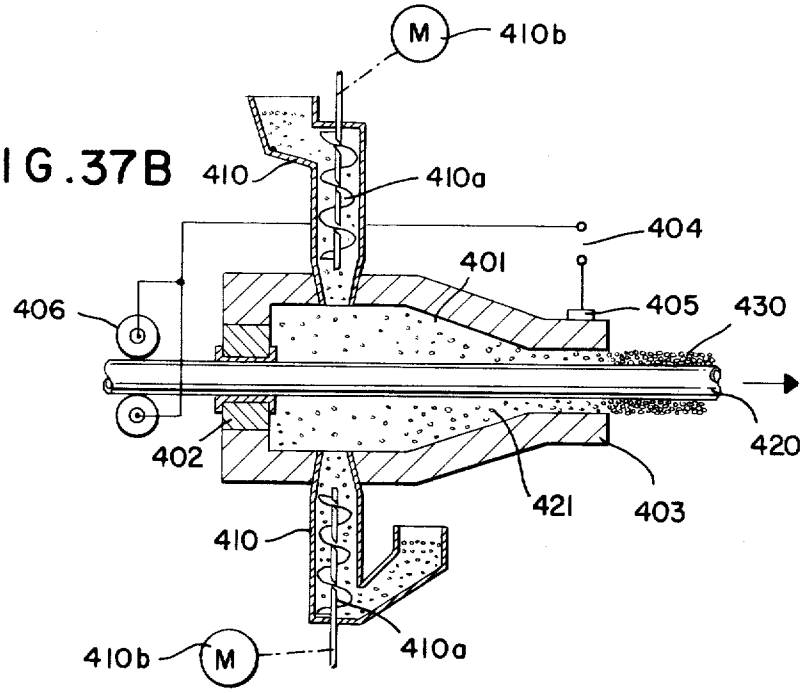


FIG. 37A

FIG.37B



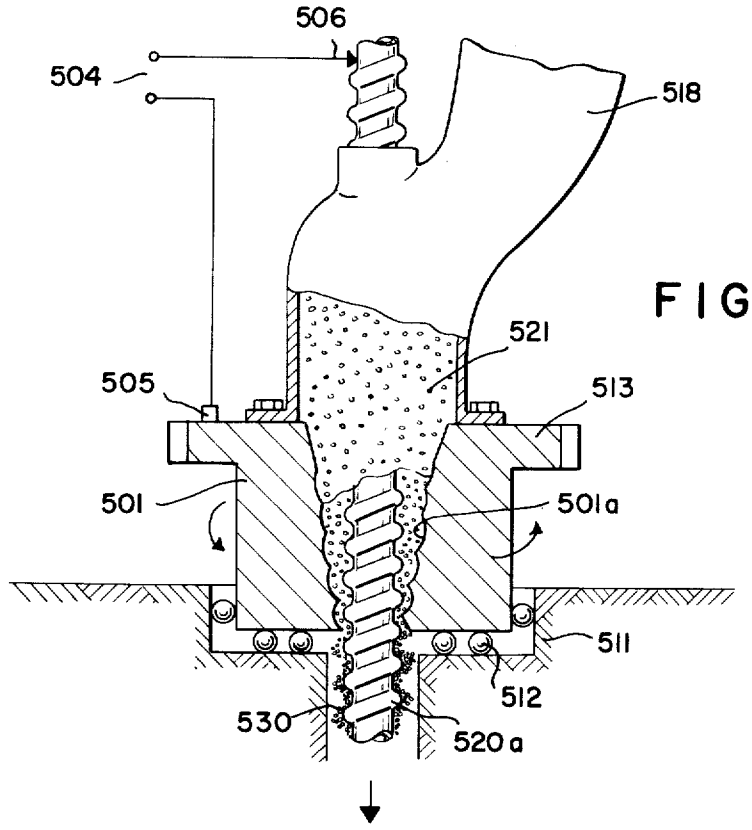


FIG.38

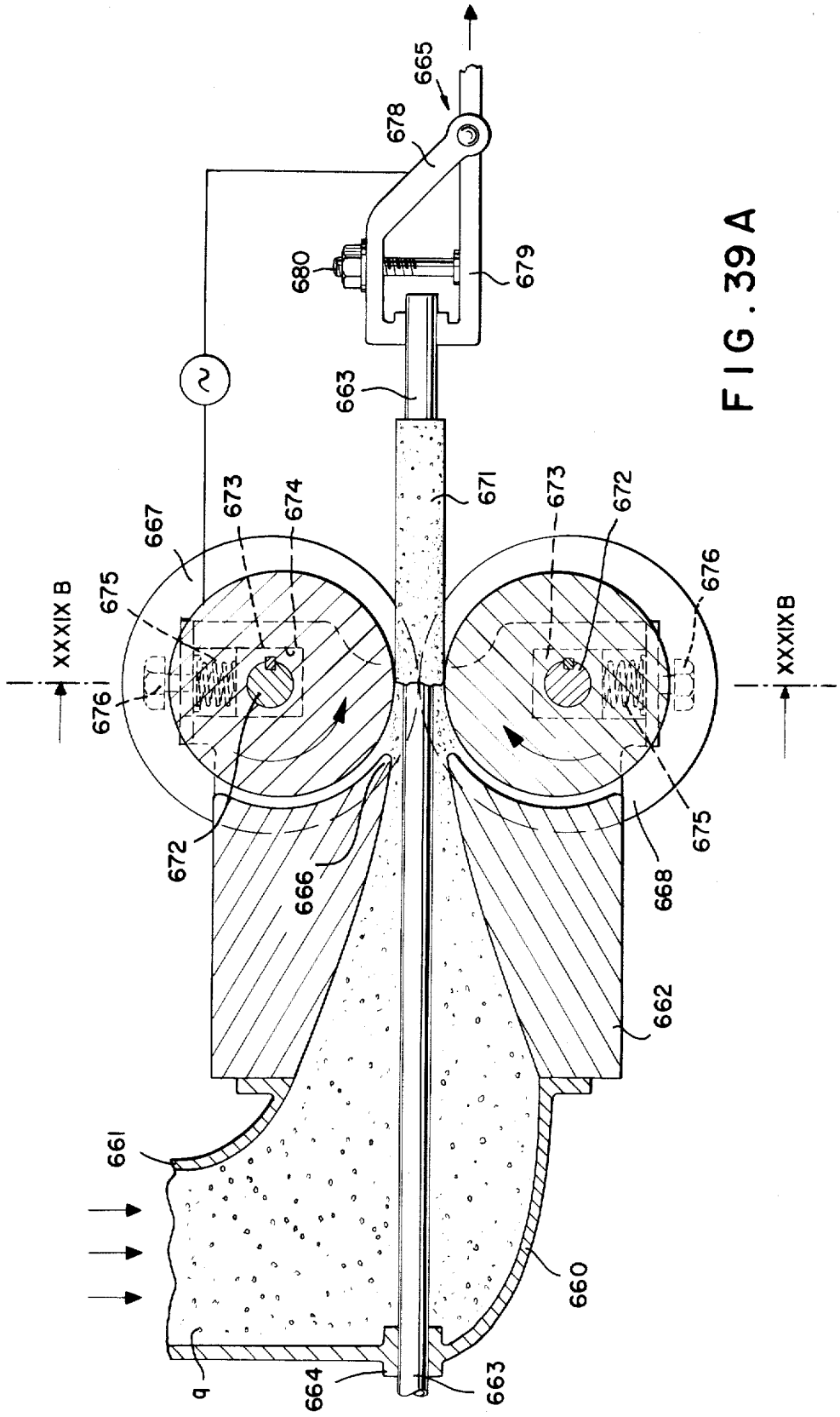
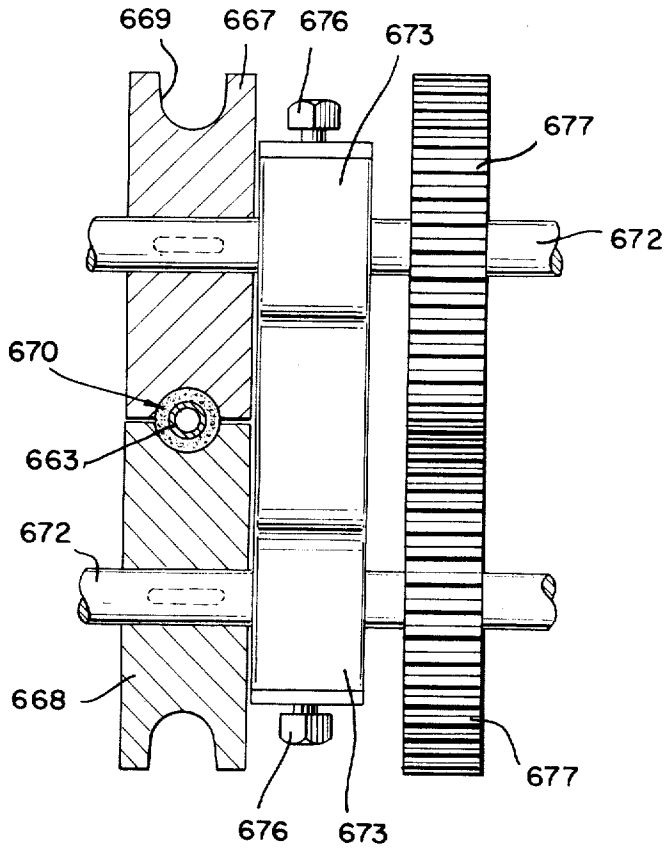

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FIG. 39A

FIG. 39B



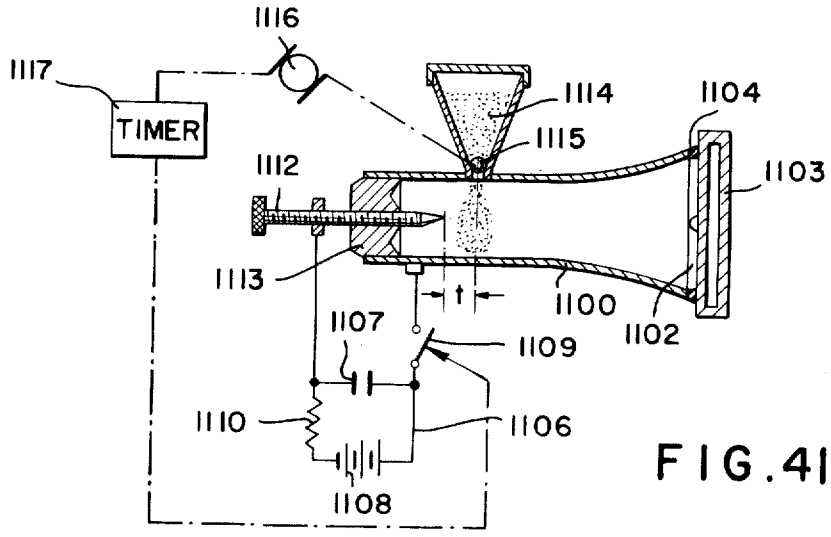


FIG. 41

FIG. 40 B

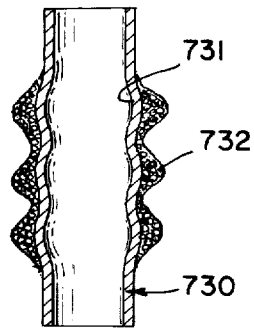


FIG. 40A

HEAT EXCHANGER

CROSS-REFERENCE TO COPENDING APPLICATION

This application is a continuation-in-part of my application Ser. No. 10,090 filed Feb. 16, 1970 as a continuation of application Ser. No. 611,497 filed Nov. 30, 1966, as a continuation-in-part now abandoned, but copending with its parent application Ser. No. 356,714 filed Apr. 2, 1964 (now U.S. Pat. No. 3,340,052 issued Sept. 5, 1967), as a continuation-in-part of then-pending application Ser. No. 247,387 filed Dec. 26, 1962, now U.S. Pat. No. 3,250,892 issued May 10, 1966.

FIELD OF THE INVENTION

The present invention relates to the sintering of discrete bodies or particles to form coherent objects and to the bonding of such bodies to substrates.

More particularly, this invention relates to a heat exchanger structure and to a method of making same using sintering techniques and, especially, electrical-sintering procedures.

BACKGROUND OF THE INVENTION

Earlier-known sintering techniques, which have found considerable utility in the field of powder metallurgy, in batteries, and in related arts can generally be classified in three categories, depending upon the specific procedure used. The principal known method of sintering involves the heating, usually in electric or gas furnaces but also by induction or dielectric processes, of the mass of particles which is subjected to extremely high pressure, generally on the order of tons/cm.^{2} (1,000 kg./cm.^{2}) to effect a welding of the particles together under the elevated pressure. The other conventional methods involve the use of lower pressures, also on the order of tons/cm.^{2}, but temperatures sufficiently high to cause considerable flowing of the particulate material, and the use of adhesives or fusion agents which permit the use of lower temperatures but nevertheless require pressures upwards of, say, 500 kg./cm.^{2}. It has also been proposed to employ resistance-heating techniques which also require elevated pressure. All of these methods are characterized by the disadvantage that uniform heating is all but impossible and necessitate recourse to expensive hydraulic or pneumatic presses to provide the elevated pressures.

In the production of articles in which a mass of particles is bonded to a substrate, I may mention that the primary problem is adhesion of the particle mass to the underlying surface. Since I first disclosed the production of heat exchangers by sintering a particulate mass to a continuous metal surface, numerous attempts have been made to overcome the disadvantages of conventional sintering. It should be noted that the basic structure of the improved heat exchanger comprised a continuous-metal body, usually a tube of a material of high thermal conductivity in which one of the fluids is conducted, sheathed in a layer of a material composed of particles and bonded to the tube. The particulate mass, which is coherent, porous and contoured to provide a large effective surface area or volume, generally is traversed by a second heat exchange fluid, liquid or gas, adapted to penetrate into the interstices of the particulate-metal body.

One of the major problems arising with such structures, especially when made by conventional techniques, is that the adhesion or bonding strength of the particulate mass to the substrate is poor unless the particulate mass has been highly compacted. The high compaction pressures reduce porosity and the heat-transfer coefficient through the duct. Even more significant, however, is the fact that the particulate mass has a different coefficient of thermal expansion and contraction from that of the substrate tube, even when the latter is composed of essentially the same metal. Since different parts of a heat exchanger are often exposed to high and/or variable temperature differentials the thermally induced stresses are considerable and inadequate bonding strength tends to result in early deterioration of the unit.

Furthermore, conventional methods of making heat-exchange surfaces of a high coefficient of heat transfer are time consuming, expensive and, frequently, unreliable for producing standardized units with coefficients and characteristics in a limited tolerance range.

Finally, I may mention a major problem which has arisen in the heat-exchanger field in attempts, by conventional sintering, soldering and other techniques, to affix the members forming the surfaces contacting the respective fluids together. At the interface or junction, corrosion of the stress-cracking type (resulting from the stress mentioned above) or of the electrolytic type (resulting from the almost inevitable formation of contact potentials at the interface) frequently is rampant. Conventional bonding techniques and even the use of the same materials for both members, are unable to avoid such corrosion.

OBJECTS OF THE INVENTION

It is the principal object of the invention to provide an improved system using sintered discrete electrically fusible bodies.

It is a corollary object of the invention to provide a method of forming sintered-metal objects having improved properties not hitherto attainable with known techniques.

Yet another object is to improve the fatigue resistance, frictional characteristics. toughness, tensile strength, wear resistance, corrosion resistance and related properties of metal objects by sintering a surface layer thereto without the use of pressures and heating techniques which would adversely affect these properties.

Another object of the invention is to provide a method of simultaneously sinter-forming and molecularly orienting bodies composed of discrete particles.

It is another object of the invention to provide an improved heat-exchanger structure adapted to obviate the aforementioned drawbacks.

Another object of the invention resides in the provision of a heat-exchanger structure which is inexpensive to produce, has improved adhesion of a sintered-particle mass to a substrate, is less sensitive to temperature variation and differentials, and is less susceptible by corrosion by comparison with prior-art arrangements.

It is yet a further object of the invention to provide an improved method of making a heat exchanger of the last-described type.

SUMMARY OF THE INVENTION

The above and other objects, which will become apparent hereinafter, are attained in accordance with the invention in part, by a method of sintering together a plurality of discrete bodies, comprising the steps of disposed the bodies in relatively light contacting relationship (i.e., under a mechanically applied pressure up to about 100 kg./cm.^{2} but as low as the gravitational force urging some of the particles against others) and effecting a spark discharge between the bodies.

This aspect of the invention is based upon the totally suprising discovery that, contrary to the weight of earlier beliefs that elevated pressures are required to carry out an effective sintering operation, relatively low mechanical pressures can be employed when spark discharge is used. The electric spark, which advantageously possesses a power on the order of hundreds and even thousands of joules, forces the articles into bonding contact with a pressure even greater than that attainable heretofore by mechanical means even when the particles are in relatively light contact. In fact, such light contact is necessary to the development of the necessary spark which also provides sufficient heat to cause the particles to bond together with great strength. It should be noted that earlier resistance-heating techniques contrast sharply with the present method in that the earlier processes required that the pressure applied to the mass of particles be sufficient to reduce the contact pressure to a level substantially equal to the internal resistance of the particles so that a high current could be passed through the mass to develop the necessary bonding heat. In contradistinction thereto, the present method requires that the contact resistance be greater than the internal resistance and, preferably, several times as great so that, at least during initial stages of the sintering operation, most of the applied energy is in the form of the spark discharge with relatively little being dissipated in resistance heating of the particles. Since the sintering action occurs immediately upon the spark discharge, the completed body can be formed in a matter of seconds as compared with earlier methods requiring tens of minutes and even hours to effect complete sintering.

According to a more specific feature of the invention, a mass of discrete electrically fusible particles, preferably consisting predominantly of conductive metallic bodies, is disposed between a pair of electrodes which sustains the spark discharge. Since this mass naturally tends to shrink as sintering proceeds, means should be provided to maintain the electrodes in contact with the mass. To this end, the electrode means may be spring or gravity loaded or some positive drive means may be provided for maintaining the contact and, if desired, providing a mechanical pressure up to, say, 100 kg./cm.^{2} when required. The spark discharge may be terminated upon the particles being welded together, at least preliminarily, while passage of the electric current may be continued without development of the spark to weld the particles further by resistance heating.

The mass of conductive particles may be admixed with up to 20 percent by weight of nonconductive particles (e.g., of a synthetic resin) which constitute a filler adapted to improve the properties of the sintered body. The filler may be designed to reduce the weight, decrease the coefficient of friction, provide voids by volatilization upon firing or the like. When a synthetic-resin filler is employed, it is desirable to choose a material which can withstand elevated temperatures and yet is thermally fusible to a certain degree so that a bond is formed between the conductive and nonconductive particles. Suitable admixes thus may be polyamides, polyesters and phenolic resins.

It is possible, according to the invention, to bond the conductive particles to continuous metal bodies. The latter may then be formed as electrodes or disposed in the particle mass in contact with the electrodes so that a firm fusion bond is produced at the interface; the continuous body, which need not be of metal, may also be imbedded in the mass of particles and physically locked within the coherent structure. Since the coherent structure may be more or less porous as required, this method has particular application in the electrochemical field wherein the unit can act as an electrode with the continuous member serving as a terminal. Advantageously, the continuous member may serve as a support for a contoured sintered body in the form of a die for electrochemical or electric-discharge machining, stamping, pressing or hot forming of objects. Moreover, the sintered particles can, according to another feature of the invention, serve to increase fatigue resistance, tensile strength and other desirable characteristics of a metallic body or to constitute a corrosion-resistant layer therefor. The particles may, consequently, be composed of a stainless steel (e.g., ferrochrome) or another material capable of resisting electrolytic action.

It is desirable to superimpose a periodic current upon a direct current applied across the spark-discharge electrodes to avoid a preheating effect. The periodic current (e.g. an alternating current of less intensity than the direct current) may be terminated upon cessation of the spark discharge so that only a unidirectional field is applied to the sintered body. The periodic current can derive from a capacitor bridged across the electrodes or from some other alternating-current source. Advantageously, the capacitor works into a resistor which may be the ohmic impedance of the spark gap or the conductors connecting the source with the electrodes, to provide a time constant which varies as sintering proceeds and eventually results in complete elimination of the periodic current. It has been discovered that such apparatus renders it possible to provide complete control of the density of the sintered articles since increased power and elevated electrical frequencies result in a greater compaction of the mass under the same mechanical pressures. It is contemplated, therefore, to provide means responsive to the density of the body (e.g. by determining the voltage drop thereacross) for controlling the power source by varying the intensity or frequency of the spark discharge. It also has been discovered that it is possible to control the density of the sintered body by controlled vibration of the particle mass before and during the spark discharge and regulating, within narrow limits as defined by the upper pressure range, the mechanical pressure applied to the particles.

Yet another feature of the invention resides in the concentration of the electric current at certain regions of the particle mass so as selectively to increase the density of the sintered body in these regions. This concentration of current can be effected by disposing a conductive member within the mass, the conductive

member having an internal resistance substantially less than the contact resistance of the particles. The current will thus preferentially pass through this member, which displaces particles having a resistance greater than its internal resistance, so that the member is both bonded firmly into the body and serves as the nucleus for a relatively dense core therein. This core, which is formed in situ, serves as a support for more porous outer regions and is particularly suited for use in electrochemical systems wherein the porosity of the body enables extremely high discharge rates. Alternatively, it is possible to concentrate the current density at certain regions of the sinterable mass by forming the electrodes so that there is a predetermined "shortest current path" through the region to be densified. It is also possible to effect densification by varying the intensity of the spark as it traverses the particle mass. Thus, if it is desired to produce an elongated porous body having relatively dense supporting extremities, the initial spark intensity may be three to four times that employed as the spark traverses the central portion of the mass. The spark intensity is again increased as the spark approaches the other extremity. In general, the spark will proceed from one electrode to the other as a consequence of the unidirectional basic electrical field applied across the electrodes although under certain circumstances a spark may proceed from each electrode toward the center. It is also contemplated to carry ou the entire sintering operation with a single spark discharge in which case a space discharge between the electrodes is employed. To distribute the space discharge to peripheral portions of the mass, a nonconductive member may be disposed within the latter approximately midway between the electrodes. A dense region can also be obtained by disposing therein relatively small-sized particles while relatively large-sized particles are present elsewhere in the body.

The sintering operation can be carried out under any ambient atmosphere (e.g., oxidizing, inert or reducing, as desired) and even under liquid. In the latter case it is preferred that the liquid be a dielectric so as not to sustain the passage of spark-dissipating electrical currents by electrolytic action. This method of sintering also permits the molecular orientation of the sintered body so that the latter can, in effect, constitute a single crystal in many instances. It should be noted that molecular orientation can only be achieved with the aid of a relatively strong unidirectional electromagnetic force field. This force field is, in effect, present in the spark discharge and is maintained by the passage of unidirectional electric currents between the electrodes and through the mass. It has also been discovered that vibration of the mass and/or the electrodes during the spark discharge permits control of the crystal size and orientation.

The present method is also adaptable to continuous formation of sintered bodies. As mass of sinterable particles can be continuously passed through a spark gap formed between a pair of electrodes, one of which may be constituted by the coherent, previously sintered material. It is also possible to provide means for repeatedly removing sintered bodies from between the electrodes for the protection of the tablets, pellets or the like. During continuous operation the die, mold and electrode may be cooled by air or water to dissipate the heat developed. In many cases the sinterable particles may be contained in a mold under their own weight while the spark discharge is carried out between electrodes extending into or forming part of the mold. It should be understood, however, that the slight mechanical pressure required may derive from one or more electrodes which may be spring biased or urged against the particles by gravitational force.

I have discovered, most surprisingly, that substantially all systems for applying metal particles to a substrate, while leading to an improved heat-exchanger structure by comparison with conventional finned systems in which continuous metal bodies are affixed by soldering or the like to metal tubes, have been prone to certain difficulties endemic in the heat-exchanger art. For example, the particle-particle bond and the particle-substrate bond are frequently unsatisfactory to the point that thermal stress induces separation of the particle mass from the substrate or break-up of the particle mass. Additionally, many, if not all, particle-particle interfaces and particle-substrate interfaces present sites for corrosion which is promoted when corrosion fluids form the heat exchange media and/or variable temperatures are encountered.

This can be avoided, according to the invention, by homogenizing the system metallurgically and electrically. More specifically, the present invention comprises the electrical sintering of a particle mass to a substrate, concurrently with or prior to an electrical homogenization whereby the particle-particle bond and the particle-substrate bond is produced at sites which monolithically combine the material of the two members. I have discovered, most surprisingly that the application of a high-frequency electric current of the order of 1 to 10 MHz is capable of effecting such homogenization at current intensities of a level sufficient to effect resistance welding. In other words, I may fuse the particles to the substrate by the spark-sintering method previously described or by any other method and then apply a high frequency train of pulses at a frequency of 1 to 10 MHz to effect homogenization. Furthermore, where the particles are magnetically permeable, i.e. consist of a ferromagnetic material, I apply the high frequency current pulses together with a superimposed direct current for homogenization and I may use the high-frequency pulses alone or in combination with direct current to effect the actual sintering. While I do not wish to be bound by any theory in this regard, I believe that the homogenization is accomplished by a skin effect heating of the particles and the substrate at their contact interfaces. Thus, when the particle mass is compacted around the substrate, and high-frequency pulses are applied, preferably of the order of 1 to 10 MHz and an amplitude of 0.1 to 100 kilo amperes, the resistive heating is most significant along the surfaces of the bodies and may even result in an intermelting at these localized areas while a total melting of the particles of substrate does not occur and the porosity is not adversely effected. For reasons which are not fully apparent, material of the conducting particles interdiffuses and material of the particles interdiffuses with material of the substrate so that a monolithic structure is created at the contact points. The electrical treatment may be accompanied by the application of mechanical or fluid pressure to densify the mass against the substrate if reduction of the porosity is desired.

Whereas prior-art systems for the sinter-bonding of particles to a substrate, generally using mechanical pressure and furnace-type heating, are characterized

by poor bond strength, corrosion resistance and mechanical strength so that descaling treatments may damage these heat-exchange surfaces and thermal stress may produce cracking or sloughing of the particle layer, the electrical homogenization technique of the present invention avoids all of these problems and additionally provides reproducible control of the porosity which is difficult with the prior-art systems.

The particles employed in accordance with the present invention to form the improved heat-exchanger structure are preferably of a spherical configuration of a selected size, as disclosed in my aforementioned application, so that point-like contact is established between adjacent particles. Thus, the particles are bonded intimately or monolithically to form a maximum number of pores of uniform pore size and in a greater number than is possible with particles of random or other configuration. These particles may be of selected different sizes, i.e., a homogeneous mixture of large-diameter spherical particles and small-diameter spherical particles, or may be stratified to provide large-diameter particles distal from the surface of the duct to which they are bonded and small-particles proximal to the duct. Some of the particles included in the mixture may be of a synthetic-resin material or some other material which is volatile at an elevated temperature achieved during the coarse of electrical sintering or electrical homogenizaton to provide voids or pores of a greater size, corresponding at least to the volume of the volatile particles in the resulting structure.

Thus, many of the techniques described below for the formation of sintered bodies of metallic particles and the formation of sintered masses of metallic and nonmetallic particles, e.g., metal particles and synthetic-resin particles, can be used in the production of heat-exchanger walls according to the present invention and subjected to electrical homogenization. The temperature during the electrical processing and, if desired, prior to electrical homogenization as long as the treatment step is carried out in a furnace, can then be raised to the thermal decomposition temperature of the nonmetallic particles if a nonoxidizing atmosphere is employed or the combustion temperature if an oxidizing atmosphere is provided.

DESCRIPTION OF THE DRAWING

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 following drawing in which:

FIG. **1** is an axial cross-sectional view through a mold for forming a tubular sintered body with the circuit means therefor;

FIG. **2** is a perspective view of the body produced by this apparatus;

FIG. **3** is a plan view of a sintered electrode for batteries;

FIG. **4** is a cross-sectional view taken on line IV—IV of FIG. **3**;

FIG. **5** is an axial sectional view through an apparatus for making the electrode;

FIG. **6** is a diagrammatic cross-sectional view through an apparatus for the mass production of sintered bodies;

FIG. **7** is a diagrammatic cross-sectional view illustrating the production of a conductive seal;

FIG. **8** is a view of this seal as employed in a battery;

FIG. **9** is an axial crsos-sectional view of a device for producing a sintered die;

FIG. **10** is a cross-sectional view diagrammatically illustrating the manufacture of a forming die or mold using the sintering technique of the invention;

FIG. **11** is a partial cross-sectional view of still another apparatus according to the invention;

FIG. **12** illustrates a circuit diagram according to a modification;

FIG. **13** is an axial cross-sectional view through a heat-exchanger tube in accordance with the invention;

FIG. **14** is a perspective cross-sectional view through a radiator produced by the present method;

FIGS. **15** and **16** are partial cross-sectional views diagrammatically illustrating two stages of the instant method;

FIG. **17** is a representation of a sintered body prior to molecular orientation;

FIG. **18** is a similar view of this body subsequent to such orientation in accordance with the invention;

FIG. **19** is an elevational view, partly in section, of an apparatus for continuously depositing a sintered layer upon a substrate;

FIG. **20** is a cross-sectional view through a sintered body having a continuous metal core and multiple layers;

FIG. **21** is an axial cross-sectional view through a mold for producing sintered bodies by spark discharges;

FIG. **22** is a view similar to FIG. **9** illustrating selective densification of the sintered body;

FIG. **23** is a partial bottom view of an apparatus for continuously producing sintered rods according to the invention;

FIG. **24** is a cross-sectional view taken along the line XXIV—XXIV of FIG. **23**;

FIG. **25** is a view similar to FIG. **24** illustrating a modification of the continuous process;

FIG. **26** is a diagrammatic cross-section of a heat-exchanger tube produced according to the present invention;

FIG. **27** is a perspective cross-section illustrating a plate of a plate-type heat exchanger;

FIG. **28** is a detail view of a portion of another heat exchanger in cross-section;

FIG. **29** is a perspective view of a lattice structure for heat-exchange purposes, e.g., in a regenerative type of heat exchanger;

FIG. **30** shows another lattice substrate in a partial perspective view, prior to application of the powder;

FIG. **31** is an elevational view, partly broken away and partly in diagrammatic form, of an apparatus for producing a corrugated heat-exchanger tube according to the invention;

FIG. **32** is a diagrammatic end view thereof;

FIG. **33** is a cross-section of a part of a wall of a heat-exchanger tube according to another feature of the invention;

FIG. **34** is a view similar to FIG. **33** but illustrating another embodiment;

FIGS. **35A** through **35C** are diagrammatic views of portions of a heat-exchanger wall drawn to vastly enlarged scale and illustrating the principles of the present invention;

FIG. 36A is a transverse cross-sectional view through another apparatus for producing heat-exchanger tubes in accordance with the invention;

FIG. 36B is a cross-sectional view taken along the line XXXVIB — XXXVIB of FIG. 36A, the receptacle containing the powder surrounding the tube;

FIG. 37A is a view similar to FIG. 36A wherein, however, the powder is fed by respective conveyors from four sides to the chamber surrounding the tube;

FIG. 37B is a longitudinal cross-section of the apparatus illustrated in FIG. 37A;

FIG. 38 is a vertical cross-sectional view through yet another apparatus for producing corrugated heat-exchanger pipes having a sintered-particle coating;

FIG. 39A is an axial cross-section through an apparatus for compacting the powder around the tube;

FIG. 39B is a cross-sectional view taken along the line XXXIXB — XXXIXB of FIG. 39A;

FIG. 40A is a vertical cross-sectional view through an apparatus in which the coating is compacted around the tube by shock-wave distortion of the tube;

FIG. 40B is a cross-sectional view through the deformed tube; and

FIG. 41 is a cross-sectional view of another device for carrying out the process of the present invention.

SPECIFIC DESCRIPTION

In FIG. 1 there is shown an apparatus for producing tubular porous bodies which can serve as filters or the like. The apparatus comprises a conductive base plate 1 upon which is disposed a tubular mold 2 having a core 2'. The mold cavity 3 of this mold contains a mass of sinterable particles which is compacted under the weight of an electrode 4. The shank 5 of this electrode is surrounded by a coil 7 which is supplied by an alternating-current source 8 for vibration of the electrode 4 in the direction of the arrow 6. Electrode 4 is urged downwardly (in the direction of arrow 9) by gravitational force. A battery 13 is bridged, in series with the secondary of a transformer 14 across the electrodes 1 and 4 while another direct-current source is connected in series with a load resistance 17 represented as a separate resistor but actually the resistance of the conductors tied to transformer 14. A capacitor 16 is connected across the battery 18 and resistor 17.

A mass of conductive powder or an admixture of conductive powder with up to 20 percent by weight of a nonconductive powder is disposed in the mold cavity 3 and vibrations initiated in the direction of arrow 6. With a frequency determined by the time constant of resistor 17 and capacitor 16, the latter periodically charges from battery 18 and discharges across the primary winding of transformer 14 when the switch 15 is closed. A pulsed current superimposed upon direct current of battery 13 is thus applied to the electrodes 1 and 4. A spark discharge is initiated between the electrodes 1 and 4 and the particle mass in contact therewith. Since the particles are in relatively light contacting relationship, this spark proceeds through the mass to form a coherent sintered body therefrom.

The mass of particles disposed in a graphite mold cavity serves as the workpiece below.

EXAMPLE I

The particle mass within the graphite mold 3 comprises a first layer 12 of relatively small-sized particles (e.g. having a particle size of approximately 0.025 mm). This layer is followed by a relatively larger layer of large-sized particles 11 having a particle size of about 0.1 mm. and is followed by another layer 10 of the small-size particles. The mass of particles consists, substantially uniformly, of 70 percent by weight copper and 30 percent by weight zinc. The resulting body, which is formed by a 400-cycle-per-second spark discharge having an overall intensity of approximately 250 kilojules over a processing time of 25 seconds, has a tensile strength of 7 kg. per mm.^{2} as compared with 5.3 kg. per mm.^{2} for a similarly dimensioned porous body produced by thermal fusion in a furnace and under elevated pressures. The total mechanical pressure applied to the mass of particles is approximately 50 kg. per cm.^{2}. Microscopic examination of the body fracture indicates that the pore distribution is substantially uniform (at a magnification of 50X) in contradistinction to the irregular pore formation of earlier bodies. In addition, the porosity is approximately 67 percent as compared with 60 percent for bodies formed by the known techniques. A total spark discharge of approximately 250 kilojoules was employed. The body was characterized by terminal zones 10 and 12 of relatively densely packed material which served to reinforce these regions of the body which had a total weight of approximately 450 g.

EXAMPLE II

The metal particles of Example I were replaced by a mass of particles consisting substantially of 80 percent by volume of copper, 5 percent by volume of a synthetic resin (Bakelite phenolic), 5 percent carbon (graphite) and 10 percent lead. All of these materials were present as powders passing 325 mesh. The tube which had a diameter of 20 mm., an internal diameter of 10 mm. and a length of 15 mm., was formed by the passage of a spark discharge (repetition frequency approximately 400 cycle/sec.) having a total energy of 10 kilojoules for a period of 3 seconds. The mechanical pressure applied was approximately 500 g. per cm.^{2}. The resulting bearing sleeve had a friction coefficient (0.02) which was substantially improved over a conventional sintered copper lead bearing (friction coefficient 0.065; wear ratio 2.7 mm./km.) having similar proportions of copper and lead; the improved bearing had a wear ratio of 0.87 mm./km. at 8 meters/sec. speed against carbon steel with motor oil lubricant and a contact pressure of 12 kg./cm.^{2}.

In FIGS. 3 and 4 there is shown a sintered nickel electrode for use in nickel/cadmium batteries and capable of highrate discharges. The electrode 19 has a peripheral zone 20 of relatively porous material and an internal core 21 of relatively dense material which is bonded to a contact plate 22. Zone 21 is formed in situ by the concentration of electric current as can be seen in FIG. 5. In the latter figure, a nonconductive mold 23 is disposed upon a conductive electrode plate 24 which is juxtaposed with a rotatable electrode 25. A direct-current source 27 is bridged across these electrodes in parallel with an alternating-current source 26.

EXAMPLE III

A mass of nickel powder having a particle size of approximately 2 microns is disposed in the mold 23 and a nickel plate set eccentrically in the mass. This nickel plate has a thickness of 0.2 mm. and is of 3 mm. width and 5 mm. length and rests against the electrode 25 (15

mm. diameter, 5 mm. thickness), which is rotated to prevent adhesion of the particles thereto. A mechanical pressure of 150 g./cm.^{2} is applied to the mass and a spark discharge (repetition frequency 400 cycles/sec.) of approximately 180 kilojoules is passed therethrough for about six seconds. The alternating-current power (400 cycles/sec.) is approximately 60 percent of the direct-current power with a frequency of about 10 kc./sec. The resulting body had a diameter of 15 mm. and a thickness of about 5 mm. with a central region **21** having a thickness of approximately 1 mm. while the peripheral zones **20** had thicknesses of about 2 mm. The porous outer shell was characterized by a specific gravity of approximately 2 while the dense inner core had a specific gravity of approximately 7. Examination of the sintered body structure indicated a relatively sharp separation between the core and the shell. The resulting electrode was capable of discharging rates up to ten times that attainable by known practices in a nickel-cadmium cell charged at 30 ma. for 12 hours and discharged at 50 ma. over a period of 6 hours.

The apparatus in FIG. **6** serves for the serial production of sintered bodies and comprises a piston **28** which urges a mass **37** of sinterable powder within a casing **29** into the cavity formed within a mold **30.** The mechanical pressure is, however, less than 100 kg./cm.^{2}. A pair of electrodes **31, 32** are slidable into the mold cavity, electrode **32** being provided with a drive source **34** for reciprocating it in the direction of arrow **35.** Electrode **31** is spring biased by a coil spring **33** and yields as member **32** is positively reciprocated so that a pressure of up to 100 kg./cm.^{2} is maintained upon the mass within the mold cavity. The electrodes are connected across a source of direct current and of periodic current superimposed thereon. With each reciprocation of electrode **32,** a spark discharge is sustained between the electrodes, which results in sintering of a body within the cavity of mold **30.** As electrode **32** moves into its extreme left-hand position, it pushes the sintered body thus formed out of the cavity from which it falls in the direction of arrow **36.** When electrode **32** is again withdrawn from the cavity, piston **28** pushes additional powder into the latter for repetition of the operation.

In FIG. **7,** I show the in situ formation of a sintered body in forming a liquid-tight seal. A battery casing **38** is provided with a bore which constitutes a mold for a mass of sinterable particles **39** which is disposed between electrodes **40** and **41.** The latter are bridged by a direct-current source **44** in series with a resistor **43** and by a capacitor **42.** The spark discharge developed across the electrodes **40, 41** results in a sintering together of the particles **39** and a thermobonding of the sintered body with the battery casing **38** which may be of thermoplastic plastic or synthetic-resin material. Particles, having a maximum size of approximately 10 microns, can be used in this connection to produce a liquid-impermeable seal which nevertheless permits the escape of gases and is conductive.

As can be seen in FIG. **8,** the sintered body **39'** thus resulting may be spark welded to a mass **45** of sintered particles carried by a battery electrode **46** and to a mass **47** of similarly sintered particles provided on the terminal tab **48.** This arrangement, wherein all of the particles may, advantageously, provide means for completely sealing the terminal to the case to prevent the escape of liquids.

In FIG. **9** there is shown an arrangement for producing dies. A conductive block **49** is formed with a contoured mold cavity **50** which contains a mass of particles **51.** A counterelectrode **52** overlies this mass of particles and is provided with a support rod **53** via which it is spring biased into contact with the particles. A battery **54** is bridged across the electrodes **52** and **49** together with a capacitor **55** while a delay line, consisting of inductances **57** and capacitances **56,** is also connected across capacitor **55.** This delay line provides a series of secondary pulses which follow the initial spark discharge as produced by capacitor **55.**

EXAMPLE IV

A mass of ferrochrome (18–8) stainless-steel particles having an approximate particle size of about 14 microns is disposed in the cavity **50** of block **49** which consists of carbon. The vertically vibrating electrode **52,** which is composed of high-carbon steel, provides a mechanical pressure downwardly of 0.56 kg./cm.^{2} (maximum pressure 270 kg./cm.^{2}). The direct-current voltage of source **54** is about 50 volts while the delay line **56, 57** together with capacitor **55** superimposes an alternating-current voltage thereon of approximately 400 cycles per second with an intensity of 120 volts. The spark repetition frequency was 400 cycles/second and the total discharge intensity **27** kilojoules. The sintered body is bound firmly to the electrode **52** and has a specific gravity equal to 99 percent of the specific gravity of solid ferrochrome when the electrode is vibrated in the direction of arrow **58.** This vibration takes place at 100 cycles per second. Without such vibration this specific gravity is only 98 percent of that of the solid material. To produce a die having a length of 20 mm., a width of 10 mm. and a thickness of 10 mm. approximately, 10 seconds are required. The duration of the spark discharge is, however, only a fraction of the total processing period (e.g., less than 1 second). A die sintered in a conventional furnace has a specific gravity of 88 percent of the solid material.

In FIG. **10** I show another arrangement, this time for the production of a female die, wherein the carbon-steel block **59** is provided with a cavity **60** containing the particles **61.** An electrode **51'** of sintered metal is carried by a plate **52** and serves to form the contoured sintered female die. The entire unit is enclosed in a casing **62** from which air may be aspirated at **63** and into which a suitable atmosphere may be introduced via an inlet **64.**

The block **59** is carried by a pair of leaf springs **65** and is vibrated in the direction of arrow **66** by suitable means not shown. In the present embodiment the delay line disclosed in connection with FIG. **9** is dispensed with and the circuit means includes a spark gap **67** of predetermined dimension which is tied in series with the capacitor **68** across the electrodes **52** and **59.** A battery **69** in series with a choke **70** and the lead resistance **71** is bridged across the capacitor **68** with a switch **72.** The characteristics of this circuit are so selected that the pulsed direct-current discharge of capacitor **68** and battery **69** is insufficient to bridge the spark gap **67** during initial sintering when a sintering gap is present between the electrodes but is, however, capable of continuously discharging across gap **67** when an initial sintering of the powder has been effected. To produce a breakdown or discharge across gap **67** during the earlier stages of operation there is

provided an additional circuit consisting of a rectifier bridge **73** which is tied to the secondary of an isolating transformer **74** supplied by an alternating-current source **75.** This direct current does not flow across the gap **67** and the capacitor **68** until supplemented by a triggering pulse derived from a rotatable inductor **76** of magnetically permeable material. An energizing coil **78** is supplied by a direct-current source **78** to develop a constant magnetic field which, when traversed by the projections of wheel **76,** is concentrated and swept across a pick-up coil **80,** in series with rectifier bridge **73.** Rotation of wheel **76** by motor **81** results in the periodic sweeping of coil **80** by the tabs with a consequent induction of a primary breakdown pulse and a plurality of lesser pulses. The pulsed current (e.g., at a frequency of about 400 cycles per second) for ferrochrome powder as employed under the conditions indicated in Example IV continues only until the spark discharge through the particles **61** terminates. Thereafter, with gap **76** in a substantially constant state of discharge, a direct current is applied to the electrode by battery **69** as supplemented by bridge **73.**

The apparatus shown in FIG. **11** can be used for the production of sintered bodies under continuously controlled conditions. The nonconductive mold **82** is disposed upon an electrode plate **83** and contains the powder **84** which is lightly compressed by a counter electrode **85.** The mechanical pressure of the latter is determined by the position of its piston **86** which is received within a hydraulic cylinder **87.** Hydraulic fluid is supplied to the latter by a distributing valve **88** which is fed by a pump **89** from a reservoir **90.** The distributing valve **88** is controlled by a solenoid coil **91** bridged across the electrodes **83** and **85** and responsive to the potential drop thereacross. It will be immediately apparent that this potential drop is a direct measure of the density of the particles since greater compaction involves a decreased resistance thereacross. Additionally, there is provided a magnetostrictive vibrator for oscillating the electrode **85** within limits. This vibrator comprises a pair of windings **91, 92** connected in aiding relationship and wound about the shanks of a D-shaped coil **93.** These coils are energized by an alternating-current source **94** whose output is superimposed upon a direct-current voltage derived from a battery **95.** A capacitor **96** is tied in series with source **94** across the coils **91, 92** while a choke **97** is serially connected with battery **95.** The direct-current biasing potential applied to the electrodes **83, 85** derives from a rectifier bridge **98** which is fed by a secondary winding of transformer **99** whose other secondary applies a superimposed alternating current. Again the electrodes are bridged by a capacitor **100.**

Whereas the arrangement shown in FIG. **12** permits control of the density of the sintered body by varying the mechanical pressure applied thereto, it is preferable in many instances to control the density by the characteristics of the spark discharge. This may be effected by regulating the frequency of the discharge at least during the early stages. To this end the direct-current source **101** is connected in series with the output winding of a transformer **102.** This transformer forms part of a varying-frequency oscillator and is saturable to control this oscillator. The oscillator consists of a pair of push-pull transistors **103, 104** whose emitters are energized by a battery **105** in series with respective sections of the primary winding of the transformer. The base of each transistor is serially connected with the energizing windings of the transformer and returned to the emitter via a suitable biasing resistor **106.** The transformer is also provided with a control winding **107** in series with a rectifier **108** and a variable resistor **109** for determining the degree of saturation of the core and thus the frequency of oscillation. The control circuit is bridged across the electrode **110, 111** and detects the direct-current-voltage drop thereacross. This circuit is poled so as to increase the frequency of the oscillation should the density of the sintered body, below a predetermined value, fall.

In FIGS. **13** and **14** there are illustrated heat-exchange arrangements produced by the method and apparatus of the present invention. The structure of FIG. **13** makes use of a sintered sheath **112** to provide a fluid-permeable layer of high-surface area around and through which a gas or liquid can pass as indicated by the arrows **113.** This layer can be formed with the usual fins **114** and is bonded to the metallic tube **115** which is internally contoured (i.e., provided with annular depression **116**) to increase turbulence in the fluid flowing therethrough. A radiator **117** of FIG. **14** is provided with channels **118** formed by relatively coarse particles (particle size between **60** and **100** microns) between dense rows formed by fine particles (**5** to **6** microns). The entire body, which can be formed in a single sintering operation by the methods previously described, can be composed of copper particles and has excellent heat-exchange characteristics.

FIGS. **15** and **16** are schematic illustrations as to what occurs in the course of the present method. During the initial stages of sintering, the bodies **119** and **120,** which are generally of irregular configuration in practice, are in light contact or even slightly spaced so that a spark discharge is formed between them. This discharge forces them into contact under considerable pressure and effects a flow of material between them at their contact region. Subsequent passage of current (FIG. **16**) causes the particles to flow together to a greater extent and, since it is effected under the force field of a unidirectional electric current, results in an internal crystal orientation so that the fusion point is indistinguishable from the remainder of each particle. They thus constitute a single crystal. This effect characterized substantially all of the methods presently described.

The molecular orientation of sintered bodies is more dramatically represented in FIGS. **17** and **18** wherein magnifications of oriented and nonoriented bodies of sintered dendritic material are shown.

EXAMPLE V

A mass of dentritic Alnico alloy particles, having a mean particle size of 0.1 mm., are formed into a rod having a diameter of about 2 mm. and a length of 5 mm., is formed in an apparatus of the type shown in FIG. **12** (graphite holder). A spark-discharge sintering operation (total time 10 sec.) was performed and a total energy of 10,000 joules at an ambient pressure of 10^{-2} mm. A pressure of 250 kg./cm.^{2} was applied during sintering. The sintered body was removed immediately after the first discharges (about 2,500 joules — 5 seconds) and found to have a random distribution of 10-micron dendrites when etched with HNO_3+alcohol (FIG. **17**). When the operation was carried out again with about 5,000–7,500 joules required (10 seconds

used), the dendrites were found to be aligned in uniform rows about 0.5 mm. in length and 0.3 mm. in width (FIG. **18**). The corrodability of the molecularly oriented body was found to be less than that of the similarly sintered but not oriented body when exposed to etching liquid. In addition, similar test conditions indicated that the resistance-sintered conventional magnet had a strength of 1,500 to 2,000 gauss while spark-sintered bodies had a minimum strength of 2,000 gauss to molecular orientation and from 3,500 to 4,000 gauss subsequent thereto.

EXAMPLE VI

Similar techniques were employed with a magnetic mixture consisting by weight of 85 percent iron, 10 percent zinc and 5 percent Cu_2O. The mixture was formed in suspension in a volatile vehicle (ethyl alcohol) and a discharge current passed therethrough at a pressure of 130 kg./cm.^{2} applied to the particles in the holder. About 5,000 joules were employed during the discharge sintering and the remainder for orientation. A total time of 3 seconds was required for a rod having a length of 5 mm. and a diameter of 10 mm. in a graphite holder. All of the particles ranged in size between 5 and 10 microns. The ferrite rod was found to have greater magnetic retention (1.7 oersteds) than rods having similar Fe contents but formed by conventional techniques from iron oxide (1.5 oesteds).

The apparatus of FIG. **19** permits continuous formation of sintered layers upon a metal substrate. The substrate **121** may be a metal sheet to be clad with the sintered metal layer to improve its fatigue and corrosion resistance, is passed between a pair of rollers **122, 123** serving as counterelectrodes for the sheet. As the upper layer of, say, ferrochrome powder **124** is deposited upon the sheet and bonded thereto while being sintered into a coherent coating upon passage into the spark zone at electrode **112,** the lower layer **126** is carried by the conductive band **125** into the spark zone and bonded thereat to the substrate.

EXAMPLE VII

A dumbbell-shaped rod having enlarged extremities (50 mm. diameter) and a shank of smaller diameter (30 mm.), the total rod length being about 150 mm. with the shank having a length of 50 mm., is provided with a surface coating of 0.02 mm. of tungsten carbide by spark discharge. The rod was poled negative with the counter-electrode positive while a total power of 2,000 joules was employed for a sintering time of 4 seconds at a pressure of 3 kg./cm.^{2}. The particle size was 0.5 micron. Repeated bending under a stress of 50 kg./mm.^{2} on an ONO-type rotary fatigue-testing machine demonstrated that an uncoated high-carbon steel rod broke after 5×10^3 cycles while the treated rod broke only after 5×10^5 cycles.

The substrate **127** of FIG. **20** is shown to be provided with a plurality of superimposed layers of sintered metal. It is thus possible, merely by positioning a series of layers of different metal particles in one of the molds previously described to bond, say, an aluminum layer **128, 129** to a layer of copper **130, 131.** This in turn may be fused directly to the metal or to a nickel layer **132** thereon. Since the atomic size of aluminum is less than that of the steel substrate, there will be little tendency for the aluminum to adhere directly to it.

In the arrangement of FIG. **21,** a casing **133** forms a separable mold into which extend the juxtaposed spaced electrodes **134** and **135.** The circuit means **136** develops a space discharge, which is spread by the dielectric distributor **137** to the periphery of the body, between the electrodes to sinter the particles together and imbed the electrodes therein.

Another device for localizing the passage of current in the sintering of powders is illustrated in FIG. **22.** The conductive but highly resistant block **138,** which may be composed of carbon, is engaged by spaced contacts **139** of an electrode **140.** The spark discharge developed between a counterelectrode **141** and the block **138** is localized in the region of contacts **139** since these regions constitute low-resistance paths, thereby producing a sintered body having increased density at these regions.

The apparatus of FIGS. **23** and **24** is designed to permit the continuous sintering of particles into a coherent rod. The apparatus comprises a pair of shaping rollers **142** which are spaced from each other and pass a spark discharge through powdered metal **143,** supplied by the hopper **144,** therethrough. The emanating rod is coherent and may constitute an electrode as indicated in FIG. **25.** In this case the feed plunger **146** applies a light mechanical pressure to the powder within the hopper **147** whose constriction **148** forms a die. Since the previously formed rod **149** is coherent and conductive, it may constitute an electrode so that a spark discharge results at the die. A magnetic shaping of the coherent rod, which nevertheless is somewhat plastic as a result of its elevated temperature, is carried out by applying a pulsed current through a surrounding winding. This pulsed current is developed across a spark gap **151** by a capacitor **152** as previously described.

A pair of rollers **153, 153'** serve as contacts for the rod **149.** Roller **153'** is connected to one output terminal of a circuit whose battery **154** bridges the electrodes in parallel with an alternating current source **155.** The latter is, in turn, tied to a saturable reactor **156** which controls the A-C power level and has its biasing winding in series with the wiper of a potentiometer **157.** The latter is in circuit with a biasing battery **158** across the rollers **153, 153'.** Should the density of the rod **149** suddenly fall, the voltage drop detected across rollers **153, 153'** will increase to cause the saturable reactor to raise the power level and vice versa.

In FIGS. **26** through **34,** I have shown the application of some of the above principles to other heat-exchanger forms while FIGS. **35A** through **35C** illustrate these principles as applied to heat-exchanger surfaces. In FIG. **35A,** for example, I have shown a heat-exchanger substrate **200** which may represent the wall of a heat-exchanger tube or a heat-exchanger plate. It will be understood that, throughout this discussion, the heat-exchanger members may be used in conventional heat-exchanger structures and that the term "heat exchanger" is intended to be used in its broadest sense to include any member involved in heat transfer from one fluid to another. For example, heat-exhanger tubes according to the present invention may be collected in the tube nests or bundles and provided with the usual headers and housings to pass liquid through the tubes while a gas is passed along the outer surfaces thereof. The heat exchanger may be a boiler or can form part thereof, in which case one wall of the heat exchanger

may be exposed to combustion products while the other is in contact with the fluid to be heated.

Moreover, the heat exchanger may be of the liquid-liquid type in which liquid contacts both sides of the heat-exchanger surface, of the liquid-gas type, wherein liquid contacts one surface and gas contacts the other, of the gas-gas type in which gaseous fluids contact both surfaces of the heat exchanger, and of the regenerative type in which a first fluid contacts the heat-exchange body at one type and another fluid contacts the body at a different time to transfer heat to or abstract heat from this body.

Referring to FIG. **35A**, however, I have described the invention generally in terms of an indirect or nonregenerative heat exchanger in which heat transfer is effected between a fluid in contact with the inner surface **201** of the tube and another fluid in contact with the outer surface **202** thereof by heat transfer through the tube wall. In this case, the tube wall consists of the continuous-metal member **203** of a metal of high thermal conductivity, e.g. aluminum or copper, upon the outer surface **204** of which has been deposited a particle layer **205**, discrete particles of which are designated at **206.** The particles have been applied by any conventional compacting technique, e.g., high energy rate forming as described in U.S. Pat. No. 3,566,647 or any of the prior applications or patents described therein, as described in U.S. Pat. No. 3,552,653, as described in the parent applications of the present case, or as described in the sintering art whereby mechanical compaction is followed by furnace heating. Wherever conventional procedures are used, however, the particle-to-particle interfaces **207** and the particle-to-substrate interfaces **208** are insufficiently monolithic to prevent corrosion.

In FIG. **35B**, is can be seen that the electrical sintering methods previously described in the constant application tend to result in homogenization of the particle-to-particle bonds so that discrete particles are seldom discernible and the metal of the particle mass forms bridges around the pores **209** which remain. However, a contact interface tends to remain at **210** between the particle mass and the substrate **203**, although bonding occurs, for the most part.

With the homogenization step of the present invention, practiced upon a conventionally compacted particulate mass or even upon the electrically sintered mass previously described, substantially no interface remains at **211** and a monolithic structure is formed. The homogenization step is, therefore, effectively a welding operation using pulsed electric current with preferably square-wave pulses, although sinusoidal signals have been successfully used, at a frequency of 1 to 10 MHz, a current of 0.1 to 100 kiloamps. and conditions in which fusion welding may occur.

In FIGS. **31** and **32**, moreover, I have shown an apparatus for effecting such fusion. In this embodiment, a copper tube **220** forms the substrate and is coated with aluminum, copper, nickel or iron powder shown as a mass **221**, the powder having a particle size ranging in order from a 0.1 millimeter to 5 millimeters and preferably between 0.1 and 0.5 mm. In this diagrammatic illustration a mass of particles **221** is fed around the tube **220** between a plurality of compaction dies **223, 224, 225** and **226** which are movable readily toward and away from the copper tube by, for example, fluid cylinders **227** only one of which has been shown in FIGS. **31** and **32.** All of the cylinders are triggered simultaneously by a timer **228.**

I have found it to be highly desirable to provide a graduated cross-section for the shaping die so that the opening of the latter is reduced progressively in the direction of feed of the powdered material and the substrate and I preferably accomplish this by providing matching undulating profiles **229** along the confronting faces of the dies. The dies may also be replaced by rollers or the like which define the progressively tapering cross-section and may be profiled to form ridges, fins or undulations **230** on the finished pipe as illustrated. A source of high-frequency welding pulses is provided at **231** (diagrammatically illustrated) the source being connected between the substrate **220** and the individual die members **223** through **226.**

When iron or other ferromagnetic particles are used, however, I prefer a superimposed direct current from a source **233** upon the high-frequency pulses by closing a switch **234.** Diodes **235** may be provided in the d-c circuit to prevent short circuting of the high-frequency source through the d-c source. The d-c contribution may be of the same order of magnitude as the pulse contribution in terms of the current amplitude and may range between 0.1 and 100 kiloamps., although I prefer to provide a pulse current/total current ratio of substantially 20 percent to substantially 80 percent, the balance being the direct current contribution. The operation of the apparatus of FIGS. **31** and **32** is evident, the pulses being passed as the powder is compacted progressively around the substrate at pressures ranging between 10 kgs/cm^2 and tons/cm^2. The welding current pulses and, in the case of ferromagnetic powders, the superimposed pulse and direct current, produce a homogeneous bond as described in connection with FIG. **35C.**

In FIG. **26,** I have shown an embodiment of the tube, according to the invention, wherein the outer surface of the copper substrate **240** is provided with an undulating layer **241** of the powder while an undulating layer **242** of the powder is provided on the internal surface. The substrate in this case is undeformed, i.e. is not corrugated to correspond to the corrugations of the powder layers. However, the thicknesses of the powder mass may remain constant and the substrate may be deformed to provide the desired turbulance-promoting formations. The corrugations in this embodiment are shown to be substantially parallel, although a helical arrangement fo the formations may be provided as well. The plate-type heat exchanger **243** illustrated in FIG. **27** comprises a copper sheet **244** deformed to have cup-shaped recesses **245** and generally spheroidal bulges **246** and is covered with a uniform coating **247** and **248** of powder in the manner described, both along its exterior and interior surfaces. As shown in FIG. **28,** the bulges **250** may be provided with perforations **251** opening into cup-shape layers **252** of powder. In this case, the powder layer covers only the protuberance on bulges of the plate and serves as both a diffusion layer, through which a fluid is dispersed, and a heat-exchange surface of high area and porosity. The regenerative heat-exchange body **253** illustrated in FIG. **29** comprises a lattice work of tubules or rods covered by the powder layer **255** in the manner previously described; in FIG. **30,** I have shown a lattice-like array of bars **256** adapted to form the substrate.

In FIG. **33**, the substrate is shown to be a tube **260** provided wtih steep corrugations on fins **261** which are coated with a layer **262** of the powder in a uniform thickness whereas the contours of the powder layer **263** of the tube **264** of FIG. **34** do not necessarily follow those of the pipe.

EXAMPLE VIII

A copper tube having an outside diameter of 25 mm serves as the substrate and is coated with a layer of copper particles with a particle size 0.34 mm to a thickness of 3mm. The tube and the layer are uniformly corrugated with a pitch of 5 mm using the apparatus generally illustrated in FIGS. **31** AND **32.** The tube is fed at the rate of 3 cm/sec through the apparatus and has an internal diameter of 19 mm. The applied pressure is 47.5 kgs/cm^2, the temperature fusion is 970°C and pulses of a mean current of 1,000 amps where applied at a frequency of 1.8 MHz. The tube is compared with an otherwise similar tube heated to 970°C in a furnace and formed with the same pressure. With liquid-flow rates of 250 mm/sec through the interior of the tube, with a temperature differential of 5° Centigrade across the tube, the heat conductivity in kilocalories/m^2 per hour per degree was about 2×10^3 for the nonhomogenized tube while the heat conductivity was about 4×10^4 for the electrically homogenized tube. At 10°C temperature differential, the heat conductivity was about 5×10^3 for the conventional tube but about 10^5 for the tube according to the present invention. When iron particles were substituted, the pulse current was 600 amps and 800 amps of direct current was superimposed thereon. The bonding speed was 8 cm/sec and the bond strength was 15 kg/cm^2 as compared with a bond strength of 3 to 4 kg/cm^2 obtainable by soldering.

In the arrangement shown in FIGS. **36**A and **36**B, a copper heat-exchanger tube **320** is imbedded in discrete copper or aluminum particles **321** of spherical shape and passed through a bonding chamber **301** machined from graphite and which retains the particles in a loosely packed mass under a light pressure p up to, say, 10 kg/cm^2. The chamber **301** is provided with an inlet guide **302** formed by an annular insulator through which the tube **320** is introduced and an outlet mouth **303** which constitutes a shaping die. A power source **304** is connectable, by means of switch **304***a*, across an electrode **305** in contact with the chamber **301** and roller electrodes **306** in contact with the tube **320** to pass through the latter and the particles **321** a single or succession of impulsive current thereby electrically fusing the particles in the region of the tube and, especially, surrounded by the forming die **303,** intimately against the tube **320.** Thereupon, a feed drive **307** may be actuated to axially advance the tube in the direction of arrow to feed out that length of the tube to which the particles bonded as represented at **330** and may then be deactuated to close the switch **304***a* to recommence the sintering operation over the next given length of the tube **320.** A timer **308** is here associated with the switch **304***a* and the feed drive **307** to determine the duration of each cycle of such progressive sintering operation and intervals or the unit length of such stepped feed. It has been already noted that use of spherical particles is preferable because of the advantage that they, when relatively loosely packed and then bonded together especially according to the present process, assure such a porous structure having intercommunicated voids and being essentially free from blind pores but with each particle-to-particle and particle-to-substrate bond forming a monolithic junction. Spherical particles are conveniently available commercially and may be those prepared by atomizing a molten metal into a liquid coolant.

EXAMPLE VIII

A copper tube having an outside diameter of 3mm and a thickness of 0.5 mm is fed through a chamber as diagrammatically shown in FIGS. **36**A and **36**B and in which spherical copper particles of a diameter of 0.4 mm are retained under a pressure of 1.5 kg/cm^2. When an impulsive electric current of 360 joules is applied between the electrodes, the copper tube receives over a length of **40** mm a uniform layer of 2 mm thickness of the particles bonded thereto, with the bond strength of 8.2 kg/mm^2. Those particles located at a distance beyond 2 mm from the tube surface are considerably heated but not fused together or to the graphite die surface and are dislodged as the tube is fed out from the die mouth.

In a further embodiment shown in FIGS. **37**A and **37**B which represents a modification of the preceding embodiments, a plurality of particle feeders **410** are associated with the forming chamber **401** and provided each with a screw conveyor **410***a* and a motor **410***b* for driving same to feed a quantity of particles into the interior of the chamber **401** and to have them uniformly distributed around the tube body **420** under a light pressure maintained substantially constant. Here the feed of the tube **420** is either continuous or intermittent in conjunction with the feed of the tube **420** and a source of impulsive current **404** is connectable across electrodes **405** and **406** and may be replaced by a source of a high-frequency current as shown in connection with FIGS. **31** and **32.** The particle-cladding of a tubular heat exchanger substrate having a helical corrugation can be achieved using a modification shown diagrammatically in FIG. **38** which makes use of a die chamber **501** having a forming surface helically corrugated correspondingly to the exterior surface of tube **520.** This die member, mounted rotatably upon a base **511** by way of bearings **512,** is formed with gears at its annular flange **513** which engage with worm gears of a disk rotated by a motor. Particles **521** to be bonded together and the tube **520** are introduced in the region of the die surface **501***a* from an upper chamber **518** defined with the die chamber **501** and a source of impulsive or high-frequency fusion current is again provided across the die member **501** and the tube body **520,** the latter being biased downwardly. Thus, as the die member **501** is rotated axially while the fusion current is passed through the particles **521** and the tube **520,** the latter is nonrotatably driven out progressively with the particles sheath **530** intimately and uniformly bonded on the corrugated surface **520***a* of the tube **520.**

In some cases and, expecially where an additional machining such as bending is required of particle-bonded heat exchanger members, I have found it desirable to anneal the member before such machining so that any internal strain as produced in the member as a result of it being relatively rapidly cooled from the bonding high temperature to a room temperature and which would adversely affect such machining may be eliminated. I have found that members when annealed

at a temperature about 60 percent of the melting point of the constituent material permit a considerable bending without dislodgement of bonded particles.

In FIG. 39A, I show a high-frequency fusion process wherein the particles *q* are fed by a supply duct **660** under pressure from a conveyor of the like applied at **661,** axially to a funnel-shaped feeder **662,** coaxially surrounding the tube **663** which is fed through a guide bushing **664** in the axial direction by a gripper **665** engaging the leading end of the tube. At the mouth **666** of the funnel, there is provided a pair of compaction rolls **667** and **668,** driven in opposite senses, and having a concave periphery as shown at **669** to define a circular die **670** within which the powder is compacted and sintered around the tube **663** to form a layer **671.** The rolls **667** and **668** are keyed to shafts **672** which are mounted in vertically shiftable bearing blocks **673** guided at **674** for radial movement perpendicular to the tube. Compression springs **675,** set at the desired pressure by screws **676,** urge the rolls toward one another and bear against tthe journal blocks **673.** The shafts **672** carry meshing gear wheels **677** which are driven by a motor (not shown) or are simply entrained by the axial movement of the tube to which they are tangential. The displacement mechanism **665** includes a clamp whose jaws **678** and **679** are connected by a hinge and can be tightened by a bolt **680.** A welding current and sintering current source **681** is provided in the manner previously described.

In operation, the system functions as previously described to provide compaction, sintering and electrical homogenization.

In FIGS. **40A** and **40B,** I show another system for compacting a particle sheath about a thermally conductive tube according to the present invention, the tube being thereafter subjected to electrical homogenization as described. In this case, hydrostatic and spark forming may be used to deform the tube simultaneously with the coating thereof and any of the systems for this prupose set forth in my copending applications Ser. No. 805,117, filed Mar. 4, 1969 (as a continuation-in-part of my then pending applications Ser. No. 574,056; Ser. No. 629,633; and Ser. No. 696,757; the latter two having issued as U.S. Pat. Nos. 3,461,268 and 3,522,653 respectively, while the first has been abandoned and replaced by Ser. No. 64,104 of July 29, 1970) may be used. More particularly, the apparatus illustrated in FIG. **40A** comprises a liquid-containing chamber **701** which may be connected at **702** to a pump and is provided with a shock-wave generator represented generally at **703.** At the mouth of the tube, there is provided a die **704** in the form of a cylinder threaded into the barrel at **705** and provided with annular cavities **706, 707, 708** open inwardly and communicating with the atmosphere via air vents **709.** The die **704** may also be of the split type. A prebonded mass, e.g., lightly sintered ring or loose particle mass **710** may fill each of these cavities, whereupon the workpiece **711,** here a cylindrical tube, is inserted. The end of the die is closed by a cap **712.**

The shock-wave generator comprises a distructable conductor **713** which may be fed through an electrical insulated bushing **714** to the right from a supply reel **715** by a motor **716.** At the opposite side of the chamber, a fixed main-discharge electrode **717** is juxtaposed with the end of the electrode **713** across a discharge gap **718** and is received in the insulated bushing **719.** Transversely to the fusible electrode **713** extends a movable spark-discharge electrode **720** which is vertically shiftable in an insulating bushing **721** by the drive motor **722** whose wheel **723** may be formed as a pinion-engaging rack teeth on electrode **721.** A capacitor **724** is connected across the electrodes **717, 720** and is chargeable through a resistor **725** from a battery **726** or other direct-current source when a switch **727** is closed.

When a purely hydrostatic mode of operation is preferred, the entire chamber and the die are filled with the substantially incompressible, preferably dielectric liquid, e.g., kerosene or transformer oil and a spark is generated at **703** to produce a shock wave which is transmitted through the liquid to the workpiece simultaneously expanding the latter into the die cavities and compacting particles thereagainst to yield a tube structure as shown at **730** in FIG. **40B.** The corrugations **731,** produced by the annular die cavities, are shown to be coated with compacted powder **732** which can be in the form of the usual particle sheath subjected to electrical homogenization.

The apparatus of FIG. **40A** can also be used in a hydrodynamic mode. Thus the liquid level may be maintained at **733** in the chamber prior to spark discharge and the shock wave produced to propel the liquid into and compress gas trapped in the die to deform the workpiece and simultaneously clad it under the shock-wave pressure. Furthermore, I may prefer to operate the pump **702** to create a liquid stream which is directed against the workpiece or in the direction thereof and to superimpose the discharge thereon.

As described in application Ser. No. 805,117, moreover, the discharge can be triggered in any of several ways. Firstly, the capcitor can simply be allowed to charge to the breakdown potential of one of the gaps **718, 735,** whereupon incipient fusion of the electrode **713** and ionization along its length will permit a high energy discharge to pass initially between the electrodes **717** and **720** and the consumable electrode **713.**

As the electrode **713** is destroyed, the discharge bridges the electrode **717** and **720.** Furthermore, in addition or, as an alternative, it is possible to move either electrode **720** toward electrode **713,** or electrode **713** toward electrode **717** to reduce the gap and bring about the aforementioned breakdown.

It has also been found to be advantageous, in many instances, to apply high pressure to the chamber and thereby mechanically deform the workpiece with hydrostatic pressures before the shockwave is applied.

Another method of coating a substrate with the powder or applying the powder to the substrate has been illustrated in FIG. **41** and is based upon the teachings contained in my application Ser. No. 64,104 mentioned earlier. This application is a continuation of application Ser. No. 574,056 which, in turn, also is a continuation-in-part of application Ser. No. 311,061 (U.S. Pat. No. 3,267,710) and application Ser. No. 508,487, also mentioned above. In this system as well, the substrate coated with the powder can be subjected to electrical homogenization. The discharge chamber in this embodiment is formed as a barrel **1100** whose mouth **1101** is trained at the surface **1102** of the substrate **1103** which is thermally conductive and may be, as illustrated, a duct-forming part of a heat-exchange assembly. A gap **1104** is provided around the zone of the sur-

face **1102** surrounded by the barrel **1100** to prevent pressure increases therein from reducing the kinetic energy of the particles projected against the surface **1103.**

At the other end of the barrel **1100,** an insulating block **1113** receives a needle-type electrode **1112** which can be threaded into the barrel **1100** axially to a variable distance *t* from the region at which a hopper **1114** feeds the pulverulent material **1105** transversely into the barrel. The hopper **1114** is provided with a feed or metering mechanism **1115** whose motor **1116** is driven intermittently by a timer **1117** which also controls a switch **1109** in the supply circuit for the coating gun. The supply circuit **1106** comprises a direct-current source, shown as a battery **1108,** across which is bridged a capacitor **1107** in series with a charging resistor **1110.** The distance *t* is adjusted in this embodiment until closure of switch **1109** will result in a discharge behind the mass of particles **1105** whose presence reduces the breakdown voltage which must be applied between the needle **1112** and the barrel **1100** across which the pulsing source **1106** of the shock tube is connected.

When larger quantities of conductive powder are supplied at **1105** in the region of needle **1112,** the breakdown voltage is reduced and rapid pulses can be generated so that a train of discharges, at a repetition frequency determined by the timer **1117** and synchronized with the particle-feed means, can drive these particles against the surface **1102.** In general, the discharge takes place rearwardly of the particle mass **1105** and among these particles to partially ionize them trap their oxide films and effect direct transfer of kinetic energy to the particles in accordance with shock-wave principles. It will also be understood that the timer means need not be used inasmuch as closure of the switch **1109** will apply a given potential between the needle **1112** and the barrel **1100** so that firing of the discharge can be initiated either by advancing the needle **1112** or by introducing a sufficiently large mass of particles at **1105.**

I claim:

1. A heat-exchanger member comprising a thermally conductive metallic tube of cylindrical configuration and respective binderless layers of thermally conductive metal particles lying among the interior and exterior surfaces of said tube and intimately bonded together with monolithic junctions at the interfaces between the particles and bonded to said surfaces at monolithic junctions therewith, said layers being fluid permeable, said particles having a substantially spherical configuration and being molecularly bonded together and both said layers having an undulated profile.

* * * * *