US 20070131555A1

(19) United States
(12) Patent Application Publication
Thon et al.
(10) Pub. No.: US 2007/0131555 A1
(43) Pub. Date: Jun. 14, 2007

(54) APPARATUS FOR MANUFACTURING COMPONENTS USING ELECTROPHORETIC DEPOSITION

(75) Inventors: **Assaf Thon**, Haifa (IL); **Barry Neal Breen**, Givat Ze'ev (IL)

Correspondence Address:
MARSTELLER & ASSOCIATES
P O BOX 803302
DALLAS, TX 75380-3302 (US)

(73) Assignee: **CEREL (CERAMIC TECHNOLOGIES) LTD.**, Tirat Hacarmel (IL)

(21) Appl. No.: **11/313,100**

(22) Filed: **Dec. 20, 2005**

(30) **Foreign Application Priority Data**

Dec. 8, 2005 (IL) 172478

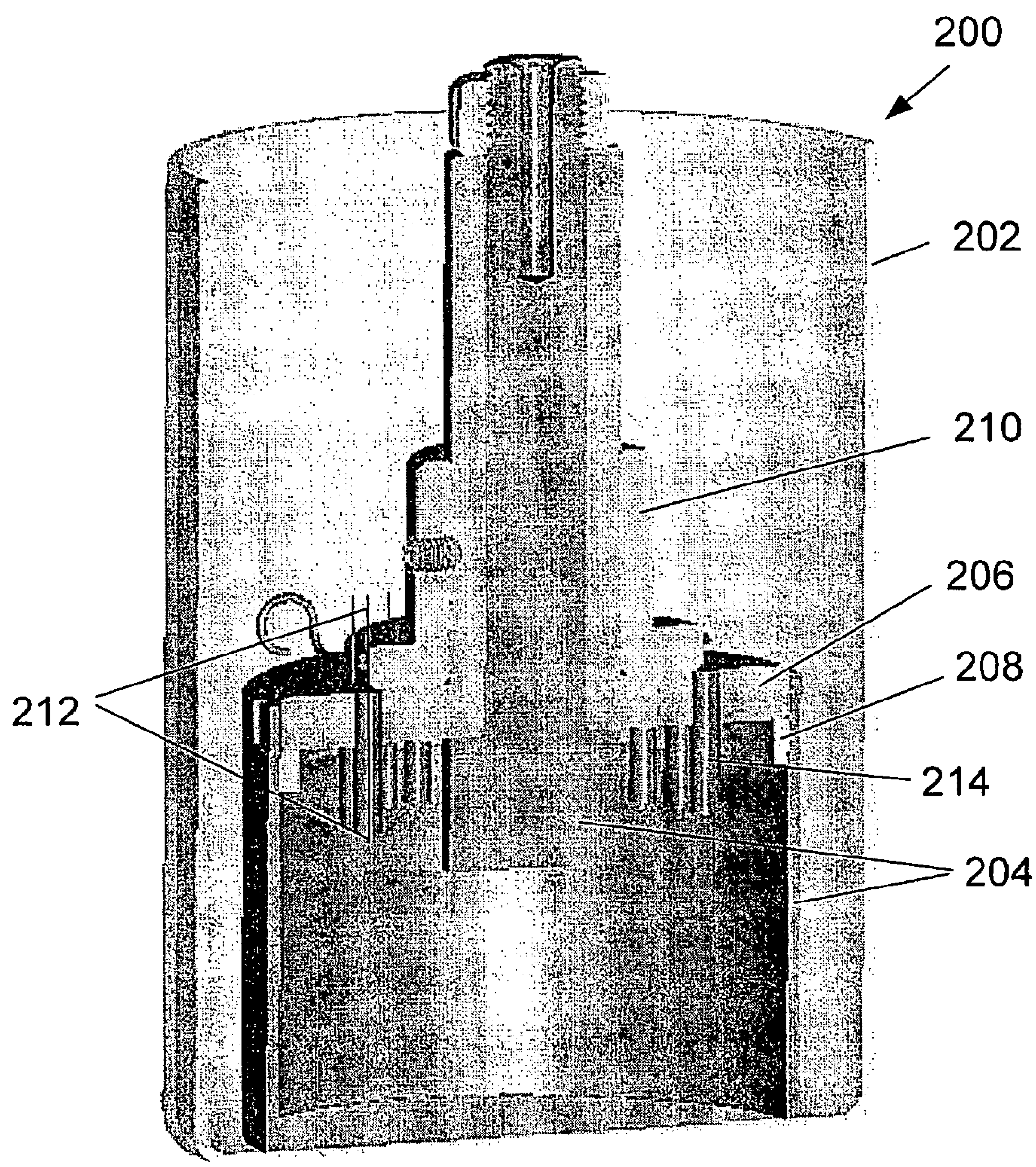
Publication Classification

(51) **Int. Cl.**
C25D 1/12 (2006.01)

(52) **U.S. Cl.** **204/622**

(57) **ABSTRACT**

The invention is an apparatus, methods and systems for the production of coatings or small components having defined pre-set dimensions and properties by electrophoretic deposition (EPD) on electrically conducting or semi-conducting substrates. The invention provides efficient and precise mass manufacturing of components by EPD, such as anodes of electrolytic capacitors, by achieving high utilization of expensive raw materials and by consistently achieving tight dimensional tolerances of defined component shapes in repeated depositions. This includes production sequences of discrete components, batches of components, and production by semi-continuous operation.



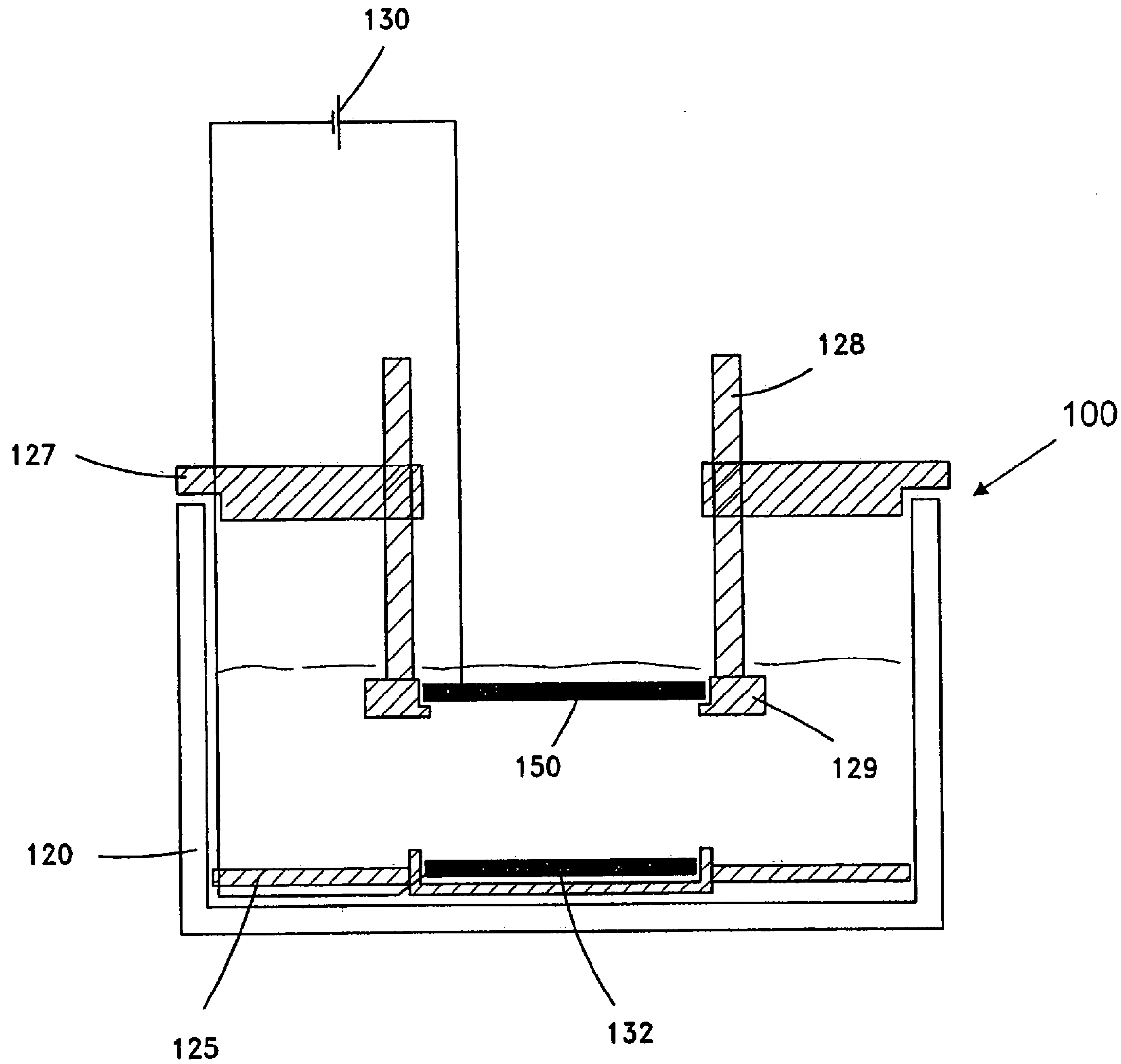


Fig. 1
PRIOR ART

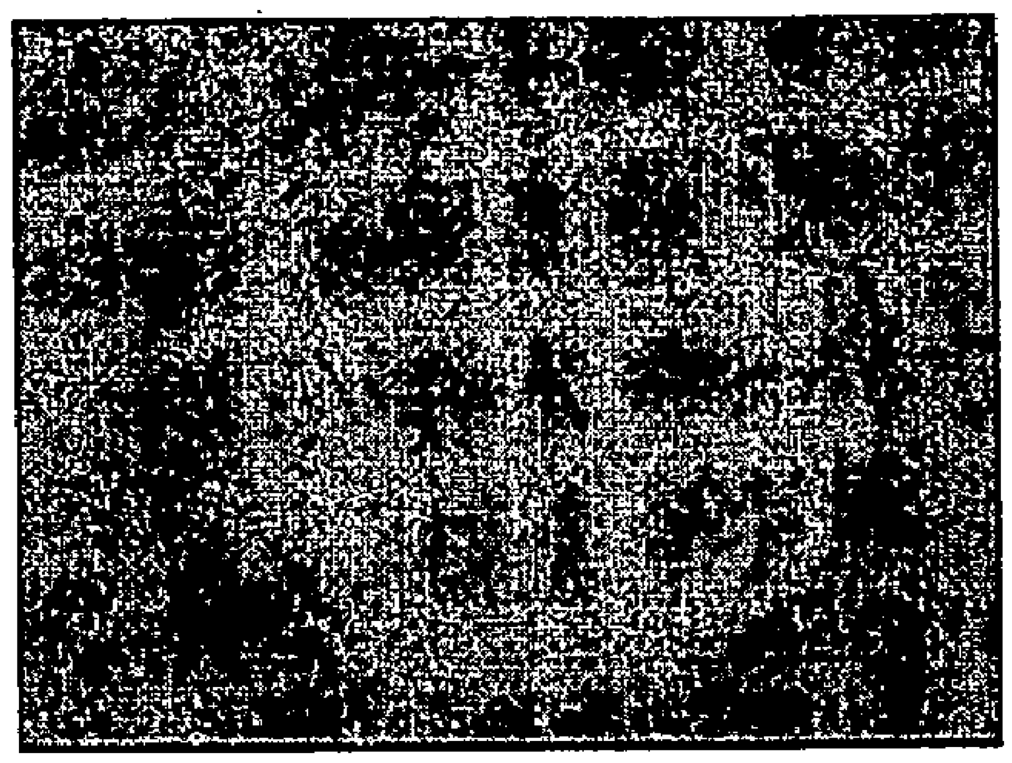


Fig. 2A

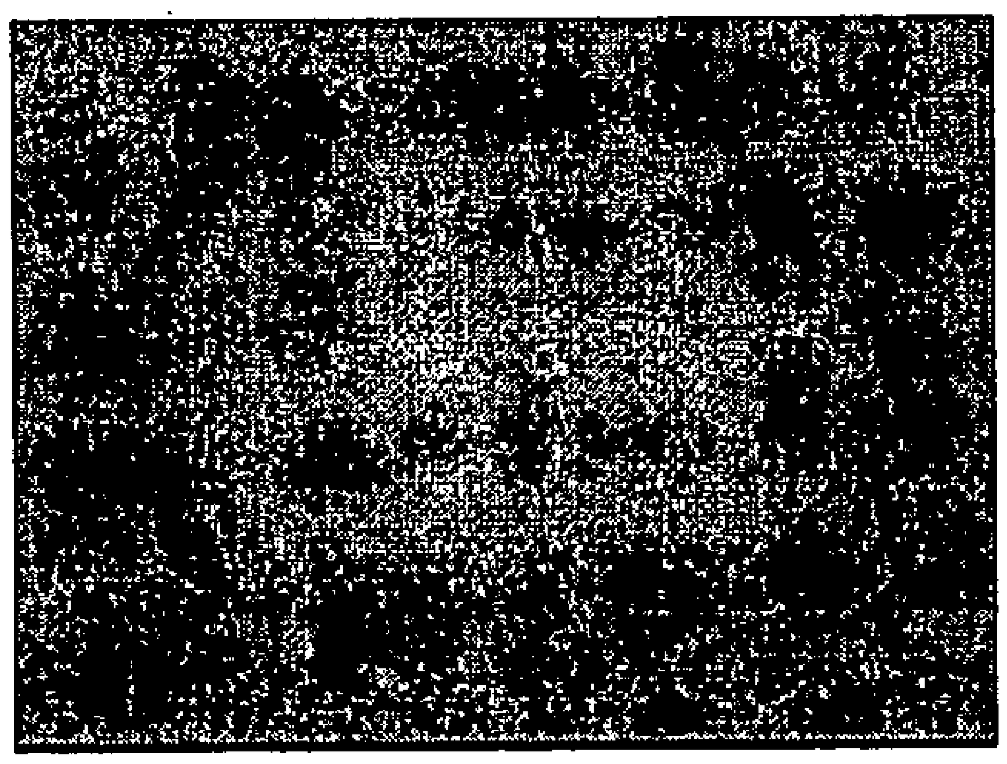


Fig. 2B

Fig. 2C

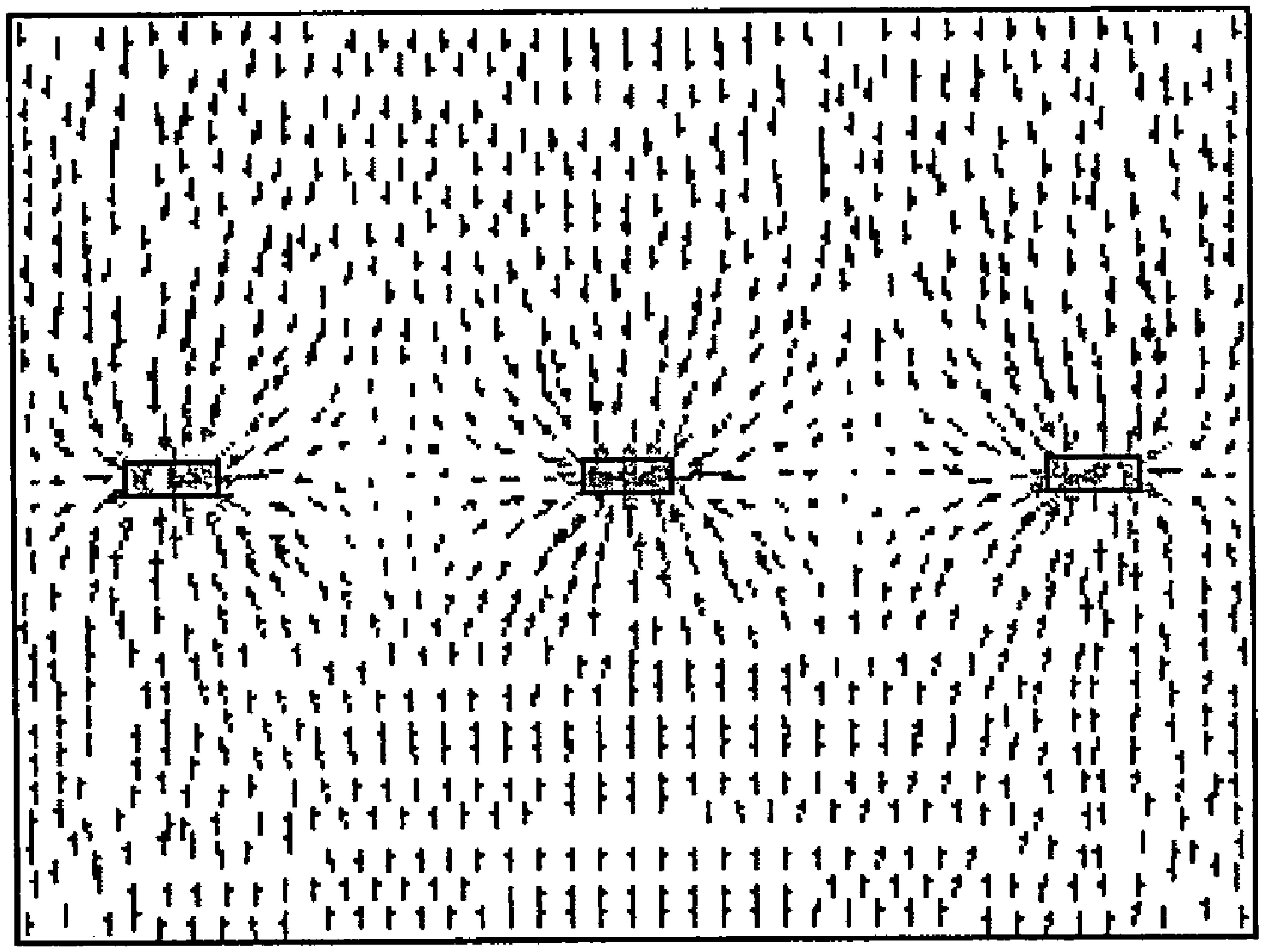


Fig. 3A

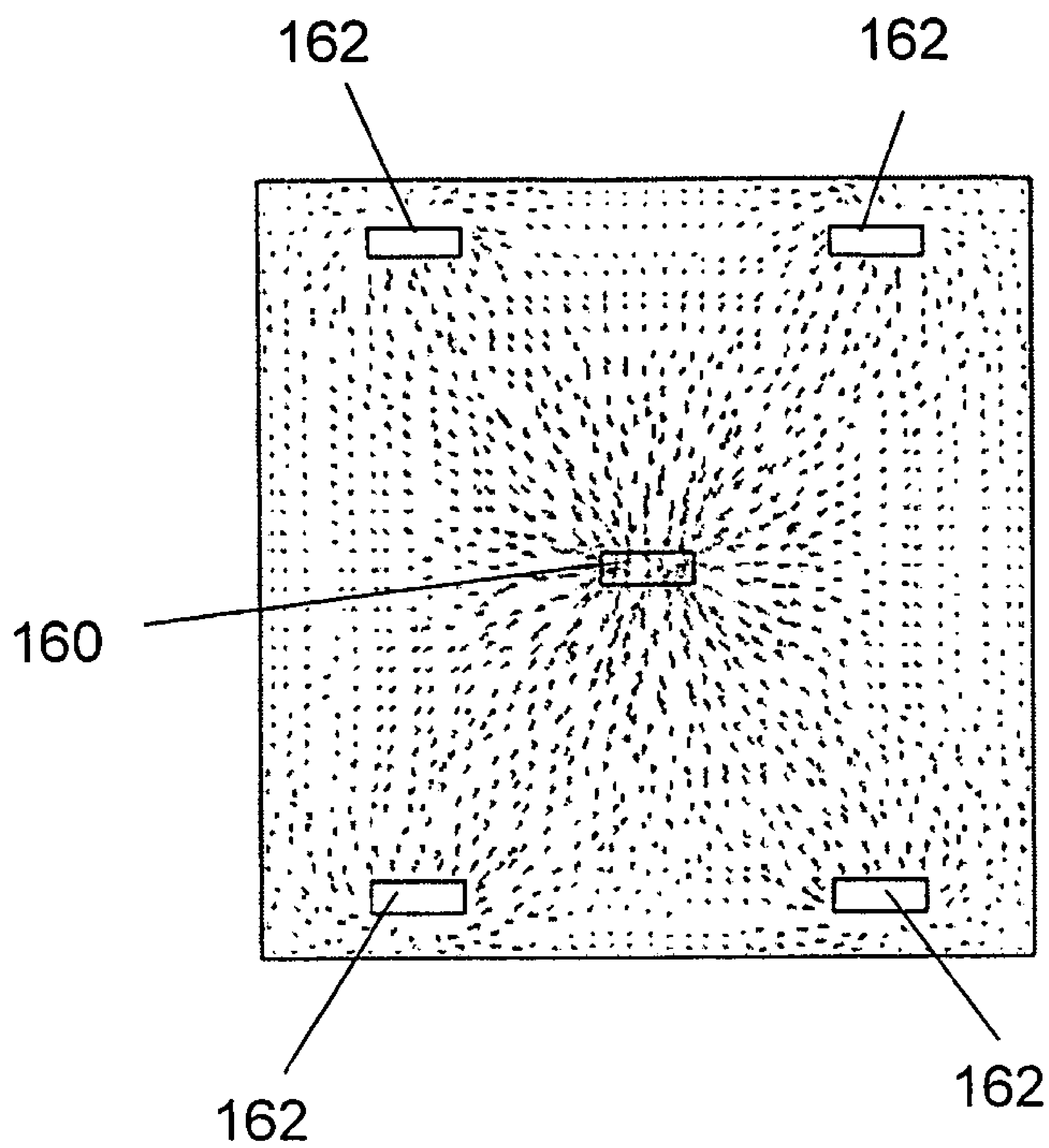


Fig. 3B

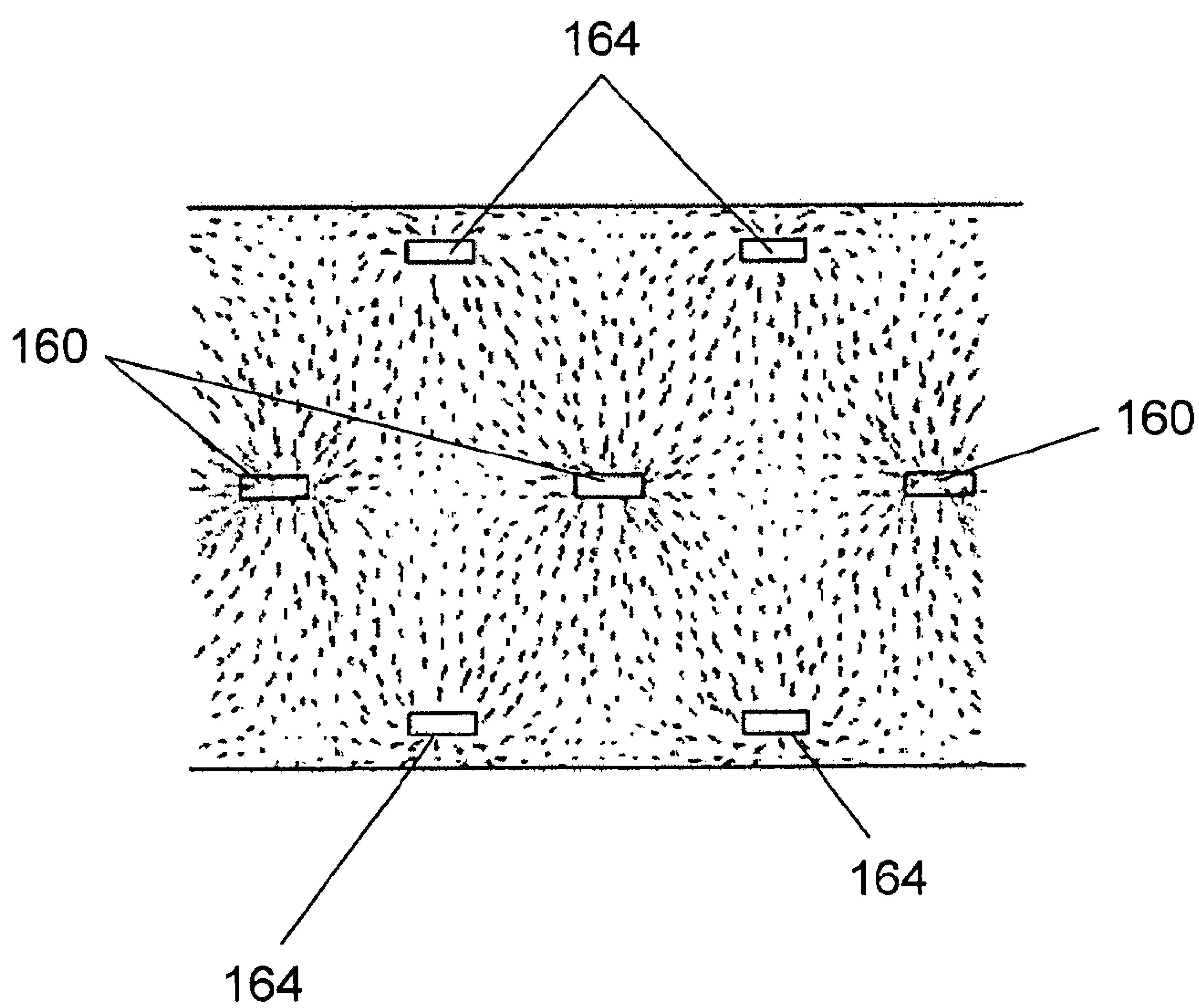


Fig. 3C

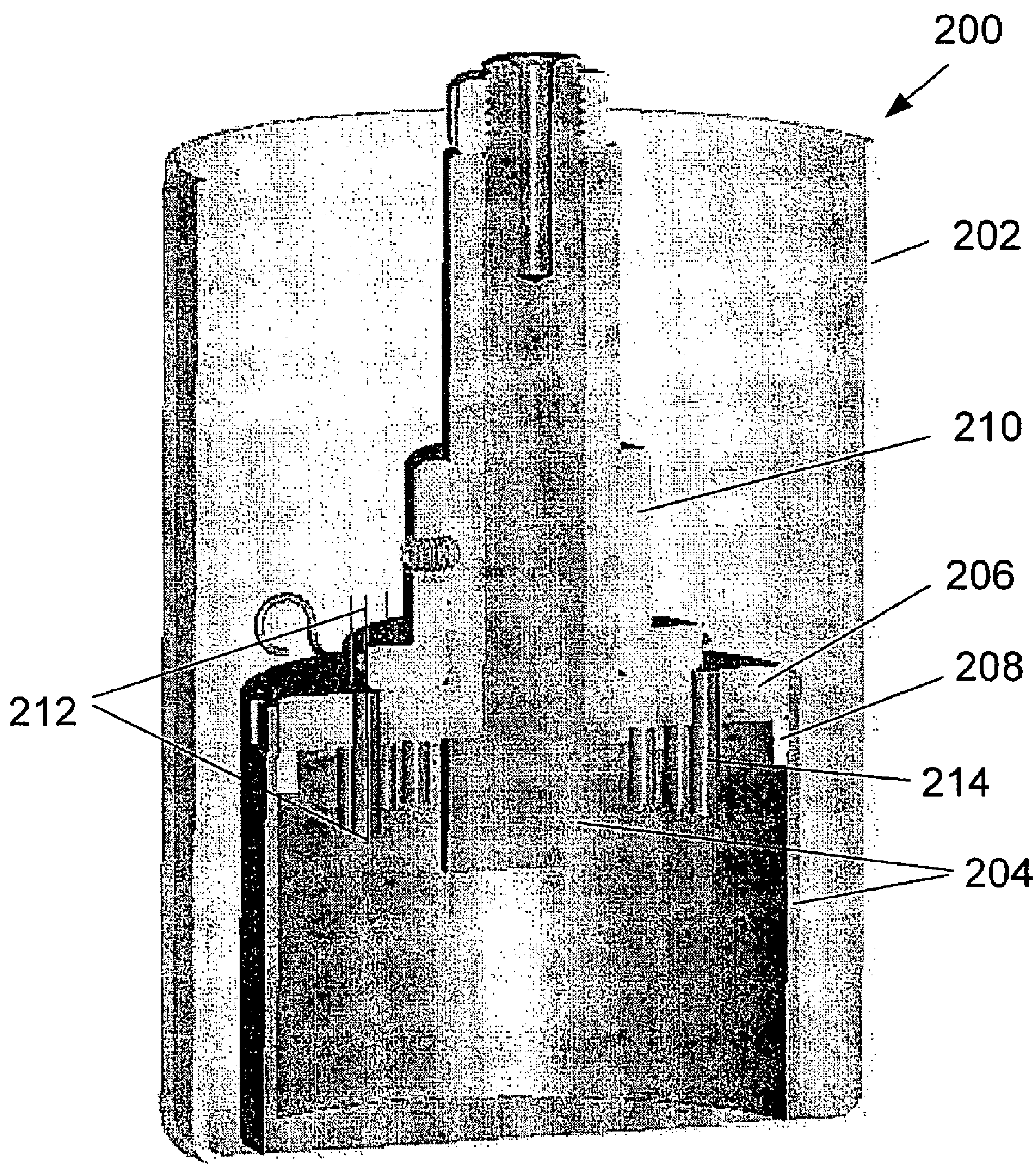


Fig. 4

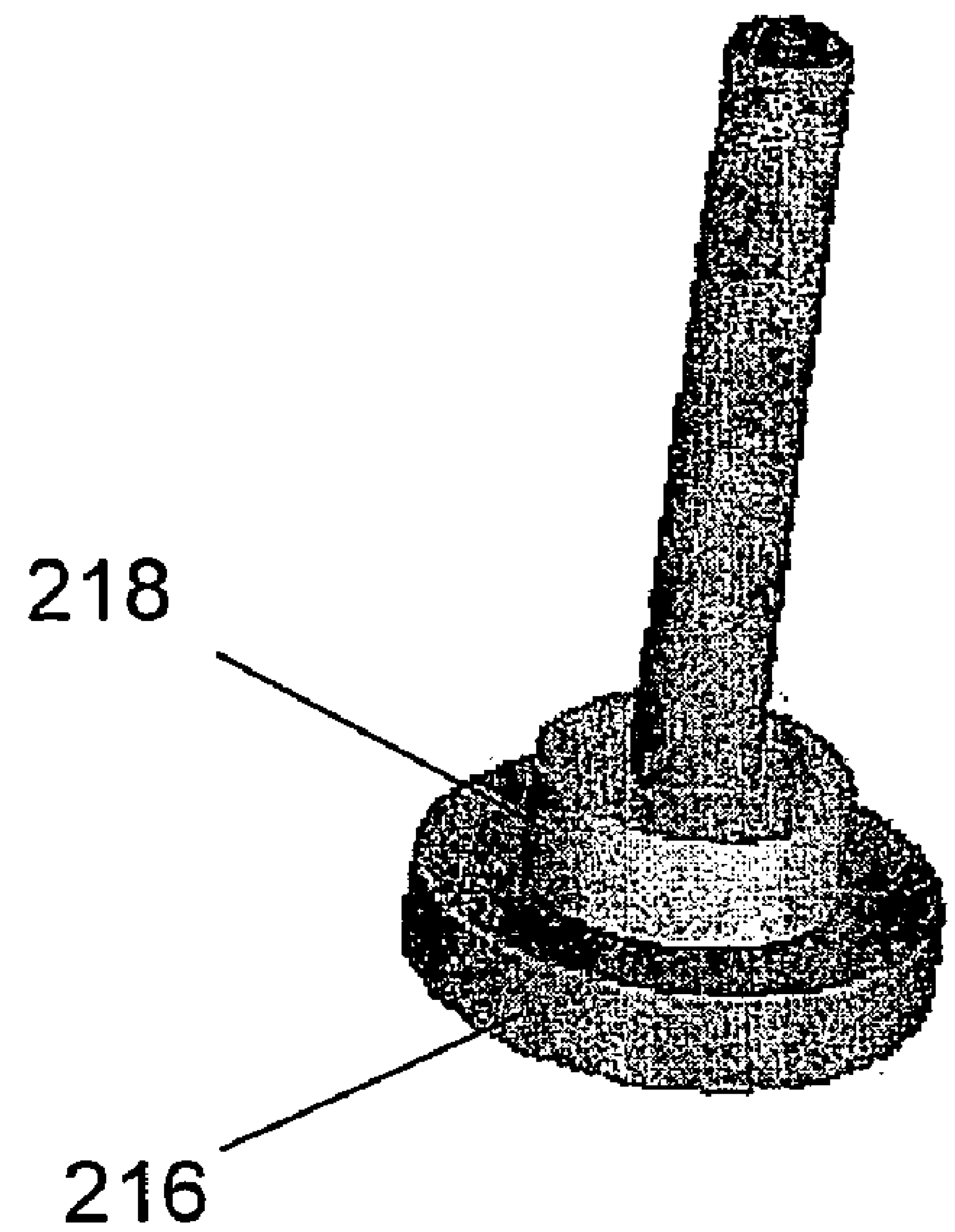


Fig. 5A

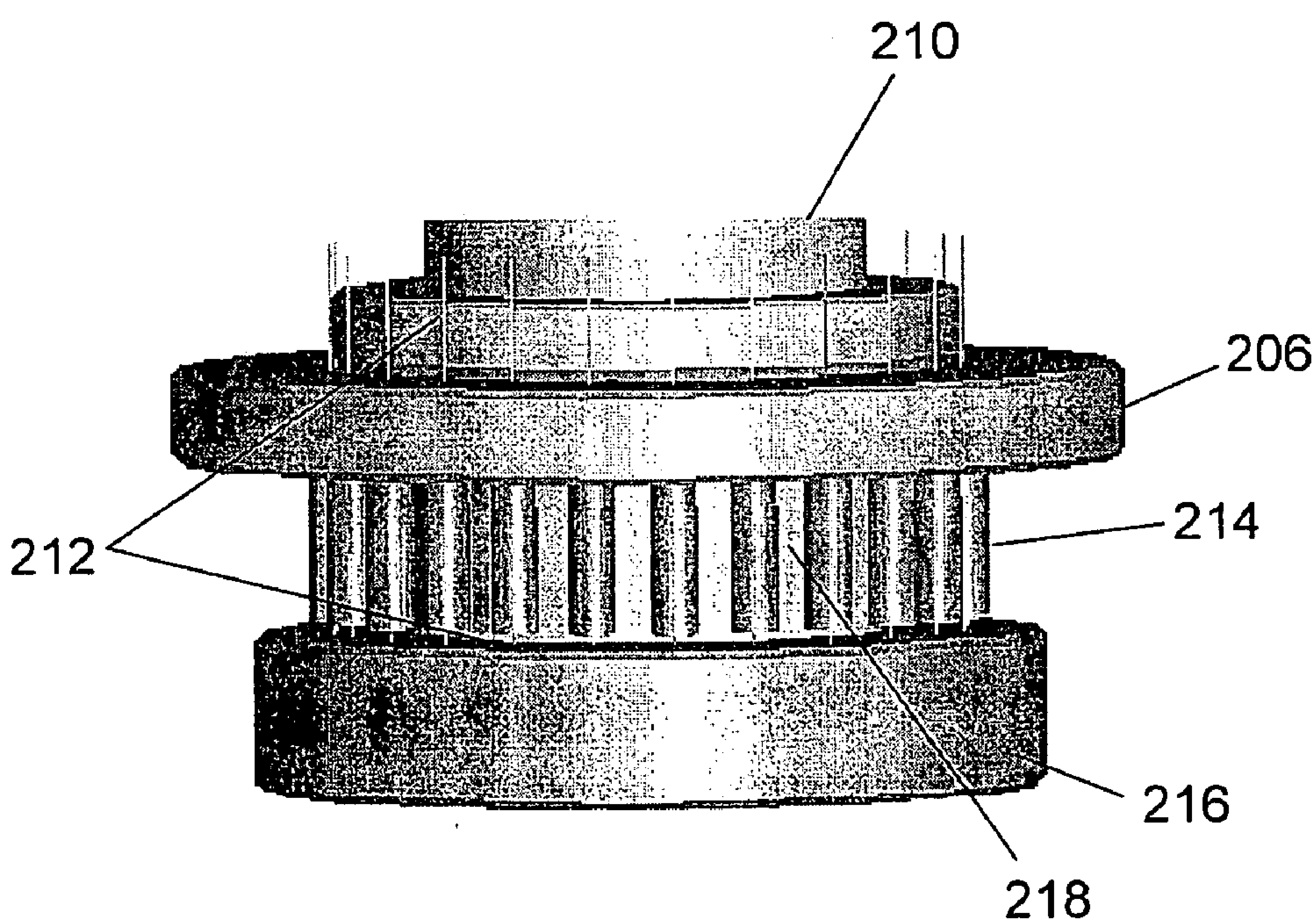


Fig. 5B

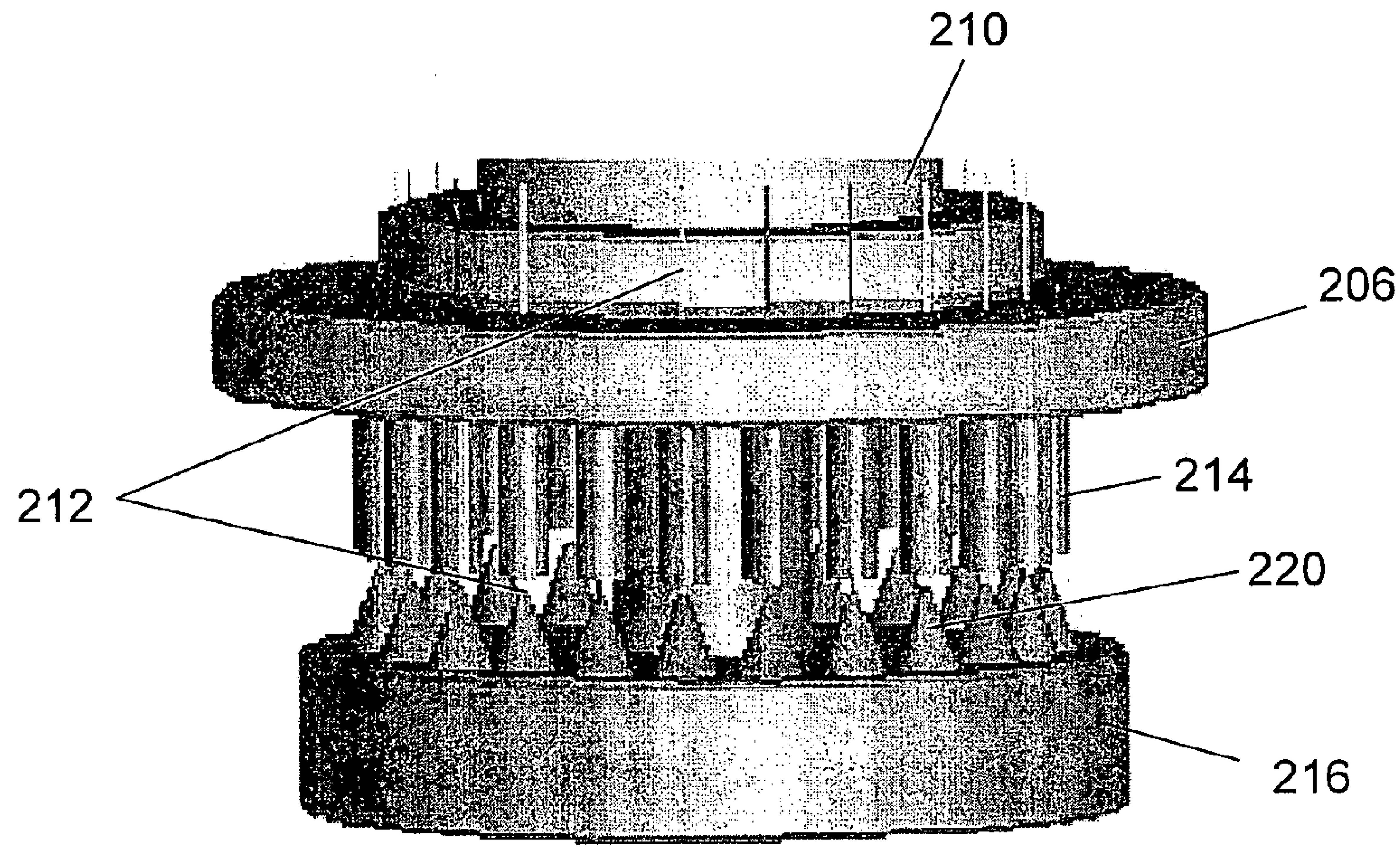


Fig. 6

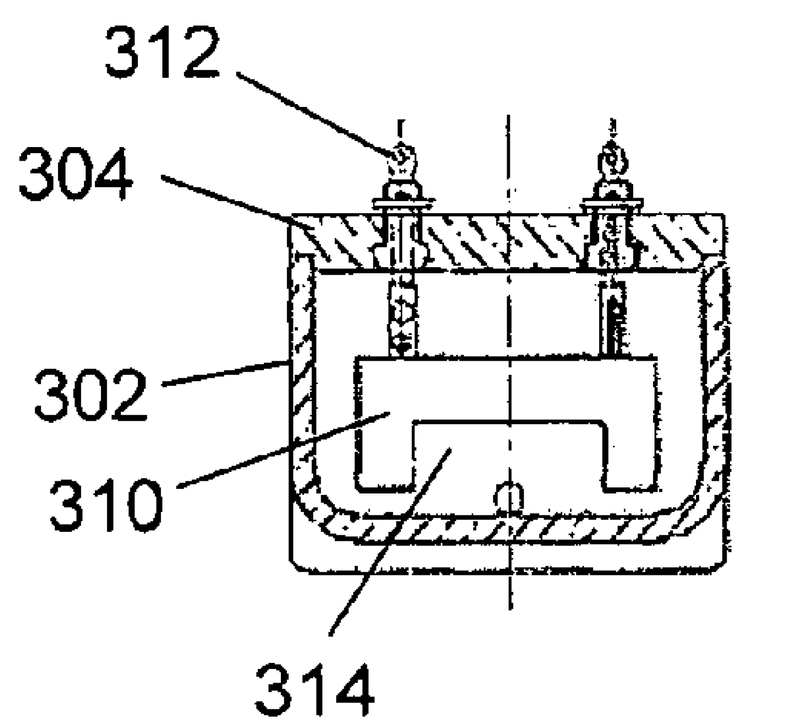


Fig. 7C

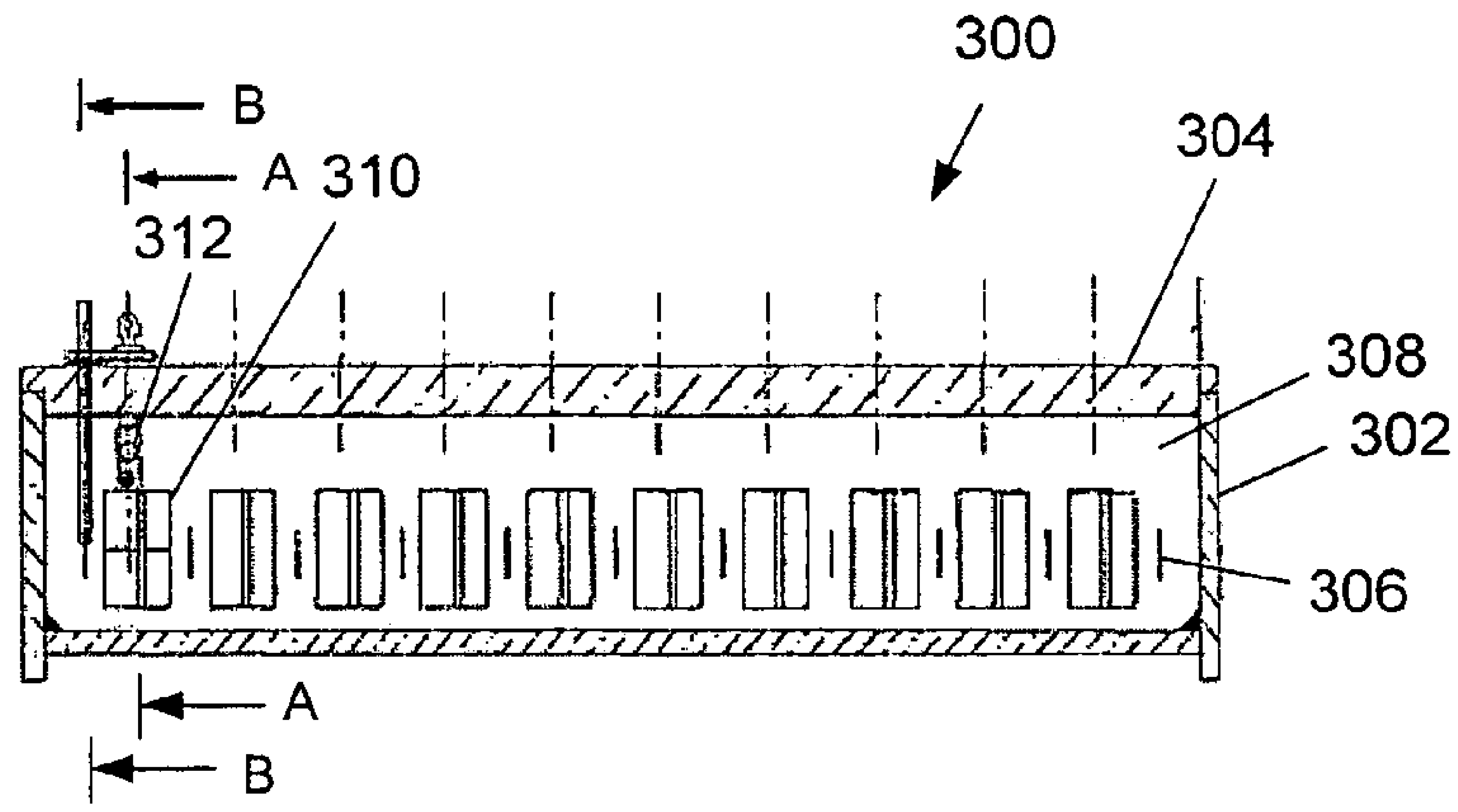


Fig. 7A

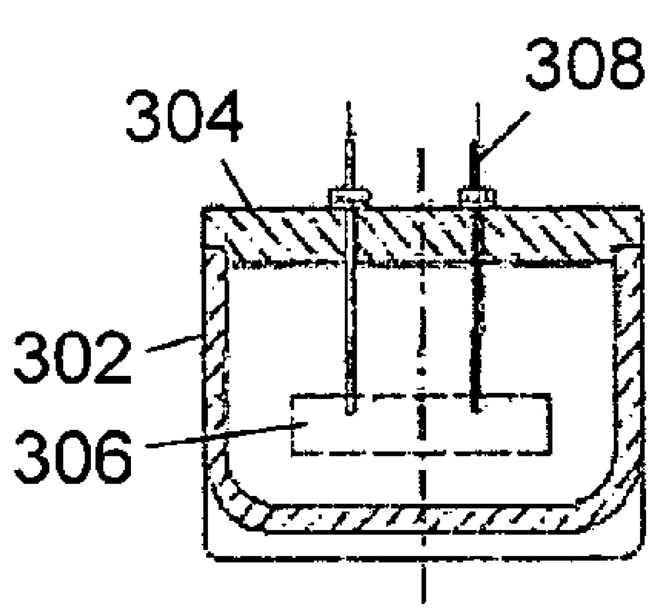


Fig. 7D

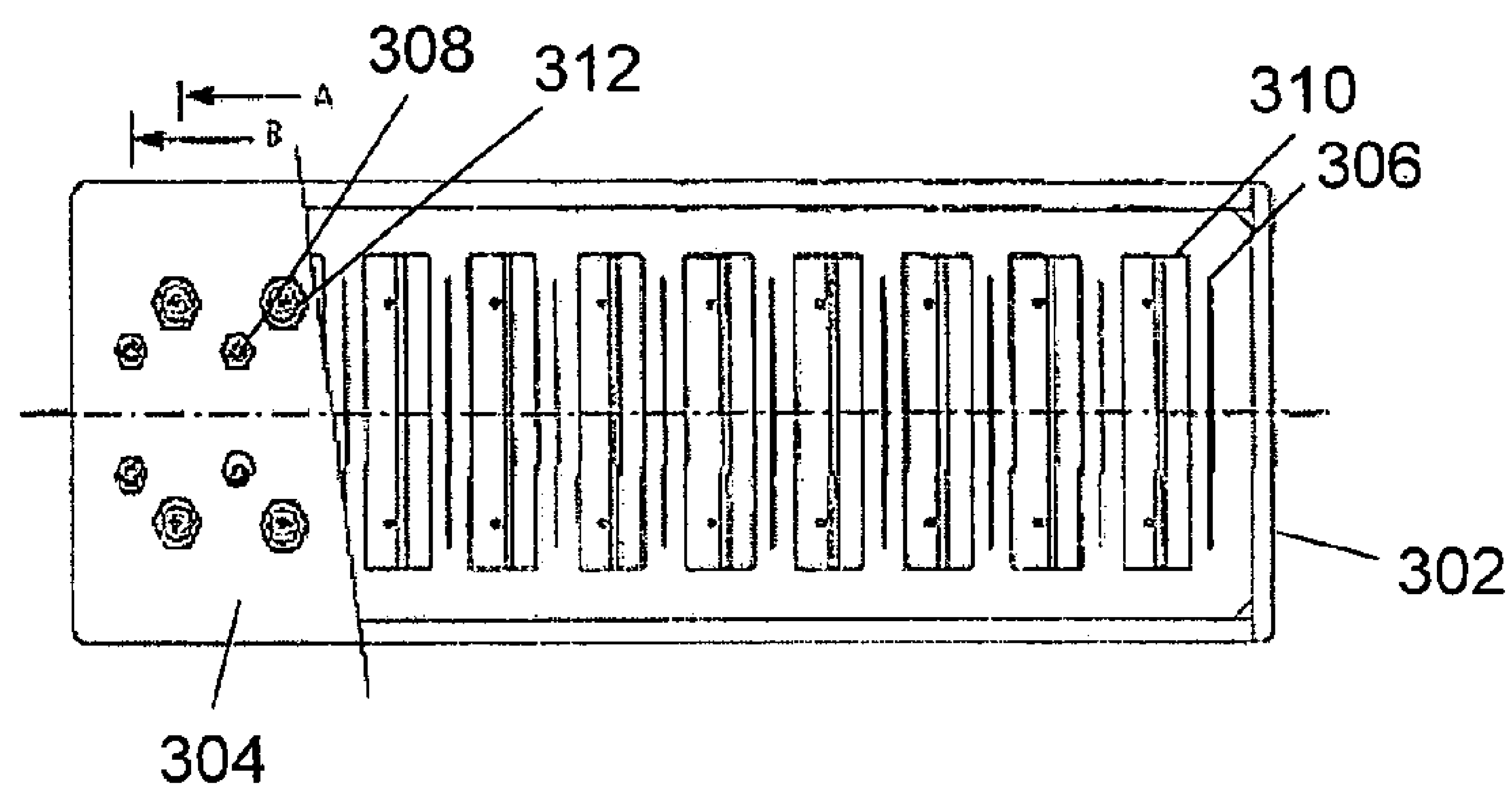


Fig. 7B

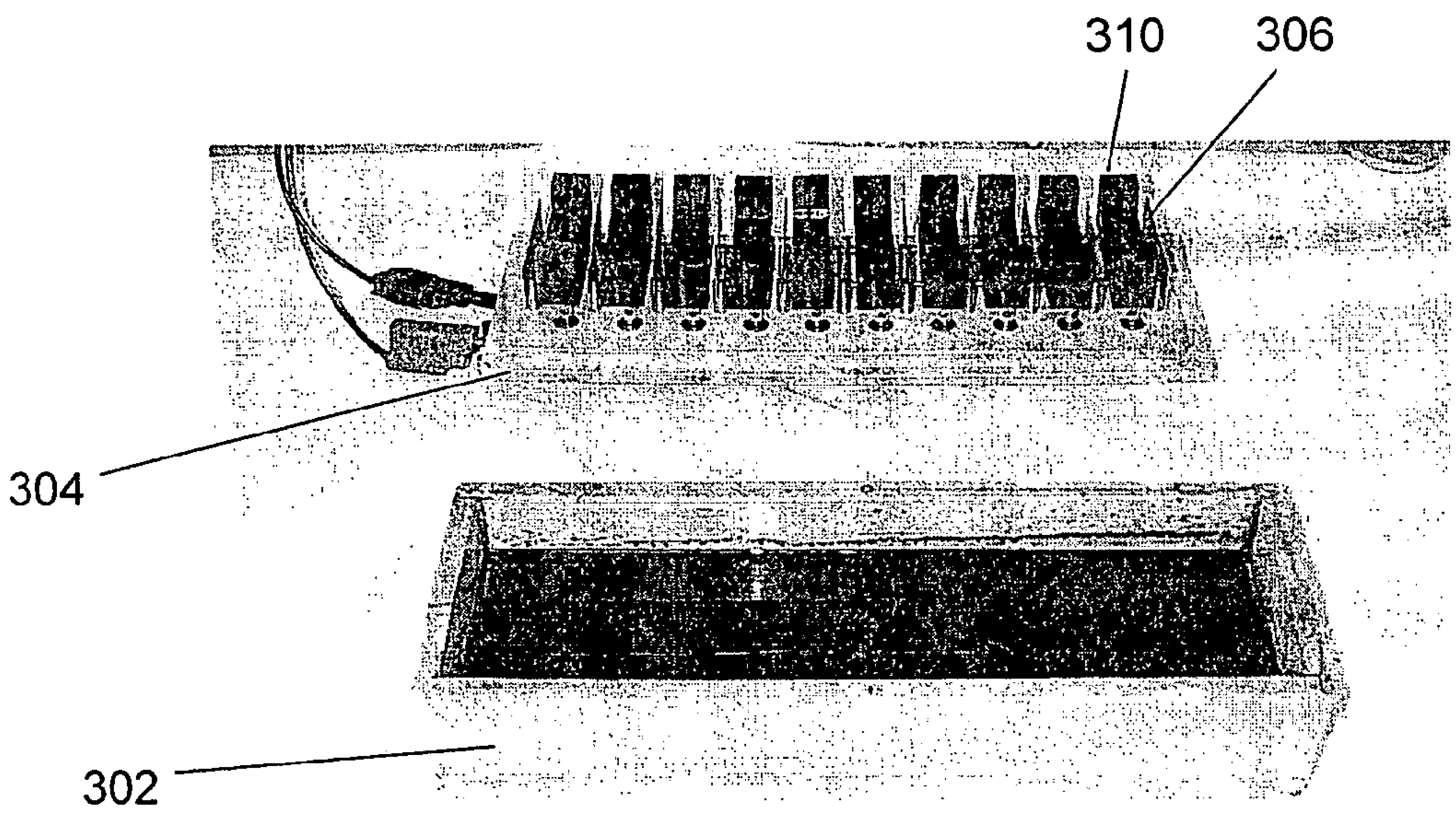


Fig. 7E

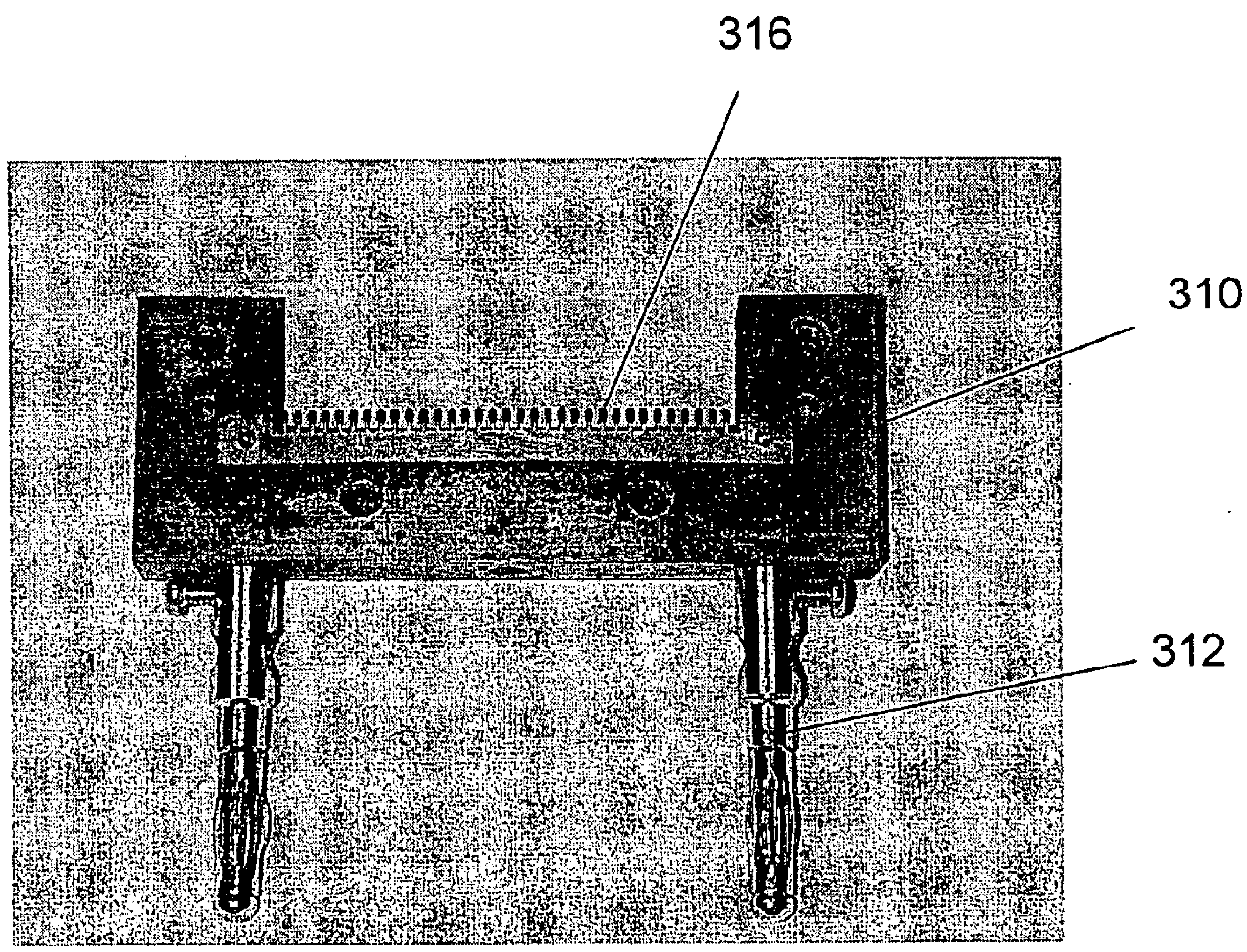


Fig. 7F

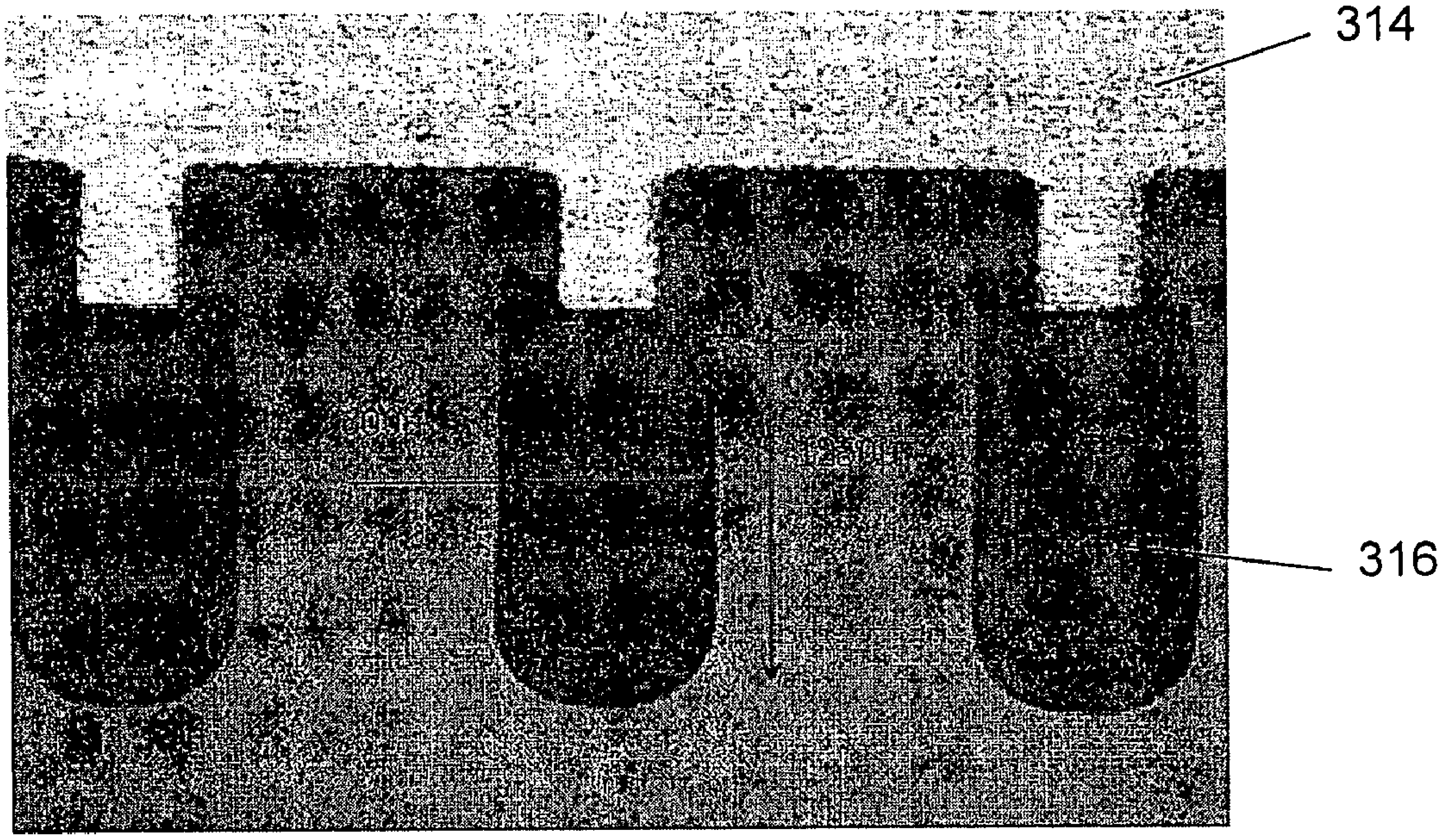


Fig. 7G

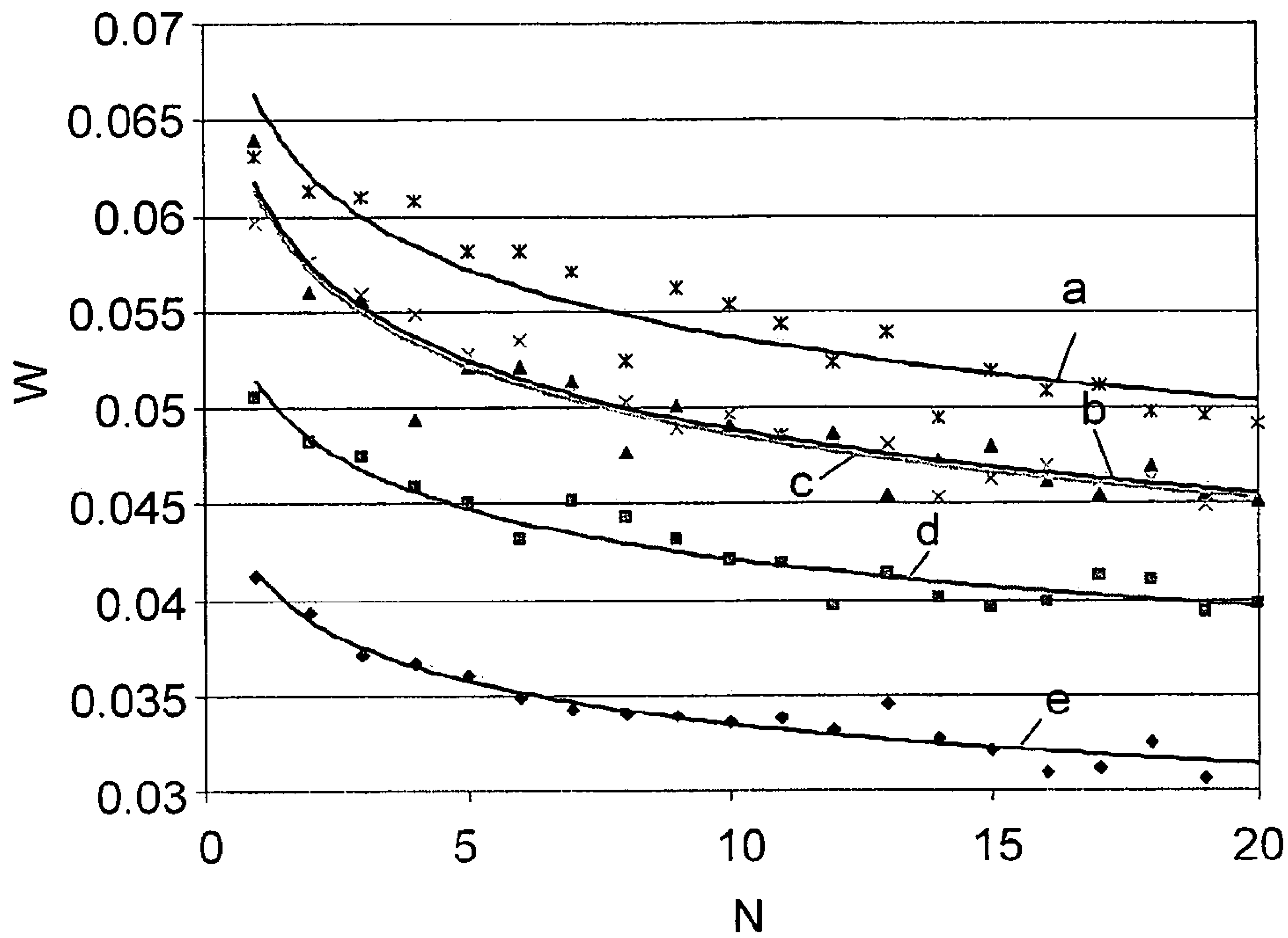

0.07
0.065
0.06
0.055
0.05
0.045
0.04
0.035
0.03
W
0
5
10
15
20
N
a
b
c
d
e

Fig. 8A

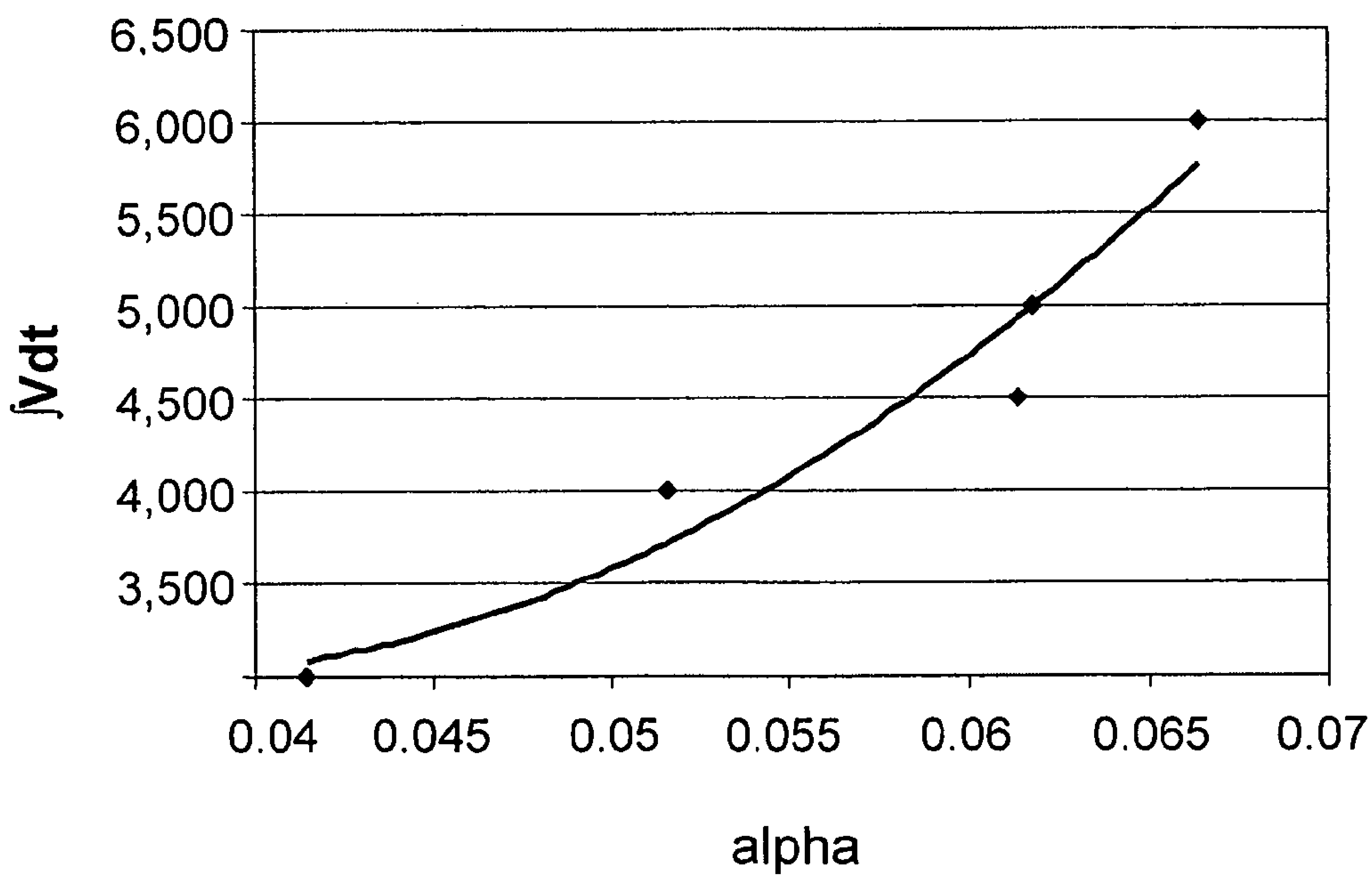

6,500
6,000
5,500
5,000
4,500
4,000
3,500
∫Vdt
0.04
0.045
0.05
0.055
0.06
0.065
0.07
alpha

Fig. 8B

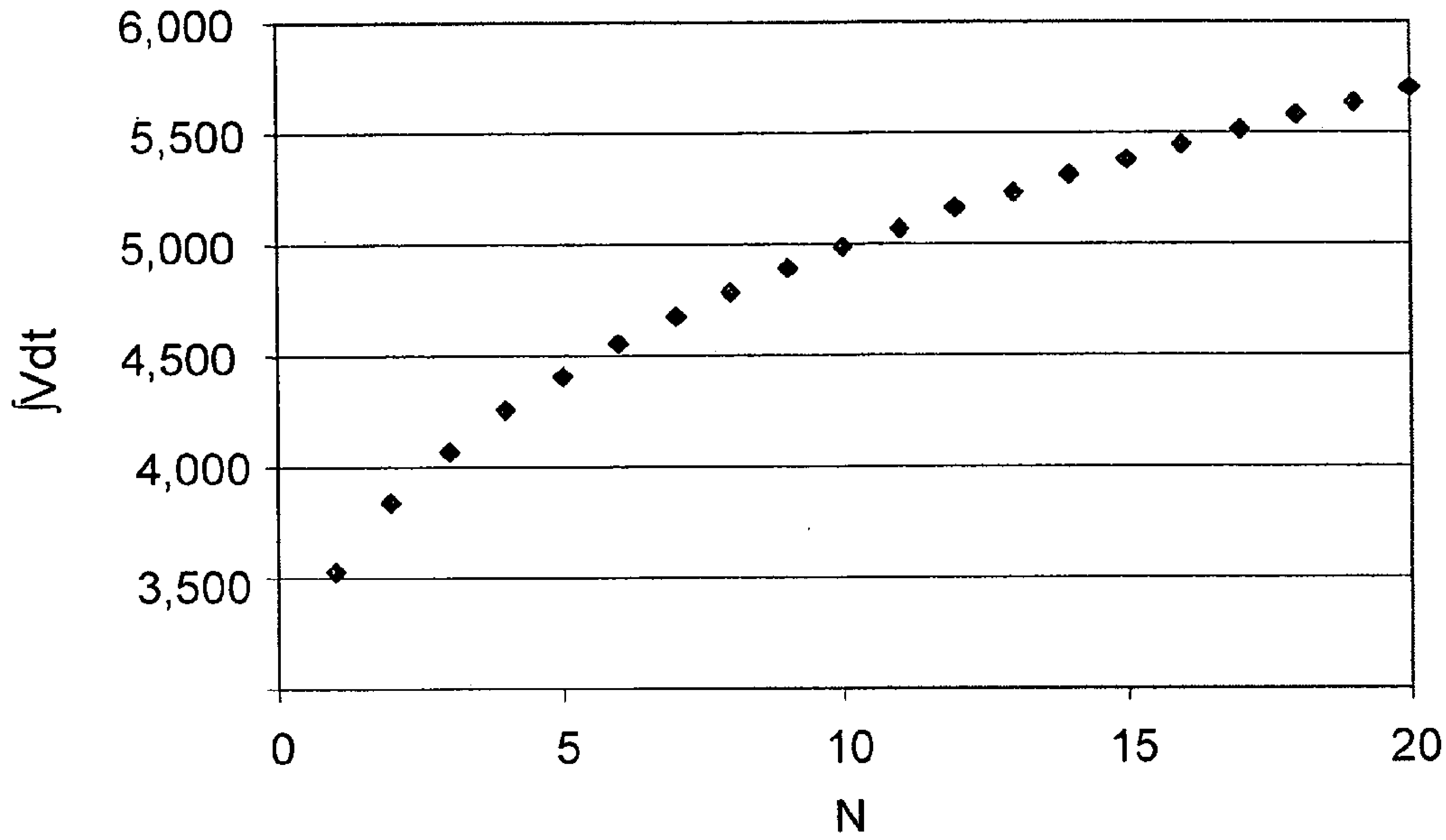


Fig. 8C

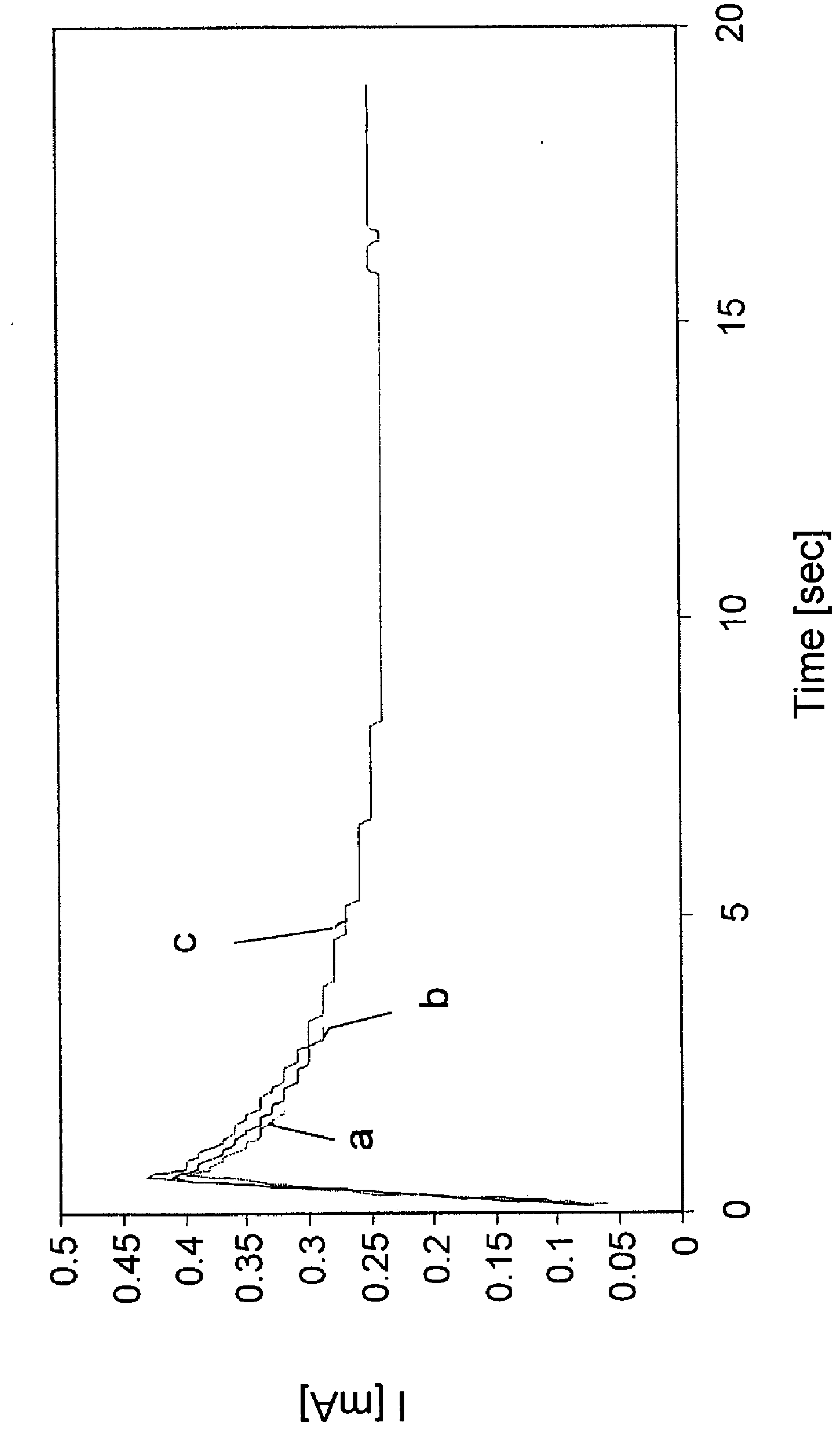


Fig. 9

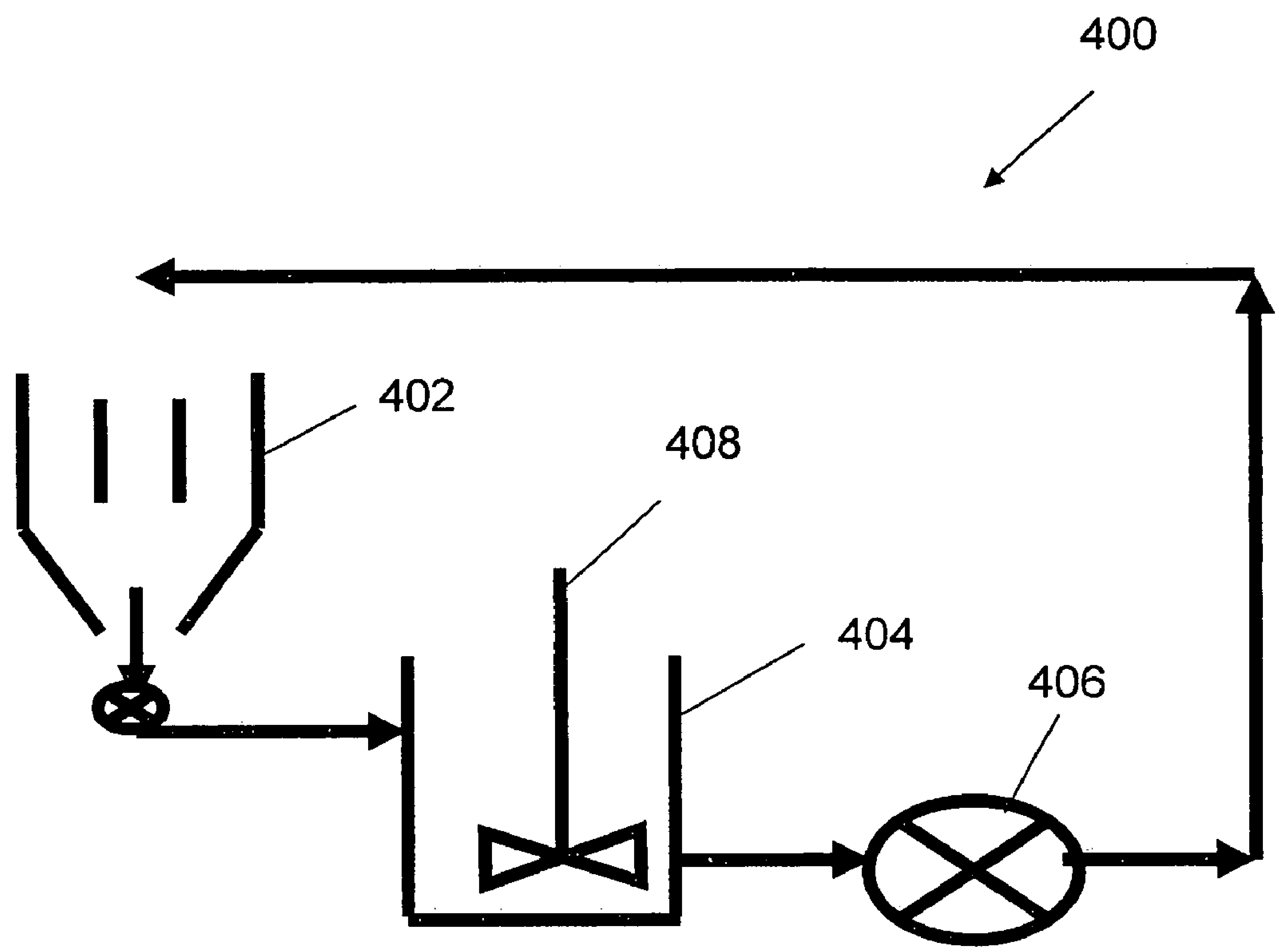


Fig. 10

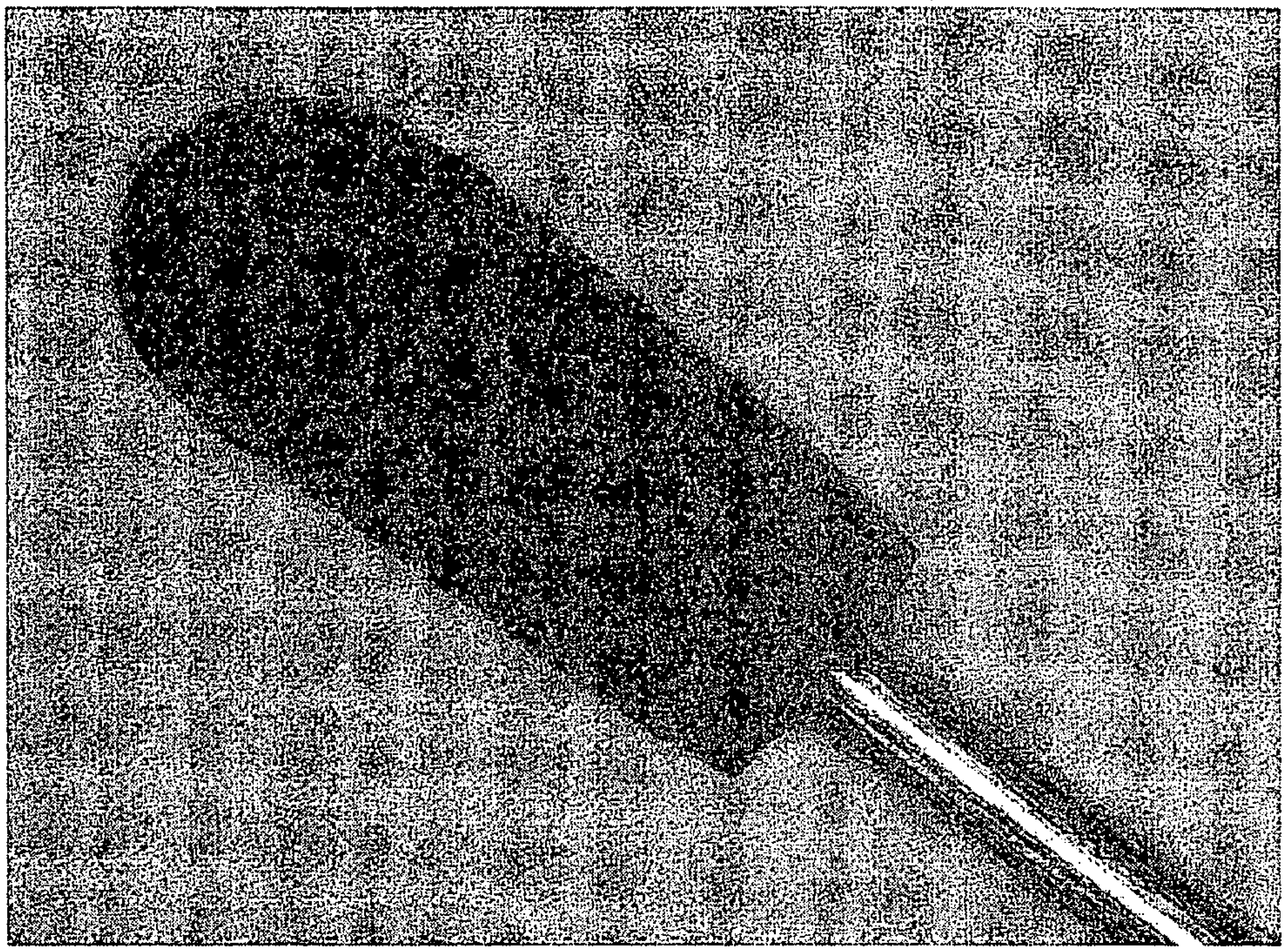


Fig. 11A

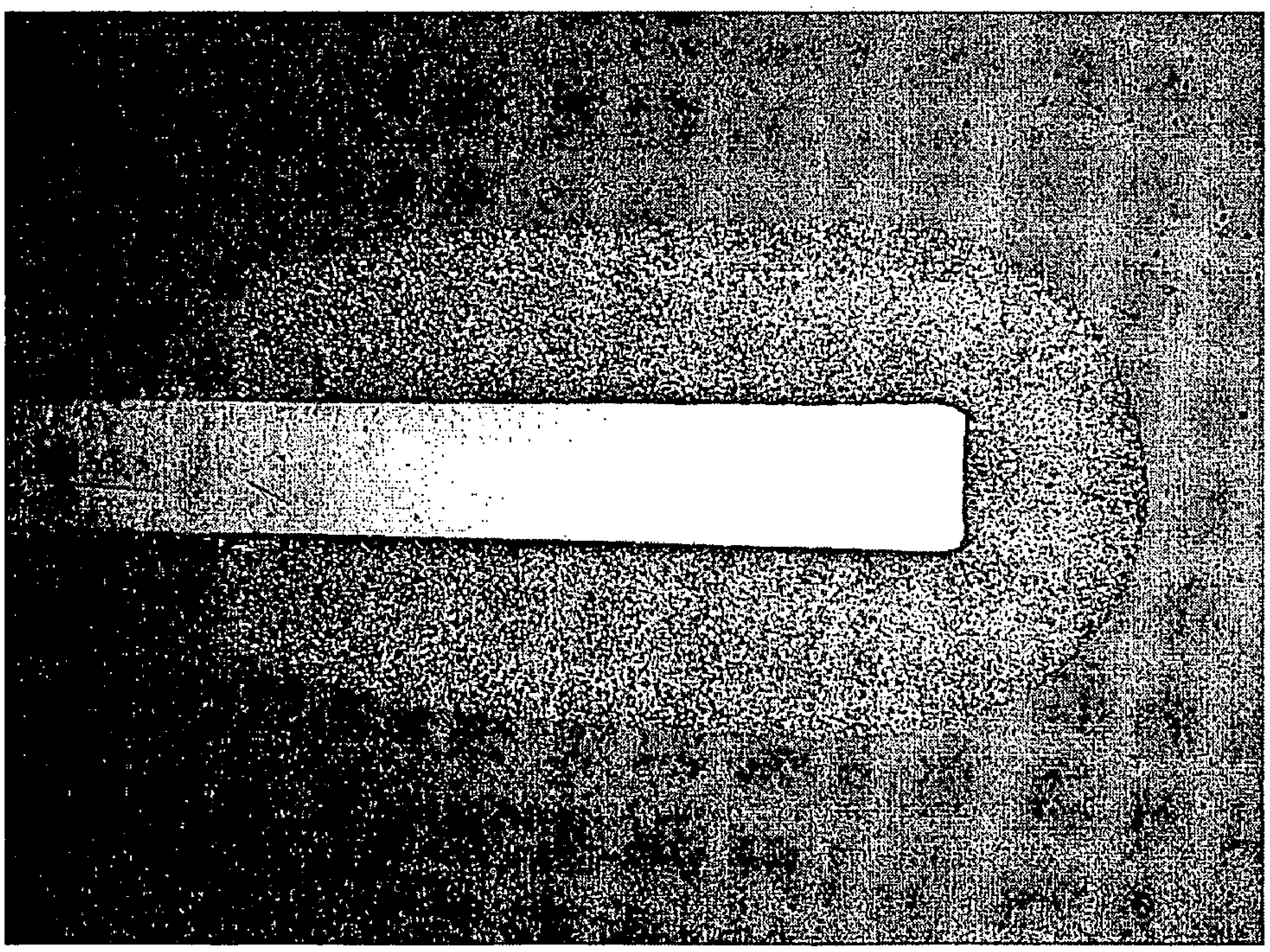


Fig. 11B

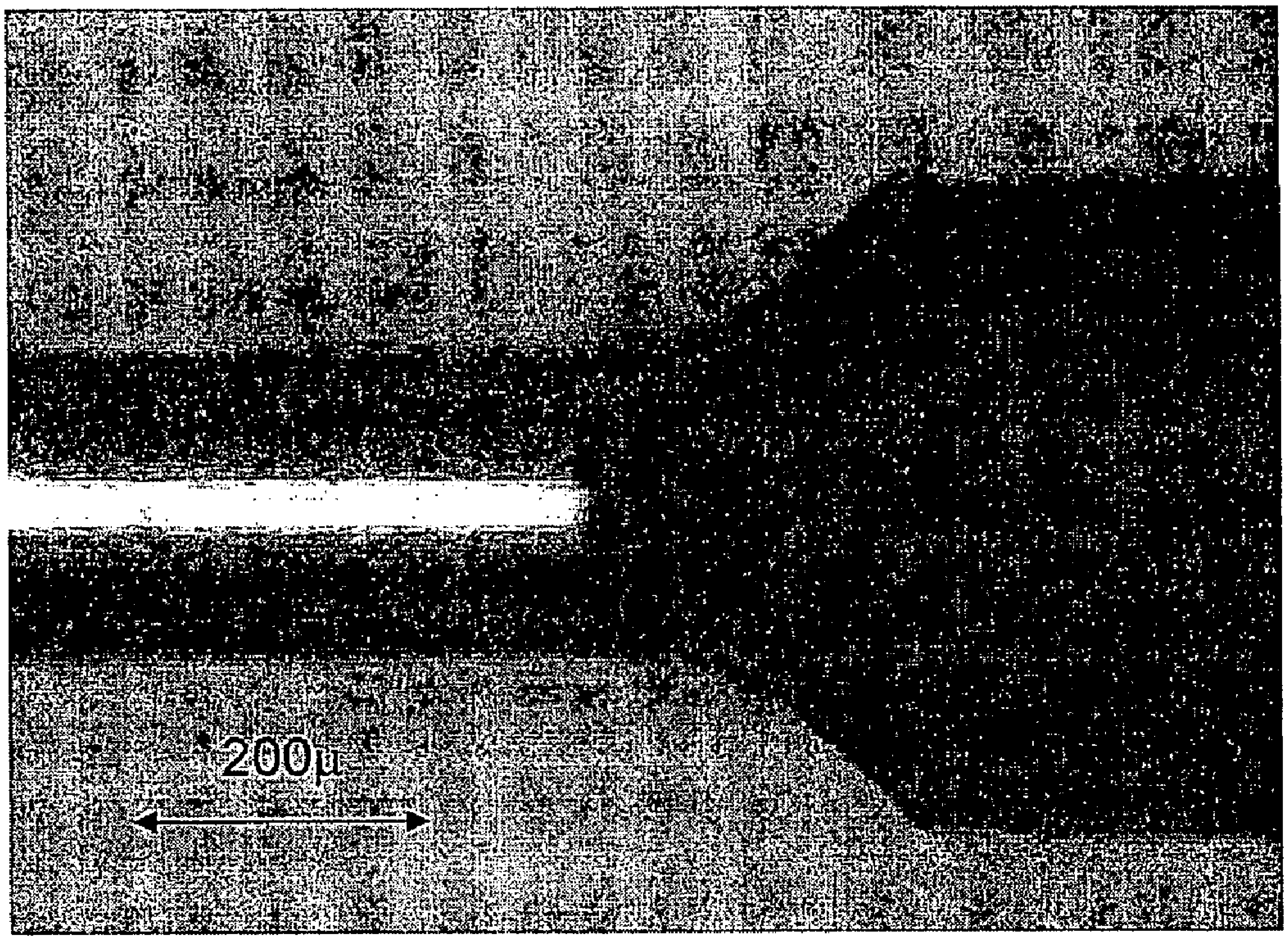


Fig. 11C
(PRIOR ART)

APPARATUS FOR MANUFACTURING COMPONENTS USING ELECTROPHORETIC DEPOSITION

FIELD OF THE INVENTION

[0001] The present invention relates to apparatus, methods and systems for applying electrophoretic deposition (EPD) to produce small components and coatings. More specifically, this invention describes a system for manufacturing anodes for solid electrolytic capacitors by electrophoretic deposition (EPD).

BACKGROUND OF THE INVENTION

[0002] The present invention relates to apparatus, systems and methods for electrophoretic deposition (EPD). Precisely shaped, small metal and ceramic bodies are used in many applications including as anodes for electrolytic capacitors, as pitch bonding capillaries in microelectronics, as high temperature nozzles, as ferrules for connecting optical fibers, as high temperature engine components, as dental crowns, and as bearing parts. To achieve the precise shaping required for some of these applications, like electrolytic capacitor anodes and bonding capillaries, it has been necessary to use the process of pressing to fabricate the components. Pressing is generally a discrete operation, producing one part at a time where agglomerated powders are used.

[0003] More recently, electrophoretic deposition (EPD) processes have become available for producing small bodies, coatings and components. EPD uses non-agglomerated powders and provides a way for production in batch mode or discrete operation.

[0004] Electrophoresis is well known in the art as a process to form green bodies. EPD has been used by Sarkar, Haung and Nicholson [Electrophoretic deposition and its use to synthesize A1.sub.2 O.sub.3 /YSZ micro-laminate ceramic composites, Ceram. Eng. Sci. Proc., vol. 14, pp. 707-716 (1993)] to deposit laminated composites of alumina and yttria-stabilized zirconia (YSZ). Electrophoretic deposition processes are described in U.S. Pat. No. 5,919,347 "Method of Electrophoretic Deposition of Laminated Green Bodies", in Published International Patent Application WO 02/103728 "Process for Manufacturing a Metal Electrode", in Israeli Patent application IL168397 "Solid Electrolyte Capacitor with Controlled Properties and a Method for Manufacturing the Same", and in International Patent Application WO/IL2005/000763 "Fabrication of Electrical Components and Circuits by Selective Electrophoretic Deposition (S-EPD) and Transfer" all by the applicant of the present application, the descriptions of which, including references cited therein, are incorporated herein by reference in their entirety.

[0005] The prior art extensively covers dispersion composition and process parameter requirements for producing components by EPD; however, little innovation is known for the EPD apparatus and deposition system. A typical design of prior art apparatus **100**, which includes a power supply **130**, dispersion cell **120**, holding fixtures **125129**, and electrodes **132150**, is shown in FIG. **1**. At the bottom of the typically cylindrical cell **120** that contains the EPD suspension, an electrode holder **125** made of a non-conducting material is inserted to hold the counter electrode, in this case the anode **132**, horizontal and coaxial with the symmetry axis of cell **120**. The substrate upon which the material in the dispersion is to be deposited, in this example the cathode, **150** is held by a cathode holder **129** supported by supporting rods **128**. The supporting rods **128** are secured to a cell cover **127** in such a way that the height of the cathode **150** can be adjusted at 3 points until the best conditions for EPD are found. The cathode holder **129** and the supporting rods **128** are made of a non-conducting material. The best conditions for EPD are dependent upon several factors, including the voltage supplied by the power supply **130** and the separation distance between the anode **132** and the cathode **150**.

[0006] Prior art apparatus, such as that shown in FIG. **1**, limits the capability of EPD to produce components with very tight dimensional tolerances or monolithic components having unique shapes, such as flat ends and sharp corners. Furthermore, multiple deposition cycles in such apparatus lead to significant differences in deposited mass between sequential depositions unless the dispersion is replaced frequently, in which case a fresh dispersion might be necessary even for each deposition cycle.

[0007] Use of prior art EPD technology for manufacturing monolithic bodies like electrolytic capacitor anodes produces shapes of limited dimensional tolerances. Furthermore, deposition weight changes significantly for each deposition cycle for a given EPD dispersion. For laboratory or research purposes, a fresh dispersion can be used for each deposition cycle; however, this is not practical for large scale manufacturing.

[0008] The limitations that restrict the use of EPD in mass production of monolithic bodies like capacitor anodes can be further highlighted by comparison with the process of electrolytic deposition. Typical industrial solutions used for electro-deposit of metal exhibit only minor side reactions. The ratio between deposition mass and transferred coulombs is well known and fixed, providing easy control of total deposited mass. By comparison, charge transfer to the deposition electrode cannot be used as a control parameter for mass production by EPD, since most of the electrical charge transferred to the electrode is not carried by the deposited powder particles, but rather by ions from the EPD dispersions. In EPD, preexisting particles are charged and transferred to an electrode under an electric field. Changes in the EPD dispersion chemistry, particle mass load and particle size distribution occur during each deposition cycle. These changes modify the amount of mass deposited per coulomb of charge collected at the electrode.

[0009] Prior art EPD technology does not provide methods or apparatus to tightly control deposited mass in subsequent depositions from a given dispersion.

[0010] There exists a need for reconsideration of and improvement over the prior art in several aspects of any mass production EPD process and apparatus. Some of these aspects include:

[0011] 1. stable large volume EPD dispersions;

[0012] 2. electrical field design in the EPD cell;

[0013] 3. EPD cell design;

[0014] 4. EPD substrate handling

[0015] 5. EPD process control; and

[0016] 6. efficient mass utilization in EPD processing.

[0017] Only careful and full consideration of all of these aspects can yield a cost effective EPD mass production that consistently meets predetermined specifications.

[0018] It is, therefore, an object of the present invention to make EPD a feasible industrial manufacturing process for small components; a process which achieves the desired shapes having tight dimensional tolerances and material properties that meet the requirements of high volume assembly lines.

[0019] It is a still further object of the present invention to manufacture a batch constituting a plurality of discrete components by EPD wherein a large number of components are deposited simultaneously.

[0020] It is a still further object of the present invention to manufacture by EPD a batch constituting a plurality of components; wherein a large number of components are deposited on a single substrate.

[0021] Yet another object of the present invention is to manufacture by EPD small components and coatings from non-agglomerated powders having small particle size and a narrow particle size distribution.

[0022] It is another object of the present invention to provide an EPD manufacturing apparatus and system capable of operating in an 'open loop' mode with predetermined work parameters, or alternatively in a 'closed loop' mode with real time process monitoring and control.

[0023] It is still another object of the present invention to design the local electrophoretic electric field around the substrate undergoing deposition in order to shape the component to a desired form.

[0024] It is still another object of the present invention to shape the component being formed by EPD by use of physical barriers which restrict the deposited material in one or more dimensions with tight dimensional tolerance and further providing a flat or otherwise shaped surface to the component.

[0025] It is still another object of the present invention to exploit EPD dispersions used to near depletion while maintaining tight control on deposit mass in sequential production runs.

[0026] It is another object of the present invention to provide cost effective EPD manufacturing apparatuses and systems.

[0027] It is still another object of the current invention to correct EPD dispersion chemistry and particle content by means of recycling EPD dispersion by drawing fluid from the EPD cell to an external tank and transferring the corrected dispersion to the EPD cell.

[0028] It is still another object of the present invention to manufacture components with EPD apparatus that incorporates capillary structures or other structures of different cross sections, yet having small inside dimensions for containing the substrates undergoing deposition.

[0029] It is still another object of the present invention to manufacture by EPD components as discrete units, in batches, or in a semi-continuous manner.

[0030] It is a further object of the present invention to manufacture by EPD components using many kinds of substrates including wire, foil, mesh, perforated substrates, 3D shapes and substrates with masking for selective deposition on designated areas of the substrate.

[0031] It is a still further object of the present invention to manufacture components by EPD with minimum precipitation of particle contamination on surfaces within the EPD apparatus.

[0032] It is a still further object of the current invention to provide an EPD manufacturing process and apparatus for efficient production of solid electrolytic capacitor anodes.

[0033] Other objects and advantages of the invention will become apparent in the following description of this invention.

SUMMARY OF THE INVENTION

[0034] The invention described herein provides for a high yield and low cost EPD industrial manufacturing apparatus with efficient materials utilization for the manufacture of small metal and ceramic components, such as anodes of electrolytic capacitors. The invention further provides component shapes and dimensional tolerances not obtained by prior art EPD apparatus.

[0035] The EPD apparatus of the invention incorporates one or more design features to achieve the desired components and dimensions.

- [0036] Robust and uniform EPD dispersion around the components during their formation by EPD;
- [0037] Minimized contamination of support structure that is immersed
- [0038] Secondary counter electrodes and insulated inserts that modify the local electric field around the components during their formation, thereby shaping the components to desired dimensions;
- [0039] Physical barriers in close proximity to the components that limit and tightly define dimensions of the component being formed by EPD;
- [0040] Use of capillary and capillary like structures as fixtures for holding substrates undergoing EPD, where the capillary or capillary like structure may optionally be filled with a liquid. Said fixtures modify the shape and dimensional tolerances of the components being produced by EPD.

[0041] In another aspect of the invention, control systems are incorporated into the EPD apparatus in order to perform one or more of the following functions.

- [0042] Model based algorithms to modify power supply operating conditions for each production run in a sequence of electrophoretic depositions, whereby the modified operating condition compensates for changes of dispersion chemistry and depletion of particle mass load in each subsequent EPD deposition;
- [0043] Monitoring of electrophoretic current under constant voltage operation for determining endpoint for usage of depleted dispersion, indicating needed replacement with fresh dispersion;
- [0044] Reconstitution and recycling of partially depleted dispersion by incorporation of a tank external

to the EPD cell where dispersion chemistry, particle mass load and particle size distribution are restored to near their original values, and the corrected dispersion is recycled back to the EPD cell.

[0045] The apparatus and methods of the invention may be used with a variety of substrates including but not limited to foil substrates, wire, substrates that are masked for selective deposition in designated areas, 3D shapes and substrates which are perforated or in the shape of sieves.

[0046] The invention may be applied to sequential production of discrete components or to batch production. The invention may also be applied to semi-continuous production of components as may be carried out by attaching substrates to a strip and transferring the substrates through the EPD cell using a reel to reel or similar process. The invention may further be applied to semi-continuous operation in a carousel type process, where substrates are inserted into the carousel, transferred through the EPD cell and finished green components are extracted from the carousel.

[0047] In a first aspect the invention is an apparatus for the production of small components having defined pre-set dimensions and properties. The method of the invention is based on electrophoretic deposition (EPD) on electrically conducting or semi-conducting substrates. The apparatus comprises:

[0048] a. an electrical circuit comprising a power supply;

[0049] b. an EPD cell containing a homogenous EPD suspension;

[0050] c. substrate fixtures for holding the substrates, for immersing the substrates in the EPD suspension, and for making electrical contact between the substrates and the electrical circuit;

[0051] d. counter electrodes; and

[0052] e. elements for shaping the component or providing tight dimensional tolerances.

[0053] The apparatus of the invention can comprise components for monitoring the chemical and electrical properties of the EPD dispersion, for controlling the shape and strength of the electrical field in the EPD cell, or for controlling the electrical current flowing through the external electrical circuit and the voltage across the circuit.

[0054] The substrate can be wire-shaped, flat-shaped, sieve-shaped, or have a 3D shape. The substrate can be comprised of conductive and non-conductive areas.

[0055] The elements for shaping the component or providing tight dimensional tolerances can be one of the following:

[0056] a. components for protecting selective areas on the conductive substrates from being exposed to the EPD dispersion, thereby sharply demarcating the part of the substrate upon which material is deposited by EPD and the part of the substrate that is clean of the deposit;

[0057] b. a structure in which part of the substrate is contained which sharply demarcates the part of the substrate upon which material is deposited by EPD from that part of the substrate that is clean of the deposit;

[0058] c. a physical barrier or masking structure placed near the end of the substrate undergoing electrophoretic deposition, thereby shaping or improving the dimensional tolerance of the end of the component made by EPD deposition on the substrate; and

[0059] d. multiple or secondary electrodes arranged around the components undergoing EPD, thus shaping the electric field around the component and thereby shaping the dimensions of the component.

[0060] In some embodiments of the invention, the substrate fixture covers a part of the substrate, thereby protecting selective areas on the conductive substrates from being exposed to the EPD dispersion. In other embodiments the substrate is contained is a capillary or a tube or a slit which is slightly wider and thicker than the substrate.

[0061] In embodiments of the apparatus of the invention the structure in which part of the substrate is contained is filled with clean solvent compatible with the dispersion fluid, thereby further reducing diffusion of particles into the gap between the substrate the walls of the structure. In these embodiments pressure can be applied to the top end of the structure for example by means of a fluid reservoir at the upper end of the structure. The applied pressure will create a small amount of flow of clean solvent from the structure into the dispersion fluid, thereby further reducing diffusion of particles into the gap between the substrate and the walls of the structure. In embodiments in which the structure is a capillary, preferably the applied pressure is made equal to the pressure exerted by the capillary force, thereby preventing capillary flow of dispersion fluid into the structure. If the clean solvent is immiscible with the dispersion fluid, it will create a sharp barrier between the end of the structure and the dispersion fluid, thereby further reducing diffusion of particles into the gap between the substrate and the walls of the structure.

[0062] In preferred embodiments of the apparatus the chemical and particle composition of the dispersion is maintained uniform throughout the deposition cell and a uniform electric field is created within the deposition cell around the components undergoing electrophoretic deposition.

[0063] The structures in the EPD cell, which are necessary for structural support or other functions, are preferably made of conductive material and charged to the potential of the counter electrode, thereby reducing deposition of dispersion particles on the structures.

[0064] A preferred embodiment of the apparatus of the invention comprises a system for recycling the EPD dispersion. The system removes the dispersion from the EPD cell, either continuously or between deposition cycles, and causes it to flow to a recycling cell, wherein the properties of the dispersion are changed before returning it to the EPD cell. The properties of the dispersion that are changed before returning it to the EPD cell can include the particle concentration, the pH, the Z-potential, and/or the electrical conductivity. The concentration of the dispersion transferred to the recycling cell can be corrected to its original concentration before returning it to the EPD cell.

[0065] In some embodiments the recycling cell comprises ultrasonic agitation means to break down agglomerates to their original size distribution. In other embodiments the dispersion in the recycling cell is allowed to undergo sedimentation for a predetermined time in order to remove large agglomerates not compatible with the original particle size distribution and/or excessively fine particles that are not in compliance with the original particle size distribution are removed from the dispersion in the recycling cell. The chemistry of the dispersion fluid in the recycling cell can be corrected by the addition of tiny amounts of chemical additives.

[0066] The apparatus of the invention can be configured to form the small components by electrophoretic deposition as discrete components or in batches. The small components can be formed by electrophoretic deposition in a semi-continuous operation on a substrate in the form of a continuous strip or ribbon or on substrates that are arranged on a carousel.

[0067] The apparatus of the invention can be used to form small components having many types and uses, for example those selected from the group comprising: porous anodes of electrolytic capacitors, pitch bonding capillaries in microelectronics, high temperature nozzles, ferrules for connecting optical fibers, high temperature engine components, dental crowns, and bearing parts.

[0068] In another aspect, the invention is a method for controlling the use of the apparatus of the invention for the preparation of a component by electrophoretic deposition. The method comprises making use of one of the following:

[0069] a. maintaining constant deposit mass from run to run in constant current operation by applying a new ∫Vdt for each deposition run in accordance with the control model;

[0070] b. monitoring of the electrophoretic current under constant voltage operation in order to determine the endpoint for usage of the depleted dispersion; or

[0071] c. maintaining constant deposit mass from run to run by adjustment of the deposition time of sequential depositions.

BRIEF DESCRIPTION OF THE FIGURES

[0072] The invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only. They are presented to provide what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the invention in more detail than is necessary for a fundamental understanding of the invention. The description of the invention below taken together with the drawings makes apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

[0073] FIG. **1**A is a schematic view of a prior art electrophoretic deposition (EPD) cell;

[0074] FIG. **2**A is a low magnification sectional view of a green tantalum anode made by method and apparatus of EPD that does not incorporate modification of the local electric field about the substrates;

[0075] FIG. **2**B and FIG. **2**C are low magnification sectional views of green tantalum anodes produced made by modification of the local electric field about the substrates in an EPD cell in accordance with the method and apparatus of the invention;

[0076] FIG. **3**A is a simulation result showing the electrical field lines in an EPD cell with large counter electrodes symmetrically placed about the substrates;

[0077] FIGS. **3**B, and **3**C are simulation results showing the electrical field lines in an EPD cell that comprises insulated inserts;

[0078] FIG. **4** is a schematic view of EPD apparatus with capillary fixturing of substrates according to an embodiment of the invention;

[0079] FIG. **5**A and FIG. **5**B are schematic views of an apparatus for fixing tight length dimensional tolerances of a batch of components made by EPD according to an embodiment of the invention;

[0080] FIG. **6** is a schematic view of an apparatus for improving the dimensional tolerances and modifying the shape of green bodies made by EPD according to an embodiment of the invention;

[0081] FIGS. **7**A to **7**D show a schematic plan of an EPD apparatus according to another embodiment of the invention;

[0082] FIG. **7**E and FIG. **7**F are photographs of parts of the shown in FIG. **7**A;

[0083] FIG. **7**G is a photograph of green tantalum anodes made using the apparatus of FIG. **7**A;

[0084] FIGS. **8**A to **8**C and FIG. **9** show typical data used for producing EPD control systems for operating the apparatus of the invention;

[0085] FIG. **10** is a schematic view of EPD recycling apparatus and method according to an embodiment of the invention;

[0086] FIG. **11**A is a low magnification view of a green niobium oxide anode made by the method and apparatus of the invention;

[0087] FIG. **11**B is a low magnification sectional view of the green niobium oxide anode of FIG. **11**A; and

[0088] FIG. **11**C is a low magnification view of a green niobium oxide anode made by EPD using the method and apparatus of prior art.

DETAILED DESCRIPTION ON THE PREFERRED EMBODIMENT

[0089] As is well known, EPD is carried out by applying a voltage between two electrodes immersed in a suitable dispersion. Suitable EPD dispersions are composed of a powder of the material that will be deposited as a green film or body and which has been dispersed within a solvent of relatively high dielectric constant, typically above 6. Particle size used for stable dispersions will typically be in the submicron range up to about 10 microns.

[0090] Various additives may be added to the dispersion to adjust pH, Z-potential, conductivity and other dispersion characteristics. Processes are known in the art for producing from such dispersions various components in green form ready for sintering, such as porous anodes of electrolytic capacitors. However, lacking in the art are apparatus and methods for maximizing utilization of the powder in the dispersion or for achieving dimensional tolerances and shapes in subsequent manufacturing runs as required for mass production of such components. This invention provides efficient and precise mass manufacturing of components by EPD, such as anodes of electrolytic capacitors, by achieving high utilization of expensive raw materials like tantalum powder and by consistently achieving tight dimensional tolerances of defined component shapes in repeated depositions. This includes production sequences of discrete components, batches of components, and production by semi-continuous operation.

[0091] The apparatus of this invention is designed so that the substrates undergoing electrophoretic deposition are submerged a significant depth below the free surface of the dispersion with minimal structural elements in their vicinity.

[0092] In another embodiment of the invention, the apparatus substrate fixtures and the support structures used for placement of EPD cell elements such as substrate fixtures, counter electrodes, etc. are designed with minimal surface area exposed to the dispersion liquid. Submersed insulated structures tend to become contaminated by dispersion particles and to disturb the electrical field in the EPD cell and the quality of the EPD deposits. Therefore a preferred embodiment of the invention is based on producing symmetrical support structures of conducting material and charging these to the counter electrode potential, thereby reducing the sticking of dispersion particles to the structure. Similarly, the support structure and the counter electrode may be the same entity. Furthermore, a support structure that is distant from the substrates undergoing deposition is preferred, thereby minimizing interference with dispersion uniformity and particle transport in the vicinity of the substrates.

[0093] In other embodiments of this invention described herein, secondary structures such as physical barriers or electrodes for shaping the local EPD cell electric field are supplied for the purpose of achieving shaped or anisotropic deposition. These embodiments of the invention are designed so that restriction of the dispersion volume around the substrates undergoing deposition is minimized.

[0094] In another embodiment of the invention, EPD cell counter electrodes are arranged symmetrically around the substrates undergoing deposition in order to provide a uniform and equal global electric field within the EPD cell around all of the substrates undergoing deposition. Preferred embodiments include cylindrical counter electrodes surrounding the substrates undergoing deposition or arranging the substrates symmetrically between inner and outer cylindrical electrodes.

[0095] The surface area of the counter electrode is chosen to be much larger than the substrate area in order to minimize electrical polarization at the counter electrode, as is known to occur in the art. According to the invention, the preferred counter electrode area is at least five times the substrate area. Although the global EPD cell electric field is designed to be uniform, this invention provides means for shaping the local electric field around the substrates in order to shape the deposit in accordance to specifications of the final part.

[0096] Particles deposit on a substrate in an isotropic manner when placed in a uniform dispersion and a uniform electric field is applied. However, many components, such as anodes of electrolytic capacitors, require specific non-symmetrical shapes, extremely tight dimensions, and/or flat surfaces. Prior art restricts the EPD deposit to specified parts of the substrate by application of a thin insulating mask to certain areas of the substrate so that deposition takes place selectively on the surface of the substrate; however, thick deposits, as required for monolithic parts like anodes of electrolytic capacitors, creep over the top of the thin insulating mask due to the isotropic nature of the deposition process. Furthermore, for applications like capacitor anodes the mask layer must be separated from the green body after completion of the EPD process, which may be problematic.

[0097] The present invention shapes the electrophoretic deposit by use of engineered counter electrodes, secondary counter electrodes, current thieves, and non-conductive inserts to modify the local electric field around the substrate; thereby resulting in a defined anisotropic deposition. Anisotropic deposition through use of specifically engineered, multiple counter electrodes are demonstrated in the photographs reproduced in FIGS. **2**A and **2**B. FIG. **2**A shows the essentially circular cross sectional shape of a typical green tantalum body when deposited on the legs of a tantalum foil placed between two large stainless steel counter electrodes. The tantalum foil is 5 cm long. The foil is cut in the shape of a comb having multiple legs, or teeth, at its edge that are 0.3 mm long by 0.1 mm wide. The distance between the legs is 1.2 mm. The counter electrodes are 1.5 cm×6 cm in size and located 1.3 cm from the tantalum foil. The cross sectional dimensions of the green tantalum body deposited onto the legs of the tantalum foil are 690 μ×630 μ.

[0098] FIG. **2**B shows the cross-sectional shape that can be achieved when the green tantalum body is deposited in the presence of multiple counter electrodes according to the invention. In the example shown in FIG. **2**B, an oval shaped cross section was achieved by placing multiple parallel counter electrodes charged to 80V at 1 mm spacing from the substrate undergoing deposition. The small counter electrodes are located at intermediate positions between the legs of the tantalum foil. The cross sectional dimensions of the deposit are 650 μ×510 μ.

[0099] Anisotropic deposition through use of insulated inserts in proximity to the substrate undergoing deposition is demonstrated in the photographs reproduced in FIGS. **2**A and **2**C. FIG. **2**A is described hereinabove and shows the shape of a typical green tantalum body when deposited by EPD. FIG. **2**C shows the shape achieved when the green tantalum body is deposited in the presence of insulted inserts. FIG. **2**C shows a cross section of an EPD tantalum deposit in the presence of a pair of insulators, according to the method and using an apparatus of the invention. The insulators are located between the substrate undergoing deposition (cathode) and the anode (counter electrode) at a

0.8 mm space from the anode. The lateral location of the insulated inserts is at an intermediate position between the legs of the tantalum foil. The cross sectional dimensions of the deposit are 860 μ×640 μ. The cross-sectional shape shown in FIG. **2**C is to be compared with that obtained in the apparatus without insulating inserts as shown in FIG. **2**A.

[**0100**] Electric field simulations may be utilized in design of such secondary counter electrodes and insulated inserts that shape the component. Typical examples of electrophoretic field simulation are presented in FIGS. **3**A to **3**C, in which the small arrows show the calculated direction of the electric field lines in an EPD cell. FIG. **3**A shows the setup used to produce the deposition shown in FIG. **2**A. The legs of the tantalum foil **160** are shown, The large counter electrodes (not shown) are placed parallel to the row of legs at a distance of 1.3 cm on each side. FIG. **3**B shows the setup used to produce the deposition shown in FIG. **2**B. The small counter electrodes **162** are shown positioned around one of the tantalum legs **160**. It is to be noted that in FIG. **3**B the small counter electrodes are used alone, however in other embodiments the multiple small counter electrodes can be used together with large area counter electrodes, such as those used in FIG. **3**A. FIG. **3**C shows the setup used to produce the deposition shown in FIG. **2**C. The inserts **164** are located 0.8 mm from the large area stainless steel counter electrodes (not shown).

[**0101**] In cases in which a very flat surface is required at the end or edge of the green body formed by EPD, a physical barrier in very close proximity to the end or edge of the substrate is used. The EPD deposit grows until it fills the gap between the substrate and the barrier. The end or edge of the green body attains the shape of the barrier surface. In order to minimize interference with dispersion convection and uniformity in the vicinity of the substrates undergoing deposition, the barrier is designed as an element having the minimal size and support structure required to achieve shaping of the EPD deposit. Preferably, the surface of the barrier is smooth or coated with a material that reduces adhesion between the green body and the barrier, so that the green body is readily separated from the barrier surface after deposition. A typical example of a product that can be advantageously produced using barriers in the EPD cell according to the invention is the anode of an electrolytic capacitor.

[**0102**] Anodes of electrolytic capacitors require tight dimensional tolerances for high yield mass assembly and tight tolerances on anode weight for exact and repeatable capacitance values. One or more flat surfaces are often required to facilitate accurate, high speed assembly of the anode into the capacitor package. An example of a preferred anode shape is an anode deposited about a wire substrate, having an abrupt end for the EPD deposit at a designated point on the wire with tight dimensional tolerance.

[**0103**] In the case of a wire immersed in an EPD dispersion in a prior art system, particles would deposit well beyond the desired endpoint. This would occur even if the wire were masked with a thin insulator to prevent deposition beyond the desired endpoint on the wire since typical EPD processes are isotropic. Therefore the deposit will creep up on top of the insulating mask to a length similar to the deposit thickness.

[**0104**] In one embodiment of the present invention, the substrate or wire is held within a capillary or capillary like structure, with only the part of the substrate designated for deposition extending beyond the end of the capillary or capillary like structure. For a wire substrate, the capillary is a tube. For a flat substrate, the capillary structure has in internal cross section that is only slightly longer and wider than the substrate dimensions. A preferred size of the capillary structure is <0.1 mm larger than the dimensions of the substrate thickness and width. The small capillary gap greatly reduces diffusion of dispersion particles to parts of the substrate where material deposition is not desired. Furthermore, a flat deposit surface is formed at a well defined point on the substrate or wire with tight dimensional tolerance. FIG. **4** schematically shows one embodiment of an EPD apparatus **200** designed for fixing a plurality of capillaries and substrates according to the invention, but variations of this design are within the scope of this invention.

[**0105**] Apparatus **200** comprises a container **202** for holding the EPD suspension. In container **202** are suspended counter electrodes **204**, which are held in position by insulated holder **206** that is seated on seating ring **208** on the inner surface of the outer cylindrical counter electrode. Inserted into the insulated holder **206** are capillary tubes **214**. Each capillary tube has a substrate **212** passing through its interior with the portion of the substrate designated for deposition extending beyond the end of the capillary. In this example, the substrates are wires, having circular cross-sections. External contact ring **210** is in electrical contact with the upper end of each of the wire substrates **212**.

[**0106**] In a preferred embodiment, the apparatus **200** comprises a base **216** and spacer **218**, an example of which is schematically shown in FIG. **5**A and FIG. **5**B. By use of the base and spacer, the exposed section of the substrate for electrophoretic deposition is set to a specified dimension having a tight tolerance. The base and spacer can be conveniently used for loading and setting the position of the substrates in the capillaries after which the substrates may be locked in place by a spring or other clamping arrangement. After loading the substrates, the base and spacer are removed before mounting the assembly onto the counter electrodes in the dispersion bath, as shown in FIG. **4**.

[**0107**] In one preferred embodiment, a barrier, which is present in the bottom of the cell during deposition, may be designed having a cone shaped structure **220** as shown schematically in FIG. **6**. Such a shape not only contributes to improving the dimensional tolerances but also modifies the shape of the material deposited by EPD.

[**0108**] In a preferred embodiment of the invention, the capillary extends a significant depth into the dispersion, where uniformity and diffusion of dispersion components is optimal.

[**0109**] In a preferred embodiment of this invention, the end of the capillary structure is polished or coated with a material to reduce adhesion of the green body formed by the EPD process, thereby facilitating easy separation of the green body from the capillary structure at the conclusion of deposition.

[**0110**] In a preferred embodiment of this invention, contamination of the substrate within the capillary structure is further reduced by filling the capillary structure with liquid before its immersion into the EPD dispersion. The liquid used to fill the capillary structure may be a clean solvent that is compatible with the EPD dispersion composition. For example, for a dispersion based upon ethanol, the clean solvent used to fill the capillary structure will be ethanol. The presence of clean solvent in the capillary gap reduces diffusion of particles to parts of the substrate within the capillary.

[0111] The liquid used to fill the capillary structure may be immiscible with the EPD dispersion. This immiscible liquid creates a robust and impenetrable physical barrier to the diffusion of particles to that part of the substrate within the capillary structure.

[0112] A liquid reservoir may further be supplied at the upper end of the capillary structure above the EPD cell, or other means to create hydrostatic pressure within the capillary structure. For a capillary filling solvent that is compatible with the EPD dispersion, the generated pressure creates a very low fluid flow within the capillary, opposing diffusion of particles into the capillary gap. For a capillary filling liquid that is immiscible with the dispersion, location of the meniscus demarcating the capillary filling liquid and the dispersion fluid can be more accurately maintained at the very end of the capillary structure when a slight overpressure is applied.

[0113] FIGS. **7**A to **7**D show the schematic plan of an embodiment of the invention used to produce low profile anodes for electrolytic capacitors by immersing comb shaped tantalum foil into a suitable suspension. Each tantalum foil includes a plurality of anodes. The apparatus simultaneously processes a large number of foils, so that a large batch of anodes is processed in each electrophoretic deposition cycle. The EPD apparatus **300** that holds the tantalum foils also incorporates counter electrodes alternating with the tantalum foil substrates. Furthermore, the support used to hold the foil creates a physical barrier to the EPD deposit at a designated location on the tantalum foil substrate, providing tight tolerance on the length of the deposit and a deposit with a flat surface at the upper end.

[0114] As shown in FIGS. **7**A to **7**D, EPD apparatus **300** comprises a container **302** with a cover **304**. FIG. **7**A is a side view and FIG. **7**B a top view with most of the cover **304** removed to show the alternating arrangement of counter electrodes **306** and foil holders **310**. The counter electrodes **306** act as anodes in this embodiment and are suspended from the cover **304** by electricity conducting supporting rods **308**. The foil holders **310** act as cathodes in this embodiment and are suspended from the cover **304** by electricity conducting supporting rods **312**. FIG. **7**C is section A-A in FIG. **7**A and shows details of the shape of foil holder **310** and its supporting rods **312**. FIG. **7**D is section B-B in FIG. **7**A and shows details of the shape of counter electrode **306** and its supporting rods **308**.

[0115] FIG. **7**E is a photograph showing the apparatus of FIGS. **7**A to **7**D with the cover **304** removed from the container **302** and turned over to reveal the arrangement of foil holders **310** and counter electrodes **306**.

[0116] FIG. **7**F is a photograph of one of the foil holders **310** showing the plurality of green tantalum anodes **316** that have been deposited on the "teeth" of the comb shaped piece of tantalum foil.

[0117] The resulting tantalum anodes **316** are shown in FIG. **7**G, prior to cutting the discrete anodes **316** from the comb shaped tantalum foil substrate **314**. In other embodiments, the apparatus **300** can be used with discrete wire substrates rather than tantalum foil substrates with similar results and other types of foil can be used instead of tantalum.

[0118] In some embodiments of the invention, innovative control systems are an integral part of the deposition system. For efficient and low cost manufacturing, dispersions used for manufacturing components by electrophoretic deposition must be utilized to near exhaustion or alternatively, the dispersion chemistry, particle mass load, and particle size distribution should be corrected during electrophoretic deposition or between batch depositions. This is particularly true for dispersions of high cost powders such as tantalum for anodes of electrolytic capacitors. In one embodiment of the invention, consistent deposit weight is achieved in subsequent depositions from an original dispersion through a model based system that modifies current, voltage and time for subsequent depositions. Deposition weight achieved from dispersion is a complex function of electrophoretic voltage, current, and deposition time. Each deposition cycle alters the particle mass load, particle size distribution, and chemistry of the dispersion fluid. Deposited mass is sensitive to these parameters. In order to achieve the consistency of EPD mass deposit which is essential for manufacturing, this embodiment incorporates model based parameter adjustment into the EPD apparatus for multiple deposition cycles from partially depleted dispersion.

[0119] This embodiment is realized for a specific EPD apparatus by performing test runs with various control parameters. Knowing the relationship between the weight W and the deposition number N over different values of the control variables, a control algorithm is developed for that particular apparatus to compensate for depletion of the dispersion from run to run, thereby achieving consistent mass deposit for all runs.

[0120] A preferred control variable is $\int Vdt$ (I=constant), where V is the applied electrophoretic voltage and I is the current in the EPD cell. The control model is constructed by performing linear regression as is known in the art using exponential models of the form $W=\alpha N^{-\beta}$(W=deposit weight; N=sequential deposition run number using the depleted dispersion) and determining the α and β coefficients for each $\int Vdt$. An example of data used for building such a control model is presented in FIG. **8**A. The electrophoretic deposition system using this innovative model-based control parameter of $\int Vdt$ maintains constant deposit mass from run to run by applying a new $\int Vdt$ for each deposition run in accordance with the control model. The experimental results shown in FIG. **8**A are summarized in the following table:

Curve	$\int Vdt$	Symbol	Equation of curve
a	6000	*	$W = 0.0664N^{-0.0921}$
b	5000	Δ	$W = 0.0618N^{-0.1019}$
c	4500	x	$W = 0.0614N^{-0.1017}$
d	4000	■	$W = 0.0515N^{-0.0872}$
e	3000	◆	$W = 0.0415N^{-0.0933}$

[0121] The data in the above table are used to calculate the control model. In this particular case, the exponent $\beta$is roughly constant at 0.09524. On the other hand, for the above example, α is approximately a quadratic function of ∫Vdt as can be seen in FIG. **8**B, where the following is a quadratic fit for these data:

$\int Vdt = 3.00\times10^6\alpha^2 - 2.18\times10^5\alpha + 6.93\times10^3$.

[**0122**] Using this quadratic fit for α and a constant value of 0.0952 for β, the control model equation for this particular example is:

$$\begin{aligned} u_N &= \left(\int V dt\right)_N \\ &= 3.00\times10^6\alpha^2 - 2.18\times10^5\alpha + 6.93\times10^3 \\ &= 3.00\times10^6\left(\frac{W}{N^{-0.0952}}\right)^2 - 2.18\times10^5\left(\frac{W}{N^{-0.0952}}\right) + 6.93\times10^3 \end{aligned}$$

where W/N^{β} has been substituted for α in the above equation in accordance with the curve fit for deposit weight W shown in FIG. **8**A and the above table of the form $W=\alpha N^{-\beta}$, as stated hereinabove.

[**0123**] A typical example of a control model built from such data using a target deposit weight of 0.05 gram is shown in FIG. **8**C. By increasing ∫Vdt each deposition run in accordance with the control model, consistent deposition weight is maintained despite use of increasingly depleted dispersion.

[**0124**] Other preferred control variables that can be used are ∫Idt (V=constant) or simply t (time). According to the invention, the power supply of the EPD apparatus is programmed to apply the specified value of the control parameter for subsequent depositions in accordance with the experimentally established model, which is specific to that particular EPD apparatus, dispersion composition and desired deposit weight.

[**0125**] Another embodiment of a control method for partially depleted dispersion in EPD apparatus is based on monitoring of the electrophoretic current under constant voltage operation in order to determine the endpoint for usage of the depleted dispersion, i.e. the time at which replacement with fresh dispersion is necessary. FIG. **9** exhibits typical current vs. time curves at constant voltage for an electrophoretic deposition process. Curve a is for ∫Idt=0.5; Curve b is for ∫Idt=1; and Curve a is for ∫Idt=5 . In this embodiment, control limits are set based upon these characteristic curves. Deposition beyond the control limits that are set above and below the characteristic curve requires replacement of the depleted dispersion.

[**0126**] In another embodiment, which is shown schematically in FIG. **10**, dispersion fluid is recycled in order to restore its original particle mass load, particle size distribution and chemistry. Such chemistry and particle load compensation of the dispersion fluid not only maintains tight tolerance on the mass of the electrophoretic deposit, but also maintains tight control of other deposit characteristics such as porosity and surface roughness. This embodiment of EPD apparatus **400** incorporates a recycling tank **404** external to the EPD cell **402** where depleted dispersion is adjusted for particle mass load, particle size distribution, and chemistry before being returned to the EPD cell. In this way high powder utilization, high process uniformity, and low cost are achieved.

[**0127**] The method and apparatus **400** includes low flow rate transfer of dispersion fluid from the EPD cell **402** to an external recycling tank **404** using a circulation pump **406** through a short piping system. The fluid transfer may occur in small batches between deposition cycles or may be a continuous and constant flow. Chemical and emulsion and particle property monitoring detectors (not shown in the figure) are incorporated within the recycling tank **404**. Chemistry monitoring includes pH, Z-potential, conductivity, additives concentration, concentration of contaminants and more. Particle monitoring includes mass per cc of dispersion and particle size distribution. Small quantities of chemicals are added in accordance with monitor results in order to correct the dispersion chemistry and counteract contaminants. Particle mass load is corrected by addition of powder while performing ultrasonic agitation **408** in the recycling tank **404**. Particles that have coalesced into large agglomerates settle to the bottom of the recycling tank **404** by gravity and are removed from the recycling bath, thereby maintaining the original dispersion particle size distribution. Also methods are applied to remove excessively fine particles in the dispersion in the recycling cell that are not in compliance with the original particle size distribution.

[**0128**] Although the above description of the different embodiments of the invention generally refers to the manufacture of batches of components, where a batch may consist of a single component or a large number of components, it will be understood that the invention is also applicable to manufacturing by semi-continuous operation. Such semi-continuous production is achieved by systems such as reel to reel continuous or stepwise transfer through the EPD cell of components attached to a tape or strip. Such semi-continuous production may also be achieved by systems utilizing a carousel continuously or stepwise moving through the EPD cell, where completed green bodies are extracted from the carousel and new substrates are inserted for electrophoretic deposition of the green component body.

[**0129**] For all of the embodiments described herein, it will be understood that specific mention of wire or flat substrates does not limit the invention. The invention may be used with any kind of substrate including but not limited to 3D shapes and substrates which are perforated or in the shape of sieves.

[**0130**] Furthermore, although some of the embodiments herein specifically reference mass production of capacitor anodes using the invention, it will be understood that this is by way of example and does not limit applicability of the invention to manufacture of many kinds of small components by EPD.

[**0131**] The following examples are provided merely to illustrate the invention and are not intended to limit the scope of the invention in any manner.

EXAMPLE 1:

Niobium Oxide Capacitor Anode Manufactured by Fixturing in a Capillary Tube and Immersing in an EPD Cell

[**0132**] FIGS. **11**A and **11**B are optical photographs showing an overall view and longitudinal cross section, respectively, of a green niobium oxide anode as deposited on a tantalum wire by EPD, produced by using a specially designed holder to fix the wire in position in a capillary tube in accordance with one of the embodiments of this invention.

[0133] The dispersion was prepared by dispersing 5 g capacitor grade niobium oxide powder in 100 ml of 2-Propanol. The suspension was subjected to ultrasonic treatment in a Fisher Scientific Sonic Dismembrator 550 at 20 KHz and a power level of 550 Watts for 5 minutes in pulse regime, 2 sec pulse on and 2 sec pulse off. 150 μl of Polyethylenimine 17 wt % aqueous solution was added to the suspension and pulsed sonification repeated for 1 minute. The dispersion was further stirred for 20 minutes. A dispersion pH in the range of 9 to 10 and conductivity of 1 μS/cm were obtained.

[0134] The 0.142 mm diameter tantalum wire was inserted into a capillary tube of 0.152 mm ID and 3 mm OD and extended beyond the end of the capillary tube by 0.7 mm. The end of the capillary tube was then immersed to a depth of 1 cm into the dispersion. Cathodic voltage of 100 volts was applied to the tantalum wire for 50 seconds. The counter electrode was a large diameter cylindrical platinum foil surrounding the capillary tube and wire. A green niobium oxide anode of 0.9 mm in length and 0.5 mm in diameter was deposited on the tantalum wire.

[0135] The sharply defined upper end of this anode is to be compared to FIG. 11C, which shows the shape of an anode produced by EPD by simple immersion of tantalum wire to a defined depth below the free surface of the dispersion.

EXAMPLE 2:

Restoring Particle Size Distribution by Agglomerate Sedimentation

[0136] A narrow particle size distribution was produced in niobium oxide dispersion, where the dispersion included large agglomerates. This process applies to both improvement of fresh dispersion by reducing dispersion particle size and narrowing particle distribution, and to restoring particle size distribution of used dispersion where particle size distribution has degraded due to particle agglomeration.

[0137] The niobium oxide dispersion was composed of the following material:

Material	Catalog No.	Supplier	Batch No.
Niobium Oxide powder (NbO)	NbO-0401	Hermann Starck	209-2-1
2-propanol (IPA)	16260521	BIO LAB	40989
Polyethylenimine (PEI 17%)	181978	Sigma Aldrich	NA

[0138] The equipment used for preparation of the dispersion and its characterization and measurements is as follows:

Apparatus	Description	Supplier	Model
Sonicator	Used for particle dispersion by sonic energy	Fisher Scientific	550 Sonic dismembrator
Mastersizer	Measurement of particle size distribution	Malvern	2000 Superfine
Sedimentation tool	Pyrex beaker of dimensions height = 6.5 [cm] diameter = 11 [cm]	—	—

[0139] Preparation of dispersion:

[0140] add 15 gr NbO to 300 ml IPA

[0141] sonification for 5 minutes

[0142] add 240 μl PEI 17%

[0143] sonification for 1 minute

[0144] Stir while cooling.

[0145] The pH of the above dispersion was 8.37 and its conductivity was 0.7 μS/cm at 25.2° C.

[0146] Particle size distribution was analyzed for the above dispersion. A one hour sedimentation process was then performed, removing particle agglomerates from the dispersion. The particle size distribution measurement was then repeated. The results are as shown in the following table, where 10% of the dispersion particles have particle size larger than D [0.1], 50% of the dispersion particles have particle size larger than D [0.5], and 90% of the dispersion particles have particle size larger than D [0.9]:

	Dispersion				
	D [0.1]	D [0.5]	D [0.9]	Error	Ratio D [0.9] to D [0.1]
As-prepared	0.954 μm	2.438 μm	12.611 μm	1.809%	13.2
After sedimentation process	0.584 μm	1.469 μm	2.917 μm	0.644%	5.0

[0147] The sedimentation process successfully removed particle agglomerates, thereby narrowing the dispersion particle size distribution and reducing average particle size.

[0148] While some embodiments of the invention have been described by way of illustration, it will be apparent that the invention can be applied in practice with many modifications, variations and adaptations, and with the use of numerous equivalent or alternative solutions that are within the capacity of persons skilled in the art, without departing from the spirit of the invention or exceeding the scope of the claims.

1. Apparatus for production of small components with defined pre-set dimensions and properties by electrophoretic deposition (EPD) on electrically conducting or semi-conducting substrates, said apparatus comprising:

a. an electrical circuit comprising a power supply;

b. an EPD cell containing a homogenous EPD suspension;

c. substrate fixtures for holding said substrates, for immersing said substrates in said EPD suspension, and for making electrical contact between said substrates and said electrical circuit;

d. counter electrodes; and

e. elements for shaping the component or providing tight dimensional tolerances.

2. The apparatus of claim 1 comprising components for monitoring the chemical and electrical properties of the EPD dispersion.

3. The apparatus of claim 1 comprising components for controlling the shape and strength of the electrical field in the EPD cell.

4. The apparatus of claim 1 comprising components for controlling the electrical current flowing through the external electrical circuit and the voltage across said circuit.

5. The apparatus of claim 1 wherein the substrate has a shape chosen from the group:

a. wire-shaped;

b. flat-shaped;

c. sieve-shaped; and

d. 3D shaped.

6. The apparatus of claim 1 wherein the substrate comprises of conductive and non-conductive areas.

7. The apparatus of claim 1 wherein the elements for shaping the component or providing tight dimensional tolerances comprise one of the following:

a. components for protecting selective areas on the conductive substrates from being exposed to the EPD dispersion, thereby sharply demarcating the part of said substrate upon which material is deposited by EPD and the part of said substrate that is clean of said deposit;

b. a structure in which part of said substrate is contained which sharply demarcates the part of said substrate upon which material is deposited by EPD from that part of said substrate that is clean of said deposit;

c. a physical barrier or masking structure placed near the end of said substrate undergoing electrophoretic deposition, thereby shaping or improving the dimensional tolerance of said end of the component made by EPD deposition on said substrate; and

d. multiple or secondary electrodes arranged around said components undergoing EPD, thus shaping the electric field around said component and thereby shaping the dimensions of said component.

8. The apparatus of claim 7, wherein the substrate fixture covers a part of the substrate, thereby protecting selective areas on the conductive substrates from being exposed to the EPD dispersion.

9. The apparatus of claim 7, wherein the structure in which part of the substrate is contained is a capillary or a tube.

10. The apparatus of claim 7, wherein the structure in which part of the substrate is contained is a slit which is slightly wider and thicker than said substrate.

11. The apparatus of claim 7, wherein the structure in which part of the substrate is contained is filled with clean solvent compatible with the dispersion fluid, thereby further reducing diffusion of particles into the gap between said substrate the walls of said structure.

12. The apparatus of claim 11, wherein pressure is applied to the top end of the structure.

13. The apparatus of claim 12, wherein the applied pressure creates a small amount of flow of clean solvent from the structure into the dispersion fluid, thereby further reducing diffusion of particles into the gap between the substrate and the walls of said structure.

14. The apparatus of claim 12, wherein the structure is a capillary and the applied pressure is equal to the pressure exerted by the capillary force, thereby preventing capillary flow of dispersion fluid into the structure.

15. The apparatus of claim 12, wherein the applied pressure is caused by a fluid reservoir at the upper end of the structure.

16. The apparatus of claim 11, wherein the clean solvent is immiscible with the dispersion fluid, thereby creating a sharp barrier between the end of the structure and said dispersion fluid, thereby further reducing diffusion of particles into the gap between the substrate and the walls of said structure.

17. The apparatus of claim 1, wherein the chemical and particle composition of the dispersion is maintained uniform throughout the deposition cell.

18. The apparatus of claim 1, wherein structures in the EPD cell, which are necessary for structural support or other functions, are made of conductive material and charged to the potential of the counter electrode, thereby reducing deposition of dispersion particles on said structures.

19. The apparatus of claim 1, wherein a uniform electric field is created within the deposition cell around the components undergoing electrophoretic deposition.

20. The apparatus of claim 1, comprising a system for recycling the EPD dispersion, said system removing said dispersion from the EPD cell and causing it to flow to a recycling cell, wherein the properties of said dispersion are changed before returning it to said EPD cell.

21. The apparatus of claim 20, wherein the dispersion is removed from and returned to the EPD cell in one of the following ways:

a. continuously; or

b. between deposition cycles.

22. The apparatus of claim 20, wherein the properties of the dispersion that are changed before returning it to the EPD cell are chosen from the group comprised of:

a. particle concentration;

b. pH;

c. Z-potential; and

d. electrical conductivity.

23. The apparatus of claim 22, wherein the concentration of the dispersion transferred to the recycling cell is corrected to its original concentration before returning it to the EPD cell.

24. The apparatus of claim 20, wherein the recycling cell comprises ultrasonic agitation means to break down agglomerates to their original size distribution.

25. The apparatus of claim 20, wherein the dispersion in the recycling cell is allowed to undergo sedimentation for a predetermined time in order to remove large agglomerates not compatible with the original particle size distribution.

26. The apparatus of claim 20, wherein excessively fine particles that are not in compliance with the original particle size distribution are removed from the dispersion in the recycling cell.

27. The apparatus of claim 20, wherein the chemistry of the dispersion fluid in the recycling cell is corrected by the addition of tiny amounts of chemical additives.

28. The apparatus of claim 1, wherein the small components are formed by electrophoretic deposition in one of the following ways:

a. as discrete components; or

b. as batches.

29. The apparatus of claim 1, wherein the small components are formed by electrophoretic deposition in a semicontinuous operation.

30. The apparatus of claim 29, wherein the small components are formed on a substrate in the form of a continuous strip or ribbon.

31. The apparatus of claim 29, wherein the small components are formed on substrates that are arranged on a carousel.

32. The apparatus of claim 1, wherein the small components are selected from the group comprising:

a. porous anodes of electrolytic capacitors;

b. pitch bonding capillaries in microelectronics;

c. high temperature nozzles;

d. ferrules for connecting optical fibers;

e. high temperature engine components;

f. dental crowns; and

g. bearing parts.

33. A method for controlling the use of the apparatus of claim 1 for the preparation of a component by electrophoretic deposition, said method comprising making use of one of the following:

a. maintaining constant deposit mass from run to run in constant current operation by applying a new fVdt for each deposition run in accordance with the control model;

c. monitoring of the electrophoretic current under constant voltage operation in order to determine the endpoint for usage of the depleted dispersion; or

d. maintaining constant deposit mass from run to run by adjustment of the deposition time of sequential depositions.

* * * * *