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(54) MAGNETORHEOLOGICAL POLISHING DEVICES AND METHODS

MAGNETORHEOLOGISCHE POLIERVORRICHTUNGEN UND VERFAHREN

DISPOSITIFS ET PROCEDES DE POLISSAGE MAGNETORHEOLOGIQUE

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Description

FIELD OF THE INVENTION

[0001] This invention relates to methods of polishing surfaces using magnetorheological fluids.

BACKGROUND OF THE INVENTION

[0002] Workpieces such as glass optical lenses, semiconductors, tubes, and ceramics have been polished in the art using one-piece polishing tools made of resin, rubber, polyurethane or other solid materials. The working surface of the polishing tool should conform to the workpiece surface. This makes polishing complex surfaces complicated, and difficult to adapt to largescale production. Additionally, heat transfer from such a solid polishing tool is generally poor, and can result in superheated and deformed workpieces and polishing tools, thus causing damage to the geometry of the workpiece surface and/or the tool.
[0003] US 4,821,466 describes a method and apparatus for grinding whereby a work is immersed in a magnetic fluid having abrasive grains and a floating pad. US 2,735,231 describes a device for sharpening or polishing objects whereby the object is suspended in an abrasive bath containing magnetic powders which has a consistency that changes under the influence of a magnetic field.

SUMMARY OF THE INVENTION

[0004] This invention is directed to improved devices and methods for polishing objects in a magnetorheological polishing fluid (MP-fluid). More particularly, this invention is directed to a highly accurate method of polishing objects, in a magnetorheological fluid, which may be automatically controlled, and to improved polishing devices. The method of this invention is defined in claim 1.
[0005] The polishing of this invention is defined in claim 14.
[0006] Preferred embodiments are specified in the dependent claims.
[0007] In the method and devices of this invention, the magnetorheological fluid is acted upon by a magnetic field in the region where the fluid contacts the object to be polished. The magnetic field causes the MP-fluid to acquire the characteristics of a plasticized solid whose yield point depends on the magnetic field intensity and the viscosity. The yield point of the fluid is high enough that it forms an effective polishing surface, yet still permits movement of abrasive particles. The effective viscosity and elasticity of the magnetorheological fluid when acted upon by the magnetic field provides resistance to the abrasive particles such that the particles have sufficient force to abrade the workpiece.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008]

Figure 1 is a cross-sectional side view of a polishing device of the invention.
Figure 2 is a cross-sectional side view of another embodiment of the invention.
Figure 3 is a cross-sectional side view of another embodiment of the invention.
Figure 4 is a graph showing the amount of material removed, as a function of distance from the center of the workpiece, for an exemplary workpiece.
Figure 5 is a schematic diagram illustrating the parameters used in the method of the invention to control polishing for a flat workpiece.
Figure 6 is a schematic diagram illustrating the parameters used in the method of the invention to control polishing for a curved workpiece.
Figure 7 is a graph showing the relationship between the rate of material removal during polishing and the magnetic field intensity.
Figure 8 is a graph showing the relationship between the rate of material removal during polishing and the clearance between a workpiece and the bottom of a vessel in which the workpiece is polished.
Figure 9 is a cross-sectional side view of another embodiment of the invention.
Figure 10 is a cross-sectional side view of another embodiment of the invention.
Figure 11 is a cross-sectional side view of another embodiment of the invention.
Figure 12 is a cross-sectional side view of another embodiment of the invention.
Figure 13 is a cross-sectional side view of another embodiment of the invention.
Figure 14 is a cross-sectional side view of another embodiment of the invention.
Figure 15 is a cross-sectional side view of another embodiment of the invention.

Figure 16 is a cross-sectional side view of another embodiment of the invention.
Figure 17 is a cross-sectional side view of another embodiment of the invention.
Figure 18 is a cross-sectional side view of another embodiment of the invention.
Figure 19 is a cross-sectional side view of another embodiment of the invention.
Figure 20 is a cross-sectional side view of another embodiment of the invention.
Figure 21 is a cross-sectional side view of another embodiment of the invention.
Figure 23 is a cross-sectional side view of another embodiment of the invention.
Figure 24 is a cross-sectional side view of another embodiment of the invention.
Figure 28 is a cross-sectional side view of another embodiment of the invention.
Figure 29 is a cross-sectional side view of another embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0009] Figure 1 is a schematic of a polishing device which may be operated according to the method of the present invention. In Fig. 1, a cylindrical vessel 1 contains magnetorheological polishing fluid (MP-fluid) 2. In a preferred embodiment, the MP-fluid 2 contains an abrasive. Vessel 1 is preferably constructed of a non-magnetic material which is inert to the MP-fluid 2. In Figure 1, vessel 1 is semi-cylindrically shaped in cross-section and has a flat bottom. However, the particular shape of vessel 1 may be modified to suit the workpiece to be polished, as will be described in greater detail.

[0010] An instrument 13, such as a blade, is mounted into vessel 1 to provide continuous stirring of the MP-fluid 2 during polishing. A workpiece 4 to be polished is connected to a rotatable workpiece spindle 5. Workpiece spindle 5 is preferably made from a non-magnetic material. Workpiece spindle 5 is mounted on a spindle slide 8, and can be moved in the vertical direction. Spindle slide 8 may be driven by a conventional servomotor which operates according to electrical signals from a programmable control system 12.

[0011] Rotation of vessel 1 is controlled by vessel spindle 3, which is preferably positioned in a central location below vessel 1. Vessel spindle 3 can be driven by conventional motor or other power source.

[0012] An electromagnet 6 is positioned adjacent to vessel 1 so as to be capable of influencing the MP-fluid 2 in a region containing the workpiece 4. Electromagnet 6 should be capable of inducing a magnetic field sufficient to carry out the polishing operation, and preferably will induce a magnetic field of at least about 100 kA/m. Electromagnet 6 is activated by winding 7 from power supply unit 11 which is connected to control system 12. Winding 7 can be any conventional magnetic winding. Electromagnet 6 is set up on an electromagnet slide 9 and can be moved in a horizontal direction, preferably along the radius of vessel 1. Electromagnet slide 9 may be driven by a conventional servomotor which operates according to electrical signals from the programmable control system 12.

[0013] Winding 7 is activated by power supply unit 11 during polishing to induce a magnetic field and influence the MP-fluid 2. Preferably, MP-fluid 2 is acted on by a nonuniform magnetic field in a region adjacent to the workpiece 4. In this preferred embodiment, equal-intensity lines of the field are normal, or perpendicular, to the gradient of said field, and the force of the magnetic field is a gradient directed toward the vessel bottom normal to the surface of workpiece 4. Application of the magnetic field from electromagnet 6 causes the MP-fluid 2 to change its viscosity and plasticity in a limited polishing zone 10 adjacent to the surface being polished. The size of the polishing zone 10 is defined by the gap between the pole-pieces of the electromagnet 6 and the shape of the tips of the electromagnet 6. Abrasive particles in the MP-fluid are preferably acted upon by the MP-fluid substantially only in polishing zone 10, and the pressure of MP-fluid against the surface of workpiece 4 is largest in the polishing zone 10.

[0014] In a preferred embodiment, an MP-fluid comprising a plurality of magnetic particles, a stabilizer, and a carrying fluid selected from the group consisting of water and glycerin, is used. In a further preferred embodiment, the magnetic particles (preferably carbonyl iron particles) are coated with a protective layer of a polymer material which inhibits their oxidation. The protective layer is preferably resistent to mechanical stresses, and as thin as practicable. In a preferred embodiment, the coating material is teflon. The particles may be coated by the usual process of microcapsulation.

[0015] The polishing machine shown in Figure 1 can operate as follows. Workpiece 4 is coupled to workpiece spindle 5, and positioned by spindle slide 8 at a clearance, h, with respect to the bottom of vessel 1 so that preferably a portion of the workpiece 4 to be polished is immersed in the MP-fluid 2. Said clearance h may be any suitable clearance which will permit polishing of the workpiece. The clearance h will affect the material removal rate V for the workpiece 4, as illustrated in Figure 8, and will also affect the size of a contact spot R_z at which the polishing zone 10 contacts the workpiece 4. The clearance h is preferably chosen so that the surface area of the contact spot R_z is less than one third of the surface area of the workpiece 4. The clearance h may be changed during the polishing process.

[0016] In a preferred embodiment, both workpiece 4 and vessel 1 are rotated, preferably counter to each other. Vessel spindle 3 is put into rotating motion, thereby rotating vessel 1. Vessel spindle 3 rotates about a central axis and preferably rotates vessel 1 at a speed sufficient to effect polishing but insufficient to generate a centrifugal force sufficient to substantially eject or spray MP-fluid 2 out of vessel 1. In a preferred embodiment, the vessel is rotated at a constant velocity. The motion of vessel 1 provides continuous delivery of a fresh portion of MP-fluid 2 to the region where workpiece 4 is located, and provides continuous motion of the MP-fluid 2 in contact with the surface of the workpiece being polished in the polishing zone 10. In a preferred embodiment additional carrying fluid, preferably water or glycerin, is added during polishing to replenish carrying fluid that has vaporized, and thus maintain the properties of the fluid.

[0017] Workpiece spindle 5 is also rotated, about a central axis, to provide rotating movement to workpiece 4. In a preferred embodiment, workpiece spindle 5 operates at speeds of up to 2000 rpm, with about 500 rpm particularly preferred. The motion of workpiece spindle 5 continuously brings a fresh part of the surface of the workpiece 4 into contact with the polishing zone 10, so that material removal along the circumference of the surface being polished will be substantially uniform.

[0018] As abrasive particles in the MP-fluid 2 contact the workpiece 4, a ring-shaped area having a width of the polishing zone is gradually polished on to the surface of the workpiece 4. Polishing is accomplished in one or more cycles, with an incremental amount of material removed from the workpiece in each cycle. Polishing of the whole surface of the workpiece 4 is achieved by radial displacement of the electromagnet 6 using electromagnet slide 9, which causes the polishing zone 10 to move relative to the workpiece surface.

[0019] The radial motion of the electromagnet 6 may be continuous, or in discrete steps. If the movement of the electromagnet 6 is continuous, the optimal velocity U_z of electromagnet 6 for each point of the trajectory of motion is calculated. The velocity of the electromagnet, UZ, can be calculated according to the following formulae:

$$\text{(I)} \qquad U_z = 2R_z/t$$

or

$$\text{(II)} \qquad U_z \leq 2R_zV/k_3$$

wherein R_z is the radius of the contact spot, in mm, in the polishing zone 10 which contacts the workpiece 4, t is the time, in seconds, for which the contact spot R_z is polished during one cycle, V is the material removal rate, in µm/min, and k_3 is the thickness, in µm, of the workpiece material layer to be removed during one cycle of polishing.

[0020] R_z is a function of the clearance h, as described above. The material removal rate, V, can be empirically determined given the clearance h and the velocity at which the vessel 1 is rotated. The material removal rate V may be determined by measuring the amount of material removed from a given spot in a given time. The thickness of the workpiece material layer to be removed during one polishing cycle, k_3, is a function of the accuracy required for the finished workpiece; k_3 may be selected to minimize local error accumulation. For example, when optical glass is polished, the value of k_3 is determined by the required fit to shape in waves. The amount of time for which the contact spot R_z should be polished during one cycle, t, is calculated according to the formula:

$$t \leq k_3/V$$

[0021] When k_3 and the velocity of the magnet, U_z, have been determined, the number of cycles required and the time required for polishing may be determined. To calculate the total number of cycles, N, to polish the workpiece 4, the thickness of the layer of material to be removed during polishing, K, is calculated according to the formula:

$$K \leq k_1 + k_2$$

where k_1 is the initial surface roughness in µm, and k_2 is the thickness of the subsurface damage layer in µm. The number of cycles required, N, may then be determined using the formula:

$$N = K/k_3$$

[0022] The amount of time required for one cycle, t_c, may be calculated using the following formula:

$$t_c = R_w/U_z$$

where R_w is the radius of the workpiece. Figure 5 shows the relationship of the radius of the workpiece R_w, the contact spot R_z, the clearance h, and the velocity of the magnet U_z for a flat workpiece such as is shown in Figure 1.

[0023] The total time T required for polishing may be calculated using the formula:

$$T = NR_w/U_z$$

where N is the number of cycles required, R_w is the radius of the workpiece, and U_z is the velocity of the electromagnet 6.

[0024] If the electromagnet 6 is moved in discrete steps, the dwell time at each step must be determined. In a preferred embodiment, the overall material removal is maintained constant at each step. To remove a constant amount of material during stepwise polishing, it is necessary to take into account material removal due to overlapping of the contact spots R_z at successive steps. The coefficient of overlapping, I, is determined by the formula:

$$I = r/2R_z$$

where r is the displacement of the workpiece in a single step, in mm, and R_z is the radius of the contact spot. The displacement in a single step, r, may be determined empirically using results from preliminary trials, such as those detailed in the example given below.

[0025] The dwell time for each step in a given cycle, t_d, may be determined according to the formula:

$$t_d = k_3 I/V$$

where k_3 is the thickness of the workpiece material layer to be removed during one polishing cycle, I is the coefficient of overlapping, and V is the material removal rate for the workpiece at a given clearance h and a given velocity of the vessel 1.

[0026] The number of steps in one cycle, n_s, for stepwise polishing may be determined using the formula:

$$n_s = R_w/r$$

where R_w is the radius of the workpiece, and r is the displacement of the workpiece in a single step. The total number of cycles, N, required to polish the workpiece may be calculated using the formula used with continuous polishing, that is:

$$N = K/k_3$$

where K is the thickness of the layer of material to be removed during polishing, and k_3 is the thickness of the workpiece material layer to be removed during one polishing cycle. The total time required for stepwise polishing, T, may be calculated using the formula:

$$T = t_d n_s N$$

where t_d is the dwell time for each step, n, is the number of steps in one cycle, and N is the total number of cycles.

[0027] In a preferred embodiment of the invention, a computer program for control unit 12 may be prepared on the basis of these calculations, for either continuous or stepwise polishing. The whole process of polishing a workpiece 4 may then be conducted under automatic control. As shown in Figure 1, the control unit 12 preferably includes an input device 26, a processing unit 27, and a signal generator 28.

[0028] In an alternate embodiment of the invention, the accuracy of figure generation, or correspondence of the finished workpiece to the desired shape and tolerances, may be improved by conducting tests to determine the spatial distribution of the removal rate of the material as a function of R_z, $V[R_z]$, in the contact spot R_z. The spatial distribution of the removal rate may be determined by the method of successive approximation, as detailed in the example given below and in Figure 4. The spatial distribution of the removal rate may then be used to more accurately determine the parameters of the polishing program, such as the dwell time, t_d, using the formulas previously discussed. In this case, the dwell time can be determined using the formula:

$$t_d = k_3 I/V[R_z]$$

[0029] Referring to Figure 2, there is shown an alternate embodiment of the invention. This embodiment achieves highly efficient polishing of convex workpieces 204, such as spherical and nonspherical optical lenses. In Figure 2, the vessel 201 is a circular trough, and the radius of curvature of the internal wall, adjacent to polishing zone 210, is larger than the largest radius of curvature of workpiece 204. During polishing, it is desirable to minimize the movement of the fluid 202 relative to the vessel 201. To minimize this movement, or slippage, of the MP-fluid 202, the internal wall of the vessel 201 may be covered with a layer of a nap, or porous, material 215 to provide reliable mechanical adhesion between the MP-fluid 202 and the wall of the vessel 201.

[0030] Workpiece spindle 205 is connected with spindle slide 208, which is connected with a rotatable table 216. The rotatable table 216 is connected to a table slide 217. Spindle slide 208, rotatable table 216, and table slide 217 may be driven by conventional servomotors which operate according to electrical signals from programmable control system 212. Rotatable table 216 permits workpiece spindle 205 to be continuously rocked about its horizontal axis 214, or permits its positioning at an angle α with the initial vertical axis 218 of spindle 205. Axis 214 preferably is located at the center of curvature of the polished surface at the initial vertical position of the workpiece spindle. Spindle slide 208 permits vertical displacement δ of the center of polished surface curvature relative to axis 214. Table slide 217 moves the rotatable table 216 with spindle slide 208 and workpiece spindle 205 to obtain, and maintain, the desired clearance h between the polished surface of workpiece 204 and the bottom of vessel 201. In this embodiment, an electromagnet 206 is stationary, and is positioned below the vessel 201 such that its magnetic gap is symmetric about the workpiece spindle axis 218 when this axis is perpendicular to the plane of polishing zone 210. The device illustrated in Figure 2 is the same as the device shown in Figure 1 in all other respects.

[0031] The polishing machine operates as follows. To polish workpiece 204, workpiece spindle 205 with attached workpiece 204 is positioned so that the center of the radius of curvature of workpiece 204 is brought into coincidence with the pivot point (axis of rotation 214) of the rotatable table 216. The removal rate for the workpiece to be polished is then determined experimentally, using a test workpiece similar to the workpiece to be polished. Polishing of work piece 204 may then be conducted automatically by moving its surface relative to polishing zone 210 using rotatable table 216, which rocks workpiece spindle 205 and changes the angle α according to calculated regimes of treatment.

[0032] The maximal angle α to which the spindle 205 may be rocked is determined using the formula:

$$\cos \alpha_{max} = (R_{sf} - L)/R_{sf}$$

where R_{sf} is the radius of the total sphere. As shown in Figure 6, R_{sf} represents what the radius of the workpiece would be if it were spherical, based upon the radius of curvature of the actual workpiece 204. L represents the thickness of the workpiece 204, as indicated on Figure 6, and it may be calculated using the formula:

$$L = R_{sf} - R^2{}_{sf} - R^2{}_{w}$$

[0033] The angle dimension of the contact spot, β, also indicated on Figure 6, may be determined using the formula:

$$\cos \beta = (R_{sf} - h_0)/R_{sf}$$

where R_{sf} is the radius of the total sphere and h_0 is the clearance between the bottom of the vessel 201 and the edge of the contact spot R_z for a curved workpiece, as shown in Figure 6. The height of the contact spot, h_0, may be determined using the formula:

$$h_0 = R_{sf} - R^2{}_{sf} - R^2{}_{z}$$

where R_{sf} is the radius of the total sphere and R_z is the width of the contact spot.

[0034] Rocking of workpiece spindle 205 may be continuous or stepwise. If the workpiece spindle 205 is continuously rocked, the angular velocity ω_z of this motion is determined by the formula:

$$\omega_z \geq \beta V/k_3$$

where β is the angle dimension of the contact spot, V is the material removal rate, and k_3 is the thickness of the workpiece material layer to be removed during one cycle of polishing. The duration of one cycle, t_c, may then be calculated using the formula

$$t_c = \alpha_{max}/\omega_z$$

where α_{max} is the maximal angle α to which the spindle 205 may be rocked, and ω_z is the angular velocity of the rocking motion.

[0035] To calculate the total number of cycles, N, to polish the workpiece 204, the thickness of the layer of material to be removed during polishing, K, is calculated according to the formula

$$K = k_1 + k_2$$

where k_1 is the initial surface roughness in μm, and k_2 is the thickness of the subsurface damage layer in μm. The number of cycles required, N, may then be determined using the formula

$$N = K/k_3$$

where k_3 is the thickness of the workpiece material layer to be removed during one cycle of polishing.

[0036] The total time T required to polish the workpiece may then be calculated using the formula

$$T = t_c N$$

where t_c is the duration of one cycle, and N is the number of cycles required.

[0037] If the workpiece spindle 205 is rocked in discrete steps, the dwell time for each step must be calculated. In calculating the dwell time for each step, it is necessary to take the coefficient of overlapping I into account. The coefficient of overlapping I is determined by the formula

$$I = \alpha_s/\beta$$

where β is the angle dimension of the contact spot, and α_s is the angle displacement for one step. The angle displacement for one step, α_s, may be calculated by the formula:

$$\alpha_s = \alpha_{max}/n_s$$

where α_{max} is the maximal angle α to which the spindle 205 may be rocked, and n_s is the number of steps in one cycle. The number of steps per cycle, n_s, may be calculated using the formula

$$n_s = \alpha_{max}/\beta$$

where α_{max} is the maximal angle α to which the spindle 205 may be rocked, and β is the angle dimension of the contact spot. The current angle α during polishing may be calculated using the formula:

$$\alpha = \alpha_s N_s$$

where α_s is the angle displacement for one step, and N_s is the number of the current step.

[0038] To calculate the total number of cycles, N, to polish the workpiece 204, the thickness of the layer of material to be removed during polishing, K, is calculated according to the formula:

$$K = k_1 + k_2$$

where k_1 is the initial surface roughness in µm, and k_2 is the thickness of the subsurface damage layer in µm. The number of cycles required, N, may then be determined using the formula:

$$N = K/k_3$$

where k_3 is the thickness of the workpiece material layer to be removed during one cycle of polishing.

[0039] The dwell time at each step may be calculated using the formula:

$$t_d = k_3 I/V$$

where k_3 is the thickness of the workpiece material layer to be removed during one cycle of polishing, I is the coefficient of overlapping, and V is the material removal rate. The total time T required to polish the workpiece may then be calculated using the formula:

$$T = t_d n_s N$$

where t_d is the dwell time for each step, n_s is the number of steps per cycle, and N is the number of cycles required.

[0040] The polishing may be conducted under conditions which yield uniform material removal from each point of the surface, if it is desired that the surface figure should not be altered, or specific material removal goals for each point on the surface may be achieved by varying the dwell time.

[0041] When a non-spherical workpiece 204 is to be polished, the procedure is generally the same as described for a spherical workpiece. A non-spherical workpiece 204 may be polished to the desired shape by varying the dwell time depending upon the radius of curvature of the section of the workpiece being polished. In an alternate embodiment for polishing a non-spherical workpiece, workpiece spindle 205 may also be moved vertically during polishing. To polish a non-spherical object, the calculations previously described may be carried out for each section of the workpiece having a different radius of curvature. As it is rocked to angle α, the radius of curvature of the section of a non-spherical workpiece being polished changes. To bring the momentary radius of curvature for the section of the workpiece 204 being polished into coincidence with pivot point 214, rocking of the workpiece spindle 205 is accompanied with vertical motion by spindle slide 208 when polishing non-spherical objects.

[0042] The magnetic field strength may also be varied for each stage of treatment during polishing, if desired. The material removal rate V is a function of the magnetic field intensity G, as shown in Figure 7. It is therefore possible to change the quantities of the operating parameters, such as dwell time or clearance. Thus the magnetic field strength may be used as another means for controlling the polishing process.

[0043] Referring to Figure 3, there is shown an alternate embodiment of the invention. In Figure 3, the internal wall of the vessel 301 has an additional circular trough which passes through the gap of the electromagnet 306. This configuration of the internal wall of the vessel 301 results in a smaller, more focused, polishing zone 310, and an increase in adhesion between the MP-fluid 302 and the vessel 301 is achieved. The smaller, more focused, polishing zone will result in a smaller contact spot R_z. In all other respects the embodiment depicted in Figure 3 is the same as that depicted in Figure 2.

<u>Example 1</u>

[0044] The polishing of a glass lens was accomplished, using a device as shown in Figure 2. The workpiece 204 had the following initial parameters:

a)	Glass type	BK7
b)	Shape	Spherical
c)	Diameter, mm	20
d)	Radius of curvature, mm	40
e)	Center thickness, mm	15
f)	Initial fit to shape, waves	0.5

(continued)

g)	Initial surface roughness, nm, rms	100

[0045] A vessel 201, in which the radius of curvature of the internal wall adjacent to the electromagnet pole pieces 206 was 200 mm, was used. The radius from central axis 219 was 145 mm and the width of the vessel trough was 60 mm. The vessel 201 was filled with 300 ml of the MP-fluid 202, having the following composition:

Component	Weight Percentage
Polirit (cerium oxide)	10
Carbonyl iron powder	60
Aerosil (fumed silica)	2.5
Glycerin	5.5
Distilled water	balance

[0046] To determine the material removal rate, a test workpiece 204 identical to the workpiece to be polished was polished at arbitrarily chosen standard parameters. The test workpiece was attached to the workpiece spindle 205 and positioned by spindle slide 208 so that the distance between the workpiece surface to be polished and the pivot point of the rotatable table 216 (axis 214) was equal to 40 mm (the radius of curvature of the workpiece 204 surface). Using rotatable table 216, the axis of rotation of workpiece spindle 205 was set up in a vertical position where angle $\alpha = 0°$. The clearance h between the surface of workpiece 204 to be polished and the bottom of the vessel 201 was set at 2 mm using the table slide 217.

[0047] Both the workpiece spindle 205 and the vessel 201 were then rotated. The workpiece spindle rotation speed was 500 rpm, and the vessel rotation speed was 150 rpm. The electromagnet 206, having a magnet gap equal to 20 mm, was turned on to a level where the magnetic field intensity near the workpiece surface was about 350 kA/m. All parameters were kept constant, and the workpiece was polished for about 10 minutes, which was sufficient to create a well-defined spot.

[0048] Next, the workpiece was removed from the workpiece spindle 205. Using a suitable optical microscope, measurements were then conducted to determine the amount of material H (in μm) removed from the original surface as a function of distance R (in mm) away from the center of the workpiece. In the example described here, a Chapman Instrument MP2000 optical profiler was used to measure the amount of material removed. Depending on the metrology available, about 20 measurements are made over a 20 mm distance. In this example, 16 measurements were made over 19.7 mm. The results of these measurements for this example are plotted in Figure 4. These results define the polishing zone for the machine set-up, and they are used as input for calculating the polishing program required to finish the workpiece. The inputs obtained in this example for calculating the polishing program are as follows:

1. Parameters of the workpiece:

a)	radius of the total sphere, R_{sf}, mm	39.6
b)	radius of workpiece, R_w, mm	24.3

2. Parameters of the polishing zone:

a)	radius of the contact spot, R_z, mm	17.9
b)	radius of the point where (d/dr) (dH/dr) = O, R_d, mm	10
c)	maximum of H, H_{max}, μm	21.5
d)	minimum of H, H_{min}, μm	0.5

3. Spatial distribution of removed material in the polishing zone:

R, mm	H, μm
0.0	15.2
3.3	19.5
5.1	21.5

(continued)

R, mm	H, µm
6.4	20.9
7.5	19.2
8.9	16.8
10.8	11.9
12.4	9.8
13.8	6.7
15	5.1
16.2	3.8
17.2	3.0
18.2	1.9
18.6	1.3
19.3	1.3
19.7	0.5

[0049] Using these inputs, the polishing required to finish the workpiece is determined. In a preferred embodiment of the present invention, a computer program is used to calculate the necessary parameters and control the polishing operation. Determination of the polishing requirements includes determination of the number of steps for changing angle α, the value of angle α for each step, and the dwell time for each step in order to maintain constant the material removal over the surface of the workpiece by overlapping polishing zones, as described above.

[0050] The parameters of the workpiece, parameters of the polishing zone, and spatial distribution of removed material in the polishing zone given above for this example are used to control the system during the polishing method. In this example, the results were entered into a computer program for this purpose. The results of the calculations were as follows:

Polishing regime

[0051]

Table 1

Angle, α mm	Time coefficient	Control radiuses,
0.00	1.000	0.00
1.79	1.000	1.25
3.58	1.000	2.49
5.37	1.000	3.74
7.16	1.000	4.98
8.95	1.000	6.22
10.74	1.208	7.45
12.53	1.208	8.68
14.32	1.208	9.89
16.11	1.416	11.10
17.90	1.624	12.29
19.70	1.832	13.48
21.49	2.040	14.65
23.28	2.040	15.81
25.07	2.040	16.95
26.86	1.624	18.07
28.65	1.832	19.18
30.44	38.119	20.26

[0052] As used here, the control radius represents the relative position of the polishing zone with respect to the central vertical axis of the workpiece. The control radius is determined by the angle α; during polishing it is the angle α, rather than the control radius, that is controlled.

[0053] The dwell times for each angle are then converted to minutes by multiplying the time coefficients in table 1 by a constant factor. The constant factor used to convert the time coefficients to dwell times will depend upon the characteristics of the workpiece. For the example given here, this constant was empirically determined to be 5 minutes.

[0054] Using the results from table 1, the programmable controller 212 was programmed. The workpiece 204 to be polished was attached to the workpiece spindle 205, and the procedure described for the test workpiece was repeated under the automatic control of the programmable controller 212. The following results were obtained.

Results of polishing

[0055]

Final fit to shape, waves	1
Final roughness, μm	0.0011

[0056] In addition to the embodiments described above, there are numerous alternate embodiments of the device of the present invention. Some of these alternate embodiments are shown in Figures 9 through 30. As illustrated by these figures, only a magnetorheological fluid, a means for inducing a magnetic field, and a means for moving the object to be polished or the means for inducing the magnetic field relative to one another are required to construct a device according to the present invention. For example, Figures 9 through 11 illustrate an embodiment of the invention in which the magnetorheological fluid is not contained within a vessel.

[0057] In Figure 9, an MP-fluid 902 is placed at the poles of an electromagnet 906. Electromagnet 906 is positioned so that the magnetic field that it creates acts only upon a particular surface section of the object to be polished 904, thereby creating a polishing zone. In operation, object 904 is put into rotation. Either electromagnet 906, or object 904, or both electromagnet 906 and object 904, are then moved such that step-by-step the entire surface of the object is polished. Electromagnet 906, object to be polished 904, or both, may be displaced relative to each other in the vertical and/or horizontal planes. During polishing the magnetic field strength is also regulated, as required, to polish the object 904. Rotation of the object 904, movement of the electromagnet 906 and/or the object 904, and regulation of the magnetic field strength according to a predetermined program of polishing permits controlled removal of material from the surface of the object to be polished 904.

[0058] Figure 10 illustrates a device for polishing curved surfaces. In Figure 10, an MP-fluid 1002 is placed at the poles of electromagnet 1006. The electromagnet 1006 is configured such that it generates a magnetic field affecting only some surface section of an object to be polished 1004. Object to be polished 1004, which has a spherical or aspherical surface, is put into rotation. Electromagnet 1006 is displaced to an angle α along the trajectory which corresponds to the radius of curvature of the object 1004, as indicated by the arrows in Figure 10, such that the electromagnet is moved parallel to the surface of the object, according to a predetermined program of polishing, thus controlling material removal along the part surface.

[0059] In Figure 11, an MR-fluid 1102 is also placed at the poles of electromagnet 1106. The electromagnet is configured such that it generates a magnetic field acting only upon some surface section of the object to be polished 1104. In operation, an object to be polished 1104 having a spherical or aspherical surface is put into rotation. The object to be polished 1104 is then rocked, such that an angle α, indicated on Fig. 11, varies from 0 to a value which depends upon the size and shape of the workpiece. Rocking the workpiece 1104 relative to the electromagnet 1106, thus varying the angle α, according to a predetermined program of polishing, controls material removal along the surface of the object to be polished.

[0060] In Figure 12, MR-fluid 1202 is placed into a vessel 1201. An electromagnet 1206 is positioned beneath vessel 1201 and configured such that the electromagnet 1206 initiates a magnetic field which acts only upon a section, or polishing zone 1210, of the MP-fluid 1202 in the vessel 1201. The MP-fluid in the polishing zone 1210 acquires plastic properties for effective material removal in the presence of a magnetic field. Object to be polished 1204 is put into rotation, and electromagnet 1206 is displaced along the surface to be polished. The workpiece may then be polished according to a predetermined program which controls material removal along the surface of the object to be polished.

[0061] In Figure 13, an MP-fluid 1302 is placed into a vessel 1301. Electromagnet 1306 is configured such that it induces a magnetic field acting only upon a section, or polishing zone 1310, of the MP-fluid 1302. The MP-fluid 1302 thus acts only upon the section of the object to be polished 1304 positioned in the polishing zone 1310. Object to be polished 1304 and vessel 1301, with their axes coinciding, are put into rotation at the same or different speeds in the same or opposite directions. Displacing electromagnet 1306 radially along the vessel surface according to an assigned program displaces the polishing zone 1310, and controls material removal along the surface of the object to be polished.

[0062] In Figure 14, an MP-fluid 1402 is placed into a vessel 1401. A casing 1419 which contains a system of permanent magnets 1406 is set under the vessel 1401. An electromagnetic field created by each magnet 1406 affects only a section, or polishing zone 1410, of the object to be polished. In operation, object to be polished 1404 and vessel 1401 are simultaneously put into rotation. The rotation axes of object to be polished 1404 and vessel 1401 are eccentric relative to each other. The casing 1419, or the object to be polished 1404, or both, are simultaneously displaced according to a predetermined program of polishing, thus controlling material removal along the object to be polished surface.

[0063] In Figure 15, an MP-fluid 1502 is placed into a vessel 1501. Electromagnet 1506 is positioned under the vessel such that its magnetic field affects only a section, or polishing zone 1510, of the MP-fluid 1502 in the vessel 1501. Object to be polished 1504, which has a spherical or curved shape, and vessel 1501 are put in rotation in the same or opposite directions. While polishing, object 1504 is rocked such that an angle α, indicated on Fig. 15, varies from 0 to a value which depends upon the size and shape of the object 1504. The rotation of the object 1504 and the vessel 1501, and the angle α, are controlled according to a predetermined program of polishing. As a result, material removal along the surface of the object to be polished is controlled.

[0064] In Figure 16, an MP-fluid 1602 is placed into a longitudinal vessel 1601. The shape of the inner cavity of the vessel 1601 is chosen to parallel the surface of the object 1604, such that the inner wall of the vessel is equi-distant from the generatrix of object 1604 at $\alpha = 0$. An electromagnet 1606 is positioned below the vessel 1601 such that it induces a magnetic field in a section, or polishing zone 1610, of the MP-fluid 1602. In operation, the electromagnet 1606 is displaced along the bottom of the vessel 1601 while the object 1604 and the vessel 1601 are rotating. The object is also rocked to an angle α during the polishing program. Rotation of the object 1604 and vessel 1601, movement of the electromagnet 1606, and rocking the object 1604 according to a predetermined program of polishing permits controlled removal of material from the surface of the object to be polished 904.

[0065] In Figure 17, MP-fluid 1702 is placed into a circular vessel with an annular cavity 1701. Electromagnet 1706 is positioned under the vessel 1701. Electromagnet 1706 is chosen such that its magnetic field affects a section, or polishing zone 1710, of the MP-fluid 1702. Object to be polished 1704 and vessel 1701 are put into rotation in the same or opposite directions at equal or different speeds. Displacing electromagnet 1706 radially along the bottom of the annular cavity of the vessel 1701, according to a program of polishing, controls material removal along the surface of the object to be polished 1704.

[0066] In Figure 18, an MP-fluid 1802 is placed into a circular vessel with an annular cavity 1801. The vessel bottom is coated with a nap material 1815, which hinders slippage of the MP-fluid 1802 relative to the vessel bottom 1801, and enhances the rate of material removal from the surface of the object. Electromagnet 1806 is mounted under the vessel cavity 1801. The pole pieces of the electromagnet 1806 are chosen such that its field will affect only a section, or polishing zone 1810, of the MP-fluid, and therefore it will only affect a portion of the surface of the object to be polished 1804.

[0067] The object to be polished 1804, the longitudinal vessel 1801, or both, are put into rotation at the same or different speeds, in the same or opposite directions. Electromagnet 1806 is also displaced relative to the surface of the object to be polished 1804 according to a program of polishing.

[0068] In Figure 19, MP-fluid 1902 is placed into an annular cavity in a circular vessel 1901. The radius of curvature of the vessel cavity is chosen to correspond to the desired radius of curvature of the object 1904 after polishing, such that the inner wall of the cavity 1901 will equi-distant to the surface of the polished object 1904. Object to be polished 1904, which is mounted on a spindle 1905, and vessel 1901 are put into rotation at equal or different speeds in the same or opposite directions. Electromagnet 1906 is displaced along the bottom of the vessel cavity 1901 according to a predetermined program, thus controlling material removal along the surface of the object to be polished.

[0069] In Figure 20, the MP-fluid 2002 is also placed into a circular vessel with an annular cavity 2001. An electromagnet 2006 is mounted under the vessel 2001. The pole pieces of the electromagnet 2006 are chosen such that its field will affect only a section, or polishing zone 2010, of the MP-fluid 2002, and therefore will affect only a surface section of the object to be polished 2004.

[0070] Object to be polished 2004 and the vessel 2001 are put into rotation at the same or fferent speeds in the same or opposite directions. The object to be polished 2004 is also rocked, or swung, relative to the vessel. The object is rocked from a vertical position to an angle $\propto$ during polishing according to a predetermined program, thereby controlling material removal along the surface to be polished.

[0071] In Figure 21, an MP-fluid 2102 is placed in a circular vessel 2101 with an annular cavity having a valley 2120. The pole pieces of electromagnet 2106 are chosen such that its magnetic field will affect only a portion, or polishing zone 2110, of the MP-fluid 2101. In Fig. 21, the portion of the MP-fluid 2102 affected by the magnetic field is located within, or above, the valley 2120.

[0072] An object to be polished 2104 is put into rotation. The object to be polished 2104 is also rocked, or swung, relative to its axis normal to the vessel rotation plane to an angle $\propto$, according to an assigned program, thus controlling material removal along the surface of the object to be polished.

[0073] In Figure 23, an MP-fluid 2302 is placed into a vessel 2301. An electromagnet 2306 is installed below the vessel bottom. The pole pieces of the electromagnet are chosen such that it will create a magnetic field which acts only upon a portion, or polishing zone 2310, of the MP-fluid 2302 in the vessel 2301. Objects to be polished 2304a, 2304b, etc. are mounted on spindles 2305a, 2305b, etc., which are capable of rotating relative to a disc 2321 on which they are installed. Disc 2321 is also capable of rotating relative to vessel 2301.

[0074] Disc 2321, objects to be polished 2304a, 2304b, etc., and vessel 2301 are put into rotation at equal or different speeds, in the same or opposite directions. Electromagnet 2306 is also radially displaced along the surface of the vessel. This rotation, and displacing electromagnet 2306 along the vessel surface, are regulated to control material removal from the surface of the object to be polished.

[0075] In Figure 24, an MP-fluid 2402 is placed into a vessel 2401. Electromagnets 2406a, 2406b, etc. are mounted near the vessel bottom. The pole pieces of electromagnets 2406a, 2406b, etc. are chosen such that each will create a field acting only upon a section, or polishing zone 2410a, 2410b, etc., of the vessel fluid 2402. Objects to be polished 2404a, 2404b, etc. are mounted on spindles 2405a, 2405b, etc. which are capable of rotating relative to a disc 2421 on which they are installed. Disc 2421, objects to be polished 2404a, 2404b, etc. and vessel 2401 are put into rotation with equal or different speeds, in the same or opposite directions. Electromagnets 2406a, 2406b, etc. are also radially displaced along the bottom surface of the vessel 2401. This rotation, and displacing electromagnets 2406a, 2406b, etc. along the vessel surface, are regulated to control material removal from the surface of the object to be polished.

[0076] In Figure 28, an MP-fluid 2802 is placed into vessel 2801. Two units 2822a and 2822b equipped with permanently mounted magnets 2823 are installed inside the vessel 2801.

[0077] A flat object to be polished 2804 is mounted between units 2822a and 2822b. Units 2822a and 2822b are rotated about their horizontal axes. These units are rotated at the same speed such that a magnetic field, and polishing zones 2810, will be created when different-sign poles are on the contrary with each other. Object to be polished 2804 is moved in such a way that polishing zones are created for both object surfaces. The material removal rate is controlled by the rotation speed of units 2822a, 2822b and the speed at which the object 2804 is vertically displaced.

[0078] In Figure 29, an MP-fluid 2902 is placed into vessel 2901. Units 2922 equipped with magnets 2923 are mounted inside vessel 2901 and are capable of rotating along the axis normal to the displacement direction of the object to be polished 2904. The magnets are mounted in the unit so that the permanent magnets mounted side by side would have different-sign poles relative to each other, so as to create a polishing zone 2910 between the magnets.

[0079] The polishing is carried out by rotating unit 2922 and giving a scanning motion to object to be polished 2904 in the vertical plane. The material removal rate is controlled by changing the rotational speeds of units 2922 and the speed at which object to be polished 2904 is displaced.

Claims

1. A method of polishing a workpiece surface using magnetorheological fluid (2), comprising:

positioning the workpiece (4) at a clearance (h) from a surface adapted to carry magnetorheological fluid (2);

introducing a flow of magnetorheological fluid (2) through said clearance (h);

applying a magnetic field substantially at said clearance (h) to create a polishing zone (10) in the magnetorheological fluid (2), said zone (10) forming a transient tool for engaging and causing material removal at a portion of the workpiece surface, said zone (10) engaging said workpiece surface at an area smaller than the area of the workpiece surface to be polished; and

moving the workpiece (4) or the zone (10) relative to the other to expose different portions of the workpiece surface to the zone (10) for predetermined dwell times to selectively polish said portions of said workpiece surface to predetermined degrees.

2. The method of claim 1, wherein at least a portion of said clearance (h) decreases in height from a first section to a second section, and said magnetorheological fluid (2) flows through said clearance (h) in a direction from said first section to said second section.

3. The method of claim 1 or 2, wherein said magnetorheological fluid (2) comprises non-magnetic abrasive particles to enhance material removal at the workpiece surface.

4. The method of claim 1, 2 or 3, further comprising the step of recirculating magnetorheological fluid (2) having flowed through said clearance (h) by reintroducing the fluid (2) through said clearance (h).

5. The method of claim 4, further comprising the step of stirring magnetorheological fluid (2) having flowed through said clearance (h).

6. The method of claim 5, wherein said magnetorheological fluid (2) includes a carrier fluid and further comprising the step of adding carrier fluid to the magnetorheological fluid (2) to replace evaporated carrier fluid.

7. The method of any of claims 1 to 6, wherein said step of introducing a flow of magnetorheological fluid (2) through said clearance (h) comprises depositing magnetorheological fluid (2) on the surface adapted to carry magnetorheological fluid (2) and moving said surface relative to the workpiece (4) to force magnetorheological fluid (2) to flow through the clearance (h).

8. The method of any of claims 1 to 7, wherein said step of applying a magnetic field comprises the step of maximizing the magnetic field at the clearance (h).

9. The method of any of claims 1 to 8, further comprising the step of rotating the workpiece (4) relative to the zone (10).

10. The method of any of claims 1 to 9, wherein said workpiece (4) is mounted on a pivoting workpiece holder and said step of moving the workpiece (4) or the zone (10) relative to the other comprises pivoting the workpiece holder to sweep the surface of the workpiece (4) across the zone (10).

11. The method of any of claims 1 to 9, wherein said step of moving the workpiece (4) or the zone (10) relative to the other comprises moving the workpiece (4) along a plane.

12. The method of claim 11, wherein the step of moving the workpiece (4) along a plane comprises moving the workpiece (4) along a plane in a direction substantially perpendicular to the direction of flow of the magnetorheological fluid (2) through said clearance (h).

13. The method of any of claims 1 to 9, wherein said step of moving the workpiece (4) or the zone (10) relative to the other comprises moving the zone by moving the magnetic field relative to said surface adapted to carry magnetorheological fluid (2).

14. An apparatus for polishing a workpiece surface using magnetorheological fluid (2), comprising:

a surface for carrying a volume of magnetorheological fluid (2);

a workpiece holder for holding and positioning the workpiece (4) at a clearance (h) from said surface such that said surface forces a flow of magnetorheological fluid (2) through said clearance (h);

a magnet for applying a magnetic field at said clearance (h) to create a polishing zone (10) in the magnetorheological fluid (2) flowing through said clearance (h) for forming a transient finishing tool for engaging and causing material removal at a portion of the workpiece surface, said zone (10) engaging said workpiece surface at an area smaller than the area of the workpiece surface to be polished; and

means for moving the workpiece (4) or the zone (10) relative to the other to expose different portions of the workpiece surface to the zone (10) for predetermined dwell times to selectively polish said portions of said workpiece surface in predetermined degrees.

15. The apparatus of claim 14, wherein at least a portion of said clearance (h) decreases in height from a first section to a second section, and said magnetorheological fluid (2) flows through said clearance (h) in a direction from said first section to said second section.

16. The apparatus of claim 14 or 15, further comprising means for adding carrier fluid to the magnetorheological fluid (2) to compensate for evaporation of carrier fluid from said magnetorheological fluid (2).

17. The apparatus of claim 16, further comprising a mixer for stirring the magnetorheological fluid (2).

18. The apparatus of any of claims 14 to 17, further comprising means for rotating the workpiece (4) relative to the zone (10).

19. The apparatus of any of claims 14 to 18, wherein said workpiece (4) is mounted on a pivoting workpiece holder to sweep the surface of the workpiece (4) across the zone (10).

20. The apparatus of any of claims 14 to 18, further comprising means for moving the workpiece (4) along a plane in a direction substantially perpendicular to the direction of flow of magnetorheological fluid (2) through said clearance (h).

21. The method according to any of claims 1 to 13, wherein said magnetorheological fluid (2) comprises magnetic particles coated with a layer of protective material to inhibit oxidation thereof, a stabilizer and a carrying fluid.

22. The method of claim 21, wherein said protective material comprises a polymer.

23. The method of claim 21 or 22, wherein said protective material comprises teflon.

24. The method of any of claims 21 to 23, wherein said carrying fluid comprises water.

25. The method of any of claims 21 to 24, wherein said carrying fluid comprises glycerin.

26. The method of any of claims 21 to 25, wherein said magnetic particles comprise carbonyl iron particles.

27. The method of any of claims 21 to 26, wherein said magnetorheological fluid further comprises abrasive particles.

28. The method of claim 27, wherein said abrasive particles comprise CeO_2.

29. The method according to any of claims 1 to 13, further comprising the steps of:

controlling the consistency of the fluid (2) in the polishing zone (10);

determining the rate of material removal for the workpiece (4);

determining the direction and velocity of movement of the polishing zone (10) relative to the workpiece (4); and

determining the number of cycles of polishing required, comprising:

determining the initial root mean square height of surface irregularities of the workpiece (4);

determining the thickness of a subsurface damage layer;

determining the initial surface shape; and determining the thickness of the material layer to be removed during one cycle of polishing.

30. The method of claim 29, wherein the step of determining the rate of material removal for the workpiece (4) comprises determining the spatial distribution of material removal.

31. The method of claim 29 or 30, wherein the movement of the polishing zone (10) relative to the workpiece (4) is continuous.

32. The method any of of claims 29 to 31, wherein the step of determining the direction and velocity of movement of the polishing zone relative to the workpiece (4) comprises:

determining the size of a contact section of the workpiece (4) in contact with the polishing zone (10) at any given time;

determining the thickness of the material layer to be removed during one cycle of polishing; and determining the velocity of the polishing zone (10).

33. The method of claim 29 or 30, wherein the movement of the polishing zone (10) relative to the workpiece (4) is in discrete steps.

34. The method of claim 33, wherein the step of determining the direction and velocity of movement of the polishing zone (10) relative to the workpiece (4) comprises:

determining the size of a contact section of the workpiece (4) in contact with the polishing zone (10) at any given time; determining the displacement of the polishing zone (10) in a single step;

determining the coefficient of overlapping;

determining the thickness of the material layer to be removed during one cycle of polishing;

determining the dwell time for each step of polishing; and

determining the number of steps required.

35. The method of any of claims 29 to 34, further comprising displacing the workpiece (4) from its vertical axis to an angle α.

36. The method of claim 35, wherein the workpiece (4) is displaced from its vertical axis to an angle α at a continuous velocity.

37. The method of claim 36, wherein displacing the workpiece (4) from its vertical axis to an angle α at a continuous velocity further comprises:

determining the angle dimension of the contact spot;

determining the thickness of the material layer to be removed during one cycle of polishing; and

determining the angular velocity of the displacement of the workpiece (4) to angle α.

38. The method of claim 35, wherein the workpiece (4) is displaced from its vertical axis to an angle α in discrete steps.

39. The method of claim 38, wherein displacing the workpiece (4) from its vertical axis to an angle α in discrete steps further comprises:

determining the angle dimension of the contact spot;

determining the thickness of the material layer to be removed during one cycle of polishing;

determining the value of the angle displacement of a single step;

determining the coefficient of overlapping; and

determining the dwell time at each step.

40. The method of any of claims 29 to 39, wherein the magnetorheological fluid (2) comprises:

a plurality of magnetic particles;

a stabilizer; and

a carrying fluid.

41. The method of claim 40, further comprising the step of controlling the properties of the magnetorheological fluid

(2) by replenishing the carrying fluid during polishing.

42. The method of any of claims 29 to 41, wherein the magnetorheological fluid is contained within a vessel having a reference surface.

43. The method of claim 42, wherein the vessel is moved relative to the workpiece (4).

44. The method of claim 43, wherein the vessel is rotated at specified velocities.

45. The method of claim 42, wherein the polishing zone (10) is nominally one third of the surface area of the workpiece (4) or less.

46. The method of any of claims 42 to 45, wherein the step of creating a polishing zone (10) within a magnetorheological fluid (2) comprises:

inducing a magnetic field in the vicinity of the magnetorheological fluid; and

controlling the direction and intensity of the magnetic field.

47. The method of any of claims 42 to 45, wherein the step of creating a polishing zone (10) within a magnetorheological fluid (2) comprises:

subjecting the magnetorheological fluid to a nonuniform magnetic field, having magnetic field lines that are perpendicular to the gradient of said field, in a region adjacent to the workpiece (4).

48. The method of claim 47, wherein the gradient of the magnetic field is directed toward the bottom of the vessel reference surface.

49. The method of claim 46, wherein the magnetic field is created by a means for inducing a magnetic field which is located outside of the vessel.

50. The method of any of claims 42 to 49, further comprising the step of determining the clearance (h) between the workpiece (4) and the vessel reference surface.

51. The method of claim 46, further comprising controlling the polishing of the workpiece (4) by controlling the magnetic field intensity and the location of the polishing zone (10) relative to the surface of the workpiece (4).

52. The method of claim 51, wherein the polishing is controlled by a programmable control unit.

53. The method of any of claims 29 to 52, wherein said magnetorheological fluid (2) comprises polishing abrasive material therein.

54. The method of any of claims 29 to 53, wherein said step of determining the number of cycles comprises determining the number of cycles according to the expression (initial root mean square height of surface irregularities + subsurface damage layer thickness) % (thickness of material layer to be removed).

55. The method of claim 34, wherein said step of determining the velocity of the polishing zone (10) comprises determining the velocity of the polishing zone (10) according to the expression

$$\frac{\text{2 x contact section x material removal rate}}{\text{thickness of the material layer to be removed}}.$$

56. The method of claim 34, wherein said step of determining the coefficient of overlapping comprises determining the coefficient of overlapping according to the expression

$$\frac{\text{displacement in a single step}}{\text{2 x contact section}};$$

and wherein said step of determining the dwell time for each step of polishing comprises determining the dwell time for each step of polishing according to the expression

$$\frac{\text{thickness of the material layer to be removed x coefficient of overlapping}}{\text{material removal rate}}$$

and wherein said step of determining the number of steps required comprises determining the number of steps according to the expression

$$\frac{\text{radius of the workpiece to be polished}}{\text{displacement in a single step}}$$

57. The method of claim 37, wherein said step of determining the angular velocity of the displacement of the workpiece to angle α comprises determining the angular velocity according to the expression

$$\frac{\text{angle dimension of contact spot x material removal rate}}{\text{thickness of the material layer to be removed}}$$

58. The method of claim 39, wherein said step of determining the dwell time at each step comprises determining the dwell time according to the expression

$$\frac{\text{thickness of the material layer to be removed x coefficient of overlapping}}{\text{material removal rate}}$$

59. The method of any of claims 40 to 58, wherein said magnetorheological fluid (2) comprises polishing abrasive material.

Patentansprüche

1. Verfahren zum Polieren einer Werkstückoberfläche unter Verwendung eines magnetorheologischen Fluids (2) mit den Schritten:

Positionieren des Werkstücks (4) mit einem Zwischenraum (h) von einer Oberfläche, die dazu geeignet ist, ein magnetorheologisches Fluid (2) zu tragen;
Erzeugen einer Strömung des magnetorheologischen Fluids (2) durch den Zwischenraum (h);
Erzeugen eines Magnetfeldes im wesentlichen in dem Zwischenraum (h), um den Polierbereich (10) im magnetorheologischen Fluid (2) zu erzeugen, wobei der Polierbereich (10) ein Übergangswerkzeug bildet, das mit einem Abschnitt der Werkstückoberfläche in Eingriff kommt und veranlaßt, daß in diesem Abschnitt Material von der Werkstückoberfläche abgetragen wird, wobei der Polierbereich (10) mit der Werkstückoberfläche in einem Flächenbereich in Eingriff kommt, der kleiner ist als der zu polierende Flächenbereich der Werkstückoberfläche; und
Bewegen des Werkstücks (4) bezüglich des Polierbereichs (10) oder des Polierbereichs (10) bezüglich des Werkstücks (4), um verschiedene Abschnitte der Werkstückoberfläche für vorgegebene Verweilzeiten dem Polierbereich (10) auszusetzen, um die Abschnitte der Werkstückoberfläche in vorgegebenen Graden selektiv zu polieren.

2. Verfahren nach Anspruch 1, wobei mindestens ein Teil des Zwischenraums (h) in der Höhe von einem ersten zu einem zweiten Abschnitt abnimmt, und wobei das magnetorheologische Fluid (2) in Richtung vom ersten Abschnitt zum zweiten Abschnitt durch den Zwischenraum strömt.

3. Verfahren nach Anspruch 1 oder 2, wobei das magnetorheologische Fluid (2) nicht-magnetische Schleifpartikel aufweist, um die Materialabtragung an der Werkstückoberfläche zu verbessern.

4. Verfahren nach Anspruch 1, 2 oder 3, ferner mit dem Schritt zum Wiederzuführen des magnetorheologischen Fluids (2), das durch den Zwischenraum (h) geströmt ist, in den Zwischenraum (h).

5. Verfahren nach Anspruch 4, ferner mit dem Schritt zum Rühren des magnetorheologischen Fluids (2), das durch den Zwischenraum (h) geströmt ist.

6. Verfahren nach Anspruch 5, wobei das magnetorheologische Fluid (2) ein Trägerfluid aufweist, und ferner mit dem Schritt zum Hinzufügen von Trägerfluids zum magnetorheologischen Fluid (2), um verdampftes Trägerfluid zu ersetzen.

7. Verfahren nach einem der Ansprüche 1 bis 6, wobei der Schritt zum Erzeugen einer Strömung eines magnetorheologischen Fluids (2) durch den Zwischenraum (h) das Aufbringen von magnetorheologischem Fluid (2) auf die Oberfläche, die dazu geeignet ist, das magnetorheologische Fluid (2) zu tragen, und das Bewegen der Oberfläche bezüglich des Werkstücks (4) aufweist, um das magnetorheologische Fluid (2) durch den Zwischenraum (h) zu zwingen.

8. Verfahren nach einem der Ansprüche 1 bis 7, wobei der Schritt zum Erzeugen eines Magnetfeldes den Schritt zum Maximieren des Magnetfeldes im Zwischenraum (h) aufweist.

9. Verfahren nach einem der Ansprüche 1 bis 8, ferner mit dem Schritt zum Drehen des Werkstücks (4) bezüglich des Polierbereichs (10).

10. Verfahren nach einem der Ansprüche 1 bis 9, wobei das Werkstück (4) auf einem schwenkbaren Werkstückhalter angeordnet ist, und wobei der Schritt zum Bewegen des Werkstücks (4) bezüglich des Polierbereichs (10) bzw. des Polierbereichs (10) bezüglich des Werkstücks (4) das Schwenken des Werkstückhalters aufweist, um die Oberfläche des Werkstücks (4) über den Polierbereich (10) zu bewegen.

11. Verfahren nach einem der Ansprüche 1 bis 9, wobei der Schritt zum Bewegen des Werkstücks (4) bezüglich des Polierbereichs (10) bzw. des Polierbereichs (10) bezüglich des Werkstücks (4) das Bewegen des Werkstücks (4) entlang einer Ebene aufweist.

12. Verfahren nach Anspruch 11, wobei der Schritt zum Bewegen des Werkstücks (4) entlang einer Ebene das Bewegen des Werkstücks (4) entlang einer Ebene in eine Richtung aufweist, die im wesentlichen senkrecht zur Strömungsrichtung des magnetorheologischen Fluids (2) durch den Zwischenraum (h) ausgerichtet ist.

13. Verfahren nach einem der Ansprüche 1 bis 9, wobei der Schritt zum Bewegen des Werkstücks (4) bezüglich des Polierbereichs (10) bzw. des Polierbereichs (10) bezüglich des Werkstücks (4) das Bewegen des Polierbereichs durch Bewegen des Magnetfeldes bezüglich der Oberfläche aufweist, die dazu geeignet ist, das magnetorheologische Fluid (2) zu tragen.

14. Vorrichtung zum Polieren einer Werkstückoberfläche unter Verwendung eines magnetorheologischen Fluids (2) mit:

einer Oberfläche zum Tragen eines Volumens eines magnetorheologischen Fluids (2);
einem Werkstückhalter zum Halten und Positionieren des Werkstücks (4) mit einem Zwischenraum (h) von der Oberfläche, so daß die Oberfläche eine Strömung des magnetorheologischen Fluids (2) über den Zwischenraum (h) erzwingt;
einem Magneten zum Erzeugen eines Magnetfeldes in dem Zwischenraum (h), um einen Polierbereich (10) im magnetorheologischen Fluid zu erzeugen, das durch den Zwischenraum (h) strömt, um ein Übergangspolierwerkzeug zu bilden, das mit einem Abschnitt der Werkstückoberfläche in Eingriff kommt und veranlaßt, daß in diesem Abschnitt Material von der Werkstückoberfläche abgetragen wird, wobei der Polierbereich (10) mit der Werkstückoberfläche in einem Flächenbereich in Eingriff kommt, der kleiner ist als der zu polierende Flächenbereich der Werkstückoberfläche; und
einer Einrichtung zum Bewegen des Werkstücks (4) bezüglich des Polierbereichs (10) oder des Polierbereichs (10) bezüglich des Werkstücks (4), um verschiedene Abschnitte der Werkstückoberfläche für vorgegebene Verweilzeiten dem Polierbereich (10) auszusetzen, um die Abschnitte der Werkstückoberfläche in vorgegebenen Graden selektiv zu polieren.

15. Vorrichtung nach Anspruch 14, wobei mindestens ein Teil des Zwischenraums (h) in der Höhe von einem ersten zu einem zweiten Abschnitt abnimmt, und wobei das magnetorheologische Fluid in Richtung vom ersten Abschnitt zum zweiten Abschnitt durch den Zwischenraum (h) strömt.

16. Vorrichtung nach Anspruch 14 oder 15, ferner mit einer Einrichtung zum Hinzufügen eines Trägerfluids zum magnetorheologischen Fluid (2), um das Verdampfen von Trägerfluid vom magnetorheologischen Fluid (2) zu kompensieren.

17. Vorrichtung nach Anspruch 16, ferner mit einem Mischer zum Rühren des magnetorheologischen Fluids (2).

18. Vorrichtung nach einem der Ansprüche 14 bis 17, ferner mit einer Einrichtung zum Drehen des Werkstücks (4) bezüglich des Polierbereichs (10).

19. Vorrichtung nach einem der Ansprüche 14 bis 18, wobei das Werkstück (4) auf einem schwenkbaren Werkzeughalter angeordnet ist, um die Oberfläche des Werkstücks (4) über den Polierbereich (10) zu bewegen.

20. Vorrichtung nach einem der Ansprüche 14 bis 18, ferner mit einer Einrichtung zum Bewegen des Werkstücks (4) entlang einer Ebene in eine Richtung, die im wesentlichen senkrecht zur Strömungsrichtung des magnetorheologischen Fluids (2) durch den Zwischenraum (h) ausgerichtet ist.

21. Verfahren nach einem der Ansprüche 1 bis 13, wobei das magnetorheologische Fluid (2) magnetische Partikel, die mit einer Schutzmaterialschicht beschichtet sind, um zu verhindern, daß sie oxidieren, einen Stabilisator und ein Trägerfluid aufweist.

22. Verfahren nach Anspruch 21, wobei das Schutzmaterial ein Polymer aufweist.

23. Verfahren nach Anspruch 21 oder 22, wobei das Schutzmaterial Teflon aufweist.

24. Verfahren nach einem der Ansprüche 21 bis 23, wobei das Trägerfluid Wasser aufweist.

25. Verfahren nach einem der Ansprüche 21 bis 24, wobei das Trägerfluid Glyzerin aufweist.

26. Verfahren nach einem der Ansprüche 21 bis 25, wobei die magnetischen Partikel Carbonyleisenpartikel aufweisen.

27. Verfahren nach einem der Ansprüche 21 bis 26, wobei das magnetorheologische Fluid ferner Schleifpartikel aufweist.

28. Verfahren nach Anspruch 27, wobei die Schleifpartikel CeO_2 aufweisen.

29. Verfahren nach einem der Ansprüche 1 bis 13, ferner mit den Schritten:

Steuern der Konsistenz des Fluids (2) im Polierbereich (10);
Bestimmen der Materialabtragrate für das Werkstück (4);
Bestimmen der Richtung und der Geschwindigkeit der Bewegung des Polierbereichs (10) bezüglich des Werkstücks (4); und
Bestimmen der erforderlichen Anzahl von Polierzyklen mit:

Bestimmen des anfänglichen quadratischen Mittelwertes der Höhe von Oberflächenunregelmäßigkeiten des Werkstücks (4);
Bestimmen der Dicke einer defekten Schicht unter der Oberfläche;
Bestimmen der anfänglichen Oberflächenform; und
Bestimmen der während eines Polierzyklus abzutragenden Materialschichtdicke.

30. Verfahren nach Anspruch 29, wobei der Schritt zum Bestimmen der Materialabtragrate für das Werkstück (4) das Bestimmen der räumlichen Verteilung der Materialabtragung aufweist.

31. Verfahren nach Anspruch 29 oder 30, wobei die Bewegung des Polierbereichs (10) bezüglich des Werkstücks (4) kontinuierlich ist.

32. Verfahren nach einem der Ansprüche 29 bis 31, wobei der Schritt zum Bestimmen der Richtung und der Geschwindigkeit der Bewegung des Polierbereichs bezüglich des Werkstücks (4) aufweist:

Bestimmen der Größe eines Kontaktabschnitts des Werkstücks (4), der mit dem Polierbereich (10) in Kontakt steht, zu jedem vorgegebenen Zeitpunkt;
Bestimmen der während eines Polierzyklus abzutragenden Materialschichtdicke; und
Bestimmen der Geschwindigkeit des Polierbereichs (10).

33. Verfahren nach Anspruch 29 oder 30, wobei die Bewegung des Polierbereichs (10) bezüglich des Werkstücks (4) in diskreten Schritten erfolgt.

34. Verfahren nach Anspruch 33, wobei der Schritt zum Bestimmen der Richtung und der Geschwindigkeit der Bewegung des Polierbereichs (10) bezüglich des Werkstücks (4) aufweist:

Bestimmen der Größe eines Kontaktabschnitts des Werkstücks (4), der mit dem Polierbereich (10) in Kontakt steht, zu jedem vorgegebenen Zeitpunkt;
Bestimmen des Versatzes des Polierbereichs (10) in einem einzelnen Schritt;
Bestimmen eines Überlappungskoeffizienten;
Bestimmen der während eines Polierzyklus abzutragenden Materialschichtdicke;
Bestimmen der Verweilzeit für jeden Polierschritt; und
Bestimmen der erforderlichen Anzahl von Polierschritten.

35. Verfahren nach einem der Ansprüche 29 bis 34, ferner mit dem Schritt zum Versetzen des Werkstücks (4) von seiner vertikalen Achse um einen Winkel α.

36. Verfahren nach Anspruch 35, wobei das Werkstück (4) mit einer kontinuierlichen Geschwindigkeit um einen Winkel α von seiner vertikalen Achse versetzt wird.

37. Verfahren nach Anspruch 36, wobei der Schritt zum Versetzen des Werkstücks (4) um einen Winkel α von seiner vertikalen Achse mit einer kontinuierlichen Geschwindigkeit ferner aufweist:

Bestimmen des Winkelmaßes des Kontaktbereichs;
Bestimmen der während eines Polierzyklus abzutragenden Materialschichtdicke; und
Bestimmen der Winkelgeschwindigkeit des Versatzes des Werkstücks (4) um den Winkel α.

38. Verfahren nach Anspruch 35, wobei das Werkstück (4) in diskreten Schritten um einen Winkel α von seiner vertikalen Achse versetzt wird.

39. Verfahren nach Anspruch 38, wobei das Versetzen des Werkstücks (4) in diskreten Schritten um einen Winkel α von seiner vertikalen Achse aufweist:

Bestimmen des Winkelmaßes des Kontaktbereichs;
Bestimmen der während eines Polierzyklus abzutragenden Materialschichtdicke;
Bestimmen des Winkelversatzes für einen einzelnen Schritt;
Bestimmen des Überlappungskoeffizienten; und
Bestimmen der Verweilzeit für jeden Schritt.

40. Verfahren nach einem der Ansprüche 29 bis 39, wobei das magnetorheologische Fluid (2) aufweist:

mehrere magnetische Partikel;
einen Stabilisator; und
ein Trägerfluid.

41. Verfahren nach Anspruch 40, ferner mit dem Schritt zum Steuern der Eigenschaften des magnetorheologischen Fluids (2) durch Nachfüllen des Trägerfluids während des Poliervorgangs.

42. Verfahren nach einem der Ansprüche 29 bis 41, wobei das magnetorheologische Fluid in einem Behälter mit einer Referenzoberfläche angeordnet ist.

43. Verfahren nach Anspruch 42, wobei der Behälter bezüglich des Werkstücks (4) bewegt wird.

44. Verfahren nach Anspruch 43, wobei der Behälter mit vorgegebenen Geschwindigkeiten gedreht wird.

45. Verfahren nach Anspruch 42, wobei der Polierbereich (10) eine nominelle Größe von höchstens einem Drittel der Oberfläche des Werkstücks (4) hat.

46. Verfahren nach einem der Ansprüche 42 bis 45, wobei der Schritt zum Erzeugen eines Polierbereichs (10) in einem magnetorheologischen Fluid (2) aufweist:

Induzieren eines Magnetfeldes in der Nähe des magnetorheologischen Fluids; und
Steuern der Richtung und der Intensität des Magnetfeldes.

47. Verfahren nach einem der Ansprüche 42 bis 45, wobei der Schritt zum Erzeugen eines Polierbereichs (10) in einem magnetorheologischen Fluid (2) aufweist:

Veranlassen, daß das magnetorheologische Fluid in einem Bereich in der Nähe des Werkstücks (4) einem ungleichmäßigen Magnetfeld ausgesetzt wird, das Magnetfeldlinien aufweist, die senkrecht zum Gradienten des Feldes verlaufen.

48. Verfahren nach Anspruch 47, wobei der Gradient des Magnetfeldes zum Boden der Referenzoberfläche des Behälters hin gerichtet ist.

49. Verfahren nach Anspruch 46, wobei das Magnetfeld durch eine außerhalb des Behälters angeordnete Einrichtung zum Induzieren eines Magnetfeldes erzeugt wird.

50. Verfahren nach einem der Ansprüche 42 bis 49, ferner mit dem Schritt zum Bestimmen des Zwischenraums (h) zwischen dem Werkstück (4) und der Refrenzoberfläche des Behälters.

51. Verfahren nach Anspruch 46, ferner mit dem Schritt zum Steuern des Poliervorgangs des Werkstücks (4) durch Steuern der Magnetfeldintensität und der Position des Polierbereichs (10) bezüglich der Oberfläche des Werkstücks (4).

52. Verfahren nach Anspruch 51, wobei der Poliervorgang durch eine programmierbare Steuereinheit gesteuert wird.

53. Verfahren nach einem der Ansprüche 29 bis 52, wobei das magnetorheologische Fluid (2) Polierschleifmaterial aufweist.

54. Verfahren nach einem der Ansprüche 29 bis 53, wobei der Schritt zum Bestimmen der Anzahl von Zyklen das Bestimmen der Anzahl von Zyklen gemäß dem folgenden Ausdruck aufweist:

(anfänglicher quadratischer Mittelwert der Höhe von Oberflächenunregelmäßigkeiten

+ Dicke einer defekten Schicht unter der Oberfläche)/ (abzutragende

Materialschichtdicke).

55. Verfahren nach Anspruch 34, wobei der Schritt zum Bestimmen der Geschwindigkeit des Polierbereichs (10) das Bestimmen der Geschwindigkeit des Polierbereichs (10) gemäß folgendem Ausdruck aufweist:

[2 x (Kontaktabschnitt) x (Materialabtragrate)]/(abzutragende Materialschichtdicke).

56. Verfahren nach Anspruch 34, wobei der Schritt zum Bestimmen des Überlappungskoeffizienten das Bestimmen des Überlappungskoeffizienten gemäß dem folgenden Ausdruck aufweist:

(Versatz in einem einzelnen Schritt)/(2 x Kontaktabschnitt);

und wobei der Schritt zum Bestimmen der Verweilzeit für jeden Polierschritt das Bestimmen der Verweilzeit für jeden Polierschritt gemäß dem folgendem Ausdruck aufweist:

(abzutragende Materialschichtdicke x Überlappungskoeffizient)/Materialabtragrate;

und wobei der Schritt zum Bestimmen der erforderlichen Anzahl von Schritten das Bestimmen der erforderlichen Anzahl von Schritten gemäß dem folgendem Ausdruck aufweist:

(Radius des zu polierenden Werkstücks)/(Versatz in einem einzelnen Schritt).

57. Verfahren nach Anspruch 37, wobei der Schritt zum Bestimmen der Winkelgeschwindigkeit des Versatzes des Werkstücks um einen Winkel α das Bestimmen der Winkelgeschwindigkeit gemäß dem folgendem Ausdruck aufweist:

[(Winkelmaß des Kontaktbereichs)x(Materialabtragrate)]/(abzutragende Materialschichtdicke).

58. Verfahren nach Anspruch 39, wobei der Schritt zum Bestimmen der Verweilzeit in jedem Schritt das Bestimmen der Verweilzeit gemäß dem folgenden Ausdruck aufweist:

[(abzutragende Materialschichtdicke) x Überlappungskoeffizient]/Materialabtragrate.

59. Verfahren nach einem der Ansprüche 40 bis 58, wobei das magnetorheologische Fluid (2) Polierschleifmaterial aufweist.

Revendications

1. Procédé pour polir une surface de pièce utilisant un fluide magnéto-rhéologique (2), comprenant :

le positionnement de la pièce (4) à un écartement (h) d'une surface adaptée pour supporter un fluide magnéto-rhéologique (2);
l'introduction d'un courant de fluide magnéto-rhéologique (2) à travers ledit écartement (h);
l'application d'un champ magnétique sensiblement audit écartement (h) pour créer une zone de polissage (10) dans le fluide magnéto-rhéologique (2), ladite zone (10) formant un outil momentané pour entrer en contact et provoquer l'enlèvement de matière sur une partie de la surface de pièce, ladite zone (10) étant en contact avec ladite surface de pièce sur une aire inférieure à l'aire de la surface de pièce à polir; et
le déplacement de la pièce (4) ou de la zone (10) l'une par rapport à l'autre pour exposer différentes parties de la surface de pièce à la zone (10) pour des durées prédéterminées pour polir sélectivement lesdites parties de ladite surface de pièce à des degrés prédéterminés.

2. Procédé selon la revendication 1, dans lequel au moins une partie dudit écartement (h) décroît en hauteur d'une première section à une seconde section, et ledit fluide magnéto-rhéologique (2) coule dans ledit écartement (h) dans une direction allant de ladite première section à ladite seconde section.

3. Procédé selon la revendication 1 ou 2, dans lequel ledit fluide magnéto-rhéologique (2) comprend des particules abrasives non magnétiques pour augmenter l'enlèvement de matière à la surface de pièce.

4. Procédé selon la revendication 1, 2 ou 3, comprenant en outre l'étape de refaire circuler le fluide magnéto-rhéologique (2) ayant coulé dans ledit écartement (h) en réintroduisant le fluide (2) dans ledit écartement (h).

5. Procédé selon la revendication 4, comprenant en outre l'étape consistant à agiter le fluide magnéto-rhéologique (2) ayant coulé à travers ledit écartement (h).

6. Procédé selon la revendication 5, dans lequel ledit fluide magnéto-rhéologique (2) comprend un fluide porteur et comprenant en outre l'étape consistant à rajouter du fluide porteur au fluide magnéto-rhéologique (2) pour remplacer le fluide porteur évaporé.

7. Procédé selon l'une quelconque des revendications 1 à 6, dans lequel ladite étape consistant à introduire un courant de fluide magnéto-rhéologique (2) à travers ledit écartement (h) comprend la déposition de fluide magnéto-rhéologique (2) sur la surface adaptée pour supporter du fluide magnéto-rhéologique (2) et le déplacement de ladite surface par rapport à la pièce (4) pour forcer le fluide magnéto-rhéologique (2) à couler à travers l'écartement (h).

8. Procédé selon l'une quelconque des revendications 1 à 7, dans lequel ladite étape consistant à appliquer un champ magnétique comprend l'étape consistant à maximiser le champ magnétique dans l'écartement (h).

9. Procédé selon l'une quelconque des revendications 1 à 8, comprenant en outre l'étape consistant à faire tourner la pièce (4) par rapport à la zone (10).

10. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel ladite pièce (4) est montée sur un porte-pièce pivotant et ladite étape consistant à déplacer la pièce (4) ou la zone (10) l'une par rapport à l'autre comprend le pivotement du porte-pièce pour faire balayer à la surface de la pièce (4) la zone (10).

11. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel ladite étape consistant à déplacer la pièce (4) ou la zone (10) l'une par rapport à l'autre comprend le déplacement de la pièce (4) le long d'un plan.

12. Procédé selon la revendication 11, dans lequel l'étape consistant à déplacer la pièce (4) le long d'un plan comprend le déplacement de la pièce (4) le long d'un plan dans une direction sensiblement perpendiculaire à la direction du courant de fluide magnéto-rhéologique (2) à travers ledit écartement (h).

13. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel ladite étape consistant à déplacer la pièce (4) ou la zone (10) l'une par rapport à l'autre comprend le déplacement de la zone en déplaçant le champ magnétique par rapport à ladite surface adaptée pour supporter un fluide magnéto-rhéologique (2).

14. Appareil pour polir une surface de pièce utilisant un fluide magnéto-rhéologique (2), comprenant :

une surface pour supporter un volume de fluide magnéto-rhéologique (2) ;
un porte-pièce pour maintenir et positionner la pièce (4) à un écartement (h) de ladite surface de façon telle que ladite surface force un courant de fluide magnéto-rhéologique (2) à travers ledit écartement (h) ;
un aimant pour appliquer un champ magnétique audit écartement (h) pour créer une zone de polissage (10) dans le fluide magnéto-rhéologique (2) coulant à travers ledit écartement (h) pour former un outil de finition provisoire pour entrer en contact et provoquer l'enlèvement de matière à une partie de la surface de pièce, ladite zone (10) entrant en contact avec ladite surface de pièce sur une aire inférieure à l'aire de la surface de pièce à polir; et
des moyens pour déplacer la pièce (4) cu la zone (10) l'une par rapport à l'autre pour exposer différentes parties de la surface de pièce à la zone (10) pour des durées prédéterminées pcur polir sélectivement lesdites parties de ladite surface de pièce à des degrés prédéterminés.

15. Appareil selon la revendication 14, dins lequel au moins une partie dudit écartement (h) cécroît en hauteur d'une première section à une seconde section, et ledit fluide magnéto-rhéologique (2) coule à travers ledit écartement (h) dans une direction de ladite première section à ladite seconde section.

16. Appareil selon la revendication 14 ou 15, comprenant en outre des moyens pour ajouter du fluide porteur au fluide magnéto-rhéologique (2) pour compenser l'évaporation de fluide porteur dudit fluide magnéto-rhéologique (2).

17. Appareil selon la revendication 16, comprenant en outre un mélangeur pour agiter le fluide magnéto-rhéologique (2).

18. Appareil selon l'une quelconque des revendications 14 à 17, comprenant en outre les moyens pour faire tourner la pièce (4) par rapport à la zone (10).

19. Appareil selon l'une quelconque des revendications 14 à 18, dans lequel ladite pièce (4) est montée sur un porte-pièce pivotant pour faire balayer à la surface de la pièce la zone (10).

20. Appareil selon l'une quelconque des revendications 14 à 18, comprenant en outre des moyens pour déplacer la pièce (4) le long d'un plan dans une direction sensiblement perpendiculaire à la direction du courant de fluide magnéto-rhéologique (2) à travers ledit écartement (h).

21. Procédé selon l'une quelconque des revendications 1 à 13, dans lequel ledLt fluide magnéto-rhéologique (2) comprend des particules magnétiques enveloppées d'une couche de matériau de protection pour éviter leur oxydation, un stabilisateur et un fluide porteur.

22. Procédé selon la revendication 21, dans lequel ledit matériau de protection comprend un polymère.

23. Procédé selon la revendication 21 ou 22, dans lequel ledit matériau de protection comprend du téflon.

24. Procédé selon l'une quelconque des revendications 21 à 23, dans lequel ledit fluide porteur comprend de l'eau.

25. Procédé selon l'une quelconque des revendications 21 à 24, dans lequel ledit fluide porteur comprend de la glycérine.

26. Procédé selon l'une quelconque des revendications 21 à 25, dans lequel lesdites particules magnétiques comprennent des particules de fercarbonyle.

27. Procédé selon l'une quelconque des revendications 21 à 26, dans lequel ledit fluide magnéto-rhéologique (2) contient en outre des particules abrasives.

28. Procédé selon la revendication 27, dans lequel lesdites particules abrasives comprennent du CeO_2.

29. Procédé selon l'une quelconque des revendications 1 à 13, comprenant en outre les étapes consistant à :

contrôler la consistance du fluide (2) dans la zone de polissage (10);
déterminer le taux d'enlèvement de matériau de la pièce (4);
déterminer la direction et la vitesse de mouvement de la zone de polissage (10) par rapport à la pièce (4) ; et
déterminer le nombre de cycles de polissage requis, ce qui comprend :

déterminer la hauteur quadratique moyenne initiale des irrégularités de surface de la pièce (4);
déterminer l'épaisseur d'une couche de sous-surface détériorée;
déterminer la forme initiale de la surface; et déterminer l'épaisseur de la couche de matériau à enlever pendant un cycle de polissage.

30. Procédé selon la revendication 29, dans lequel l'étape consistant à déterminer le taux d'enlèvement de matière de la pièce (4) comprend la détermination de la distribution spatiale de l'enlèvement de matière.

31. Procédé selon la revendication 29 ou 30, dans lequel le mouvement de la zone de polissage (10) par rapport à la pièce (4) est continu.

32. Procédé selon l'une quelconque des revendications 29 à 31, dans lequel l'étape consistant à déterminer la direction et la vitesse de déplacement de la zone de polissage par rapport à la pièce (4) comprend :

déterminer la taille d'une surface de contact de la pièce (4) en contact avec la zone de polissage (10) à tout moment donné ;
déterminer l'épaisseur de la couche de matière à enlever pendant un cycle de polissage ; et
déterminer la vitesse de la zone de polissage (10).

33. Procédé selon la revendication 29 ou 30, dans lequel le mouvement de la zone de polissage (10) par rapport à la pièce (4) se fait par étapes discrètes.

34. Procédé selon la revendication 33, dans lequel l'étape consistant à déterminer la direction et la vitesse du mouvement de la zone de polissage (10) par rapport à la pièce (4) comprend :

déterminer la taille d'une surface de contact de la pièce (4) en contact avec la zone de polissage (10) à tout moment donné; déterminer le déplacement de la zone de polissage (10) pendant une étape unique;
déterminer le coefficient de recouvrement;
déterminer l'épaisseur de la couche de matière à enlever pendant un cycle de polissage;
déterminer la durée pour chaque étape de polissage; et
déterminer le nombre d'étapes requises.

35. Procédé selon l'une quelconque des revendications 29 à 34, comprenant en outre le déplacement de la pièce (4) de son axe vertical jusqu'à un angle α.

36. Procédé selon la revendication 35, dans lequel la pièce (4) est déplacée de son axe vertical jusqu'à un angle α à une vitesse continue.

37. Procédé selon la revendication 36, dans lequel le déplacement de la pièce (4) de son axe vertical jusqu'à un angle α à une vitesse continue comprend en outre :

déterminer la dimension angulaire du point de contact;
déterminer l'épaisseur de la couche de matière à enlever pendant un cycle de polissage; et
déterminer la vitesse angulaire du déplacement de la pièce (4) jusqu'à un angle α.

38. Procédé selon la revendication 35, dans lequel la pièce (4) est déplacée de son axe vertical jusqu'à un angle α par étapes discrètes.

39. Procédé selon la revendication 38, dans lequel le déplacement de la pièce (4) de son axe vertical jusqu'à un angle α par étapes discrètes comprend en outre :

déterminer la dimension angulaire du point de contact;
déterminer l'épaisseur de la couche de matière à enlever pendant un cycle de polissage;
déterminer la valeur du déplacement angulaire d'une étape simple;
déterminer le coefficient de recouvrement; et
déterminer la durée de chaque étape.

40. Procédé selon l'une quelconque des revendications 29 à 39, dans lequel le fluide magnéto-rhéologique (2) comprend :

une pluralité de particules magnétiques;
un stabilisateur; et
un fluide porteur.

41. Procédé selon la revendication 40, comprenant en outre l'étape consistant à contrôler les propriétés du fluide magnéto-rhéologique (2) en réapprovisionnant le fluide porteur pendant le polissage.

42. Procédé selon l'une quelconque des revendications 29 à 41, dans lequel le fluide magnéto-rhéologique est contenu dans un récipient ayant une surface de référence.

43. Procédé selon la revendication 42, dans lequel le récipient est déplacé par rapport à la pièce (4),

44. Procédé selon la revendication 43, dans lequel le récipient est mis en rotation à des vitesses spécifiées.

45. Procédé selon la revendication 42, dans lequel la zone de polissage (10) est en fait un tiers de la surface de la pièce (4) ou moins.

46. Procédé selon l'une quelconque des revendications 42 à 45, dans lequel l'étape consistant à créer une zone de polissage (10) dans un fluide magnéto-rhéologique (2) comprend :

induire un champ magnétique dans le voisinage du fluide magnéto-rhéologique ; et
contrôler la direction et l'intensité du champ magnétique.

47. Procédé selon l'une quelconque des revendications 42 à 45, dans lequel l'étape consistant à créer une zone de polissage (10) dans un fluide magnéto-rhéologique (2) comprend :

soumettre le fluide magnéto-rhéologique à un champ magnétique non uniforme, ayant des lignes de champ magnétique qui sont perpendiculaires au gradient dudit champ, dans une région adjacente à la pièce (4).

48. Procédé selon la revendication 47, dans lequel le gradient du champ magnétique est dirigé vers la surface de référence du fond du récipient.

49. Procédé selon la revendication 46, dans lequel le champ magnétique est créé par des moyens pour induire un champ magnétique qui sont situés en dehors du récipient.

50. Procédé selon l'une quelconque des revendications 42 à 49, comprenant en outre l'étape consistant à déterminer l'écartement (h) entre la pièce (4) et la surface de référence du récipient.

51. Procédé selon la revendication 46, comprenant en outre l'étape consistant à contrôler le polissage de la pièce (4) en contrôlant l'intensité du champ magnétique et la situation de la zone de polissage (10) par rapport à la surface de la pièce (4).

52. Procédé selon la revendication 51, dans lequel le polissage est contrôlé par une unité de contrôle programmable.

53. Procédé selon l'une quelconque des revendications 29 à 52, dans lequel ledit fluide magnéto-rhéologique (2) comprend un matériau abrasif de polissage.

54. Procédé selon l'une quelconque des revendications 29 à 53, dans lequel ladite étape consistant à déterminer le nombre de cycles comprend l'étape consistant à déterminer le nombre de cycles selon l'expression :

(hauteur quadratique moyenne initiale des irrégularités

de surface + épaisseur de la couche de sous-surface

détériorée)

÷

(épaisseur de la couche de matière à enlever).

55. Procédé selon la revendication 34, dans lequel ladite étape consistant à déterminer la vitesse de la zone de polissage (10) comprend la détermination de la vitesse de la zone de polissage (10) selon l'expression :

(2 × section de contact × taux d'enlèvement de matière)

÷

(épaisseur de la couche de matière à enlever).

56. Procédé selon la revendication 34, dans lequel ladite étape consistant à déterminer le coefficient de recouvrement comprend la détermination du coefficient de recouvrement selon l'expression :

(déplacement durant une étape simple)

÷

(2 × section de contact)

et dans lequel ladite étape consistant à déterminer la durée de chaque étape du polissage comprend la détermination de la durée de chaque étape du polissage selon l'expression :

(épaisseur de la couche de matière à enlever

coefficient de recouvrement)

÷

(taux d'enlèvement de matière);

et dans lequel ladite étape consistant à déterminer le nombre d'étapes nécessaires comprend la détermination du nombre d'étapes selon l'expression :

(rayon de la pièce à polir)

÷

(déplacement durant une étape simple).

57. Procédé selon la revendication 37, dans lequel ladite étape consistant à déterminer la vitesse angulaire du déplacement de la pièce jusqu'à un angle α comprend la détermination de la vitesse angulaire selon l'expression :

(dimension angulaire du point de contact × taux

d'enlèvement de matière)

÷

(épaisseur de la couche de matière à enlever).

58. Procédé selon la revendication 39, dans lequel ladite étape consistant à déterminer la durée de chaque étape comprend la détermination de la durée de chaque étape selon l'expression :

(épaisseur de la couche de matière à enlever ×

coefficient de recouvrement)

÷

(taux d'enlèvement de matière).

59. Procédé selon l'une quelconque des revendications 40 à 58, dans lequel ledit fluide magnéto-rhéologique (2) comprend un matériau abrasif polissant.

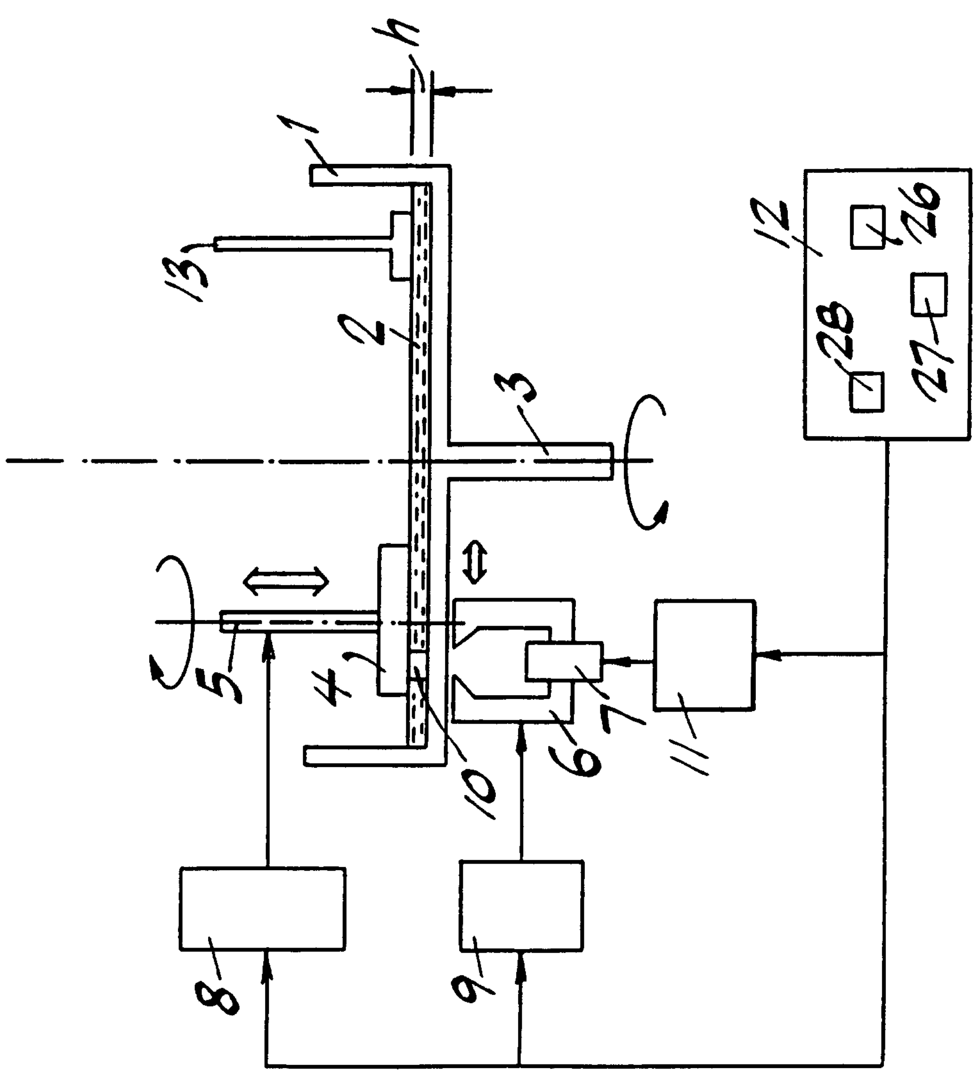

FIG. 1

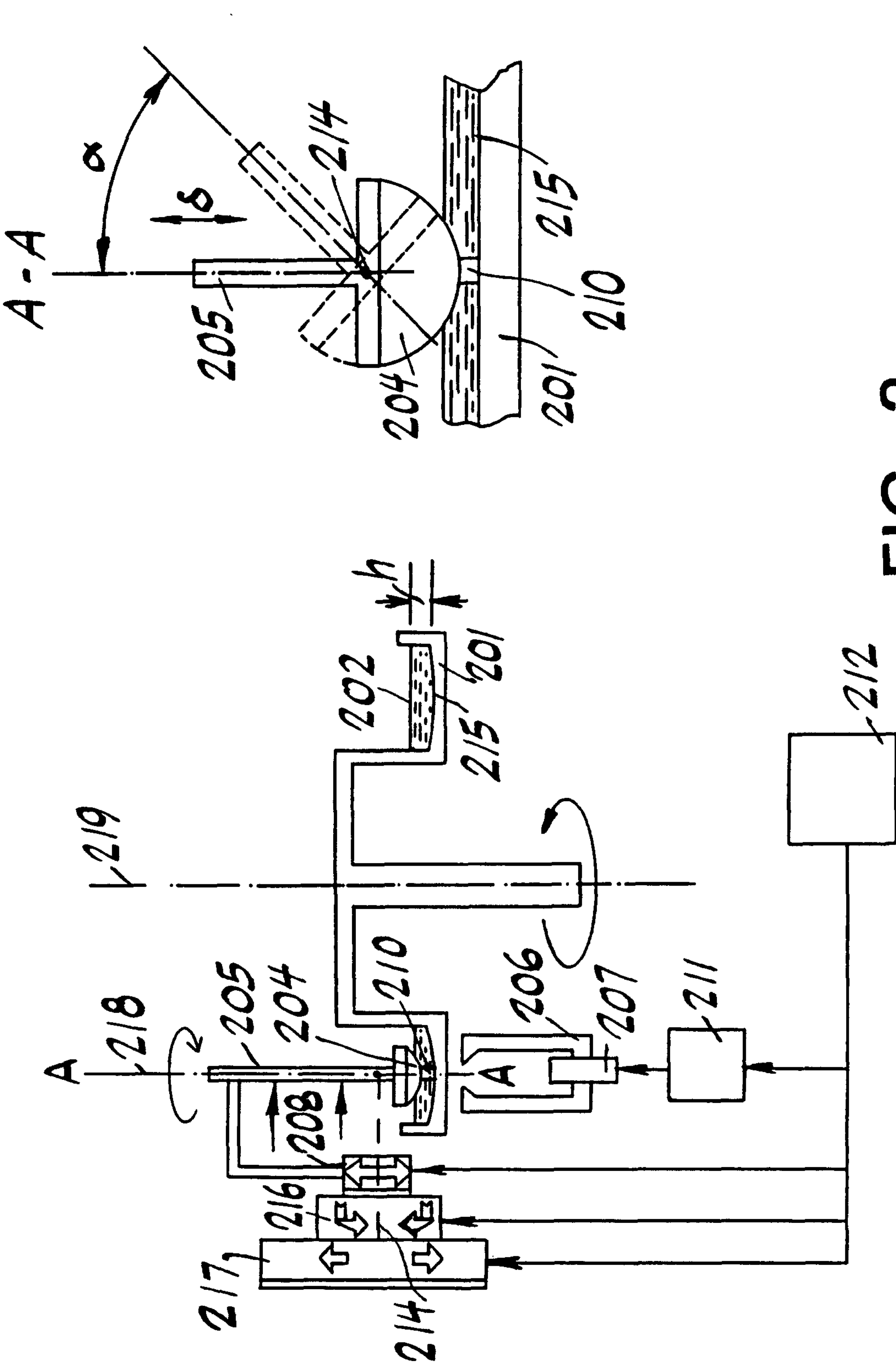
A - A
α
δ
205
214
204
201
210
215
A
218
208
216
217
219
202
h
206
207
211
212

FIG. 2

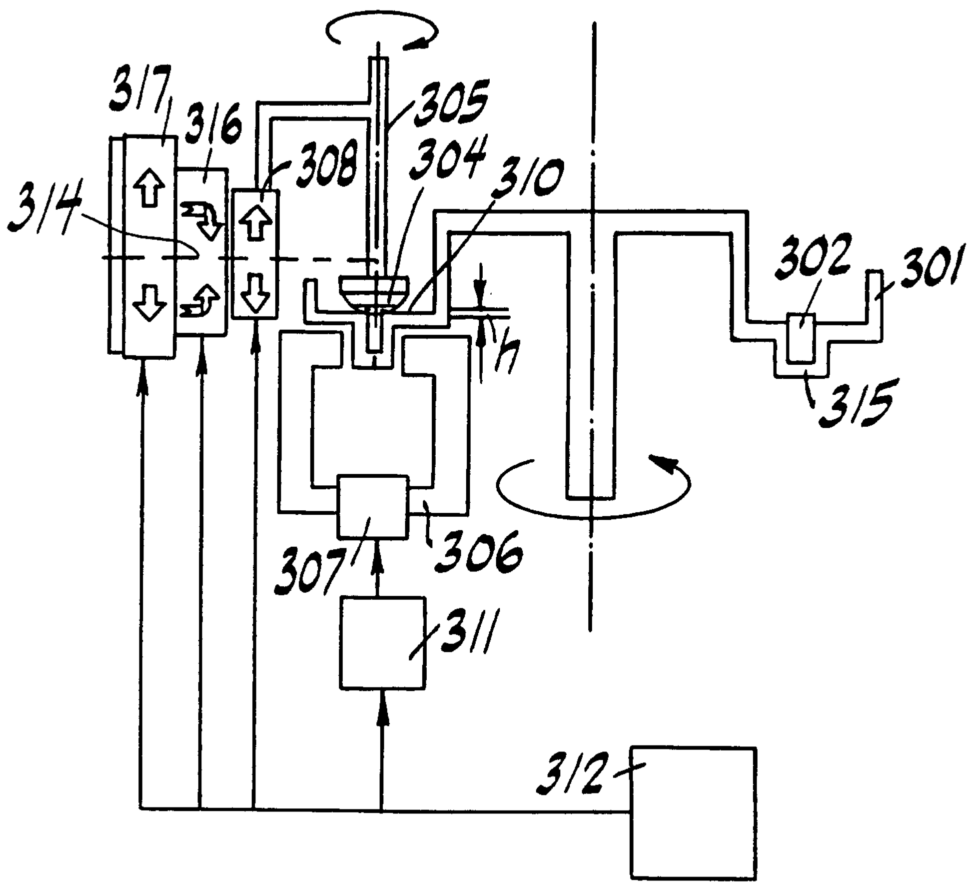

FIG. 3

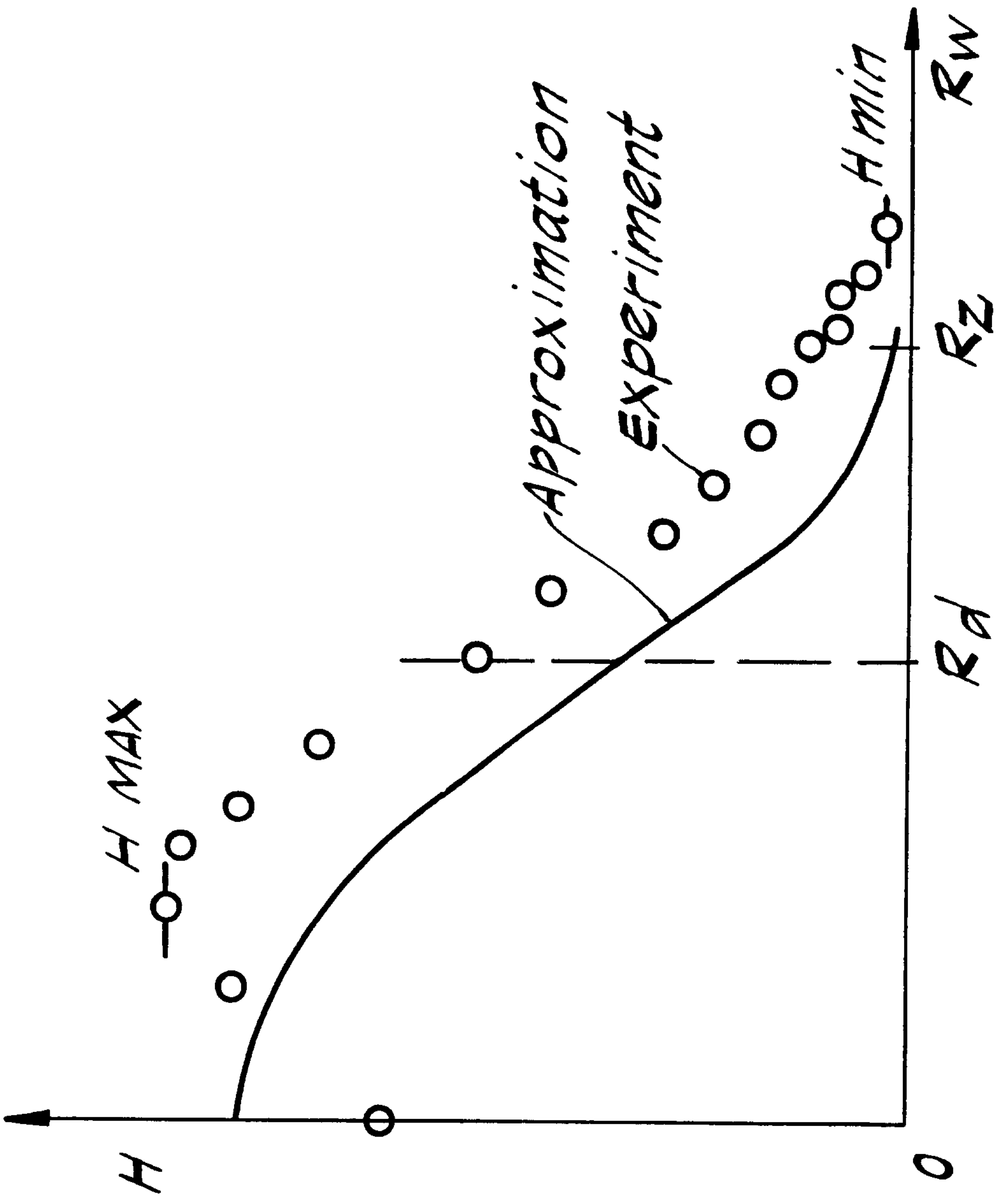

FIG. 4

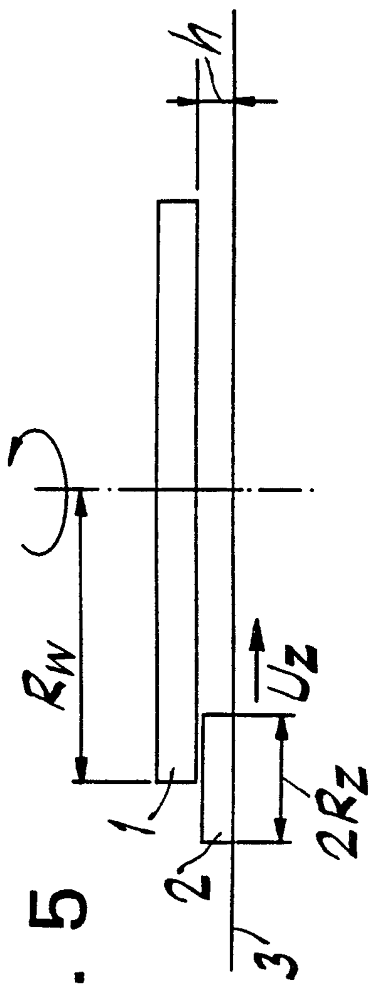

FIG. 5

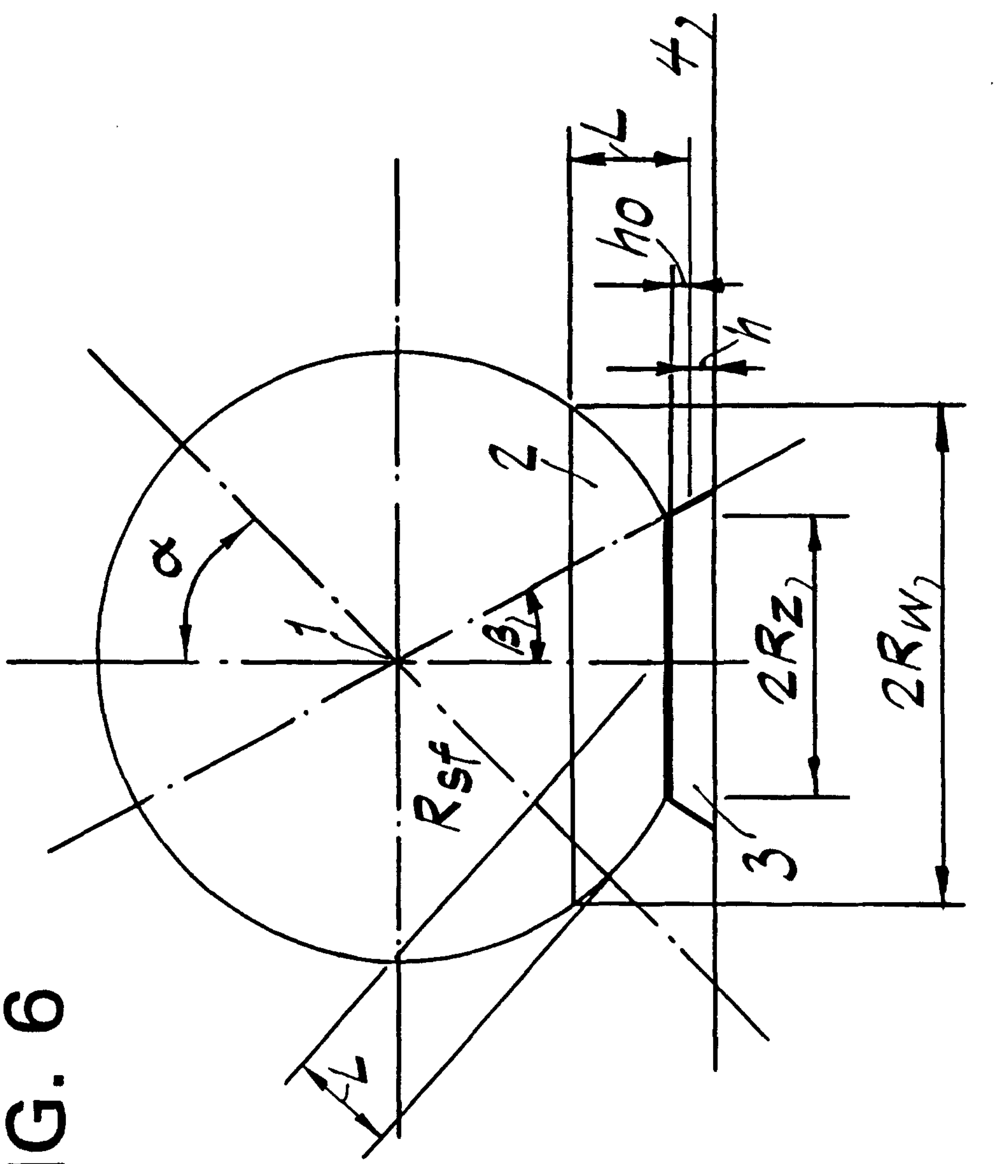

FIG. 6

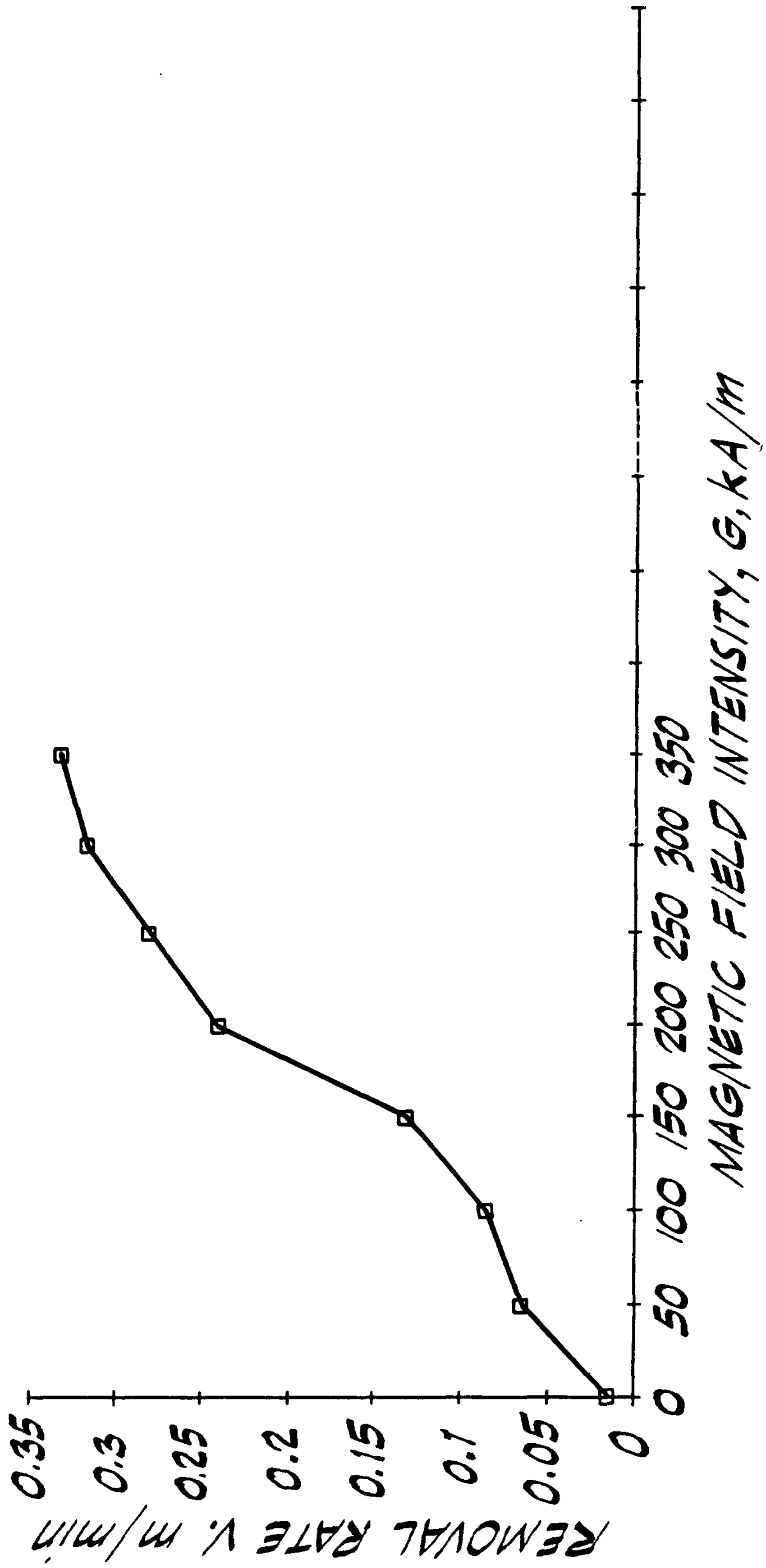
REMOVAL RATE V, m/min
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
MAGNETIC FIELD INTENSITY, G, kA/m

FIG. 7

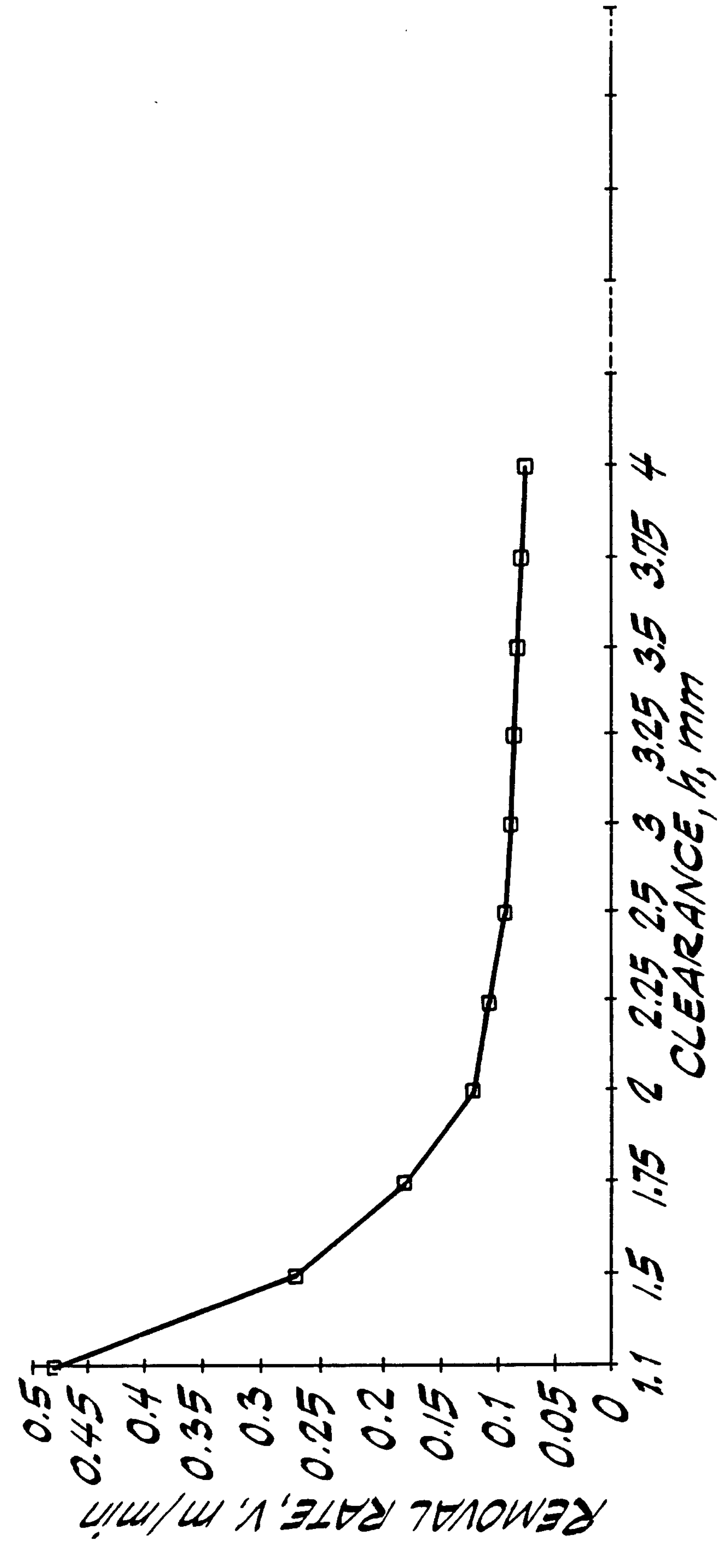
REMOVAL RATE, V, m/min
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.1
1.5
1.75
2
2.25
2.5
3
3.25
3.5
3.75
4
CLEARANCE, h, mm

FIG. 8

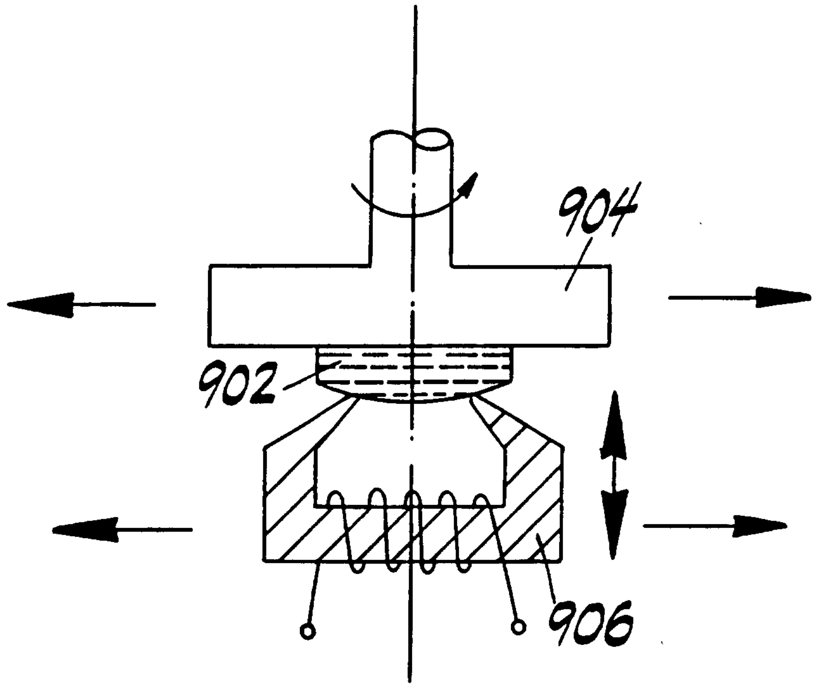

FIG. 9

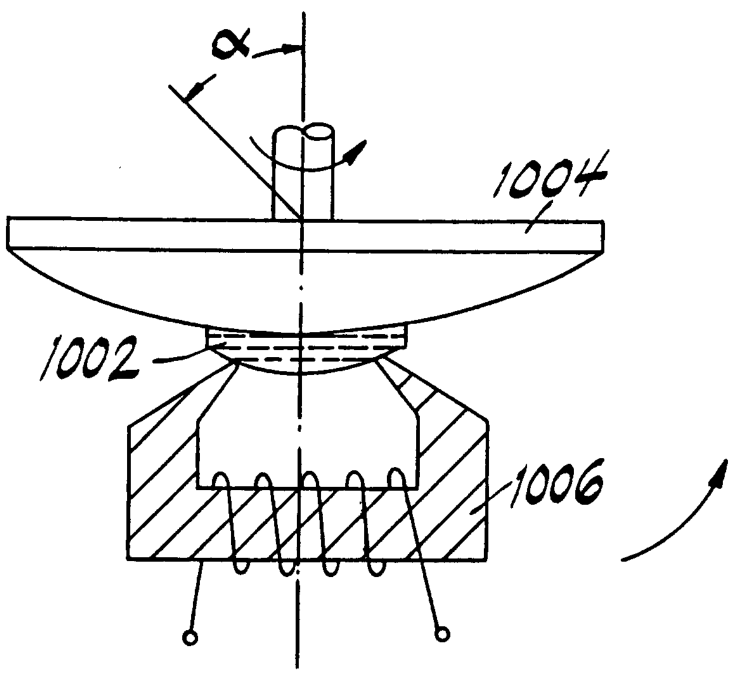

FIG. 10

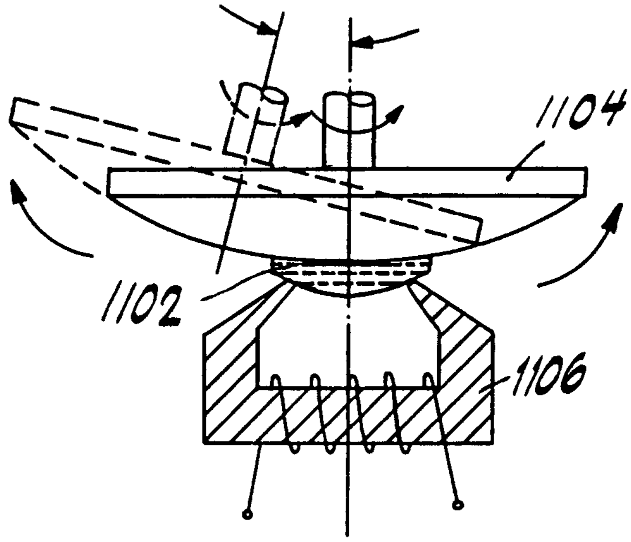

FIG. 11

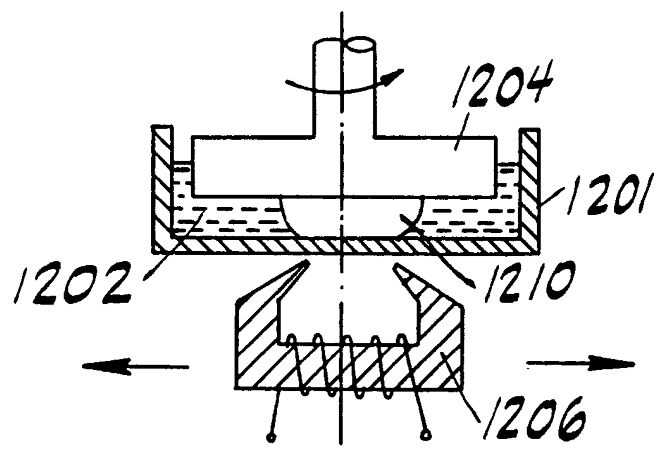

FIG. 12

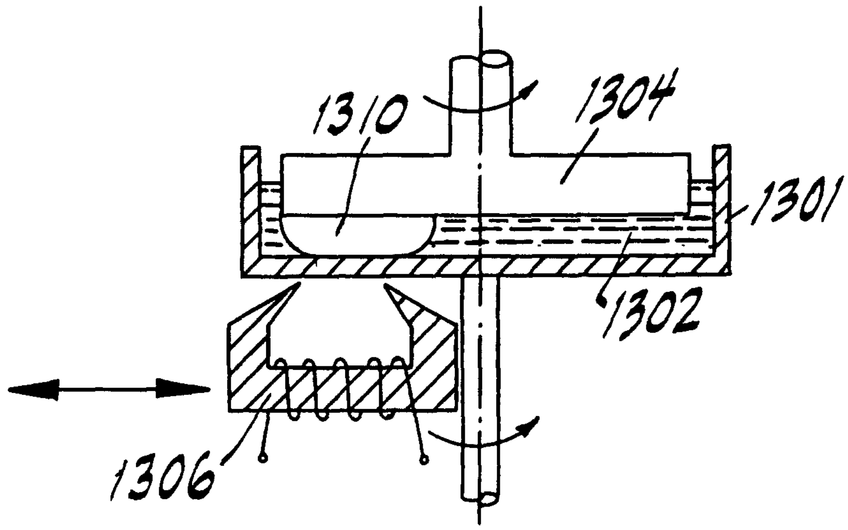
1310
1304
1301
1302
1306

FIG. 13

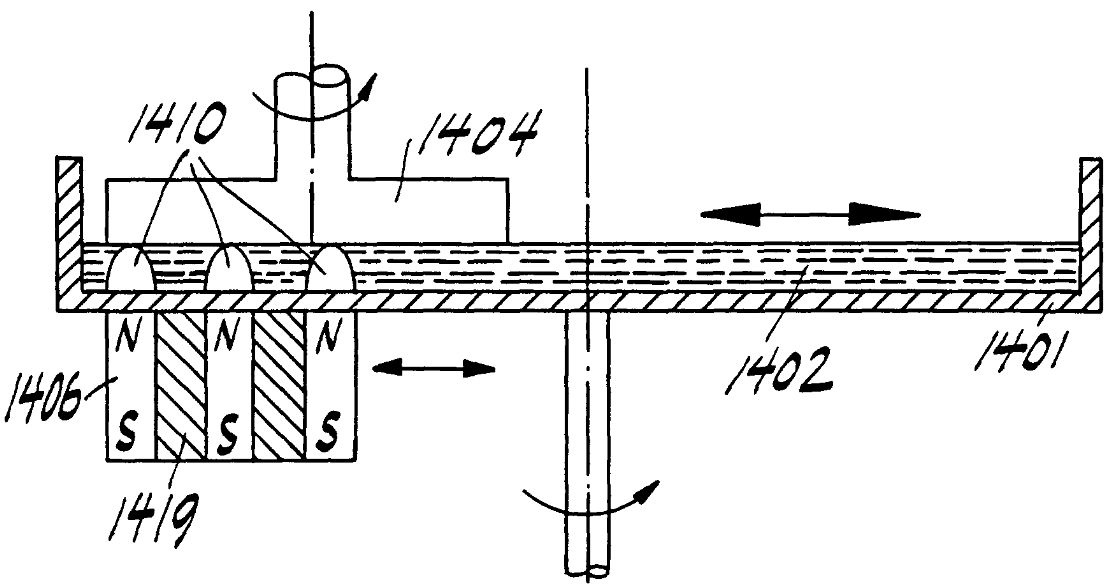
1410
1404
N
N
N
S
S
S
1406
1419
1402
1401

FIG. 14

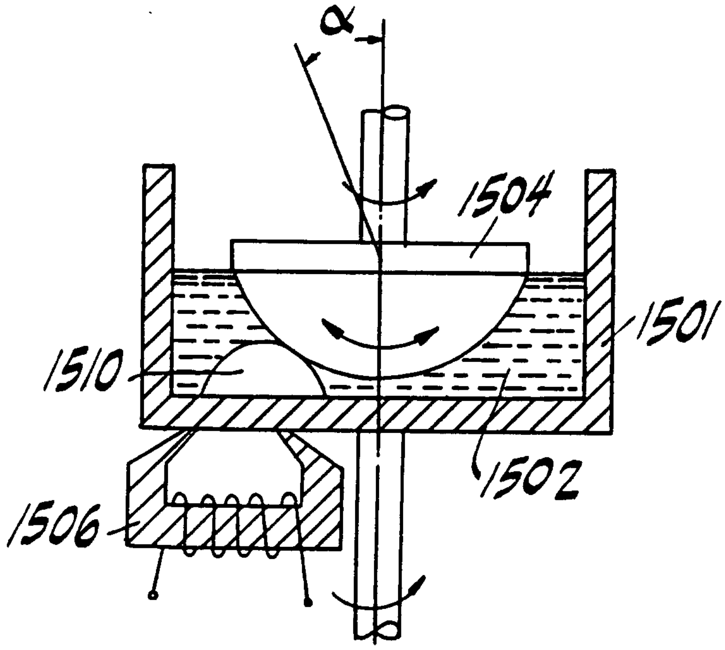

FIG. 15

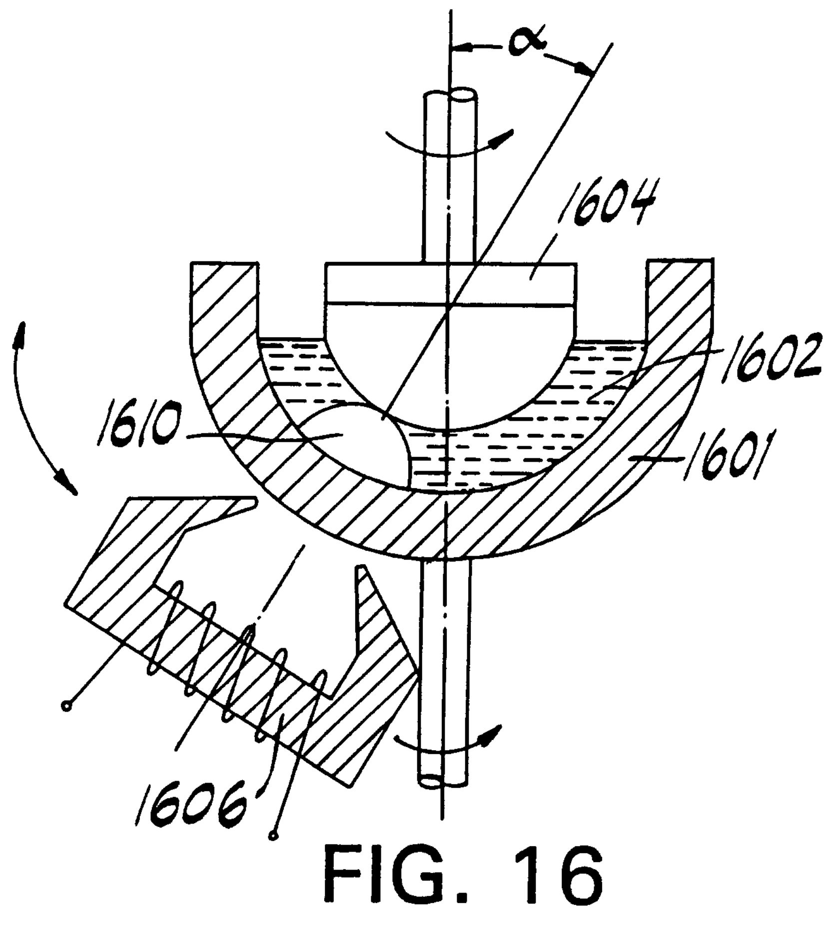

FIG. 16

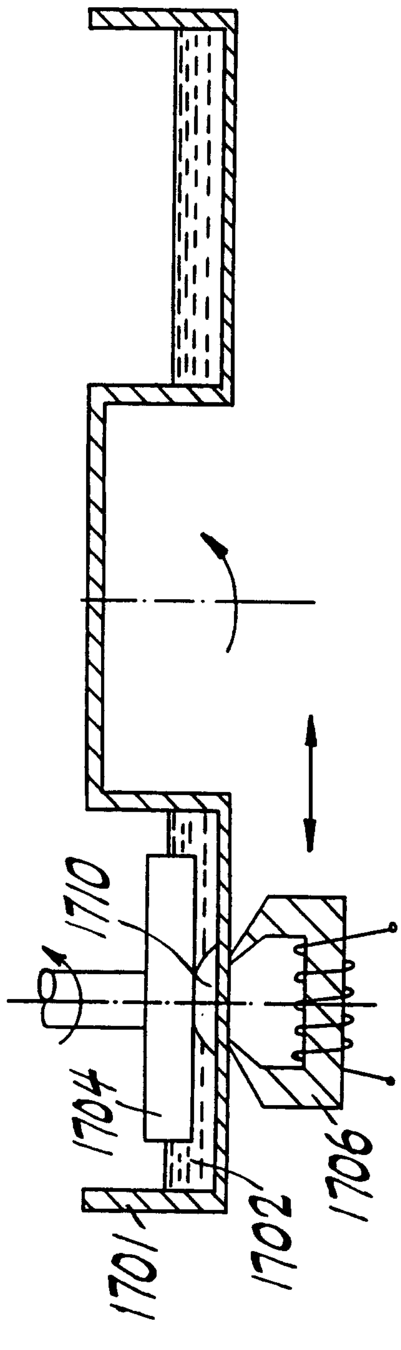

FIG. 17

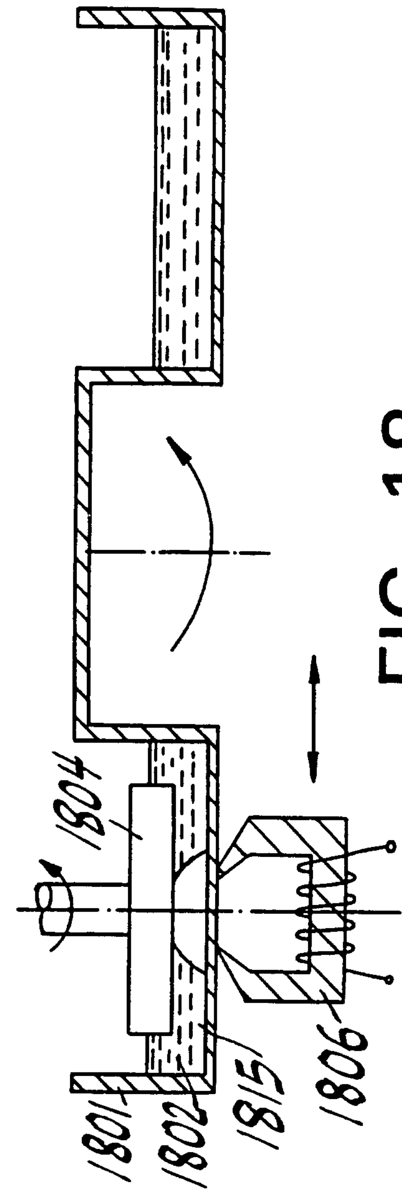

FIG. 18

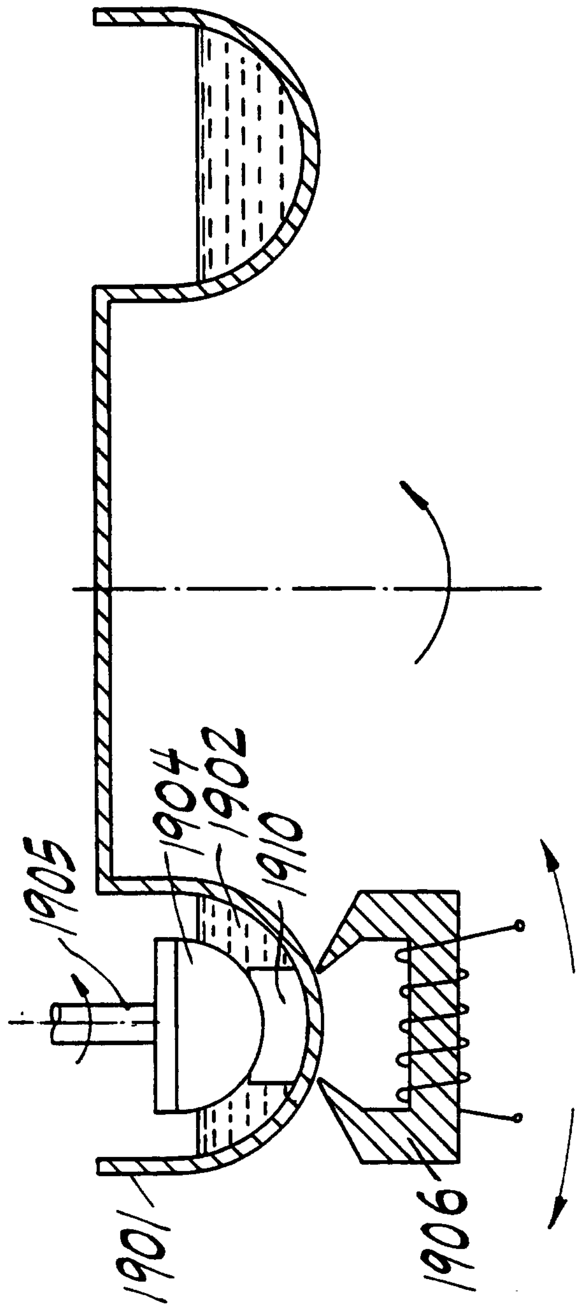

FIG. 19

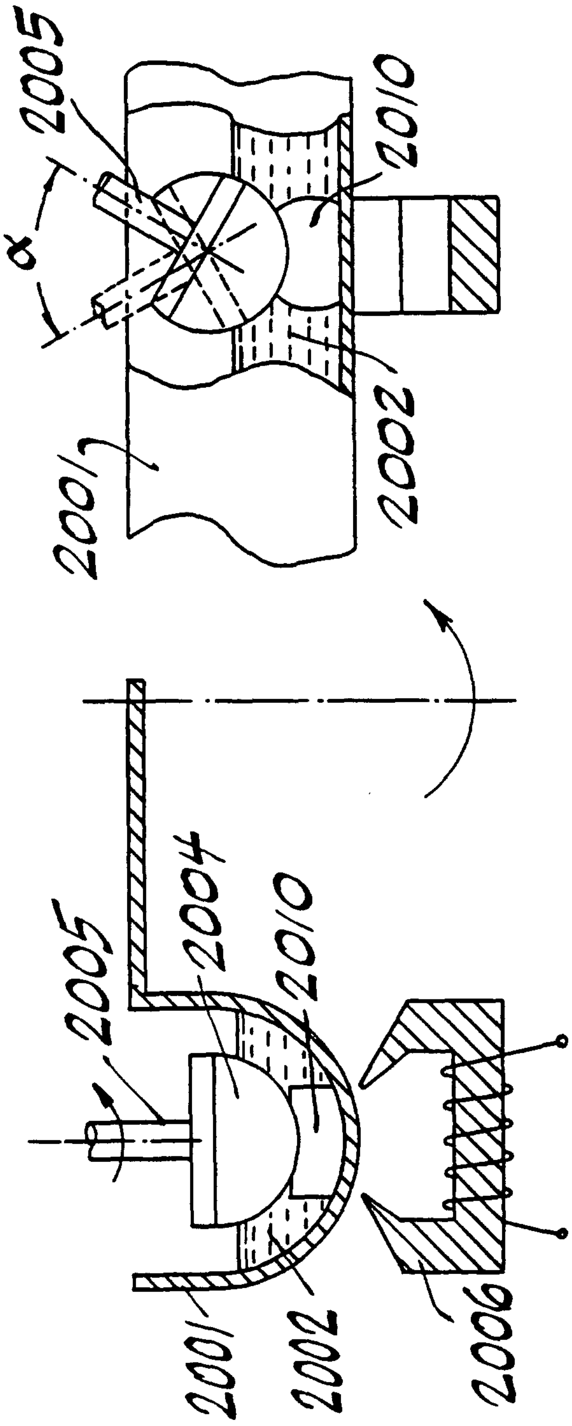

FIG. 20

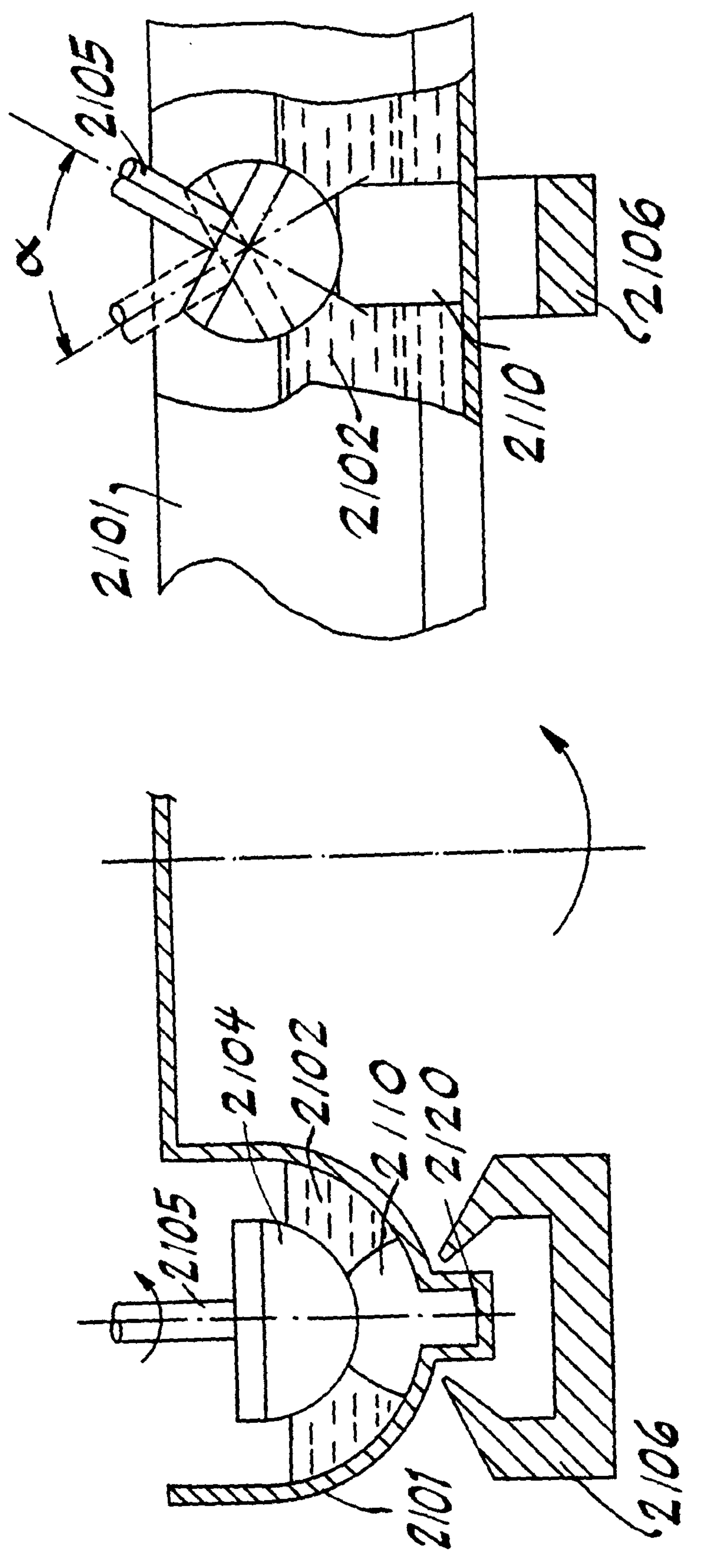

FIG. 21

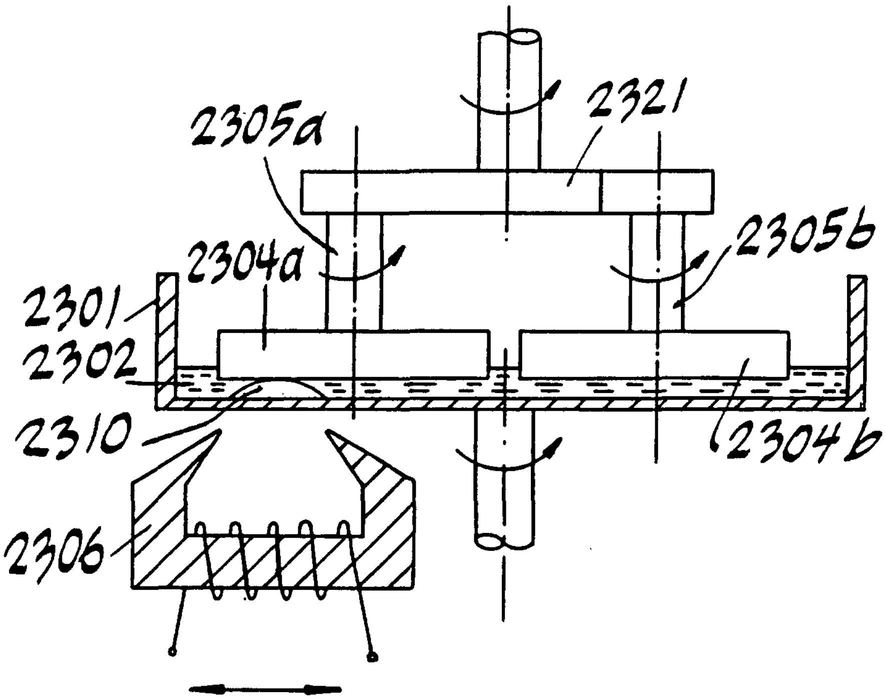
2321
2305a
2305b
2304a
2301
2302
2310
2304b
2306

FIG. 23

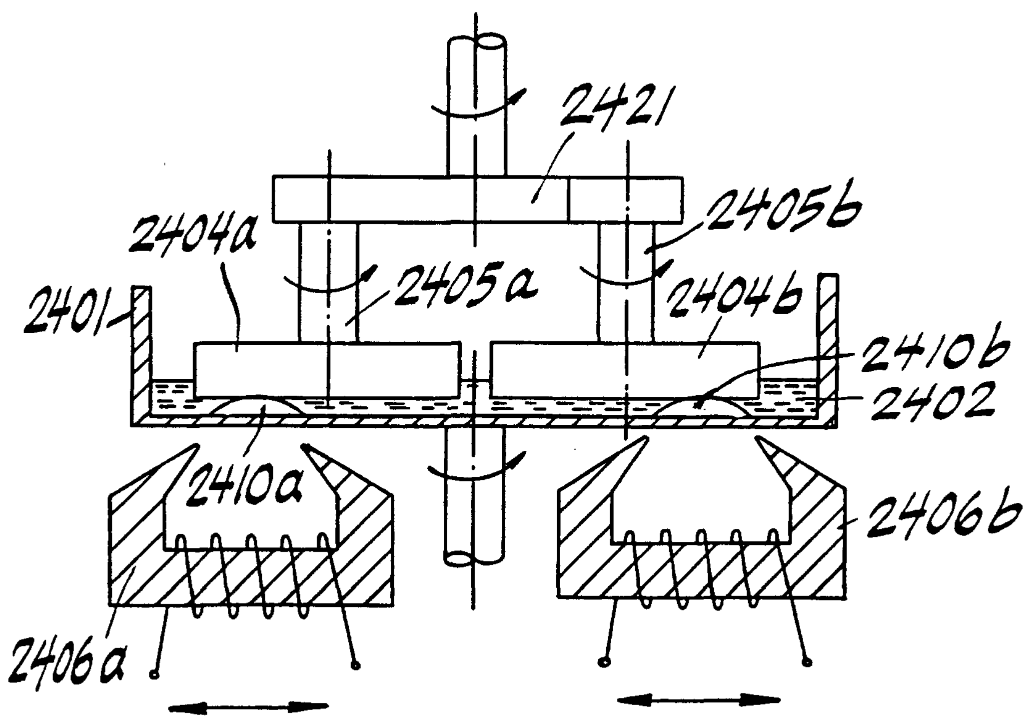
2421
2405b
2404a
2405a
2401
2404b
2410b
2402
2410a
2406b
2406a

FIG. 24

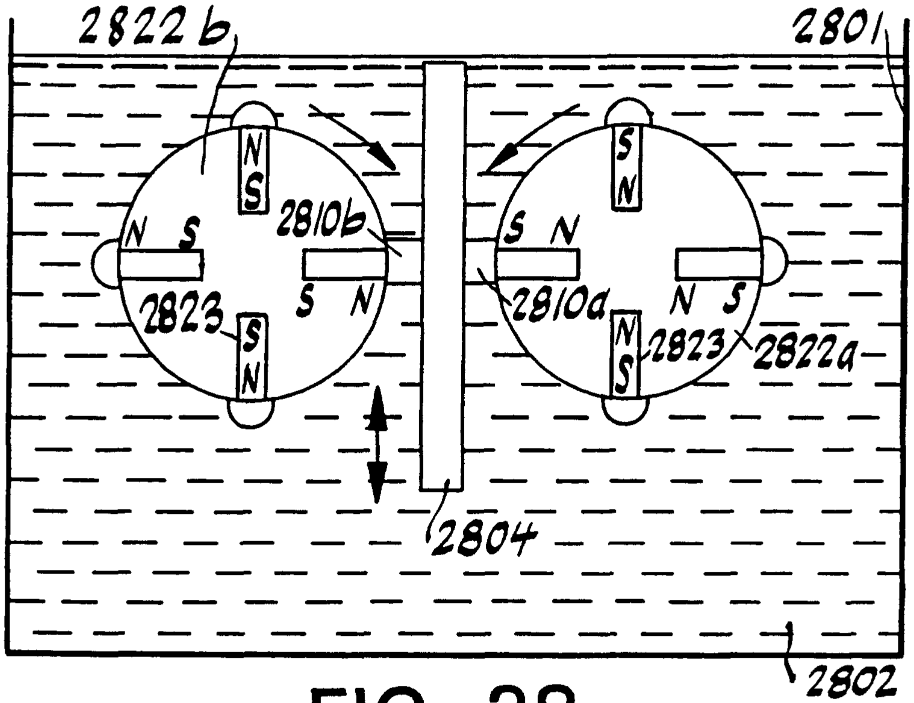
2822b
2801
N
S
S
N
N S
2810b
S N
S N
2810a
N S
2823
S
N
N
S
2823
2822a
2804
2802

FIG. 28

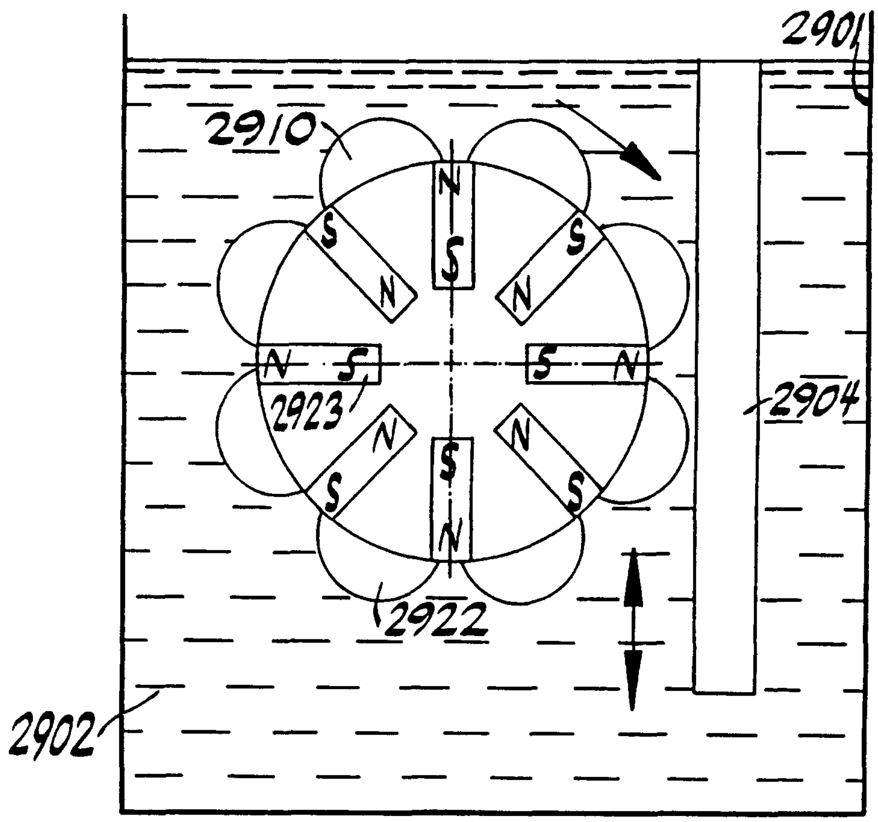
2901
2910
N
S
S
S
N
N
N S
S N
2923
N
S
S
N
S
N
N
S
2904
2922
2902

FIG. 29