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[54] **APPARATUS USING A BEAM OF POSITIVE IONS FOR CONTROLLED EROSION OF SURFACES**

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[21] Appl. No.: **833,335**

[52] **U.S. Cl....250/49.5 TE,** 219/121 EB, 250/49.5 P
[51] **Int. Cl.**..**H01j 37/28**
[58] **Field of Search**....................219/68, 121 EB, 69; 250/49.5 R, 49.5 TE, 49.5 PI

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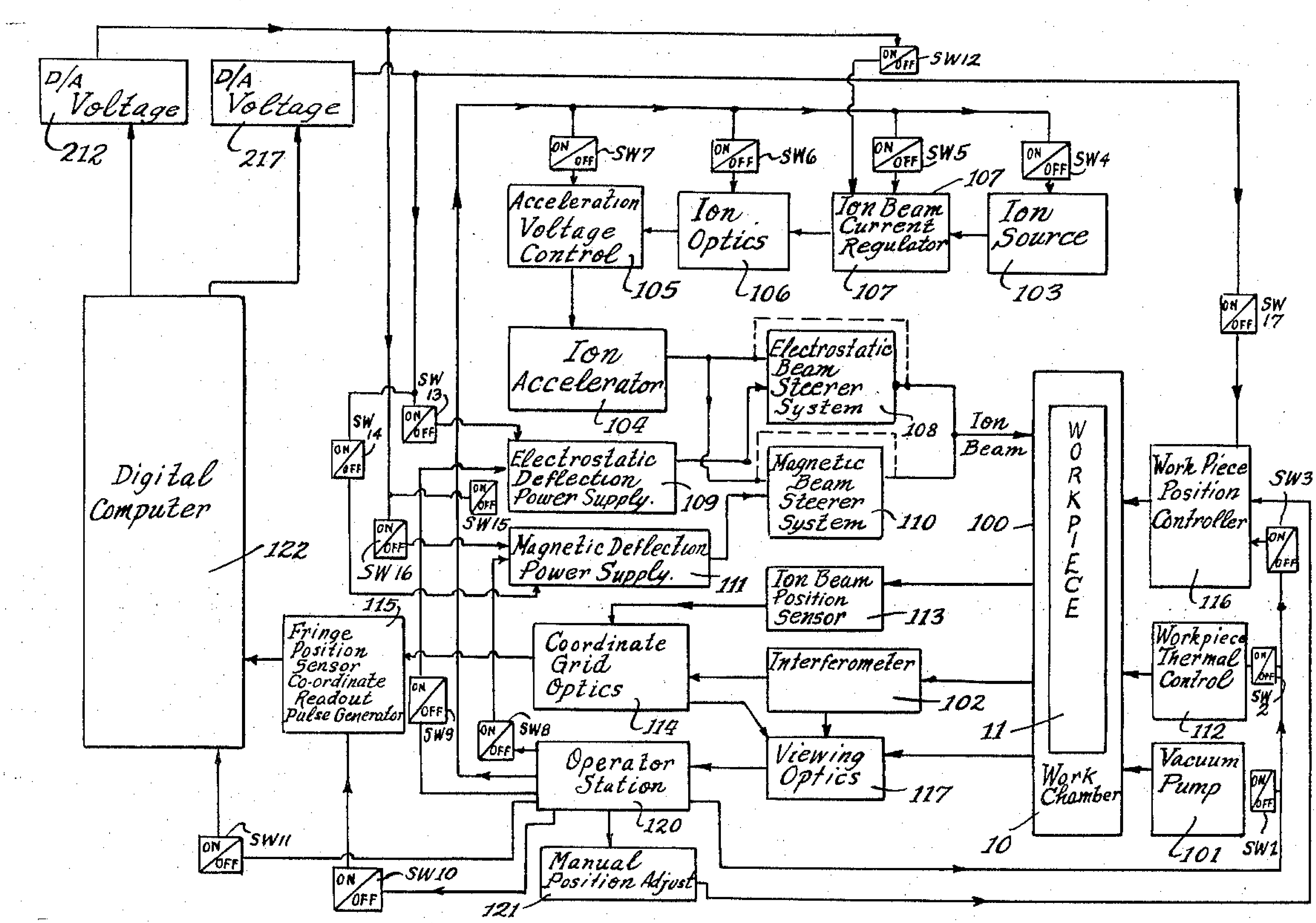
[57] **ABSTRACT**

A process and apparatus for controllably eroding the surface of hard materials such as fused quartz, glass, metals and ceramics by the bombardment of the positive ions. Focused argon ions accelerated by potentials of up to 120,000 volts and with a constant beam current are controlled in direction to cause surface erosion of a workpiece to accuracies of up to one-one hundredth of a wavelength of green light. The workpiece is moved at a controlled rate in combination with the control of the beam direction to obtain a controlled erosion pattern over the surface of the workpiece. In another embodiment, an intensity modulated beam current is used. An electron beam is directed at the workpiece in a pattern which surrounds the ion beam to prevent the building up of a positive charge on the work surface. The progress of the erosion is observed and measured by an interferometer system. The movement of the ion beam and workpiece can follow a programmed automatic sequence.

6 Claims, 3 Drawing Figures



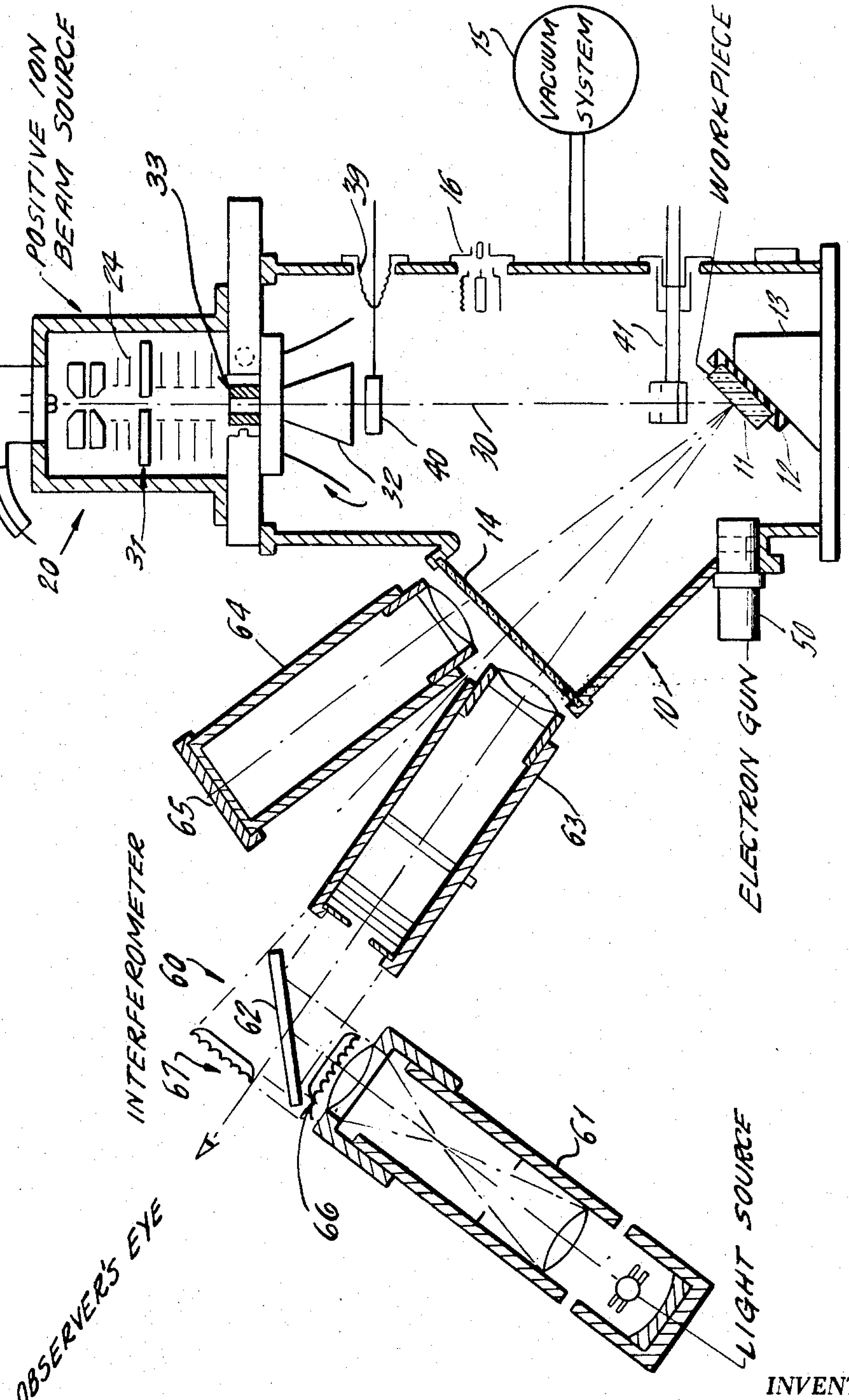


FIG. 1

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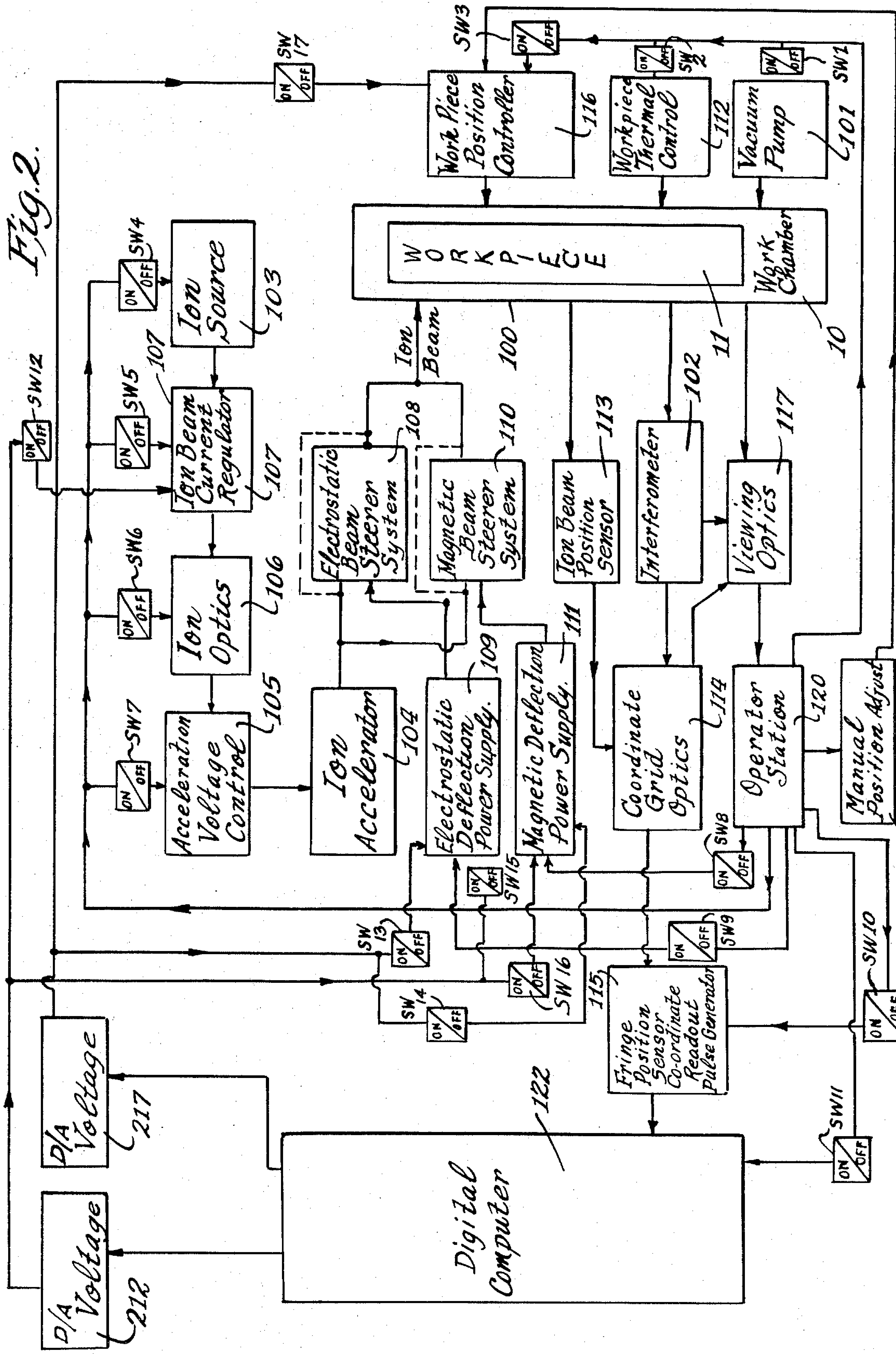
Work Piece Position Controller
116
Workpiece Thermal Control
112
Vacuum Pump
101
SW3
SW2
SW1
SW 17
WORKPIECE
Work Chamber
10
11
100
Ion Beam
Ion Source
103
SW4
Ion Beam Current Regulator
107
SW5
SW12
Ion Optics
106
SW6
Acceleration Voltage Control
105
SW7
Ion Accelerator
104
Electrostatic Beam Steerer System
108
Magnetic Beam Steerer System
110
Electrostatic Deflection Power Supply
109
Magnetic Deflection Power Supply
111
Ion Beam Position Sensor
113
Interferometer
102
Viewing Optics
117
Coordinate Grid Optics
114
Operator Station
120
Manual Position Adjust
121
SW8
SW9
SW10
SW11
SW 13
SW 14
SW15
SW 16
Fringe Position Sensor Co-ordinate Readout Pulse Generator
115
Digital Computer
122
D/A Voltage
217
D/A Voltage
212
ON
OFF

Fig. 2.

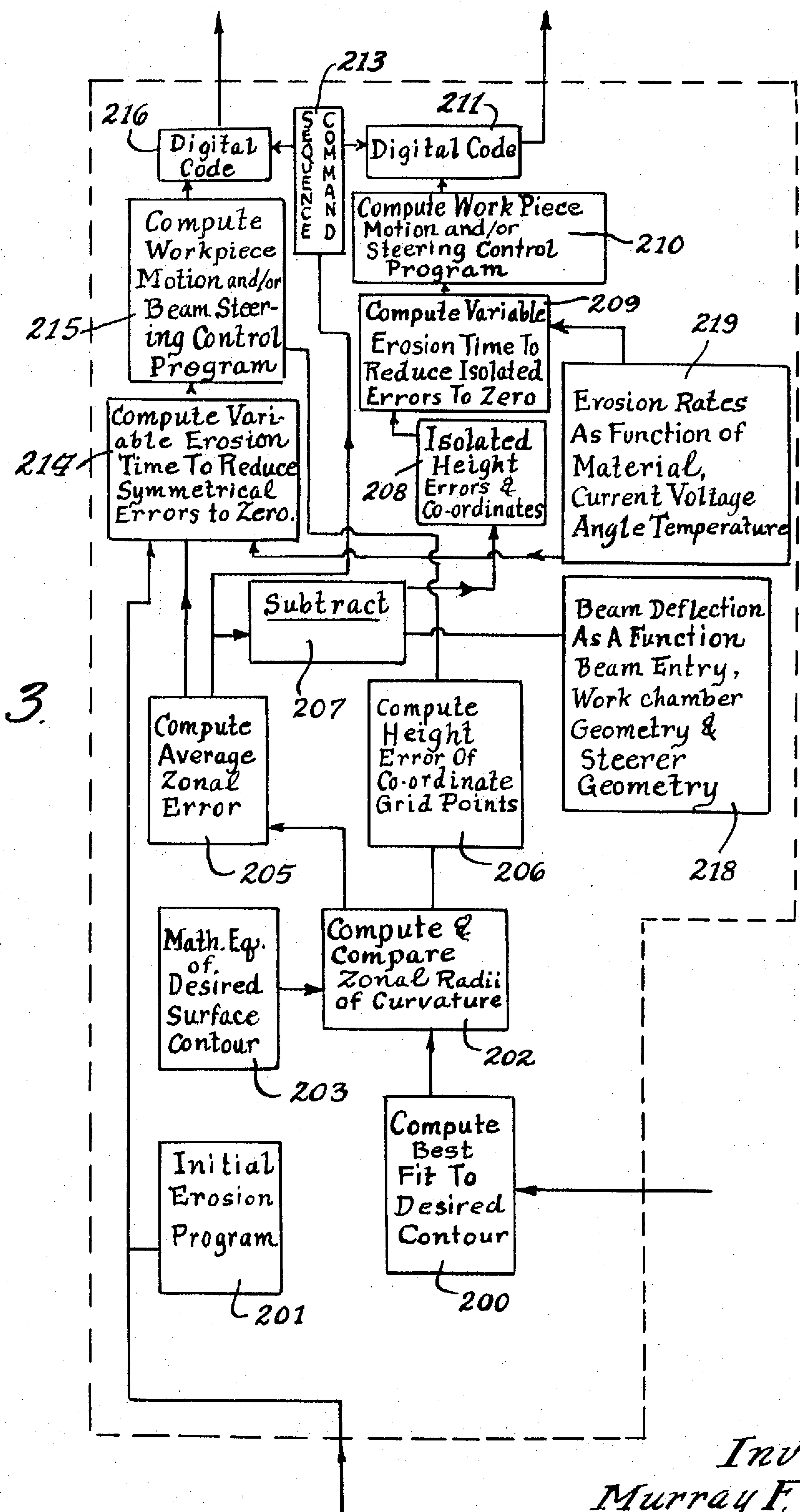

Fig. 3.

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APPARATUS USING A BEAM OF POSITIVE IONS FOR CONTROLLED EROSION OF SURFACES

This invention relates to a method and apparatus for accurately shaping the surface of a relatively hard material, and more particularly relates to the use of a positive ion beam for controllably eroding surfaces to a particular pattern with accuracies of up to one one-hundredth of a wavelength of green light.

Many applications require the accurate shaping of the surface of a hard material. Typical examples are:

a. Precise flat plates of dielectric material for mirrors and beam splitters.

b. Radially symmetric surfaces such as spheroids for optical elements.

c. Complex aspheric surface shapes such as needed for Schmidt corrector plates for correction of spherical aberration.

d. Surfaces with compound curvature such as jet turbine blades made of titanium, inconel, or other hard materials.

e. General polishing of surfaces to remove undesired surface films and to obtain good surface finishes.

f. Production of complex-shaped semiconductor devices.

g. Production of bearing surfaces for ball bearing races, retainers and the like.

It is known that a beam of argon ions may be used to erode a glass surface, as described in an article by R. L. Hines, Journal of Applied Physics, Volume 28, No. 5, May 1957, pages 587–591. The erosion of some glasses by energetic ion beams is described in an article by Meinel, Bashkin and Loomis, Applied Optics, Vol. 4, No. 12, December 1965, page 1674. In this later work, positive ions of low mass and relatively high energy of the order of one Mev were used.

The present invention is directed to a novel erosion system using a relatively low energy ion beam which may be controlled in direction, and in which the workpiece may have a controlled motion. By constantly scanning the beam with respect to a localized surface area of the surface being patterned, undesirable surface effects such as crazing and localized overheating are avoided.

In accordance with a further aspect of the invention, an electron beam is directed toward the workpiece surface to prevent the build-up of a positive charge on the surface, with the erosion of the surface being constantly monitored by an interferometer system. The motion of the beam and of the workpiece is then controlled by an automatic program to produce the ultimately desired surface configuration.

Accordingly, a primary object of this invention is to produce a highly accurate surface configuration by controlled erosion of a surface with a relatively low energy positive ion beam within the range of 20 to 100 KV.

Another object of this invention is to produce surfaces which have a geometry accurate to within one one-hundredth of the wavelength of green light or less.

A further object of this invention is to provide a novel surface-shaping system for hard material which automatically produces a complex surface pattern.

Yet another object of this invention is to provide a novel method for the production of surface patterns on a hard material.

These and other objects of the present invention will become apparent when the following description is read in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic diagram of the apparatus used in connection with the present invention.

FIG. 2 is a block diagram of the automatic control system for controlling the shape of a surface to be produced by the apparatus of FIG. 1.

FIG. 3 is a block diagram of the operation of the computer, shown in FIG. 2.

In FIG. 1, all of the components used are commercially available, and a detailed description of the individual subassemblies is unnecessary. The functions of the parts of the subsystem shown in FIG. 1 are as follows:

A chamber **10** is formed, which receives a specimen or workpiece **11** which is to have the contour of its upper surface controlled in accordance with the invention. Workpiece **11** is secured in a suitable holder **12** which is rotatably and tiltably carried on a drive housing **13**, which contains a suitable drive motor and connecting linkage to cause workpiece **11** to rotate and translate at a controlled speed and to adjust the angle or tilt of the surface of work piece **11**. A transparent window **14** is provided in housing **10**, through which the surface of workpiece **11** may be observed.

Vacuum system **15** connected to the interior of chamber **10** holds the chamber to a vacuum of about 10^{-6} Torr. Preferably, the vacuum connection is made where it will provide a clean vacuum without turbulent flow adjacent to the workpiece **11**. The vacuum is monitored by a vacuum gauge **16**.

An ion beam generator **20** is then secured to the top of chamber **10** and generally consists of a source **21** of a suitable gas such as argon or krypton, a vacuum valve **22**, a filament **23** and suitable focusing and accelerating grids and plates **24**. A suitable source of positive ions is the commercially available positive ion source known as the ORTEC 350 Duoplasmatron. This device generates a beam of argon ions having a current of up to 2 milliamperes, using an 8 mil exit aperture with ion energies of up to about 120,000 volts. The ions are focused into a beam having a diameter of between 1 and 5 mm.

The beam **30**, produced by beam generator **20**, is focused by an electrostatic lens **31** of any suitable type, such as an Einzel lens, and a set of electrostatic deflection plates **32** surround beam **30** to provide 2 axis deflection of the beam. Typically, deflection plates **32** are about 6 inches long and are spaced about 3 inches apart.

A superconducting magnetic lens **33** of, for example, a niobium tin alloy may be advantageously used to provide very high field strength for focusing and steering beam **30**. The cryogenic housing of such a lens would further provide condensation of impurities and will produce the additional benefit of a higher vacuum in the work chamber.

A shutter **40**, carried on bellows **39**, may be interposed in the path of beam **30** and can be used as a stencil where a particular pattern is to be produced on workpiece **11**, as where fiducial marks are to be formed on the specimen.

A Faraday cup ammeter **41** is also movable into the path of beam **30** to monitor the beam current.

In order to prevent the accumulation of a positive charge on workpiece **11** when the surface thereof is of insulation material, an electron gun assembly **50** directs a low energy electron beam toward the surface of workpiece **11**. The accumulation of positive charge on the work piece **11**, in the absence of the electron beam, is especially noticeable in the case of materials such as BK 7 glass.

An interferometer **60** is then provided for monitoring the erosion of the surface of workpiece **11** through window **14**. Interferometer **60** includes a suitable light source, collimating lens and mirror within housing **61**, a beam splitter **62**, housing **63** and housing **64**, which includes reentrant mirror **65**. The interferometer may be a Burch scatter plate interferometer where identical scatter plates **66** and **67** are mounted as shown. An interference pattern may then be observed through beam splitter **62** from the position shown while the workpiece **11** is being moved, and as it is being eroded by the ion beam **30**.

The surface of the workpiece **11** is positioned in the holder **12** so as to be disposed at an angle of about 45° to the ion beam **30**. The interferometer **60** has an enantiostigmatic or doubly traversing lightpath which is disposed so as to impinge on the surface of the workpiece **11** at an angle close to 90°.

In the general operation of the systems of FIG. **1**, erosion rates are about 1–2 Angstroms in depth per microampere of beam current per square cm per minute. For a typical beam current of 100 microamperes, this amounts to the removal of a depth of material equal to one-half wavelength of green light per minute for metal, glass and dielectric surfaces.

Starting with a specimen having a previously smooth, contoured surface which may be flat, spherical, aspherical or without radial symmetry such as jet turbine blades and which is correct within 1 to 10 wavelengths of green light, the positive ion system will produce a desired surface within one one-hundredth of a wavelength of green light by observing the erosion and polishing and controlling said erosion and polishing either by human operator control, or by use of automatic beam steering and workpiece moving devices.

As an example of one embodiment of the invention, a specific sequence of beam scans can be imposed on the ion beam by means of a preprogrammed electronic computer to effect a predictable alteration of the surface within a small fraction of the wavelength of green light. These scan patterns may be continuous spirals, quantized circles, TV rasters or discontinuous pulsed beams due to a shutter, electronic control of the ion source, or a stencil which provides the necessary discontinuity of pattern on to the specimen or by intensity modulation of the ion beam current. It is to be noted that relatively low voltages are used in the system and are in the range of from about 20,000 to 100,000 volts, using heavy ions such as Argon, Krypton or Xenon.

The successive paths of movement of the ion beam relative to the workpiece are offset preferably a small fraction, typically 1 to 10 percent, of the beam diameter in order to provide a suitable overlap for a suitable smooth and continuous polished surface. Thus a beam diameter of 1 mm would travel across the specimen in the predetermined scan pattern and on its next overlap may be moved approximately 10 to 100 microns from the center of the previous beam diameter. The typical energy distribution of an ion beam is a Gaussian distribution and this in turn may be modified by suitable electron optics in order to provide a more nearly cosine wave distribution if desired.

The beam generator **20** contains controls which enable both the beam current and the beam shape to be varied. The controls are of such a nature so that these parameters can be changed either simultaneously or independently. These controls are capable of varying the current density (beam current/beam area) within the range of 50 microamperes per square centimeter and 2,000 microamperes per square centimeter. The beam is focused dynamically so that the current density remains constant at large angles of incidence and a beam is always focused on the near and far portions of the workpiece by means of varying the electron lens voltage as well as the extractor voltage, magnet voltage and accelerator voltage as a function of workpiece distance from the aperture.

The range of beam parameters that maximize the desired effect are typically beam sizes from 1 mm to 5 mm in diameter with a current from 30 microamperes to 500 microamperes, respectively, of singly ionized argon between 20,000 and 100,000 volts and angles of incidence from 0° to 85°. A **30** microampere beam of 1 mm diameter gives a current density of about 40 microamperes/mm^2 and a 500 microampere beam of 5 mm diameter gives a current density of about 25 microamperes/mm^2. For an Argon beam impinging upon glass or fused silica, typical operating conditions are 30,000 volts, a 0.1 milliampere current and a 1 mm diameter beam. Typical mechanical rotation of the workpiece for mechanical spiral scanning results in approximately 60 rotations for an annulus three-quarter inch in width over a 2 inch diameter specimen.

The number of degrees of freedom which are possible in changing the point of impingement of the beam relative to the surface of the workpiece are three axes of translation and one axis of rotation. The mechanical operation of the workholder **12** provides one axis of translatory motion and one axis of rotary motion, while the set of electrostatic deflection plates **32** which surrounds the beam provides two axes of deflection of the beam.

If an optically flat surface is to be eroded, the rate of rotation is varied in order to provide a uniform tangential velocity at any radial zone by a suitable mechanical cam follower which controls the rotational speed of a DC motor which is used to rotate the specimen. In other words, if the beam proceeds from the outer diameter at slow rates, the velocity of rotation of the specimen increases until the beam reaches the center of the workpiece where the rotational speed theoretically becomes infinite. In practice, therefore, a center pedestal is generated by not eroding the central zone which is then removed by switching to another scan technique such as quantized circular scans using electrostatic deflection of the ion beam. For rectangular pieces, a two axis linear scan motion can be used for complete erosion of the entire surface portion.

As one example of the use of the apparatus of FIG. **1**, an *f*/6, 10 cm diameter pyrex lens having a parabolic surface was figured from a workpiece irradiated with argon ions. The original blank which was figured had a concave spherical surface radius of curvature of 120 cm and the blank was rotated and translated with respect to the impinging beam. The argon ion beam had a beam energy of about 30 KV, and a diameter of about 3 mm which traced out a spiral path on the blank surface. The exposure time was about 11 hours using a beam current of 100 microamperes, thus corresponding to a beam density of about 15 microamperes/mm². The resulting figure was observed by a Burch scatter plate interferometer and the resulting surface formed had a R.M.S. value of 0.046 wavelengths (at 5,500 A) figure deviation from a best fit paraboloid.

The apparatus of FIG. 1 as schematically shown in FIG. 2 consists of the block **100** which represents the chamber **10** having the workpiece **11** mounted therein; block **101** representing the vacuum pump of vacuum system **15** of FIG. 1; block **102** representing the interferometer system **60** of FIG. 1; and ion source block **103** representing the ion source **20** of FIG. 1, The ion generating apparatus and beam control elements as represented in block form in FIG. 2 include an ion accelerator **104**, an accelerator voltage control **105**, ion optics **106** having beam focus and shaping electrodes, a beam current regulator **107**, an electrostatic beam steerer system **108** and corresponding power supply **109**, a magnetic beam steerer system **110** and corresponding power supply **111**.

The arrangement shown in FIG. 2 also includes a workpiece thermal control **112** for regulating the temperature of the workpiece, which in turn affects the rate of erosion for a given beam current and energy.

To adapt the apparatus of FIG. 1 to automatic operation, there is added, as shown in FIG. 2, an ion beam position sensor **113** which in addition to the interferometer **102** supplies information to the coordinate grid optics **114** which in turn provides the input for the fringe position sensor and coordinate readout system **115** whose output is fed into a computer.

The apparatus can be operated in one of two modes. Mode 1 is essentially an open loop operation in which the operator at the operator station **120** can assume manual control of the machine in order to preferentially erode surface regions. This mode can also be used to erode a contour in accordance with a stored program. Mode 2 is a closed loop process in which the figuring of a contour is performed automatically under computer control.

In a typical erosion sequence, Mode 1 operation will first be used to generate a contour to within specified tolerances. The operator will then switch the apparatus to Mode 2 operation in which the ion beam is computer controlled to complete the necessary preferential erosion based on optical surface contour information as derived from the interferometric system **102,113,114.**

A typical erosion process would proceed in the following manner:

Operator actuates switches SW1 and SW2 to evacuate work chamber and set workpiece temperature to desired level. The operator uses the manual adjustment control **121** to set the workpiece at a desired orientation and position with respect to position of ion beam. The operator according to the erosion characteristics of the particular substrate material turns on switch SW4 to actuate ion source **103**, switch SW5 to set current level, switch SW6 to shape and focus ion beam upon workpiece, and switch SW7 to set the proper acceleration voltage level. The operator then switches on SW8 and/or SW9 to supply power to either the magnetic beam steerer system **110** or the electrostatic beam steerer system **108**. If SW13 and SW14 are left in "off" position, the ion beam is not steered by either **108** or **110** but merely impinges directly upon the workpiece **11**. In this case, pure mechanical manipulation of the workpiece **11** is controlled by workpiece motion position controller **116**.

In an alternative embodiment of the erosion system, **116** is a numerically controlled servo system with a prepunched tape or IBM card program. In this version, the operator would not activate SW11 to the computer **122**, or SW10 to activate the input to the computer from the interferometric system **113,102,114**.

The operator can watch the piece through the viewing optics **117** and also can watch the fringe pattern in the interferometer **102**. The operator also can see the relative position of the ion beam by observing the beam position through viewing optics **117**. The beam would show as a bright fluorescent spot against a coordinate grid image in **114**.

In this open loop mode, the operator lets the machine run for a predetermined length of time based on his a priori knowledge of erosion rates for the particular set of operational conditions being used. At the end of this time, the workpiece may be removed for inspection and test or the operator can now activate the system for closed loop operation as will be explained later.

In further variations of the open loop mode, the workpiece motion controller may be deactivated by turning SW3 to the "off" position. Operator may at his option activate SW8 or SW9 and effect the erosion of the surface by beam steering techniques alone. Operator may at his option effect his erosion program by operating electrostatic beam steerer system **108** in a one or two axis mode or he may effect the program by purely magnetic deflection with magnetic beam steerer system **110** alone. At operator option a combination of electrostatic beam steering **108**, magnetic beam steering **110** and workpiece motion control **116** can be used to achieve a particular erosion result. Again, the erosion takes place for a predetermined length of time and is terminated at the discretion of the operator.

After completion of the open loop operation the system can be switched to closed loop operation. In the closed loop operation, the interferometer would be adjusted by the operator to obtain a fringe pattern of approximately 8 to 10 relatively straight fringes across the aperture of the workpiece. Optical tests are applied to determine the position of the zero order fringe. This must be done in order that the computer will be able to determine if a fringe singularity is a "hill" or a "valley," i.e., the sign of the defect must be determined if meaningful erosion is to take place. A calibrated rectilinear coordinate scale **114** has its grid lines superimposed on the field of view of the interferometer **102** and is used to derive information on the eroded contour. Usually, the center of the coordinate system is arranged to coincide with the center of the zero order fringe. The fringe sensor device of block **115** is devised so that it optically scans the interferometric pattern and the rectilinear coordinate scale associated therewith. A voltage pulse output is sent to the computer. A pulse is sent out each time the scanner **115** passes over the center of gravity of a fringe. In addition, a very sharp pulse is sent when the scanner **115** sees one of the coordinate grid lines.

The positions of SW**12**, **13**, **14**, **15**, **16** and **17** can be placed under the control of the computer. These switches could be activated by coded pulses as required by the computer program.

In the closed loop mode, the pulses from the pulse generator **115** relating fringe position to a coordinate grid reference are fed into the computer **122**. The computer, in block **200**, determines the figure that will best fit the observed figure. This is compared with the equation for the desired figure stored in **203**. The computer then compares, in block **202**, the radius of curvature for each zone of the actual and ideal figure. An average height error is obtained at each zone **205**; also a height error is computed at discrete coordinate grid points **206**. These errors are subtracted **207** in order to obtain both errors of symmetry and isolated height errors. At this point, if the average zonal height error is greater than some preset tolerance, a pulse is sent to the sequential command station **213** which allows the erosion to proceed until errors of symmetry are reduced to zero. This takes place in blocks **214–217** in which the program to reduce the symmetrical errors to zero is computed; the output in digital pulses is then converted to analog voltages in the D/A converter. When errors of symmetry are reduced to zero, then the sequential command system allows the system to operate so as to reduce isolated errors to a preset level, blocks **208–212**.

Included in the system is the ability to operate variable beam current intensity process. This adaptation of the process of the invention is based on the fact that erosion depth at any point is approximately linearly proportional to the beam current. Thus, varying the beam current as a function of workpiece coordinates is a valuable method for controlling erosion depths at any point. When switch SW**12** is activated allowing analog voltages from D/A converter of block **216** to be impressed upon the beam current regulator **107**, intensity modulation of the beam current is thus achieved.

Thus, while preferred constructional features of the invention are embodied in the structure illustrated herein, it is to be understood that changes and variations may be made by those skilled in the art without departing from the spirit and scope of the pending claims.

The embodiments of the invention in which an exclusive privilege or property is claimed are defined as follows:

1. Apparatus for controllably eroding a surface of a workpiece to provide a predetermined contour thereon comprising means for mounting the workpiece in an evacuated chamber; means for producing a beam of positive ions traveling through said chamber towards said workpiece including means for variably determining the working characteristics of the ion beam; means for producing relative scanning movement between said beam and said workpiece including electrostatic deflection means, magnetic deflection means, and means for rotating the workpiece on an axis generally perpendicular to said surface, all selectively or concurrently operable for deflecting the path of the ion beam to continuously vary the point of impingement of the beam upon said surface; monitoring means for representing the pattern of erosion of the surface of the workpiece; reference grid means associated with the monitoring means and defining a series of zones thereon; sensing means for producing a first signal containing information from said monitoring means and said reference grid means representing instantaneous depth contour at each point and zone on said surface; and programmed computer control means including means for producing a second signal representing the desired depth contour at each point and zone on said surface, means for comparing each of said signals and for computing average depth errors for each of said reference grid zones and for each of said reference grid points, and means for generating a resultant signal to regulate the ion beam to produce the predetermined surface contour.

2. Apparatus in accordance with claim **1** wherein said monitoring means is an interferometer having a view field registered on said surface and said reference grid means is a calibrated rectilinear coordinate scale superimposed on the view field of the interferometer.

3. Apparatus in accordance with claim **1** wherein said resultant signal includes a portion representing the average zonal error for regulating said ion beam to produce the desired contour and a second portion representing the coordinate point error for regulating said ion beam to correct isolated height errors.

4. Apparatus in accordance with claim **1** wherein said resultant signal is converted from digital pulses to analog voltages in a converting means and said analog voltages are used to control the working characteristics of the ion beam to produce the predetermined surface contour.

5. Apparatus in accordance with claim **1** wherein said means for determining the working characteristics of the ion beam includes an ion beam focusing and shaping control, a beam current regulating control and an ion acceleration control.

6. Apparatus for controllably eroding a surface of a workpiece to provide a predetermined contour thereon comprising means for mounting the workpiece in an evacuated chamber; means for producing a beam of positive ions traveling through said chamber towards said workpiece including means for variably determining the working characteristics of the ion beam; means for producing relative scanning movement between said beam and said workpiece for deflecting the path of the ion beam to continuously vary the point of impingement of the beam upon said surface; monitoring means for representing the pattern of erosion at defined discrete points and zones on the surface of the workpiece; sensing means for producing a first signal representing instantaneous depth contour at each point and zone on said surface; and programmed computer control means including means for producing a second signal representing the desired depth contour at each point and zone on said surface, means for comparing each of said signals and for computing average depth errors for each of said reference grid zones and for each of said reference grid points, and means responsive to said control signals for generating a resultant signal to regulate the ion beam to produce the predetermined surface contour.

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