

ELECTROEROSION MACHINING OF A CAVITY IN A WORKPIECE

The present invention relates generally to electroerosion and, more particularly, to a method of and apparatus for electroerosively machining a 3D
5 (three-dimensional) cavity in a workpiece by using a tool electrode (preferably slender, e.g. a wire or rod electrode) of which the machining surface at its free end is generally independent in shape of that of the desired cavity. The term "electroerosion" and
10 "electroerosive machining" is used herein to refer to a machining process whereby material is removed from a workpiece juxtaposed with a tool electrode by means of the actions of successive electrical discharges effected therebetween, which actions may partially
15 include actions of an electrolytic or electrochemical material removal nature.

It has been generally accepted that the electroerosion technique, when applied to the machining of a 3D cavity in a workpiece, commonly
20 requires a tool electrode having a machining surface which is three-dimensionally shaped to conform to the shape of the desired cavity in the workpiece. Furthermore, a multiplicity of such electrodes of identical or similar configuration and size must be
25 prepared in order to compensate for the wear which the electrodes or tools suffer during the erosion process or in the interest of minimizing the machining time to achieve the end of a desired machined precision and surface finish. Preparation
30 of such precision-formed and multiple electrodes is obviously time-consuming and laborious. Furthermore, the conventional sinking-type operation makes it difficult to keep the machining gap free from the debris of machined chips and other products which
35 tend to cause machining instability.

The present invention seeks to provide (a) an improved method of electroerosively machining a 3D cavity in a workpiece; (b) an electroerosion method of machining a 3D cavity whereby the desired cavity
5 can be formed in a workpiece with a simple electrode; (c) an electroerosion method which is capable of yielding a desired 3D cavity in a workpiece with an increased efficiency; (d) an improved apparatus for electroerosively machining a 3D cavity in a
10 workpiece; (e) an electroerosion apparatus whereby a desired 3D cavity can be formed in a workpiece with a simple electrode; and (f) an electroerosion apparatus which is capable of yielding a desired 3D cavity in a workpiece with an increased efficiency.

15 According to the present invention there is provided, in accordance with a first aspect thereof, a method of machining a cavity in a workpiece by electroerosion with a tool electrode having at its free end portion a machining surface contour of which
20 the shape is generally independent of the shape of the desired cavity, which method comprises the steps of:

axially juxtaposing said tool electrode with the workpiece to position said machining surface
25 contour in spaced juxtaposition therewith, across a machining gap flooded with a machining liquid;

imparting a high-frequency vibration to said tool electrode whereby to vibrationally
30 fluctuate said machining surface contour and thereby dynamically enlarge the effective machining area thereof by a small amount determined by the amplitude of said high-frequency vibration;

applying a succession of electrical pulses between said vibrating tool electrode and the
35 workpiece across the machining gap to effect

successive localized electrical discharges jumping between the workpiece and said machining surface contour brought proximal thereto by the vibrational fluctuations, thereby electroerosively removing material from the workpiece adjacent said vibrationally fluctuating machining surface contour providing the said enlarged effective machining area; and

effecting a multi-axial relative displacement of said vibrating tool electrode and said workpiece along three coordinate axes which include a pair of coordinate axes defining a plane substantially orthogonal to the longitudinal axis of said tool electrode and a coordinate axis substantially orthogonal to said plane, while simultaneously maintaining the average width of said machining gap substantially constant, thereby three-dimensionally machining said workpiece at least in part by said electrical discharges with said vibrationally fluctuating machining surface contour to form the desired cavity in the workpiece.

Specifically, the tool electrode may be composed of copper, a copper-containing alloy such as brass or copper-tungsten, silver-tungsten or graphite. The tool electrode is preferably a wire or rod which should preferably be of a diameter of 0.05 to 1 mm, but may be of 3 to 5 mm where rough machining is satisfactory, and 1 to 3 mm where medium machining is desired. The range of 0.05 to 1 mm is preferred to achieve fine finishing or where this is a requirement. The tool electrode may alternatively be in the form of a tube.

The machining liquid may be of any type commonly used in the conventional sinking-type EDM (electrical discharge machining) practice, but

preferably there is used here water or a distilled water having a specific resistivity ranging between 1×10^3 and 5×10^6 ohm-cm.

5 The vibration may be imparted to the tool electrode in its axial or longitudinal direction and may also, as a variant form, be applied transversely to the axis thereof. The frequency of vibration is generally in a range between 1 to 100 kHz and preferably between 10 to 50 kHz and may also range
10 between 100 kHz to 100 MHz. The amplitude of the vibration is generally in the range between 1 and 50 microns and, preferably between 1 and 10 microns.

Preferably, said multi-axial relative displacement of said vibrating tool electrode and the
15 workpiece is effected incrementally, with increments of displacement of the order of 1 micron.

In accordance with a second aspect of the present invention an apparatus for machining a cavity in a workpiece by electroerosion comprises:

20 a tool electrode with a machining surface contour of which the shape is generally independent of the shape of the desired cavity, which electrode is arranged to be juxtaposed with the workpiece so as to position said machining surface contour in spaced
25 juxtaposition therewith across a machining gap flooded (when in operation) with a machining liquid;

means for imparting a high-frequency vibration to said tool electrode whereby to vibrationally fluctuate said machining surface
30 contour and thereby dynamically enlarge the effective machining area thereof by a small amount determined by the amplitude of said high-frequency vibration;

power supply means electrically connectable to said tool electrode and said workpiece for
35 applying electrical pulses between said vibrating

tool electrode and said workpiece across the machining gap to effect successive localized electrical discharges through said gap between said workpiece and said machining surface contour brought proximal thereto by the vibrational fluctuations, thereby electroerosively removing material from the workpiece adjacent said vibrationally fluctuating machining surface contour providing the said enlarged effective machining area; and

feed means for effecting a multi-axial relative displacement of said tool electrode and said workpiece along three-coordinate axes which include a pair of coordinate axes defining a plane substantially orthogonal to the longitudinal axis of said tool electrode and a coordinate axis substantially orthogonal to said plane, while simultaneously maintaining the average width of said machining gap substantially constant, whereby said vibrationally fluctuating machining surface contour is swept three-dimensionally over the surface of said workpiece in which the desired cavity is to be formed.

For maintaining the average gap width substantially constant there is preferably provided wear detecting means which is responsive to the machining wear of the tool electrode machining surface contour and supplies to an auxiliary feed means an output signal dependent on the amount of said wear, said auxiliary feed means being responsive in a wear compensating way to effect additional feed of said tool electrode.

The wear-detecting means may respond to a change in the mode of the vibration imparted to the tool electrode, which change represents the wear of the tool electrode. The change in the mode of

vibration can be sensed as a change in the frequency, amplitude and/or energy of the vibration imparted to the tool electrode. The reflection of the ultrasonic vibration transmitted via the machining liquid to the workpiece may also be used, and a change in the echo period may then be used to indicate the wear of the tool electrode.

Wear of the tool electrode can also be sensed by monitoring the characteristic of a sonic or ultrasonic wave generated by the machining discharge and transmitted via the machining liquid.

Wear of the tool electrode can also be sensed by monitoring the ratio of the number of machining discharges to the number of input machining pulses applied to the machining gap per a given or unit time.

A plurality of different electrodes each carried by a tool holder may be used and stored in a magazine of an automatic tool changing (ATC) arrangement which is operated in such a manner that a given used tool electrode upon ascertainment of the wear thereof is collected into the magazine and a new electrode is mounted in the machine head to replace it.

In accordance with a further feature of the invention, means for dressing the tool electrode is provided so as to compensate for the wear thereof during the course of given machining operation. The dressing means may include a dressing electrode in the form of a wire or band selectively brought into juxtaposition with the worn machining surface of the tool electrode in response to a signal, and an electroerosion power supply for energizing the tool electrode and the dressing electrode when in a dressing position whereby to dress said machining

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surface by an electroerosion process. The dressing electrode arrangement may be disposed in a worktank in which the machining of the workpiece is carried out.

5 The dressing of the worn tool electrode may also be effected by positively machining the unworn portion of the tool electrode so that a flat machining face may be always exposed in a predetermined machining relation to the workpiece
10 surface being machined.

 These and other objects, features and advantages of the present invention will become more readily apparent from a reading of the following description of certain embodiments thereof, reference
15 being made to the accompanying drawings in which:

 FIG. 1 is a schematic view diagrammatically illustrating a 3D electroerosion machining system incorporating a vibration head, in accordance with the invention;

20 FIG. 2 is a schematic view diagrammatically illustrating another system according to the invention including a modified electrode vibration head for providing a compensation feed of the worn electrode;

25 FIG. 3 is a schematic view diagrammatically illustrating a vibration head with a modified energization arrangement;

 FIG. 4 is a waveform diagram of the vibration signal imparted to the tool electrode
30 according to the arrangement of FIG. 3;

 FIG. 5 is a schematic view diagrammatically illustrating a further embodiment of the invention in which the electrode is a tube;

 FIG. 6 is a schematic view diagrammatically
35 illustrating another vibration-sensing arrangement

according to the invention to ascertain the wear of the tool electrode;

FIG. 7 is a schematic view diagrammatically illustrating another system of the invention in which the tool electrode is a continuous wire;

FIGS. 8 and 9 are schematic views illustrating paths along X and Z axes to be followed by the system of the invention in which a flexible tool electrode relative to the workpiece in 3D machining operations;

FIG. 10 is a schematic view diagrammatically illustrating a further wear-detecting system according to the invention in which the ratio of actual electrical discharges to input machining pulses in number is monitored;

FIG. 11 is a schematic view diagrammatically illustrating an automatic tool changing (ATC) arrangement adapted for practice of the present invention;

FIG. 12 is a schematic view diagrammatically illustrating a further embodiment of the invention in which the gap resistance is monitored to inspect the machining accuracy afforded the workpiece during the 3D cavity forming operation;

FIG. 13 is a schematic view diagrammatically illustrating a pictorial display system which can be used with the arrangement of FIG. 12 according to the invention;

FIG. 14 is a schematic view partly in section diagrammatically illustrating an embodiment of the invention incorporating means for dressing the tool electrode;

FIG. 15 is a schematic view partly in section diagrammatically illustrating a modification

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of the arrangement of FIG. 14;

FIG. 16 is a schematic view diagrammatically illustrating the operation of the dressing arrangements of FIGS. 14 and 15;

5 FIG. 17 is a schematic view partly in section diagrammatically illustrating a further modification of the system of FIG. 14;

10 FIG. 18 is a schematic view diagrammatically illustrating a portion of the system of FIG. 17;

FIG. 19 is a schematic view diagrammatically illustrating the operation of the system of FIG. 17;

15 FIG. 20 is a schematic view diagrammatically illustrating a numerical-control (NC) system for effecting the 3D machining feed and automatic dressing of the tool electrode in accordance with a further feature of the invention;

20 FIGS. 21(A), (B), (C) and (D) are waveform diagrams illustrating signal pulses and machining pulses which appear in the system of FIG. 20;

25 FIGS. 22-24 are schematic views partly in section diagrammatically illustrating how machining wear occurs on the machining surface of a tool electrode in a 3D operation;

FIG. 25 is a schematic view diagrammatically illustrating contour lines of a worn electrode tip; and

30 FIGS. 26 and 27 are schematic views illustrating various paths along X and Z axes to be followed by the tool electrode relative to the workpiece in 3D machining operations.

35 Referring first to FIG. 1, a tool electrode 1 is shown juxtaposed with a workpiece 2 across a machining gap G flooded with an electroerosive

machining medium supplied from a fluid source (not shown). The tool electrode 1 is here of a simple configuration which is independent of an intricate shape of the cavity 2a to be machined in the workpiece, thus for example a solid or tubular wire or rod which may, as typical with a conventional sinking-type EDM or ECDM electrode, be composed of copper, brass, silver-tungsten, copper-tungsten or graphite and which is preferably thin, say, of a diameter or thickness ranging normally between 0.05 to 1 mm and in some cases up to 5 mm, depending upon a particular grade of machining desired. Thus, for roughing a thickness or diameter 3 to 5 mm would be satisfactory. For medium and finishing the ranges of 1 to 3 mm and of 0.05 to 1 mm are desirable, respectively.

The machining medium may be any conventional EDM or ECDM liquid but is preferably water of a specific resistivity ranging from 1×10^3 to 5×10^6 ohm-cm which, especially when used in the present process, has been found to allow machining to proceed with stability and excellent results.

The workpiece 2 which may be either a virgin blank or one rough-machined previously is carried by a worktable 3 driven by feed motors 4, 5 and 6 to provide displacement of the workpiece 2 relative to the tool electrode 1 along three mutually orthogonal axes, X, Y and Z. The motors 4, 5 and 6 are each a stepping motor or a DC motor equipped with an encoder, and are driven in response to drive signals supplied from a numerical-control (NC) unit 7 in accordance with digital data preprogrammed therein and dictating a predetermined three-dimensional contouring path to be followed by relative displacement between the tool electrode 1 and the

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workpiece 2 and thus a desired three-dimensional contouring pattern to be machined in the workpiece 2.

5 A machining power supply 8 which may be a conventional EDM generator is connected to the tool electrode 1 and the workpiece 2 to apply a series of machining pulses across the machining gap G to effect time-spaced, discrete electrical discharges between the tool electrode 1 and the workpiece 2 through the
10 machining medium to remove material from the workpiece 2. The machining action may include partly an electrolytic or electrochemical action.

The tool electrode 1 is carried by a holder 9 which here comprises an ultrasonic vibration horn
15 designed to propagate and amplify an ultrasonic vibration produced by a transducer 10, the latter being energized by a high-frequency power supply 11. The transducer 10 may comprise any conventional piezoelectric element (e.g. quartz, Rochelle salt, barium titanate), any conventional magnetostrictive
20 element (e.g. nickel, aluminium-iron alloy) or an electromagnet, and the vibration supply system 9, 10, 11 is adapted to vibrate the tool electrode 1 in the longitudinal direction at a frequency generally
25 between 1 and 500 kHz and with an amplitude 1 to 50 microns, although a greater amplitude and frequency may also be used. By virtue of imparting a high-frequency vibration say, at a frequency of 10 to 50 kHz, to the tool electrode 1 while the latter three-
30 dimensionally sweeps over the surface of the workpiece 2 to advance machining towards a desired contouring end, it has been found that the machining stability is markedly enhanced and the removal rate is increased to a value three to five times as great
35 as that obtained when there is no vibration.

Because the discharge stricken area of the tool electrode 1 is much smaller than that of the workpiece, the electrode 1 tends to wear away at its tip portion. It has been found that the wear can be effectively detected by monitoring a change in the mode of vibration of the tool electrode 1, or a vibrational response of the workpiece 2. For example, the change in the time of arrival Δt of an echo resulting from a vibration signal transmitted from the electrode tip and incident on the workpiece and reflected back to the electrode is generally proportional to the change in the electrode length or gap size Δl as follows: $\Delta t = \alpha \Delta l$ where α is a constant. By detecting the change Δt , the change Δl or electrode wear can be ascertained.

In the arrangement shown, a vibration sensor 12 is accordingly provided comprising a detector 12a, a preset threshold or reference setting device 12b and a comparator or discriminator 12c. The detector 12a may detect the time of echo arrival t which is compared at the discriminator 12c with a preselected reference value therefor corresponding to a given electrode length or gap size l_0 . When a deviation is found to develop, a signal is issued by the discriminator 12c and is applied to a control circuit 13 associated with a stepping motor 14. When vibration of a frequency, say, of 10 to 500 MHz is used to vibrate the tool electrode 1, an electrode wear of 0.05 to 0.1 mm is ascertained with a high degree of accuracy in this manner.

The sensor 12 may also respond to a change in the vibration frequency, and then the detector 12a is constituted by a frequency detector and the setting unit 12b has a predetermined reference setting corresponding to the frequency incoming when

the tool electrode has suffered no wear and the machining gap G has an optimum spacing. The discriminator 12c is then adapted to provide a signal representing a frequency shift and is thus capable of similarly detecting the electrode wear. It is found that with an input frequency ranging between 10 and 50 kHz, the electrode wear of an amount as mentioned above gives rise to a frequency shift or increase of 4 to 5 kHz.

10 The tool electrode 1 is supported by the holder 9 through a chuck 15 in which it is carried by guide rollers 16 and feed rollers 17 operatively connected to the motor 14. Thus, the control circuit 13 operates, in response to a signal of the discriminator 12c indicating a wear of the tool electrode, to furnish the motor 14 with a drive pulse or pulses and the motor 14 in turn drives the feed rollers 17 to allow the tool electrode 1 to be advanced by a preselected number of incremental displacements through the guide way in the chuck 15, thereby compensating for the wear. The increment of displacement is set, preferably, at a small value, say, 1 micron so that an optimum gap spacing can be re-established with a high degree of accuracy.

25 EXAMPLE

 A ferrous workpiece is three-dimensionally machined with an arrangement as shown in FIG. 1 and as described using a copper wire or rod electrode which is vibrated at a frequency of 28 kHz and using various electrical machining conditions. It has been found that the wear compensation feed is required once for every 10^4 discharge pulses under a wear condition to yield a surface roughness of 5 μR_{max} , and once for every 10^6 discharge pulses under a low-wear condition to yield the same roughness; once

for every 5×10^3 discharge pulses under a wear condition to yield $10 \mu R_{max}$, and once for every 5×10^5 discharge pulses under a low-wear condition to yield the same roughness; and once for every 5×10^2 discharge pulses under a wear condition to yield $20 \mu R_{max}$, and once for every 5×10^4 discharge pulses under a low-wear condition to yield the same roughness.

In this manner, the electrode wear compensation is achieved with a high degree of accuracy constantly to allow the single tool electrode 1 of a simple configuration to consistently perform 3D machining to yield a desired 3D cavity or pattern with a high degree of accuracy.

In order to sense a change in the mode of vibration, the amplitude may be detected as well. Then a piezoelectric element may be attached to the transducer 10 or the horn 9 to derive a signal corresponding to a change in the vibrational amplitude with a due precision. Still alternatively, a change in the energy transmitted from the source 11 to the transducer may be detected by using, for example, an ammeter. Irrespective of which parameter is detected, a sharp change is detectable and used as a signal to determine tool wear with reliability, thereby permitting wear compensation feed to be achieved with precision.

The tool electrode 1 need not be of round or circular cross section; it may be of other simple cross section such as square or triangular. Then the chucking unit 15 may include an adapter designed to hold such other cross-sectioned electrode and to be displaceably carried by the guide rollers 16 and 17 through the opening of the horn 9. The wear compensation feed is alternatively effected through a

machine head (not shown) for carrying the horn 9 and the transducer 10.

In the embodiment of FIG. 2 in which the parts or elements basically the same as those shown in FIG. 1 are designated by the same reference numerals, the tool electrode 1 is fixedly supported at a coupling 115 by the ultrasonic horn 9 which in turn depends displaceably from a machine head 18. In this arrangement, the head 18 is displaceable vertically on a lead screw 106a by a Z-axis motor 106 to move the tool electrode 1 along the Z-axis or in its axial direction, while the worktable 3 is displaced along the X- and Y-axes by the feed motors 4 and 5, respectively, to move the workpiece 2 in an X-Y plane so that a predetermined relative contouring movement is produced between the working portion of the tool electrode 1 and the workpiece to machine a desired 3D cavity or pattern in the latter.

The machining power supply 8 is connected on one hand to the tool electrode 1 via the chucking unit 115 and on the other to the workpiece 2 via the worktable 3 to provide electroerosive pulses across the machining gap G. A shunt resistor 19 is connected across the gap G in parallel with the power supply 8 to sense the gap voltage. A V-F (voltage to frequency) converter 20 is connected to the sensing resistor 19 to convert the voltage signal into a train of pulses whose frequency is proportional to the gap voltage. The frequency signal is then applied to the NC unit 7 so that the rate of displacement along each of the X-, Y- and Z-axes is controlled as a function of the gap voltage.

The horn 9 supporting the tool electrode 1 is shown received in a chamber defined by a frustoconical housing 21 attached at its upper end to

the machine head 18. The housing 21 has its lower end formed with guide rolls or rollers 22 between which the wire or the like tool electrode 1 is guided out to establish the machining relationship with the workpiece 2 while being vibrated by reason of a vibration signal imparted thereto via the horn 9 from the transducer 10 energized by the power supply 11. The horn 9 is here displaceably carried on a lead screw 23 driven by a motor 114 which is again preferably a stepping motor or a DC motor equipped with an encoder. Thus, the control circuit 13 is responsive to tool wear sensed by the vibration sensor 12 to furnish the motor 114 with a drive signal. The motor 114 is driven to move the horn 9 to axially advance the tool electrode 1 and to compensate for the tool wear 1 so that a preselected length thereof remains projected from the electrode guide means 22 in a machining relationship with the workpiece 2.

20 The ultrasonic arrangement shown in FIG. 3 includes a first transducer 210a attached to the amplifying horn 9 and energized by a first power supply 211a of a low-frequency output and a second transducer 210b attached to the first transducer and energized by a second power supply 211b of a high-frequency output. The output of the first source 211a is connected to the input of the second source 211b so that the second source 211b provides successive trains of high-frequency pulses with the trains occurring at the frequency of the low-frequency source 211a, say, at 10 to 50 kHz, and the pulses occurring at the frequency of the high-frequency source 211b, say, at 10 to 100 MHz. As a result, the wire electrode attached at the end of the amplifying horn 9 acquires vibration signals of a

waveform as shown in FIG. 4 to enable detection of the tool wear with precision while enhancing the machining stability.

5 The resonant frequency of the vibration is expressed as follows:

$$F = \frac{n}{2l} \sqrt{\frac{pg}{r}}$$

10 where n is the number of nodes, l is the length of wire electrode, p is the tension of wire electrode 1, r is the weight of wire electrode per unit length and g is gravity. Since p, r and g are constant and assuming that n is constant, it is seen that the vibration frequency F changes in inverse proportion
15 to the tool length l, and the tool wear in terms of change in length Δl is obtained by sensing the vibration frequency F and is compensated for.

FIG. 5 shows an embodiment of the invention in which the tool electrode is a tube 301 with an
20 internal bore through which a machining liquid introduced from a supply (not shown) via an inlet 24 is forced to flow into the machining gap G. The machining liquid is preferably distilled water which is deionized from raw water so as to have a
25 resistivity ranging, preferably, from 5×10^3 ohm-cm, and is forced through the minute machining gap G between the tube end and the workpiece 2. The horn 9 here acts to impart an ultrasonic vibration of a frequency in the range, say, 1 to 100 MHz generated
30 by the transducer 10 to the machining liquid. Thus, the ultrasonic vibration propagates at a velocity of 1500 m/sec through the machining liquid, 2 to 3 times higher than through the metallic body of the tubular electrode 301. By sensing a change in the echo
35 period or any other vibration parameter as described,

the wear of tool electrode 301 is detected with a high precision. The tubular electrode 301 is shown movably supported by guide rollers 317 driven by a motor 314 to advance the electrode 301 in compensation for the detected electrode wear.

5 In this arrangement, the machining gap G may also be made use of as a source of ultrasonic vibration imparted to the tool electrode 301. The production of intermittent electrical discharges at
10 the machining gap provides a cyclic production of discharge pressure and hence generation of a mechanical oscillation which is propagated through the electrode 301 and can be sensed by a transducer (not shown in this FIGURE) disposed in contact with
15 the electrode 301 to detect the electrode wear.

In the embodiment of FIG. 6, the tool wear is detected by a combination of the transducer 10 imparting the ultrasonic vibration to the tool electrode 1 and a microphone 25 disposed in the
20 vicinity of the machining gap. A comparator 26 is used to compare the two signals sensed by these two means to thereby indicate the tool wear.

In the embodiment of FIG. 7, the tool electrode is a continuous wire 401 supplied from a
25 reel 27 and guided through guide rollers 417. The guide rollers 417 are driven by a motor 414 to feed the continuous electrode wire 401 in compensation for the wear of the end portion thereof.

An embodiment of the invention shown in
30 FIG. 10 is shown as including an electrode assembly, vibrating head and three-dimensional machining feed unit essentially the same as described previously, particularly in connection with FIG. 2, and additionally includes an electrode-wear detecting
35 system responsive to the rate of production of

machining discharges.

The system comprises a first signal pulser 30 providing a series of first signal pulses corresponding to input machining pulses furnished from the power supply 8 to the machining gap G between the tool electrode 1 and the workpiece 2. A second signal pulser 31 is connected with the gap resistor 19 to provide a series of second signal pulses corresponding to actual machining discharge pulses produced through the machining gap G. The outputs of the first and second signal pulsers 30 and 31 are fed into the first inputs of AND gates 32 and 33, respectively, which have their respective second inputs fed with timing signals furnished from a timer circuit 34. The outputs of the AND gates 32 and 33 are fed into preset counters 35 and 36, respectively, which are adapted to furnish output signals synchronously by virtue of a coupling 37, the output signals being fed into a divider 38. The latter supplies its output to a discriminator 39 which, when the output of the divider 38 exceeds a threshold value preset therein, provides an output signal which is applied to a control circuit 40. The control circuit 40 when actuated provides a feed pulse or pulses which is/are applied to drive an electrode-wear compensation motor 114 as previously described.

In a machining operation, the tool electrode 1 which may be a wire of a thickness of 0.1 to 1 mm, or a rod or tube of a diameter of 2 to 10 mm and which is carried by the tool head 18 is fed vertically along the Z-axis by means of the motor 106 to be positioned in a machining relationship with the workpiece 2 as shown. Then the worktable 3 is driven to feed the workpiece 2 in an X-Y plane by the X-axis motor 4 and the Y-axis motor 5. As previously

described, drive pulses for the motors 4, 5 and 106 are furnished from the numerical controller 7 based upon data of desired path movements preprogrammed therein. An EDM machining fluid is supplied into the region of the machining gap G while a succession of electrical machining pulses are furnished from the power supply 8 to the tool electrode 1 and the workpiece 2. As a result, electrical discharges are produced between the tip or lateral surface proximate the tip of the tool electrode 1 and the workpiece 2 to successively remove material from the latter.

As previously indicated, the machining fluid is preferably distilled water of a specific resistivity ranging in the order of 10^3 to 10^5 ohm-cm. It has been noted that with the water machining fluid of that type, a surface finish markedly superior to that obtainable with kerosine results. Thus, an R_{max} is halved under an identical pulse condition. For example, with a pulse on-time τ_{on} of 1 microsecond, a pulse off-time τ_{off} of 3 microseconds and a pulse peak current I_p of 20 amperes, a surface roughness of 3 to 4 microns R_{max} is obtainable with the water machining fluid.

The motors 4, 5 and 106 are each a pulse motor or a DC motor equipped with an encoder. Drive pulses may be applied to each pulse motor at a fixed frequency but preferably at a frequency controlled to vary as a function of the gap state so that the rate of feed along each axis may vary as a function of the latter as described previously.

During the machining operation, a high-frequency vibration is imparted to the tool electrode 1 by means of an ultrasonic oscillation arrangement 9, 10 and 11 as previously shown. The machining stability is thus markedly enhanced and a removal

rate as high as three-times as great as that without electrode vibration is obtainable.

5 The tool electrode 1 tends to wear from its tip portion serving as a machining face, and the wear is particularly noticeable with a thinner electrode which is positioned in a machining relationship with a wide workpiece machinable surface.

10 The tool-wear sensing and compensation system operates as follows. The timer 34 provides periodically a timing signal which is applied to the AND gates 32 and 33 to enable them. During the enabling period, the signal pulses from the input pulser 30 are passed through the gate 32 and applied to the counter 35 for counting thereby. Meanwhile, 15 the signal pulses representing gap discharge pulses issued from the pulser 31 are passed through the gate 33 and applied to the counter 36 for counting thereby. When the first counter 35 counts up a number of input or source pulses preset therein, it 20 provides an output signal. Meanwhile, when the second counter 36 counts up a number of gap discharge pulses preset therein, it provides an output signal. These two output signals are fed to the divider 38 which then provides an output signal representing the 25 ratio or difference of these two counter outputs.

30 As the electrode 1 wears, the gap spacing G between the tool electrode 1 and the workpiece 2 is widened so that machining discharges occur with progressively increasing difficulty. This causes a decrease in the number of discharges relative to a substantially fixed number of source pulses furnished from the power supply 8 per unit time. Consequently, the signal pulser 31 provides a reduced number of signal pulses which are counted by the counter 36. 35 The divider 38 then compares the outputs of

counters 35 and 36 and provides a ratio signal which is proportional to the tool wear. When the ratio exceeds a threshold value, the discriminator 39 furnishes a signal which actuates the control circuit 40 which in turn furnishes a drive pulse, the latter being applied to the compensation feed motor 114. The counters 35 and 36 are then self-cleared and become ready for a next counting cycle. At this stage, the gates 32 and 33 continue to be enabled by the timing signal from the timer circuit 34 and the input pulses and the gap discharge pulses are allowed to pass to reach the counters 35 and 36, respectively, for counting thereby. The divider 38 continues to provide the ratio signal to permit the control circuit 39 to continually operate to cause the motor 114 to continually be driven to perform the compensation feed for the tool electrode 1.

As the gap spacing is reduced as a result of wear compensation feed by the motor 114, the ratio of gap discharge pulses to source pulses will be increased. When the ratio rises above the threshold value, the discriminator 39 is deactuated to cease driving the motor 114. The gates 32 and 33 are disabled upon expiration of the timing signal from the timer circuit 34 to block the signal pulses from the pulsers 30 and 31.

FIG. 11 shows a further embodiment of the invention in which an automatic tool changer unit 41 is provided. The unit 41 comprises a tool storage magazine 42 in the form of a disk on which are removably mounted a plurality of tool electrode units 1a, 1b, 1c ... with different electrode configurations which may be round, triangular, square etc and/or with difference sizes, each unit having an ultrasonic vibrator assembly 9,10 supporting the

electrode body 1 and adapted to be carried by the tool head 18 as previously described. The magazine 42 is rotated in response to a signal furnished from a controller successively into given tool changing positions. A tool changing arm 44 with a grip is also provided and responds to a signal from the controller 43 to collect from the machine head 18 a used electrode unit, say, 1a and to transfer it to the magazine 42, and then to remove a next programmed electrode unit, say, 1b from the latter for mounting on the machine head 18 to permit a subsequent machining step to be performed thereby on the workpiece 2.

A further arrangement shown in FIG. 12 makes use of a tool vibration assembly to inspect the machining accuracy of a workpiece prior to, during and subsequent to, a given electrical machining operation. As previously described, a tool electrode 1 is securely supported at a coupling 115 by an ultrasonic horn 9 having a transducer 10 attached thereto, the transducer being energized by a high-frequency supply 11 of a variable output to permit the amplitude of a vibration imparted to the tool electrode to be variably adjusted. The horn 9 is secured to the machine head 18 which is displaceable vertically along the Z-axis by the motor 106, while the worktable 3 carrying the workpiece 2 is displaced in an X-Y plane by the motors 4 and 5. Thus, a three-dimensional machining displacement is effected by motors 4, 5 and 106 as in the embodiments already described under preprogrammed instructions of the numerical controller 7.

In this arrangement, a monitoring power supply 50 independent of the machining power supply 8 is connected to the machining gap between the tool

electrode 1 and the workpiece 2 via a sensing resistor 51 of which tapped terminals are connected to a discriminator circuit 52. A pictorial display 53 is connected on one hand to the output of the
5 discriminator circuit 52 and on the other to an output of the numerical controller 7.

Assume that a given three-dimensional machining operation has been performed on the workpiece 2. The tool electrode 1 is then vibrated
10 at a frequency in a range, say 2 to 3 kHz or 10 to 50 kHz and with an amplitude in a range, say 0.1 to 1 micron or 5 to 10 microns by actuating the vibration assembly 9, 10 and 11, and the tool electrode 1 is caused to move over the machined contour 2a of the
15 workpiece 2 three-dimensionally, by operating the feed motors 4, 5 and 106, along the same path as has been followed during the machining operation under the command signals of the numerical controller 7. The frequency and the amplitude of the tool vibration
20 are held constant at values depending upon a particular degree of precision of inspection desired. The vibrating tool electrode 1 will then be juxtaposed with the workpiece 2 across a minute average gap spacing which may optionally be filled
25 with the machining fluid. The tool electrode 1 thus makes and breaks a light contact with the workpiece surface 2a and, given a fixed frequency and amplitude of vibration, the electrical resistance can be detected as a function of the neutral and hence
30 effective position of the tool electrode 1 relative to the workpiece surface 2a. The time of approach or contact varies proportionally to the average proximity and is closely reflected in the electrical resistance monitored.

35 The discriminator circuit 52 may have one

or more threshold levels corresponding to a desired gap spacing or spacings and hence a degree or degrees of machining precision desired, and provides discriminated outputs which are applied to the pictorial display unit 53.

The display unit 53 acquires position signals corresponding to the programmed three-dimensional (X,Y,Z) machining displacement of the tool electrode 1 relative to the workpiece 2 and, corresponding to each of these positions, registers a discriminated machining precision signal received from the discriminator circuit 52.

FIG. 13 shows a certain form of the pictorial display unit 53 shown in FIG. 12. A recording head 54 supports a recording pen 55 in engagement with a record paper 56 which is fixed in position, the head being carried by an arm 57 which is displaced in exactly the same way as the tool electrode 1 is displaced relative to the workpiece 2 along X- and Y-axes. The head 54 stores within separate chambers 54a, 54b and 54c three different colored inks, say, red (R), yellow (Y) and blue (B) and has separate valves associated respectively therewith, the valves being actuated selectively by output signals of the discriminator circuit 52 representing different degrees of machining precision. Thus, for example, when the discriminator ascertains a gap resistance in the range between 1 and 50 ohms, the valve (R) is opened to supply the red ink to the pen 55. When a gap resistance in the range between 51 to 100 ohms is ascertained, the valve (Y) is opened to supply the yellow ink to the pen 55. When a gap resistance is in the range between 101 and 300 ohms, the valve (B) is opened to supply the blue ink to the pen 55. Thus, on the

record paper 56, a curve 58 is drawn by the pen 55 corresponding to the two-dimensional relative machining path between the tool electrode 1 and the workpiece 2 and may vary locally in colors, depending upon the degrees of precision of the machined contour on the workpiece 2 from position to position. The portions of the curve drawn in blue represent the lowest degree of machining precision, the portion drawn is yellow represent the medium degree of machining precision and portions drawn in red represent the highest degree of machining precision. A highly accurate inspection of the machining precision is thus obtained on the record paper 56 and can be used to perform a subsequent finishing of the machined workpiece 2.

FIG. 14 shows another embodiment of the invention including means for dressing the tool electrode during a given course of machining operation. In this system, a tool electrode 501 is shown secured to a tool holder 521 by means of a chuck 515 and an O ring 515a, and the tool holder 521 is fixedly mounted to a stem or machine head 518 which is displaceable vertically or along the Z-axis. The tool electrode 501 and the tool holder 521 are coaxially hollow and the latter is formed with a fluid inlet 521a through which a machining liquid, preferably a distilled water of a specific resistivity previously indicated, is furnished under a high pressure from a supply unit including a pump 560a. The machining liquid thus passes interiorly through the tool holder 521 and the tool electrode 501 and is delivered under an elevated pressure in excess of 5 Kg/cm^2 , preferably, greater than 10 Kg/cm^2 and more desirably greater than 25 Kg/cm^2 , into the machining gap G formed between the latter

and a workpiece 502 which is securely mounted in a worktank 561. The machining liquid collected in the worktank 561 is returned to the fluid supply unit via a pump 560b. The worktank 561 is carried on a
5 worktable 503 which is displaceable by X-axis and Y-axis motors (not shown in this FIGURE) to displace the workpiece 502 in an X-Y plane as previously described.

10 An ultrasonic vibrator 562 is here attached to a plate 518a of the stem 518 and is energized by a high-frequency power supply 562a to generate an ultrasonic vibration which is transmitted via the machining liquid to the region of the machining gap G and via the tool holder 521 to the tool
15 electrode 501.

An EDM power supply includes a DC source 508a and a power switch 508b connected in series with the tool electrode 501 and the workpiece 502. The switch 508b is energized by a signal pulser 563 via a
20 line 563a to pulse the output of the DC source 508a so that a succession of machining pulses are applied across the machining gap G between the tool electrode 501 and the workpiece 502.

The electrode dressing unit is generally
25 designated at 564 and includes a belt electrode 564a of a width of 1 to 2 cm and a thickness of about 0.1 mm which is axially fed from a supply reel 564b and collected on to a takeup reel 564c, the reels 564b and 564c being mounted on a bracket 564d. The path
30 of travel of the belt electrode 564a between the supply and takeup reels 564b and 564c includes a current conducting roller 564e having a brush 564f, brake rollers 564g and 564h, a reference electrode table 564i, guide rollers 564j, 564k and 564l, a
35 capstan 564m and a pinch roller 564n. The

capstan 564m is driven by a motor (not shown) to axially advance the belt electrode 564a along these elements. A dressing power supply generally designated at 565 includes a DC source 564a and a power switch 565b connected to the tool electrode 501 (via tool holder 521) and the brush 564f. The power switch 565b is energized by the signal pulser 563 via a line 563b to pulse the output of the DC source 565a, thereby supplying a succession of a dressing current pulses between the tool electrode 501 and the belt electrode 564a when positioned adjacent one another for electroerosive dressing purposes.

FIG. 15 shows a modified arrangement for imparting a vibration to the tool electrode 501. Here, the tool holder 521' is composed of a magnetostrictive substance and has an energizing coil 562' wound thereon, the coil being energized by a high-frequency power supply 562'a. In this arrangement, a control unit 566 is provided and operated by a numerical controller (not shown in this FIGURE), and is also responsive to a voltage drop detected at a resistor 566a in series with the machining power supply 508a, and to a voltage drop detected at a resistor 566b in series with the dressing power supply 565a. Amplifiers 566c and 566d are connected between the resistor 566a and the control unit 566 and between the resistor 566b and the control unit 566, respectively. In this arrangement, the signal pulser of FIG. 14 is divided into a first pulser 563' for energizing the switch 508b and a second pulser 563" for energizing the switch 565b.

The control unit 566 operates in response to the numerical controller and monitors through the amplifier 566c and 566d the machining current and the

dressing current respectively, and acts on the three-dimensional machining drive motors, the signal pulsers 563' and 563" and the high-frequency power supply 562a so that these individual functions may be performed at an optimum efficiency.

The high-frequency vibration applied to the tool electrode is used to stabilize the machining condition as described previously and may at the same time serve to minimize, and to improve the uniformity of, the wear of the tool electrode 501. Nevertheless the wear of the tool electrode 1 and its irregularity to a certain extent is not avoidable. To perform the dressing function, the unit 564 is thus required. As shown in FIG. 16, the reference table 564i is then displaced below the tool electrode 501 while the capstan 564m is driven to axially displace the belt electrode 564a so that the latter moves in contact with the upper surface of the reference table 564i. The pulser 563 via the line 563b or the pulser 563" is operated to alternately turn on and off the power switch 565b and the tool electrode 501 is displaced from the position 501' to the position 501" and held there for a predetermined period so that the machining face 501a' thereof which has been worn irregularly is electroerosively dressed into a flat surface 501a".

In a modified arrangement shown in FIG. 17, the tool holder 621 formed with a fluid supply plug 621a and supporting the tool electrode 601 in the manner previously shown, is carried by a horizontally extending arm 618 and is displaceable vertically therewith relative to a column 618a of the machine. The tool electrode 601 as in the previous arrangement is tubular and may be of an outer diameter of 0.5 mm to 10 mm.

As in the previous arrangement an electrode dressing unit 664 is shown disposed in the worktank 561 and has a structure generally as shown in FIG.

18. The unit 664 comprises a dressing electrode 664a in the form of a continuous wire or belt which is fed from a supply reel 664b and collected into a receptacle 664c upon cutting into pieces 664a' by means of a cutter 664o after traveling over guide rollers 664j, 664k and 664l, a capstan 664m and a pinch roller 664n. In the path of travel of the dressing electrode 664a there is provided a preliminary dressing chip 664q between the guide rollers 664k and 664l. A spring brake 664r is attached to a bracket portion 664s of the preliminary dressing chip 664q to apply a braking force on to the reel 664b which is carried by a pair of support rollers 664t and 664u. These elements are securely arranged in the casing 664v.

The casing 664v is open-topped to allow installation and removal of the reel 664b and stretching of the wire or belt electrode 664a over the guide elements, and has the bracket 664s secured at an upper region thereof. The bracket 664s having the preliminary dressing chip 664q mounted thereon is formed along its upper surface with a guide groove for accepting the wire or belt electrode 664a and the bracket 664s is, as shown in FIG. 19, covered along part of its upper surface with an insulating coating 664w to protect it against electrical discharge erosion.

The wire or belt electrode 664a is drawn from the supply reel 664b, guided over rollers 664j and 664k, passed through the guide groove on the bracket 664s, guided over the roller 664l, passed between the capstan 664m and the pinch roller 664n

and eventually cut by the cutting unit 664o into pieces 664a which are collected into the receptacle 664c.

5 The reel 664b is rotatably supported by the rollers 664t and 664u and is given an adequate braking torque through the spring brake 664r. Accordingly, with the capstan 664m driven by a motor (not shown), a tension greater than a desired minimum is kept always applied to the wire or belt electrode 664a.

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15 The upper face of the chip 664q and the wire or belt electrode 664a passing through the guide groove on the bracket 664s are arranged to be precisely parallel with a horizontal reference machining plane of the machine.

20 The electrode dressing unit 664 is operated as follows. The worktable 503 is displaced to position the chip 664q so as to come immediately below the tool electrode 601 and the pulser 563" is actuated. The pump 560a is driven to allow the machining liquid to be delivered to the region of the chip 664q while the arm 618 is displaced downwardly to bring the tool electrode 601 from a position 601' to a preliminary dressing position 601". The chip 664q then is capable of rough-dressing the worn machining surface 601a. Subsequently, the downward movement of the arm 618 is halted and the worktable 503 is driven to finish-dress the tool electrode 601 while it is being displaced from the position 601" to a position 601"' as shown in FIG. 19 over the dressing electrode 664a.

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35 In FIG. 20 there is shown a further system for detecting the wear of a tool electrode and controlling the three-dimensional machining feed so as to compensate for the tool wear. In this system

as well, the power supply generally designated at 708 comprises a DC source 708a and a power switch 708b connected in series with the tool electrode 701 and the workpiece 702. The switch 708b is controlled by a signal pulser 708c via a line 708d to pulse the output of the source 708a, thereby applying a succession of machining pulses between the tool electrode 701 and the workpiece 702. The signal pulser 708c acts also via a line 708e on a switch 719b which is connected in series with the DC source 708a and a resistor 719a. A gap detecting circuit 719c is responsive to the voltage drop across the resistor 719a when each signal pulse is applied to the switch 719b to connect the resistor 719a to the machining gap G.

The worktable (not shown in this FIGURE) carrying the workpiece 702 is displaced three-dimensionally along an X-axis, Y-axis and Z-axis by motors 704, 705 and 706 having encoders 704a, 705a, and 706a respectively, as described previously. A clock pulser 770 is provided to furnish a train of clock pulses which are properly distributed by a numerical controller 707 to drive the X-axis, Y-axis and Z-axis motors 704, 705 and 706 in a manner well known in the art. To this end, distributory networks 771, 772 and 773 as well as amplifying polarity-determining networks 774, 775 and 776 are provided in the respective input channels for the motors 704, 705 and 706 as shown.

The signal pulser 708c issues high-frequency signal pulses as shown in FIG. 21(A) along the line 708d and low-frequency signal pulses as shown in FIG. 21(B) along the line 708e, these separate trains of pulses being applied to the switch 708b and the switch 719b respectively. Each signal

pulse issued along the line 708e (FIG. 21(B)) is made synchronous to any one of signal pulses issued along the line 708d.

5 In the absence of any pulse along the line 708e, the switch 708b is turned on and off by signal pulses issuing along the line 708d to apply a series of high-voltage pulses across the tool electrode 701 and the workpiece 702, the pulses resulting in electrical discharges at the gap whose voltage and current waveforms are shown at A in FIGS. 21(C) and 10 21(D), respectively. In the presence of a pulse issuing along the line 708e synchronously with a pulse along the line 708d, both the switches 708b and 719b are turned on and the source 708a is shunted by 15 the resistor 719a. As a consequence, the gap pulse has a reduced voltage and current magnitudes as shown at B in FIGS. 21(C) and 21(D), which are incapable of bringing about a machining discharge under a normal gap condition. When, however, the gap state is 20 unsatisfactory, an increased current develops through the machining gap G and is detected as an increased voltage drop at the sensing resistor 719a.

Referring to FIGS. 22 to 24 it is interesting to observe how the tool electrode suffers 25 wear during an EDM operation in which the tool electrode 701 in the form of a cylinder is used to machine a groove 702a of a depth D extending in the direction of an X axis. It is seen that the lateral gap spacing g in the advance direction along the X-axis is smaller than the gap spacing G in the 30 vertical direction or along the Z-axis, and material removal from the workpiece 702 proceeds predominantly along a semi-cylindrical surface, and also to a lesser extent along a base portion, of the tool 35 electrode 701 in the advance direction, leaving a

machined surface 702a therein. As a result, an irregular wear 701a with an inclination develops on the electrode surface. The configuration of this wear which develops when the tool electrode is advanced in the single direction or along the X-axis is also illustrated in FIG. 25 and becomes complex when the direction of its advance is variously altered.

When the tool electrode 701 is caused to descend or move in the downward direction (along the Z-axis) at a point Q in a sequence of feed paths as shown in FIG. 26 and then to move back so that an increased depth 702c is achieved, an irregular machined inclination 702d tends to develop on the surface 702c as shown in FIG. 24. It is also seen that there is a difference in the effective gap spacing g between the state in FIG. 22 and that in FIG. 23. An irregular wear of the tool electrode is also caused on its cylindrical surface as well as on its base portion as shown.

These problems are overcome by compensatorily feeding the tool electrode by a distance d while it is being advanced from a point P' to Q' in FIG. 27 in accordance with a predetermined program when a change in the machining state is not detected by the detector 719c so that the unworn portion 701b on the base of the tool electrode shown in FIG. 24 may be positively machined or worn.

It is also advisable to adopt one of the weaving feed patterns as shown in FIGS. 8 and 9. In FIG. 9, positions A, B, C, D and E and arrows associated therewith illustrate a sequence of paths to be followed.

With reference back to FIG. 20, a control system for governing stepping motors 704 and 705 and

a control system for governing the stepping motor 706 are mutually separate although associated. The former is operated under a numerical-control program to effect a contouring feed in an X-Y plane while
5 being responsive to the detector 719c to effect the rate of contouring feed so that the gap spacing g may be properly held constant. On the other hand, the latter is operated to effect a descending motion (of a distance D) at a turning point and additionally to
10 effect small up- and down-feeds in a unidirectional or weaving wear-compensatory movement along a Z-axis. In this manner, the wear of tool electrode 701 is highly equalized to establish the state shown in FIG. 22 as will be appreciated from the schematic diagrams
15 of FIGS. 24 to 27 and FIGS. 8 and 9.



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CLAIMS

1. A method of machining a cavity in a
workpiece by electroerosion with a tool electrode
having at its free end portion a machining surface
5 contour of which the shape is generally independent
of the shape of the desired cavity, said method
comprising the steps of:
- axially juxtaposing said tool electrode
with the workpiece to position said machining surface
10 contour in spaced juxtaposition therewith across a
machining gap flooded with a machining liquid;
imparting a high-frequency vibration to
said tool electrode whereby to vibrationally
fluctuate said machining surface contour and thereby
15 dynamically enlarge the effective machining area
thereof by a small amount determined by the amplitude
of said high-frequency vibration;
- applying a succession of electrical pulses
between said vibrating tool electrode and the
20 workpiece across the machining gap to effect
successive localized electrical discharges jumping
between the workpiece and said machining surface
contour brought proximal thereto by the vibrational
fluctuations, thereby electroerosively removing
25 material from the workpiece adjacent said
vibrationally fluctuating machining surface contour
providing the said enlarged effective machining
area; and
- effecting a multi-axial relative
30 displacement of said vibrating tool electrode and
said workpiece along three coordinate axes which
include a pair of coordinate axes defining a plane
substantially orthogonal to the longitudinal axis of
said tool electrode and a coordinate axis
35 substantially orthogonal to said plane, while



simultaneously maintaining the average width of said machining gap substantially constant, thereby three-dimensionally machining said workpiece with said vibrationally fluctuating machining surface contour to form the desired cavity in the workpiece.

2. The method defined in Claim 1 wherein said tool electrode is composed of copper, a copper alloy, silver-tungsten or graphite.

3. The method defined in Claim 2 wherein said tool electrode has a diameter or thickness in the range 0.05 to 1 mm.

4. The method defined in Claim 2 wherein said tool electrode has a diameter or thickness p mm in the range $1 < p < 3$.

5. The method defined in Claim 2 wherein said tool electrode has a diameter or thickness p mm in the range $3 < p < 5$.

6. The method defined in any one of the Claims 2 to 5 wherein said machining liquid is water having a specific resistivity in the range 1×10^3 to 5×10^6 ohm-cm.

7. The method defined in any preceding claim wherein said vibration has a frequency in the range 1 to 100 kHz.

8. The method defined in Claim 7 wherein said frequency is in the range 10 to 50 kHz.

9. The method defined in any one of the Claims 1 to 6 wherein said vibration has a frequency in the range 100 kHz to 100 MHz.

10. The method defined in Claim 7, Claim 8 or Claim 9 wherein said vibration has an amplitude in the range 1 to 50 microns.

11. The method defined in Claim 10 wherein said amplitude is in the range 1 to 10 microns.

12. The method defined in any preceding claim,

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wherein said multi-axial relative displacement of said vibrating tool electrode and the workpiece is effected incrementally, with increments of displacement of the order of 1 micron.

5 13. A method as defined in any preceding claim, further comprising the steps of: detecting machining wear of said tool electrode along said machining surface contour to produce a signal representing said machining wear and, in response to said signal,
10 axially advancing said tool electrode, independently of said multi-axial relative displacement, so as to maintain the average gap width substantially constant as said wear progresses.

14. The method defined in Claim 13 wherein said
15 machining wear is detected by sensing a change in the mode of said vibration imparted to said tool electrode to produce said signal.

15. The method defined in Claim 14 wherein said
20 change in the mode of vibration is sensed as a change in the frequency of said vibration.

16. The method defined in Claim 14 wherein said change in the mode of vibration is sensed as a change in the amplitude of said vibration.

17. The method defined in Claim 14 wherein said
25 change in the mode of vibration is sensed as a change in the energy of said vibration.

18. The method defined in claim 13 wherein said
30 machining wear is detected by sensing an echo resulting from the reflection of said vibration by said workpiece to produce said signal.

19. The method defined in Claim 13 wherein said machining wear is detected by sensing a sonic or ultrasonic wave resulting from electrical discharges at said machining gap to produce said signal.

35 20. The method defined in Claim 13 wherein said



machining wear is detected by monitoring the ratio of the number of electrical discharges to the number of input machining pulses applied to said gap per a given time period to produce said signal.

5 21. An apparatus for machining a cavity in a workpiece by electroerosion, comprising:

10 a tool electrode with a machining surface contour of which the shape is generally independent of the shape of the desired cavity, which electrode is arranged to be juxtaposed with the workpiece so as to position said machining surface contour in spaced juxtaposition therewith across a machining gap flooded (when in operation) with a machining liquid;

15 means for imparting a high-frequency vibration to said tool electrode whereby to vibrationally fluctuate said machining surface contour and thereby dynamically enlarge the effective machining area thereof by a small amount determined by the amplitude of said high-frequency vibration;

20 power supply means electrically connectable to said tool electrode and said workpiece for applying electrical pulses between said vibrating tool electrode and said workpiece across the machining gap to effect successive localized electrical discharges through said gap between said
25 workpiece and said machining surface contour brought proximal thereto by the vibrational fluctuations, thereby electroerosively removing material from the workpiece adjacent said vibrationally fluctuating
30 machining surface contour providing the said enlarged effective machining area; and

35 feed means for effecting a multi-axial relative displacement of said tool electrode and said workpiece along three-coordinate axes which include a pair of coordinate axes defining a plane

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substantially orthogonal to the longitudinal axis of said tool electrode and a coordinate axis substantially orthogonal to said plane, while simultaneously maintaining the average width of said machining gap substantially constant, whereby said vibrationally fluctuating machining surface contour is swept three-dimensionally over the surface of said workpiece in which the desired cavity is to be formed ~~at least in part by electrical discharges.~~

10 22. Apparatus as defined in Claim 21, wherein said tool electrode is composed of copper, a copper alloy, tungsten, silver-tungsten, or graphite.

23. Apparatus as defined in Claim 21 or Claim 22, wherein said tool electrode has a diameter or thickness p mm, where p lies in one of the ranges $0.05 < p \leq 1$, $1 < p \leq 3$, and $3 < p \leq 5$.

24. Apparatus as defined in any one of the Claims 21 to 23, wherein when said apparatus is in operation said machining gap is flooded with water having a specific resistivity in the range 1×10^3 to 5×10^6 ohm-cm.

25. Apparatus as defined in any one of the Claims 21 to 24, wherein said vibration imparting means is arranged, when in operation, to vibrate said tool electrode at a frequency lying in the range 1 kHz to 100 kHz.

26. Apparatus as defined in any one of the Claims 21 to 24, wherein said vibration imparting means is arranged, when in operation, to vibrate said tool electrode at a frequency in the range 100 kHz to 100 MHz/

27. Apparatus as defined in Claim 25 or Claim 26, wherein said vibration imparting means is arranged to impart to said tool electrode a vibration having an amplitude in the range 1 to 50 microns.



28. Apparatus as defined in any one of the claims 21 to 27, wherein for maintaining the average gap width substantially constant said feed means includes means for effecting said multi-axial
5 relative displacement of said tool electrode and said workpiece regardless of the occurrence of machining wear of said tool electrode along said machining surface contour to form a said desired cavity, and auxiliary feed means for effecting an additional feed
10 of said tool electrode in a direction and by an amount such as to substantially compensate for said machining wear occurring at said electrode machining surface contour during the machining operation.
29. Apparatus as defined in Claim 28, including
15 means for detecting, during a machining operation, machining wear of said tool electrode machining surface contour, and for supplying to said auxiliary feed means a signal dependent on the amount of said machining wear, said auxiliary feed means being
20 responsive in a wear-compensating way to effect said additional feed of said tool electrode.
30. Apparatus as defined in claim 29, wherein said wear detecting means senses, and produces in response thereto as said wear dependent signal a
25 signal dependent on, a change in a mode of said vibration imparted to said tool electrode.
31. Apparatus as defined in Claim 30, wherein said change in the mode of vibration is sensed as a change in the frequency of said vibration.
- 30 32. Apparatus as defined in Claim 30, wherein said change in the mode of vibration is sensed as a change in the amplitude of said vibration.
33. Apparatus as defined in Claim 30, wherein said change in the mode of vibration is sensed as a
35 change in the energy of said vibration.

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34. Apparatus as defined in claim 29, wherein said wear detecting means senses, and produces in response thereto as said wear dependent signal a signal dependent on, the delay in receiving echoes resulting from the reflection of said vibrations by said workpiece.

35. Apparatus as defined in Claim 29, wherein said wear detecting means senses, and produces in response thereto as said wear dependent signal a signal dependent on, sonic or ultrasonic waves resulting from electrical machining discharges at said machining gap.

36. Apparatus as defined in Claim 29, wherein said wear detecting means senses, and produces in response thereto as said wear dependent signal a signal dependent on, the ratio of the number of electrical discharges to the number of input machining pulses applied to said gap per a given time period.

37. Apparatus as defined in any one of the Claims 21 to 36, and including dressing means for placing periodically during a machining operation in juxtaposition with the machining surface of said tool electrode, said dressing means being arranged, when so placed, to dress said machining surface of the tool electrode so as to restore it to a desired form in readiness for continuation of the machining operation.

38. Apparatus as defined in Claim 37, wherein said dressing means includes an electroerosion machining means arranged to effect dressing of said machining surface contour of said tool electrode by an electroerosion process.

39. Apparatus as defined in any one of the Claims 21 to 38, wherein said vibration-imparting



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means includes: an ultrasonic horn assembly comprising an electromechanical transducer and an amplifier horn having one end of greater cross section attached to said transducer and the other end of smaller cross section adapted to support said tool electrode so as to project therefrom and to extend substantially coaxially with said horn; means for supporting said ultrasonic horn assembly to bring said tool electrode machining surface contour into spaced juxtaposition with the workpiece across said machining gap; and means for electrically energizing said electrochemical transducer to impart said high-frequency vibrations to said tool electrode.

40. Apparatus for machining a cavity in a workpiece by electroerosion, substantially as hereinbefore described with reference to, and as illustrated in, any single figure or group of associated figures of the accompanying drawings.

41. A method as defined in any one of the Claims 1 to 20, including the step of periodically during a machining operation bringing the machining surface contour of said tool electrode and a dressing means into juxtaposition, and causing said dressing means to thereupon dress said machining surface whereby to restore that machining surface contour to a desired form in readiness for a continuation of the machining operation.

42. A method of machining a cavity in a workpiece by electroerosion, substantially as hereinbefore described with reference to, and as illustrated by, any single figure or group of associated figures of the accompanying drawings.

43. A workpiece having a cavity formed therein by a method according to any one of the Claims 1 to 20, 41 and 42, or by means of an apparatus according to any one of the Claims 21 to 40.