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(54) IMPROVEMENTS RELATING TO ELECTRICAL DISCHARGE MACHINING

(71) We, INOUE-JAPAX RE-
SEARCH INCORPORATED of 5289 Aza
Michimasa, Nagatsudamachi, Midoriku,
Yokohamashi, Kanagawaken, Japan, a
Japanese company, do hereby declare the
invention for which we pray that a patent
may be granted to us and the method by
which it is to be performed to be particularly
described in and by the following state-
ment:-

The present invention relates to electric-
al-discharge machining (EDM) and, more
particularly, to a method of, and an appar-
atus for electrical-discharge machining uti-
lizing a wire electrode caused to travel
through a machining zone in a workpiece re-
latively displaced thereto and transversely
to the direction of travel of the wire elec-
trode.

In electrical-discharge machining of this
type, which is commonly called "wire-cut
EDM" or "travelling-wire EDM", the wire
electrode held under tension is displaced to
travel through a machining zone to be cut in
the workpiece and flushed with a machining
liquid which is usually distilled water or a
liquid dielectric and a series of electric
pulses are applied across the machining gap
between the wire electrode and the work-
piece to effect time-spaced electrical dis-
charges between them to remove material
from the workpiece.

Typically, the wire electrode is fed from a
supply reel and, passing through the
machining zone between a pair of support
and guide members which act to stretch the
travelling wire electrode thereacross, fed to
a take-up reel by a drive motor, the tension
of the wire electrode between the guide
members being controlled by a suitable
brake mechanism arranged at a location or
locations in the travelling path thereof.

The transverse displacement of the work-
piece relative to the travelling wire elec-
trode to follow the material removal is

usually effected automatically by a control
system under programmed instructions
which define a predetermined cutting path
or pattern.

In order to achieve a satisfactory machin-
ing accuracy, it is necessary to use a wire
electrode as thin as 0.05 to 0.5 mm in dia-
meter. This requirement has heretofore im-
posed restrictions in machining performance.
Such thin wire, given a desired tension, tends
to be broken when arcing or short-circuiting
with the workpiece takes place occasionally.
Thus, the machining efficiency or removal
rate achievable has been limited to an un-
satisfactory level since wire breakage is un-
avoidable when an enhancement of
machining or an increase in the rate of rela-
tive displacement is attempted.

It is therefore an object of the present in-
vention to provide a method of electrical-
discharge machining of the type described
whereby the occurrence of the breakage of a
wire electrode is substantially eliminated
and an increased machining efficiency or re-
moval rate without sacrifice of machining
accuracy is obtained.

Another object of the invention is to pro-
vide an apparatus for carrying out the
method.

In accordance with the present invention
in a first aspect thereof, there is provided a
method of electrical discharge machining of
a conductive workpiece with a continuously
axially travelling wire electrode, wherein:
said travelling wire electrode and the work-
piece are relatively displaced transversely to
the direction of travel of the wire electrode
and define a machining gap between them; a
machining liquid is supplied to said gap; a
series of electrical pulses are applied across
the workpiece and the electrode to generate
machining discharges in the gap to remove
material from the workpiece, and a vibra-
tion is imparted to the travelling wire elec-
trode in the region of said gap and in a direc-

tion transverse to the areas of the travelling wire electrode, said vibration being a frequency not lower than 100 Hz.

5 It has now been found that by imparting such a vibration to the travelling wire electrode, it is possible to practically eliminate the breakage of the wire electrode and to permit steady machining to proceed thereby enabling the removal rate and machining efficiency to be markedly enhanced.

10 The frequency of the vibration is preferably in a range between 1 and 50 KHz and the amplitude is preferably in a range between 1 and 5 microns but may be as large as slightly smaller than the size of the machining gap, say 50 microns.

15 The vibration is imparted to the wire electrode in a direction transverse to the axis of the travelling wire electrode so that an undulating oscillatory motion with more than two nodes and antinodes or loops is produced in the wire travelling between the two guide members positioned at opposite sides with respect to the workpiece.

20 By imparting a vibration or undulating oscillatory motion to the stretched wire electrode, axially travelling between a pair of wire guide members, it appears that a pumping action is generated in the machining zone to facilitate removal or carrying away therefrom of machined products, i.e. chips and gases and, of even more importance, a dispersive production of successive discharges in the machining zone over the entire workpiece thickness is assured, thus not permitting the discharges to be concentrated on a single point or region of the wire electrode travelling through the workpiece. It is also conceivable, though possibly less important that the contact resistance on the guide members and other contact portions with the wire electrode is substantially reduced.

45 In accordance with the present invention, in a second aspect thereof, electrical discharge machining apparatus of the kind having a wire electrode which is arranged to travel continuously axially through a machining zone of a conductive workpiece, for performing a method according to said first aspect, comprises: vibrator means for imparting a vibration at a frequency not lower than 100 Hz to the wire electrode in the region of said machining zone and in a direction transverse to the axis of the wire electrode; displacement means for causing said relative transverse displacement of said wire electrode and said workpiece; means for applying said electrical pulses across the workpiece and the electrode; and means for supplying said machining fluid to said gap.

60 The vibrator means is preferably in contact with a wire guide member for the electrode and may be an electro-magnetic or a sonic or ultrasonic vibrator. The vibrator

means may be a magnetostrictive or piezoelectric vibrator.

A control system is preferably provided, in operation of the apparatus, to respond to the machining state in the gap and to cause a parameter of the vibration to be modified in response to the state. The vibrator means are preferably arranged to be cooled by a coolant fluid.

70 In use of the apparatus, the machining liquid is advantageously supplied to the wire by flowing through the location where the vibrating end of the vibrator arrangement comes in contact with the wire so that the heat generated at the vibrating body is sufficiently dissipated to avoid a detrimental heating of the wire electrode.

75 It is also preferable to keep the plane of the wire vibration coincident with the direction of the relative displacement of the workpiece to the travelling wire electrode.

80 These objects, features and advantages of the invention will become more readily apparent from the following description of embodiments thereof with reference to Examples I to IV and the accompanying drawings, the latter being given by way of example only, and in which:-

85 Fig. 1 is a diagrammatic cross-sectional view of an apparatus embodying the invention;

90 Fig. 2 is a diagrammatic cross-sectional view of another embodiment of the invention;

100 Figs. 3 (a), 3(b), 3(c) and 3(d) are enlarged diagrammatic cross-sectional views of certain different embodiments of a vibrator arrangement according to the invention;

105 Fig. 4 is a diagrammatic, partly cross-sectional view illustrating another embodiment of the invention;

110 Fig. 5 is a similar view of a further embodiment of the invention including a unit controlling the mode of operation of the vibrator arrangement in response to the condition in the machining zone.

115 Figs. 6 and 7 are diagrammatic views illustrating the wire electrode vibrating in juxtaposition with the workpiece;

120 Fig. 8 is a diagrammatic cross-sectional view illustrating a still further embodiment of the invention including means for cooling the body of the vibrator;

125 Fig. 9 is a graphical representation showing several machining characteristics vs. the resistance of machining liquid to show a preferred range of the latter for better machining results;

130 Fig. 10 is likewise a graphical representation showing the change of resistance of machining liquid with respect to lapse of time;

Fig. 11 is a diagrammatic cross-sectional view of a modified embodiment of the invention including a unit designed to opti-

mize the mode of operation of the wire vibrator; and

Figs 12 (a), 12(b) and 12(c) are diagrammatic views illustrating a wire electrode vibrating with different numbers of nodes and antinodes or loops.

Referring now to Fig. 1, a wire electrode 1 is shown fed from a supply reel 2 and wound on a take-up reel 3 while being supported and guided by a pair of support and guide members 4 and 5. The travelling displacement of the wire electrode 1 is effected by means of a motor (not shown) with a suitable brake mechanism (not shown) being provided to cause the wire 1 to travel under a controlled tension between the support and guide members 4 and 5 and through the machining gap formed between the wire 1 and a workpiece 6 juxtaposed therewith. A pair of nozzles 7 and 7' are provided for supplying a machining liquid the machining gap, across which a series of electric pulses are applied from a power source (not shown) to effect machining discharges between them.

The workpiece 6 is secured on a work table (not shown) and a relative displacement is effected between the work table and the wire electrode 1 along *x* and *y* axes in a programmed pattern.

In contact with one of the support and guide members 5, there is provided a vibrator magnet 8 energizable by a high-frequency alternating current source 9 of a frequency not lower than 100 Hz to impart a vibration to the wire electrode 1 travelling between the support and guide members 4 and 5 under tension. Thus, if an arc discharge or short circuiting takes place in the machining gap, it can be extinguished mechanically by the high-frequency vibration of the wire electrode and contact friction over the guide members is markedly reduced. Furthermore, the removal of machining products and gases produced in the machining gap which tend to disturb the machining stability is facilitated by the wire vibration with the result that steady machining is continued with a stability without breakage of the wire electrode and with an increased removal rate.

The vibration is effected at an amplitude in the range between 1 and 50 microns, preferably between 1 and 5 microns and at a frequency not less than 100 Hz, preferably in the range between 1 and 50 kHz.

EXAMPLE I

A workpiece of alloy tool steel having a thickness of 10 mm was machined using a copper wire electrode of a diameter of 0.2 mm and distilled water having a resistivity of 5×10^4 ohm-cm. Electric pulses applied had a peak current of 30 amperes, a pulse duration of 10 microseconds and a pulse off-time

of 20 microseconds. When no vibration was imparted to the wire electrode, the removal rate was 1.2 mm/minute whereas when a vibration was imparted to the wire electrode at a frequency of 30 kHz and an amplitude of 1 micron, at 30 kHz and 3 microns, and at 1 kHz and 2 microns, the removal rate was increased to 2.3 mm/minute, 2.0 mm/minute and 1.8 mm/minute, respectively.

Providing the vibrator 8 for the guide member 5 is especially advantageous. Friction resistance on that portion is thus markedly reduced permitting the wire electrode to be displaced at a high speed and under an increased tension without breakage.

Fig. 2 shows an embodiment of the invention in which a periodic pulling force is applied to the travelling wire electrode 1 to vibrate it by an arrangement consisting of a magnet 10, a moving coil 11 and a wire 12 provided in the vicinity of one of the guide members 5. Here, the moving coil 11 is energized by a high-frequency alternating current source (not shown) to apply a vibration with a corresponding frequency to the electrode 1 through the coupling wire 12 in the direction indicated by the arrows. The result is that the discharge point, short circuiting point or contact point on the workpiece 6 with the wire electrode 1 shifts or fluctuates constantly so that the short circuiting which may occur is instantaneously extinguished or prevented to protect the wire electrode 1 from breaking, permitting machining to continue with an increased stability.

EXAMPLE II

In machining an alloy tool steel workpiece of the type described in connection with Example I, when the travelling wire electrode held under tension of 600 g was given a tension change of ± 100 g at a frequency of 1 kHz, the removal rate was then 1.9 mm/minute. When the same tension change is effected at a frequency of 3 kHz, the removal rate was 2.0 mm/minute. It has been found that with a tension change in a range between 300 g and 5 g under average tension of 600 g, a frequency between 1 and 50 kHz is preferably used.

Figs 3(a), 3(b), 3(c) and 3(d) show different embodiments of the vibrator arrangement according to the invention. More specifically, in Fig. 3(a) a guide member 13 has a magnetostrictive element or piezoelectric element 14 connected thereto and energizable by a winding 15 to vibrate the wire electrode 1, in Fig. 3(b) the guide member is comprised of a magnetostrictive element or piezoelectric element 16 in Fig. 3 (c) the guide member 17, arranged to receive the travelling wire electrode 1, has a magnetos-

trictive element or piezoelectric element 18 connected thereto; and in Fig. 3 (d) the guide member itself is comprised of a magnetostrictive or piezo-electric element 19.

5 The vibrator alternatively may be a thermostrictive element or supersonic horn.
By applying a vibration to the wire electrode 1 in the direction coincident with the cutting direction as shown in the embodiment of Fig. 1, it is possible to hold the machining overcut at a small value.

10 Fig. 4 illustrates an embodiment of the invention in which the direction of vibration is numerically controlled. Here, a work table 20 carrying a workpiece (not shown) is displaced in the x-y plane under numerical control by an X-axis motor 22 and a Y-axis motor 21 which are controllably driven by an NC (numerical control) equipment 23 to displace the workpiece relatively to the travelling wire electrode 1 along a programmed path. The electrode guide member 24 has a first vibrator element 25 energized by a power source 26 for vibrating the wire electrode 1 in the Y direction and a second vibrator element 27 energized by a power source 28 to vibrate the wire electrode 1 in the X direction. Thus, when machining feed is effected along the X-axis by the motor 22, the vibrator element 27 is operated to vibrate the wire electrode 1 in the X-direction whereas when machining is along the Y-axis by the motor 21, the vibrator element 25 is operated to impart a vibration to the wire electrode 1 in the Y-direction to keep the vibrating direction coincident with the machining direction.

By making the wire vibrate at all times in the direction coincident with the machining direction in this manner, it is possible to achieve an increased accuracy and minimized overcut which is approximately half the overcut that may result with a vibration without directional control.

EXAMPLE III

45 A copper wire electrode of a diameter of 0.2 mm, passed over a lap-surface sapphire guide at a speed of travel of 1 m/minute and held under tension of 500 g was vibrated in a direction coincident with the machining direction at a frequency of 100 kHz by using a piezoelectric element composed of 55% PbZrO₃ and 45% PbTiO₃ applied at the guide surface. The resultant machining accuracy and overcut were 25 microns and 21 microns, respectively.

60 In the embodiment of Fig. 5 in which the same reference numbers are used to indicate the same parts as in the previous embodiments, there is provided a control system 30 designed to respond to the machining state in the gap between the travelling electrode 1 and the workpiece 6 displaced relatively

thereto, and terminals 29 electrically connecting a power supply (not shown) to the workpiece 6 and the wire electrode 1. Thus, the control system 30 leads from a potentiometer 31 shunted across the workpiece 6 and the wire electrode 1 to monitor the voltage across the machining gap thereby controlling the amplitude and/or the frequency of the vibration imparted to the wire electrode 1 by the vibrator 8 through the control of the power supply 9.

As shown in Fig. 6, an undulating motion is produced in the travelling wire electrode 1 by imparting a vibration thereto. Fig. 7 shows a similar undulating motion at a lower frequency or with a lower number of nodes and antinodes or loops. These Figures indicate that by imparting an undulating oscillatory motion to the travelling wire electrode 1, the workpiece 6 is approached at every instant by a portion or portions of the wire electrode which forms a loop or loops of the undulating motion to facilitate machining discharges thereat, without the disadvantage that the machining action may not be restricted by the frequency of the vibration.

The control system or circuit 30 is operated so as to increase the frequency of the vibration when the gap voltage drops as a result of the development of a short-circuiting or arc discharge and to reduce the frequency when a normal discharge is resumed. It may also be operated so as to permit the vibration to continue at a low or zero amplitude as long as discharges proceed in a normal mode and to increase the vibration amplitude when a short circuit or arcing develops.

Fig. 8 shows an embodiment of the invention in which a vibrator unit, here comprising a vibrator head 32, a transducer 33 and a transmitting cone or horn 34, is cooled by a coolant fluid. The vibrator head 32 is disposed in contact with one of the wire support and guide members 4 and 5 and the entire vibrator unit is received in a housing 35 filled with the coolant fluid introduced therein through an inlet 36 although only the head portion 32 may alternatively be received in such a housing 35.

As a vibration is continuously applied, the vibrating head tends to heat up so that the mechanical accuracy of such machine parts as guide members may deteriorate and the vibration in a desired mode may not be achieved with the result of discontinuance of a stable vibration and even of the breakage of the wire electrode 1. Such disadvantages are effectively overcome with the coiling arrangement of Fig. 8.

As the coolant fluid, the machining liquid may be used; a gas such as air may likewise be utilized.

According to another preferred feature of

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the invention, the machining liquid (e.g. water) of an electric resistivity in a range between 5×10^2 and 5×10^4 ohm-cm, much lower than those used heretofore, is advantageously utilized, especially when a vibration or undulating oscillatory motion at a frequency not less than 100 Hz and preferably in a range between 10 and 50 kHz is imparted to the travelling wire electrode displaced transversely relative to the workpiece. It has been a common requirement in the art of EDM that a machining liquid, e.g. kerosin or transformer oil of a sufficient dielectric strength or electric resistivity be used. As the machining liquid, water processed or distilled to have an electric resistivity not less than 10^6 to 10^7 ohm-cm has also been used. Thus the machining gap between the electrode and the workpiece must be sufficiently narrow (typically 10 to 20 microns) to allow electrical discharge to be readily produced thereacross. As a consequence, the removal of machining chips and other products from the machining gap has not readily been effectuated and the resultant production of arcing and short-circuiting has undesirably limited the machining stability and the machining current and hence the removal rate or cutting speed attainable.

It has now been found that the use of water machining fluid of a low resistivity in a range set forth above allows the use of a machining gap expanded in size by as much as 2 to 3 times, thus facilitating the removal of machining products and further has the result of an increased machining current and stability. It should also be noted that tap water not particularly processed, viz. of a resistivity between 10^2 and 10^3 ohm-cm may be directly utilized.

EXAMPLE IV

Using a copper wire electrode of a diameter of 0.02 mm, a workpiece composed of alloy tool steel was machined with electrical pulses of a pulse duration of 5 microseconds, a pulse off-time of 20 microseconds and a pulse peak current of 27 amperes. Tap-water machining liquid was used with its resistivity varied from 10 ohm-cm to 10^7 ohm-cm by an ion-exchange processing.

In Fig. 9, there are shown results obtained, in which the spacing of the machining gap in mm, the removal rate in mm/minute, the relative electrode wear in %, the overcut in mm and the surface roughness in μR_{max} are plotted along the ordinate against the resistivity in ohm-cm of water machining liquid along abscissa. It is seen that the machining gap which must be 0.01 to 0.02 mm with the use of distilled water of a resistivity of 10^6 to 10^7 ohm-cm as conventional may be expanded to 0.04 to

0.05 mm while its resistivity remains as low as 10^2 to 10^4 ohm-cm. The removal rate increases sharply when the resistivity becomes less than 5×10^4 ohm-cm, whereas the relative electrode wear decreases sharply at a resistivity lowered to 10^4 to 5×10^5 ohm-cm, it being specifically noted that a relative electrode wear which is 80% at a resistivity higher than 10^6 drops to 20% at a resistivity of 10^3 to 10^4 ohm-cm. The overcut which increases with the decrease of the resistivity rises sharply at a resistivity in the range of 10^2 to 5×10^2 ohm-cm whereas the surface roughness μR_{max} is reduced with the decrease of the resistivity.

From these machining characteristics, it will be evident that better machining results are obtainable with water machining liquid whose resistivity ranges between 5×10^4 ohm-cm and 5×10^2 ohm-cm the former being the value around which the removal rate increases markedly whereas the relative electrode wear drops and the latter being the value around which the overcut increases with the resultant drop in the machining accuracy.

It has also been observed that the resistivity of machining liquid while subjected to electrical discharges in the machining gap decreases gradually with lapse of time. In Fig. 10, there is shown a graph indicating how the resistivity of water which has an initial resistivity of 50×10^4 ohm-cm varies with respect to time plotted in minutes. A possible explanation for this change is that the resistance coefficient of water is negative with respect to rise in its temperature and the rate of dissolution of carbon dioxide from air and hence its absolute concentration dissolved in water increase with rise of the temperature. This clearly indicates why it is important to flush or pass the machining liquid through the machining zone. The resistivity change may also be avoided by travelling the electrode through the machining zone as noted previously. Thus, with both measures taken, it will be evident that an electrical discharge machining operation with a maximum efficiency and accuracy can be effectuated by using water machining liquid whose resistivity is in a range between 5×10^2 and 5×10^4 ohm-cm.

In Fig. 11, there is shown a further modified embodiment of the invention in which a timer 40 is provided for the transducer energizing oscillator 9 to variably control the operating condition of the vibrator unit 8 so as to vary the positions or number of loops or nodes of an undulating vibration imparted to the travelling wire electrode during the course of a machining operation.

As noted previously, the vibrator unit 8 is provided with a vibrator head 32, a transmitting cone or horn 34 and a transducer 33 and, when the latter is energized by the

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oscillator 9, the head 32 actuated through the transmitter applies a vibration to the guide member 4 so that an undulating vibration having nodes *a* and loops *b* as illustrated in FIGS. 12(a), 12(b) and 12(c) is imparted to the wire electrode 1 travelling under tension between the guide members 4 and 5 and propagated into the machining gap between the workpiece 6 and the wire electrode 1. The mode of the undulating vibration is properly regulated by adjustment of the distance between the guide members 4 and 5, the tension applied to the wire electrode 1 and the frequency and the amplitude of the oscillator 9.

If the undulating vibration characteristics are held constant, those portions of the workpiece which confront the loops and those portions which confront the nodes will, respectively, remain constant so that the loop confronting portions may be cut excessively compared with the node confronting portions, bringing about an irregularly machined or undulatingly profiled frontal cut surface in the workpiece. This disadvantage is overcome by the embodiment of Fig. 11.

In the system of Fig. 11, the time control unit 40 is designed to change the oscillating frequency of the oscillator 9 at predetermined time intervals. As readily appreciated, by changing the oscillating frequency of the oscillator 9, the numbers of undulations created on the wire electrode 1 between the guide members 4 and 5 will be altered and the position of the nodes and the loops thereof displaced. If the wire electrode which has been vibrating in the mode of Fig. 12 (a) has its vibrating frequency increased by increasing the frequency of the oscillator 9, a wire vibration in the mode of Fig. 12 (b) or Fig. 12 (c) will develop with a corresponding displacement of nodes and loops. It follows that if any combination of these modes of vibration are alternated at preselected time intervals, there results a constant change or displacement of the positions of the undulating nodes and loops, assuring, uniformly machined frontal surface in the workpiece.

For the purpose of changing modes of vibration in accordance with this aspect of the invention, various modifications may be made. Thus, a ring counter circuit may be employed to establish the different modes of vibration successively. The displacement of nodes and loops may also be effected by changing tension applied to the wire electrode 1 between the guide members 4 and 5 through control on a brake roller 41 and a drive roller 42. It is also possible to change the distance between the guide members 4 and 5 periodically or to provide a third guide member (not shown) between them and alter its position periodically.

WHAT WE CLAIM IS:-

1. A method of electrical discharge machining of a conductive workpiece with a continuously axially travelling wire electrode, wherein:

said travelling wire electrode and the workpiece are relatively displaced transversely to the axis of the travelling wire electrode and define a machining gap therebetween;

a machining liquid is supplied to said gap; a series of electrical pulses are applied across the workpiece and the electrode to generate machining discharges in the gap to remove material from the workpiece; and

a vibration is imparted to the travelling wire electrode in the region of said gap and in a direction transverse to the axis of the travelling wire electrode, said vibration being at a frequency not lower than 100 Hz.

2. A method according to claim 1, wherein the frequency is in the range between 1 and 50 kHz.

3. A method according to claim 1 or claim 2, wherein the amplitude of the vibration is in the range between 1 and 40 microns.

4. A method according to claim 3, wherein the amplitude of the vibration is in the range between 1 and 5 microns.

5. A method according to any one of the preceding claims wherein the wire electrode is stretched and passed between a first and a second guide member and the vibration is imparted to the wire electrode in the vicinity of one of said guide members.

6. A method according to claim 5, wherein said one of said guide members is cooled by a coolant.

7. A method according to any one of the preceding claims wherein the plane of said vibration is controlled to be held in coincidence with the direction of machining by said wire electrode of the workpiece.

8. A method according to any one of the preceding claims wherein a parameter of said vibration is modified in response to the machining condition in said machining gap.

9. A method according to any one of the preceding claims wherein said machining liquid is water of a resistivity in the range between 5×10^2 and 5×10^4 ohm-cm.

10. A method according to any one of the preceding claims wherein a or the said parameter of said vibration is periodically modified.

11. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore described with reference to, as the case may be, any one or more of Figures 1 to 4 of the accompanying diagrammatic drawings.

12. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore



oscillator 9, the head 32 actuated through the transmitter applies a vibration to the guide member 4 so that an undulating vibration having nodes *a* and loops *b* as illustrated in FIGS. 12(a), 12(b) and 12(c) is imparted to the wire electrode 1 travelling under tension between the guide members 4 and 5 and propagated into the machining gap between the workpiece 6 and the wire electrode 1. The mode of the undulating vibration is properly regulated by adjustment of the distance between the guide members 4 and 5, the tension applied to the wire electrode 1 and the frequency and the amplitude of the oscillator 9.

If the undulating vibration characteristics are held constant, those portions of the workpiece which confront the loops and those portions which confront the nodes will, respectively, remain constant so that the loop confronting portions may be cut excessively compared with the node confronting portions, bringing about an irregularly machined or undulatingly profiled frontal cut surface in the workpiece. This disadvantage is overcome by the embodiment of Fig. 11.

In the system of Fig. 11, the time control unit 40 is designed to change the oscillating frequency of the oscillator 9 at predetermined time intervals. As readily appreciated, by changing the oscillating frequency of the oscillator 9, the numbers of undulations created on the wire electrode 1 between the guide members 4 and 5 will be altered and the position of the nodes and the loops thereof displaced. If the wire electrode which has been vibrating in the mode of Fig. 12 (a) has its vibrating frequency increased by increasing the frequency of the oscillator 9, a wire vibration in the mode of Fig. 12 (b) or Fig. 12 (c) will develop with a corresponding displacement of nodes and loops. It follows that if any combination of these modes of vibration are alternated at preselected time intervals, there results a constant change or displacement of the positions of the undulating nodes and loops, assuring, uniformly machined frontal surface in the workpiece.

For the purpose of changing modes of vibration in accordance with this aspect of the invention, various modifications may be made. Thus, a ring counter circuit may be employed to establish the different modes of vibration successively. The displacement of nodes and loops may also be effected by changing tension applied to the wire electrode 1 between the guide members 4 and 5 through control on a brake roller 41 and a drive roller 42. It is also possible to change the distance between the guide members 4 and 5 periodically or to provide a third guide member (not shown) between them and alter its position periodically.

WHAT WE CLAIM IS:-

1. A method of electrical discharge machining of a conductive workpiece with a continuously axially travelling wire electrode, wherein:

said travelling wire electrode and the workpiece are relatively displaced transversely to the axis of the travelling wire electrode and define a machining gap therebetween;

a machining liquid is supplied to said gap; a series of electrical pulses are applied across the workpiece and the electrode to generate machining discharges in the gap to remove material from the workpiece; and

a vibration is imparted to the travelling wire electrode in the region of said gap and in a direction transverse to the axis of the travelling wire electrode, said vibration being at a frequency not lower than 100 Hz.

2. A method according to claim 1, wherein the frequency is in the range between 1 and 50 kHz.

3. A method according to claim 1 or claim 2, wherein the amplitude of the vibration is in the range between 1 and 40 microns.

4. A method according to claim 3, wherein the amplitude of the vibration is in the range between 1 and 5 microns.

5. A method according to any one of the preceding claims wherein the wire electrode is stretched and passed between a first and a second guide member and the vibration is imparted to the wire electrode in the vicinity of one of said guide members.

6. A method according to claim 5, wherein said one of said guide members is cooled by a coolant.

7. A method according to any one of the preceding claims wherein the plane of said vibration is controlled to be held in coincidence with the direction of machining by said wire electrode of the workpiece.

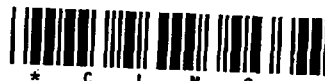
8. A method according to any one of the preceding claims wherein a parameter of said vibration is modified in response to the machining condition in said machining gap.

9. A method according to any one of the preceding claims wherein said machining liquid is water of a resistivity in the range between 5×10^2 and 5×10^4 ohm-cm.

10. A method according to any one of the preceding claims wherein a or the said parameter of said vibration is periodically modified.

11. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore described with reference to, as the case may be, any one or more of Figures 1 to 4 of the accompanying diagrammatic drawings.

12. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore



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described with reference to, as the case may be, any one or more of Figures 5 to 7 of the accompanying diagrammatic drawings.

13. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore described with reference to Figure 8 of the accompanying diagrammatic drawings.

14. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore described with reference to Figure 9 or Figure 10 of the accompanying diagrammatic drawings.

15. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore described with reference to, as the case may be, any one or more of Figures 11, 12A, 12B and 12C of the accompanying diagrammatic drawings.

16. A method of electrical discharge machining of a conductive workpiece, said method being substantially as hereinbefore described with reference to any one of Examples I to III.

17. A method of electrical discharge machining of a conductive workpiece, said method being essentially as hereinbefore described with reference to Example IV.

18. Electrical discharge machining apparatus of the kind having a wire electrode which is arranged to travel continuously axially through a machining zone of a conductive workpiece, for performing the method according to Claim 1, said apparatus comprising: vibrator means for imparting a vibration at a frequency not lower than 100 Hz to the wire electrode in the region of said machining zone and in a direction transverse to the axis of the wire electrode; displacement means for causing said relative transverse displacement of said wire electrode and said workpiece; means for applying said electrical pulses across the workpiece and the electrode; and means for supplying said machining fluid to said gap.

19. Apparatus according to claim 18, wherein said vibrator means is in contact with a wire guide member for the electrode.

20. Apparatus according to claim 18 or claim 19, wherein said vibrator means is an electromagnetic or a sonic or ultrasonic vibrator.

21. Apparatus according to claim 18 or claim 19, wherein said vibrator means is a magnetostrictive or piezo-electric vibrator.

22. Apparatus according to any one of claims 18 to 21, wherein a control system is provided, in operation of the apparatus, to respond to the machining state in said gap and to cause a parameter of said vibration to be modified in response to said state.

23. Apparatus according to any one of

claims 18 to 22, wherein said vibrator means are arranged to be cooled by a coolant fluid.

24. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, as the case may be, any one or more of Figures 1 to 4 of the accompanying diagrammatic drawings.

25. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, as the case may be, any one or more of Figures 5 to 7 of the accompanying diagrammatic drawings.

26. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, Figure 8 of the accompanying diagrammatic drawings.

27. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, Figure 9 or Figure 10 of the accompanying diagrammatic drawings.

28. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, as the case may be, any one or more of Figures 11, 12A 12B, and 12C of the accompanying diagrammatic drawings.

29. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to any one of Examples I to III.

30. Apparatus for electrical discharge machining of a conductive workpiece, said apparatus being constructed, arranged and adapted to operate substantially as hereinbefore described with reference to Example IV.

31. A conductive workpiece which has been electrical discharge machined by a method according to any one of Claims 1 to 17, or in apparatus according to any one of Claims 18 to 30.

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Page 6, line 80, *for frm read from*

Page 6, line 82, *after of delete sand fap insert said gap*

THE PATENT OFFICE
November 1979

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