

SPECIFICATION

Electrical discharge machining

5 The present invention relates to electrical discharge machining (EDM). In particular, it relates to a method of and apparatus for electrical-discharge-machining a workpiece with a tool electrode across a dielectric-filled machining gap with machining surfaces whose active area changes as the tool electrode is advanced relatively toward the workpiece with the progress of material removal or machining. The invention is applicable to various modes of EDM operation including boring, cavity-sinking or three-dimensional cutting, traveling-wire (TW) or wire-cut (WC) EDM and numerous other particular operations.

In electrical discharge machining, electric energy is applied in the form of discrete electrical pulses across the machining gap filled with a machining fluid or liquid dielectric (e.g., kerosine, transformer oil, distilled water) to effect a succession of electrical discharges between the tool electrode and the workpiece to remove material from the latter. As material removal proceeds, the tool electrode is advanced relatively toward the workpiece by servo feed means adapted for functioning to maintain the machining gap spacing substantially constant thereby to allow material-removal discharges to be successively created. The contamination of the machining gap region with chips, tar and gases produced by machining discharges may be clarified by continuously or intermittently flushing fresh machining fluid into the gap and/or intermittently or cyclically retracting the tool electrode away from the workpiece to allow fresh machining medium to be pumped into the machining gap and the machining contaminants to be carried away from the latter.

Parameters of individual and successive electrical discharges, i.e. pulse on-time τ_{on} , peak current I_p and off-time τ_{off} , are determinative of machining results, e.g. removal rate, surface roughness and relative electrode wear, and therefore are individually and in combination particularly adjusted to establish a particular machining condition suitable to achieve desired machining results.

As pointed out in US Patent No. 3,536,881 issued 27 October 1970 to Kiyoshi Inoue, one of the problems arising in electrical discharge machining is the problem of the progressively changing current density that occurs as the working face of the tool electrode is successively juxtaposed with a larger or a smaller surface of the workpiece so that discharges must occur over progressively changing surface areas. Thus, a given total current resulting from uniform application of successive discharges will provide diminished current density as the working area increases, and vice versa. With the machining gap maintained constant, for example, changes in the working surface area vary the current density with reduced performance even when various measures, such as for gap short-circuit and arc prevention, are taken in an attempt to hold the machining gap under an optimum machining condition. This particular deficiency and the

inconvenience thereof are overcome, as disclosed in the above-quoted patent, by maintaining the current density substantially constant by providing a current-control circuit responsive to the rate of advance of the tool electrode advanced by a gap-controlling servo for compensatorily varying the current. This is based upon the fact that, when the position of the tool electrode is adjusted by a servo-mechanism or servo feed means to maintain a substantially constant optimum machining gap, the rate of change of the feed with time is a function of the change in surface area exposed to electrical discharges along the machining surface. Consequently, a reduced surface area is equivalent to a higher removal rate and a correspondingly higher electrode feed rate, while an increased machining area is equivalent to a lower rate of material removal and a corresponding decrease in the rate of advance of the electrode.

Consequently, the afore-said patent provides sensing means responsive to the rate of advance of the electrode for indicating the variation in surface area exposed to the machining operation, and mean-current control means in the power supply circuit electronically regulated in any of various manners by the rate sensing means. Specifically, as described therein, the mean-current control means may include a source of direct-current which is switched on and off to provide a train of discharge pulses whose parameters are modified to maintain the current density substantially constant, in response to change in machining area, by: (a) varying the on-time τ_{on} of the pulses of the pulse train while maintaining the pulse frequency f substantially constant; (b) varying the off-time τ_{off} of the train while maintaining the pulse frequency f substantially constant; (c) varying the on-time τ_{on} of the pulses of the train while maintaining the off-time τ_{off} of the pulses constant; or (d) varying the off-time τ_{off} of the pulses of the train while maintaining the on-time τ_{on} of the pulses constant.

The modification of individual pulse parameters has, however, been found to be disadvantageous in that preset machining conditions, such as relative electrode wear, are adversely affected and the machining operation becomes unstable. Hence, the earlier measures enunciated in the aforementioned US Patent are of limited value in putting the concept into practice and are in practice inconvenient.

The present invention therefore seeks to provide an improved method for carrying out EDM at an optimum rate independent of variation in the machining area without substantially changing the preset machining conditions and with continued stability of operation in spite of change in the surface area.

The present invention also seeks to provide an improved EDM apparatus whereby change in the machining surface area is effectively compensated for while avoiding fluctuation of basic pulse parameters, so that a given machining operation is carried out with stability and to achieve desired machining results.

In accordance with the present invention there is provided a method of electrical-discharge-

machining a workpiece juxtaposed with a tool electrode across a dielectric-filled machining gap with machining surfaces of area variable as the tool electrode is advanced relatively toward the

5 workpiece, which method comprises the steps of:

applying across said machining gap pulse trains individually consisting of elementary pulses of predetermined on-time t_{on} and off-time t_{off} and having a duration T_{on} with the successive trains

10 being separated by a cut-off time interval T_{off} ;

producing a signal dependent on the instantaneous area of said machining surfaces during application of said pulse trains across said machining gap; and

15 controlling at least one of said duration T_{on} and said cut-off time interval T_{off} in accordance with said instantaneous machining area signal so as to maintain the current density along said machining surfaces substantially constant in spite of change in
20 said machining area during relative advance of said electrode and workpiece.

According to one preferred feature of the present invention the advancement of the tool electrode relative to the workpiece is controlled in a manner
25 such as to maintain the machining gap spacing between them substantially constant; the instantaneous machining area signal is produced by detecting the rate of advance of said tool electrode relative to said workpiece during application of said
30 pulse trains; and said at least one of said duration T_{on} and said interval T_{off} is controlled in accordance with said detected rate of relative advance of the tool electrode.

According to a second aspect of the present invention there is provided an apparatus for electrical-discharge-machining a workpiece with a tool electrode across a dielectric-filled machining gap with machining surfaces of area variable as the tool electrode is advanced relatively toward the

40 workpiece, which apparatus comprises:-

power supply means for applying across said gap pulse trains individually consisting of elementary pulses of predetermined on-time t_{on} and off-time t_{off} and having a duration T_{on} with the successive

45 trains being separated by a cut-off time interval T_{off} ;

means for producing a signal dependent on the instantaneous area of said machining surfaces during application of said pulse trains across said machining gap; and

50 means for controlling at least one of said duration T_{on} and said interval T_{off} in accordance with said instantaneous machining area signal so as to maintain the current density along said machining surfaces substantially constant in spite of change in
55 said machining area during relative advance of said electrode and workpiece.

According to one preferred feature of this second aspect of the invention one of said tool electrode and workpiece is advanced relatively toward the other by
60 servo feed means in a manner such as to maintain the machining gap spacing between them substantially constant; and said signal producing means comprises circuit means responsive to the rate of said relative advance movement of said

65 electrode and workpiece for producing said signal

dependent on said instantaneous area of said machining surfaces during application of said pulse trains across said machining gap.

At this point, it should be noted that the term
70 "current density" is used throughout this specification and the appended claims to refer to "the mean current divided by the machining area over which discharges are occurring".

The machining area over which discharges are
75 occurring may be more accurately ascertained by dividing the number of "satisfactory" discharges occurring per unit time by the rate of relative advance movement of the electrodes, on the assumption that each "satisfactory" discharge
80 results in an identical amount of stock removal, using the relationship that the machining area equals the removal rate divided by distance travelled by the electrode per unit time, and an output signal derived by such division may be used to control at
85 least one of the duration T_{on} of the individual pulse trains and the cut-off time interval T_{off} between the successive trains, to achieve the end described.

Where the electrode has a relatively simple configuration and its active machining face
90 comprises a plurality of surfaces stepped in the feed direction with each surface extending perpendicular thereto, the feed positions at which the machining surface changes from one area to another can be detected and used to provide corresponding
95 switch-over signals to change the controllable magnitude (T_{on} and/or T_{off}) from one preset value to another to achieve the end described.

Broadly stated, therefore, the method embodying the principles of the present invention may include
100 the detection step of detecting change in the machining area over which machining discharges are occurring and the control step of controlling at least one of the said duration T_{on} and the said interval T_{off} in accordance with the detected change
105 in the machining area. Likewise, an apparatus including means for performing these particular steps may be provided.

These and other features and advantages of the present invention will become more readily
110 apparent from the following description of certain exemplary embodiments thereof given with reference to the accompanying diagrammatic drawings in which:

Figure 1 is a waveform diagram illustrating pulse trains utilized in the present invention, with the pulse train interval varied in accordance with the principles thereof;

Figure 2 is a diagrammatic representation illustrating a basic system embodying the present
120 invention;

Figure 3 is a circuit diagram illustrating the control portion of an oscillator defining a parameter of such pulse trains of elementary pulses, which trains are cyclically interrupted and controlled in accordance
125 with the invention;

Figure 4 is a diagrammatic circuit representation illustrating a practical system in accordance with the present invention;

Figure 5 is a diagrammatic illustration of an
130 alternative machining surface area detecting

arrangement for use in carrying out the invention; and

Figures 6 and 7 are circuit diagrams showing different pulse forming circuitry for use with the invention.

In Figure 1 there is shown a succession of pulse trains A1, A2, A3 employed in accordance with the invention, which pulse trains individually consist of elementary pulses *a* of predetermined on-time τ_{on} and off-time τ_{off} , and have a duration T_{on} with the successive trains being separated by a cut-off time interval T_{off} . The on-time τ_{on} and off-time τ_{off} of the elementary pulses are selected usually in the range between 1 and 100 μsec primarily according to the electrode materials or combination, although wider ranges may also be used. Thus, the on-time τ_{on} and off-time τ_{off} may range between 1 μsec and 3 msec and between 1 and 200 μsec , respectively, and each range may be divided into subranges depending upon degree of surface roughness desired.

In accordance with the present invention, the successive pulse trains are modified with regard to the duration T_{on} and/or cut-off time interval T_{off} in response to change in the machining area so as to maintain the current density in the machining area substantially constant. In the illustrated diagram, by way of example the cut-off time T_{off} is shown varied as the machining area varies, with T_{on} held constant and within which a fixed number of elementary pulses *a* of predetermined on-time τ_{on} and off-time τ_{off} occur. In general, however, in order to allow the current density to be constant, hence to make the electrode feed rate constant, the variation of duration T_{on} and interval T_{off} needs to be such that as the machining area increases, T_{on} is increased and/or T_{off} is reduced, and vice versa. The duration T_{on} and interval T_{off} may each range between 200 μsec and 5 msec and be variable in this range.

The variation of T_{off} and especially that alone is particularly advantageous in that preset machining conditions are substantially not affected at all. For example, it has been found in the course of developing the invention that relative electrode wear η (tool electrode wear divided by stock removal from workpiece) is expressed by:

$$\eta = \beta \left(\frac{\tau_{on}}{\tau_{off}} \right)^{1/3} T_{on}^{-1/3} f (I_p)$$

where β is a constant. This expression shows (a) that the earlier attempts to increase the pulse interval τ_{off} between successive discharge pulses lead to changes in the relative electrode wear, and (b) that by way of contrast the relative electrode wear is invariable with increase of the pulse train interval T_{off} for fixed values of duration T_{on} and pulse peak current I_p .

In Figure 2 there is shown an automatic detection and control system embodying the present invention whereby the duration T_{on} and/or cut-off time interval T_{off} are varied in response to change in the rate of advance of a tool electrode 1 toward a workpiece 2 in an EDM machine. The tool electrode 1 and the workpiece 2 are juxtaposed with one another

to form a machining gap *G* therebetween which is supplied with a machining fluid. A DC power supply 3 is connected to the electrode 1 and the workpiece 2 via switching means 4, shown as a power transistor, which is turned on and off by a switching network 4A to alternately connect and disconnect the output of the DC source 3 across the machining gap *G*.

The switching network 4A comprises a first oscillator 5 operating at a frequency *f* to provide switching pulses of predetermined on-time τ_{on} and off-time τ_{off} which are applied to the power switch 4, and a second oscillator 6 operating at a frequency *F* which is lower than the frequency *f* of the oscillator 5 to provide control pulses of duration T_{on} and interval T_{off} which are applied to the oscillator 5. Accordingly, the switch 4 is operated to turn on and off the DC source 3 and provide across the machining gap *G* pulse trains *A* individually consisting of elementary pulses *a* of predetermined on-time τ_{on} and off-time τ_{off} and having duration T_{on} with successive trains *A* being separated by cut-off time interval T_{off} (Figure 1), and with the regulated peak current I_p being determined by the output of supply 3. Each of the first oscillator 5 and the second oscillator 6 may be an astable or other form of multivibrator having a time-constant or pulse-defining network in a configuration well known in the pulse switching and shaping art to provide predetermined, adjustably variable pulse on-time or duration and pulse off-time or interval, τ_{on} , τ_{off} in the oscillator 5 and T_{on} , T_{off} in the oscillator 6.

Servo feed means is shown comprising a motor 7, which is preferably a pulse motor but may be a DC motor or any other drive means (including a hydraulic drive), connected with the tool electrode 1 and arranged to advance the same toward the workpiece 2 as EDM proceeds in the machining gap *G* so as to maintain the gap spacing constant. To the motor 7 there is coupled an encoder 8 which is designed to detect the rate of advance of the tool electrode 1 by providing pulses proportional in number to the rotation of the motor 7, and thus a pulse for each incremental distance through which the electrode 1 is advanced. Such tool-advance responsive pulses generated at the encoder 8 are counted by an integrating counter 9 which provides a signal representative of the electrode feed displacement per unit time, which signal is applied to the first input of a comparator circuit 11. The counter 9 is preferably a reversible counter so that signal pulses corresponding to any backward displacement of the tool 1 are subtracted from the count accumulated in the counter 9. In an EDM operation, the tool electrode 1 may be moved back or retracted in response to a servo signal which indicates an excessive narrowing of the gap, or a gap short-circuiting or other abnormality; moreover, it is also customary to provide an intermittent retraction of the tool electrode 1 so as to replenish the gap *G* with fresh machining medium for the purposes of cyclic gap decontamination.

The second input of the comparator circuit 11 is supplied with a preset reference signal from a setting circuit 10. The comparator circuit 11 thus

provides a comparison of the electrode advance signal per unit time with the reference value, and issues an output signal representing the change in the machining area of the electrode 1 juxtaposed with the workpiece 2. A plurality of different, pre-selectable reference values are desirably preset at the setting circuit 10, and may be applied sequentially to the comparator circuit 11 by switching means such as that shown later in Figure 5, so that for every step-wise change in the machining area detected or sensed, an appropriate output signal is provided by the comparator circuit 11.

The second oscillator 6 for defining the duration T_{on} and cut-off time interval T_{off} of pulse trains A is associated with a control circuit 12 adapted to respond to the output signal of the comparator circuit 11 indicating change in the machining area, thereby controllably changing T_{on} and/or T_{off} and, preferably T_{off} alone. Figure 3 illustrates an example of the time-defining portion of the oscillator 6 which comprises a variable time-constant network 6A consisting of a resistor R and a plurality of capacitors C1, C2, C3, C4 and C5 of varying capacitances connected in parallel with one another and in series with the resistor R, and in which a switch S1, S2, S3, S4, S5, preferably electronic, is inserted in each branch connecting a respective capacitor with the common resistor. The switches S1 to S5 are selectively closed in response to the output signal of the comparator 11 to selectively connect the capacitors C1 to C5 with the resistor R to establish corresponding time-constant networks. Control of pulse trains A is thus effected so as to decrease and increase the cut-off time interval T_{off} when the machining area is indicated as increasing and decreasing, respectively, and, possibly also to correspondingly increase and decrease the duration T_{on} of said pulse trains individually constituted of elementary pulses a of pre-determined on-time t_{on} and off-time t_{off} .

The use of elementary pulses supplied cyclically with intervals and in trains or groups results, with extreme ease, in the recurrent generation of the desired machining discharges. Desired machining conditions are readily established at will by presetting the pulse duration t_{on} and interval t_{off} accordingly. Thus, a given mode of electrical discharge machining is accomplished at a maximum stock removal rate and efficiency and with a superior surface finish and preset minimum electrode wear by the suitably preset individual elementary pulses. Furthermore, control of the individually-adjustable parameters T_{on} and T_{off} of the trains or groups of elementary pulses provides an extremely ready means of modifying the machining current in accordance with change in the machining area, yet without affecting the established machining conditions, and with stability of operation at a maximum machining efficiency.

In Figure 4 there is shown a further and improved embodiment of the present invention which includes a modified detection system. The detection system in this embodiment includes a gap sensor 13 connected to the machining gap G for classifying

gap pulses in each controlled train or group into "satisfactory" and "unsatisfactory" pulses, and a preset counter 14 for selectively counting "satisfactory" pulses. In this case, a gap pulse will be determined to be "satisfactory" and result in a normal discharge-accompanying stock removal unless it is sensed to result in an open-circuit or no-load pulse, or an arc-discharge or short-circuiting of the gap. In this embodiment, a divider 15 is provided having two inputs, the first fed from the counter 9 described earlier which provides a pulse accumulation representing the distance of advance of the tool electrode 1 per unit time, and the second fed from the counter 14 which provides a signal corresponding to an accumulation of "satisfactory" pulses per unit time. In order for the two counters 9 and 14 to be synchronized, a timer 16 is provided to apply a timing signal to the counters 9 and 14 so that the counting in each thereof is effected at a predetermined, synchronous time interval.

The divider 15 accordingly provides a signal representing the ratio removal rate divided by the rate of advance of the tool electrode 1, which ratio equals the instantaneous machining area. If there is a change in the machining area detected, the control circuit 12 (which may here be adapted to serve a threshold function) responds to execute a change or switch-over of the duration T_{on} and/or interval T_{off} of the pulse trains, as previously described.

In Figure 5 there is shown another embodiment of the system for detecting change in the machining area for practising the present invention. This system is designed for use with a tool electrode 1 having a plurality of machining sections with areas A, B and C, respectively, which are progressively enlarged ($A < B < C$) and stepped in the tool feed or advance direction with each extending perpendicular to the latter. The system makes use of a movable spindle 17 securely supporting the tool electrode 1 and having a horizontal projection 18 attached thereto and a fixed shaft 19 extending in parallel with the spindle 17. On the shaft 19 there are mounted limit switches 20, 21 and 22 whose contacts are adapted to be successively closed in response to engagement of their respective contact operating means with the projection 18 as the electrode 1 is progressively advanced to place in machining position the machining faces A, B and C, respectively, relative to the workpiece 2. In this arrangement, the closure of each limit switch 20, 21, 22 is responded to by a control circuit 23 having a function similar to the control circuit 12 to act on a time-determining section of the oscillator 6 defining the duration T_{on} and/or interval T_{off} of the pulse trains as already described in accordance with the detected change in the machining area.

In the arrangements of Figures 6 and 7, the pulse forming unit 40A for operating the switch 4 comprises a first oscillator 50 (e.g., a multivibrator) operating to provide a series of elementary pulses of predetermined on-time t_{on} and off-time t_{off} , and a second oscillator 60 (e.g., a multivibrator) operating to provide a series of pulses of duration T_{on} and interval T_{off} of which alternatively T_{off} alone is variable and T_{on} is substantially fixed (Figure 6), or

both of which are variable (Figure 7), the outputs of the first and second oscillators being connected to an AND gate 70 whose output is fed into the control elements of the power switch 4. As a result, pulse trains individually consisting of elementary pulses of ton and toff and having duration Ton with the successive trains being separated by interval Toff are impressed across the machining gap G as in the system described earlier. Here again, the rate of advance of the tool electrode 1 is shown sensed by the encoder 8 coupled with the motor 7 driving the electrode 1, the encoder output being fed into a unit 100 which includes (a) the components (9, 10, 11; 13, 14, 15) and function as have been described above to derive from the encoder output a signal representing the instantaneous machining area, and (b) a controller (12) acting in response to such signal on the oscillator 60 to vary the train duration Ton in which elementary pulses are permitted to be applied to the machining gap and/or the inter-train interval Toff during which the elementary pulses are interrupted, so as to maintain the current density over the machining area, and hence the rate of advance of the tool electrode relative to the workpiece, substantially constant.

Alternatively, the oscillator 60 may to the same end be controlled in response to a preset electrode position detector as shown and described in connection with Figure 5, in which the tool electrode 30 1 has a relatively simple shape and for which such arrangement is applicable.

It should also be noted that the rate of advance of the tool electrode relative to the workpiece may be detected by any other arrangement. Thus, for example, displacement of the tool electrode or a spindle or ram carrying the same may be detected directly by a magnetic, electromagnetic or optoelectrical scale having a reading head operatively mounted thereon and an encoder or coding unit for producing a signal pulse upon each incremental displacement of the tool electrode, with the pulses being counted by an arrangement as described.

There is thus provided an improved EDM method and apparatus which allow machining on a fully automatic basis with an increased stability, efficiency and reliability.

CLAIMS

1. A method of electrical-discharge-machining a workpiece juxtaposed with a tool electrode across a dielectric-filled machining gap with machining surfaces of area variable as the tool electrode is advanced relatively toward the workpiece, the method comprising the steps of:

applying across said machining gap pulse trains individually consisting of elementary pulses of predetermined on-time ton and off-time toff and having a duration Ton with the successive trains being separated by a cut-off time interval Toff; producing a signal dependent on the instantaneous area of said machining surfaces during application of said pulse trains across said machining gap; and

controlling at least one of said duration Ton and said cut-off time interval Toff in accordance with said instantaneous machining area signal so as to maintain the current density along said machining surfaces substantially constant in spite of change in said machining area during relative advance of said electrode and workpiece.

2. The method defined in claim 1, wherein said duration Ton of each train is substantially fixed and said time Toff is varied in accordance with the sensed machining area.

3. The method defined in claim 1 or 2, wherein ton ranges between 1 microsecond and 3 milliseconds, toff ranges between 1 and 200 microseconds, and Ton and Toff each range between 200 microseconds and 5 milliseconds.

4. The method defined in claim 3, wherein ton and toff each range between 1 and 100 microseconds.

5. The method defined in any one of the preceding claims, wherein said tool electrode has a plurality of machining sections with respective machining faces stepped in the advance direction with each such face extending perpendicular to said direction; and said instantaneous machining area signal is produced by detecting the respective positions of said tool electrode corresponding to entry of the respective machining faces into machining relationship with said workpiece and varying a signal quantity accordingly.

6. The method defined in any one of claims 1 to 4, wherein the advancement of the tool electrode relative to the workpiece is controlled in a manner such as to maintain the machining gap spacing between them substantially constant; the instantaneous machining area signal is produced by detecting the rate of advance of said tool electrode relative to said workpiece during application of said pulse trains; and said at least one of said duration Ton and said interval Toff is controlled in accordance with said detected rate of relative advance of the tool electrode.

7. The method defined in claim 6, wherein said rate of relative advance of said electrode is detected by (a) producing a series of pulses in which each such pulse is produced in response to a predetermined incremental advance displacement of the tool electrode relative to the workpiece, (b) determining the number of such incremental pulses produced in unit time, and (c) deriving a control signal therefrom as representative of said rate of relative advance for controlling said at least one of said duration Ton and said interval Toff of said pulse trains.

8. The method defined in claim 7, wherein said number of incremental pulses is counted in an integrating counter whose accumulated count is compared with a reference signal to provide said control signal.

9. The method defined in claim 7, wherein said number of such incremental pulses produced in unit time is compared with the number of machining pulses effected across said machining gap in the same unit time, to produce said control signal.

10. An apparatus for electrical-discharge-



both of which are variable (Figure 7), the outputs of the first and second oscillators being connected to an AND gate 70 whose output is fed into the control elements of the power switch 4. As a result, pulse trains individually consisting of elementary pulses of τ_{on} and τ_{off} and having duration T_{on} with the successive trains being separated by interval T_{off} are impressed across the machining gap G as in the system described earlier. Here again, the rate of advance of the tool electrode 1 is shown sensed by the encoder 8 coupled with the motor 7 driving the electrode 1, the encoder output being fed into a unit 100 which includes (a) the components (9, 10, 11; 13, 14, 15) and function as have been described above to derive from the encoder output a signal representing the instantaneous machining area, and (b) a controller (12) acting in response to such signal on the oscillator 60 to vary the train duration T_{on} in which elementary pulses are permitted to be applied to the machining gap and/or the inter-train interval T_{off} during which the elementary pulses are interrupted, so as to maintain the current density over the machining area, and hence the rate of advance of the tool electrode relative to the workpiece, substantially constant.

Alternatively, the oscillator 60 may to the same end be controlled in response to a preset electrode position detector as shown and described in connection with Figure 5, in which the tool electrode 1 has a relatively simple shape and for which such arrangement is applicable.

It should also be noted that the rate of advance of the tool electrode relative to the workpiece may be detected by any other arrangement. Thus, for example, displacement of the tool electrode or a spindle or ram carrying the same may be detected directly by a magnetic, electromagnetic or optoelectrical scale having a reading head operatively mounted thereon and an encoder or coding unit for producing a signal pulse upon each incremental displacement of the tool electrode, with the pulses being counted by an arrangement as described.

There is thus provided an improved EDM method and apparatus which allow machining on a fully automatic basis with an increased stability, efficiency and reliability.

CLAIMS

1. A method of electrical-discharge-machining a workpiece juxtaposed with a tool electrode across a dielectric-filled machining gap with machining surfaces of area variable as the tool electrode is advanced relatively toward the workpiece, the method comprising the steps of:

applying across said machining gap pulse trains individually consisting of elementary pulses of predetermined on-time τ_{on} and off-time τ_{off} and having a duration T_{on} with the successive trains being separated by a cut-off time interval T_{off} ;

producing a signal dependent on the instantaneous area of said machining surfaces during application of said pulse trains across said machining gap; and

controlling at least one of said duration T_{on} and said cut-off time interval T_{off} in accordance with said instantaneous machining area signal so as to maintain the current density along said machining surfaces substantially constant in spite of change in said machining area during relative advance of said electrode and workpiece.

2. The method defined in claim 1, wherein said duration T_{on} of each train is substantially fixed and said time T_{off} is varied in accordance with the sensed machining area.

3. The method defined in claim 1 or 2, wherein τ_{on} ranges between 1 microsecond and 3 milliseconds, τ_{off} ranges between 1 and 200 microseconds, and T_{on} and T_{off} each range between 200 microseconds and 5 milliseconds.

4. The method defined in claim 3, wherein τ_{on} and τ_{off} each range between 1 and 100 microseconds.

5. The method defined in any one of the preceding claims, wherein said tool electrode has a plurality of machining sections with respective machining faces stepped in the advance direction with each such face extending perpendicular to said direction; and said instantaneous machining area signal is produced by detecting the respective positions of said tool electrode corresponding to entry of the respective machining faces into machining relationship with said workpiece and varying a signal quantity accordingly.

6. The method defined in any one of claims 1 to 4, wherein the advancement of the tool electrode relative to the workpiece is controlled in a manner such as to maintain the machining gap spacing between them substantially constant; the instantaneous machining area signal is produced by detecting the rate of advance of said tool electrode relative to said workpiece during application of said pulse trains; and said at least one of said duration T_{on} and said interval T_{off} is controlled in accordance with said detected rate of relative advance of the tool electrode.

7. The method defined in claim 6, wherein said rate of relative advance of said electrode is detected by (a) producing a series of pulses in which each such pulse is produced in response to a predetermined incremental advance displacement of the tool electrode relative to the workpiece, (b) determining the number of such incremental pulses produced in unit time, and (c) deriving a control signal therefrom as representative of said rate of relative advance for controlling said at least one of said duration T_{on} and said interval T_{off} of said pulse trains.

8. The method defined in claim 7, wherein said number of incremental pulses is counted in an integrating counter whose accumulated count is compared with a reference signal to provide said control signal.

9. The method defined in claim 7, wherein said number of such incremental pulses produced in unit time is compared with the number of machining pulses effected across said machining gap in the same unit time, to produce said control signal.

10. An apparatus for electrical-discharge-



machining a workpiece with a tool electrode across a dielectric-filled machining gap with machining surfaces of area variable as the tool electrode is advanced relatively toward the workpiece, said

5 apparatus comprising:

power supply means for applying across said gap pulse trains individually consisting of elementary pulses of predetermined on-time t_{on} and off-time t_{off} and having a duration T_{on} with the successive

10 trains being separated by a cut-off time interval T_{off} ; means for producing a signal dependent on the instantaneous area of said machining surfaces during application of said pulse trains across said machining gap; and

15 means for controlling at least one of said duration T_{on} and said interval T_{off} in accordance with said instantaneous machining area signal so as to maintain the current density along said machining surfaces substantially constant in spite of change in
20 said machining area during relative advance of said electrode and workpiece.

11. The apparatus defined in claim 10, wherein said tool electrode is securely carried by a spindle, and said signal producing means comprises a

25 plurality of limit switches spacedly mounted on a shaft extending in parallel with said spindle, said spindle having limit switch operating means secured thereto for co-operation with said limit switches whereby to provide indication of said instantaneous
30 machining area by the condition of the respective limit switches.

12. The apparatus defined in claim 10, wherein one of said tool electrode and workpiece is advanced relatively toward the other by servo feed means in a

35 manner such as to maintain the machining gap spacing between them substantially constant; and said signal producing means comprises circuit means responsive to the rate of said relative advance movement of said electrode and workpiece
40 for producing said signal dependent on said instantaneous area of said machining surfaces during application of said pulse trains across said machining gap.

13. The apparatus defined in claim 12, wherein

45 said circuit means comprises means for producing a series of pulses in which each such pulse is representative of a predetermined incremental displacement of said tool electrode relative to said workpiece, and a counter for accumulating said
50 incremental pulses and producing in response thereto an output (referred to later as 'said first output') representing the number of incremental pulses received per unit time.

14. The apparatus defined in claim 13, wherein

55 said circuit means further comprises means coupled with said machining gap for counting the number of machining discharge pulses effected across said machining gap per unit time and producing in response thereto a second output, and divider
60 means for dividing one of said first and said second outputs by the other of said first and second outputs to produce said instantaneous machining area signal.

15. The apparatus defined in claim 13 or 14,

65 wherein said counter is a reversible counter whose

count level is reduced by a pulse representing a backward incremental displacement of said tool electrode relative to said workpiece.

16. Electrical discharge machining apparatus

70 constructed, arranged and adapted to operate substantially as hereinbefore described with

reference to any single figure or group of associated figures of the accompanying diagrammatic drawings.

75 17. A method of electrical discharge machining substantially as hereinbefore described with reference to any single figure or group of associated figures of the accompanying diagrammatic drawings.

80 18. A workpiece which has been machined by a method according to any one of Claims 1 to 9 or Claim 17 or by use of apparatus according to any one of Claims 10 to 16.

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