Study of workpiece thermal profile in Electrical Discharge Machining (EDM) process

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Abstract: Electric Discharge Machining (EDM) removes metal with sparks. A shaped graphite or copper electrode is used to make a cavity that is the mirror image of the electrode, without direct contact with the workpiece. Sparks travel through a dielectric fluid, typically a light oil, at a controlled distance. EDM can machine cavities with thin walls and fine features, achieve difficult part geometry, produce burr-free parts, and is insensitive to workpiece hardness.The values of these parameters significantly affect such machining outputs as material removal rate and electrodes wear. In this paper, the mathematical relationships between input and output parameters of EDM are established using regression method and the best set of models is chosen. Genetic Algorithm is then used to optimally determine input parameters levels in order to obtain any desired set of outputs. Numerical simulation of process in ANSYS software an for gaining the thermal profile, the effect of parameter variation on temperature field and process optimization are done. The numerical results show the time-dependant distributions of arc pressure, current density, and heat transfer at the workpiece surface are different from presumed Gaussian distributions in previous models.

Key-Words: EDM parameters, Workpiece, Discharge , Machining, ANSYS

1 Introduction

In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium. Generally kerosene or deionised water is used as the dielectric medium. A gap is maintained between the tool and the workpiece. Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established. Generally the tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal. As the electric field is established between the tool and the job, the free electrons on the tool are subjected to electrostatic forces. If the work function or the bonding energy of the electrons is less, electrons would be emitted from the tool (assuming it to be connected to the negative terminal). Such emission of electrons are called or termed as cold emission. The "cold emitted" electrons are then accelerated towards the job through the dielectric medium. As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules. Such collision may result in ionisation of the dielectric molecule depending upon the work function or ionisation energy of the dielectric molecule and the energy of the electron. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap. The concentration would be so high that the matter existing in that channel could be characterised as "plasma". The electrical resistance of such plasma channel would be very less. Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the job to the tool. This is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark. Thus the electrical energy is dissipated as the thermal energy of the spark.

The high speed electrons then impinge on the job and ions on the tool. The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux. Such intense localised heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of $10{,}000^{o}C$.

EDM process shows in Fig.1.a. Also Fig.1.b shows schematically the basic working principle of EDM process.

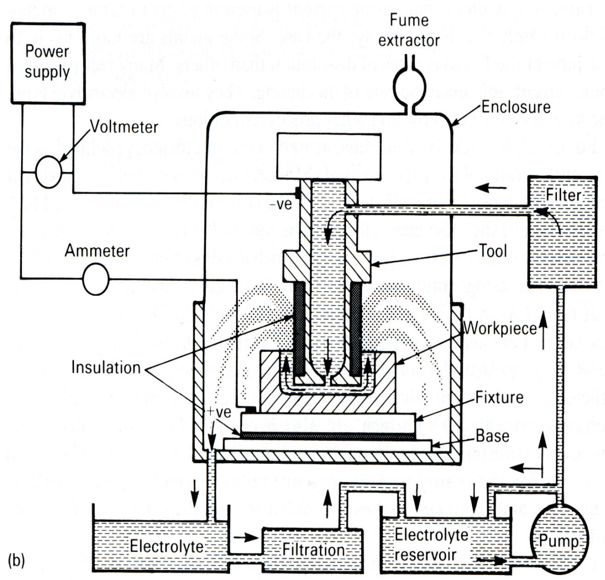

Fig.1.a. Electro Discharge Machining (EDM) process

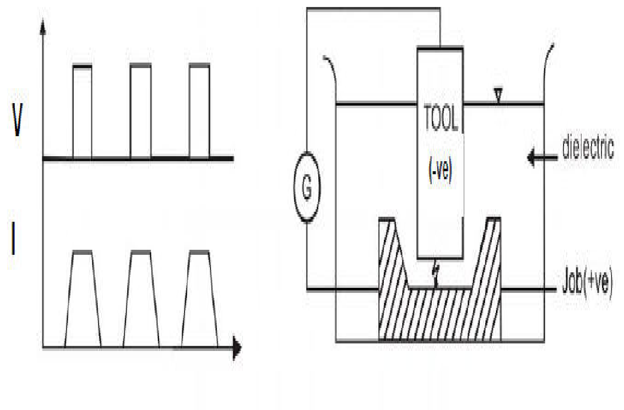

Fig.1.b. Schematic representation of the basic working principle of EDM process.

Some of the advantages of EDM include machining of:

Complex shapes that would otherwise be difficult to produce with conventional cutting tools

Extremely hard material to very close tolerances

Very small work pieces where conventional cutting tools may damage the part from excess cutting tool pressure.

There is no direct contact between tool and work piece. Therefore delicate sections and weak materials can be machined without any distortion.

A good surface finish can be obtained.

Very fine holes can be easily drilled.

Some of the disadvantages of EDM include:

The slow rate of material removal.

The additional time and cost used for creating electrodes for ram/sinker EDM.

Reproducing sharp corners on the workpiece is difficult due to electrode wear.

Specific power consumption is very high.

Power consumption is high.

"Overcut" is formed.

Excessive tool wear occurs during machining.

Electrically non-conductive materials can be machined only with specific set-up of the process.

Characteristics of EDM :

(a) The process can be used to machine any work material if it is electrically conductive

(b) Material removal depends on mainly thermal properties of the work material rather than its strength, hardness etc

(c) In EDM there is a physical tool and geometry of the tool is the positive impression of the hole or geometric feature machined

(d) The tool has to be electrically conductive as well. The tool wear once again depends on the thermal properties of the tool material

(e) Though the local temperature rise is rather high, still due to very small pulse on time, there is not enough time for the heat to diffuse and thus almost no increase in bulk temperature takes place. Thus the heat affected zone is limited to 2 – 4 μm of the spark crater

(f) However rapid heating and cooling and local high temperature leads to surface hardening which may be desirable in some applications

(g) Though there is a possibility of taper cut and overcut in EDM, they can be controlled and compensated.

In EDM, as has been discussed earlier, material removal mainly occurs due to thermal evaporation and melting. As thermal processing is required to be carried out in absence of oxygen so that the process can be controlled and oxidation avoided. Oxidation often leads to poor surface conductivity (electrical) of the workpiece hindering further machining. Hence, dielectric fluid should provide an oxygen free machining environment. Further it should have enough strong dielectric resistance so that it does not breakdown electrically too easily but at the same time ionise when electrons collide with its molecule. Moreover, during sparking it should be thermally resistant as well.

Generally kerosene and deionised water is used as dielectric fluid in EDM. Tap water cannot be used as it ionises too early and thus breakdown due to presence of salts as impurities occur. Dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material.

6. Electrode Material

Electrode material should be such that it would not undergo much tool wear when it is impinged by positive ions. Thus the localised temperature rise has to be less by tailoring or properly choosing its properties or even when temperature increases, there would be less melting. Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM. Thus the basic characteristics of electrode materials are:

-High electrical conductivity – electrons are cold emitted more easily and there is less bulk electrical heating

- High thermal conductivity – for the same heat load, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear

- Higher density – for the same heat load and same tool wear by weight there would be less volume removal or tool wear and thus less dimensional loss or inaccuracy

- High melting point – high melting point leads to less tool wear due to less tool material melting for the same heat load

-Easy manufacturability

Cost – cheap

The followings are the different electrode materials which are used commonly in the industry:

- Graphite
- Electrolytic oxygen free copper
- Tellurium copper –99% Cu + 0.5% tellurium
- Brass

2 Generalities

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. EDM typically works with materials that are electrically conductive, although methods for machining insulating ceramics with EDM have also been proposed. EDM can cut intricate contours or cavities in pre-hardened steel without the need for heat treatment to soften and re-harden them. This method can be used with any other metal or metal alloy such as titanium, hastelloy, kovar, and income. Also, applications of this process to shape polycrystalline diamond tools have been reported.

EDM is often included in the 'non-traditional' or 'non-conventional' group of machining methods together with processes such as electrochemical machining (ECM), water jet cutting (WJ, AWJ), laser cutting and opposite to the 'conventional' group (turning, milling, grinding, drilling and any other process whose material removal mechanism is essentially based on mechanical forces).

Ideally, EDM can be seen as a series of breakdown and restoration of the liquid dielectric in-between the electrodes. However, caution should be exerted in considering such a statement because it is an idealized model of the process, introduced to describe the fundamental ideas underlying the process. Yet, any practical application involves many aspects that may also need to be considered. For instance, the removal of the debris from the inter-electrode volume is likely to be always partial. Thus the electrical proprieties of the dielectric in the inter-electrodes volume can be different from their nominal values and can even vary with time. The inter-electrode distance, often also referred to as spark-gap, is the end result of the control algorithms of the specific machine used. The control of such a distance appears logically to be central to this process. Also, not all of the current between the dielectric is of the ideal type described above: the spark-gap can be short-circuited by the debris. The control system of the electrode may fail to react quickly enough to prevent the two electrodes (tool and workpiece) to get in contact, with a consequent short circuit. This is unwanted because a short circuit contributes to the removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and workpiece. Ultimately, a description of this process in a suitable way for the specific purpose at hand is what makes the EDM area such a rich field for further investigation and research.

To obtain a specific geometry, the EDM tool is guided along the desired path very close to the work; ideally it should not touch the workpiece, although in reality this may happen due to the performance of the specific motion control in use. In this way, a large number of current discharges (colloquially also called sparks) happen, each contributing to the removal of material from both tool and workpiece, where small craters are formed. The size of the craters is a function of the technological parameters set for the specific job at hand. They can be with typical dimensions ranging from the nanoscale (in micro-EDM operations) to some hundreds of micrometers in roughing conditions.

The presence of these small craters on the tool results in the gradual erosion of the electrode. This erosion of the tool-electrode is also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the workpiece. One possibility is that of continuously replacing the tool-electrode during a machining operation. This is what happens if a continuously replaced wire is used as electrode. In this case, the correspondent EDM process is also called wire EDM. The tool-electrode can also be used in such a way that only a small portion of it is actually engaged in the machining process and this portion is changed on a regular basis. This is, for instance, the case when using a rotating disk as a tool-electrode. The corresponding process is often also referred to as EDM grinding.

A further strategy consists in using a set of electrodes with different sizes and shapes during the same EDM operation. This is often referred to as multiple electrode strategy, and is most common when the tool electrode replicates in negative the wanted shape and is advanced towards the blank along a single direction, usually the vertical direction (i.e. z-axis). This resembles the sink of the tool into the dielectric liquid in which the workpiece is immersed, so, not surprisingly, it is often referred to as die-sinking EDM (also called conventional EDM and ram EDM). The corresponding machines are often called sinker EDM. Usually, the electrodes of this type have quite complex forms. If the final geometry is obtained using a usually simple-shaped electrode which is moved along several directions and is possibly also subject to rotations, often the term EDM milling is used.

In any case, the severity of the wear is strictly dependent on the technological parameters used in the operation (for instance: polarity, maximum current, open circuit voltage). For example, in micro-EDM, also known as μ-EDM, these parameters are usually set at values which generates severe wear. Therefore, wear is a major problem in that area.

The problem of wear to graphite electrodes is being addressed. In one approach, a digital generator, controllable within milliseconds, reverses polarity as electro-erosion takes place. That produces an effect similar to electroplating that continuously deposits the eroded graphite back on the electrode. In another method, a so-called "Zero Wear" circuit reduces how often the discharge starts and stops, keeping it on for as long a time as possible.

3 Numerical simulation

Finite elements simulations are done in 3 steps with the main pieces:

1- Modeling by FEMB

2- The thermal study and processing

3- Post-Processing result of analysis by ANSYS software for results discussion

Finite-Element techniques:

1-Finite elements modeling, types and properties for model different parts.

2- The definition of material properties

3- parameter definition

4- Loading

5- Boundary and initial value definition

6- Common interfaces definition

7- Control parameter definition

Small hole drilling EDM is used in a variety of applications.

On wire-cut EDM machines, small hole drilling EDM is used to make a through hole in a workpiece in through which to thread the wire for the wire-cut EDM operation. A separate EDM head specifically for small hole drilling is mounted on a wire-cut machine and allows large hardened plates to have finished parts eroded from them as needed and without pre-drilling.

Small hole EDM is used to drill rows of holes into the leading and trailing edges of turbine blades used in jet engines. Gas flow through these small holes allows the engines to use higher temperatures than otherwise possible. The high-temperature, very hard, single crystal alloys employed in these blades makes conventional machining of these holes with high aspect ratio extremely difficult, if not impossible.

Small hole EDM is also used to create microscopic orifices for fuel system components, spinnerets for synthetic fibers such as rayon, and other applications.

There are also stand-alone small hole drilling EDM machines with an *x–y* axis also known as a super drill or *hole popper* that can machine blind or through holes. EDM drills bore holes with a long brass or copper tube electrode that rotates in a chuck with a constant flow of distilled or demonized water flowing through the electrode as a flushing agent and dielectric. The electrode tubes operate like the wire in wire-cut EDM machines, having a spark gap and wear rate. Some small-hole drilling EDMs are able to drill through 100 mm of soft or through hardened steel in less than 10 seconds, averaging 50% to 80% wear rate. Holes of 0.3 mm to 6.1 mm can be achieved in this drilling operation. Brass electrodes are easier to machine but are not recommended for wire-cut operations due to eroded brass particles causing "brass on brass" wire breakage, therefore copper is recommended.

Difficulties have been encountered in the definition of the technological parameters that drive the process.

Two broad categories of generators, also known as power supplies, are in use on EDM machines commercially available: the group based on RC circuits and the group based on transistor controlled pulses.

In the first category, the main parameters to choose from at setup time are the resistance(s) of the resistor(s) and the capacitance(s) of the capacitor(s). In an ideal condition these quantities would affect the maximum current delivered in a discharge which is expected to be associated with the charge accumulated on the capacitors at a certain moment in time. Little control, however, is expected over the time duration of the discharge, which is likely to depend on the actual spark-gap conditions (size and pollution) at the moment of the discharge. The RC circuit generator can allow the user to obtain short time durations of the discharges more easily than the pulse-controlled generator, although this advantage is diminishing with the development of new electronic components.[13] Also, the open circuit voltage (i.e. the voltage between the electrodes when the dielectric is not yet broken) can be identified as steady state voltage of the RC circuit.

In generators based on transistor control, the user is usually able to deliver a train of pulses of voltage to the electrodes. Each pulse can be controlled in shape, for instance, quasi-rectangular. In particular, the time between two consecutive pulses and the duration of each pulse can be set. The amplitude of each pulse constitutes the open circuit voltage. Thus, the maximum duration of discharge is equal to the duration of a pulse of voltage in the train. Two pulses of current are then expected not to occur for a duration equal or larger than the time interval between two consecutive pulses of voltage.

The maximum current during a discharge that the generator delivers can also be controlled. Because other sorts of generators may also be used by different machine builders, the parameters that may actually be set on a particular machine will depend on the generator manufacturer. The details of the generators and control systems on their machines are not always easily available to their user. This is a barrier to describing unequivocally the technological parameters of the EDM process. Moreover, the parameters affecting the phenomena occurring between tool and electrode are also related to the controller of the motion of the electrodes.

A framework to define and measure the electrical parameters during an EDM operation directly on inter-electrode volume with an oscilloscope external to the machine has been recently proposed by Ferri *et al.*[14] These authors conducted their research in the field of μ-EDM, but the same approach can be used in any EDM operation. This would enable the user to estimate directly the electrical parameter that affect their operations without relying upon machine manufacturer's claims. Finally, it is worth mentioning that when machining different materials in the same setup conditions, the actual electrical parameters of the process are significantly different.

The first serious attempt of providing a physical explanation of the material removal during electric discharge machining is perhaps that of Van Dijck. Van Dijck presented a thermal model together with a computational simulation to explain the phenomena between the electrodes during electric discharge machining. However, as Van Dijck himself admitted in his study, the number of assumptions made to overcome the lack of experimental data at that time was quite significant.

Further models of what occurs during electric discharge machining in terms of heat transfer were developed in the late eighties and early nineties, including an investigation at Texas A&M University with the support of AGIE, now Agiecharmilles. It resulted in three scholarly papers: the first presenting a thermal model of material removal on the cathode,[16] the second presenting a thermal model for the erosion occurring on the anode[17] and the third introducing a model describing the plasma channel formed during the passage of the discharge current through the dielectric liquid.[18] Validation of these models is supported by experimental data provided by AGIE.

These models give the most authoritative support for the claim that EDM is a thermal process, removing material from the two electrodes because of melting and/or vaporization, along with pressure dynamics established in the spark-gap by the collapsing of the plasma channel. However, for small discharge energies the models are inadequate to explain the experimental data. All these models hinge on a number of assumptions from such disparate research areas as submarine explosions, discharges in gases, and failure of transformers, so it is not surprising that alternative models have been proposed more recently in the literature trying to explain the EDM process.

Among these, the model from Singh and Ghosh reconnects the removal of material from the electrode to the presence of an electrical force on the surface of the electrode that could mechanically remove material and create the craters. This would be possible because the material on the surface has altered mechanical properties due to an increased temperature caused by the passage of electric current. The authors' simulations showed how they might explain EDM better than a thermal model (melting and/or evaporation), especially for small discharge energies, which are typically used in μ-EDM and in finishing operations.

Given the many available models, it appears that the material removal mechanism in EDM is not yet well understood and that further investigation is necessary to clarify it,[14] especially considering the lack of experimental scientific evidence to build and validate the current EDM models. This explains an increased current research effort in related experimental techniques.

Sinker EDM, also called cavity type EDM or volume EDM, consists of an electrode and workpiece submerged in an insulating liquid such as, more typically, oil or, less frequently, other dielectric fluids. The electrode and workpiece are connected to a suitable power supply. The power supply generates an electrical potential between the two parts. As the electrode approaches the workpiece, dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.

These sparks usually strike one at a time because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the workpiece. As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters. These controlling cycles are sometimes known as "on time" and "off time", which are more formally defined in the literature.

The on time setting determines the length or duration of the spark. Hence, a longer on time produces a deeper cavity for that spark and all subsequent sparks for that cycle, creating a rougher finish on the workpiece. The reverse is true for a shorter on time. Off time is the period of time that one spark is replaced by another. A longer off time, for example, allows the flushing of dielectric fluid through a nozzle to clean out the eroded debris, thereby avoiding a short circuit. These settings can be maintained in micro seconds. The typical part geometry is a complex 3D shape, often with small or odd shaped angles. Vertical, orbital, vectorial, directional, helical, conical, rotational, spin and indexing machining cycles are also used.

4 Design of Experiments

Design of Experiments (DOE) is a method to obtain useful information about a process by conducting only minimum number of experiments. Each controllable variable (I, ton, toff, C) can be set on EDM machine at five consecutive levels from 1 to 5, and hence the design consisting of 31 experiments based on Central Composite Design (CCD) was generated at these levels using Minitab statistical software.

Other factors given in Table 2 were kept constant. Table 3 shows the design matrix with experimental and predicted results. MRR and EWR values can be predicted within error range of ± 16% (except experiment no. 29) and ± 19%, respectively. Experimental and predicted results for MRR and EWR are compared in Fig.2.

The adequacy of generated model is measured based on Analysis of Variance. The determination coefficient (R2) defines a measure of the degree of fit between actual and predicted data. Higher value of R2 exhibits better fit. The model has produced R2 values of 85.5% and 72.7% for MRR and EWR, respectively.

5 Modeling of Material Removal and Product Quality

Material removal in EDM mainly occurs due to intense localised heating almost by point heat source for a rather small time frame. Such heating leads to melting and crater formation as shown in Fig. 3.

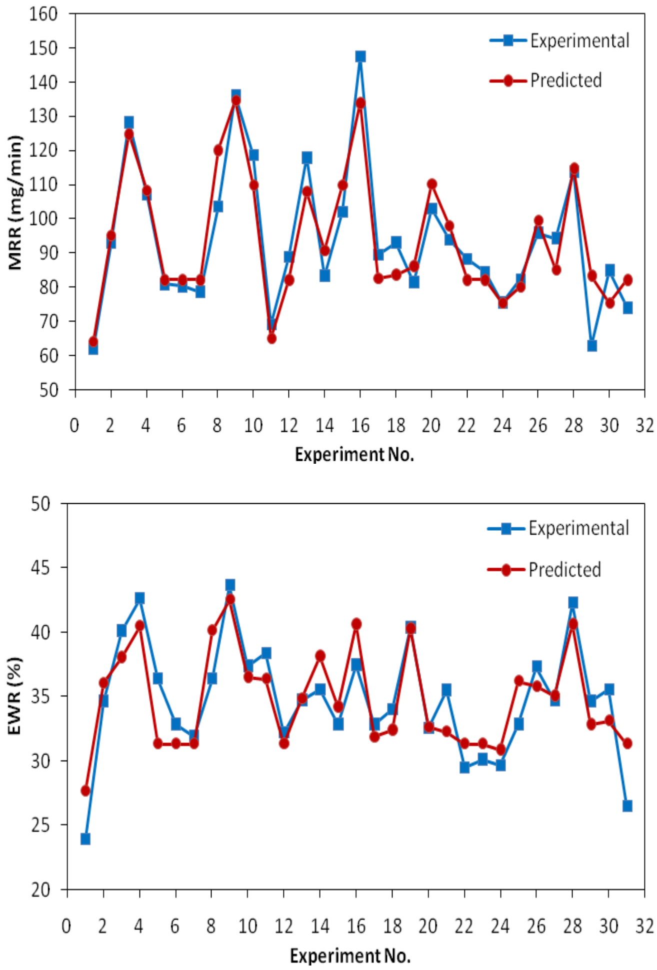

Fig.2. Comparison of experimental and predicted values for MRR and EWR.

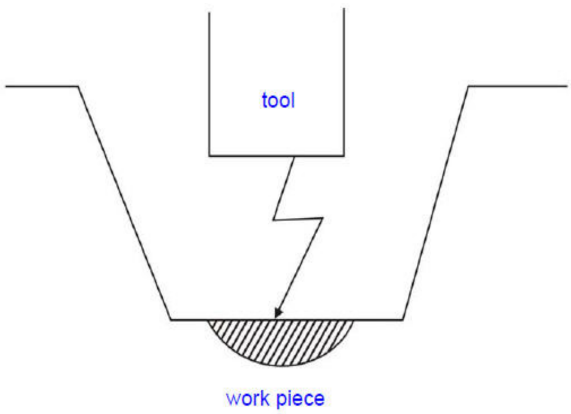

Fig.3. *Schematic representation of crater formation in EDM process.*

The model presented above is a very simplified one and linear relationship is not observed in practice. But even then such simplified model captures the complexity of EDM in a very efficient manner. MRR in practice does increase with increase in working voltage, current, pulse on time and decreases with increase in pulse off time.
Product quality is a very important characteristic of a manufacturing process along with MRR. The followings are the product quality issues in EDM

- Surface finish
- Overcut
- Taper cut

No two sparks take place side by side. They occur completely randomly so that over time one gets uniform average material removal over the whole tool cross section. But for the sake of simplicity, it is assumed that sparks occur side by side as shown in Fig. 4.

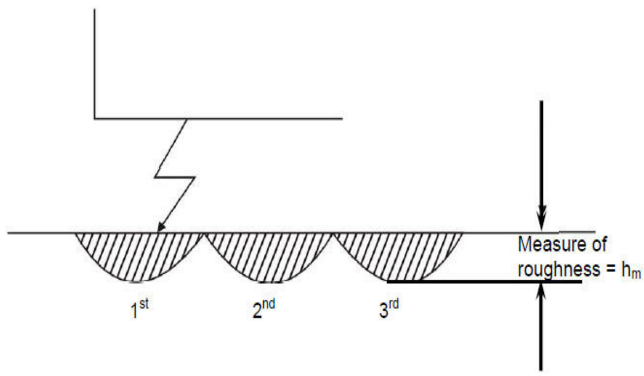

Fig. 4 Schematic representation of the sparks in

EDM process.

Thus it may be noted that surface roughness in EDM would increase with increase in spark energy and surface finish can be improved by decreasing working voltage, working current and pulse on time.

In EDM, the spark occurs between the two nearest point on the tool and workpiece. Thus machining may occur on the side surface as well leading to overcut and tapercut as depicted in Fig. 5. Taper cut can be prevented by suitable insulation of the tool. Overcut cannot be prevented as it is inherent to the EDM process. But the tool design can be done in such a way so that same gets compensated.

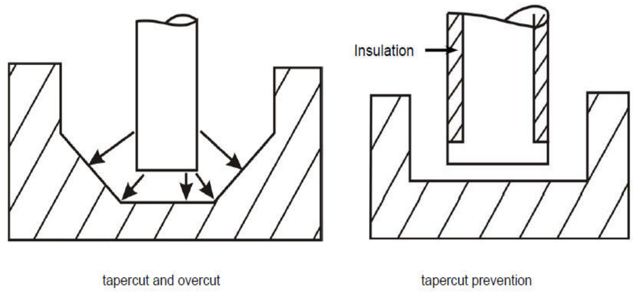

Fig. 5 Schematic depiction of taper cut and over cut and control of taper cut

6 Analysis of RC type Relaxation EDM Generator

In RC type generator, the capacitor is charged from a DC source. As long as the voltage in the capacitor is not reaching the breakdown voltage of the dielectric medium under the prevailing machining condition, capacitor would continue to charge. Once the breakdown voltage is reached the capacitor would start discharging
VC t RC Vo VC C iC id id Ic RC C VC Vo - Rotary impulse generator with rectifier Rectifier R Generator E t R E t Electronic pulse generator R C E t and a spark would be established between the tool and workpiece leading to machining. Such discharging would continue as long as the spark can be sustained. Once the voltage becomes too low to sustain the spark, the charging of the capacitor would continue. Fig. 8 shows the working of RC type EDM relaxation.

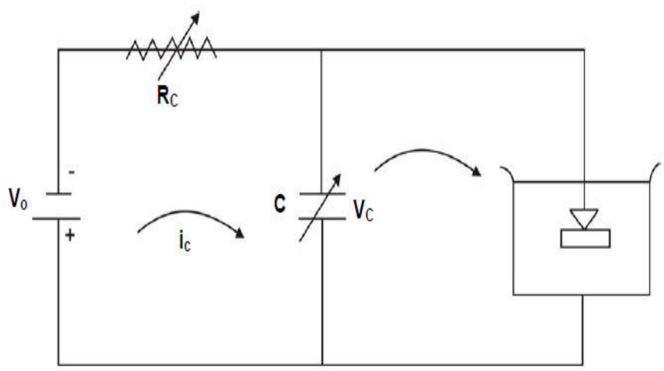

Fig. 8 Schematic of the working principle of RC type EDM relaxation circuit.

7 Conclusions

In this paper, the finite element method is used to simulate the vibration assisted EDM process. The simulation result shows that good quality surfaces are achieved when vibration of median values of amplitude is applied to the worktable. This is attributed to the effect of surface tension and the additional shear forces developed in the melted metals by vibrating the worktable, which can smooth the workpiece surface. The optimal vibration conditions are found at a medium vibration amplitude and high vibration frequency.

Therefore, vibrating the worktable during the EDM process would be a potential solution to eliminate the micro-craters, which are inevitable in the conventional EDM process. A vibration system developed to generate high frequency for the vibration assisted EDM process is described in a companion paper.

The following conclusions can be derived based on the obtained results:

1. Experimental values of MRR and EWR can satisfactorily be predicted using the developed model by performing minimum number of experiments.

2. Reproducibility analysis and R2 values prove that consistent and reliable results can be achieved within acceptable error ranges.

3. Mathematical modelling of EDM hole drilling process using RSM technique can enable the prediction of MRR and EWR values without performing unnecessary experiments. This leads to considerable savings on time, material and effort which results in efficient, sustainable and economical production.

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