Finite-Element Simulation of Electrical Discharge Machining (EDM) Process

Ali. Moarrefzadeh

***Abstract*– Electrical discharge machining (EDM) is one of the most important non-traditional machining processes. The important process parameters in this technique are discharge pulse on time, discharge pulse off time and gap current. 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.**

***Keywords*–** EDM Parameters, Regression Modeling, Optimization, Machining and ANSYS

I. INTRODUCTION

Electric discharge machining (EDM), sometimes colloquially also referred to as spark machining, spark eroding, burning, die sinking or wire erosion, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks). Material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the 'tool' or 'electrode', while the other is called the workpiece-electrode, or 'workpiece'.

When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric (at least in some point(s)), which breaks, allowing current to flow between the two electrodes. This phenomenon is the same as the breakdown of a capacitor (condenser) (see also breakdown voltage). As a result, material is removed from both the electrodes. Once the current flow stops (or it is stopped – depending on the type of generator), new liquid dielectric is usually conveyed into the inter-electrode volume enabling the solid particles (debris) to be carried away and the insulating proprieties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly referred to as flushing. Also, after a current flow, a difference of potential between the two electrodes is restored to what it was before the breakdown, so that a new liquid dielectric breakdown can occur. EDM process shows in Fig.1.

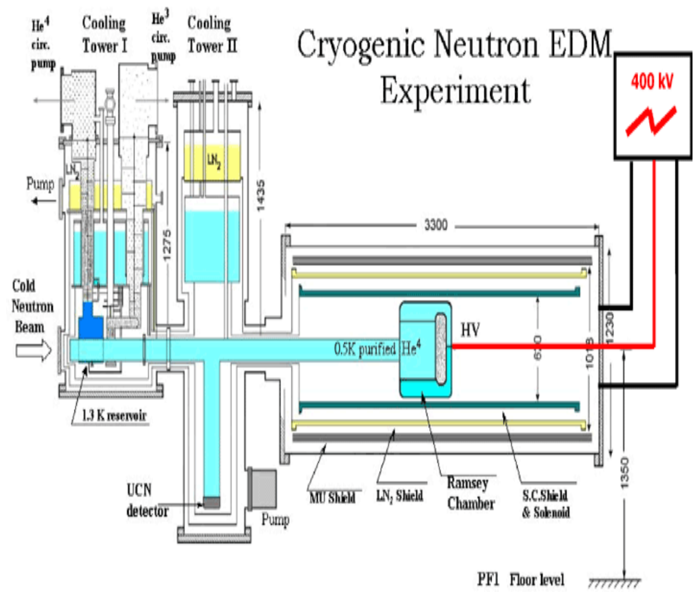


Fig.1. Electro Discharge Machining (EDM) process

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.

In 1770, English physicist Joseph Priestley studied the erosive effect of electrical discharges. Furthering Priestley's research, the EDM process was invented by two Russian scientists, Dr. B. R. Lazarenko and Dr. N. I. Lazarenko, in 1943. In their efforts to exploit the destructive effects of an electrical discharge, they developed a controlled process for machining of metals. Their initial process used a spark machining process, named after the succession of sparks (electrical discharges) that took place between two electrical conductors immersed in a dielectric fluid. The discharge generator effect used by this machine, known as the Lazarenko circuit, was used for many years in the construction of generators for electrical discharge.

Additional researchers entered the field and contributed many fundamental characteristics of the machining method we know today. In 1952, the manufacturer Charmless created the first machine using the spark machining process and was presented for the first time at the European Machine Tool Exhibition in 1955

In 1969 Agie launched the world's first numerically controlled wire-cut EDM machine. Seibu developed the first CNC wire EDM machine 1972 and the first system manufactured in Japan.

II. 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 generate 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.

III. 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 deionized 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.

IV. DEFINITION OF THE TECHNOLOGICAL PARAMETERS

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 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 affects 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.

V. 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.

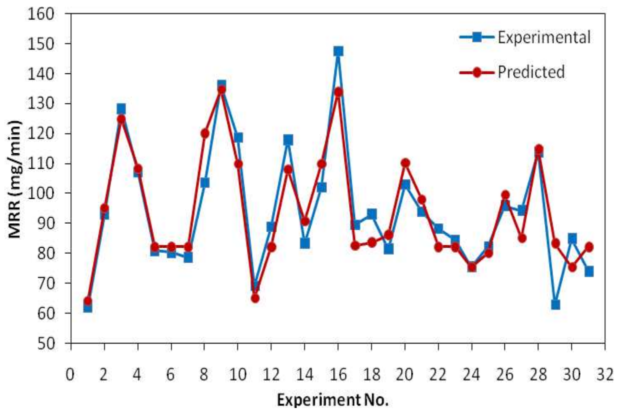
The adequacy of generated model is measured based on Analysis of Variance. The determination coefficient (R2) defines a measure of the degree of fit between actual and predicted data. Higher value of R2 exhibits better fit. The model has produced R2 values of 85.5% and 72.7% for MRR and EWR, respectively.

VI. CONCLUSIONS

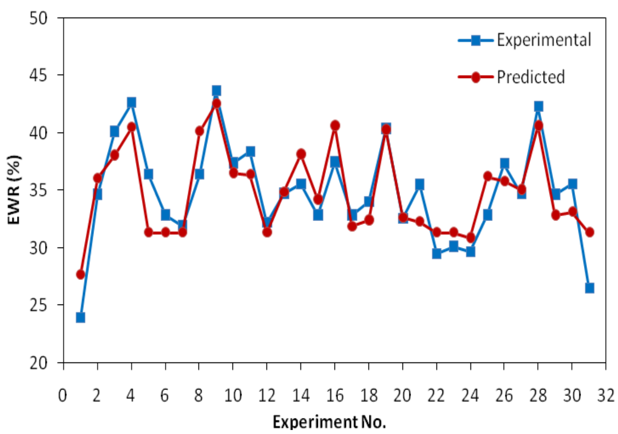
The following conclusions can be derived based on the obtained results:

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 modeling 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.



(a)



(b)

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

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Ali. Moarrefzadeh

Young Researchers Club, Islamic Azad University, Mahshahr Branch, Mahshahr, Iran

F. A. Faculty member of Department of Mechanical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr , Iran
E-mail: a_moarrefzadeh@yahoo.com
a.moarefzadeh@mahshahriau.ac.ir
Tel: +989123450936